A review of biolubricants in drilling fluids: Recent research, performance, and applications

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A R T I C L E   I N F O

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Lubricant additives are added to drilling fluids to lower the drag and torque between the drill strings and rock formation. They impart lubricating properties into two moving surfaces contacts under extreme temperature and pressure conditions. Currently, there is a significant interest in developing biolubricants derived from organic sources. Biolubricants offer several valuable friction-reducing physicochemical properties, including high lubricity, wide viscosity range, low pour point, high flash point, high thermal stability, and biodegradability when applied in drilling operation. This study reviews the applications of general lubricants in drilling fluids and the potential of biolubricants derived from vegetable oils in exceeding the performance of hydrocarbon and mineral-based lubricants. Overall, biolubricants possess most of the physicochemical properties required as a lubricant for drilling fluids. The utilization of organic ester-based biolubricant might result in faster and deeper drilling, lower bioaccumulation and high biodegradability characteristic, less waste volume, and reduced in overall operation cost. Among the available biolubricants, polyol esters of vegetable oils demonstrate the most suitable lubricants for many drilling conditions, even though their application is still very limited.

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Abbreviations: AFM, Atomic Force Microscopy; CEC, Coordinating European Council; CoF, coefficient of friction; cST, centistokes; HFRR, high frequency reciprocating rig; NPG, neopentyl glycol; OBM, oil-based mud; PAG, polyalkylene glycols; PAO, polyalphaolefin; PE, pentaerythritol; SBM, synthetic-based mud; SEM, Scanning Electron Microscopy; TAN, total acid number; TME, trimethylolethane; TMP, trimethylolpropane; VI, viscosity index; WBM, water-based mud; XPS, X-ray Photoelectron Spectroscopy

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1. Introduction

Lubricants are added to the drilling fluid as an additive to improve the lubricating effect and minimize the friction (Espagne et al., 2014). High lubricity drilling fluid can also increase the rate of penetration, which may lead to substantial cost savings (Li et al., 2015). On the other hand, poor lubrication can lead to drill bit bearing wear, casing wear, over-pulls in trip-outs and drag, torque problem, and differential sticking (Brandon et al., 1993; Foxenberg et al., 2010). Although they may come from similar sources, such as oil shales and tar sands (Gunstone et al., 2007), derived products, high lubricity drilling fluids can also increase the rate of penetration, which may lead to substantial cost savings (Li et al., 2015). On the other hand, poor lubrication can lead to drill bit bearing wear, casing wear, over-pulls in trip-outs and drag, torque problem, and differential sticking (Brandon et al., 1993; Foxenberg et al., 2010). Nevertheless, when the desired lubrication can no longer be achieved by such means, synthetic-based mud (SBM) will be used to replace WBM. SBMs have been known for its natural lubricating properties which result in lower coefficient of friction. SBM is generally an invert emulsion which consist of a three-phase system, which are synthetic oil, water, and fine particle solids. SBM has been known for its natural lubricating properties. However, when drilling in a harsh condition, there is strong incentive and requirements to further enhance the lubricating performance of SBM (Maker and Muller, 2012; Teng et al., 2013).

A very small quantity of lubricants is adequate to provide sufficient lubricity of the mud. As low as 1% of lubricant can reduce the torque by 20% (Teng et al., 2013), while the average optimum concentration of lubricant is below 3% (Mueller et al., 2004a, 2004b; Amorim et al., 2011; Patel et al., 2013). The common lubricants used in drilling fluid are oils, graphite, powder, surfactant and soaps (Skalle, 2011; Li et al., 2015). They are mainly petroleum derived products, although they may come from similar sources, such as oil shales and tar stands (Gunstone et al., 2007). Polyalphaolefins (PAOs) and polyalkylene glycols (PAGs) are the most common commercial type of lubricant for drilling fluids. PAOs and PAGs have been applied in SBM as a base fluid due to its good lubricating properties. In drilling operation, PAO fluids are specifically favorable in wellbore cleaning, shale stabilization, and bit lubrication and cooling (Rudnick, 2005). The disadvantages of PAO include small viscosity range and low polarity (Dawson and Carpenter, 1995). Meanwhile, one known disadvantage of PAGs is their poor miscibility in API Groups I–III oils which limits their use as co-base fluids (Bart et al., 2012).

At the recent time, there is a high growing interest in an alternative energy using biodegradable lubricants derived from organic sources. The stricter off-shore and natural-gas drilling regulations on drilling fluid component have put increased pressure on the drilling company and offshore oil explorations to move towards greener lubricant application. It was confirmed by many studies that waste petroleum-based lubricants are highly toxic to human health and environment and slow in degradation (Getliff and James, 1996; Neff et al., 2000). In this regard, vegetable oils were found to be suitable alternatives as they are biodegradable, readily available and non-toxic (Addy et al., 1984; Mueller et al., 2004a; Campanella et al., 2010; Darley et al., 2011; Atahani et al., 2013). The generic term for biodegradable and renewable lubricants is biolubricants (Bart et al., 2012).

