VARIOUS ANALYTICAL AND PERFORMANCE TEST METHODS TO DEVELOP GREASES USED IN COAL MINING

Surface mining has evolved from the use of simple, manually operated tools to massive mechanical machinery such as rock drills, front-end loaders, grinding mills, hydraulic mining shovels, and draglines. These machines can exceed the size of conventional houses, with some booms extending as far as 300 feet. The sheer size of the large machinery components has also created unique challenges for the design and engineering of support systems that lubricate and sustain the machines.

Proper lubrication of open gears plays a vital role. These sophisticated high-value machines require lubricants with enhanced components to include extra pure solids within the additive package that can be readily pumped and sprayed during any seasonal period of the year. This must occur while preventing dirt and dust from getting into the components which would accelerate wear rates. The fluidity of the lubricant should be such that it can drain freely from gear shrouds.

Coal mining is a significant global industry as coal is an important resource used for both energy and the manufacturing of steel. In fact, coal was the second largest fuel source, contributing up to 26% of global energy consumption during 2017 [1]. The mining equipment supporting the coal industry is highly specialized and, in many cases, extremely large. These tools help excavate coals with great efficiency and speed when compared to earlier methods that relied on manual labor with simple tools. Modern mining equipment has up scaled components such as gears and bearings and often undergoes periodic maintenance with defined periodicity to ensure high reliability and continued availability. Lubrication tasks for coal mining machinery are vital and fundamental to the industry.

Faci et al. (2016) briefly described the development of type 1 open gear lubricants from the first heavy open gear compounds and fortified lubricants to the recent solvent free compounds and environmentally friendly lubricants. Specific lubrication challenges vary depending upon the type of gear drives utilized. Type 1 open gear drives are often utilized in open pit mining. They transmit power via a pinion and rack system commonly used for swing motion drives and the hoist and drag drives of mining shovels; however, type 1 open gear drives are challenged by bi-directional motion and typically suffer from thin lubrication films.

Overcoming the inherent issues of type 1 open gear drive lubrication requires that a number of properties must first be analyzed. These properties include tackiness/adhesion, resistance to high loads/shock loading, film strength, resistance to water spray, ability to cushion vibration, protection against wear/corrosion, sprayability, spreadibility, mobility, and thermal retention. Formulations of open gear lubricants have evolved from asphaltic compounds and resin materials towards lithium greases developed in the 1940s. In the current day, bio-based lubricants have begun to show promise in maintaining performance standards and reducing risks to safety and the environment. Laboratory results of a biodegradable open gear lubricants were found to have equivalent mechanical stability, water resistance, EP and antiwear properties, corrosion inhibition, thermal retention, and pumpability compared to standard commercial mining industry lubricant [2].

Drost et al. (2016) highlighted the relationship between thickeners and their effects on the low temperature properties of open gear lubricants. They mainly focused on type 1 open gear drives and compared four thickener types: aluminum complex, lithium complex, calcium sulfonate complex, and organo-clay. Each sample consisted of the same proprietary base oil and additive system with only the thickener type varied for each sample. The samples were then tested at 25°C and 0°C for pumpability, mobility, cone & plate viscosity, and Brookfield viscosity. Some of the data generated was not representative of typical open gear lubricants, notably the cone & plate viscosity and the Brookfield viscosity. This information however was included for comparison of additional points of interest.

The test samples formulated from aluminum complex thickeners had the best performance for both pumpability and mobility overall. The aluminum complex sample and the calcium sulfonate complex sample performed slightly better than the lithium complex sample while the organo-clay sample performed the worst. These observations suggest that the thickeners utilized for an open gear lubricant must be carefully selected especially for low temperature applications in order to optimize performance, as low temperature applications can further inhibit a greases mobility and pumpability [3].

The De Vaal and Meister (2005) study developed around the constant temperature FZG test for open gear lubricants was designed to determine the effects of temperature on various parameters that dictate lubrication performance such as wear protection, coolant flow rate, and oil film thickness. They conducted a test on four different open gear lubricants to test mass loss per load stage and the final temperature achieved per load change. They found that coolant flow rates affect constant operating temperatures, which then allows differences in performance of the studied lubricants to be distinguished. Further findings show that at cooler temperatures, the lubricant film thickness increases while at high temperatures, additives become more active offering better wear protection. This work implied an optimal operating temperature to obtain both the benefits of film thickness and additive activation [4].

