# THE EFFECT OF DIFFERENT DRILLING FLUIDS ON MECHANICAL FRICTION

**Jan David Ytrehus**
Sintef Petroleum AS
Trondheim, Norway

**Ali Taghipour**
Sintef Petroleum AS
Trondheim, Norway

**Arash Golchin**
Luleå University of Technology
Luleå, Sweden

**Arild Saasen**
Det norske oljeselskap, Oslo;
UiS, Stavanger, Norway

**Braham Prakash**
Luleå University of Technology
Luleå, Sweden

## ABSTRACT

A very important aspect in highly inclined wellbores is the mechanical friction. For extended reach drilling (ERD) and through tubing extended reach drilling (TTERD) this can be a limiting factor. Friction caused by the contact between the drill string and the well casing or borehole is dependent on the drilling weight and fluid properties. Drilling fluids play an important role in determining mechanical friction. The use of oil based drilling fluids with higher lubricity can reduce torque and drag behavior and minimize stick and slip. Reducing mechanical friction will improve drilling efficiency in general, and will in particular enable longer reach for ERD wells.

This paper presents results from experimental laboratory tests where mechanical friction has been investigated.

Friction behavior was investigated for different drilling fluids; water based and oil based drilling fluids both with and without solid particles. A pin on disc setup was used for these experiments where a spherical ended steel pin was slid against a rotating disc made of granite. The test results show that mechanical friction in general is smaller with oil based than water based drilling fluids in the presence of solid particles.

## INTRODUCTION

A significant challenge in drilling operations, and especially in inclined and highly deviated wells, is to handle the mechanical friction between casing/drill string and formation/drill string interfaces. The friction between the rotational drill string and the formation causes excessive torque and drag. Excessive torque and drag often leads to the inability of reaching the target in high-angle extended reach drilling wells (ERD). In the most severe cases, the friction between the drill string and the casing wall or borehole exceeds the maximum torque that can be tolerated by the drill string. Consequently, the depth to which wells can be drilled is limited. The longest ERD well drilled as recorded in 2012 was 12 345 meters. As stated by Walker [1] surface torque and poor weight transfer to the bit were the two main mechanical challenges.

Understanding the mechanical friction in more detail is important for planning well operations. If small scale experiments can provide quantifiable data relevant for field conditions this may be a valuable tool for optimizing planning and well operations. This data is only relevant for evaluating the friction between casing and drill string and non-permeable formation and drill string.