In this paper, an overview of the state of recent research, significance, development, and several application of synthetic lubricants and biolubricants in drilling fluid from recent publications are presented. Even though a considerable amount of research has been conducted and published on lubrication in drilling operation, only a few of these studies have reviewed lubricants as additives in drilling fluids, especially vegetable oil-based biolubricants. The knowledge of biolubricant types and performance in drilling fluid is important for the industries as well as university researchers in developing a large-scale market for biolubricant, especially with a wide range of vegetable oil and biolubricant available to choose from. Finally, this paper also suggests a direction for future study and development.

2. Measurement of lubricant performance in drilling fluids

In order to investigate the performance of biolubricants in drilling fluids, investigation on lubricity, rheological, filtration, and differential sticking tendency are required. These measurements will determine if the developed fluid with biolubricant added are useful when severe conditions during drilling occurs.

2.1. Mud lubricity

The performance of lubricants in reducing the friction in drilling fluid is estimated by lubricity test. It simulates the speed of
rotation of the drill pipe and the pressure with which the pipe bears against the wall of the hole (Sönmez et al., 2013). Lubricity test provides the measurement of mud lubricity coefficient as coefficient of friction (CoF) using the torque reading and the correction factor on the equipment. This test is also able to determine the required type and quantity of lubricants.

The use of lubricants results in a 15–20% of CoF reduction from a generic 0.24 to 0.19 (Livescu and Craig, 2015). It was also found that the quality of the mud, filter cake, lubricant type and concentration, contact-surface roughness, and temperature affect the CoF (Maidla and Wojtanowicz, 1990; Livescu et al., 2014). The CoF increases when temperature increases above 50 °C. Hence, it was suggested that the CoF values obtained from laboratory or field tests should be specified together with the temperature and surface roughness. Moreover, as laboratory tests conducted at room temperature, the CoF values obtained must be confirmed in the field. It was reported that the differences between laboratory rotational test and field test are in the range of 43–83% (Livescu et al., 2014).

2.2. Differential sticking coefficient

The tendency of differential sticking, which is one of the common reasons for a stuck drill pipe, can be estimated by measuring the differential sticking coefficient. Differential sticking coefficient can be obtained using Fann differential sticking tester. The equipment allows the interaction between the mud cake and flat torque plat, simulating the differential sticking condition. Biolubricant might prevent the differential sticking by reducing torque and friction, improving the quality of mud cake and destroy binding wall cake without polluting the marine life.

2.3. Filtration properties

Filtration properties are determined by measuring the fluid loss and characterizing the properties of the filter cake. Low fluid loss is one of the key performance of a drilling fluid system. The relationship between the characteristic of the filter cake and the differential sticking has also been studied. Differential sticking happens when the drilling pipe becomes embedded in the filter cake. The differential sticking decreases when the filter cake is thinner (Degeare et al., 2003). The thickness of thin filter cake is less than 2 mm API, while thicker filter cake is around 4–6 mm API (Courtteille and Zurdo, 1985).

2.4. Rheological properties

Rheological properties are measured using a viscometer in order to investigate the effects of lubricants on flow behavior of the mud. Rheological properties consist of viscosity and gel strengths. The addition of biolubricants in a relatively low concentration does not produce noticeable rheology changes in a mud (Argillier et al., 1996).

3. Vegetable oils as base stocks for biolubricants

Castor, jojoba, palm, coconut, tallow, soybean, olive, sunflower, and rapeseed oils are among the various vegetable oils that have been used as the base stock for biolubricants. The biodegradable and renewable characteristics of natural oil derived from plants were the incentive that have encouraged people to find their application in drilling fluids (Addy et al., 1984; Mueller et al., 2004a; Patel et al., 2013; Sönmez et al., 2013; Zhou et al., 2013). Triglycerides, the primary content of vegetable oils, are glycerol molecules with three long chain polar fatty acids attached at the hydroxyl groups via ester linkages (Yunus et al., 2004; Fox and Stachowiak, 2007; Aziz et al., 2014). Triglyceride texture of vegetable oil is known to provide lubricant film with strong interaction with metallic surfaces. It is believed that the stronger this interaction, the higher reduction in friction and wear (Rudnick, 2005; Amorim et al., 2011).

