

Experimental Study of Torque-Reducing Additives for Extended Reach Drilling

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Abstract

As development of oil and gas fields pushes drilling deeper and farther, well profiles are becoming more complex and frictional loads are increasing, particularly between the wellbore and the drillstring. With drilling now being extended for miles, it has become critical to lubricate the wellbore to achieve lower friction, so that the resulting torque does not exceed the capacity of the top drive.

The driller has many options for reducing wellbore/drillstring friction, including liquid lubricants, mechanical subs and drillpipe protectors. Solid lubricants (sometimes called mechanical lubricants) also have made their way into the drilling arena. They generally have the advantages of being chemically inert and environmentally friendly. Solid lubricants, which are subject of this study, offer considerable promise for long-lasting friction reduction with minimal side effects.

This paper describes a laboratory investigation of the effects of solid lubricants on torque reduction in drilling. As the industry does not possess a standard method to evaluate the performance of solid lubricants, several protocols were developed, that are complementary and give consistent results. The tests were carried out in a Stickance™ Tester, the Drag Lubricity Tester, the Torque Lubricity Tester and the Small Indoor Flow Loop at the University of Tulsa. Solid lubricants added to water-based drilling fluid were tested in a flow loop designed to simulate pipe rotation in casing. Experimental results indicate that reduction of the coefficient of friction, μ , depends on the shape and size of lubricants. The effects on lubricant performance based on drilling parameters like flow rate and pipe rotation rate, along with physical characteristics of the solid lubricants, are discussed. The findings of this paper can aid drilling personnel in selection of solid lubricants to minimize torque in extended reach drilling (ERD).

Introduction

In today's world of drilling engineering, extended reach drilling (ERD) has created a revolution in thought and reach. ERD is more economical and environmentally friendly, but the well profiles that are often required are more difficult to drill. With the change of well inclinations from vertical to highly inclined and the extension of wells to targets beyond the horizon, drillers are faced with unique challenges to control the magnitude of torque and drag.¹

Importance of Torque Management

Excessive torque and drag can cause a drilling operation to exceed critical limitations, such as top-drive and derrick lifting capacities, drillstring design and failure to land a casing string.² These effects impact the efficiency of drilling a quality hole with available rig capacities at stipulated time and cost. Maehs et al.³ mention that surface torque is becoming an important factor in the decision-making process to determine if certain wells can be drilled or not. Friction is an important factor that makes a major contribution to the magnitude of torque, as well as drag.

To demonstrate the importance of friction, an example is considered. For a simple extended reach well consisting of a build-up and horizontal section with measured depth of 11,000 feet long, the calculated torque capacity of top drive is about 9,800 ft-lb for a coefficient of friction, μ , of 0.3.

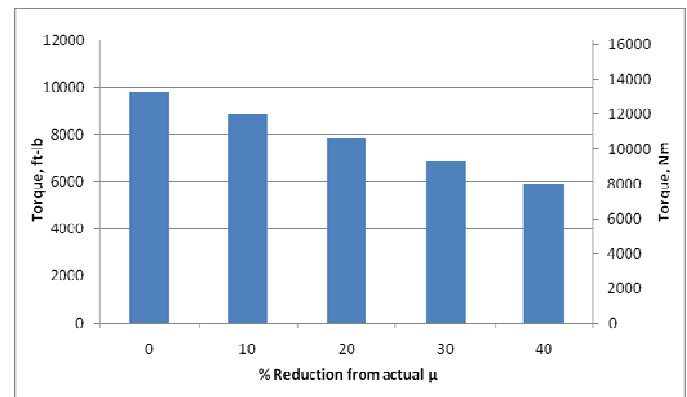


Figure 1: Torque vs. Percentage reduction of μ

From Fig. 1, if μ decreases by 40%, the torque for the top drive also decreases approximately 40%. Through modification of μ , torque may be controlled at a level that can make the difference between a successful and an unsuccessful operation. Hence the management of torque has become a crucial part of both well design and well operations.

Solid Lubricants

The sources of torque and drag are numerous and include cuttings beds, filter cake, hole instability, doglegs, keyseating and bit balling. Quigley⁴ noted that mud lubricants are commonly used to treat these problems, because they can lower the coefficient of friction, improve filter cake, stabilize the wellbore and reduce bit balling. The first two mechanisms

can be tested in the laboratory; the latter two are best evaluated with rigorous field tests.

