

Measurement of Drilling Fluid Rheology and Thixotropy

Hans Joakim Skadsem and Amare Leulseged

International Research Institute of Stavanger, Stavanger, Norway/DrillWell

ABSTRACT

Drilling fluids are usually designed to be structured fluids with shear thinning and yield stress behavior. Most drilling fluids are also thixotropic, meaning that the fluid rheology exhibits a gradual and transient response to changing shear conditions, and that the rheological properties of the fluid are sensitive to recent shear history.

We report a detailed rheological characterization of a water-based drilling fluid and an invert emulsion oil-based drilling fluid. The rheological characterizations cover steady state flow curves, transient responses to step changes in shear rate, viscoelasticity and stress overshoots following different resting times. The thixotropic behavior of the drilling fluids is attempted fitted to a structural kinetics model.

INTRODUCTION

Drilling fluids serve a number of functions during a drilling operation, including those of transporting drilled cuttings to the surface, lubricating the contact between the drill string and the wellbore wall, and ensuring hole stability by providing necessary wellbore pressure to balance formation pressures. To meet the diverse functional requirements, drilling fluids are usually designed to be shear thinning yield stress fluids. Most drilling fluids are also thixotropic, meaning that the fluid rheology exhibits a transient response to changing shear conditions, and that the rheological properties of the fluid are sensitive to recent

shear history¹. Drilling fluids share this rheological profile with a wide range of industrially important fluids, such as cosmetics, paints, cement slurries, greases and gels.

Hydraulic modelling of fluid circulation during drilling is often based on simplifying assumptions such as steady state rheology and that the drill string is maintained in a fixed, possibly eccentric orientation in the hole. Downhole conditions evolve continuously while drilling however, and effects such as lateral motion and vibration of the drill string and local wellbore irregularities generate additional friction pressure losses due to inertia and the thixotropic rheology of drilling fluids that are very difficult to capture in a general model².

Although modelling the flow of thixotropic fluids in realistic wellbore geometries is still a formidable future challenge to be solved, valuable insights can be gained by studying rheometric flows of such fluids. As pointed out by Saasen², oil-based and water-based drilling fluids build their viscosities differently, leading to different rheological behavior even if their steady state viscosities are similar. Motivated by this observation, we study one water-based and one invert emulsion oil-based drilling fluid. We investigate the thixotropic response of the two fluids to rapid step-wise changes in the shear rate, and we measure the flow start-up following static periods of varying durations. Since most drilling fluids gel and become increasingly viscous during periods of no flow, start-up measurements

are particularly relevant for estimating the pressure transient when resuming circulation in a well. In an attempt to model the rheometric flow of the two drilling fluids, we fit measurements of the steady state flow curve and the thixotropy measurements to the structural kinetics model proposed by Dullaert and Mewis³.

EXPERIMENTAL METHODS

The rheological measurements are performed with an Anton Paar MCR301 rheometer using a smooth coaxial cylinder Couette geometry with rotating inner bob of outer diameter 26.653 mm, and a cup with smooth inner wall of diameter 28.910 mm. All measurements have been performed at constant fluid temperature of 293.15 K.

Table 1. Ingredients used to prepare the two drilling fluids.

OBM	WBM
EDC 99	FreshWater
OneMul NS	KCl
Lime	Soda Ash
Bentone 128	DuoTec NS
VersaTrol M	Trol FL
Freshwater	Glydril MC
CaCl2	

The compositions of the two fluids are based on the ingredients listed in Table 1. Several of the rheological tests performed on the two drilling fluids last up to a couple of hours. To avoid the risk of altered effective rheological properties over time due to sedimentation or particle migration to low shear regions in the Couette measurement geometry, the fluids were prepared without solid weighting material. The densities of the OBM and the WBM are 930 kg/m³ and 1080 kg/m³, respectively.