Vegetable oils obtained from the plants are unlikely to be applied directly in drilling fluid formulation. The use of untreated vegetable oil in invert emulsion drilling mud has shown that the vegetable oils are extremely prone to hydrolysis, which leads to viscosity increase (Fink, 2011). Their application in petroleum drilling is also restricted due to poor cold flow behavior, low thermal and oxidative stability (Borugadda and Goud, 2015). Moreover, the viscosity range of vegetable oils, which is in the small range of 27.2–53.6 mm²/s (Demirbas, 2007), is considered not flexible and less attractive.

Although vegetable oils might be considered unstable to be used directly in drilling fluid, the information and knowledge on the fatty acid composition of different type of vegetable oils are useful in designing biolubricants. For example, oil that contains a significant quantity of oleic, linoleic, or linolenic acids or other unsaturated components is hydrogenated to produce a saturated version, the new material would have the properties of grease (Rudnick, 2005). The fatty acid composition of different type of vegetable oils is listed in Table 1.

4. Organic esters

Esters are the reaction products of acids or their derivatives with alcohols (Rizvi, 2009). They are tailored to a specific structure. Organic esters derived from soybean oil, peanut oil, corn oil, linseed oil, and rice oil have been suggested to be used as a replacement of mineral oil in drilling fluids (Larson et al., 1983; Barthel, 1984; Maker and Muller, 2012). Most of esters used as lubricants in drilling fluid are derived from polyhydric alcohols, which consist of more than one hydroxyl group. Only a few used esters derived from monohydric alcohols, including aliphatic esters and diesters.

4.1. Diesters

Dibasic acid esters or diesters may be prepared from dibasic acid which contains dicarboxylic groups, and monohydric alcohol. For lubrication purposes, there are two suitable types of dicarboxylic acid esters: esters of branched primary alcohols with straight dicarboxylic acids; and esters of straight primary alcohols with straight dicarboxylic acids.

<table>
<thead>
<tr>
<th>Vegetable oils</th>
<th>Palmitic (16:0)</th>
<th>Stearic (18:0)</th>
<th>Oleic (18:1)</th>
<th>Linoleic (18:2)</th>
<th>Linolenic (18:3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunflower oil</td>
<td>6.1</td>
<td>2.5</td>
<td>6.4</td>
<td>3.5</td>
<td>2.6</td>
</tr>
<tr>
<td>High oleic sunflower oil</td>
<td>3.5</td>
<td>4.4</td>
<td>80.3</td>
<td>10.4</td>
<td>–</td>
</tr>
<tr>
<td>Safflower oil</td>
<td>6.4</td>
<td>2.5</td>
<td>17.9</td>
<td>73.2</td>
<td>–</td>
</tr>
<tr>
<td>High oleic safflower oil</td>
<td>4.6</td>
<td>2.2</td>
<td>77.5</td>
<td>13.2</td>
<td>–</td>
</tr>
<tr>
<td>High linoleic safflower oil</td>
<td>6.7</td>
<td>2.6</td>
<td>14.6</td>
<td>75.2</td>
<td>–</td>
</tr>
<tr>
<td>Soybean oil</td>
<td>6.0</td>
<td>5.2</td>
<td>20.2</td>
<td>63.7</td>
<td>5.0</td>
</tr>
<tr>
<td>High oleic soybean oil</td>
<td>6.2</td>
<td>3.0</td>
<td>83.6</td>
<td>3.7</td>
<td>1.7</td>
</tr>
<tr>
<td>Corn oil</td>
<td>10.6</td>
<td>2.0</td>
<td>26.7</td>
<td>59.8</td>
<td>0.9</td>
</tr>
<tr>
<td>Cottonseed oil</td>
<td>18.0</td>
<td>2.0</td>
<td>4.10</td>
<td>38.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>
with branched dicarboxylic acids (Dudek and Popkin, 1962). Diesters have excellent lubricating properties, high thermal stability high VI, and low pour point.

4.2. Polyol esters

Polyols esters are produced by reacting a monobasic acid with polyhydric alcohol. The polyhydric alcohol forms the backbone with the acid groups attached to it. The polyol esters include esters derived from hindered neopentyl alcohols such as NPG, trimethylolethane (TME), TMP, higher trimethyloalkanes, PE, dipentaerythritol or triplentaerythritol (Bart et al., 2012). As the bisallylic protons on the fatty acid chain are not present, polyol esters possess high oxidative stability, high hydrolytic stability, excellent low temperature performance and relatively high biodegradability. Polyol esters have wider range of viscosities available compared to diesters, although they have similar properties.