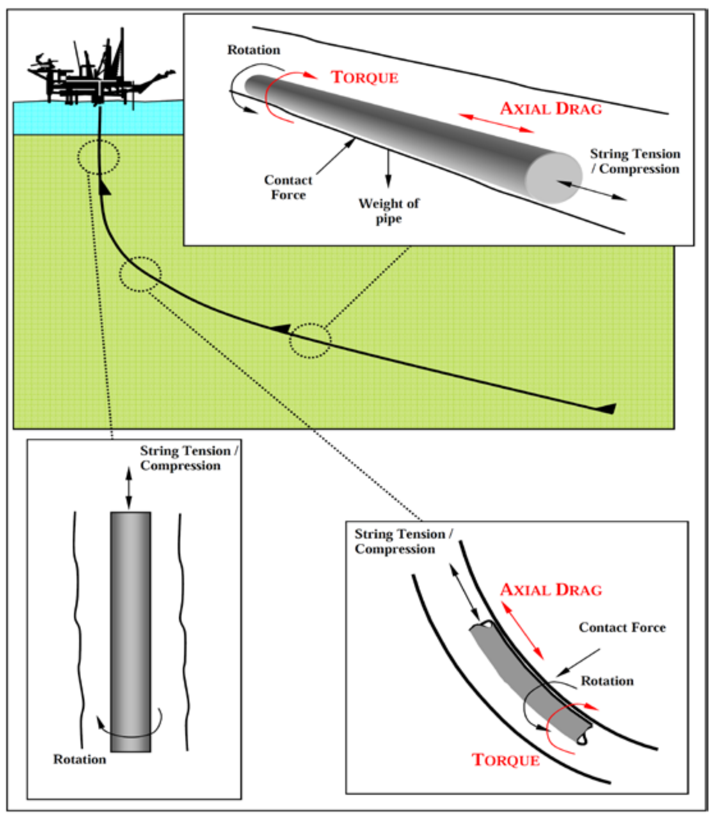


**Figure 1:** Drill string forces in different wellbore sections (K&M Technology Group)

For drilling with over-pressure in permeable formations the differential sticking can be a severe problem if the drilling fluid properties are inadequate. Filter cake properties like thickness, shear strength, and lubricity have a major effect on this differential sticking [2]. However, effects like differential sticking caused by a finite thickness filter cake have not been discussed. Also the effects of different drill bit cutters on the rotation torque [3, 4] that may be measured as friction have not been investigated in this work.

Drill string torque and drag are mainly generated by the frictional resistance from contact between the drill string and the borehole. Tubular twist off or buckling may result from borehole drag and torque. In all drilling operations, the drill string has a tendency to rest against the low side of the borehole, but this tendency is much greater in directionally drilled wells because of the effect of gravity. As the drill string increases in length or degree of vertical deviation, the amount of friction created by the drill string also increases. Figure 1 illustrates the torque and drag forces in different wellbore sections.

For wellbores in good condition, the primary factor affecting mechanical friction is the drill string weight. The friction resulting from rock and pipe interaction in the open hole is a complex process affected by other drilling parameters. An earlier investigation showed that parameters such as mud properties, well trajectory, and the quality of hole cleaning have influence on the mechanical friction. This has been stated by several researchers; [5, 6].

Weight of drill string components, especially the bottom hole assembly (BHA) in the horizontal section can dramatically alter the borehole friction force. Selecting a reduced drill pipe weight and shorter BHA section decrease the contact forces and thereby affects both torque and drag. One method for reducing the friction between the drill string and the wellbore wall is to use Aluminum drill string because it is lighter than steel. Aluminum alloys have an average density of 2800 kg/m$^3$, which is about 2.8 times less than the density of steel. With less normal force, the friction contributed by the drill string at any point in the well path is much less. However, the aluminum drill string is expensive, and it is not compatible with many types of drilling fluids or rig site handling tools.

Complex well path geometry is also one of the reasons for excessive torque and drag in drilling. Drilling a smooth and straight wellbore is important to reduce torque and drag. Dog leg severity (DLS) in build-up, drop-off and bends, as illustrated in Figure 1 affect the side force distribution in the wellbore. For example, in sharp bends the side forces are more concentrated in a specific section rather than evenly distributed through the wellbore. In medium to large radius bends, distributed forces can significantly reduce torque and drag especially at the top of the well where tensile forces are greatest. Wellbore tortuosity is also one of the sources for excessive torque and drag. As stated by Mason [7] borehole spiraling and micro tortuosity may cause excessive contact forces on the sidewalls and may cause increase in the friction forces. Effective borehole drift diameter is a critical issue in the BHA section with bigger diameter than drill pipes.

Borehole mechanical friction between the drill string and the sidewalls can be reduced by improving the lubricity of the drilling fluids. Lubricants help to reduce torque and drag and minimize stick and slip concerns while drilling a longer section. Mineral or synthetic oil based fluids are often used as lubricants. In addition, there are other additives generally available as film forming liquids or solid beads, powders or fibers that can be used for drilling, running casing and completions. Solid particles such as co-polymer beads, better known as plastic beads, are very common for reducing the mechanical friction through many years [8]. Abdo and Danish Haneef [9] studied reduced mechanical friction resulting from adding nano-particles. Their measurements were conducted using an OFI Lubricity Tester Model 111-00. The friction measurements were recorded by measuring the torque in the Lubricity tester.