STEADY STATE FLOW CURVE

The effective steady state viscosities as function of shear rate have been obtained for each of the two drilling fluids by first

subjecting them to a constant high shear rate of 1021 s⁻¹ for 900 seconds, followed by measurement of shear stress for shear rates varying from 1021 s⁻¹ and down to 0.1 s⁻¹. For each of the fluids, the measurement sequence was first performed with 20 seconds measurement duration at each shear rate, then repeated with 10 seconds duration at each shear rate to confirm repeatability. The measurements are fitted to the constitutive Herschel-Bulkley model⁴:

$$\tau = \tau_y + K\dot{\gamma}^n \quad (1)$$

where τ and τ_y are the shear stress and the yield stress, respectively, $\dot{\gamma}$ is the shear rate, K is the consistency index and $n \leq 1$ is the shear thinning index.

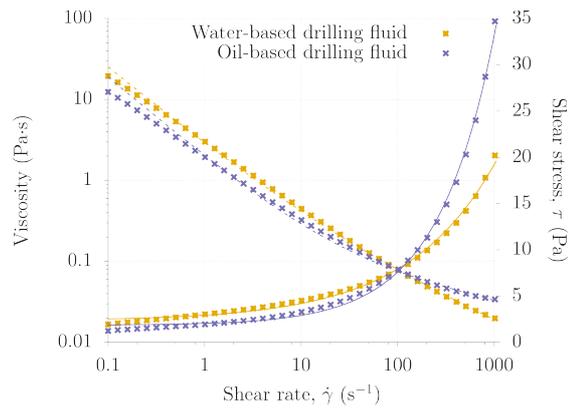


Figure 1: Steady state shear stresses and viscosities for the two drilling fluids.

Results for the water-based and the oil-based drilling fluids are shown in Fig. 1, where the points are rheometer measurements and lines are Herschel-Bulkley model fittings for each fluid. The solid lines are associated with the shear stress measurements, while the dashed lines correspond to the effective viscosities. The Herschel-Bulkley parameters are listed in Table 2 and estimated using the method of least squares. The parametrizations agree well with the measurements over the range of shear rates. Especially the WBM is highly

shear thinning, resulting in low effective viscosity at high shear rates. The low-end rheology is comparable and both fluids exhibit a small yield stress of approx. 2 Pa.

Table 2. Herschel-Bulkley parametrization of the two drilling fluids.

Parameter	OBM	WBM
τ_y	1.86 Pa	2.32 Pa
K	0.19 Pa·s ⁿ	0.62 Pa·s ⁿ
n	0.73	0.48

The model parametrizations overestimate the shear stresses at shear rates lower than approx. 1 s⁻¹. The measurement sequences using 10 seconds alternatively 20 seconds per shear rate are practically identical, but even longer durations may have improved the agreement between model and measurements at low shear rates. We repeat that the measurements have been obtained with a smooth bob and container walls, so apparent slip may also affect the measured shear stress in the low shear rate range.

STRESS OVERSHOOTS

To limit particle settling during periods of static conditions, most drilling fluids gel and develop a microstructure over time when they are left to rest. In the field, the so-called gel strength of drilling fluids is measured in a viscometer by first destructuring the fluid at high shear rate, then letting the fluid rest for a specific time, typically 10 seconds and 10 minutes. After this period of rest, the fluid is subjected to a rapid shear rate step from 0 s⁻¹ to 5.1 s⁻¹. The gel strength is recorded as the maximum shear stress during start-up of flow.

We have implemented a similar sequence to measure the evolution of shear stress during start-up of flow in the rheometer. In all cases, the fluids were subjected to a constant shear rate of 1021 s⁻¹ for 5 minutes. The rotation is next set to zero for the specified resting time. The start-up of flow is then performed by increasing the shear rate

linearly from 0 s⁻¹ to 2 s⁻¹ over the course of 0.25 seconds and 0.5 seconds for the OBM and the WBM, respectively. Following the initial ramping, the shear rate is subsequently maintained at 2 s⁻¹ for an additional 30 seconds. A shorter shear rate ramp interval was selected for the OBM in order to reach the target shear rate of 2 s⁻¹ before the maximum shear stress occurs during start-up.