Polyol esters have been recommended for use in various lubricant application, such as, crankcase engine oils (i.e., passenger car motor oils, heavy duty diesel motor oils, and passenger car diesel oils), two-cycle engine oils, catapult oil, hydraulic fluids, drilling fluids (Aldrich et al., 1998). It is suggested to evaluate the principal chemical structure of the polyol esters prior to specifying the application.

5. Physicochemical and performance properties

In drilling operation, a biolubricant must have certain physicochemical properties to ensure an excellent lubricating performance under wellbore condition. Those properties, such as viscosity, viscosity index, lubricity, solvency, thermal and oxidative stability, and hydrolytic stability, are largely affected by the presence of ester functional group. The properties of diesters and various polyol esters are presented in Table 2.

5.1. Physical properties

5.1.1. Viscosity and VI

One of the most important properties of a lubricant is viscosity. It expresses the resistance of a biolubricant to flow. The viscosity is directly related to temperature, pressure, and lubricant film thickness (Bird et al., 1960). High viscosity indicates thicker lubricant film and low viscosity suggests thinner film. It is usually tested using the Kinematic Viscosity method based on ASTM D445, which is measured at 40 °C and at 100 °C. Viscosity index (VI) is an indicator of the oil’s resistance to change as temperature changes. It is measured based on ASTM D2270 at 40 °C and at 100 °C.

Biolubricants can be tailor-made to fit a specific demand. The high-viscosity polyol esters, derived from a polyhydroxyl compound, such as NPG, TMP, and PE, are desirable in drilling fluid application (Bart et al., 2012). Their viscosity can be increased by increasing the chain length of carboxylic acid and alcohol, increasing the molecular weight of the molecule, increasing the dipolar interactions, branching the molecules, decreasing the flexibility of the molecule, or including cyclic groups in the molecular backbone (Erhan and Perez, 2002). The VI also increases with the increase of molecular structure length. Branching, however, results in decreasing the VI (Rudnick and Shubkin, 1999). Ghosh and Das (2014) suggests that multifunctional acrylate based polymeric additives, which are decyl acrylate polymers and iso-octyl acrylate polymers, have high potential to improve the VI of lubricating oil. Different polymeric additives, which are produced from acrylic acid with various alkyl chain length alcohols, have also effectively improved the VI of lubricating oils (Mohamad et al., 2012).

Generally, polyol esters have kinematic viscosities between 5–225 cSt at 40 °C and 2–20 cSt at 100 °C, while diesters have kinematic viscosities of 6–46 cSt at 40 °C and 2–8 cSt at 100 °C (Erhan and Perez, 2002; Rizvi, 2009). For most industrial applications, the required viscosities for lubricants are in the range of 5–15 cSt at 100 °C (Bart et al., 2012). Biolubricant esters have high VI and good low temperature behavior (Honary and Richter, 2011). Compared to polyol esters, diesters have better VI since the linear diacid molecules is generally long (Erhan and Perez, 2002).

5.1.2. Lubricity

Lubricity is the measure of the reduction in friction and wear by a lubricant additive. The polarity of esters is believed to generate the attraction between ester molecules and positively charged metal surface, thus increases the lubricity of esters (Rudnick, 2005; Amorim et al., 2011). When a small quantity of viscous polar ester is blended with a less viscous nonpolar base fluid such as PAO, the polar ester will stick to the surfaces and stays in the contact area, even when the base fluid is squeezed out of the contact zone. Moreover, the lubricant film created by esters is believed to be stronger than the film formed by synthetic hydrocarbons or PAOs (Nie, 2012). Most esters are ideal for severe duty application as they still provide lubricating properties at temperatures as high as 180 °C (Rudnick, 2005).

5.1.3. Solvency

Solvency of biolubricant is measured by aniline point. The measurement standard for aniline point is ASTM D611. Solvency or the solubility performance increases when aniline point decreases. The high polar nature of biolubricant esters, which is affected by the presence of oxygen in the molecules, disperses and solubilizes the by-products of oil degradation, making esters good dispersants or solvents. Most of esters derived from vegetable oils are fully blended with synthetic hydrocarbons or PAOs (Nie, 2012). Also, polyol esters, particularly, can improve the solubility of other additives in synthetic-based fluid (Torbacce et al., 2014).

