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Performance Tests of Solid Lubricants Using a Modified Lubricity Evaluation Monitor

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Abstract

Solid lubricants differ from liquid lubricants in that they prevent the rotating or sliding drill collars from physically contacting the surface of the casing or wellbore. In order to investigate this fact a Lubricity Evaluation Monitor (LEM) was modified by adding a bumping mechanism to simulate pathway for solids movement into the gap between the drillstring and casing or formation. Contact time, time of separation and gap distance can be adjusted to investigate solid particles rotation, degradation and their impact on lubrication performance. Standard PPT ceramic discs with different pore throat size were utilized to simulate formations with different permeability and 4142 steel blocks with a machined curvature were used to simulate steel casing. Solid lubricant was tested on a broad load range (1-30 lbf/inch).

At low contact load, spherical solids, such as glass, ceramic beads and carbon microspheres act as ball bearings that separate the drill string and casing apart even without the need for a bumping mechanism. With the increase in contact load, solids were squeezed out from the contact area within a short time period and the bearing mechanism failed. Graphite on the other hand, deforms under the contact load and lubricates contact surfaces for rather long time without refreshment. With the bumping mechanism, a proprietary graphite reduced the CoF of a WBM to ~0.08. Unlike hard glass and ceramic beads, graphite particles and carbon microspheres cause no wear on contact surfaces: steel or PPT ceramic/Berea sandstone disc, which would be especially beneficial in open hole drilling and while drilling horizontal wells.

Introduction

As much as 70% of all energy delivered by drilling equipment is lost through friction[1]. Friction and drag are serious problems while drilling directional, high angle and extended reach wells. Friction torque may exceed the capacity of the drilling rig while drag can severely reduce load transfer to BHA. Careful planning is essential to address the torque and drag issues that may arise or the drilling target may not be achieved.

Friction force is the product of normal force and friction coefficient.

According to McCormick et al[2], normal force is generally the highest in the build section, which may reach 1800 lbf/length (30-31feet) in certain areas, very high in the lateral section, typically in the 200-1000 lbf/length range, and the lowest in the vertical section, generally less than 300 lbf/length. Only the tool joint is in contact with casing/formation during drilling. For a 17-inch long tool joint the normal force would be in the range of 12-59 lbf/inch in the lateral section. Better hole cleaning, caternary well path and lightweight drill pipe (ADP) are some of the practices applied to reduce normal force.

Drilling fluid is the determining factor for coefficient of friction. Oil/synthetic based drilling muds are the fluids of choice for directional/horizontal drilling partially because of the intrinsic high lubricity of the base fluid. On the other hand, the use of oil based drilling fluid faces stringent regulations due to its environmental impact. Field practices over the years have established the use of lubricants as an economic way to reduce friction coefficient. In some cases, coefficient of friction numbers close to that of oil based drilling fluid can be achieved with appropriate lubricant addition.

Liquid lubricants are designed to adhere or bond on metal surfaces and lubricate the interfaces. Solid lubricants on the other hand physically separate the surfaces from contact. Additionally some forms with a high degree of sphericity are believed to act as ball bearings that separate the drillstring and casing/formation. Solid lubricants are generally very stable, chemically and thermally, and compatible with most drilling fluid systems. This is a big advantage over liquid lubricants. However, their use is not as wide spread. The lack of a method to accurately predict performance in the field could be one of the reasons. Many successes of the solid lubricant application cases came out as surprise. For example, ground walnut shell was found to be an effective torque and drag reduction agent at Wytch Farm[3], which reduced dynamic friction factor by more than 30%, similarly, graphite/$CaCO_3$ LCM was proved to have a positive effect as lubricant[4]. Unlike traditional spherical solid lubricant like glass and polymer beads, those angular/flaky loss circulation materials may not work as ball bearing. Therefore, new theory needs to be established to explain the observed torque and drag reduction, beyond the ball bearing effects.

The first equipment introduced to the oil field for lubricity measurement was the Baroid lubricity tester. It was modified from Timken extreme pressure testing apparatus, and applies 150 lb.inch torque through a 1.5 inch arm to a steel ring of approximately 0.33 inch wide in standard test. In other words the applied load is close to 333 lbf/inch. Both graphite and fine walnut hulls were shown as ineffective as lubricant[5] under the conditions of the test.