As noted by Cameron et al.,¹ experience on world-record ERD operations led to the discovery that certain fibrous lost circulation materials (LCM) have the ability to enhance hole cleaning and dramatically reduce torque and drag in inclined and horizontal wellbores.

Substantiating the above statement, Robertson et al.⁵ noted that the addition of certain LCM had a profound impact on torque and drag. Use of some LCM to drill extended reach sidetrack wells in Wytch Farm resulted in a significant reduction (30-45%) of torque. Reduction in torque is believed in many cases to be the result of a combination of better hole cleaning and increased lubricity, but limited information is available about the optimum quantity of solid additives to use and the resulting magnitude of torque reduction.

Aston et al.⁶ and Knox et al.⁷ noted that most solid lubricants have the advantage of being compatible with all mud chemistries. By contrast, liquid lubricants are often limited to certain mud chemistries and narrow pressure/temperature windows. For example, many effective water-based liquid lubricants contain surfactants and non-aqueous fluids (NAF). The surfactants can act as emulsifiers for the NAF and help to transport it to the targeted contact surfaces. However, in the presence of some drilling fluids and under moderate shear conditions, the combination of NAF, surfactant and components in the drilling fluid can produce invert emulsions with a consistency of cottage cheese, or they can "grease out" on barite weighing agent. High pH and/or high-divalent-ion environments (Ca^{2+} , Mg^{2+}) may accelerate this process. Hydrolysis also can occur under those conditions. Not only do these processes deplete the drilling fluid of lubricant, but formation of cheese- or grease-like products can blind shaker screens and the completion assembly and damage production zones. None of the compatibility issues that plague liquid lubricants applies to solid lubricants, since they generally are chemically inert.

Characterization of Solid Lubricants

In this study, five candidate solid lubricants were tested. The following table shows some physical characteristics of these materials:

Table 1: Characterization of solid lubricants					
Solids	Density	Min. Dimen.	Aspect ratio	Shape	Size
	gm/cc	mm			
S1	1.27	-	-	Granular	Irregular
S2	1.25	1.66	1.99	Cylindrical	Uniform
S3	1.07	0.4	1	Spherical	Uniform
S4	1.01	0.2	1	Spherical	Uniform
S5	1.14	0.37	-	Granular	Irregular

S1 has a very broad particle size distribution (PSD). S5 was created from S1 by removing the front and back tails of

the PSD i.e. the very large and very fine fraction; the result is a material with a PSD that ranges from 150-850 μm .

Experiments on Solid Lubricants

Currently, the industry does not possess a standard method or apparatus for testing solid lubricants. Consequently, several techniques were developed and employed to evaluate the candidate materials. These included modifications of devices available in the industry, prototype lubricity testers, and flow loops at Tulsa University Drilling Research Projects (TUDRP).

Stickance™ Tester

The Stickance Tester (**Fig.A1** in the Appendix) was built by Schlumberger in association with the University of Cambridge to measure the differential stickiness of the filter cake. This apparatus consists of a test cell, a spherical bob, a measuring head and an electronic control data acquisition panel.

The test method was modified to accommodate the candidate solid lubricants. Instead of mud cake, a bed of lubricant particles was laid in the bottom of the test cell and covered with water. Then the bob, made of polished steel and fitted with wires, was lowered into the slurry to a fixed depth, the bob was rotated at a prescribed rate, and the steady state torque was measured. A schematic diagram of the test cell is shown in **Fig. 2**.

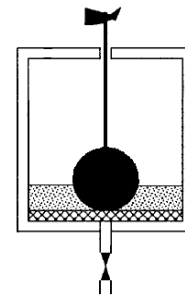


Figure 2: Schematic of Stickance Tester test cell.⁸

The body of the test cell consists of a double-ended mud filtration cell. The top end cap is perforated to allow entry of a steel wire. The end of the wire in the cell is fixed to the spherical bob; the end of the wire protruding out of the cell is connected to the electronic torque gauge. The simple design of the frame allows all the components to be supported and positioned precisely.⁸ All tests were performed at atmospheric pressure and temperature.