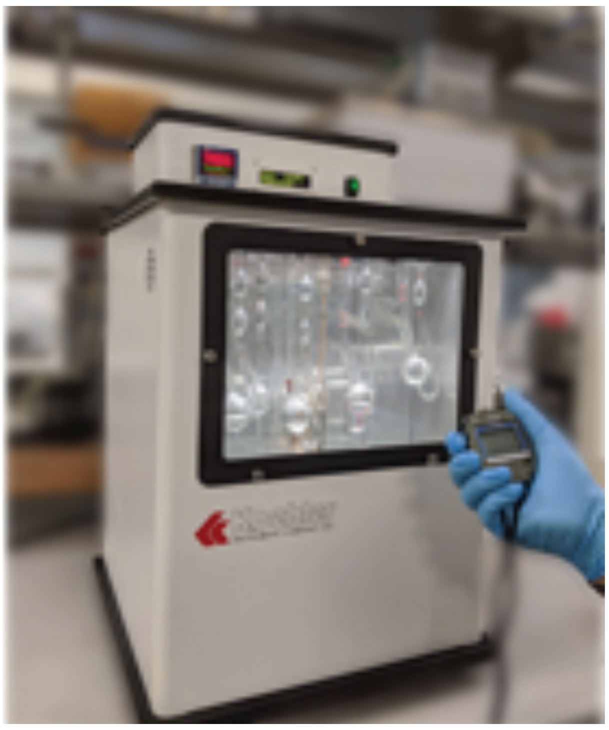

Figure 1. Kinematic Viscosity Bath

Studies of open gear and mining equipment maintenance are a popular topic amongst researchers. Researchers are designing tests for different outcomes such as the parameters of lubricants (wear protection, oil film thickness, surface roughness, coolant flowrate,

Table 1. Industrial Standards of Open Gear Lubricant

Characteristics	BE OGL SD 4731	P&H Revised 464 Spec	P&H Multi-Service 520 Spec	Test Method
1. Flash point (COC)	140 Of Base fluid	79 min.	130 min.	ASTM D 92
2. Base oil viscosity, cSt, @ 40°C @ 100°C	1860	-	300 min.	ASTM D 445
3. Apparent viscosity, poises @ -18°C	-	-	-	ASTM D 1092
4. Copper corrosion, @ 100°C, 24 hrs.	2 e	1 b	1 b	ASTM D 4048
5. Rust Protection	Pass	Pass	Pass	ASTM D 1743
7. EP properties Load wear Index, kgf Four ball weld Point, kgf	120 800 -	- 400 -	- 500	ASTM D 2596 ASTM D 2596
Four ball wear scar diameter, mm	0.7	1.0	0.7	ASTM D 2266
8. Timken OK Load, lb	-	-	50	ASTM D 2509
9. FZG DIN 51-354, 12th stage	-	-	-	DIN 51-354 / ASTM D 5182

etc.). These researchers are all looking for solutions that enhance and better the performance of mining equipment through longer service lifespans of lubricants on machinery, better maintenance management, sustainable lubricant consumption, and reduction of friction and wear. Based upon the aforementioned studies, the selected test methods to best characterize an open gear lubricant for application in coal mining are provided in Table 1 along with corresponding industry standards.

Flash Point

The flash point test according to ASTM D 92 utilizes a Cleveland Open Cup Tester as seen in Figure 1 in order to find the flash point of viscous materials. The test requires approximately 70 mL of the test sample. The sample is then heated at a rate of 5 to 17 °C per minute until it reaches 56 °C below the expected flash point at which point the rate of heating is lowered to 5 to 6 °C until the last 28 °C before the expected flash point. At 28 °C below the expected flash point the heating rate is lowered to 2 °C. After each 2 °C increment, the test flame is passed over the center of the test cup such that the center of the flame is no more than 2 mm above the upper edge of the test cup. Each pass of the flame lasts 1 ± 0.1 seconds, and the flame is passed in the opposite direction of the previous pass. Once there is a flash in the interior of the cup due to flame application the temperature reading is recorded as the observed flash point [5]. Utilizing this flash point, it is then possible to characterize the possible risk of fire when utilizing a grease and to define an upper temperature limit for the grease.

Kinematic Viscosity

Termed "base oil viscosity" in table 1, the kinematic viscosity of the base oil is determined utilizing ASTM D 445. First, a test bath must be maintained within ±0.02 °C for temperatures between 15 °C and 100 °C or within ±0.05 °C otherwise. Furthermore, thermometers must be in the upright position and in the same position as when calibrated. A clean, dry, calibrated viscometer must be used under the condition that the flow time of the manual viscometers does not exceed 200 seconds. Once the test temperature is below the dew point, the viscometer must be filled then inserted into the test bath. It is then possible to observe and record the flow times for viscosity calculation [6]. The importance of kinematic viscosity is to aid in determining a grease's film strength and ability to reduce the friction between moving surfaces. In terms of open gear greases, a low kinematic viscosity would improve the friction reduction but may not give the film strength necessary for high load applications such as in coal mining.

