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Enhanced Dynamic Lubricity Testing and Drilling Simulation Under Downhole Conditions to Characterize and Differentiate Drilling ROP Enhancers and Lubricants

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Abstract

Differentiating between ROP enhancers and lubricants has always been problematic within the drilling realm. Testing various products using dynamic lubricity (DL) and drilling simulation tests using innovative equipment illustrates how the two are discernible. During testing, the drilling fluids will either interact with a metal-metal (MM) or metal-rock (MR) interface under temperature and pressures intended to imitate downhole conditions. Tests with a series of different additives and varying concentrations to draw correlations on several parameters that the instrument records (primarily looking at the coefficient-of-friction (CoF)). A polymer water-based drilling fluid with a new additive is the main type of fluid. Additives will be categorized in terms of their basic chemistries and functionality. MR interactions will mainly focus on Mancos shale plugs.

Graphs of drilling depth vs. time and CoF vs. torque (lb.·in) to illustrate the efficacy of an additive. This will illustrate a new method to evaluate and prescreen performance-enhancing additives in a drilling fluid in a cost-effective manner and show how a low CoF does not necessarily correlate to a better ROP. The Ring and Block Lubricity test (**Table 5**) showed approximately 45-65% CoF reduction for a new product versus 15-20% reduction for conventional product. When tested on the DLT this trend was confirmed and the results were held in higher confidence (than the R&BT) because the samples were tested with the desired temperatures and pressures. In addition, the drilling rate of mud with conventional and new product showed an increase from 25-30% (see **Table 7**). This data ranks ROP enhancing additives and lubricants in a drilling fluid and its overall performance in comparison to other concentrations as well as other additives.

Introduction

Typically, in the oil and gas industry, drilling with water-based mud (WBM) can give rise to unique challenges. These can be categorized as either metal-to-rock (MR) or metal-to-metal (MM) interactions. MR encompasses challenges that could result in consequences like excessive torque and drag and substandard rates of penetration (ROP). This is partially due to cuttings from the formation getting stuck on the drill bit and bottom-hole assembly (BHA) (also known as “bit-balling” (see **Figure 1**)). The industry has faced these challenges by producing ROP enhancers (ROPE) that can prevent cuttings from adhering to the bit and BHA, thus improving ROPs and overall drilling performance.

The quality and performance of a ROPE depends on its ability to make a fluid less hydrophilic (i.e. more oil wet). Generally, these products are blends of surfactants with an oil-based carrier fluid (e.g. esters, mineral oils, various synthetics). The ROPE consists of varying hydrophobic chemistries which keep the metal surfaces oil wet. The ROPE also needs to be rugged enough to provide continuous treatment to the bit and borehole and support the drilling fluid’s ability to stabilize and suspend drilled cuttings. A successful product will result in better ROPs while observing cleaner bits, pipes, and open-holes. These products may also be instrumental in preventing pack off and may act as accretion inhibitors.

MM interactions are vitally important to understand and mediate and are a well-studied category in tribology as it applies to oil & gas drilling. One of the most frequently referenced and well received concepts is the Stribeck curve. This model correlates the coefficient of friction with 3 factors: the viscosity of the lubricating oil, the load normal to the sliding motion, and the sliding velocity (Wikipedia 2020). The Stribeck curve shows three lubrication zones which are based on interactions between two rubbing surfaces (see **Figure 2**):

1) Boundary lubrication
2) Elastohydrodynamic lubrication and mixed lubrication
3) Hydrodynamic lubrication

Moreover, when testing MM interactions, it is very important for a ROPE to ensure that each lubricity measurement starts with consistent roughness of interacting surfaces and this consistency in surface roughness is maintained throughout the measurement (Zhou et al. 2017). This can be further explained by the Stribeck curve where the surface roughness varies based on friction.

ROPE and Lubricants in the Field

In practice, it has been observed that when drilling deeper bit balling becomes more prevalent (i.e. at higher hydrostatic pressures). Obviously, downhole pressure is a major factor on how the formation interacts with the fluid and thus the drill bit and BHA. If the ideal ROPE chemistry is selected, factors associated with deeper depths will improve torque and drag which will result in better ROPs. In addition, these chemistries must be compatible with all the other components of the drilling fluid.

Mechanism of ROPE vs. Lubricants

In terms of functionality ROPEs and lubricants are discerned based on how they interact with the filter cake and metal surfaces. The driving mechanism of a lubricant is thought of as more of a system within the filter cake and/or are attracted to metal surfaces and form a film thereupon. ROPEs penetrate the filter cake after it has been formed (Patel et al. 2013) and do not have a significant relationship with any metal surfaces. Due to the resulting film and slick filter cake, the lubricant should substantially reduce torque during pipe rotation and drag during trips. On the other hand, the ROPE generally controls bit-balling as, stated before, it is almost primarily interacting with the MR interface.

