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Dynamic Viscoelasticity and Dynamic Sagging Correlation of Four Oil Based Drilling Fluids (OBM)

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Abstract

This paper presents the dynamic viscoelasticity, the rheology and the dynamic sagging parameters correlation of four OBMs. The experimental results show that as the oil water ratio (OWR) increases, the sagging index increases and the storage to loss moduli ratio decreases, which reflects the internal gel structure of the drilling fluids dissipation upon dynamic loading.

Except for high viscosity and hydraulics, the overall analysis of drilling fluids shows that the 60:40 OWR is the better in terms of sagging, filtrate loss and hole cleaning performance.

1 INTRODUCTION

Drilling fluids are an integral part of drilling operation. Among many other functions, drilling fluids maintain well pressure and transport cutting to surface. However, poorly designed drilling fluid rheology and operational conditions may lead to solid accumulations in the wellbore. Solid settling may cause several drilling related problems such as reduced drilling fluid density, differential sticking, and improper cement displacement during cement jobs and will cause fluctuation in torque and drag loads [1, 2].

Properly designed drilling fluids will handle solid settling problem. During static condition and low fluid flow velocity, the formation of gel structure in drilling fluid is an important property to hinder particles settling. The formation of gel-structure needs to be quick and having a sufficient strength.

The primary objective of this paper is to characterize the four OBMs having the same density, but different oil water ratio in terms of sagging, rheology, filtrate and viscoelasticity behaviors. Finally, based on the measured data, the paper makes an attempt to generate correlation between dynamic viscoelasticity and dynamic sagging factor of measured drilling fluids. Both of these parameters describe the internal gel structure of drilling fluids, which is a key factor for solid settling control.

2 THEORY

This section presents the theory of dynamic sagging and viscoelasticity, which are used to quantify the measured test data.

2.1 Dynamic sag

It is important to identify the sagging control parameters in order to mitigate sagging problem in oil well. Sag index is one of the method used to control sagging. The dynamic sag index measurement and calculation in this paper was performed according to MI-SWACO procedure. Drilling fluid was filled in VG-viscometer heating cup and the temperature was maintained at 50^{o}C. During testing, the bob was allowed rotating to shear at 100rpm for 40 min. 20ml of the fluid sagged was taken from bottom of a VG-viscometer heating cup and was measured. The sag factor was calculated from the initial mud weight and the sagged mud weight as:

$$Sag\ factor = \frac{Total\ mud\ weight\ after\ 40\text{min}(gm)}{2 * Initial\ mud\ weight, gm} \qquad 1$$

Sag factor with 0.5 is an indication of a homogeneous fluid system and zero change in density. Sag factor higher than 0.5 is an indication of a higher change in density, which is greater than zero. The change in density is calculated as:

$$\Delta(\rho_{mud}) = \frac{m_{final} - m_{initial}}{Volume}[sg] \qquad 2$$

Where,

- m_{final} is the mass taken after testing
- $m_{initial}$ is the mass taken before testing
- Volume is the sample volume.

2.2 Lower Shear Yield Strength (LSYS)

Controlling dynamic sag is more complicated than controlling static sag and cannot be predict by standard viscosity measurements. Some authors state that dynamic sag may be reduced by sufficient gel-strength/or/ lower shear yield stress (LSYS) value [3,4,5,6].

Scott et al, [7] have presented field case study and very effective method to reduce sagging tendencies. The authors have suggested that the LSYP value of 3.5– 7.5 Pa (7-15 lbf/100ft^2) is a suitable range to minimize barite sag. The LSYS is determined from Fann 6 RPM (θ_6) and 3-RPM (θ_3) viscometer data as [7]:

$$\text{LSYS (lbf/100ft}^2\text{)} = 2\theta_3 - \theta_6 \qquad 3$$

2.3 Viscoelasticity

Viscoelasticity is a material property. Viscoelasticity of drilling fluids are related to gel formation and has been documented in references [8, 9]. The elastic part of a viscoelastic material stores energy when being deformed and do not dissipate energy. The viscous portion dissipates energy as heat during deformation. Viscoelastic materials display time-dependent behavior upon dynamic loading and they are also temperature dependent. **Figure 1** shows an illustration of fluid sample between two-plate subjected to oscillatory loading and the resulting deformation. **Figure 2** shows the typical stress and strain responses of the oscillatory measurement of viscoelastic material.