Apparent Viscosity

An apparent viscosity test is performed by forcing grease through a capillary by means of a floating piston actuated by a hydraulic system. Using a predetermined flow rate along with the force developed in the system allows the apparent viscosity to be calculated by means of Poiseuille's equation. A series of eight capillaries and two pump speeds are used to determine the apparent viscosity at sixteen shear rates. The results are expressed as a log-log plot of apparent viscosity versus shear rate [7]. The apparent viscosity result (ASTM D 1092) predicts the flow characteristics of the grease at low temperatures, and while seemingly superfluous in areas with a temperate climate, apparent viscosity aids in characterizing the acceptable temperature operating range of an open gear grease.

Copper Corrosion

One important original equipment manufacturer (OEM) required specification is ASTM D 4048, which measures the effects of lubricating greases on copper, specifically relating to corrosion. To begin the copper corrosion test approximately 60 mL of a grease sample must be placed into a clean test jar such that the depth of the grease is about 80 mm and the top surface is smooth and flat. All excess grease on the jar walls must be wiped off. Utilizing gloves or forceps, a clean copper strip is inserted into the grease. The copper strip must be at the bottom of the test jar and completely immersed by at least 5 mm of grease. The test jar must then be loosely covered with a beaker, crucible, watch glass, or vented cork. The test jar is placed in either an oven or liquid bath maintained at 100 ± 1 °C for 24 hours ± 5 minutes. After the end of the test, the test jar is removed from the oven/liquid bath and left to cool to room temperature. Afterwards, to determine the copper corrosion of the grease, one must remove the copper strip from the test jar using gloves or forceps, taking care to disturb the test strip as little as possible. The test strip is the submerged in a wash solvent, quickly taken out, and dried using a blotting motion with filter paper. Finally, the copper test strip is inspected for color in reference to a standard strip plaque such that light reflects off of the surfaces at a 45° angle [8].

Figure 2. Copper Strip Corrosion Test Bomb Bath

Rust Protection

Opposite to the copper corrosion test ASTM D 1743 is utilized to characterize the corrosion preventive capabilities of a lubricating grease. First a bearing must be packed with a grease sample and inserted into the bearing holder assembly as specified by the test method. The entire assembly is then inserted into a plastic jar and inverted. The jar is placed on the base of a motor driven spindle and the motor is started. The motor is then run for 60 seconds at a specific load before the drive is raised allowing the bearing to coast to a stop within the bearing holder assembly. Separately distilled water must be boiled for 10 ± 5 minutes and cooled to 25 ± 5 °C. Afterwards, a timer is started as a clean syringe with 100 ± 5 mL of the previously boiled water is added into a hole on the bearing holder assembly. All the water in the syringe is added within 20 ± 5 seconds and then once the timer reaches 50 ± 2 seconds the water is withdrawn from the assembly. At 60 ± 3 seconds 70 ± 5 mL of water are withdrawn, leaving the remaining water within the assembly. The cap on the jar is then screwed on and the jar with the assembly is left in a vibration free dark oven for 48 hours at 52 ± 1 °C. Finally, the bearing is cleaned and inspected for corrosion [9].

Figure 3. Rust Preventative Properties of Grease Instrument

Four Ball

The four-ball test machine is operated with one steel ball under load which is then rotated at 1800 RPM against three steel balls held stationary in the form of a cradle to the requirements of ASTM D 2596. During the test, the ball pot is filled with the test grease, taking care to avoid the inclusion of air pockets. Test balls are imbedded in the grease. Then, a locking ring is carefully placed over the three balls and a lock nut is screwed down carefully. Excess grease is removed, and one ball is pressed into the ball chuck and mounted into a chuck holder. Lubricating greases are heated to 27 °C (80 °F) and then subjected to a series of increasing load tests in 10 second durations until welding occurs. The initial load is applied at 80 kg. Two load conditions are recorded: the load-wear index and weld point [10].

The wear protection properties are determined by the Four Ball Wear Test (ASTM D 2266).

The test machine is same for wear scare diameter test, which is used for four ball EP test. The difference in the tests is that the wear scare diameter test is run at a lower rotational speed, 1200 RPM, and at a higher temperature, 75 °C (167 °F) for 60 minutes. Three $^1/_2$-in. (12.7-mm) diameter steel balls are clamped together and covered with the lubricant to be evaluated. A fourth $^1/_2$-in. diameter steel ball, referred to as the top ball, is pressed with a force of 40 kgf into the cavity formed by the three clamped balls for three-point contact. The temperature of the lubricant specimen is regulated at 75°C (167°F) and then the top ball is rotated at 1200 rpm for 60 min. Lubricants are compared by using the average size of the scar diameters worn on the three lower clamped balls [11].