Established ROPE & Lubricity Testing

Ideally, the best 'test' is a real time field trial that includes a few wells drilled without the addition of the product to serve as a baseline (Davidson et al. 2016); which, of course, is not always practical. Traditionally, products are prescreened via measuring the lubricity coefficient using a ring & block lubricity tester (R&BT). These instruments cause inconsistencies because they do not maintain a reasonably consistent metal roughness (Mettath et al. 2011). This equipment is also limited because measurements are done at lower-than-water-boiling temperatures (there are styles that will heat fluids to 200ºF) and atmospheric pressures (Mettath et al. 2011).

Experimental

The samples tested are based off of a formulation connected to a project with the Daqing Oil Company to improve their drilling process. The base formulation is labeled 'DQWBM'.

Initially samples were prescreened by testing the prospective lubricant in a 3% by volume concentration in one lab-barrel equivalent of fresh water. These samples were hot rolled at 150°F for 16 hours. Coefficients of friction were measured with an R&B lubricity tester (i.e. MM). Afterwards, the best performing samples (i.e. with the lowest coefficient of friction) were then tested (again on the R&BT) in a DQWBM with a specific gravity of 12.5ppg (1.5 g/cm^3). They were hot rolled at 250°F for 16 hours. Rheologies and other standard properties were measured before and after aging.

The best performing additives, in regards to lubricity and mud properties (e.g. rheologies and HTHP fluid loss) were further tested with the dynamic lubricity testing & drilling simulator equipment (DLTDSE) (**Figure 3**). Tests were set to 250°F with a cell pressure of 350 psi. The torque forces applied (at 5 progressive steps) were 60, 120, 170, 260, and 360 lbs. This test can involve either a steel shoe on a metal cylinder (MM) (see **Figure 4**) or a steel shoe on a rock plug (MR). The fluid will change the force of the shoe on the cylinder and the software will record that change accordingly.

The DLT differs from the R&BT because the roughness of metal remains consistent and is run under dynamic conditions at elevated temperatures (up to 500ºF) and pressures (up to 2000 psi). Testing was conducted at 250ºF and 350 psi.

Samples that showed promise from the DLT results were then tested using the drilling simulation (DS) setup. This involves a mini-bit drilling through a small pre-fabricated cylindrical core. The DS parameters used are noted in **Table 1**. Data was recorded by the instrument's software every five seconds.

Results & Discussion

The ROPEs are loosely categorized in **Table 2**. R&BT lubricity results for the five ROPEs are described and presented below in **Table 3** and in **Figure 5**. As is the convention, the samples are tested in fresh water initially. The ROPE samples are all within the range of 0.03 to 0.07.

As shown in **Table 4,** the samples were tested in the 12.5ppg DQWBM. Their mud properties after hot rolling at 250ºF for 16 hours are detailed in **Table 4**. In terms of testing the mud traditionally, lubricity (**Table 5**) and fluid loss were the primary concern. **Figure 6** illustrates that the DQWBM with ROPE 3, 4, & 5 performed better than ROPE 1 & 2 per the R&BT.

Dynamic Lubricity Testing

Figure 7 shows how different loads effect the ROPE samples. This can illustrate how the same samples like ROPE-4 show continuing performance under more force. Samples like ROPE-1 and 2 show a slight increase under more force but are still within desired tolerance. Overall results show that ROPE-4 performed the best. All test results from the DLT are lower than the RB&T results. **Figure 8** groups the samples together in reference to the average CoF per stage to see if any trends can be discerned.

Discussion on comparing DLT (MM vs MR)

Additional DLT was performed to determine if there were any differences between MM and MR with or without ROPE. This was executed with both MM and MR (the rock being Barnett shale) schemes. **Figures 9** and **10** show the CoFs for both tests, ROPE-2 was selected for demonstration purposes. These tests showed similar results with a slightly higher CoF when the applied torque is 200 lbs. and under. This confirmed that the roughness of the surface of the core sample is not initially 'smooth'. The CoF equalizes because the surface becomes 'polished' from the friction, thus the CoFs become similar to the MM data.