5.1.4. Pour point

Pour point is the lowest temperature at which a lubricant pours or flows. It is a good indicator of its low-temperature fluidity (Salih

<table>
<thead>
<tr>
<th>Esters</th>
<th>Viscosity at 40 °C (cSt)</th>
<th>Viscosity at 100 °C (cSt)</th>
<th>Viscosity index</th>
<th>Pour points (°C)</th>
<th>Flash point (°C)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesters</td>
<td>6 to 46</td>
<td>2 to 8</td>
<td>90 to 170</td>
<td>−70 to −40</td>
<td>200 to 260</td>
<td>Rizvi (2009)</td>
</tr>
<tr>
<td>TMP® ester</td>
<td>34.9</td>
<td>7.8</td>
<td>210</td>
<td>−15</td>
<td>322</td>
<td>Yunus et al. (2003)</td>
</tr>
<tr>
<td>PE® ester</td>
<td>68.4</td>
<td>12.7</td>
<td>Not stated</td>
<td>&lt; −20</td>
<td>302</td>
<td>Azz et al. (2014)</td>
</tr>
<tr>
<td>NPG® ester</td>
<td>8.6</td>
<td>2.6</td>
<td>145</td>
<td>−55</td>
<td>Not stated</td>
<td>Erhan and Perez (2002)</td>
</tr>
</tbody>
</table>

* Trimethylolpropane.
* Pentaerythrytol.
* Neopentyl glycol.
et al., 2014). The pour point of biolubricants for drilling fluid is preferably low to prevent them to become solid/waxy during transportation in cold pipelines, especially in winter. To improve (lower) the pour point, using carboxylic acid with shorter chain length and increasing the degree of branching can be applied. Diesters have excellent pour points for lubrication purposes, which falls in a range of –70 °C and –40 °C, while polyol esters have pour points between –60 and –15 °C (Rizvi, 2009).

5.1.5. Flash point and fire point
Flash point is the lowest temperature at which a lubricant must be heated before it vaporizes. Meanwhile, fire point is the temperature at which the combustion of a lubricant continues. Flash point and fire point are the indicator of safety for transportation and storage purposes. Both flash point and fire point measurements are based on the ASTM D92 method. Most of vegetable oils have fire points of greater than 300 °C, which is higher than typical mineral oils (Honary and Richter, 2011). The flash points of diesters and polyol esters are above 200 °C which indicates a low evaporation tendency and fulfils the basic requirement as a lubricant (Rizvi, 2009).

5.2. Chemical properties

5.2.1. Thermal stability
The drilling mud components degrade with time as the result of elevated temperature during drilling. Therefore, thermal stability and the rate of degradation of biolubricants must be considered when defining the biolubricant performance (Darley et al., 2011). Ideally, the thermal stability of biolubricants must be superior or similar with the maximum limit temperature of the drilling mud. In general, esters have excellent thermal stability which makes them suitable to use as biolubricant in drilling fluids. However, the thermal stability of diesters is surpassed by polyol esters (Bart et al., 2012). The typical thermal degradation temperature of diesters and polyol esters are 273 °C and 315 °C, respectively (Rudnick, 2005).

5.2.2. Oxidative stability
Oxidation of lubricating oils may cause polymerization and increase viscosity. Erhan and Perez (2002) explained that untreated vegetable oils have low oxidative stability due to the presence of bisallylic protons on the fatty acid chain. These protons are affected to radical attack and subsequently undergo oxidative degradation to form polar oxo-compounds. Transesterification and chemical modification (i.e. epoxidation) are among the ways to enhance the poor oxidative stability of vegetable oils. For example, according to EN 14112, the oxidative stability of Jatropha curcas oil increased from 7.92 h to 13.51 h and 13.03 h after being modified into methyl and ethyl ester, respectively (Diana Da Silva Araújo et al., 2014). Oxidative stability may decrease when a higher content of polyunsaturated methyl ester presents (Zuleta et al., 2012).

Low molecular weight polyols (mostly neopentyl glycol or trimethylol propane) can be used in transesterification to produce biolubricants that offer superior oxidative stability. In general, esters have excellent oxidative stability, thus tend to function better under high temperature and severe conditions.

5.2.3. Hydrolytic stability
Hydrolytic stability implies the tendency of esters to hydrolyze. Hydrolytic stability is determined by ASTM D2619-09. Hydrolysis is the degradation of biolubricant molecules in the presence of water and high temperature to cleave back into acid and alcohol. Hydrolysis is an undesirable phenomenon in the utilization of organic esters. Biolubricants having a lower total acid number (TAN) shows higher hydrolytic stability.

Even less sensitive unsaturated ester of monocarboxylic acids and monofunctional alcohols are still considered unstable towards hydrolysis at deep offshore drilling temperature higher than 160 °C (Bart et al., 2012). On the other hand, vegetable oil-based polyol esters and diesters generally resist hydrolysis better than other lubricant base stocks. Diesters, however, are usually more prone to hydrolysis (Fink, 2011).