Mechanics of friction and the relationship between friction and wear has been investigated for several decades. The effect of various parameters such as normal load, geometry, sliding speed, material, surface roughness, lubrication and vibration etc. has been studied by several authors [10-18]. Most of these studies focus on the friction behavior between steel and steel materials used in different industries.

Therefore, in this study a detailed parametric study has been carried out to investigate the effect of water and oil based drilling fluids on mechanical friction between steel and rock. In this article, test results from using a pin on disc tribometer to investigate the effect of a bentonite type water based drilling fluid and various oil based fluids on mechanical friction are presented.

## EXPERIMENTAL SETUP

In this study, a pin on disc test rig was used to carry out the frictional studies. This setup is the same as described in Taghipour [19]. The disc specimens were made of granite whereas the pin specimens were made of steel. The tests were conducted at different loads with a constant sliding speed with and without presence of solid particles in lubricated condition. Different oil based fluids were used together with one water based fluid. The lubricant was contained in a fluid bath in which the disk rotates and is pumped into the contact area using a peristaltic pump. This ensures that the contact area is wetted at all times.

Friction force is measured by restraining the pin motion with a force transducer. The sliding speed was selected to be similar to that of a rotating drill string under typical field conditions. The tangential velocity at the tool joint of a 5" drill pipe can be about 80 m/min and the corresponding rotary speed of a disc with 60 mm diameter is 420 rpm.

## TEST CONFIGURATION AND PARAMETERS

The pin on disc configuration was selected as explained in Taghipour [19]. The test configuration is shown in Figure 2. The following parameters are varied in the test campaign:

- Pin: 10 mm diameter steel pin with spherical head, hardness of 43 HRC. The spherical shape was selected due to the use of a particle laden fluid. Particles can pass more easily under a spherical pin than under a flat ended pin.
- Lubricant: base oil, oil based drilling fluids and water based drilling fluid
- Particles: no particles or quartz sand particles
- Normal loads applied on the pin: 2.3, 5 and 10 Newton.
- Sliding speed: 80 m/min.
- Temperature was controlled at 40 °C during the tests.

The normal load over the pin was created accurately by using dead weights corresponding to 2.3, 5 and 10 Newton's directly above the pin. These loads were selected so that the results could be compared to earlier work in the same setup [19, 20].

In these experiments a ground flat natural granite disc was selected in view of its sufficient hardness to withstand the applied load. In addition practical reasons were considered, as it is easier to make suitable discs from granite than for instance sandstone or weaker rocks. All the discs were made from one single piece of rock with uniform structure. The discs were polished all together to have identical surface roughness quality.

A spherical ended pin in the experiments creates a different situation than in real borehole conditions, where the drill string has a cylindrical shape and a line contact. This might affect the results compared to the field cases since the rolling conditions of the solid particles in the contact area may be different. Using a pin with spherical end was needed to be able to adjust the new pin in identical position against the disc.