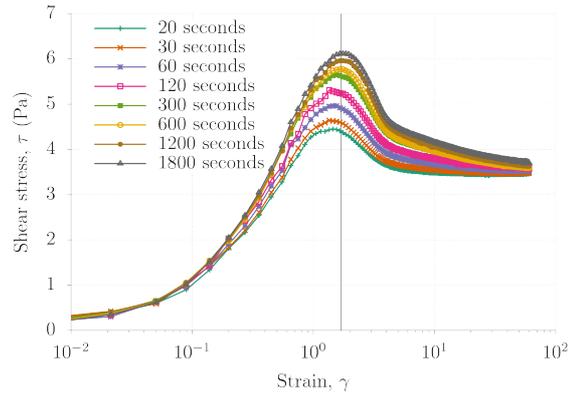


Figure 2: Stress overshoot in the WBM following different resting times.

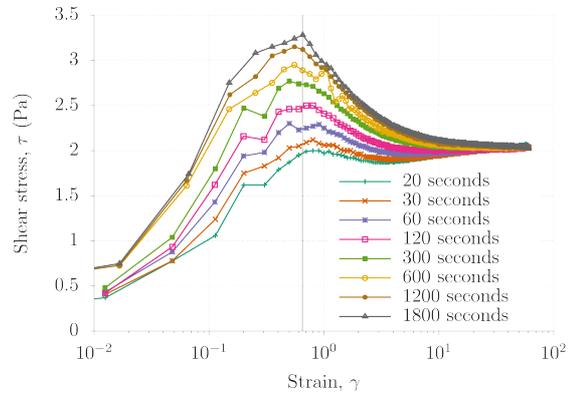


Figure 3: Stress overshoot in the OBM following different resting times.

The results are shown in Fig. 2 and Fig. 3 for the WBM and the OBM, respectively, where the measured shear stress is plotted as function of accumulated strain in the fluid. As anticipated, the measured shear stress during flow start-up increases with longer resting times. We observe that the stress build-up in the OBM occurs at a quicker rate

compared to the more elastic yielding of the WBM. The black vertical line in Fig. 2 and Fig. 3 indicate the approximate strain at which the maximum shear stress is measured, and this is greatest for the WBM, where it is found to be close to 1.7. The strain is approximately 0.65 for the OBM. We note a certain, small dependence on the resting time for the strain at which maximum stress occurs.

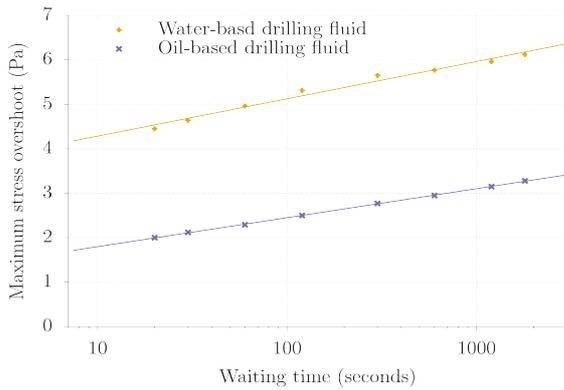


Figure 4: Maximum stress overshoot during flow start-up for different resting times.

The maximum stress overshoot values measured during flow start-up is plotted as function of resting time in Fig. 4. The maximum values for both fluids increase logarithmically with resting time at a nearly equal rate. A similar logarithmic increase in gel strength as function of resting time was reported by Bjørkevoll *et al.*⁵, who measured gel strength of a 10 g/l Laponite solution using an oilfield Fann 35 viscometer.

We note that the stress overshoot values are larger for the WBM, even though both fluids have comparable steady state yield stress values, as reported in the previous section.

