Assessment of Yield Stress in Oil-Based Drilling Fluids

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ABSTRACT
Yield stress is commonly used to describe the rheological properties of drilling fluids. There are various methods to define such yield stress. Some approaches provide yield stress values sufficient to derive a proper fluid mechanical model while other approaches define the fluid properties as comparable matters. Here logarithmic values from shear rate measurements ramped both up and down are evaluated.

INTRODUCTION
Oil-based drilling fluids, used in oil and gas industry, geothermal industries, CO2 (or other subsurface gas) storage applications, are constructed as a water in oil emulsion with added particles in a combined emulsion and dispersion. Typical oil-water ratios are from 75-25 to 85-15 with extremities above and below. In standard viscosity measurements these fluids are described using a yield stress term. The yield stress value is debated and normally derived from readings at 5 and 10 s^{-1} to be in accordance with drilling standards[1,2]. In the current article an assessment of yield stress in selected oil-based drilling fluids is presented. This assessment is based on experiments using oscillatory rheometry combined with shear stress – shear stress curves measured over several orders of magnitude of shear rates.

Much has been done on description of complex fluids in recent years. Drilling fluid differ from many other industrial interesting fluids, for instance those relevant for 3D printing or concrete. Drilling fluid rheology is comparable to that of many food colloids, but with the addition of relatively large high-density particles in suspension. The oil-based drilling fluid is built as an emulsion of water into oil. In northern Europe this oil is food grade. The water droplets have typically a size around some 5 microns. Normally the inter droplet distance is smaller than the droplet size. Into this emulsion an oil wet clay, organophilic clay, is added in order to build viscosity. Finally, weight materials are added. This is typically barite with a D50 particle size between 10 and 25 micron. Maximum 1.5% of the barite should be larger than 74 micron and maximum 20% should be less than 5 micron. In addition, particles and fibres may be added to prevent loss of fluid into porous formations. Thus, the oil-based drilling fluid is a mixture of oil, water small and large grinded particles, small and large flaky particles and fibres.

As described, these complex fluids forming the oil-based drilling fluids forms yield stresses, at least for fluid mechanical application. Experiments must therefore be performed to derive an acceptable level of understanding of these fluids' material properties and fluid mechanical properties. In the following some of these items are presented in detail.

MATERIALS

A base fluid volume of were created. The viscosity of these fluid volumes was adjusted by adding commercial organophilic clay-based viscosifiers. The viscosifier include a low temperature and a high temperature organophilic clay with proportion 42:60 as used by Ofei et al.[3]. The base fluid composition is shown in Table 1.

TABLE 1: Base fluid (OBDF-1.5) composition

	OWR = 80/20	
Product	Mass fraction (%)	Concen-tration (g/l)
Refined mineral oil	35	501.9
Emulsifier	1.4	20.0
Viscosifier (low temp. org. clay)	0.63	9.0
Viscosifier (high temp. org. clay)	0.9	13.0
Lime	1.4	20.0
Fluid loss agent	0.7	10.0
Calcium chloride brine	13.9	199.3
Calcium carbonate	3.5	50.0
API barite	42.6	610.8

The evaluated drilling fluid samples were all blended based on the composition shown in Table 1. All fluids are named OBDF-number, where the number indicate the mass percentage of organophilic clay in the fluid. All additions had the same ratio between high and low temperature clay. In blending, first the low temperature viscosifier is added and mixed for 4 minutes, then the high temperature viscosifier is added and mixed again for 4 minutes in a 1L blender with a 3-blade spindle rotating at 6000 rpm. The clay concentrations up to 2.5% are common in practical fluids. The fluids with more than 3% organophilic clay is tested to help understanding the effect on yield stress. However, these fluids will probably never be used in a drilling operation. The tested fluids OBDF-2.0 and OBDF-3.9 were prepared directly from the base fluid, OBDF-1.5. The fluids OBDF-2.8 and OBDF6.4 were based on these two fluids with further addition of clay. The organophilic clay has a particle size typically smaller than that of the emulsion droplets. For more information about organophilic clays, please consult for example van Olphen[4] or Breakwell et al.[5].

