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Predicting Rheology of Drilling Fluids Containing Large Sized LCMs

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Abstract

Lost circulation materials (LCM), such as ground marble, nut shells, and graphitic carbon, are well-known to the industry and are often the main components of solutions for preventing lost circulations. Recently, with increased drilling activity in highly depleted formations, large particle size distribution (PSD) material is often used to plug large induced fractures and prevent losses. Preferably, such large PSD LCMs are used in the form of background treatments; they are sometimes added to the LCM pills. Consequently, it could be useful to understand the effect of the addition of large PSD LCMs on the fluid rheology. This paper provides methods to predict and manage the rheology of fluids that contain large PSD LCMs, which in the past has always been challenging.

Conventionally, drilling fluid rheology is measured on an API-recommended, FANN® 35 viscometer that has a specific rotor and bob geometry. However, the gap between the rotor and bob in the conventional viscometer is small (approximately 1 mm) and is not suitable for rheology measurements of fluids containing large PSD LCMs (e.g., D50 ≥ 400 μm). To address this issue, wide gap rotor and bob combinations were used to measure the rheology of these fluids and to predict the corresponding shear stress vs. shear-rate response.

This rheology information can be used to accurately calculate the equivalent circulating density (ECD) to ensure that it remains between the pore pressure and fracture pressure. The modeling work in this paper was validated and successfully used in the field to optimize fluid and LCM combinations.

Introduction

The addition of lost circulation materials (LCM) to the treatment fluids is one of the most prominent methods used to control the loss of drilling fluids to the formation. The LCMs range from particles, cement gunk, and chemical sealants, and are applied depending on the availability of the materials and loss rates, type of formation being drilled, and economic constraints. A more effective selection of the LCMs is possible when there is detailed understanding of LCM properties, functions, and LCM/fluid interaction. In this regard, extensive studies have been performed on three widely used LCM particulates that include ground marble, resilient graphitic carbon, and nut shells. It was shown that resiliency and crush strength of these LCM particulates significantly affected lost circulation control and wellbore strengthening.[1] LCM particles were also studied from the perspective of shear degradation[2,3,4]; the degradation or particle attrition affects the fracture plugging performance of the wellbore and changes the viscosity of the base drilling fluid in which the particles are present. The effect of the LCM addition on the rheology of drilling fluids and, correspondingly on the equivalent circulating density (ECD), has been shown to be one of the important criteria for LCM selection[5]. Several viscosity models have been built to predict the viscosity of the drilling fluids that contain small LCM particulates (D50 < 400 μm) [6].

Recently, with increased drilling activity in highly depleted formations, large size particulates are often being used for LCM applications[7]. However, the literature lacks methods to predict and manage the rheology of fluids that contain large size LCMs. This paper addresses this challenge by providing methods for determining the rheology of the drilling fluids that contain large size LCMs (D50 ≥ 400 μm). The paper first demonstrates that the particle size of the LCM strongly influences the rheology of its mixture with the base drilling fluid. Next, it recommends use of wide gap rotor and bob combinations to measure the rheology of fluids that contain large LCMs and provides novel correlations to transform the viscometer data into shear stress vs. shear rate form for the wide gap geometries. Finally, a wellbore case study is presented to demonstrate the importance of the accurate determination of the rheology of fluids that contain large LCM particulates from the standpoint of wellbore hydraulics.

The convenient prediction and management of LCM rheology for a range of particulate sizes can provide a significant improvement in the LCM technology. The model could serve as a tool for mud engineers to use to evaluate the viscosity of the LCM-laden fluids, enabling them to make fast decisions at the rig site to optimize the LCM and fluid combinations based on the ECD constraints. This tool can help to prevent issues related to wellbore stability and to avoid corresponding downtime. This work may also be a part of a drilling fluid design for precisely selecting LCM treatments.

Theory: Rheology Modeling for Fluids with Large Particles

The API-recommended viscometer has a specific bob and rotor geometry. The bob is attached to a torque measurement device. The torsion spring resists rotational torque of the sheared sample disposed in the annulus between the rotor and the bob. As the rotor spins, torque is applied to the bob, which results in deflection of the bob. The deflection is measured by a dial (or a position encoder). The degree of rotation is proportional to the shear stress. The conventional rotor-bob combination, R1/B1, has a gap of approximately 1.0 mm.