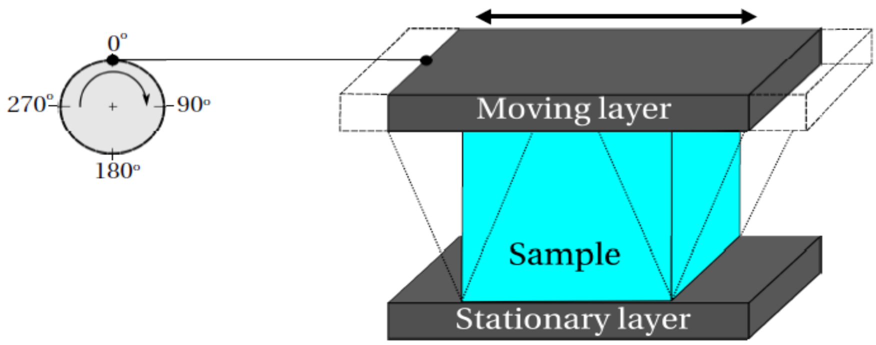

Figure 1: Illustration of the two-plate-model oscillatory test [10].

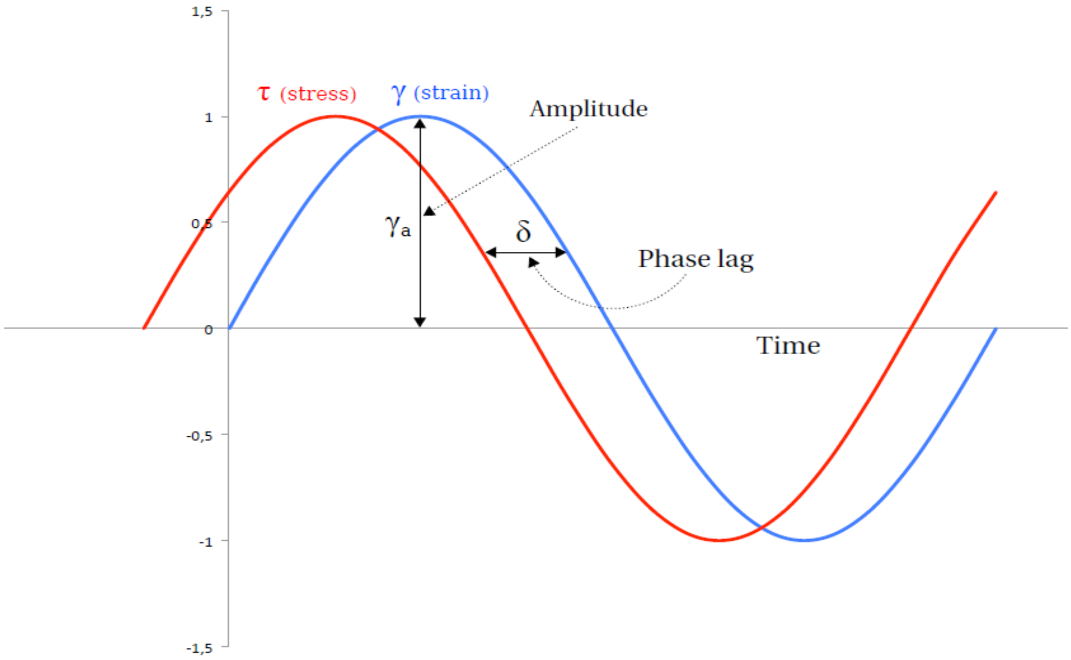

Figure 2: Stress strain response for an oscillatory measurement of a viscoelastic material [10].