Drilling Simulator Testing

The samples were then tested with the DS setup on the DLTDSE to measure each ROPE on its rate of penetration. Mancos shale was chosen as the rock due to its similarities to the formation in question. It has a lithological composition as a sand-silt shale. Mancos shale also has a similar makeup as far as being a gas-bearing formation at a similar stage of maturity (midlife).

Testing using the DS scheme (**Figure 11**) is performed on the DQWBM using the ROPE samples validated from the DLT (see **Figure 12**). Initially, the drilling rate was observed to be higher for the first 0.35-0.4 inch (which took 20-25 seconds). After which, the ROP slows down. This is due to the fact that this test does not simulate 'mud circulation' therefore the resultant drilled solids remain in the hole and coalesce around the drill bit. This may appear inconvenient, however this could provide insight towards the effectiveness of the overall fluid. **Figure 13** illustrates how one can observe the real time drill rate to compare samples. (Not all samples are shown for visual convenience). **Table 6** is the summary of the samples' drilling speed.

Tables

Table 1: DS Testing Parameters

Parameter	Value
Drilling Media	One-inch core plug (Mancos Shale)
Drill bit rotation	60 rpm
Weight on bit	60 psi (compressed air) 150 lbs. (support force)
Cell Temperature	250ºF
Cell Pressure	350 psi

Table 2: Generalized ROPEs

Product	Description
ROPE-1	Daqing commercial lubricant
ROPE-2	Field-Experimental ROP enhancer, blend of synthetic paraffin, and fatty acid derivatives
ROPE-3	Lab-Experimental additive, hydrotreated light distillates (C13-C18 hydrocarbon <2% aromatics)
ROPE-4	Lab-Experimental additive, TOFA, C14-16 alkenes
ROPE-5	Lab-Experimental additive, ester base oil

Table 3: R&BT lubricity results in fresh water after hot rolling at 150°F/16 hrs. at 3% by volume.

	ROPE-1	ROPE-2	ROPE-3	ROPE-4	ROPE-5
CoF	0.053	0.065	0.040	0.035	0.050
% Torque Reduction	80.9	75.6	85.8	85.2	80.5

Table 4: Mud properties with the respective ROPE

	DQWBM	**ROPE-1**	**ROPE-2**	**ROPE-3**	**ROPE-4**	**ROPE-5**
Temp (F), 120F	**AHR**	**AHR**	**AHR**	**AHR**	**AHR**	**AHR**
600	70.0	69.7	73.3	95.7	69.7	67.9
300	46.2	45.1	46.6	61.5	43.6	39.5
200	37	35.5	36.3	48.0	33.5	30.6
100	24.8	23.9	23.7	32.4	21.8	19.9
6	5.5	5.5	4.7	7.3	4.3	3.6
3	4.2	3.9	3.4	5.4	3.3	2.6
PV (15-45)	23.8	24.6	26.7	34.2	26.1	28.4
YP (10-50)	22.4	20.5	19.9	27.3	17.5	11.1
10" (2-14)	4.1	4.5	15.6	6.0	4.3	3.1
10' (4-50)	13.4	9.1	3.5	12.4	11.1	5.0
API HTHP fluid loss, mL	12	7	6	7	7	10

Table 5: R&BT Lubricity results in 12.5 ppg DQWBM after hot rolling at 250°F/16 hrs. at 3% by volume

	DQWBM	ROPE-1	ROPE-2	ROPE-3	ROPE-4	ROPE-5
CoF	0.22	0.187	0.181	0.121	0.071	0.140
% Torque Reduction	0.0	14.80	17.27	44.72	67.49	34.69

Table 6: Drilling time (sec) of Mancos shale (drilling 7/8-inch-deep of one inch core) for several ROPE in DQWBM.

ROPE Lubricants	Drill Time in Sec.	
ROPE-4	121	Fast drilling
ROPE-4 rpt.	135	↓
ROPE-5	148	
ROPE-2	160	
DQWBM	168	
ROPE-1	192	
ROPE-3	230	Slow drilling

Table 7: Summary for Conclusion

ROPE	Rheology, change from BM ,%	HTHP Fluid Loss, mL	Ring & Block CoF	% Reduction	DLT, (CoF)	DS, Drilling (seconds)
BM/DQWBM	-	12	0.22	0	0.25	168
ROPE-1	No change	7	0.19	15	0.05-0.06	192
ROPE-2	No change	6	0.18	18	0.07	160
ROPE-3	10-12 %	7	0.12	45	0.05	230
ROPE-4	No change	7	0.07	68	0.04-0.05	135
ROPE-5	No change	7	0.14	35	0.05	148

