Rheological Characteristics of Oil-Based and Water-Based Drilling Fluids

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ABSTRACT

Drilling fluid plays a crucial role in well construction with regards to maintaining the well integrity and hole cleaning. API/ISO standards intent to help engineers to characterize the viscosity of fluids at different shear rates, temperatures, and pressures to model the viscosity profile of drilling fluids. In this article, we present set of characterization of rheological state and rheological behaviour of oil-based and water-based drilling fluids after hot rolling.
The rheological measurements are conducted in shear rate ranging between 0 to 1020 (1/s), and constant shear stress. Time dependent behaviour of the fluids (storage stability), flow curve, strain sweep, yield stress, and oscillatory analyses are among the parameters measured. Such study may help engineers and researchers to better understand annular pressure losses, hole-cleaning, barite sag, cutting transport, mechanisms of fluid loss and formation damage, and managed pressure drilling while comparing rheological properties of the fluids.

INTRODUCTION

Measurement of rheological properties of drilling fluids has been a focus area within drilling fluid engineering for the last decades. Measurement methods have varied between standard measurements[1,2,3] and complex methods based on large amplitude oscillatory shear as described by Ewoldt et al.[4].

The shea rate dependent viscosity was analysed for frictional pressure loss calculations. Simple models like the Bingham model based on data measured at 511 and 1022 1/s was used in controlling the discharge pump pressure[5]. The shear rates for the flow inside the drill string were large enough for this model to be applicable. At the same time, by far the major pressure loss occurred inside the drill string and through the bottom hole assembly. Any inaccuracies in the frictional pressure loss in the annulus would not influence the pump pressure significantly even though the viscosity was mis-predicted by in order of magnitude 100%.

To be able to predict the pressure in the annulus, more accurate models were needed. The dominant models for application in annuli have been the Power-Law or the Herschel-Bulkley model. Within the time scales of the flow, overcoming a yield stress is required for creating a flow of drilling fluids.

For other phenomena like barite sag, consolidation of cuttings bed, lost circulation prevention and other detailed analyses, it is necessary with more sophisticated analyses than those using shear rate dependent viscosity models. Dynamic viscosity analyses are common[6].

Werner et al.[7] considered viscoelastic properties of complex water-based and oil-based muds and their influence on cutting transport. They used both rheometer and rotational viscometer to measure shear stress of the fluids. Amplitude sweep, temperature sweep test, 3-interval thixotropy, and low-shear rate flow tests were conducted in their study. The oil-based mud showed higher storage modulus (G′) and loss (G″) modulus than the water-based mud. However, the linear viscoelastic ranges (LVR) are very much smaller than those of water based fluids. In the end, this implies that even though the G’ values for the oil-based fluids are large compared to those of the water based fluids, the fluids does not show any viscoelasticity. What is measured is the elasticity in the very brittle material prior to reaching the yield stress.

Oltedal et al.[8] characterized rheological properties of oil-based drilling fluids for better understanding the hole cleaning. The Linear viscoelastic range (LVR), viscosity, yield stress, thixotropy and temperature dependency were studied. They reported an increase in elastic component of the fluids when the system is sheared at high rates; this is a time dependent behaviour or known as thixotropic properties. They also concluded that the water-based drilling fluid is more sensitive to temperature variation than the oil-based drilling fluid. Bui et al.[9] made a thorough study on viscoelastic behaviour of oil based drilling fluid. They were also able to shift the dynamic viscosity curves by an extended Cox-Merz rule method, to fit the low shear rate viscosity curves. Ansari et al.[10] investigated relationship between microstructure of oil-based drilling fluid and its performance. They characterized properties of the fluid by conducting oscillatory and constant shear rate measurements. Storage and loss moduli are found to be dominant at low shear rates (≤ 1 Pa). In other words, at very low shear rates, the elasticity is the controlling parameter with viscosity. In addition, thixotropy was reported when ramp-up and ramp-down shear rates were applied. This is related to the structure building properties of the fluid resulted from the used ingredients. Moraes et al.[11] applied oscillatory and steady state flow experiments to study rheology of graphene oxide suspended in non-Newtonian fluid with yield stress. They experienced that the fluid system has stress-independent storage and loss moduli at low stresses. This results in linear viscoelastic region at low stresses. It means that the low stress is not capable to break the microgels. Increasing the stress takes the fluid into a transition zone, decreasing elasticity. When storage and loss moduli crossed each other, while the loss modulus increases, the molecules start to move. Rodrigues et al.[12] investigated influence of sodium carboxymethylcellulose, polyacrylamide, and laponite on viscosity of drilling fluids. They performed steady shear, small amplitude oscillatory shear, and extensional rheology experiments. As result of this study, they could suggest lost circulation mitigators. These researchers used rheology as characterization technique to study behaviour or performance of fluids for the intended applications.