MEASUREMENT METHODS

Oilfield viscometers[1,2] do not provide accurate enough measurements to handle the scope of the present assessment. Hence, the rheological properties of the drilling fluids were measured using an Anton Paar MRC 102 rheometer. The measurement sequence comprises three phases: first, oscillatory tests with increasing amplitude, then two flow curves of different durations. Each of the three phases starts with pre-shear for 30 s at a shear rate of $\dot{\gamma} = 1000\ s^{-1}$, then relaxation for 10 s at $\dot{\gamma} = 0$. To obtain good accuracy of the measurements, the duration of the measurement points at low shear rates is 20s. This duration is decreased logarithmically with increasing shear rate down to 1s. To obtain two different durations of flow curves measurements, we change the number of measurement points in the flow curve, as summarized in Table 2.

TABLE 2: Summary of rheological measurement sequences

	Number of measurement points	Duration of each measurement	Total time
Oscillations – Amplitude sweep: $\omega = 10\ rad/s$			
Pre-shear			30 s
Relaxation			10 s
Amplitude sweep, $\gamma = 0.001\ \% \ \rightarrow 100\ \%$	51	1 s	51 s
Flow curve 10 min			
Pre-shear			30 s
Relaxation			10 s
Shear rate logarithmic ramp up, $\dot{\gamma} = 0.001 \rightarrow 1\ 000\ s^{-1}$	94	20 → 1 s	10 min
Shear rate logarithmic ramp down, $\dot{\gamma} = 1\ 000 \rightarrow 0.001\ s^{-1}$	94	1 → 20 s	10 min
Flow curve 3 min			
Pre-shear			30 s
Relaxation			10 s
Shear rate logarithmic ramp up, $\dot{\gamma} = 0.001 \rightarrow 1\ 000\ s^{-1}$	28	20 → 1 s	3 min
Shear rate logarithmic ramp down, $\dot{\gamma} = 1\ 000 \rightarrow 0.001\ s^{-1}$	28	1 → 20 s	3 min

VISCOUS PROPERTIES OF OIL-BASED DRILLING FLUIDS

Common properties of OBDF as measured following the advanced part of industry standards are measured using a rotational cup and bob-based viscometer ranging from 5 to 1022 1/s shear rates. Typical shear rates in the well outside the drill pipe is from 200 1/s and downwards. Inside the drill string the shear rate can be higher.

As summarized by Watson[6] it is not known if a yield stress really exists. Furthermore, it is unlikely that any fluid would be a Herschel-Bulkley fluid. Maybe the simplest model to describe a fluid behaviour accurately is the Quemada model as used by Baldino et al.[7]. However, the Herschel-Bulkley model is simple to use for most drilling applications. Thus, the question is to determine the yield stress. Oilfield practise is to determine the yield stress by linear extrapolation of the shear stress values obtained at 5 and 10 1/s shear rates[8] as these shear rates are the smallest shear rates of the very common six speed field viscometer[1,2].

It is possible to attribute the end of the linear viscoelastic range and the cross point where G' becomes less than G'' to yield stress[9]. For small amplitudes both the viscoelastic elastic spring constant, G', and the loss modulus, G", are constant. G' is larger than G". Thus, a performance of the fluid is like a solid, which means that the elasticity of a fluid where the stress has not yet reached the yield stress is observed and the material behaves like a Hookean solid.

In the yield zone the deformations become too large for a fully reversible behaviour. Irreversible deformations are occurring. However, the elastic response is still large. When the flow point is reached where G'=G'', the loss modulus becomes larger than the elastic modulus. For larger strain, the fluid now behaves like a liquid, still with some elasticity if G"/G' is close to unity. For oil-based drilling fluids there are no additives producing a real elasticity. The elastic components for such particle dispersions in emulsion is that additional forces are required to make particles and droplet leap-frog as they need to do to obtain a liquid like motion.

On the ramp up part of a flow curve, similar behaviour may exist. The very small shear rate may actually be a finite strain as illustrated in **Fig. 1** at lower shear rates than point A. However, to create this strain require time and a false shear rate may be measured. During this strain some of the particle-particle connections may break without yet making the material fluid like. Following this strain at point A, at a slightly higher shear stresses, there is a period where more and more of the internal yield stress structures may be broken. The fluid is broken into a group of structural units and the internal elastic responds is reduced. So, it continues until reaching the point B. Here all the structures are broken, and the material is fluid like. Thus, the yield stress may be measured as the stress at the inflection point of the logarithmic shear rates. When the particle and emulsion-based fluid has a shear rate less than the yield stress, the particles and droplets may form in a structure that is in average resembling a crystalline like structure, but with a continuous particle distribution. Brownian motion tries to maintain this crystalline structure. An inflection point is also observed on the ramp-down curve. The reason for this is not conclusively understood. Hence, it is investigated how this value would fit as a yield stress estimate compared to the other estimates.