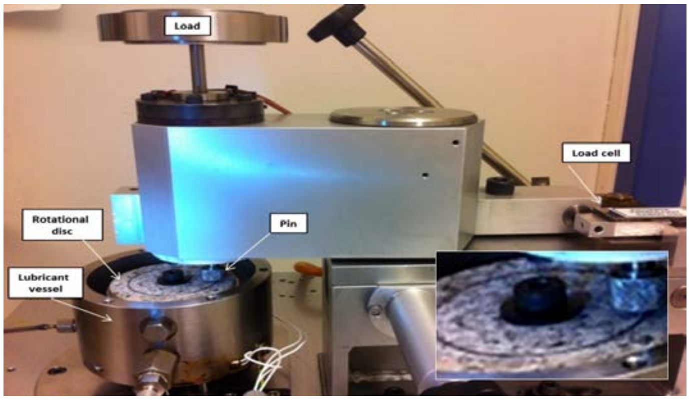


**Figure 2:** The pin on disc test configuration

## LUBRICANTS

The lubricants with different properties, all relevant to drilling operations, were investigated for their friction properties. The oil based fluids used include the base oils EDC 95-11 and EDC 99 DW, delivered by Total. These base oils are commonly used in fluids designed for drilling operations on the Norwegian Continental Shelf and are used to formulate the oil based drilling fluids which are delivered by MI-Swaco. The conventional drilling fluid was Versatec, an oil based drilling fluid with an oil/water ratio equal to 80/20 with a specific gravity of 1.28. The second oil based drilling fluid was a Warp fluid which is obtained by adding specially grinded barite to an oil based drilling fluid. The viscosity of the drilling fluids is expected to follow the non-Newtonian Herschel-Bulkley viscosity profile model. Tests with the base oils are included to illustrate the lubrication differences between base fluids and the respective drilling fluids.

As an example of water based fluids a bentonite drilling fluid with specific gravity (SG) near to 1.3 was used. This is an example of fluid relevant for drilling offshore top hole sections without return to the rig.

The following formulation was used for the bentonite fluid (all percentages are by weight).

- Fresh water approximately 63.8 %
- Barite 33.4 %
- Xanthan gum 0.1%, Soda Ash 0.8% (for adjusting the pH) and Bentonite 1.85%

The sand particles were Quartz from Dansand with an average particle diameter of 170 µm. The concentration of sand was set to 10 grams per liter fluid. The particle size was selected to correspond to a cuttings size of 1 mm in a large scale setup [19]. Similarly the sand concentration is selected to be representative for cuttings concentration in a drilling fluid when drilling at approximately 8 m/hr.

## RESULTS

As shown in Figures 3-5, the friction coefficient for all the drilling fluids converged to a fairly stable value after the running-in period. However, longer running-in period can be observed in case of Bentonite fluid at all loads.

The evolution of friction coefficient varied for each test fluid. The different trends in evolution of friction coefficient for various drilling fluids can be attributed to the dominance of various counter-acting friction mechanisms occurring in each contact condition. Formation of a metal transfer film on the granite disc, tribo-chemical reaction of lubricant additives at various load with the contacting surfaces and change in the apparent contact area between the ball and the disc due to wear are some examples of these mechanisms. In order to reveal the actual mechanisms responsible for the observed trends in friction further investigations should be carried out which due to practical reasons is not in the scope of this study.