Experiments were conducted with S1, S2, S3 and S4 for a period of 15 min each. The measured torque is the force required to rotate the bob when in contact with the solids. From the results shown in **Fig. 3** it is clear that the magnitude of the measured torque varies from one lubricant to another. The plastic beads (S2, S3 and S4) yielded lower torque than the granular materials (S1), and it appears that the spherical beads (S3 and S4) perform a little better than the cylinders (S2).

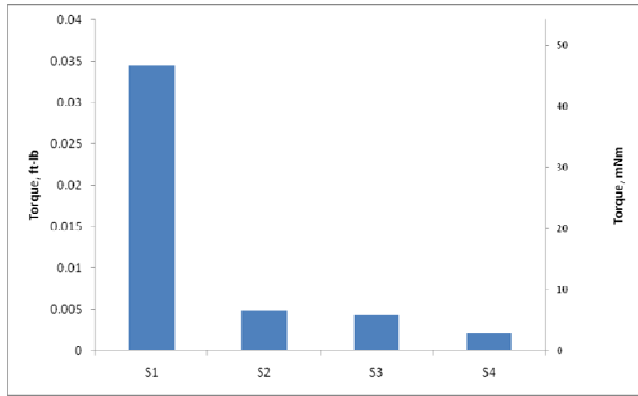


Figure 3: Torque measured with various solid lubricants in the Stickance tester.

Drag Lubricity Tester (DLT)

Results from the Stickance Tester indicated differences in the performance of the solid lubricants. While running that device, it was noted that the dynamic interface of the bob and test cell resembles two parallel plates sliding over each other. This led to the design and construction of a device with that geometry, namely the Drag Lubricity Tester (DLT).

As shown in **Fig. 4**, the DLT is a very basic device that consists of a block of mass m_1 that is pulled along a surface by a cable that travels over a pulley (assumed to be frictionless) and is attached to another block whose mass m_2 is used to pull the first block along. When a body is moving on a surface, there is an opposing force due to friction. Additional force is required to overcome this friction to move and keep the body in motion. The amount of friction depends on the roughness and type of the surface on which mass m_1 is moving.

When m_2 started moving down, m_1 starts to slide towards the pulley. For two given contact surfaces, acceleration of m_1 will vary in a manner that is inversely proportional to the surface roughness. Surfaces can be made smoother by covering the rough surface spots or by providing the objects a means to slide. Liquid lubricants conventionally are used to cover up the rough spots and provide a film to slide upon. Solid lubricants may serve as rollers or ball bearings and yield a similar result.

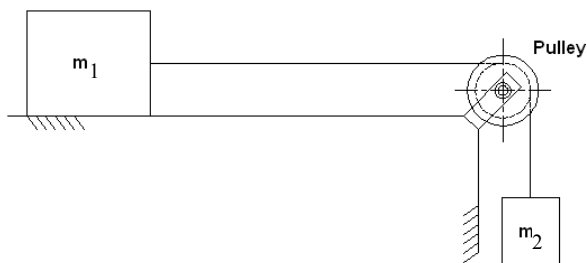


Figure 4: DLT Concept

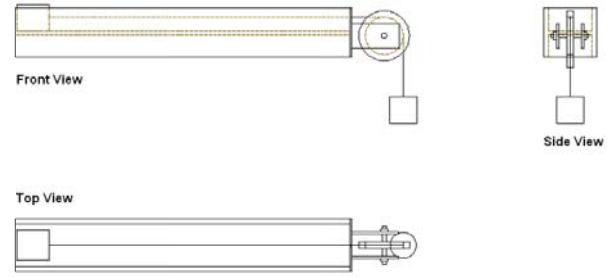


Figure 5: Schematic of DLT

Fig. 5 shows the setup of the DLT. It consists of a test section made of the H beam whose ends are closed to hold the candidate solid lubricants. A non-stretchable string is attached to both blocks. A pulley mounted on one end helps to guide the string. The entire section is positioned on a stand and adjusted to near horizontal.