The measured shear stress with controlled strain is:

$$\tau(t) = \tau_0[\sin(\omega t)\cos\delta + \cos(\omega t)\sin\delta] \quad 4$$

$$\tau(t) = \gamma_0[G'\sin(\omega t) + G''\cos(\omega t)] \quad 5$$

Where,
ω is angular frequency in rad/s.

$$G' = \frac{\tau_0}{\gamma_0}\cos\delta \quad and \quad G'' = \frac{\tau_0}{\gamma_0}\sin\delta \quad 6$$

δ is the phase angle between the deformation and the response G' is storage modulus and G'' is loss modulus. The phase shit angle is a measure of the energy dissipation of the material. For a purely viscous fluid, the phase angle will be equal to 90°, for a purely elastic material the phase angle will be equal to 0°. The phase angle for a viscoelastic material will be between 0° and 90°.

The phase angle is given as:

$$\delta = tan^{-1}(G''/G') \quad 7$$

3 EXPERIMENTAL STUDIES

3.1 Drilling fluid description

Four types of OBM drilling fluid were obtained from MI-SWACO in order characterize their properties such as rheology, sagging and gel-structure. The drilling fluids formulated with the same density, which is 1750 kg/m^3 and different OWR namely 60:40, 70:30, 80:20 and 90:10. The sum of oil and water in percentage are 57, 61, 63 and 65, respectively. The sum percentage of the rest additives (alkalinity, pH controller, fluid loss and viscosifier) are 8.7%, 3.8%, 2.5% and 1.2%, respectively. The Barite to Water ratio of 90:10 OBM is about four times the 60:40 OBM.

3.2 Measurement results

3.2.1 Rheology of the drilling fluids

Rheology deals with the study of the deformation and the flow behavior of fluids. **Figure 3** shows the FANN® Model 35 viscometer data of the four OBM measured at 20^{o}C and 50^{o}C under atmospheric pressure. As seen, the difference among the flow curves is more pronounced at higher rotational speed, which is an indication of the existence of structure in the fluid related to resistance of fluid flow. It can also be observed that as the OWR decreases, the viscometer responses of the drilling fluids at the lower rotational speed increases. This is also an indication of the increases of gel structure in the drilling fluids. Analyzing the power law model, all drilling fluids exhibit a shear-thinning behavior.

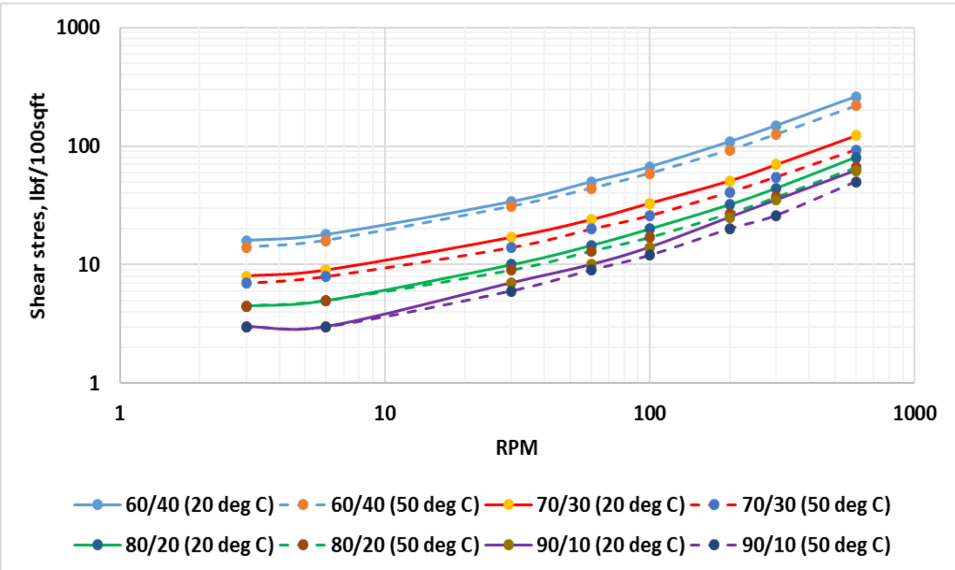

Figure 3: Measured viscometer data at 20^{o}C and 50^{o}C.