OSCILLATORY AMPLITUDE SWEEPS

To further characterize the gel-to-liquid transition in the two fluids, oscillatory amplitude sweeps have been performed. Following a 60 second preshear at constant

shear rate of 1021 s^{-1} , the fluids are left under static conditions for 10 minutes. The oscillatory tests are conducted at constant angular frequency of 10 rad/s and a strain amplitude from 0.01% up to 1000%. Results from the oscillatory amplitude sweeps with the two fluids are shown in Fig. 5, where measurements of the storage modulus G' are associated with solid lines and the loss modulus G'' with the dashed lines.

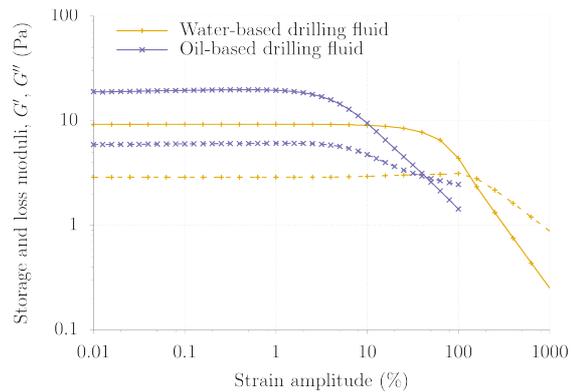


Figure 5: Oscillatory amplitude sweep at angular frequency 10 rad/sec for the two drilling fluids.

Within the linear viscoelastic regime, the storage modulus of both fluids exceeds the loss modulus, and the OBM has larger moduli than the WBM. The linear viscoelastic regime ends at a strain amplitude of about 2% for the OBM, while the WBM remains in this regime up to strain amplitudes slightly above 10%. Referring to the stress overshoot measurements shown in Fig. 2 and Fig. 3, one may correlate the relatively smoother and more gradual transition from rest to steady flow of the WBM with the smaller shear moduli and larger viscoelastic regime compared to the other fluid.

THIXOTROPY

Next, to investigate the thixotropic response of the two drilling fluids, a sequence of shear rate steps has been performed, and the measurements are fitted to the structural kinetics model proposed by Dullaert and

Mewis³. This is a so-called Type I thixotropy model, where elasticity and thixotropy are added to a viscoplastic stress equation⁶. The model has previously been used to model the stress overshoots of a drilling fluid by Negrão *et al.*⁷ with reasonable agreement between rheological measurement and model predictions. Below we briefly introduce the Dullaert and Mewis (DM) model and proceed by presenting thixotropic measurements and compare with model predictions.

Structural kinetics model

In the DM model, the equation of state for the shear stress is defined as follows:

$$\tau(\lambda, \dot{\gamma}) = \lambda(G_0\gamma_e(\lambda, \dot{\gamma}) + \eta_{st,0}\dot{\gamma}) + \eta_\infty\dot{\gamma} \quad (2)$$

where $\lambda \in [0,1]$ is a parameter describing the state of the fluid microstructure, G_0 is the shear modulus of the fluid, γ_e is the recoverable part of the total strain, $\eta_{st,0}$ is the viscosity increment of the built-up structure and η_∞ is the high shear rate viscosity. The kinetic equation for the structure parameter λ is defined as:

$$\frac{d\lambda}{dt} = \frac{1}{t^\beta} [-k_1\dot{\gamma}\lambda + k_2\dot{\gamma}^{0.5}(1-\lambda) + k_3(1-\lambda)], \quad (3)$$

where k_1 , k_2 and k_3 are constants representing shear-induced breakdown, shear-induced build-up and Brownian build-up of the fluid structure respectively. Finally, the kinetic equation for the elastic stress is defined as follows:

$$G_0 \frac{d\gamma_e}{dt} = \left(\frac{k_4}{t}\right)^\beta [\tau(\lambda, \dot{\gamma})\tau_{y,ss} - \tau_{ss}(\dot{\gamma})G_0\gamma_e] \quad (4)$$

where $\tau_{ss}(\dot{\gamma})$ is the steady state shear stress at shear rate $\dot{\gamma}$, and $\tau_{y,ss} = \lim_{\dot{\gamma} \rightarrow 0} \tau_{ss}(\dot{\gamma})$. The yield stress may be interpreted as an elastic

rupture stress⁸ at a critical strain γ_c , $\tau_{y,ss} = G_0\gamma_c$.