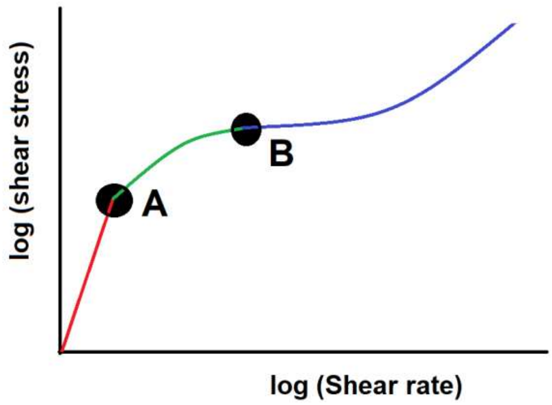

FIGURE 1: The ramp up curves of a fluid exhibiting a yield stress.

In **Fig. 2** it is shown the ramp up and ramp down measurements of the flow curve for the fluid OBDF-1.5. For a Herschel-Bulkley fluid, the shear stress τ is related to the shear rate $\dot{\gamma}$ by the relation $\tau = \tau_y + k\dot{\gamma}^n$, where τ_y is the yield stress, k is the consistency and n the flow index n. For the three models used in this paper, the consistency k is determined from the surplus stress determined at 200 1/s and the index n is determined at 1000 1/s. The Model LSYP has its yield stress based on the yield stress determined following Power and Zamora[8] during ramp down. The two other models have their yield stresses selected as the stress at the inflection point of the ramp up and ramp down measurement curves. For this particular fluid these model curves do not differ significantly as shown in **Fig. 3** in a linear scale. Note that the overall accuracy would have been improved if the surplus stress was determined at 100 1/s, say, than the selected 200 1/s.

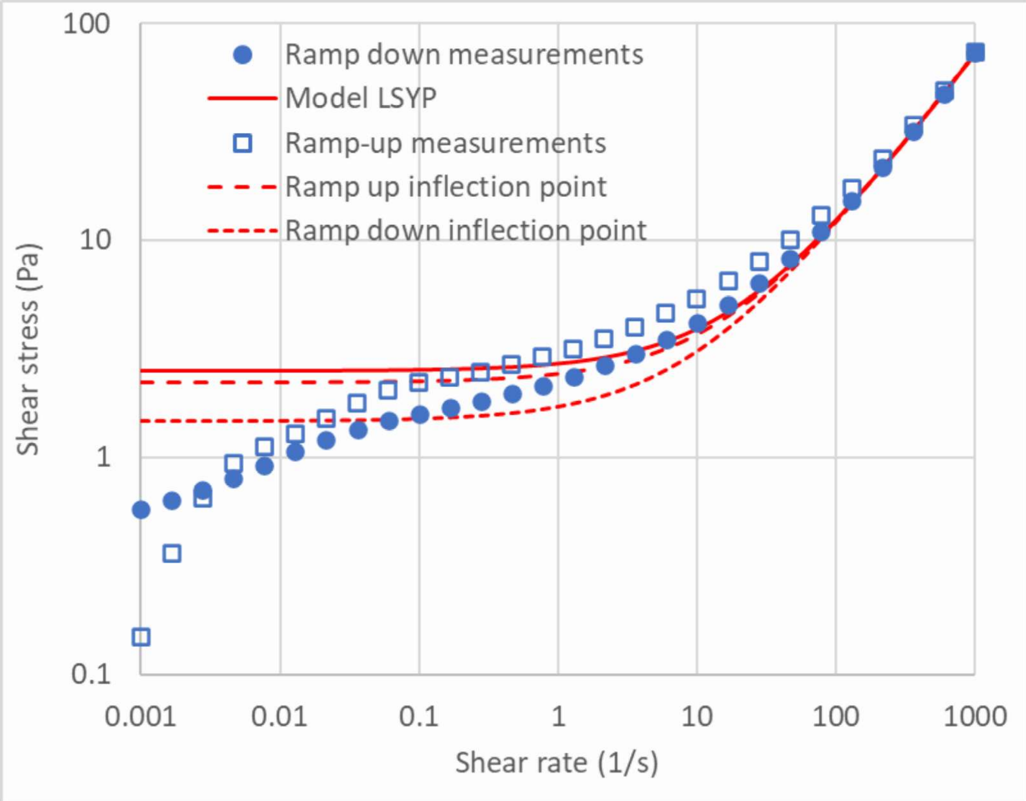

FIGURE 2: The ramp up and ramp down curves of fluid OBDF-2.0 and three Herschel-Bulkley curves with different yield stresses modelling the measurements.