Another lubricity tester, the Lubricity Evaluation Monitor (LEM) was developed by M-I Drilling Fluids Company. A contact force of 30 lbs, equivalent to 20 lbf/inch normal force, is applied to a bob of 1.5 inch long in standard test. LEM also differs from EP lubricity tester in that the mud is continuously circulated across the test surfaces, which can be sandstone core, shale pieces, filter cake or steel pipe.

One of the most sophisticated lubricity testers build to date is the HLT lubricity tester, jointly owned and operated by M-I Swaco and Westport Technology Center International. The HLT lubricity tester was built to perform experiments under downhole temperature and pressure conditions. It applies 75 lbs on a 3-inch carbon steel test bob, or 25 lbf/inch normal force.

After reviewing the pros and cons of existing lubricity testers, Aston[6] at BP Sunbury Laboratories built a lubricity tester equipped with a much longer steel testing bob (75cm). The side loads applied on the lubricity tester ranges from 11kg to 31kg in other words normal force was in the range of 0.8-2.3 lbf/inch. Commercial solid lubricants such as glass and polymer beads managed to get into the space between the rotating bob and the casing/ formation sample under the test condition, and reduced friction torque.

All the lab lubricity testers adopted the design in which a steel bob rotates against solid sample pieces. When two rigid surfaces sliding against each other under high load, the space between them narrows, preventing solid lubricant particles from entering the gap. The BP lubricity tester is a complex device and used a normal contact force that is lot lower than what is experienced in the field in standard test. In addition, it is difficult to explain the observed torque and drag reduction by graphite and walnut shell LCM through the ball bearing mechanism.

One mechanism that may help bring fresh solid lubricants into the contact gap is downhole vibration. Steel pipe that is tens of thousand feet long and less than a foot in diameter can be quite flexible. The drill bits aggressively cut into rock formation at a normal load on the order of tens of thousand pounds. The other source of vibration comes from the contact between drillstring and wellbore. As a consequence, the drillstring vibrates axially, torsionally, laterally or more commonly the combination of all three[7]. Lateral displacement of over 1 inch was predicted by Dykstra in his modeling of mass imbalance effects on downhole vibrations and was confirmed through experiments[8]. While unwelcomed because of the potential to damage drilling equipment and cause well stability problems, downhole vibration leads to temporary separation between the two otherwise closely contacting surfaces, thus providing the opportunity for fresh mud, together with solid lubricant to enter into the gap space.

Several authors made modification of existing lubricity testers to take pipe eccentricities and downhole vibration into account. Skalle[9] added a cam arrangement to an API lubricity tester to lift the block away from the rotating ring, i.e., creating a temporary gap for solid particles. Gap distance was adjustable. As the cam is mounted on the ring, the time of contact and time of separation are related to each other. It is advantageous to have the freedom of adjusting time of contact and time of separation independently as downhole dynamic events may have different frequency from pipe rotation. Normal load was reduced to 1/3 of the original; in other words tests were conducted at 100 lbf/inch normal load. The modified lubricity tester successfully demonstrated the effectiveness of extra fine polymer microbeads as lubricant for water based mud formulations. Similarly, Alford[10] introduced a camshaft to the LEM, which pushes the mud chamber back to separate the drillstring from sample rock/casing surface. The gap size is not adjustable with the design; time of separation and time of contact are also related.

As elaborated above, LEM provides a reasonable platform to investigate solid lubricants in a laboratory setting, particularly for applications where drilling torque matters the most, from the normal force standpoint. In this study, a pneumatic device was adopted as the mechanism for gap creation. Torque sensor was upgraded to enable accurate measurement at side load levels comparable to the BP study. The modified device was then used to characterize commercial solid lubricants, mainly fine grades, at various concentration (0-40 ppb) and side load (1-30 lb/inch) levels.