Shear rate stepping sequence

The measurement sequence begins with a 10 minute preshear at constant shear rate of 1021 s⁻¹. The fluid is next sheared at a constant *high* shear rate for 60 seconds to allow the fluid to approach the steady state viscosity at the current shear rate. Next, the shear rate is stepped down to a *low* shear rate and the shear stress is recorded over a period of 60 seconds to monitor the thixotropic response of the fluid at the lower shear rate. Afterward, the shear rate is stepped up to a different *high* shear rate which is again maintained for 60 seconds before stepping the shear rate down to the same *low* shear rate as before. In this manner, the thixotropic response to different step magnitudes can be compared for the same final, low shear rate. We focus primarily on the thixotropic response to a reduction in shear rate, as this produces a more visible thixotropic response compared to increasing shear rates.

As *high* shear rates we have investigated 51.1 s⁻¹, 102.1 s⁻¹, 170.2 s⁻¹, 341 s⁻¹ and 510.7 s⁻¹, and as *low* shear rates we have fixed 5.1 s⁻¹ and 10.2 s⁻¹. To achieve a controlled change in shear rate, the shear rate is stepped down linearly at a rate of approximately 500 s⁻¹ per second.

Parameter estimation

Model fitting is then performed by a nonlinear least squares approach, where both the steady state flow curve and the thixotropic shear rate step sequences are combined to estimate the eight parameters k_1 , k_2 , k_3 , k_4 , β , $\eta_{st,0}$, η_∞ and $\tau_{y,ss}$. The term G_0 is taken as the storage modulus from the oscillatory amplitude sweep. For completeness, the least squares model parameters for the OBM and the WBM are listed in Table 2. These parameter estimates reproduce the steady state flow curve

accurately and comparable to the Herschel-Bulkley parametrization in Fig. 1.

Table 2. DM model parameter estimates.

Parameter	OBM	WBM
k_1	0.084	0.46
k_2	0.063	0.082
k_3	1.40	0.73
k_4	$7.4 \cdot 10^{-4}$	$1.3 \cdot 10^{-5}$
β	0.17	0.17
$\tau_{y,ss}$	1.81	2.37
$\eta_{st,0}$	0.26	2.32
η_{∞}	0.024	0.0034

Oil-based drilling fluid

We next consider the model fitting to shear rate steps for the OBM. In Fig. 7 and Fig. 8 we present measurements and model prediction for the five steps down from a *high* shear rate to 5.1 s⁻¹ and to 10.2 s⁻¹, respectively.

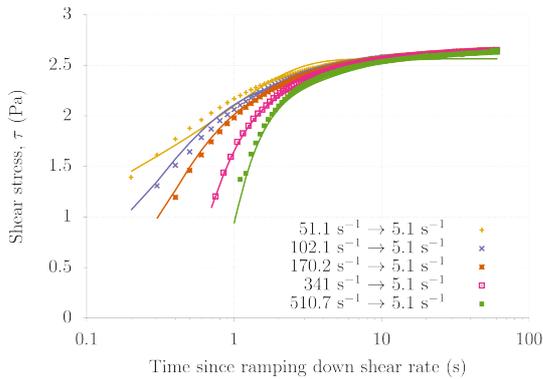


Figure 7: Measurements and model predictions for shear stresses in the OBM following shear rate steps down to 5.1 s⁻¹.