Figures

Figure 1: Picture of Bit Balling

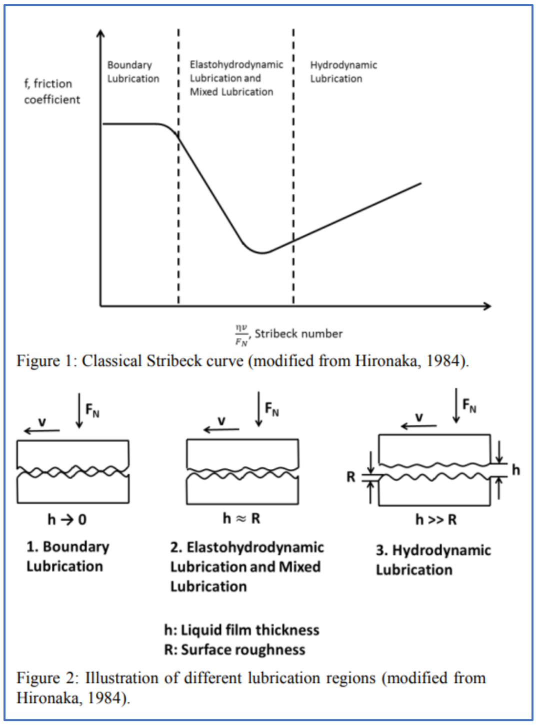

Figure 1: Classical Stribeck curve (modified from Hironaka, 1984).

Figure 2: Illustration of different lubrication regions (modified from Hironaka, 1984).

Figure 2: Stribeck Curve and Various Lubrication Types (Zhou et al. 2017)

Figure 3-Picture of DLTDS Equipment

Figure 4 - a) DLT steel and rubbing shoe,
b) Steel block after test with a visible "ring"

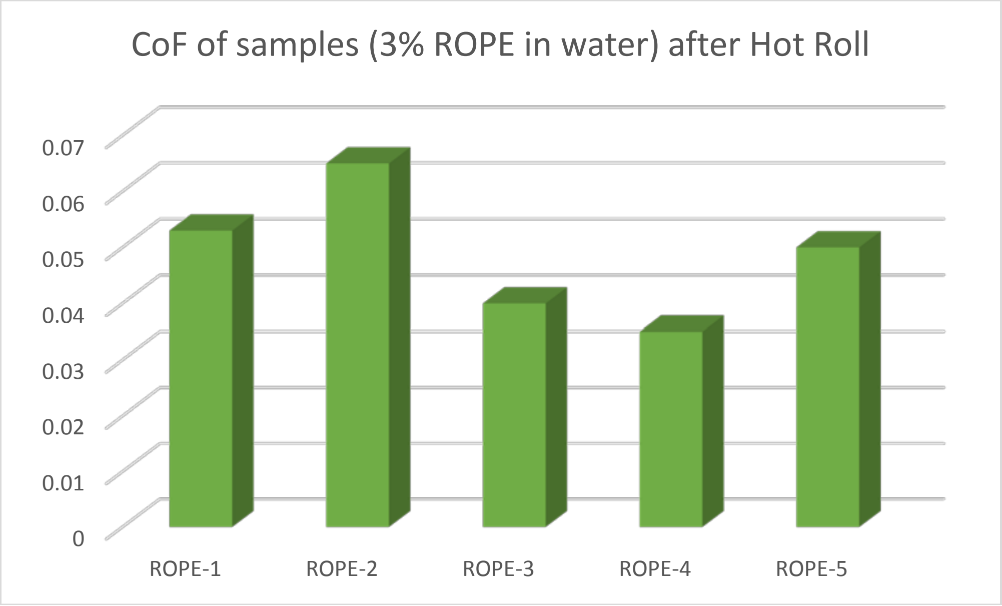

Figure 5– R&BT CoF results after hot rolling at 150°F/16 hrs. at 3% by volume in fresh water