LEM modification and testing program

A pneumatic piston assembly was adopted as the mechanism for gap creation. Contact time and time of separation between the bob and sample surface are preset using a digital timer. At the start of a bumping cycle, the piston pushes the mud chamber back a certain distance, and retracts to its original position at the end of the set separation time. The gap remains closed under the side load during the set contact time until the next cycle begins. A rigid frame was built behind the main frame and connected to the main frame through an adjustable beam. The bob maintains its position during the course of the test. The gap distance is set by the adjustable beam, in combination with minor adjustments on the pneumatic piston.

The new torque sensor improved sensitivity to eight times of the original, as a result, accurate torque measurement is possible on side load as low as 2.5 lbs, or 1.67 lbf/inch, comparable to what was used on the BP lubricity tester.

Solid lubricants are tested at increasingly higher side load and concentration levels. Solid lubricant loading in the mud ranges from 2.5 to 20-40 ppb, and side load from 2.5 to 45 lbs. Tests were conducted for 15 minutes with bumping and only 3 minutes without bumping. Mud loaded with solid lubricants is heterogeneous by nature. When the gap between rotating bob and sample piece closes, the number of solid particles captured in between the surfaces varies. As a result, the measured torque doesn’t hold a constant value, but rather changes by as much as several times. In this scenario a time average is used to characterize lubricity of the solid lubricant. Using the time average also means all the surface irregularities on the bob and sample pieces contribute to the final lubricity value. To some extent it thus resembles a test on a longer bob.

Test performed without the bumping mechanism bears the same kind of problem. Reproducibility of the test results can be very poor in some cases. However, it does provide insight on how solid particles degrade over time. In those tests, the bob and sample piece are separate at the beginning, allowing solid particles to get in.

Most of the tests were conducted in 1.75 ppb xanthan gum solution weighted to 14.0 ppg using API grade barite, which has excellent suspension power for all the solid lubricants tested. Majority of the tests were conducted on 4142 steel coupons with a build-in curvature at a radius of 1.00 inch, compared with bob radius at 0.61 inch. The sample holder was built to hold 2.5 inch API ceramic filtration discs too, which come with various pore structure and permeability values, and were used to simulate formations with different permeabilities. Limited investigation was carried out on discs made from Berea sandstone. Bob rotation speed was set at 60 RPM in all the tests.

Gap distance was found to have very limited impact on the lubricity value as long as it is big enough to allow passage of solid particles. A constant gap of 1 mm was used in majority of the tests; however, walnut shell fines were tested at a gap size of 1.5 mm due to their larger size. In addition, time of contact and time of separation were set at 4 seconds and 2 seconds, respectively, for most of the tests.

LEM test results

Angular LCM

1. Synthetic Graphite

Synthetic graphite proved to be one of the best materials for loss circulation prevention/remediation purpose[11]. One of the additional benefits graphite may provide for the drilling application is lubricity. Graphite lubricity originates from its unique layered structure[12]. Within each individual layers the atoms are linked to each other with strong covalent bonds, however, the layers themselves are bonded by weak van der Waals forces. When present in between sliding surfaces, the graphite layers align themselves parallel to the direction of relative motion and slide over one another with ease, thus providing low friction. Historically graphite is one of the most widely used solid lubricants, applied either as powder additive or in the form of coating.

In this study, a proprietary LCM grade synthetic graphite powder, with d50 around 400 microns, was tested in the weighted xanthan solution. From **Figure 1** it can be seen that graphite additive reduced friction torque by about 50% at just 2.5 ppb loading, and 60-70% with 5 ppb graphite addition. Minimum additional benefit was observed at higher loadings. One fact worth noting is that coefficient of friction values as low as 0.08 were obtained in some of those tests, a lot lower than what is typically measured for this type of graphite.

With the experimental setup, it is possible to conduct friction tests using dry powders. An enclosure was built around the sample holder so that only couple of hundred grams of powder is needed for each dry test. As the chamber was pushed back to create the gap, dry powder flows into the gap driven by gravity, so that there is always a solid layer in-between the rotating bob and the solid sample piece, in this case, 4142 steel plate. Water or mud can be easily introduced into the chamber with a peristaltic pump. Results of one such experiment are shown in **Figure 2**. Dry graphite powder reduced the friction coefficient between steel/steel to 0.17. After one hour of dry testing, with the introduction of weighted xanthan suspension, the coefficient of friction dropped again to 0.10, slightly higher than the value obtained while testing 40 ppb graphite xanthan suspension (0.08). The difference most likely caused by inadequate mixing between the mud and the graphite. It is obvious that graphite is more effective as a solid lubricant in the presence of mud/water. Similar behavior was observed while testing many other solid powders.