Oil based and inhibitive water based drilling fluids are constructed differently. Water based drilling fluids build their viscosity profiles by addition of polymers and particulate materials that may interact as a result of the surface properties. In absence of any particles, most water based systems will not show any significant yield stresses, but only very high low shear rate viscosity. Oil based drilling fluids build their viscosity profiles by addition of water, organophilic clays and other particulate materials. All these additives are blended in a non-conducting continuous phase base fluid. The emulsified water droplets are for most practical situations larger than the average distance to a neighbour droplet. Hence, to keep the internal energy to a minimum, the oil based drilling fluid components try to maintain a crystalline structure in the time average. Thus, the viscosity is formed by the fluid components’ ability to keep that minimum energy position. Therefore, oil based drilling fluid in a flowing condition can for most conditions be considered as a non-elastic fluid. Any high elasticity measured in the LVR represents the strength of the fluid's yield stress prior to flow.

In this study, we aim to characterize water-based and oil-based drilling fluids by studying their rheology. The rheological measurements are conducted in shear rate ranging between 0 to 1020 (1/s), and constant shear stress. Time dependent behaviour of the fluids, stress relaxation behaviour, creep and recovery behaviour, stress sweep (storage modulus), storage stability, frequency sweep, gel strength, yield stress, zero shear viscosity and oscillatory analyses are among the parameters measured. This study may help engineers and researchers to better understand hole-cleaning process, cutting transport, barite settling, mechanisms of fluid loss and formation damage, and managed pressure drilling while comparing rheological properties of the fluids.

EXPERIMENTAL PROCEDURES

Materials

Two different types of drilling fluid pre-mixes without barite, water- and oil-based, were produced. The mix design and mixing order for producing the water-based drilling fluid (WBDF) and oil-based drilling fluid (OBDF) are tabulated in Tables 1 and 2.

Table 1. Mix design of the water-based drilling fluid used in this study.

Compound	Quantity
Water	340 g
Soda ash (Na_2CO_3)	0.02 g
Mix for 2 minutes	
NaOH	0.25 g
Mix for 2 minutes	
Xanthan gum	1.2 g
Mix for 5 minutes	
Poly Anionic Cellulose – low viscosity	4 g
Mix for 5 minutes	
MgO	1 g
Mix for 2 minutes	
KCl	17.5 g
Mix for 5 minutes	
Bentonite	10 g
Mix for 5 minutes	

Table 2. Mix design of the oil-based drilling fluid used in this study.

Compound	Quantity
Mineral oil Sipdril 4.0	250 ml
$CaCl_2$ – solution	70 ml
Emulgator (Primary and secondary emulsifiers) One-Mul	12 ml
$Ca(OH)_2$	10 g
Mix for 5 minutes	
Organophilic clay	6.5 g
Mix for 5 minutes	
Fluid-loss reducing particles for OBM	7 g
Mix for 10 minutes	

Equipment

Roller oven – It was used to gently agitate the fluids for mimicking real-life operations. The samples were kept at 90°C for 16-hours. Then, they were left at room temperature for being cooled down when the aging cell cap was closed. After cooling, the fluids were gently mixed.