For fluids that contain large LCM particulates (D50 ≥ 400 μm), the conventional viscometer geometry (R1/B1) cannot be used because the gap/particle size ratio becomes less than 3.0[8].

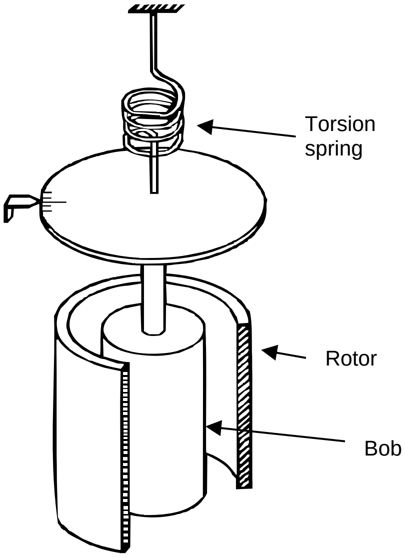

Fig. 1–Schematic of a rotor and bob combination on a conventional API viscometer.

Therefore, the R1/B1 geometry was replaced with the rotor-bob combination in which the gap between the rotor and bob is reasonably wide, e.g., R3/B1 (gap approximately 9 mm) or R1/B2 (gap approximately 6 mm) to characterize the fluids containing large LCMs (D50 ≥ 400 μm).

The method of using the wider gap rotor-bob combination is first validated for fluids that contain smaller size particles (< 400 μm), then extended to the fluids that contain larger size particulates. The data obtained using the wide gap rotor-bob geometry should be transformed into a shear stress vs. shear rate relationship that can be used for hydraulics calculations.

Experimental Study: Materials

LCM

The LCM particles of specific size ranges were obtained by sieving the resilient graphitic carbon (RGC). Three samples of various sizes were obtained by the sieving process using VWR USA mesh standard test. The D10 value of a sample is defined at diameter below which there are 10% of particles (by weight) in the given sample. Similarly, D50 and D90 are defined. **Table 1** provides the D10, D50, and D90 values of the three RGC samples. Note that RGC 50 and RGC 100 have D50 values less than 400 μm; RGC 400 has a D50 value greater than 400 μm.

Table 1–LCM Particles (RGC) of Different Sizes.

	D10 (μm)	D50 (μm)	D90 (μm)
RGC 50	8	50	123
RGC 100	13	92	220
RGC 400	271	550	744

Base Drilling Fluid (i.e., Base Fluid)

As shown in **Table 2**, an oil-based drilling fluid was formulated with a mud weight of 14 lbm/gal and oil/water (o/w) ratio of 80/20. After formulation, the drilling fluid was hot-rolled at 150°F for 16 hours before performing the rheology tests with the RGC particulates.

Table 2–Base Drilling Fluid Formulation.

Component	Amount
Base oil (lbm/bbl)	As required
Emulsifier (lbm/bbl)	14
Lime (lbm/bbl)	4
Filtration control agent (lbm/bbl)	6
$CaCl_2$ brine, (250 K)	As required
LGS I (lbm/bbl)	6
LGS II (lbm/bbl)	4
LGS III (lbm/bbl)	10
Drill solids (lbm/bbl)	20
Barite (lbm/bbl)	As required
Viscosifier (lbm/bbl)	3
(o/w ratio: 80/20; mud weight: 14 ppg)	

Experimental Methodology

Viscometer Rheology and Mud Weight

The rheology of the hot-rolled base drilling fluid was measured at 120°F using the conventional R1/B1 rotor-bob combination (gap approximately 1 mm), as well as with R1/B2 and R3/B1 rotor-bob combinations. The mud weight of the fluid was measured on a standard mud balance.

LCM Fluid Uniform Mixing

The RGC particulates of a given size (for example, RGC 50) at a concentration of 40 lbm/bbl were mixed with the base drilling fluid thoroughly with a spatula. The uniform mixture was then used for rheology measurements on a viscometer at 120°F. For a given fluid sample containing a mixture of base fluid and RGC particulates, the rheology was measured using the three rotor-bob combinations: R1/B1, R1/B2, and R3/B1.