The benefit of graphite in torque reduction is facilitated by the bumping action. If the gap is initially closed under load, graphite provides no benefit. It thus appears that because of its size and shape, graphite can't wedge in between the contact surfaces under load. The steel plate was pulled off in the middle of a non-bumping test for observation. Under the microscope, it is seen graphite as "compacted" under the load, and worn down with time. In the non-bumping test at 20 ppb graphite loading, 25 lbs side load, graphite trapped in between the surfaces typically worn off within one minute, after that torque increased to blank mud level.

2. Walnut Shell Fines

Walnut shell was tested at a larger gap of 1.5 mm, due to its size. When gap was 1 mm and smaller, the base line deviated from zero, meaning the gap was partially blocked.

As shown in **Figure 3**, fine grade walnut shell reduced friction torque by more than 30% on average at 2.5 ppb loading. The torque reduced even more at higher loading however improvement was almost negligible at 10 ppb and above. Minimum coefficient of friction values observed in the test were slightly above 0.15, which is higher than graphite. Similar results were obtained when tests were conducted without the bumping mechanism, although consistency was a problem at low loading levels (5 ppb and less).

Similar to graphite, torque reduction is possible only when the walnut shell particles are allowed to get in between the contact surface. At moderate side load of 10 lbs, fine grade walnut shell particles cannot wedge in between the contact surfaces by themselves. Once in place though, walnut shell provides consistent torque reduction. In experiment conducted without the help of bumping mechanism, i.e. a non-bumping test, at 10 ppb additive loading, 45 lbs side load, a sharp increase in torque to blank level was observed typically only after about 2 hrs of consistent torque reduction. To check whether replenishment of solid lubricant from the mud happened during the test, experiment was designed to have the original mud mixture with walnut shell addition replaced by base mud, which resulted in reduced walnut shell concentration to 0.8 ppb based on testing after the experiment.

Torque increases were observed more than one hour after the majority of the walnut shell particles were removed from the mud. Although it is difficult to completely rule out the possibility of fresh lubricant getting into the gap during tests, it is clear that walnut shell particles have superior wear resistance in between steel surfaces under high load. In another experiment, the steel plate was pulled off in the middle of the test, following a special procedure to allow extra mud solids washed off while maintaining solid lubricant in the contact area. Under optical microscope, as shown in **Figure 4**, walnut shell particles were found embedded within mud solids and appeared "polished" by the steel bob to give a shiny smooth interface. In other words, instead of those angular particles rolling in between steel surfaces, more likely they stayed on top of the steel plate and slid by the rotating bob. More solid deposit was seen on one side of the contact area, from which the rotating bob bringing mud in. Walnut shell particle beyond the point of contact appeared to have been polished too. Those particles might have contributed to torque reduction or even replenished the ones in the contact area dragging by friction force.

In the literature, torque and drag reduction by walnut shell has been attributed to the ball bearing mechanism. From the evidence presented above, the particles did not roll in between the contact surfaces; the relative movement was more of a "sliding" type. The low coefficient of friction between walnut shell and steel, the ability to maintain structural integrity under high compressive force and low wear rate made walnut shell a good solid lubricant.

Spherical and semispherical solids

1. Glass beads

Fine grade glass beads (60/200 mesh) are very good solid lubricants at low side loads. They reduced coefficient of friction to 0.06, or about 80% reduction of the original mud. However, as load increased, their effectiveness disappeared. The bumping mechanism made very little difference, although the results with bumping were much more consistent at low concentrations. The grinding noise and the fact that glass beads can wedge into the gap by themselves at 20 ppb and 10 lbs side load indicate that the glass beads do work through the ball bearing mechanism. Compressing test on a single layer of glass beads was conducted in a similar manner as Loeppke et al.[13]. At 2000 psi, glass beads were found to "explode" into much finer pieces. Those fines clearly did not provide much benefit in torque reduction. The effective load range increased with the concentration of the beads in the mixture. Wearing scars were found on both the steel coupon and the bob.