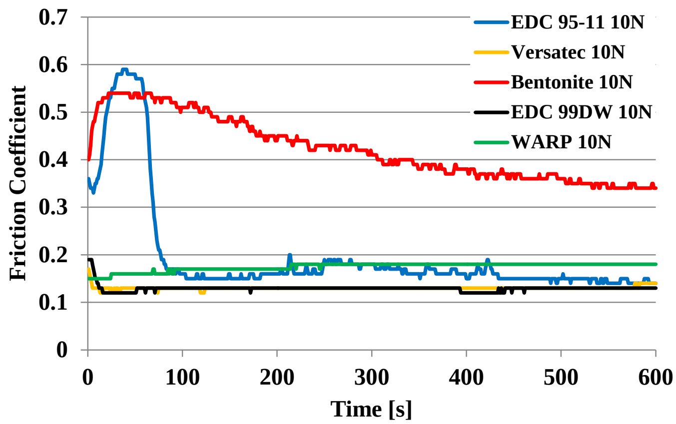


**Figure 3:** Friction coefficient with various lubricants during the test time. Normal load: 10N, Sand particles: No.

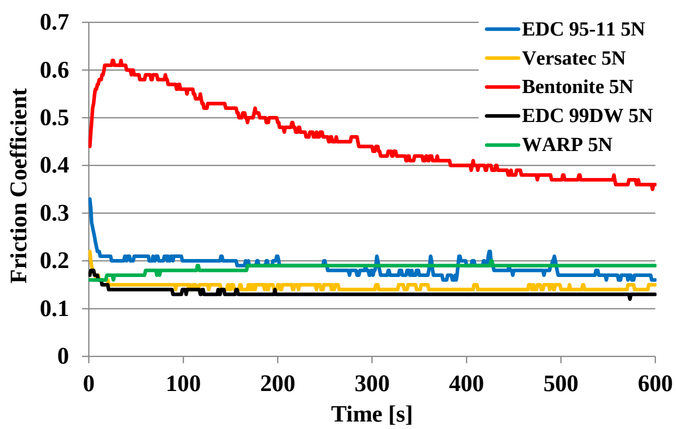


**Figure 4:** Friction coefficient with various lubricants during the test time. Normal load: 5N, sand particles: No.

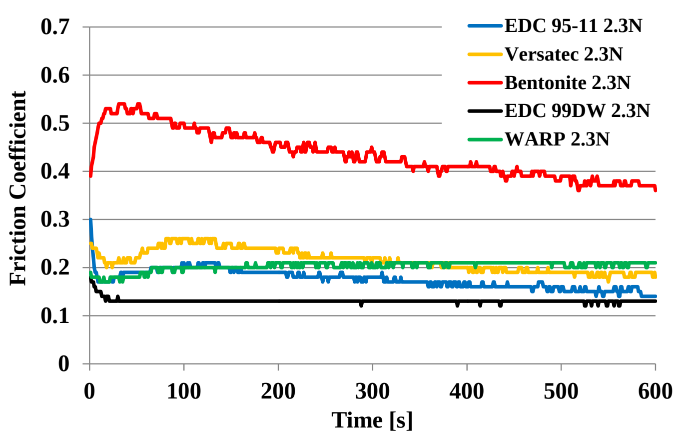


**Figure 5:** Friction coefficient with various lubricants during the test time. Normal load: 2.3N, sand particles: No.

The hierarchy in friction of the various drilling fluids seems to be independent of the normal load, however at the lowest applied load of 2.3 N (Figure 5) the trend is slightly changed as the base oils (EDC 95-11 and EDC 99DW) give lower friction coefficient compared to the oil based drilling fluids (Versatec and Warp). The bentonite fluid still has a significantly higher friction. A possible explanation can be that there are small particles in all the drilling fluids, but not in the base oils. These particles may provide additional friction resistance at the lowest load while they are not dominant at higher loads.

When sand particles with an average particle diameter of 170 µm were added to the lubricants, the coefficients of friction changed significantly for the different test fluids. Figure 6 shows the coefficient of friction for all fluids in presence of sand particles. The friction is significantly reduced when sand particles are added in the bentonite fluid. This is clearly observed in Figure 7. A possible explanation may be that the fluid contains barite particles, added in order to give the fluid the required density for drilling operation. These barite particles can cause higher friction. The sand particles may roll and counter the barite particles effect and reduces the friction.

It is observed for the Warp fluid (Fig. 8) that the sand particles apparently do not have any effect on friction. The coefficient of friction with different loads for all the fluids is shown in Figures 7-11. The coefficient of friction is reduced with increasing normal loads. This trend is clear for the oil based drilling fluids, and mostly for the bentonite fluid. The tests with bentonite fluid do not show this trend as clear in the transient region, but when a more steady state is reached its behaviour is similar to those of other drilling fluids. For the base oils, however, this effect is less pronounced. The base oil EDC 95/11 shows a coefficient of friction that is lower for 2.3 Newton load. For the EDC 99DW no significant effect of normal load is observed at all.