Table 1 shows the computed rheology parameters of the Fann 35 data presented in **Figure 3**. The results show that as the OWR increases, the LSYS, Yield stress (YS) and Bingham plastic viscosity (PV) are decreasing.

Fann 35 Measurement	**Parameters @50 deg C**	**Oil/Water (OWR)**			
		60/40	**70/30**	**80/20**	**90/10**
	PV (cP)	100	40	31	25
	YS (lbf/100sqft)	34	19	8	3
	LSYS (lbf/100sqft)	13	5	4	2.5

Table 1: Computed drilling fluids rheology parameters at 50deg C.

Table 2 shows the measured static filtrate loss of the three drilling fluids at 500psi and 98^{o}C. The increase in OWR shows an increase in filtrate loss. The 60:40 OBM with higher water content shows a better filtrate loss control.

OWR	**60:40**	**70:30**	**80:20**
Filter loss, ml (30min)	2.2	2.8	4.0

Table 2: Static filtrate loss at 500psi and 98^{o}C.

3.2.2 Dynamic Sag Measurement

As mentioned in the theory part, dynamic sagging measurement was performed according to MI-SWACO procedure. **Table 3** shows the summary of the dynamic sag measured data and the computed parameters. The experimental results show that the dynamic sagging potential increases as the OWR increases. One can observe a 0.14sg change in mud weight between the 60:40 and the 90:10OBMs. Comparing these two fluid systems, the sag index increased by 9.88% as the OWR increases from 60:40 to 90:10 OBM. In addition, one can observe that the percent change density of 60:40 and the 90:10OBMs are 5.07% and 13.08%, respectively. This indicates that the internal structure within drilling fluid decreases as the OWR increases.

Dynamic sag measurement	**Parameters @50 deg C**	**OBM drilling fluids**			
		60/40	**70/30**	**80/20**	**90/10**
	Change MW [Δ MW, s.g]	0.0888	0.1333	0.1887	0.2289
	Sag index	0.5262	0.5394	0.5624	0.5782
	% Change MW	5.07	7.62	10.78	13.08

Table 3: Summary of dynamic sag measured and calculated data.

3.2.3 Dynamic viscoelasticity measurement

The amplitude sweep test was performed to define the linear elastic viscoelasticity (LVE) region. This test mainly is designed to study the structural characteristics of the drilling fluids. While ramping the amplitude of the oscillation, the angular frequency was set to be 10 rad/s by varying the strain from $5x10^{-4}$ % to 50 %. **Figure 4** shows the test results. As shown, the LVE region is less than 1% for all samples. Except the 90:10 OWR sample, the other fluid systems exhibit a higher storage modulus than the loss modulus. This is an indication that the 90:10 fluid system exhibits more viscous dominate behavior. The other fluid systems show elastic dominance over the entire linear viscoelastic (LVE) region. **Figure 5** shows the plot of amplitude sweep test presented in **Figure 4**, which displays the phase angle vs the shear stress. The figure clearly displays a better visualization of flow point (τ_{fp}) in terms of shear stress. Vertical arrows are indicating τ_{fp}, where the phase angle is 45deg (i.e. G'=G" or tanδ =1). As can be seen, the 90:10OBM does not show flow point and it is viscous dominated fluid.