2. Ceramic beads

The lightweight ceramic beads (40/70 mesh) behaved similarly to the glass beads. They reduced coefficient of friction to 0.11 (**Figure 5**), or about 65% reduction of the original mud. The effectiveness diminished at higher side loads. The working side load range improved at higher concentration. Results were very similar with and without inclusion of a bumping mechanism. Ceramic beads were also able to wedge into a closed gap under low load. These results suggest the ceramic beads work through the ball bearing mechanism. After tests completed under 10 lbs and 25 lbs side loads and at 20 ppb loading with bumping, the beads were separated from the rest of the mud and collected on 200-mesh screen. Under optical microscope it is clear that a lot more damage was done on the beads when they were tested under 10 lbs side load, when the beads effectively reduced torque through the ball bearing mechanism. From this result we can conclude that damage caused by bumping is very limited. In addition, rolling in between contact surfaces under load weakened the structure of the ceramic beads and leads to their ultimate disintegration. It is likely that under higher side load, the beads were crushed almost instantaneously, which closed the gap and thus prevented torque reduction. Deep grooves with width comparable to bead diameter were found on both the bob and steel plate. One possible solution to the wear problem is to coat the beads with a layer of nonabrasive material. Proprietary graphite coating was applied on the ceramic beads and reduced wear on a sandstone disc by about 10 times.

3. Carbon microspheres

The carbon microspheres (mainly 70/200 mesh) tested are smaller on average than the ceramic and glass beads. They are able to penetrate in between the contact surfaces even when the gap was closed at the beginning. As much as 60% (**Figure 7**) torque reduction was observed in the experiments. The ball bearing mechanism may be used to explain the behavior at low side loads. Different from glass and ceramic beads, some limited torque reduction was also observed at 45 lbs, especially at concentrations of 20 ppb and above. It appeared as if the crushed pieces provided some torque reduction by themselves. Fresh lubricant was brought into the contact area by the bumping mechanism, without this help torque value would have increased to blank value within a short time period. Similar to graphite, the carbon microsphere and the broken pieces assumed all the wear and caused no damage on both the bob and the steel plate.

4. Polymer beads

Fine grade polymer beads (40/200 mesh) were able to reduce torque under both high and low side loads (**Figure 8**), but not so much in the intermediate range. This indicates two different working mechanisms, similarly to the carbon microspheres. The beads were able to penetrate into the gap by itself at 10 ppb and 10 lbs side load. Penetration was not possible at 45 lbs side load and the same polymer beads concentration. The ball bearing mechanism may be used to explain behavior under low load based on the evidence. Torque reduction was not as good compared with glass/ceramic beads, even though they are highly spherical. Low rigidity, i.e. deformation under compression and loss of sphericity might be the cause. After a non-bumping test at 45 lbs side load and 20 ppb additive loading, the beads "trapped" in between the steel plate and the bob were captured using the same technique as used in the walnut shell fines study. Under an optical microscope (**Figure 9**), polymer beads, with diameter slightly higher than average were found embedded within mud solids, in the form of clusters, and appear "polished" by the bob. This phenomenon cannot be explained by the ball bearing mechanism. The polymer beads do fracture under extreme impact, however the fractured interface is different from what is shown in the picture. It is more likely that under high side load, the deformed beads were "stuck" on the surface of the steel plate due to the high friction force, while sliding by the rotating bob, similar to walnut shell fine. This conclusion agrees with the finding of Skalle et al.[9], whose experiments proved that polymer beads slide instead of act as ball bearing. The reduction in friction torque results from lower coefficient of friction between polymer and steel surfaces in mud.

Coarse grade polymer beads (20/50 mesh) provided much better performance in the same side load range (**Figure 10**). Torque reduction as much as 70% was observed in some conditions. The ball bearing mechanism worked at much higher side load range, possibly due to better rigidity of the beads.