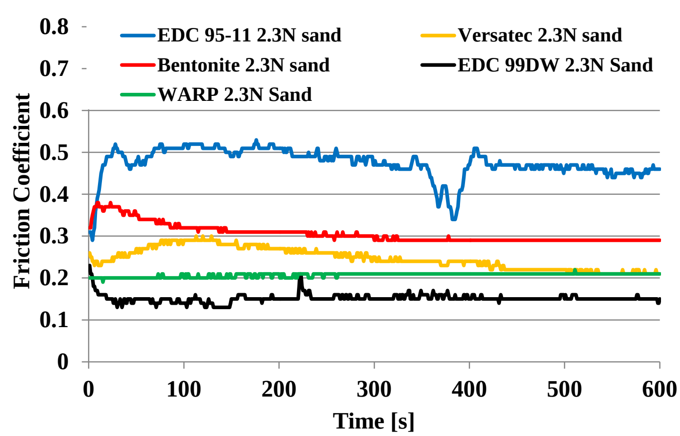


**Figure 6:** Friction coefficient with various lubricants during the test time. Normal load: 2.3N, sand particles: Yes.

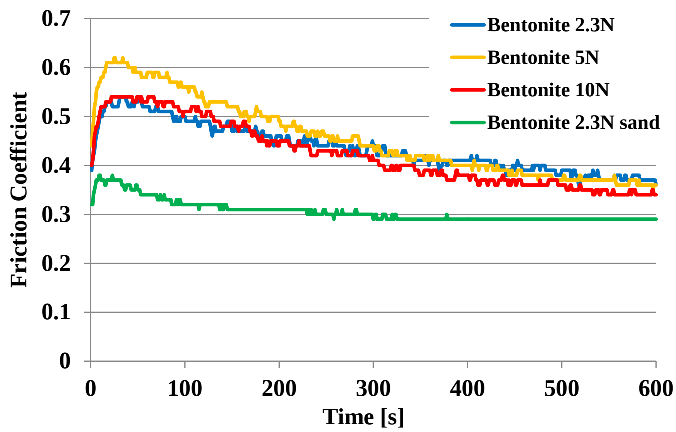


**Figure 7:** Friction coefficient for bentonite (clay) fluid at various loads. Sand particles are present for one test at 2.3N.

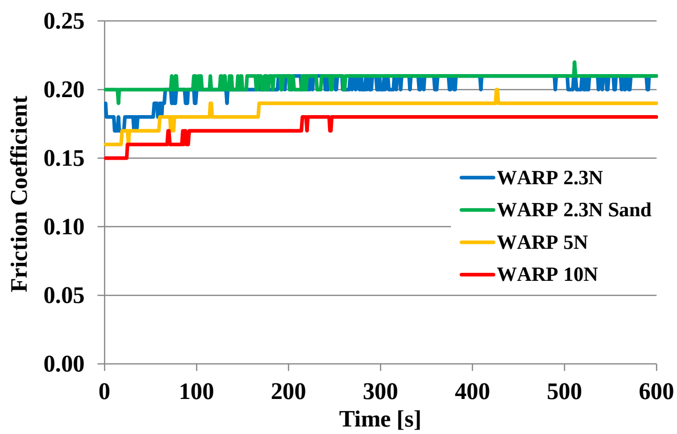


**Figure 8:** Friction coefficient for WARP fluid at various loads. Sand particles are present for one test at 2.3N.

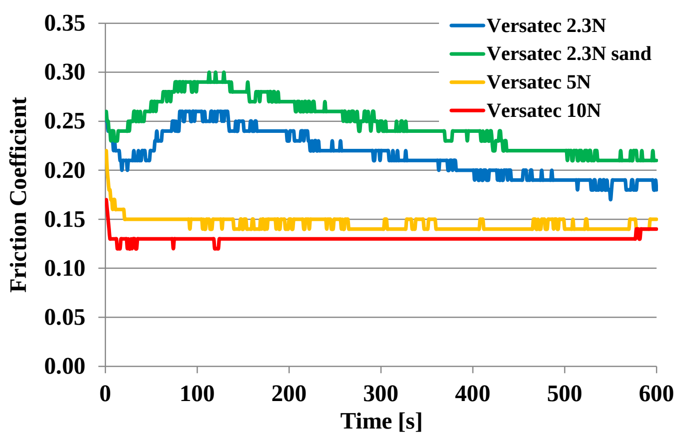


**Figure 9:** Friction coefficient for Versatec fluid at various loads. Sand particles are present for one test at 2.3N.

Some key observations from the tests with different fluids are summarized:

1. Adding sand particles to the bentonite *reduced* the coefficient of friction.
2. Adding sand particles *did not affect* the coefficient of friction for the Warp fluid.
3. The coefficient of friction *increased* with added particles for the other oil based fluids (Versatec and base oils).
4. The friction using base oil EDC 99DW is significantly lower than for EDC 95-11 when sand particles are added.
5. By adding sand the coefficient of friction was *less affected* for the oil based drilling fluids than for their respective base oils.
6. An increased load resulted in a reduction in coefficient of friction for all the drilling fluids tested in this study.

