Tribological Characteristics of Calophyllum inophyllum–Based TMP (Trimethylolpropane) Ester as Energy-Saving and Biodegradable Lubricant

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The purpose of this research is an experimental study of Calophyllum inophyllum (CI)-based trimethylolpropane (TMP) ester as an energy-saving and biodegradable lubricant and compare it with commercial lubricant and paraffin mineral oil using a four-ball tribometer. CI-based TMP ester is a renewable lubricant that is nonedible, biodegradable, and nontoxic and has net zero greenhouse gases. The TMP ester was produced from CI oil, which has high lubricity properties such as higher density, higher viscosity at both 40°C and 100°C and higher viscosity index (VI). Experiments were conducted during 3,600 s with constant load of 40 kg and constant sliding speed of 1,200 rpm at temperatures of 50, 60, 70, 80, 90, and 100°C for all three types of lubricant. The results show that CI TMP ester had the lowest coefficient of friction (COF) as well as lower consumption of energy at all test temperatures, but the worn surface roughness average (Ra) and wear scar diameter were higher compared to paraffin mineral oil and commercial lubricant. Before 80°C, CI TMP ester actually has a higher flash temperature parameter (FTP) than paraffin mineral oil and as the temperature increases, the FTP of TMP ester decreases. The worn surfaces of the stationary balls were analyzed by scanning electron microscopy (SEM) and results show that CI TMP ester has the highest wear compared to paraffin mineral oil and lowest wear compared to commercial lubricant. However, CI TMP ester is environmentally desired, competitive to commercial lubricant, and its use should be encouraged.

KEY WORDS

Tribology; Trimethylolpropane (TMP) Ester; Friction and Wear; Transesterification; Biolubricant

INTRODUCTION

Because energy is essential to many facets of life, it is necessary to determine its efficient use. Energy efficiency is seen to have a national security benefit because it can be used to minimize the level of imports of energy from foreign countries and may slow down the rate at which domestic energy resources are depleted. In addition, the depletion of the world’s crude oil reserve, increasing crude oil prices, and issues related to conservation have brought about renewed interest in the use of bio-based lubricants (Arumugam and Sriram (1)). Furthermore, crude oil is not renewable, biodegradable, and environmentally friendly (Mohjir, et al. (2)). To solve these problems, biolubricants should be produced from vegetable oil, which is renewable, biodegradable, and cheap and has no adverse effects on the environment (Asadauskas and Erhan (3); Ing, et al. (4)). In this study, Calophyllum inophyllum (CI), commonly called Alexandrian laurel, based trimethylolpropane (TMP) ester is used as the source for the production of biolubricant, which is a promising alternative to replace crude oil–based lubricant. CI oil has a high oil content, is acidic, and has better cooling characteristics than Jatropha curcas (Atabani and Cesar (5)). From Table 1 it can be seen that it has good characteristics such as high viscosity, acid value, and flash point compared to other nonedible and edible plant-based oil. As a nonedible oil seed feedstock, it will not affect food prices or spur the food versus fuel dispute (Arumugam and Ponnusami (6)). It can be produced in windy areas and salt spray areas with brackish water and there is no need to provide fertilizer, which is another reason it has potential for use as an automotive lubricant (Ong, et al. (7)). Thus, CI TMP ester has received attention as a new feedstock for use as a biolubricant.

Plant-based oil has limited usage due to its poor oxidation stability, low viscosity, high acidity, and instability at higher temperatures, which has been found to be caused by the weakness of the beta carbon hydrogen of the glycerol part of the triglycerides molecule (Habibullah, et al. (8); He and Bao (9); Petlyuk and Adams (10); Xu, et al. (11)). Some of these limitations could be overcome by reducing polysaturation in the triglyceride part of plant oil. Chemical modification, mainly transesterification (Miller, et al. (12); Ssempebwa and Carpenter (13); Uosukainen, et al. (14)), catalytic cracking (Hew, et al. (15)), catalytic esterification (Li, et al. (16)), and emulsification (Ikura, et al. (17)), is the most commonly used method to reduce the inherent shortcomings in vegetable oils by eliminating the unsaturation part. TMP was chosen as reactant in this research. Compared to other polyols such as neopentylglycol and pentaerythritol, TMP is...
Calophyllum inophyllum-Based TMP Ester

Table 1—Physicochemical Properties of Calophyllum inophyllum Oil and Other Edible and Nonedible Vegetable Oils (Sahoo, et al. (32); No (33); Sahoo and Das (34); Knothe (35); Nakpong and Woithikanokkhan (36))