Conclusions

A LEM system was modified to facilitate testing of solid lubricants through the introduction of a bumping mechanism. The equipment design allowed maximum freedom in selecting test parameters to better simulate field condition. Commercial solid lubricants like polymer and glass beads as wells as graphite and walnut shell fines showed their promises in torque reduction, consistent with field results. While the testing parameters selected in this study may not represent field condition, it is clear that solid lubricants behave very differently under increasing side load. This observation can be applied to enhance the understanding on performance of solid lubricants in drilling operations.

Some general trend observed:

1: Graphite and walnut shell are both good solid lubricants when their passage into the "work zone" is facilitated by a bumping mechanism. Graphite provides better ultimate lubricity however it is worn off faster than walnut shell. Walnut shell and graphite work through a "sliding" mechanism instead of the ball bearing mechanism suggested in literature.

2: Glass and ceramic beads work well through the ball bearing mechanism under low side load. At higher loads the particles are crushed into pieces, which provide no additional benefit to torque reduction. Their effectiveness increases with particle size and concentration. Severe damage on the bob and steel coupon was observed after tests.

3: Plastic beads and carbon microspheres behave similarly to glass and ceramic beads at low load. Under higher side loads, carbon microspheres are crushed into pieces, but still provide some torque reduction. Plastic beads either deform or being crushed under heavy load, which leads to the failing of the ball bearing mechanism; friction torque is reduced as coefficient of friction is less when steel slides against polymer in mud. Temporary separation to bring in new lubricant is necessary in this scenario. Performance may be further enhanced by improving bead rigidity to extend the working range of the ball bearing mechanism and through increased wear resistance against steel.

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Nomenclature

Define symbols used in the text here unless they are explained in the body of the text. Use units where appropriate.

PPT = *Permeability plugging test*
CoF = *Coefficient of friction*
WBM = *Water based Mud*
BHA = *Bottom hole assembly*
ADP = *Aluminum drill pipe*
LCM = *Lost circulation materials*
HLT = *High pressure high temperature lubricity tester*
ppb = *pounds per barrel*
ppg = *pounds per gallon*

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Figures

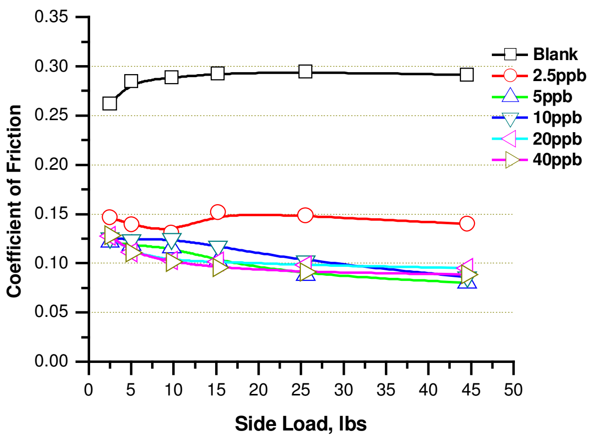

Figure 1. Graphite LCM (400) LEM test results

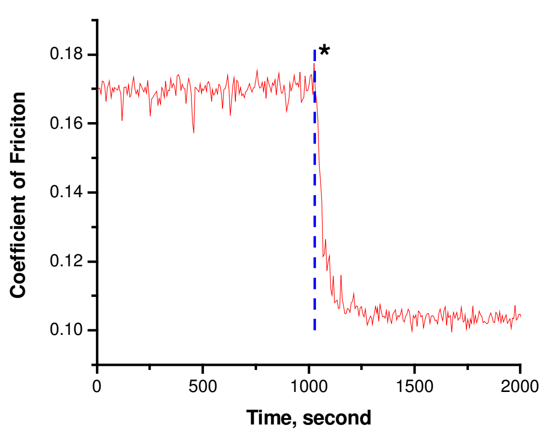

Figure 2. Influence of Xanthan solution on coefficient of friction: Graphite LCM was tested dry initially; xanthan solution was introduced in the middle of the test (*).