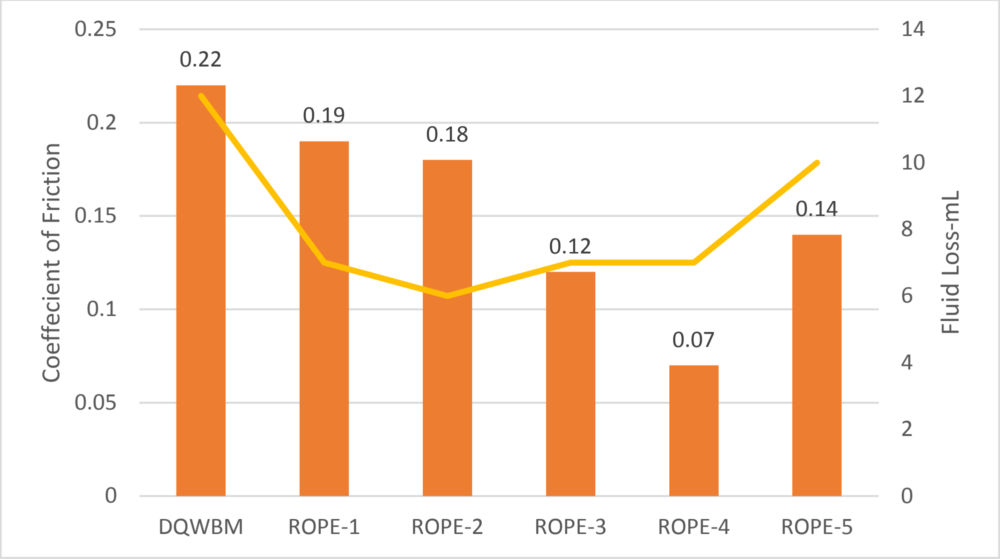

Figure 6-R&BT CoF and Fluid Loss of DQWBM with and without ROPEs

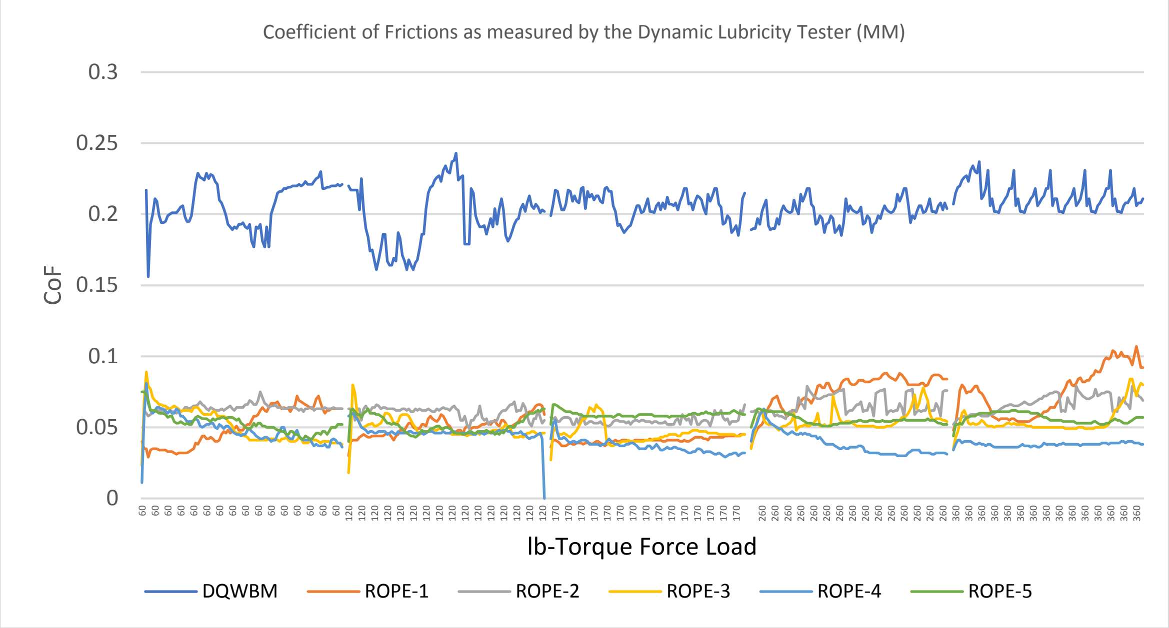

Figure 7 - DLT (MM) at 250°F and 350 psi for the ROPEs in 12.5 ppg of DQWBM

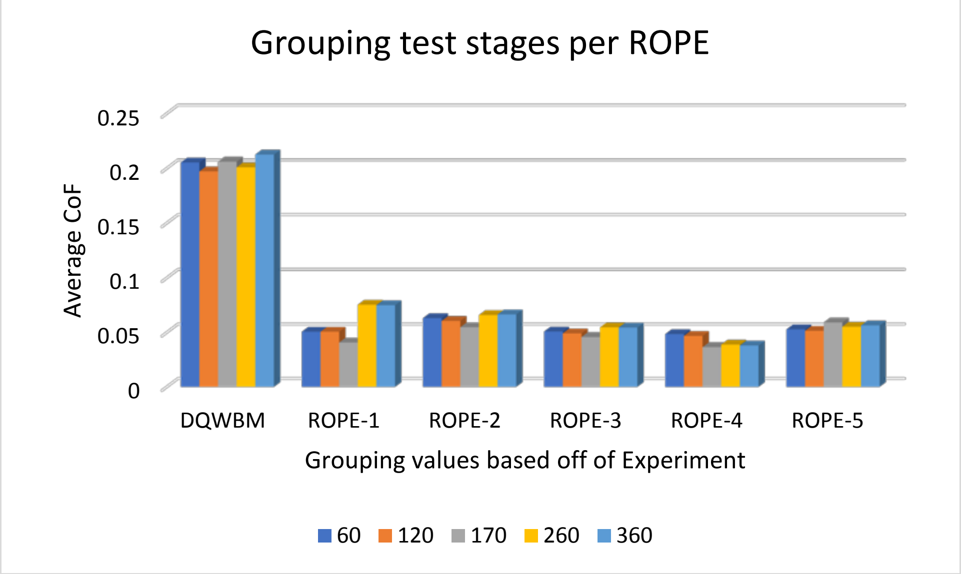