The steady state frictional behaviour of the lubricants was examined by conducting the experiments for an extended period of 1h. Figure 12 shows the friction behavior in the one hour test for all lubricants at 10N normal load. It is observed that the coefficient of friction in the base oil, Warp and water based fluid decreased slightly during the test. However, the friction coefficient for the Versatec decreased to minimum and then started to increase. This is attributed to the increased viscosity of the Versatec fluid due to inclusion of the wear particles and/or evaporation of the base fluid in the lubricant, which made it more and more difficult to pump the fluid to the contact. However, the contact was well lubricated during the tests despite this difficulty.

## DISCUSSION

The main observations are in accordance with Taghipour [19] and [20], as well as previous work done by Bhushan [21] and Blau [22]. They reported decreased friction with increased load in high load regime. Chowdhury [23] also reported reduction of coefficient of friction with increased normal load in a pin on disc setup with aluminum disc and steel pin. The reduced friction coefficient with increased contact pressure (of Molybdenum disulphide coatings) has also been observed by Kohli and Prakash [24]. They believed that producing larger quantity of wear debris under higher loads can explain the reduction of the friction coefficient.

The bentonite drilling fluid is obtained by hydration and suspension of clay (bentonite) particles in water. Bentonite is layered clay consisting of small platelets. The deformation of this structure may help explain why the friction reduced when additional particles were added.

As the sand particles simulate the presence of the cuttings in the borehole, the results obtained from these tests are more relevant to the actual application. It is observed that the designed drilling fluids, Versatec and the bentonite fluid, provide lower friction than the base oil EDC 95/11 when particles are introduced. These fluids should be designed in order to minimize friction in drilling operations and this task is most crucial when particles are present.

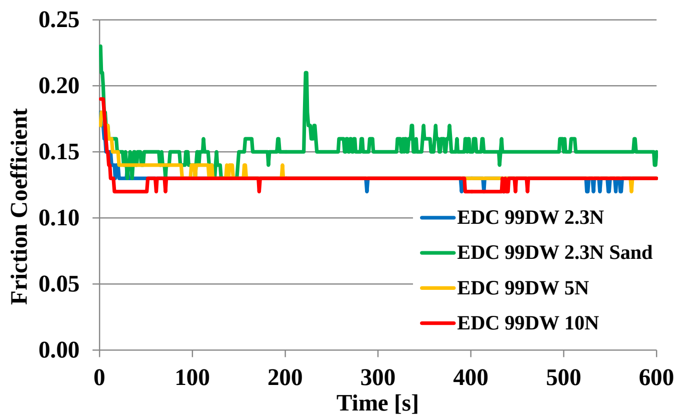


**Figure 10:** Friction coefficient for base oil EDC 99DW at various loads. Sand particles are present for one test at 2.3N.

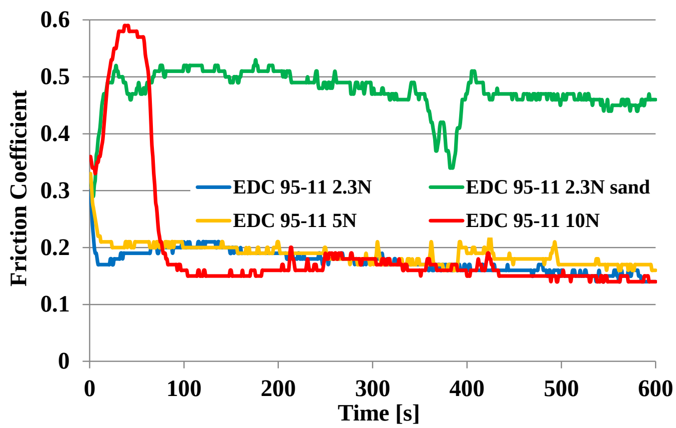


**Figure 11:** Friction coefficient for base oil (EDC 95-11) at various loads. Sand particles are present for one test at 2.3N.