In all cases, the shear stress increases with time since the fluid evolves from a relative destructured state to a more structured state at this lower shear rate. The timescale associated with the thixotropic response is longer when stepping down to 5.1 s⁻¹ compared to the steps down to 10.2 s⁻¹. The structural kinetics model fits in Fig. 7 and Fig 8 are found to represent the thixotropic

response satisfactory, both in terms of the thixotropic time scale associated with the shear rate step as well as the quantitative evolution of the shear stress toward the steady state value at the two *low* shear rates.

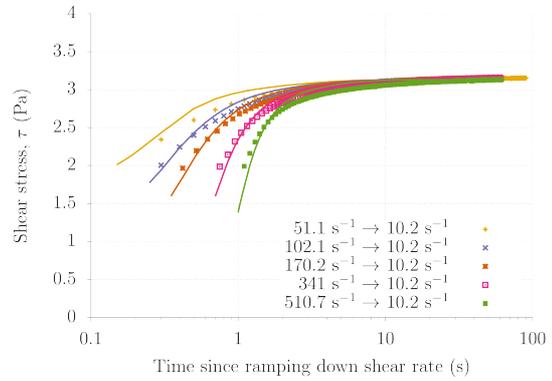


Figure 8: Measurements and model predictions for shear stresses in the OBM following shear rate steps down to 10.2 s⁻¹.

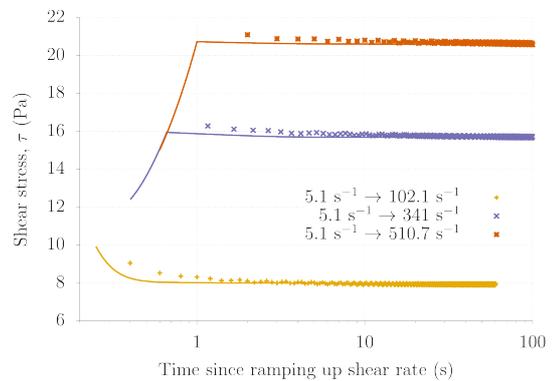


Figure 9: Measurements and model predictions for shear stresses in the OBM following shear rate steps from 5.1 s⁻¹.

Reversing the shear rate step direction by starting from a low shear rate and ramping up to a higher shear rate are also well described by the structural kinetics model, as seen in Fig. 9. The thixotropic effect is smaller when increasing the shear rate, and this is well captured by the model parametrization given in Table 2.

Water-based drilling fluid

Turning next to the WBM and the shear rate steps down to respectively 5.1 s^{-1} and 10.2 s^{-1} , we obtain the results presented in Fig. 10 and Fig. 11.

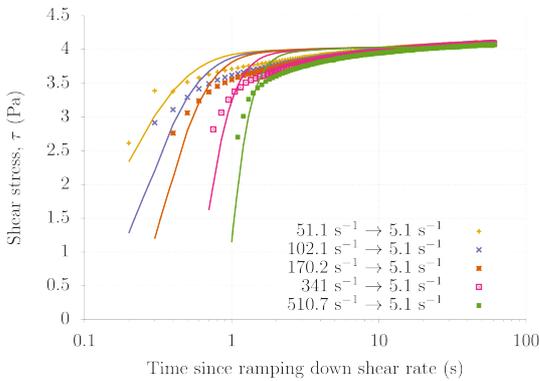


Figure 10: Measurements and model predictions for shear stresses in the WBM following shear rate steps down to 5.1 s^{-1} .