Figure 8: Average CoF (from Figure 7) from DLT to compare the different stages

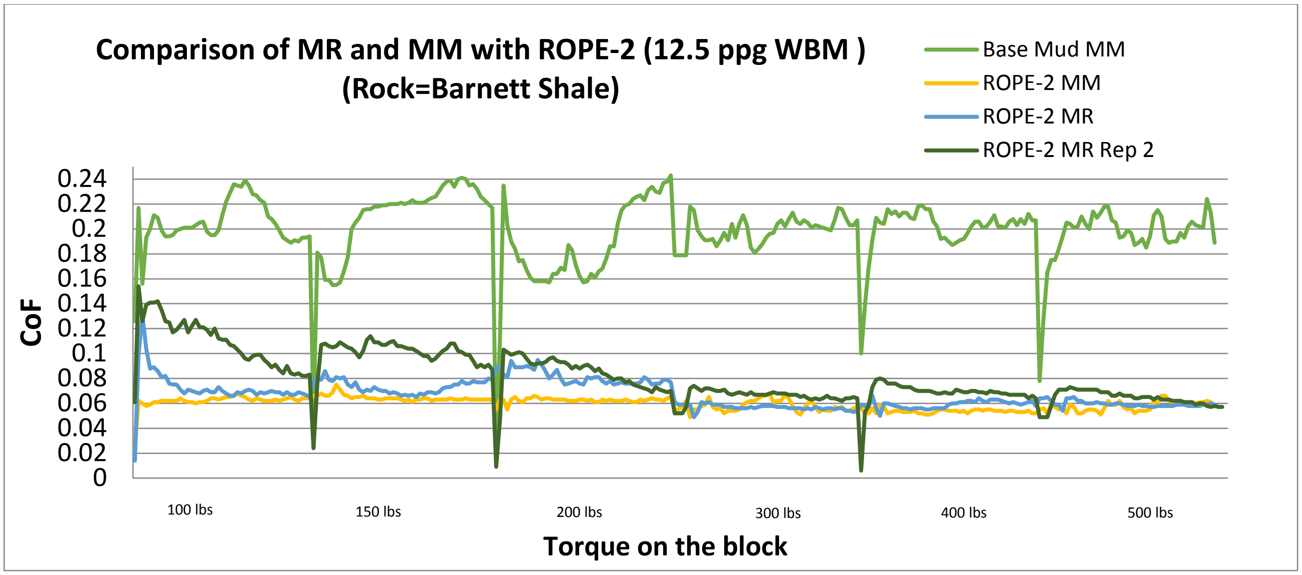

Figure 9 - DLT (MM vs MR) at 250°F and 350 psi for 12.5 ppg of DQWBM-ROPE 2

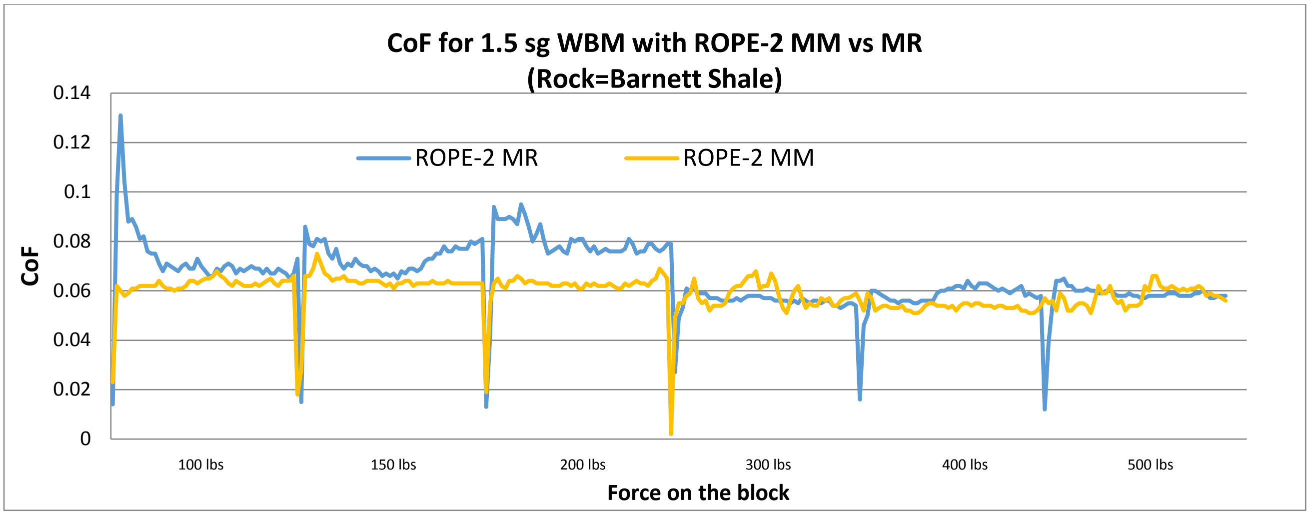

Figure 10: Dynamic Lubricity test on MM and MR at 250°F and 350 Psi for 12.5 ppg of DQWBM with various additives