At the beginning of the test, the m_1 block is placed at the end of the test section furthest from the pulley. Graduations on the test section mark the position of the m_1 block, whose movement is captured on video until it comes to rest at the conclusion of the test. Frames are generated from this video at known intervals of time, and the location of block m_1 is noted for each one. From consecutive frames, the differences in distance and time are used to calculate the velocity and acceleration of the block. From the force balance equation (see **Fig. A2** for a schematic of the relationships among the variables), the acceleration of the block can be related to coefficient of friction, μ , as given by Equation (1).^{9, 10}

$$\mu = \frac{m_2 g - a(m_1 + m_2)}{m_1 g} \quad (1)$$

Solids are added and distributed uniformly along the test section. Tests are performed for candidate solid lubricants at different concentrations. The performance trend of the solid lubricants in the DLT was similar to the pattern observed in the Stickance Tester, i.e. S3 and S4 gave lower μ than S2 and much lower than S1.

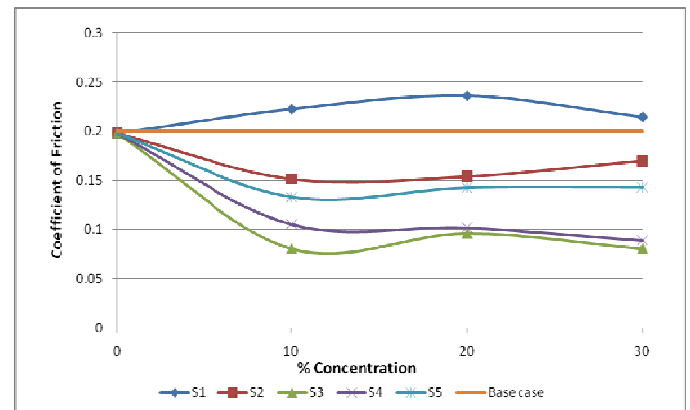


Figure 6: Coefficient of Friction vs. % Concentration of solid lubricants for experiments on DLT

In **Fig. 6**, solid S1 appeared to increase μ . In all cases, increasing the concentration of solids showed no significant change in the μ .

Torque Lubricity Tester (TLT)

While the measurement of drag with the DLT appeared to provide a way of differentiating potential solid lubricants, a primary objective of the project was to develop a way to determine μ in a torque-measuring device that simulated ERD wells more directly than the Stickance Tester. Thus was born the idea for the Torque Lubricity Tester, or TLT.

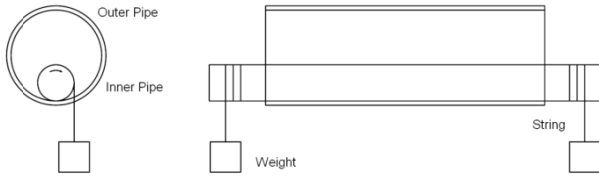


Figure 7: Schematic of TLT

The device that was built consists of inner and outer pipes which are placed eccentrically as shown in **Fig. 7**. The entire assembly is positioned horizontally to simulate a section of horizontal wellbore. The length of the inner pipe is greater than the outer pipe. Buckets are tied to strings which are wound on both ends of the inner pipe. River gravel is used as the weighting material, so as to have the flexibility of varying the weights. Candidate lubricants are spread uniformly inside the outer pipe. Weight is increased in both the buckets uniformly in steps until the inner pipe starts to rotate. Referring to the free body diagram (**Fig. A3** in the Appendix), μ can be determined from Equation (2).⁹

$$\mu = \frac{w_g}{(\sqrt{w_p} * \sqrt{(w_p + 2 w_g)})} \quad (2)$$

Tests were conducted at different concentrations of solid lubricants. The results are shown in **Fig. 8**. Comparison of the results from the TLT and DLT shows that in both types of experiments the μ generated with the solid lubricants increased (and the performance decreased) in the order

$$\mu_{S3} < \mu_{S4} < \mu_{S5} < \mu_{S2} < \mu_{S1}$$

This trend is similar to what was observed in the Stickance Tester, but with S3 and S4 reversed. As with the DLT, the TLT showed no improvement upon increasing the concentration of lubricant.