The same tests were repeated for the respective mixtures of RGC 100 and RGC 400 with the base drilling fluid.

Results and Discussion

The experiments were conducted to develop a method for predicting the rheology of fluids that contain large size particulates (D50 ≥ 400 μm). As a first step to develop this method, the influence of the LCM particle size on the rheology of the LCM and fluid mixture was investigated.

Fig. 2 shows dial readings on the viscometer obtained using the R1/B1 geometry. The dial readings are plotted against the corresponding RPMs of the rotor. The base fluid response shows a characteristic behavior of a yield-power-law fluid. When the LCM, RGC 50, is added to the base fluid in the amount of 40 lbm/bbl, as expected, the dial readings on the viscometer increase, as compared to the base fluid at all RPMs. When a slightly higher size LCM, RGC 100, is added to the base fluid in the same amount, the dial readings again increase, as compared to the base fluid; however, this increment in the dial readings is significantly smaller as compared to that when RGC 50 was added (Fig. 2). This variation clearly shows that the particle size of the LCM strongly influences the rheology of its mixture with the base drilling fluid.

Similarly**, Fig. 3** and **Fig. 4** show viscometer data using the wide gap R1/B2 and R3/B1 geometries, respectively. A more sensitive torsion spring is used for these geometries because less torque will be experienced by the bob for the same RPMs of the rotor as a result of the wider annular gaps. Fig. 3 and Fig. 4 show the variation in increments of fluid rheology when different size RGC particles are added to the fluid. The data confirms that larger the size of the RGC particles, the smaller their effect on rheology when these particles are added to the base drilling fluid.

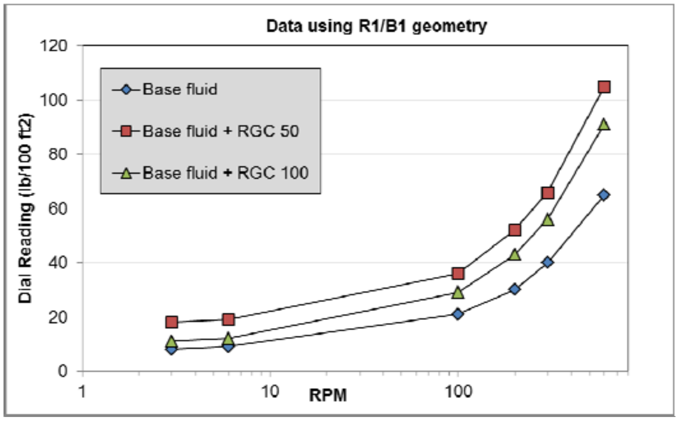

Fig. 2–Viscometer dial readings vs. RPM on the viscometer obtained using the R1/B1 geometry at 120°F for the three fluid samples.

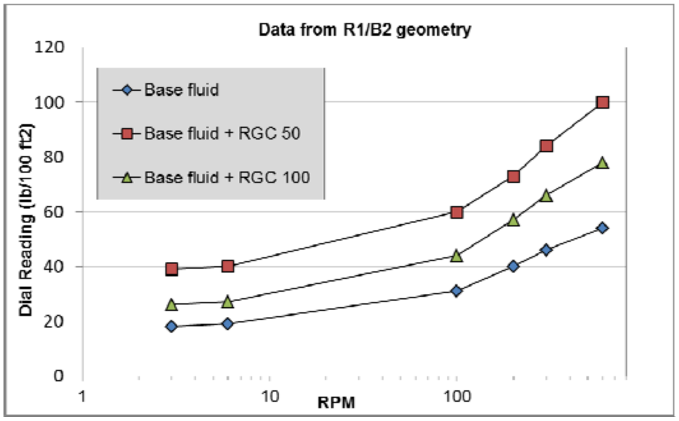

Fig. 3–Viscometer dial readings vs. RPM on the viscometer obtained using the R1/B2 geometry at 120°F for the three fluid samples.