Figure 11 – DS accessories. Drill bit with spindle blade (left).
Mancos core drilled to 7/8 inch with total 1.5inch diameter and 1inch height (right).

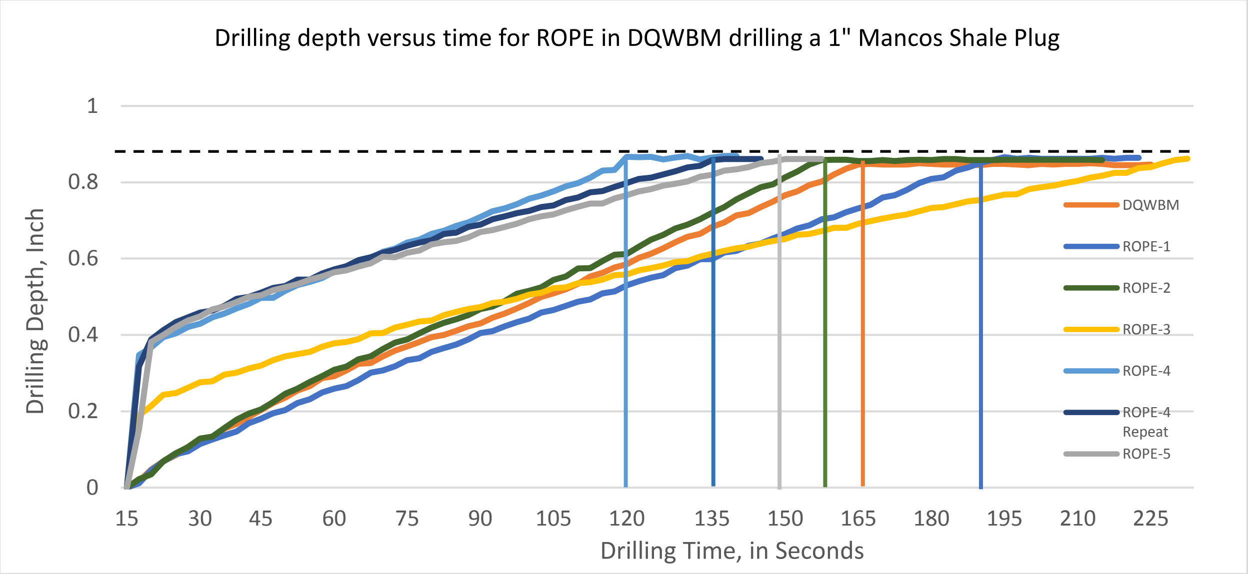

Figure 12 – Graph of drilling ROPE data for each respective ROPE in 12.5 ppg DQWBM