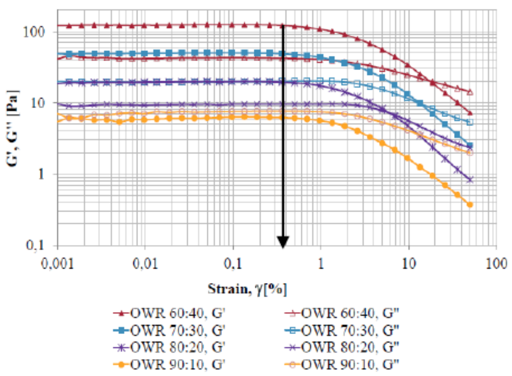

Figure 4: Amplitude sweep test performed on all fluid samples at 20^0C and ω =10rad/s. Note that ω= 20rad/s for the 90:10 sample.

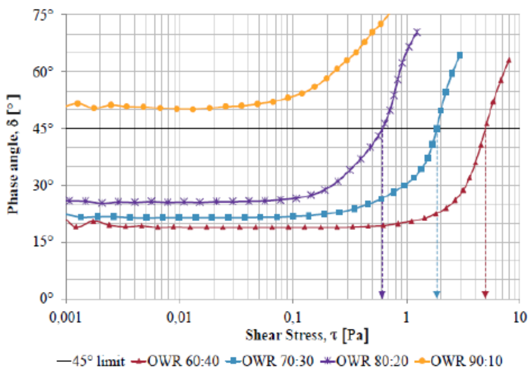

Figure 5: Amplitude sweep test presented with phase angle vs shear stress

For better presentation, the G'/G" moduli ratio determined at the plateau of the LVE region (**Figure 4**) are plotted against the OWR content (see **Figure 6**). As the OWR decreases, the G'/G" ratio is decreasing. Sasen et al [5] have studied ratio of the viscoelastic G'/G" parameters, which gives simple measurement of gel formation and hence give a good indication of static sag potential. Similarly, the flow point obtained from **Figure 5** are plotted with OWR (see **Figure 7**). As shown here also, except the 90:10, all others are in elastic dominated and the phase angle increases as the OWR increases.

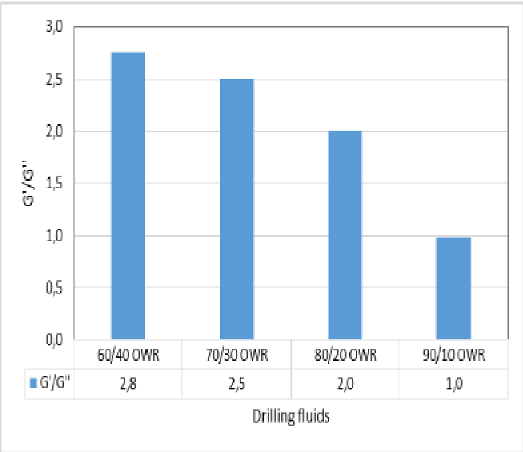

Figure 6: G'/G" ratio vs OWR at room temperature

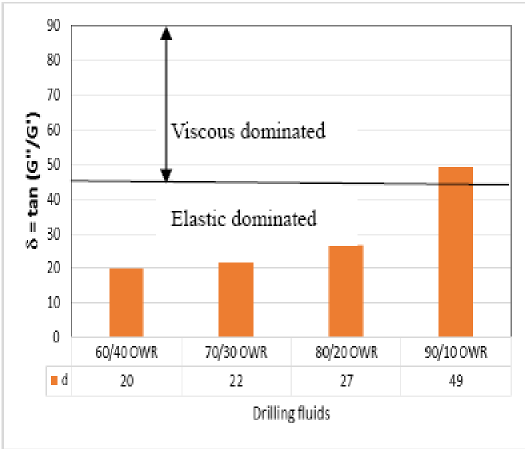

Figure 7: Phase angle (d) vs OWR at room temperature

4. CORRELATION AMONG PARAMETERS

According to Bern [3], several parameters control sagging phenomena. The combined effect of these probably make sagging predictions more complex and could be even difficult to quantify. However, the measured change in density will be correlated with other drilling fluid properties.