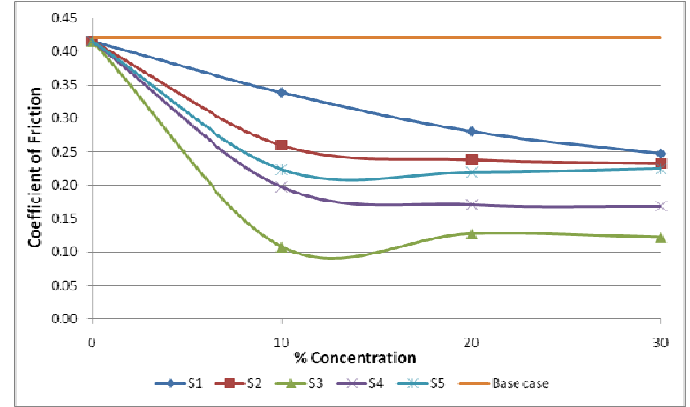


Figure 8: Coefficient of Friction vs. % Concentration of Solid Lubricants for experiments on TLT

Small Indoor Flow Loop (SIFL)

Tests were carried out in the Small Indoor Flow Loop (**Fig. A4** in the Appendix), or SIFL, to provide some insight about the mechanism by which solid lubricants reduce friction between casing and drillstring.

The SIFL consists of a 12-ft long test section made of a 2-inch polycarbonate transparent outer tube and a 1-inch inner pipe made of stainless steel. Two centrifugal pumps configured in series to generate maximum flow capacity of 32 gal/min are used to circulate the fluid in the flow loop. A 20-gal mixing tank is used to prepare the test drilling fluid. A torque meter installed on one end of the drill shaft is used to measure torque. Data measured from the flow loop are monitored and recorded through a data acquisition system.

The SIFL tests were divided into two stages. In the first stage, the experiments were conducted with the neat drilling fluid. This fluid, which consisted of a 1.25-lb/bbl polyanionic Cellulose (PAC) in fresh water, possessed a viscosity describable by a Power Law equation with Consistency Index of 0.24 lb_f-sⁿ/100 ft² and Flow Behavior Index of 0.71. In the second stage of the SIFL tests, candidate solid lubricants were added to the fluid.

The experimental test matrix used a Taguchi¹¹ design for three variables at three levels (**Table A1** in the Appendix). The Taguchi method relies on an ANOVA¹¹ technique to analyze the effect of variables on μ . The results are summarized in **Fig. 9-13**.

Fig. 9 shows the effect of various parameters on the performance of solid lubricant S2. Initially, it was thought that the cylindrical solids would align along the direction of flow (drillpipe axis of rotation) and act as rollers to reduce friction. But the experimental observations indicate that alignment is not uniform. ANOVA analysis shows that the flow rate may have a major role in aligning these cylindrical lubricants and affect the performance. The high percentage error may be the result of a low probability that alignment of all of the solids would be similar in all the tests (**Fig. 10**).

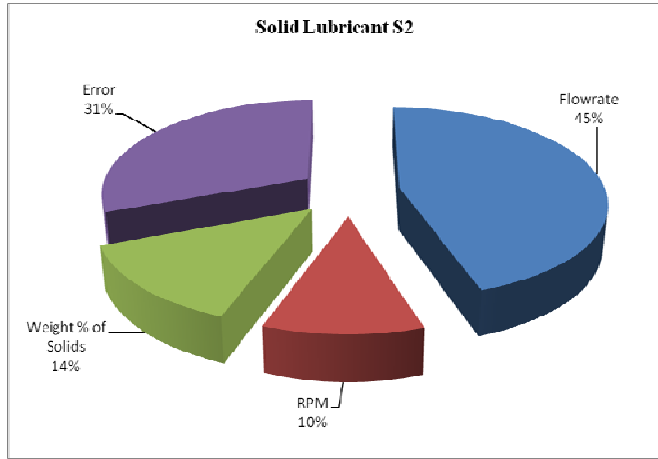


Figure 9: Effect of various parameters on the performance of solid lubricant S2.

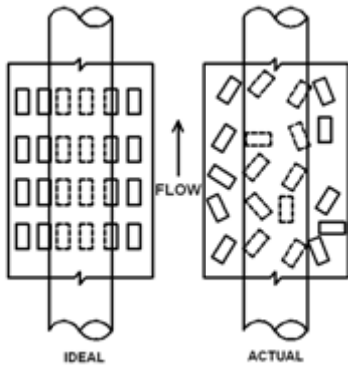


Figure 10: Alignment of solid lubricant S5.