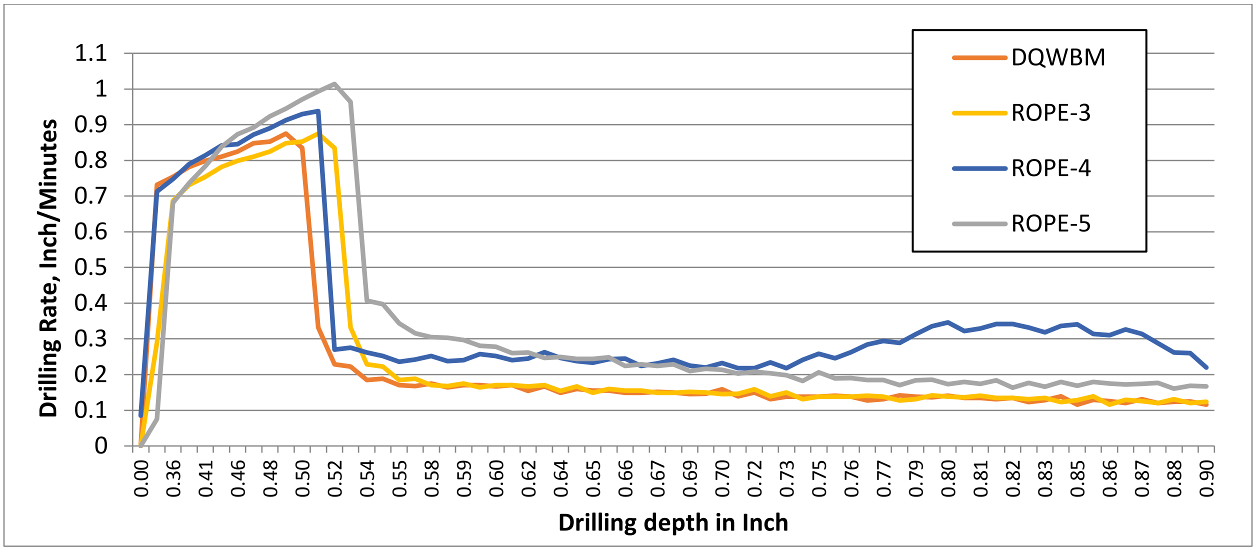

Figure 13 – Graph depicting drilling rate (in/min) versus depth (in) using 12.5ppg DQWBM without and with ROPE

Conclusions

To conclude and summarize, 6 samples were tested (including the base mud) via R&BT, DLT, and DS. Looking at both sets of data from the traditional R&BT and DLT, all samples showed promising lubrication results. Looking at the DS data one can see that at least 2 samples can be selected out of the 6 as improving the ROP. Here ROPE-4 has both exemplary lubrication and the best ROP and was thus moved forward for further testing and a field trial. See **Table 7** for a condensed summary of the data.

The results with the DLT are much more lower than the results from the R&BT. This is probably due to the fact that during testing the mud is under temperature and pressure which helps lubricate the surfaces.

The best practice to evaluate ROPE's would be:

- Initially screen samples with R&BT at ambient conditions.
- Then test the best samples from R&BT with DLTDSE using the DLT (MM) setup to evaluate their performance under downhole conditions.
- Next test the samples on the DLTDSE with the DS (MR) scheme (under downhole conditions) to determine the drilling rate as a function of time.

Below is a summary of the findings found in this study:

1. ROPEs added to base mud do not have any or significant impact on mud properties after hot rolling. Coefficient of friction of muds treated with ROPEs are within desirable ranges.
2. DLT data showed lower CoF than R&BT lubricity tester. No samples stood out significantly.
3. DS testing showed a preference for sample ROPE-4 and an interest with ROPE-5.
4. ROPE-3 could also be considered as a ROPE.
5. ROPEs 1 & 2 could still be favorable lubricants but not necessarily ROPEs.

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Nomenclature

API =*American Petroleum Institute*
BHA = *Bottomhole assembly*
CoF =*Coefficient of Friction*
DL =*Dynamic Lubricity (Testing or Equipment)*
DLT =*Dynamic Lubricity Test*
DLTDSE=*Dynamic Lubricity Testing & Drilling Simulator Equipment*
DQWBM=*Daqing Water Based Mud*
DS =*Drilling Simulator (Test or Equipment)*
HTHP =*High Temperature High Pressure*
in =*inch*
lbs =*pounds*
MM =*Metal-Metal*
MR =*Metal-Rock*
ppg =*pounds per gallon*
psi =*pounds per square inch*
PV =*Plastic Viscosity*
R&BT =*Ring and Block Test (or Tester)*
ROP =*Rate of Penetration*
ROPE =*Rate of Penetration Enhancer*
rpm =*rotations per minute*
WBM =*Water Based Mud*
YP =*Yield Point*

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Suggested Reading

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