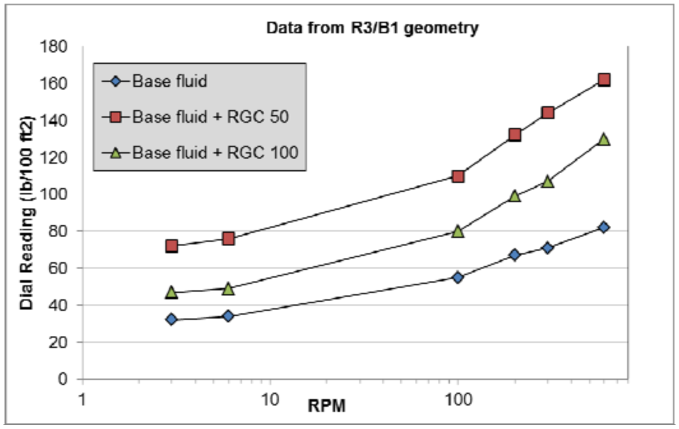

Fig. 4–Viscometer dial readings vs. RPM on the viscometer obtained using the R3/B1 geometry at 120°F for the three fluid samples.

Another important observation from Fig. 2 through Fig. 4 is that, for a given fluid sample (either the base fluid or base fluid + RGC mixture), different dial readings vs. RPM plots were obtained from the geometries with different annular gaps. Shear stress vs. shear rate is an exclusive property of a fluid and should be independent of the geometry used. Therefore, it is expected that, when transformed, the data from the different geometries for a given fluid sample will collapse on a single shear stress vs. shear rate curve. The correlations to transform the dial readings vs. RPM data into the shear stress vs. shear rate form are well-known for the conventional R1/B1 geometry[9]. However, for the wide-gap geometries, R1/B2 and R3/B1, it was challenging to transform the viscometer data into shear stress vs. shear rate data. Novel correlations are developed in this work, especially to transform RPM into shear rate for the wider gap geometries. Based on these correlations, **Fig. 5** shows that for the fluid sample of the base fluid + RGC 50, data from different geometries (R1/B1, R1/B2, and R3/B1) collapses on a single shear stress vs. shear rate curve.

Similarly**, Fig. 6** shows that, for the fluid sample of the base fluid + RGC 100, data from different geometries collapses on a single shear stress vs. shear rate curve. Thus, the novel correlations to transform the viscometer data into shear stress vs. shear rate form for the wide gap geometries have been successfully validated.

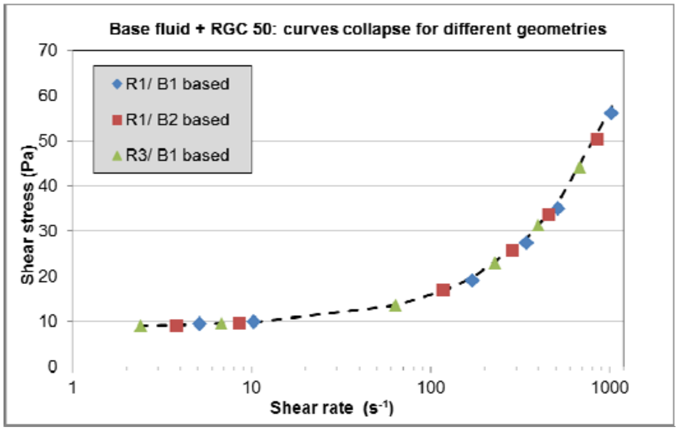

Fig. 5–Shear stress vs. shear rate data obtained by transforming viscometer data from different geometries for the fluid sample of the base fluid + RGC 50, on the viscometer at 120°F.