5.2.4. Biodegradability
Biodegradability and renewability of biolubricants is an important property for developing environmentally adapted lubricants. Biodegradable lubricants are described as products with rapid biodegradability and low eco-toxicity. According to Coordinating European Council (CEC) L-33-T-82, the measure of biodegradability is the alteration in the chemical structure of substance/microorganisms. The biodegradability of polyol esters and diesters is superior, which is between 55 and 100%. Meanwhile, mineral oil and synthetic oil (i.e. PAO) have poor biodegradability, ranges from 15–35% to 5–30%, respectively (Bart et al., 2012). Institut Francais du Petrole & Janssen has also emphasized that ester based lubricants are biodegradable, nontoxic and fully environmental friendly (Argillier et al., 1996).

6. Biolubricant application in drilling fluids

Biolubricants are applied in drilling fluids for two main reasons: when mineral oil-based lubricants cannot meet the requirements for specific performance, such as biodegradability, extreme low and high drilling temperature, and stability under extreme well bore conditions, and when biolubricants can offer an overall economic benefit from preventing bit and casing wear, differential sticking, and high energy consumption due to high torque and drag.

6.1. Application in water-based mud

Biolubricants have been proved to be non-toxic, increase the lubricity, but does not affect the rheological properties of WBM (Argillier et al., 1996; Amorim et al., 2011). It causes no greasing but does not affect the rheological properties of WBM (Argillier et al., 1996; Mueller et al., 2004b). A fatty acid, a sulfonated fatty acid, and a blend of triglycerides and alcohols usually reduces friction in all the muds (Darley et al., 2011).

Previous studies have primarily concentrated on the effect of biolubricant on CoF of the mud. Although different sources of biolubricants lead to different degree of lubricity, generally all of biolubricants has successfully reduced the CoF. Patel et al. (2013) carried out a series of experiments using a newly developed modified ethoxylated castor oil-based lubricant for WBM. Castor oil has better low temperature lubrication than most vegetable oils as a result of its high ricinoleic fatty acid. Castor oil-based lubricant were prepared by reacting ricinoleic acid with several polyol alcohols, including sorbitan. The sorbitan ricinoleate lubricant produced had hydrophilic head and lipophilic tail. The results indicate that the CoF of the mud decreases when the lubricant is presence. After the mud being subjected to a temperature of 150 °F for 16 h, the CoF of 12.5 ppg mud with 2% lubricant decreases by 11–17% compared to the base mud. In a different work, sulfonated castor oil and its derivatives have been proposed as a lubricant for WBM or other downhole fluids. Livescu et al. (2015) found that sulfonated castor oil increased the lubricity of the downhole fluids. The sulfonated castor oil in a base fluid obtained the lowest CoF compared to samples without lubricant added. A little amount of
1% of lubricant can reduce the CoF from 0.24 to 0.13. The CoF of the castor oil-based lubricant mixed with downhole fluids are maintained the same even when rapid changes of temperatures occurs. It is also worth mentioning that the CoF does not change over time, for example the CoF of a 2-week old lubricant added sample is similar with the CoF of a freshly mixed sample.

Sönmez et al. (2013) studied the lubricity improvement property of different commercial lubricants at high calcium ion content, high pH, high chloride content, and high density WBM lignosulfate. It was suggested that WBM lignosulfate was not strong enough to withstand the high torque and possessed low lubricity. The lubricants used are triglyceride and vegetable oil-based lubricant, fatty acid, glyceride-based lubricant and polypropylene glycol-based lubricant, and crude/diesel oil. It was found that highest lubricity was achieved from the mixture of lubricants and light oil. Whereas heavy oil and diesel resulted in negative lubricity performance and increased the rheological properties of the mud. On positive effect, heavy oil, light oil, and triglyceride and vegetable oil-based lubricant decrease the API fluid loss of the mud. Calcium content and pH do not cause any problems on lubricity, however high chloride content might decrease the lubricity and rheological properties. Sönmez et al. (2013) also mentioned that increasing the density of the mud along with the addition of lubricant increased the lubricity.

The lubrication mechanism of modified glicerides and xanthan gum in WBM has been studied by Nunes et al. (2014). Based on tensiometry, adsorption onto iron oxide nanoparticles, contact angle, and lubricity tests, it was concluded that monoglycerides with the carbon chains of C8, C10, C12, and C18 accomplished excellent lubricity for WBM. The lubricant performance increases when their water solubility decreases. The C6 derivative shows a much lower lubricity, possibly considering its higher solubility in water. The lubricating effect increases when xanthan gum is used in suspensions. In addition, it is beneficial when one or more free OH groups in the polar segment of the molecular structure present as they absorb strongly on the metal surface.