Mixer – Heidolph Hei-TORQUE 400 mixer was used to mix the drilling fluid prior to measuring the rheological properties of the samples. The selected mixing speed was 600 rpm. The type of selected blade was considered to minimize the damage to polymers present in the fluids (see Figure 1).

Rheometer – Two different type of rheometers were used: rotational viscometer and rheometer. Chan 35 rotational viscometer (see Figure 2) is a standard instrument[1,2,3] to measure viscosity of drilling fluids in the field. It was used to measure shear stresses of the fluids at different shear rates. Anton Paar MCR302 was used for the detailed measurements of the fluids. The setup was a truncated cone-plate system where the cone angle was 0.5°. Note that the oil based drilling fluid contained particulate material such that it was difficult to avoid measurement errors in the low shear rate tests in the cone and plate system.

Figure 1. Mixer and blade used in this study for shearing the fluid prior to measuring rheological properties of the fluids.

Figure 2. Standard rotational viscometer.

Test procedure

After aging the fluid in hot-roller oven, the sample was left at ambient temperature (22°C) for being cooled down while being in the aging cell. Then, the sample was mixed at 600 rpm with the Heidolph mixer for 3 minutes and then, its rheological behaviour was measured. All the measurements were conducted at ambient pressure.

When using the Anton Paar rheometer, the cone and plate configuration was used to measure the intended properties. This could be achieved as long as large particle sizes are not present.

Of practical reasons, the temperature was approximately 30°C for the measurements performed with the standard oilfield equipment. The temperature in the rheometer cell was set to 20°C.

MEASUREMENTS AND DISCUSSIONS

Rotational viscometer and rheometer measurements show shear thinning behaviour for both drilling fluids. When using oil field viscometers, it is normal to approximate the yield stress by extrapolation to zero shear rate from the measurements at the two lowest shear rates[13,14]. The yield stress determined following this rule is 2.0 Pa for the water based fluid and 0.8 Pa for the oil based. Hence, use of this method and the standard viscometer indicates a higher yield stress for the water based fluid. This is in contradiction with the results obtained using the rheometer. However, even though the yield stress must be considered as a material constant given the time constants of the flow, this yield stress cannot be very accurate. This yield stress is determined to provide a reasonable fit to Herschel-Bulkley parameters, and not to describe structures of the fluids. That will be shown clearly during the analysis of the dynamic viscosity experiments. The low shear rate data from the standard viscometer cannot be accurate as the are measured using concentric cylinder geometry. As was described by Whorlow[15], the shear rate at the inner cylinder is significantly larger than assumed with a Newtonian prediction. The two lowest shear rates when measuring drilling fluids can sometimes be twice the anticipated value[16].

By comparing the results shown in Fig. 3 with those shown in Fig. 5, and those shown in Fig. 4 with those shown in Fig. 6, one may get the impression that the viscosity measured using the standard viscometer gives a lower viscosity than those obtained using the rheometer. This effect, however, is the result of have measured fluid viscosities at different temperatures. The difference in viscosity fit to the difference measured by Halvorsen et al.[17] who compared viscosity of some drilling fluids at different temperatures.