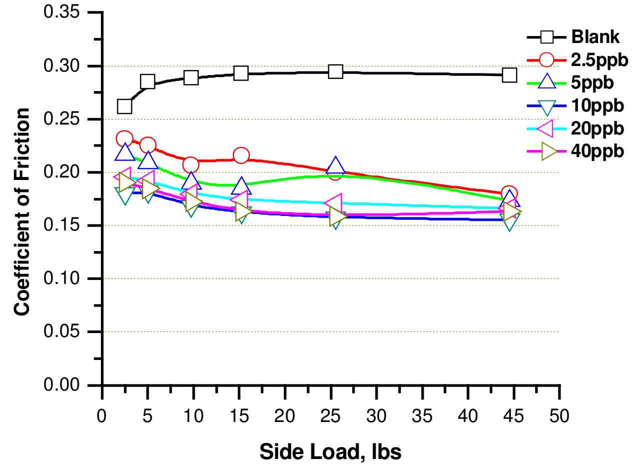

Figure 3. Fine grade walnut shell LEM test results

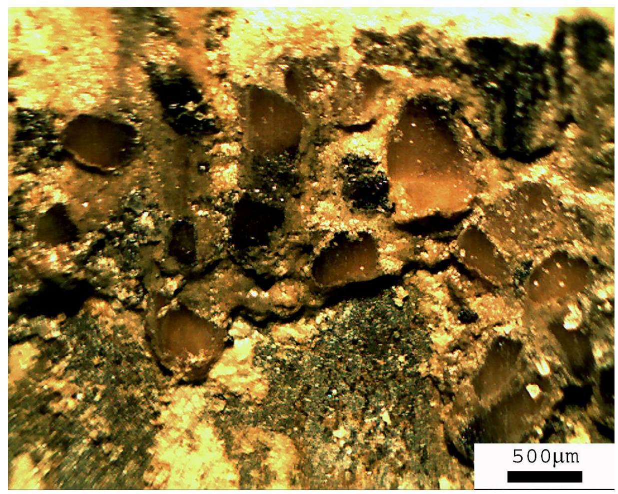

Figure 4. Walnut shell particles identified on steel plate after a non-bumping LEM test. Test conducted at walnut shell concentration 10 ppb and 45 lbs side load.