Present study also suggests that the fluorescence effect of vegetable oil-based lubricant might be unfavorable for geological logging. One of solutions to decrease the high grade of fluorescence is by adding liquid nitric acid or solid nitric acid, with the concentration of 4% (w/w) or 9% (w/w) respectively, into the ester lubricants for one to two hours (Zhou et al., 2013). After the reaction is finished, a new low fluorescence ester lubricant for drilling fluid is produced. Moreover, the lubricity of the lubricant is also increased, even after being subjected to high temperature of 180 °F for 16 h.

Researchers have studied the effect of lubricating properties of biolubricants to differential sticking as well. It was concluded that biolubricants might prevent differential sticking (Mueller et al., 2004b; Amorim et al., 2011). A study has shown fatty-alcohol based lubricant managed to prevent differential sticking and improved the lubricity significantly in highly alkaline water-based metal silicate drilling muds (Mueller et al., 2004b). The fatty-alcohol comprised of linear or branched monohydric having at least 12 carbon atoms with the effective concentration of 1–3% by weight. It was suggested that the performance of fatty-alcohol based lubricant can be further enhanced by including carboxylic acid esters in the system. The fatty-alcohols have a foam-suppressing effect which can overcome the foaming potential of esters. The recommended mixture of fatty alcohols and esters is around 25–55% by weight of esters.

Another study by Amorim et al. (2011) investigated the effect of four types of biolubricants on the tendency of differential sticking in WBM system. The lubricants are water soluble vegetable oil-based lubricant, water insoluble acid ester of a short chain and ethanol, and the mixtures of water insoluble greases extracted from vegetable oils. Results show that the addition of biolubricants reduces both CoF and differential sticking coefficient as a result of lubricants adherence to the mud cake. In the presence of water, the water insoluble lubricant forms micelles between the clay particles in the mud, making it difficult for clay particles to interact with each other. Consequently, the particles are dispersed and filtration loss was reduced respectively. When in contact with surfaces such as metal, it is believed to detach itself. It adheres to the metallic surfaces and lubricated them. Meanwhile, water soluble biolubricant which has dipoles and charges forming a film over the metal surface. The interaction occurs on the film layer is believed stronger than that of common oils. Nevertheless, too little attentions has been paid to the effect of biolubricant to the API fluid loss of the mud. WBM having high fluid loss and poor filter cake has been known to cause alteration of rock properties (Sharma and Wunderlich, 1987).

6.2. Application in synthetic-based mud

Drilling operation requirements have heightened the need for lubricity improvement for SBM. Due to its nature type of the base fluid, SBM already has good lubricating characteristic. However, particular well and drilling condition, such as a highly deviated well with frequent changes in direction, might cause a very high torque even while using SBM (Mueller et al., 2004a; Schamp et al., 2006; Teng et al., 2013). Moreover, some off-shore field regulations has demanded an increase of lubricity for SBM, such as paraffin, linear alpha paraffin or internal olefin-based mud (Maker and Muller, 2012).

Esters of different combinations of alcohols and carboxylic acids have been studied on their application in SBM. Partial glycerides of vegetable oils shows promising results for formulation of biolubricant. Partial glycerides are esters of glycerol with fatty acid, where not all the hydroxyl groups are esterified. Partial glycerides can be monoglycerides or diglycerides. Mueller et al. (2004a) performed a series of experimental investigation on soy oil sulfonate, glycerol monotalloate, or a combination of sulfphated castor oil with glycerol monotalloate as biolubricants for both WBM and OBM. Interestingly, the addition of sulfonates or glycerol monotalloate in WBM does not lead to foaming effect, a common problem associated with esters in WBM. 1.5% by weight of lubricant is added to each of the mud formulations. Meanwhile, the use of glycerol monotalloate and a combination of sulfphated castor oil with glycerol monotalloate leads to a significant friction reduction for both OBM and WBM.

In a different study, esters of fatty acids and a polyol component for SBM have been developed (Maker and Muller, 2012). The polyol component are chosen from oligoglycerols, through direct acid or base catalyzed esterification, while the fatty acids (C12 to C18) are derived from palm oil, palm kernel oil, coconut oil, or tallow oil. For example, in order to make the final oligoglycerol ester products, 924 g of oleic acid are mixed with 276 g of oligoglycerol with OH number 1178. The reaction was carried out in a tank and heated to 240 °C under a nitrogen atmosphere. When applied on paraffin-based mud, specifically linear or branched paraffins with 5 to 22 carbon atoms, the oligoglycerol ester lubricant managed to reduce the CoF of the mud. The result also shows that the mud with the oligoglycerol ester withstands the pressure more than the untreated mud when oligoglycerol esters were added to the mud in quantities of 1 to 5% by weight.