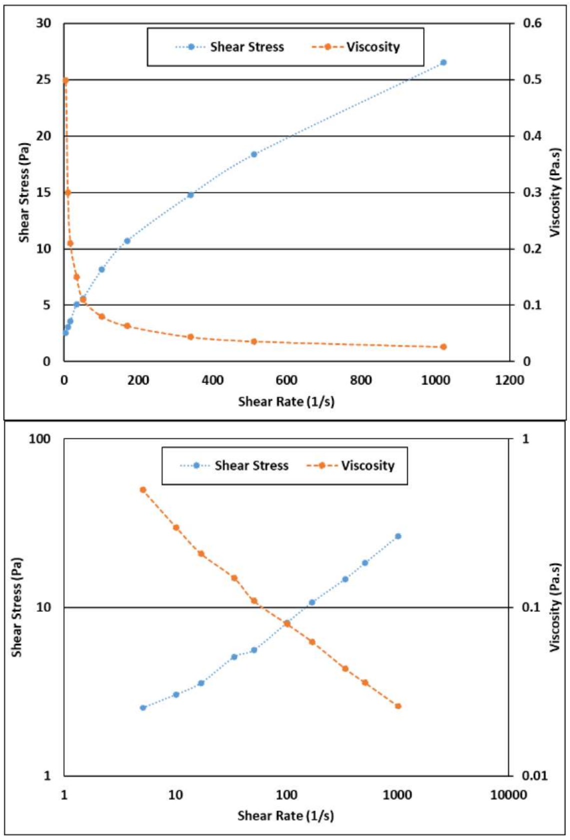

Figure 3. Flow curve and viscosity of the water based pre-mix at different shear rates based on oilfield standard procedures measured at 30°C; Top) linear scale, Bottom) log-log scale.

Amplitude sweep measurements of the water based and oil based pre-mixes are shown are Fig 7. The linear viscoelastic region of the water based premix terminated at a strain of approximately 10%, while that of the oil based left the LVR at a strain slightly less than 0.16%. The OBDF shows higher storage and loss moduli compared to the WBDF. The combination of G' and LVR is similar to the state observed by Werner et al.[7]. The shear stress in which the fluids left the LVR is similar. This could have been an indication that the fluids have approximately similar yield stress. However, there is an abrupt change in the slope of the measured stress at the strain ending the LVR for the oil based fluid. This indicates that the internal structure of the fluid is broken and that the yield stress has been reached. This implies that the oil based fluid has a yield stress around 0.7 Pa. It is also seen that the shear stress of the oil based pre-mix levels of at a value around 2.7 Pa for the very low shear rates as shown in Fig. 6, indicating that this could be the yield stress. The flow point where G'=G'' has a shear stress of 1.1 Pa. So summarizing these data, the yield stress is likely to be between 0.7 and 2.7 Pa for the oil based pre-mix.

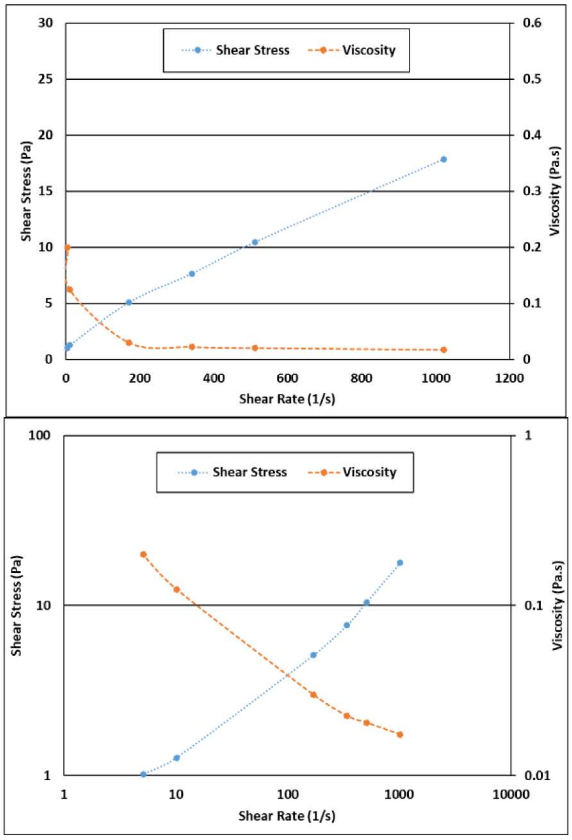

Figure 4. Flow curve and viscosity of the oil based pre-mix at different shear rates based on oilfield standard procedures measured at 30°C; Top) linear scale, Bottom) log-log scale.