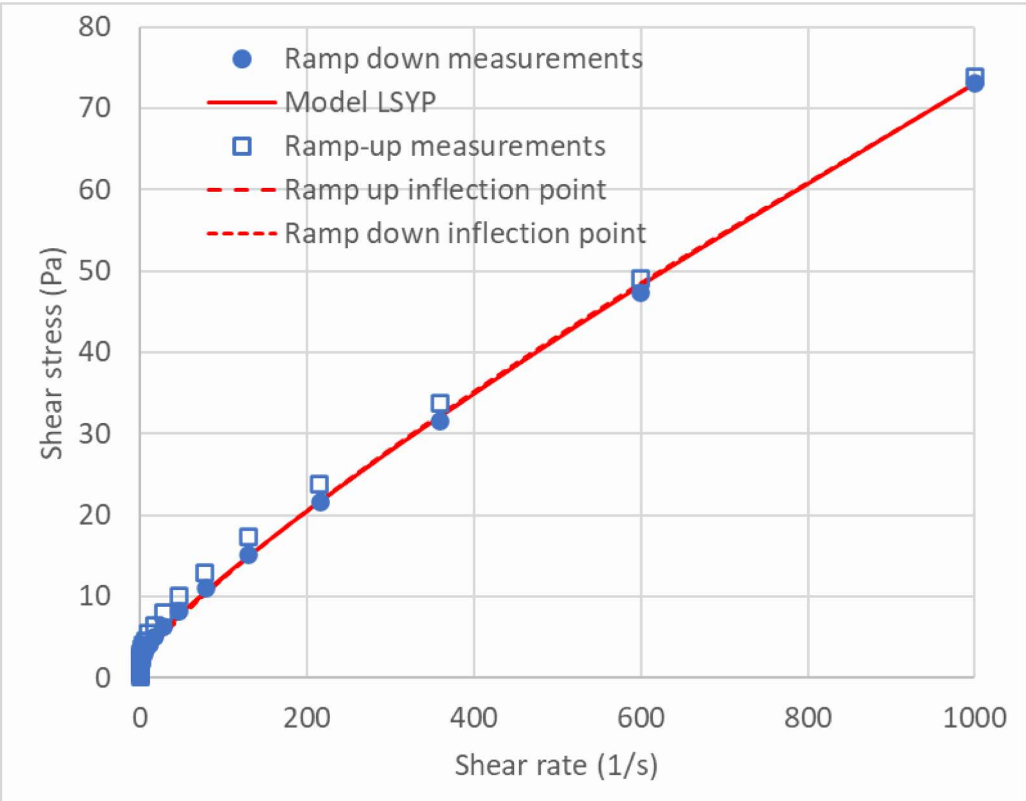

FIGURE 3: The ramp up and ramp down curves of fluid OBDF-2.0 and the Herschel-Bulkley curves shown in **Fig. 2**.

As expected, the yield stress increased with increasing organophilic clay content. This is illustrated in **Fig. 4**. The measurements performed to create **Fig. 4** were all conducted at a time period of 3 minutes. The values obtained during a 10 minute measurement period were only very slightly larger. However, all of them were larger. The exception is the fluid with 6.4% organophilic clay. Only the ramp down inflection point could be used to determine the yield stress as is shown in **Fig. 5**.