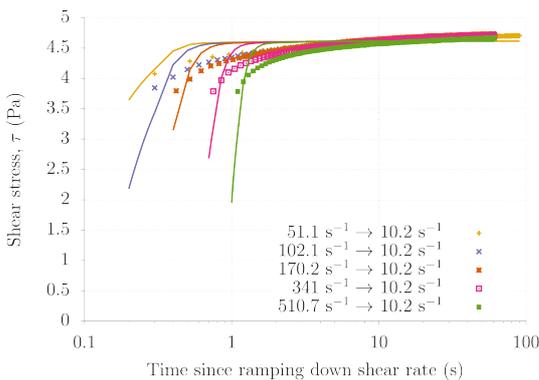


Figure 11: Measurements and model predictions for shear stresses in the WBM following shear rate steps down to 10.2 s^{-1} .

The match is now less satisfactory than for the OBM in Fig. 7 and Fig. 8. The steady state shear stresses toward the end of the measurement series are well-represented by the model, but the thixotropic time scale and the evolution of the shear stress to the final value are not matched equally well as for the other drilling fluid. Measurements of the WBM is seen to approach the steady state shear stress more slowly than the oil-based drilling fluid, with the measured shear stress

exhibiting an increasing trend even at the end of the 60 second measurement at the low shear rates.

To further evaluate the model parametrization in Table 2, we have attempted to simulate the flow start-up experiments in Fig. 2 and Fig. 3, which were not used as basis for the parameter estimation. The model parametrizations do not produce a stress overshoot for either fluid, but rather a smooth transition from an unstressed initial state up to the steady state shear stress. Inclusion of stress overshoot measurements and possibly also other transient rheology measurements in the data set used for model fitting could have improved the determination of the eight model parameters. Although several of the published thixotropy models can predict stress overshoot behaviour, we are not aware of such models that also capture the logarithmic increase in gel strength with resting time.

Thixotropic time scales

Finally, we evaluate the time from stepping down to the target shear rates and until the shear stress is within 95% of the steady state value, using the rheometer measurements. This is plotted in Fig. 12 for the two fluids.

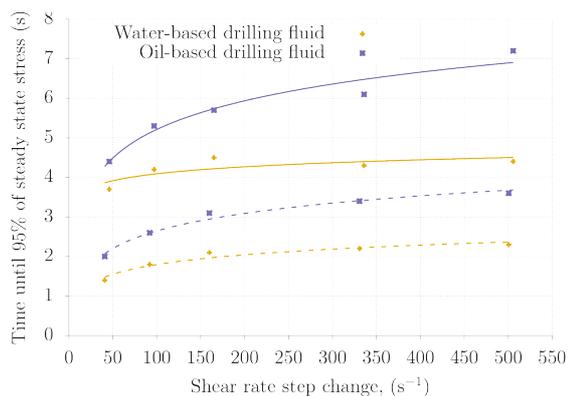


Figure 12: Time from stepping the shear rate and until the shear stress reaches 95% of the steady state value.

The lines are fitting functions that are taken to be logarithmic in the shear rate step length. Solid lines are associated with measurements at target shear rate 5.1 s^{-1} , while dashed lines are associated with measurements at 10.2 s^{-1} . We observe that the time duration is nearly twice as long for the steps down to 5.1 s^{-1} compared to the steps to 10.2 s^{-1} , suggesting that the thixotropic time scale may be inversely proportional to the target shear rate. We also note a stronger dependency for the OBM on the thixotropic response to the shear rate step length compared to the WBM.

CONCLUSIONS

We have studied transient and steady state rheology of a water-based and an invert emulsion oil-based drilling fluid. The steady state flow curves are overall well-represented by the constitutive Herschel-Bulkley model. The measurements deviate from the model at low shear rates, which may be due to apparent slip effects or insufficient measurement time.

Although the two drilling fluids have comparable steady state viscosities, stress overshoot and thixotropy measurements indicate they build viscosity differently². The thixotropic responses to rapid changes in shear rate are well characterized by the structural kinetics model of Dullaert and Mewis for the OBM, but less satisfactory for the polymeric-based WBM. As the model consists of eight parameters, several different parameter combinations may produce model predictions that fit the data set used for parameter estimation, but may perform poorly when attempting to simulate other transient rheometric flows.

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