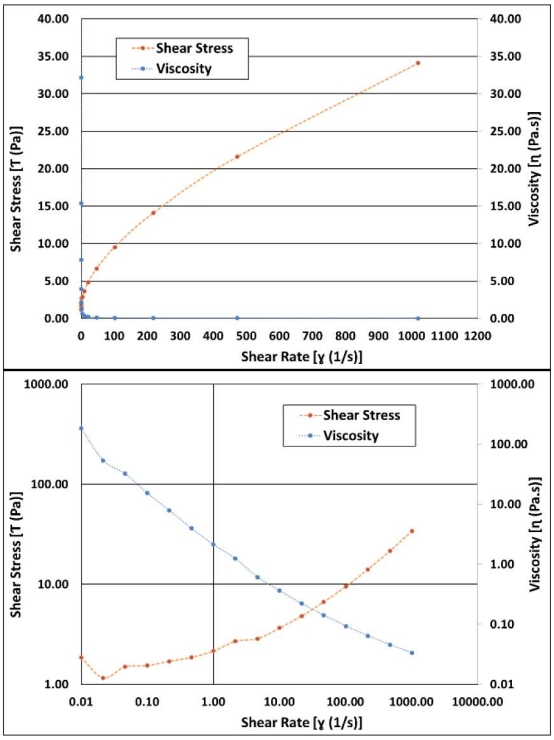

Figure 5. Flow curve and viscosity of the water based pre-mix at different shear rates measured by Anton Paar rheometer at 20°C; Top) linear scale, Bottom) log-log scale.

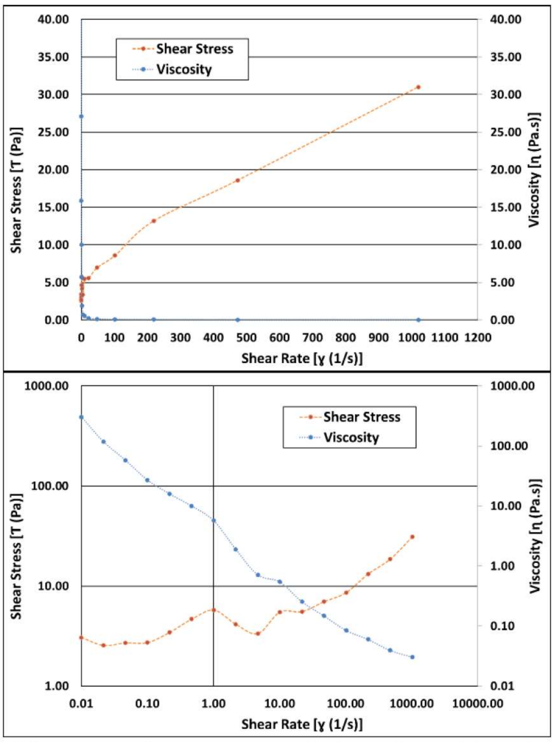

Figure 6. Flow curve and viscosity of the oil based pre-mix at different shear rates measured by Anton Paar rheometer at 20°C; Top) linear scale, Bottom) log-log scale.

The termination strain for LVR of the water based premix is larger than 25%, and the flow point would be somewhere above 100%. Within the recorded strains there are no indication that the fluid has exhibited a yield stress. If the shear stress levels off at small shear rates towards a yield stress in the flow curve shown in Fig. 5, it must be less than 1.5 Pa. The shear stress at the termination of the LVR is also around 1.5 Pa and the shear stress of the flow point is larger than 4.8 Pa. However, considering the composition of the water based pre-mix, brine and polymers in low concentration, there are no reason that this pre-mix should contain a yield stress. And the viscoelastic curves shown in Fig. 7 does not imply existence of such a yield stress either.