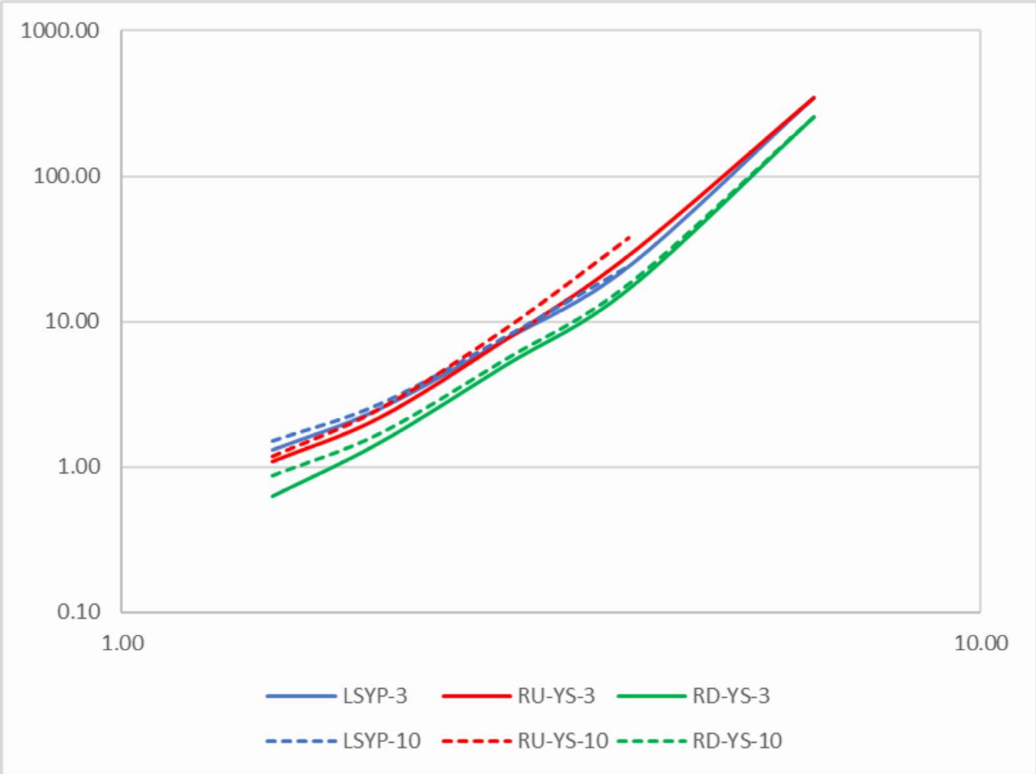

FIGURE 4: The ramp up and ramp down curves of fluid OBDF-2.0 and the Herschel-Bulkley curves shown in **Fig. 2**.

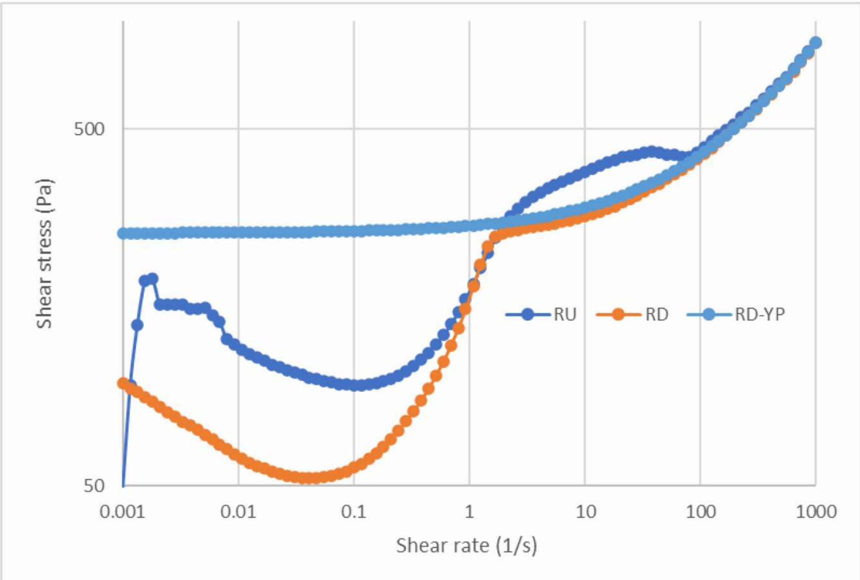

FIGURE 5: The ramp up and ramp down curves of fluid OBDF-2.0 and the Herschel-Bulkley curves for the laboratory fluid with 6.4% organophilic clay.

CONCLUSION

An assessment of the yield stress has been conducted. It was found that the shear stress of the inflection point in the logarithmic ramp up curve often provide a value similar to the low shear yield point as being determined by Power and Zamora[8].

In addition, we note that for all three models, the value of the yield stress depends on the duration of the flow curve measurement: it is slightly higher for long measurement duration (10 min) than for a shorter measurement duration (3 min).

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