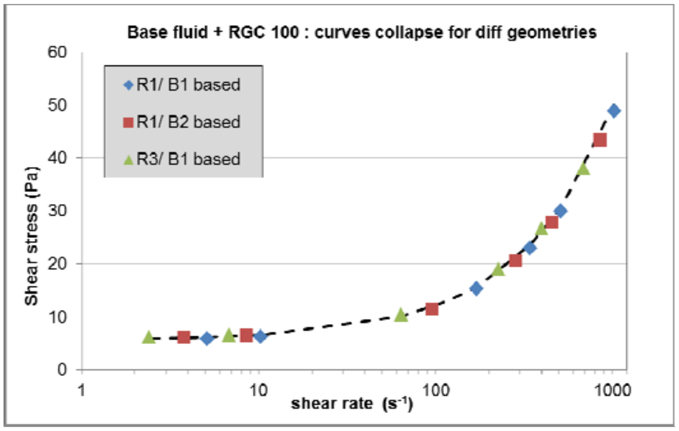

Fig. 6–Shear stress vs. shear rate data obtained by transforming viscometer data from different geometries for the fluid sample of the base fluid + RGC 100, on the viscometer at 120°F.

With the previously described validated correlations, the wide gap geometries can be readily used to estimate the rheology behavior of fluids, especially for the fluids containing larger particulates. As previously noted, for fluids containing the large particulates with D50 ≥ 400 µm, the conventional API geometries cannot be used because of the gap/particle size limitation. The application of wide gap geometries is demonstrated for a fluid sample of the base fluid + RGC 400 (in which RGC 400 added to the base fluid in the amount of 40 lbm/bbl), where RGC 400 has D50~550 µm. **Table 3** shows viscometer data obtained from R1/B2 and R3/B1 geometries for this fluid sample. The viscometer data was transformed into a shear stress vs. shear rate response using the developed correlations for wide gap geometries, as shown in **Fig. 7.** The figure shows that the viscometer data from R1/B2 and R3/B1 geometries collapses on a single shear stress vs. shear rate curve. This behavior confirmed the use of wide gap geometries to accurately estimate the rheology of fluids that contain large particulates (D50 ≥ 400 µm). The estimated rheology behavior can be used for hydraulic calculations in the wellbore.

Table 3–Viscometer Dial Readings at Various RPMs on the Viscometer Obtained for a Fluid Sample of the Base Fluid+ RGC 400 (RGC 400 is added in the amount of 40 lbm/bbl) using the R1B2 and R3/B1 geometries at 120 °F.)

	Base Fluid + RGC 400	
RPM	**Dial Reading: R1/B2 Geometry (lb/100 ft^2)**	**Dial Reading: R3/B1 Geometry (lb/100 ft^2)**
600	75	132
300	67	109
200	54	100
100	43	81
6	26	49
3	25	46

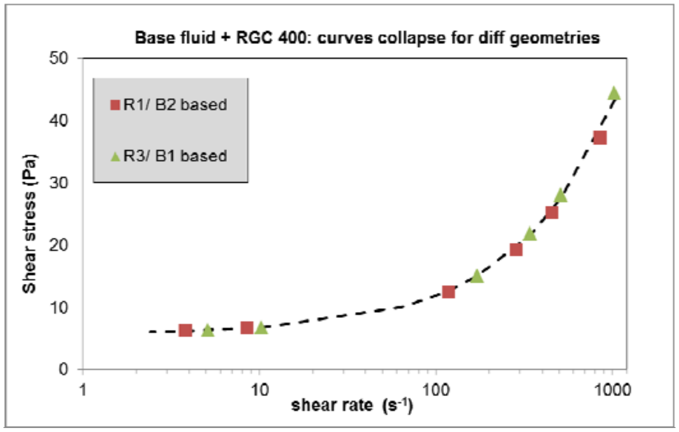

Fig. 7–Shear stress vs. shear rate data obtained by transforming viscometer data from R1/B2 and R3/B1 geometries for the fluid sample of the base fluid + RGC 400 on the viscometer at 120 °F.

A wellbore case study was performed to demonstrate the importance of the work of determining the rheology of fluids containing LCM particulates. The wellbore hydraulics calculations are performed considering the cases of circulation of the base drilling fluid that contains different sizes of RGC particulates.

Fig. 8 shows a schematic of the wellbore. The well depth is approximately 26,600 ft measured depth (MD) and 26,400 ft true vertical depth (TVD). The riser length is approximately 9,000 ft, and the riser inside diameter (ID) is 19.5 in. The casing ID is 12.335 in., and the pipe outside diameter (OD) is 6.625 in. The surface temperature is approximately 50°F, and the bottomhole temperature (BHT) is approximately 250°F. The pumps generate a fluid flowrate of 800 gpm in the well. The hydraulics simulations are performed considering the base fluid described in Table 2 in the wellbore containing RGC particulates of different sizes.