Figure 4. Benchtop Four Ball Wear and EP Tester

Timken OK Load

The Timken OK Load (ASTM D 2509) test is operated with a steel test cup rotating against a steel test block. The test method is used to differentiate between greases having low, medium, or high levels of extreme pressure characteristics. The rotating speed is 123.71 meters per minute which is equivalent to a spindle speed of 800 rpm. Grease samples are brought to room temperature. Two determinations are made: the minimum load (score value) that will rupture the lubricant film being tested between the rotating cup and the stationary block and cause abrasion; and the maximum load (OK value) at which the rotating cup will not rupture the lubricant film and cause abrasion between the rotating cup and the stationary block [12]. While the results from the Timken OK Load may not correlate with results from service, they are still useful for determining a grease's extreme pressure characteristics.

FZG

The FZG visual method (ASTM D 5182-19) is used to measure the scuffing load capacity of oils (or soft greases) used to lubricate hardened steel gears. The test gears are examined initially and after the prescribed duration at each load stage for cumulative damage (scuffing) to the gear tooth flanks. Scoring, a form of abrasive wear, is also included as a failure criterion in this test method. However, this test is primarily used to assess the resistance to scuffing.

An FZG gear test machine is operated at a constant speed of 1450 rpm for a fixed period of 21700 revolutions (approximately 15 minutes) at successively increasing loads until the failure criteria is reached. The initial oil temperature is 90°C beginning at 4th stage load. Notably, an FZG test result of 12th stage passed demonstrates that the developed lubricant has good anti-wear properties [13]. Normally, commercially available products do not have this test data for open gear lubricants.

Conclusions

Massive machinery such as mining shovels, draglines, drills, grinding mills, and excavators are essential to supporting the mining industry. These machines operate under extreme and severe loading conditions, requiring specialty lubricants to handle significant shock loads. Lubricants are also needed to provide an environmental surface barrier to protect the machinery from precipitation and contamination from the mining process. Foreign particles can collect on the lubricated surfaces resulting in abrasive wear. Thus, a premium quality lubricant is needed to fulfill many operating requirements. The lubricant would be required to ensure wear protection, manage shock loading, produce friction reduction, provide a protective coating, and have outstanding mechanical stability. As such, various test methods are vital to the proper development and characterization of open gear greases meant for the mining industry. The test methods shown here not only fulfill OEM specifications for an open gear grease but also include additional tests that provide vital information to correctly develop a grease for a variety of conditions.

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About the Authors

Dr. Raj Shah is currently a Director at Koehler Instrument Company, NY (a renowned manufacturer of petroleum testing instruments) and an active ASTM member for the last 25 years. He held numerous leadership positions within various ASTM committees and is recipient of the ASTM award of Excellence (thrice : a sui generis distinction) and the ASTM Eagle Award. A Ph.D in Chemical Engineering from Penn State University, and a Fellow from The Chartered Management Institute, London, Dr. Shah recently coedited , a reference bestseller titled "Fuels and lubricants handbook", published by ASTM.

https://www.astm.org/DIGITAL_LIBRARY/MNL/SOURCE_PAGES/MNL37-2ND_foreword.pdf

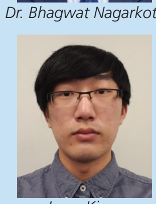
Raj has over 375 publications to his name and is an elected fellow at Energy Institute, NLGI, STLE, IChemE, INSTMC, AIC, CMI, and RSC and a Chartered Petroleum Engineer. A recently elected Fellow by the Institution of Chemical engineers, UK, Dr. Shah was also recently honored with an esteemed engineer designation by Tau Beta Pi, the highest engineering honor society in USA.

More information on Raj can be found at https://www.che.psu.edu/news-archive/2018/Alumni-Spotlight-Raj-Shah.aspx

Dr. Bhagwat Nagarkoti recently retired as Dy. General Manager, Research and Development at the Research and Development Centre of Hindustan Petroleum, Mumbai. He has over 35 years of experience in the petroleum industry during which time he presented and published more than 40 technical papers at various national and international conferences including ELGI, STLE, ICIT, and NLGI-IC meetings and the Conference of Moscow International Lubricant Week. Currently he is a Life Member of Tribology Society of India. He can be reached at bhagwatnagarkoti@gmail.com

Dr. Bhagwat Nagarkoti

Mr. Isaac Kim is a recently graduated in secundo genere chemical engineer from SUNY, Stony Brook University, where Dr. Shah is an adjunct professor and the chair of the external advisory Committee in the Dept. of Material Science and Chemical Engineering.



Isaac Kim

Author Contact Details

Dr. Raj Shah, Koehler Instrument Company • Holtsvile, NY 11742 USA • Email: rshah@koehlerinstrument.com • **Web: www.koehlerinstrument.com**