ANOVA analysis of the results for lubricant S3 (Fig. 11) indicates that RPM (rate of rotation) is the dominant factor in the performance of these particles, which are spherical in shape and of uniform in size. This is consistent with the assumption that these solid lubricants behave as ball bearings between the surfaces. Flow rate and concentration have minimal effects compared to RPM.

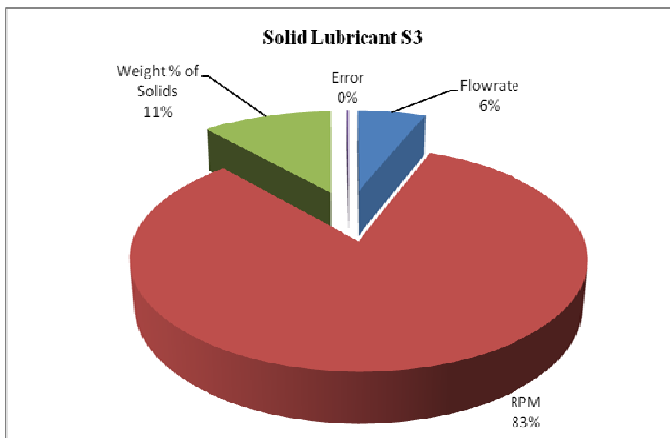


Figure 11: Effect of various parameters on the performance of solid lubricant S3.

The effects of various parameters on the performance of lubricant S4 are shown in the Fig. 12. RPM followed by concentration are the dominant factors for lubricant S4. Flow rate has a minimal effect on performance, as it did for lubricant S3. Like lubricant S3, lubricant S4 particles are spherical with a narrow particle size distribution, but they are half the size of the S3 particles. Thus with smaller size, the concentration (weight percent) of S4 in the test section appears to play a greater role in the performance of this lubricant.

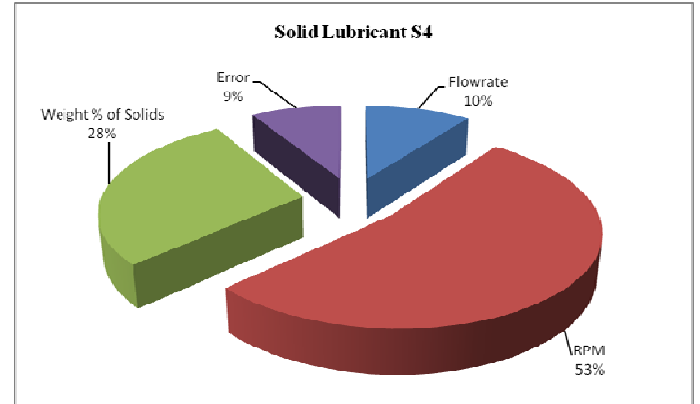


Figure 12: Effect of various parameters on the performance of solid lubricant S4.

Fig. 13 shows the effects of various parameters on the performance of lubricant S5. Concentration plays a dominant role for this lubricant. As the concentration of the material increases the lubricity effects becomes more pronounced.

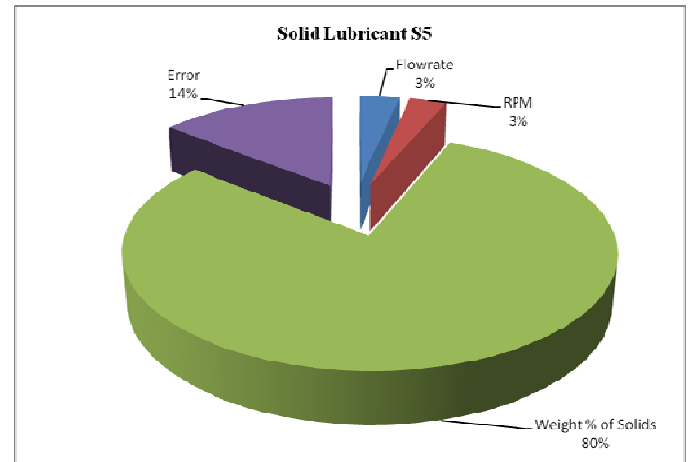


Figure 13: Effect of various parameters on the performance of solid lubricant S5.