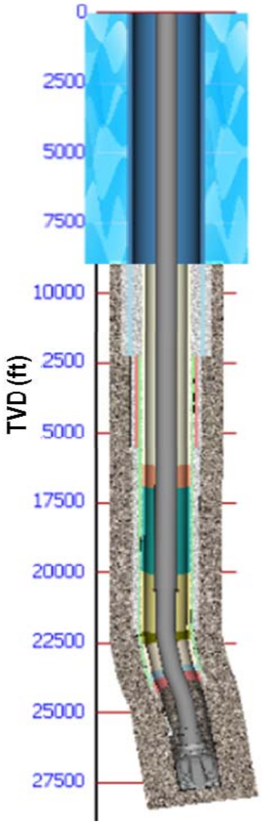

Fig. 8–Schematic of the wellbore used for hydraulics estimations considering the cases of circulation of the base fluid containing different sizes of RGC particulates.

Fig. 9 shows the plot of estimated ECD vs. wellbore depth. An accurate ECD estimate is crucial for wellbore pressure management to ensure that the ECD remains between the fracture and pore pressure gradients at all times. It is also important for the success of critical operations, such as narrow margin wells and managed pressure drilling (MPD). Fig. 9 shows that the circulation of the base fluid in the wellbore at the flowrate of 800 gpm leads to an estimated bottomhole ECD of 14.6 lbm/gal. When RGC 50 particulates (concentration = 40 lbm/bbl) are added to the base fluid, the ECD estimate increases significantly by 0.2 lbm/gal (using rheology data from Fig. 5). However, if the particle size is larger, the effect on ECD is much smaller. For example, the addition of RGC 400 particulates in the same amount only increases the ECD estimate by 0.05 lbm/gal (using rheology data from Fig. 7) as a result of the smaller change in rheology when larger particles are added. The ECD plot underlines the importance of accurate determination rheology of fluids containing particulates and correspondingly, demonstrates significance of using wide gap geometries on viscometers to precisely determine the rheology of fluids containing large particles (D50 ≥ 400 µm).

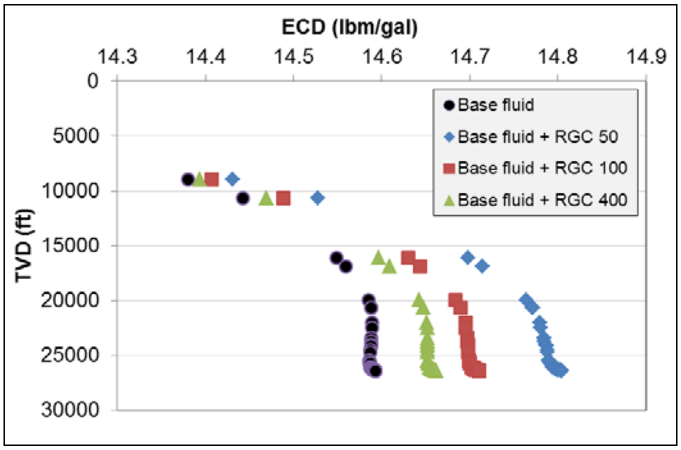

Fig. 9–Estimate of ECD vs. wellbore depth considering the cases of circulation of the base fluid and base fluid containing different sizes of RGC particulates.

Conclusions

- The larger the size of the RGC particulates, the smaller their effect on rheology when these particles are added to the base drilling fluid.
- Novel correlations were developed and validated to transform the viscometer data into shear stress vs. shear rate form for wide gap geometries.
- For fluids containing large size particulates (D50 ≥ 400 µm), the rheology information from wide gap geometries should be used to accurately calculate the ECD in the wellbore and ensure it remains safely between the pore pressure and fracture pressure.

Acknowledgments

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Nomenclature

gpm = gallons per minute
lbm/gal = pounds per gallon
lbm/bbl = pounds per barrel
R1/B1, R1/B2, R3/B1 = rotor/bob geometries on the API-recommended FANN® 35 viscometer

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