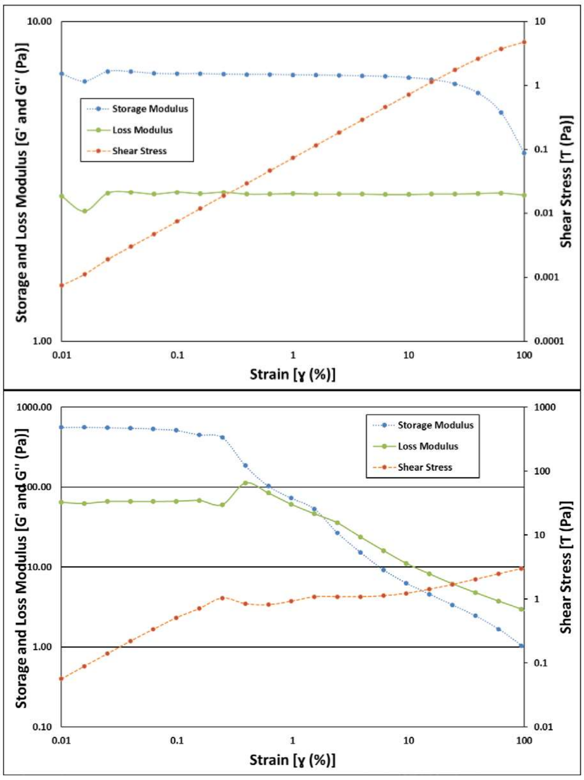

Figure 7. Oscillatory amplitude sweep measurement; Top) water based, Bottom) oil based pre-mix.

The viscoelasticity measurement as function of time is shown in Fig. 8. The curve for the water based pre-mix shows that the fluid holds its structure over the 15 minutes period of measurement. Only a slight rearrangement of the polymers is expected since the G' value increases slightly with time; especially during the first 4 minutes.

The curves for the oil based premix show a development of internal structure during the first 7 minutes. Then part of this structure is broken down as both the G', G'' and the related shear stress curves decay irregularly. These decays indicate that there may be some separation occurring within the fluid. Most likely some base oil volumes move upward because of syneresis, and some fluid loss particles sag out. These conclusions question the accuracy of the determination of the LVR for the oil based pre-mix.

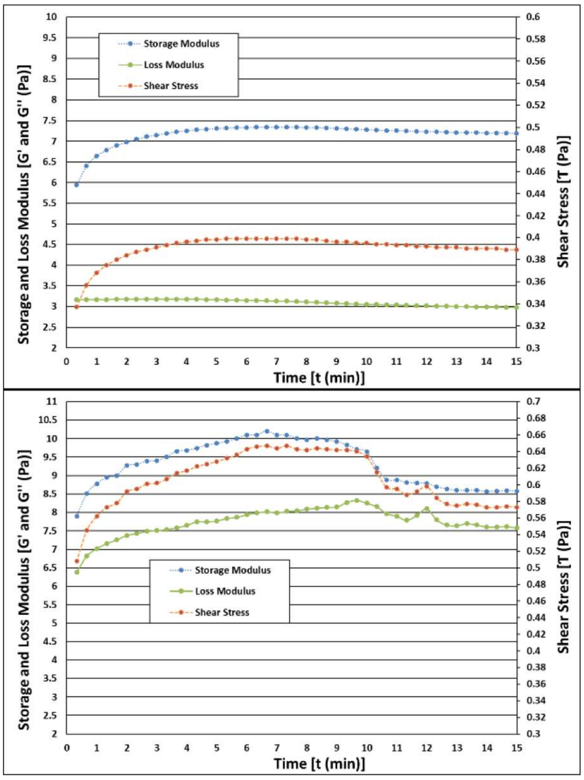

Figure 8. Viscoelasticity as function of time; Top) water based, Bottom) oil based pre-mix.

CONCLUSION

The yield stresses calculated from data measured by standard field viscometer and rheometer are not similar. A yield stress is likely to be developed in the oil based pre-mix. However, a yield stress may not be present in the water based pre-mix.

Oil based drilling fluid possess higher storage and loss moduli compared to the water based drilling fluid. Development of internal structure in oil based drilling fluid progresses differently than that of the water based drilling fluid. But water based pre-mix can hold its internal structure for longer time than the oil based drilling fluid.

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