From the results of the SIFL tests, % Lubricity can be calculated and used to evaluate the performance and effectiveness of each lubricant. The following equation is used to determine the lubricity:¹²

$$\% \text{ Lubricity} = \frac{\mu_{\text{base}} - \mu_{\text{lubricant}}}{\mu_{\text{base}}} \cdot 100\% \quad (3)$$

where $\mu_{\text{lubricant}}$ = coefficient of friction with the candidate lubricant in the base fluid, and μ_{base} = coefficient of friction with the neat base fluid.

In Equation (3), if the value of % Lubricity is positive, it implies that there is a decrease in μ as compared to the neat base fluid (no lubricants) and vice-versa. **Table 2** in the Appendix gives the % Lubricity for different solid lubricants at different SIFL test conditions. As before, S3 and S4 were far superior to S2 and S5. However, for these tests, S3 and S4 provided similar, though high, levels of lubricity (as in the Stickance™ tests), and S2 and S5 were both very poor and in most cases decreased the lubricity bestowed by the base fluid alone.

Conclusions and Recommendations

1. Several test methods have been developed which demonstrate reduced torque and drag of proven solid lubricants for drilling fluids and permit differentiation of their performance.
2. Shape and size of solid additives play important roles in their performance as drilling fluid lubricants.
3. In the tests performed in this work, uniform spherical beads, provided greater reduction in torque and drag than cylindrical beads, which perform better than granular material.
4. In the DLT and TLT, beads measuring 0.4 mm in diameter performed better than beads measuring 0.2 mm in diameter, but in the Stickance Tester and the SIFL there was little difference in performance.
5. Each candidate solid lubricant showed different dependencies on experimental variables, a result attributable to the different physical characteristics of each type of lubricant.
6. Further study of shape and size and other physical properties, as well as mechanical properties, is recommended to improve our understanding and optimize the design of solid lubricants.

Acknowledgements

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Nomenclature

a	=	Acceleration of the object, m/s ²
g	=	Gravitational Constant, 9.81 m/s ²
M	=	Torque, ft-lb
m ₁	=	Mass of object 1, g
m ₂	=	Mass of object 2, g
N	=	Normal Force, lb

w _g	=	Weight of gravel + buckets, lb _m
w _p	=	Weight of inner pipe, lb _m
μ	=	Coefficient of friction (COF)

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Appendix



Figure A1: Stickance Tester.

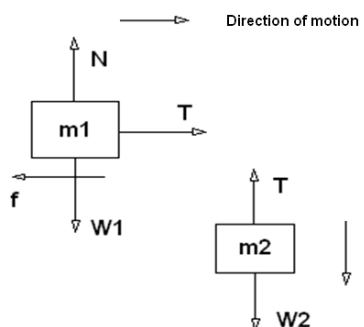


Figure A2: Free body diagram showing various forces acting on the blocks of DLT.

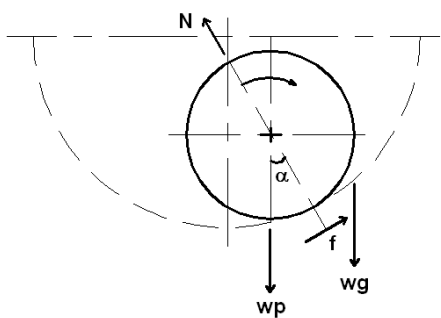


Figure A3: Free body diagram showing various forces acting on the inner pipe of TLT.^{9, 13}



Figure A4: Small Indoor Flow Loop (SIFL).

Table A1: Test matrix for SIFL using Taguchi method for three levels and three variables

Test	Flowrate gal/min	RPM min ⁻¹	% Solids
1	10	20	1
2	10	40	3
3	10	80	6
4	15	20	3
5	15	40	6
6	15	80	1
7	20	20	6
8	20	40	1
9	20	80	3

Table A2: Lubricity provided by solid additives in SIFL tests under various test conditions

Test No.	% Lubricity			
	S2	S3	S4	S5
1	-23.8	-8.9	-1.1	26.5
2	3.9	35.5	37.1	-24.9
3	31.5	54.7	57.7	32.6
4	-32.0	14.9	8.1	-61.7
5	-33.5	31.1	27.7	53.8
6	-88.8	52.0	45.8	-17.5
7	-32.1	29.0	59.0	55.5
8	-20.6	20.5	16.2	-47.2
9	-79.7	64.8	65.8	-34.2