A complex polyol fluids, which is a reaction product of methyl glucoside and polyglycerol, have been claimed to be an effective lubricating fluid in numerous Gulf of Mexico applications (Alejandro et al., 2003). Although the sources of the complex polyol fluids are not described, the results of this finding are potential insight of their ability in both WBM and SBM. In this study,
complex polyol fluids are added as a co-base fluid. The concentration of 12% v/v of complex polyol fluids in a mud may result in improved wellbore stabilization and lubricity. When combined with potassium carbonate, the fluid can generate a superior shale stability. This might due to the impact of complex polyol fluids that reduces the water activity and creating a membrane with the shale that prevents the diffusion of ions between the drilling fluid and the shale (Simpson and Dearing, 2000).

In a recent study, Dias et al. (2015) showed that corn starch has been chemically modified by esterification reaction with vinyl ester from lauric acid or vinyl ester from stearic acid exhibited high performance as filtrate controller in invert emulsion drilling fluid. It was found that the starch fatty esters produced a more stable emulsion with lower filtrate volumes compared to the standard commercial fluid.

Unfortunately, there are only a few research paper and patent available on vegetable-based biolubricants for SBM. There are several drilling fluid and chemical companies which already produced biolubricants. Some of the companies are Emery Oleo-chemical, Dover Chemical Corporation, and Newpark Drilling Fluids. However, those commercial products are not reported into a scientific research yet.

7. Challenge and future prospects

Biolubricants are attractive in general industrial market. They have been used in drilling fluid formulation, even though the market is still very small. The consumer acceptance of these oils depends largely on their cost and performance during use, not only on their biodegradability. According to Rizvi (2009), the cost of diesters and polyol esters can be twice the price of PAO or common drilling fluid lubricants. In order to produce high-performance biolubricants, chemical alteration of natural esters and improvement in the biotechnology of vegetable oils are needed to benefit the environment and the economy. Jiang et al. (2015) suggested that blending polyol esters with synthetic oils such as PAO would result in better properties and cheaper cost as well.

One of the challenge in conducting research in drilling fluid lubricant is the inconsistency and difference of lubricity measurement results between laboratory and field experience. The friction caused by solids contained in the mud, such as barite and bentonite, cannot be measured by the standard API lubricity tester (Skalle et al., 1999). This might result in misleading reading and results. Modification of the tester might alleviate the problem. The screening process in determining the suitable lubricants can also cause difficulties. Several screening methods, which are high frequency reciprocating rig (HFRR), elastohydrodynamic rig (EHDR), Fann lubricity test, and ring tribometer test, are reported to generate some inconsistent results (Teng et al., 2013).

Despite the demand for additional lubricity for SBM, work on synthetic lubricants and biolubricants for this type of drilling fluid is very few. Teng et al. (2013) explained that developing lubricants for SBM might be more challenging than WBM. Current research also shows lack of the comprehensive perspective on the factors affecting CoF of the mud, such as mud density, solid contaminant, and maximum well temperature, particularly on SBM. The evaluation of biolubricant effects on the permeability of reservoir should also be conducted. An experimental analysis of formation damage potential of non-organic lubricants by Oside (2013) suggested that lubricant permeability test is important in selecting the best performance lubricant.

Other areas that should be explored include: the relationship between molecular structure of biolubricants and their performance in reducing mud lubricity, preventing differential sticking, and improving filtration properties of the mud; the mechanism of high polar biolubricants forming lubricating film by adsorption of the polar end onto the metal surface of drill strings, which should be supported by analytical evidences, including Scanning Electron Microscopy (SEM), Atomic Force Microscopy (AFM), X-ray Photo-electron Spectroscopy (XPS), and so on; a more detail of polyol esters’ tribological performance in drilling fluids and their compatibility with other mud additives.

8. Conclusions

The strongest characteristic of vegetable oil-based biolubricants is their biodegradability and low toxicity for offshore drilling applications. The concern on environmental safety and environmental regulations on drilling fluid additives have been increased significantly, driving the drilling companies to move toward greener lubricant application. Palm oil, soybean oil, peanut oil, corn oil, linseed oil, and rice oil are among the natural oils that have been suggested to replace mineral oil.

The modification of vegetable oils to ester form leads to suitable viscosity range, high CoF, high film strength, non-corrosive, low pour point, low flammability, high solubility, high thermal and oxidative stability, and non-toxic. Ester biolubricants are not only beneficial for water-based-mud, their high lubricating effect can also improve the lubricity of synthetic-based mud, such as paraffin-based mud. Polyol esters show the highest lubricant performance potential, compared to diesters. Polyol esters have higher thermal and oxidative stability, higher VI, wider viscosity range, and higher flash point. However, the scientific study of polyol esters in drilling fluid is very limited. It is highly recommended to explore the potential use of polyol ester in the future.

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