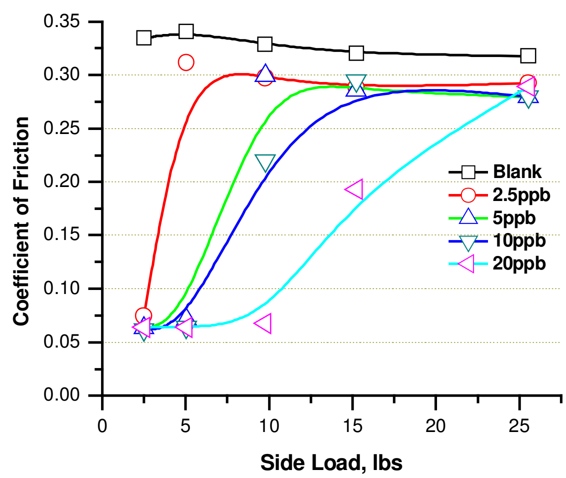

Figure 5. Fine grade glass beads LEM test results

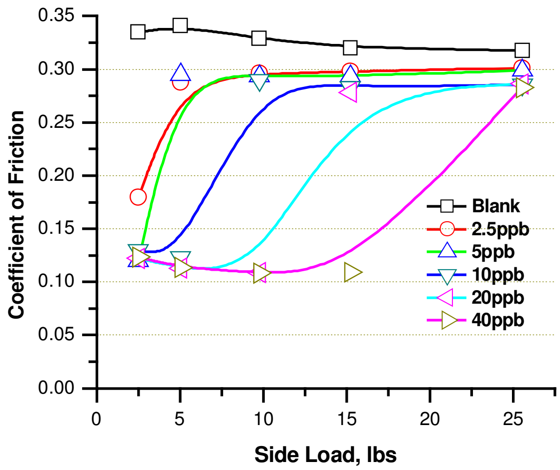

Figure 6. Fine light weight ceramic beads LEM test results

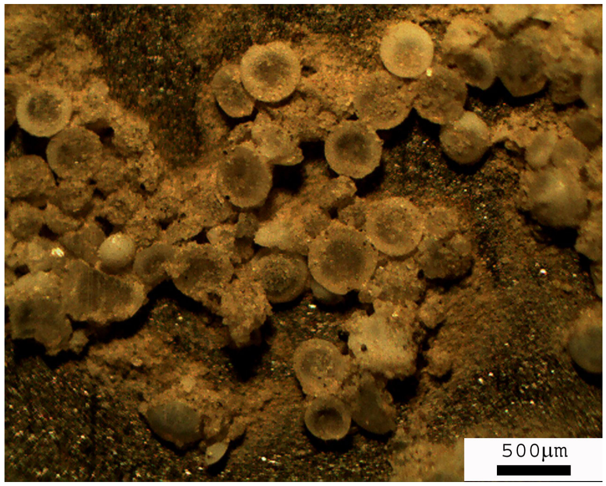

Figure 9. Fine polymer beads captured in between steel surfaces after a non-bumping test at 20 ppb additive loading and 45 lbs side load.

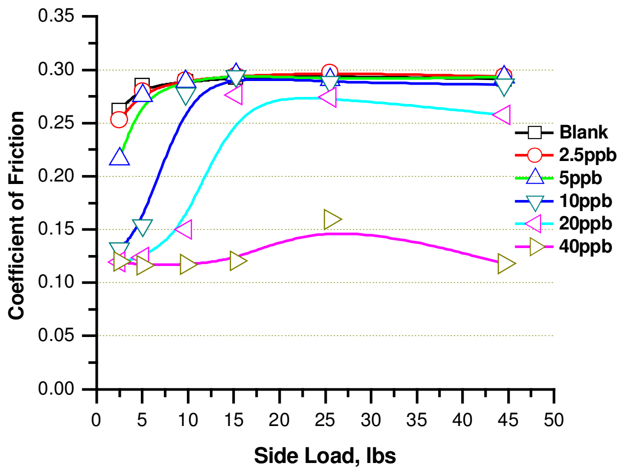

Figure 7. Carbon microspheres LEM test results

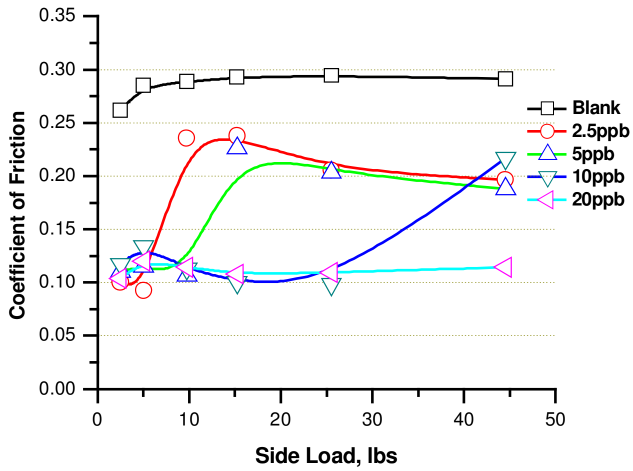

Figure 10. Coarse grade plastic beads LEM test results

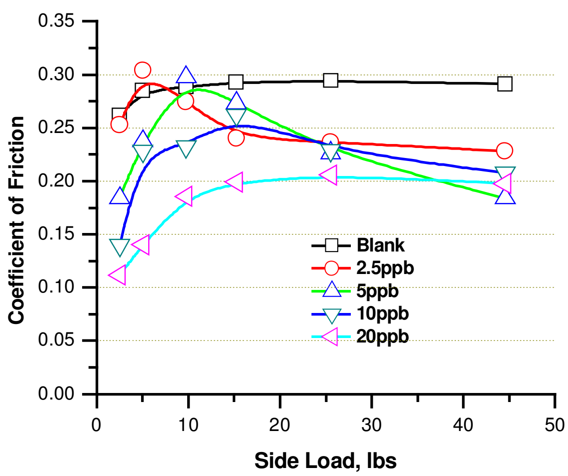

Figure 8. Fine grade plastic beads LEM test results