Figure 8 shows a correlation between the measured viscometer response at 100RPM reading (section §3.2.1) and the change in mud weight (or density) of dynamic sag (section §3.2.3). The figure shows that as the OWR increases, the change in density and sagging factor is increasing. The physical meaning of this can be interpreted, as the higher resistance for particle settling is associated with the higher gel strength and viscosities of the drilling fluid.

Figure 9 also shows the correlation between the dynamic sag with the computed rheology parameters such also LSYS, PV and YS, which shows good correlation. The figure indicates that the higher rheology parameters create better gel structure to control sagging. As the OWR increases, the rheology parameters are decreasing. This fluid system hence shows more prone to sagging due to the lesser gel structure.

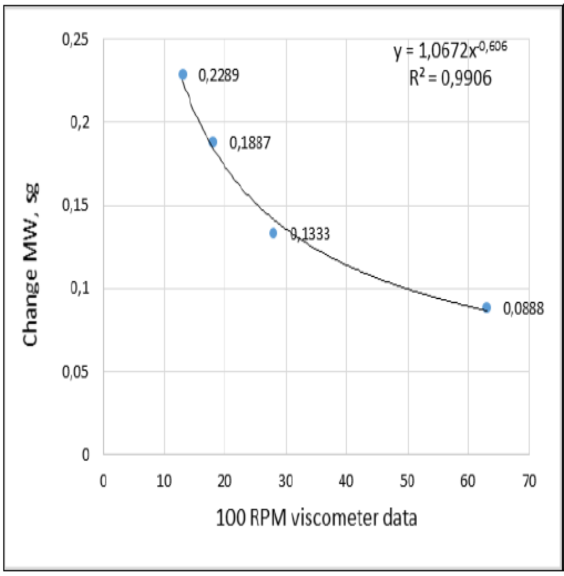

Figure 8: Comparisons of change in density and 100RPM viscometer data

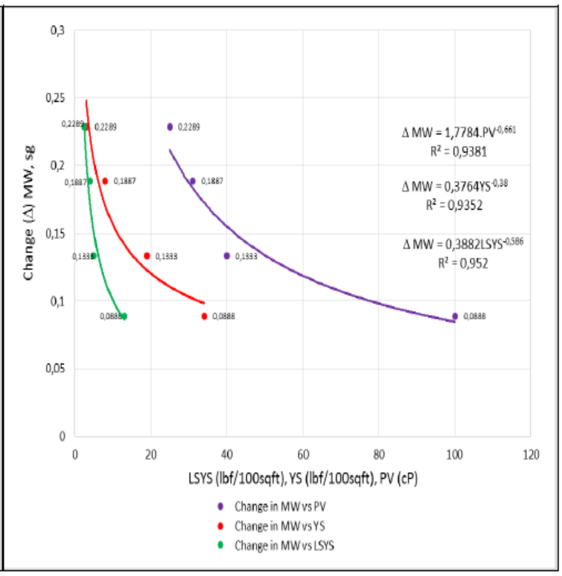

Figure 9: Comparisons of change in density vs PV, YS and LSYS parameter at 50°C

Among others, Saasen et al [5] have presented a correlation between an observed static sag data and dynamic sag with viscoelastic parameters. Their analysis shows that when the ratio of G'/G" higher than 1, the probability of sagging onset is negligible. However, the authors have also commented that this is not generally correct, as it is dependent on measurement techniques. Therefore, in this paper, we have analyzed dynamic sagging data with the dynamic viscoelasticity parameters, G'/G". According to Maxey [11], the sagging potential is severe when the sag factor is greater than 0.53. The measured data obtained from sections § 3.2.2 and § 3.2.3 are combined and displayed in **Figure 9.