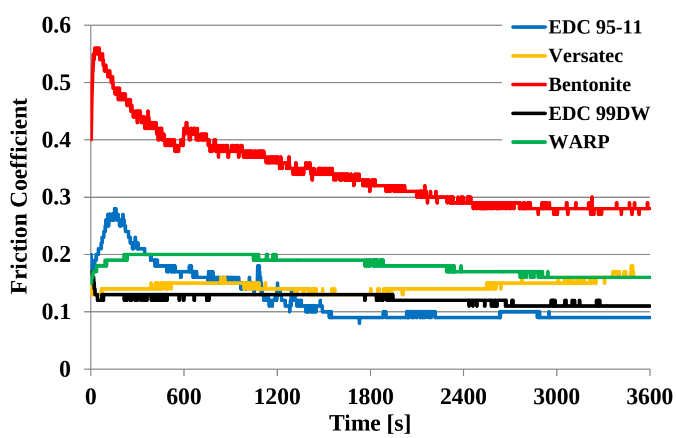


**Figure 12:** Friction coefficient for all fluids. Test duration: 1h, normal load: 10N.

The results indicate that the Warp fluid, based on the oil EDC 99DW, is relatively less effective for friction reduction than its base oil, even when particles of the reported size are added. This is not the situation for the Versatec compared to its base oil. The trends are the same for the two cases, as added particles give the drilling fluids a lower increase in friction coefficient than their base oils. These effects may be enhanced by the downscaled setup, since the added particles are scaled down from expected cuttings size while the weight of material in the drilling fluids is scaled as in a field operation.

The difference in lubricity between the two base oils is significant when sand particles are included. Such large effect is remarkable, although the EDC 99DW could be explained to have somewhat improved lubricity effect. The EDC 99DW and EDC 95-11 are quite similar oils, but in the EDC 99DW the hydrocarbons above C16 are removed. The Versatec fluid (designed with EDC 95-11) and the Warp fluid (designed with EDC 99DW) do not show significant difference in lubricity, so the observed effect seems to be valid only for the base oils. Possible explanations for the observed differences in base oil lubricity may be due to wettability and tribo-chemical effects. Such effect may occur due to the removal of C16 and higher molecules as is in the EDC 99DW.

The results with different normal loads provide the same trend as in Taghipour [19] and [20]. The data presented shows that normal force appears to have effect on the friction coefficient. These results are likely to support the theory for drilling conditions that a reduced contact area between the drill string and formation will reduce the torque resulting from the friction force.

Direct scaling from experimental conditions to field application is not possible due to multiple scales like length, velocity, fluid properties, cuttings size etc. as described in [25]. The presented results should therefore be considered relatively to each other and cannot be directly applied in field operations.

## CONCLUSION

From the friction experiments in a pin on disc test setup with water and oil based lubricants, the following conclusions have been drawn:

1. When sand particles were added to the tests the oil based drilling fluids provided a relatively better lubricating effect compared to their base oils.
2. An increased load resulted in a reduction in coefficient of friction for all the drilling fluids tested in this study. This supports previous findings in tribology work, but is not equally well known in the drilling industry.
3. Regardless of the applied load all oil based drilling fluids showed lower friction in comparison to bentonite fluid in absence of abrasive particles.
4. Depending on the type of fluid, inclusion of sand particles resulted in various changes in frictional behavior of the tribo-pairs. Most notable is the observation that the added sand showed no effect for the Warp fluid.

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