** In the figure, the vertical red line delineates the elastic and viscous dominated regions where (G'=G"). The horizontal line delineates the sag potential and the least sag potential regions. As shown, except 90:10 OBM, all others are displayed in elastic dominated region. Another observation is that the 60:40 OBM is in the least sag potential region, but all the rest are in sag potential region. As the OWR increases, the sagging factor is also increasing. One can also read from the figure that as the ratio of G'/G" increases, the sagging potential is decreasing. The observation is based on these particular drilling fluid systems. It may or may not valid for other fluid systems.

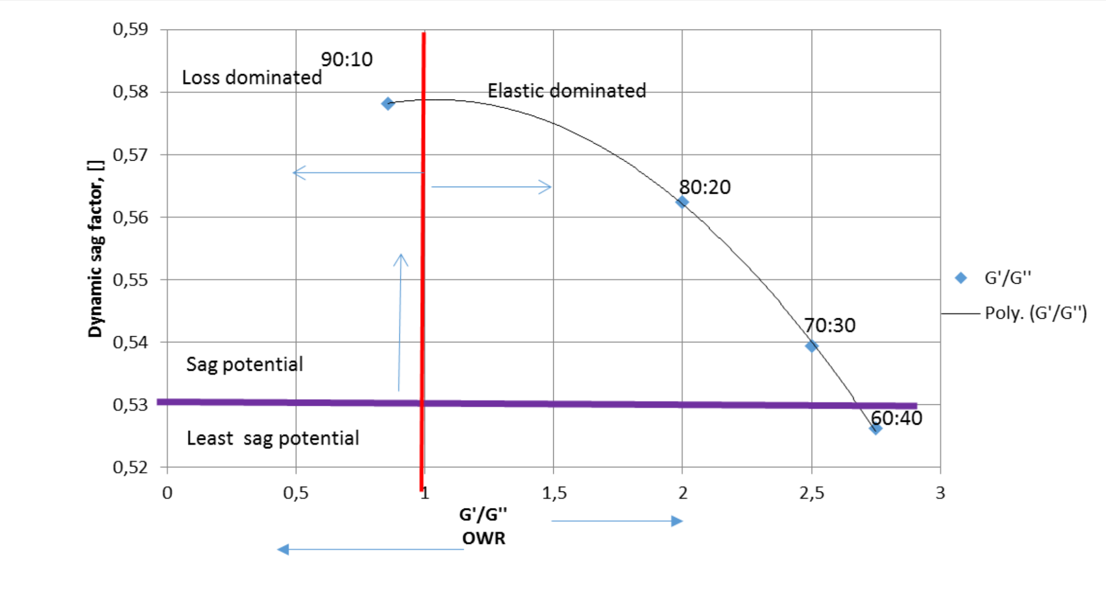

Figure 9: Comparisons of change in density and G'/G" ratio.

5. SUMMARY AND CONCLUSIONS

This paper presents the measurement and the parameter correlation of API rheology, dynamic viscoelasticity and dynamic barite sagging index of four OBMs. The drilling fluids have the same density, but different properties.

The results show that as the oil water ratio (OWR) increases, the drilling fluid rheology parameters such as LSYS and YS and PV parameters are decreasing. In addition, the viscoelastic loss and storage moduli also decrease. As a results, drilling fluids reduce their capacity for holding solid particles in suspension and hence potential for sagging increases.

For instance, as the OWR increase from 60:40 to 90:10, dynamic sagging experiment shows that the sagging factor increases by 9.88%.

The sagging factor of the drilling fluids show decreasing as the G'/G" ratio increases, which is associated with a decrease in OWR. Except with regard to high viscosity, the overall analysis of drilling fluids shows that the 60:40 OWR is the better in terms of sagging, filtrate loss and hole cleaning performance. This is in agreement with the conclusions of Aston et al., [12].

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