<table>
<thead>
<tr>
<th>Oil</th>
<th>Specific Gravity</th>
<th>Viscosity (cSt) at 40°C</th>
<th>Cetane Number</th>
<th>Flash Point (°C)</th>
<th>Acid Value (mg KOH/g)</th>
<th>Calorific Value (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calophyllum inophyllum</td>
<td>0.896</td>
<td>71.98</td>
<td>—</td>
<td>221</td>
<td>44</td>
<td>39.25</td>
</tr>
<tr>
<td>Coconut oil</td>
<td>0.92</td>
<td>28.05</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Rubber</td>
<td>0.91</td>
<td>66.2</td>
<td>37</td>
<td>198</td>
<td>34</td>
<td>37.5</td>
</tr>
<tr>
<td>Cotton</td>
<td>0.912</td>
<td>50</td>
<td>41.2–59.5</td>
<td>210</td>
<td>0.11</td>
<td>39.6</td>
</tr>
<tr>
<td>Pongamia pinnata</td>
<td>0.913</td>
<td>27.84</td>
<td>45–67</td>
<td>205</td>
<td>5.06</td>
<td>34.0</td>
</tr>
<tr>
<td>Jatropha curcas</td>
<td>0.920</td>
<td>18.2</td>
<td>33.7–51</td>
<td>174</td>
<td>3.8</td>
<td>38.5</td>
</tr>
<tr>
<td>Neem</td>
<td>0.912–0.965</td>
<td>20.5–48.2</td>
<td>51</td>
<td>34–285</td>
<td>—</td>
<td>33.7–39.5</td>
</tr>
<tr>
<td>Castor (Ricinus communis)</td>
<td>—</td>
<td>297*</td>
<td>—</td>
<td>260</td>
<td>—</td>
<td>39.500</td>
</tr>
<tr>
<td>Sunflower (Helianthus annuus)</td>
<td>37.1*</td>
<td>37.1</td>
<td>274</td>
<td>—</td>
<td>—</td>
<td>39.575</td>
</tr>
<tr>
<td>Soybean</td>
<td>32.6*</td>
<td>37.9</td>
<td>254</td>
<td>—</td>
<td>—</td>
<td>39.623</td>
</tr>
<tr>
<td>Colza (Brassica campestris)</td>
<td>37*</td>
<td>37.6</td>
<td>246</td>
<td>—</td>
<td>—</td>
<td>39.709</td>
</tr>
</tbody>
</table>

*At 37.8°C.

cheaper and it reacts at lower temperature, thus reducing the cost (Ssempebwa and Carpenter (13)). Transesterification reduces the hydrogen molecule on the beta carbon position of the CI oil substrate, thus improving the oxidative and thermal stability of the TMP ester, an important lubricity property (Makkar, et al. (18); Yunus, et al. (19)).

Many researchers are working to improve the efficiency and enhance practical use of biolubricants. Zulkifli, et al. (20) studied the wear prevention characteristics of palm oil–based TMP ester as an engine lubricant and found that for boundary lubrication, the addition of 3% palm oil–based TMP ester in commercial lubricant reduces friction by 30%, and for hydrodynamic lubrication, the addition of 7% of TMP ester reduces friction by 50%. Uosukainen, et al. (14) studied rapeseed oil–based TMP ester as a biodegradable hydraulic fluid and compared it to commercially available hydraulic fluids. They found that the rapeseed oil–based TMP ester had good friction and wear characteristics, cold stability, and resistance against oxidation at elevated temperatures. In another study, Zulkifli, et al. (21) investigated the extreme pressure and antiwear characteristics of Jatropha-based TMP ester and found that TMP ester had coefficients of friction (COFs) similar to those of fully formulated lubricant and better wear and friction characteristics compared to paraffin mineral oil under extreme pressure conditions. However, TMP ester had the lowest COF and a large wear scar diameter in terms of antiwear under extreme pressure conditions. Gunam Resul, et al. (22) studied the effect of temperature on Jatropha curcas oil–based TMP ester as a biolubricant using sodium methoxide (NaOCH3) as the catalyst at a temperature range between 120 and 200°C with constant pressure at 10 mbar and found that the basic properties of TMP ester such as viscosity, wear scar, oxidative stability, and pour point were comparable to other plant-based biolubricants. Shahabuddin, et al. (23) studied the tribological properties of biolubricant formulated from Jatropha oil using a Cygnus friction and wear testing machine and four-ball tribometer and found that the addition of Jatropha oil in the base lubricant SAE40 acted as a very good lubricant additive and reduced the friction and wear scar diameter. Both of these studies show the potential of biolubricants formulated from vegetable oil, which helps to increase lubricity and reduce wear. Polyol esters involving transesterification of fatty acid esters with TMP have been developed for preparation of a variety of lubricating oils (Zulkifli, et al. (24); Resul, et al. (25); Padmaja, et al. (26); Gunam Resul, et al. (27); Koh, et al. (28); Kamalakar, et al. (29); Madankar, et al. (30); Sripada, et al. (31)). Researchers found that the TMP esters exhibited superior properties, such as low pour point, high flash point, better oxidation stability, and high viscosity indices. In addition, TMP esters have good wear and friction reducing properties.

Although there are many works on the synthesis of biolubricant-based TMP ester, there is still little information available about CI-based TMP ester as an engine lubricant. The CI-based TMP ester had comparable properties including viscosity, density, and viscosity index, as shown in Table 2. The purpose of this research is an experimental study of CI-based TMP ester as an energy-saving and biodegradable lubricant. The results were also compared with paraffin mineral oil and commercial lubricant.

Materials and Methodology

Lubricant Sample Preparation

CI-based TMP ester was produced by the reaction of TMP with CI methyl ester (CIME) in a batch stirred reactor as shown in Fig. 1 (Resul, et al. (25)). The preparation process of CI-based TMP ester is shown in Fig. 2. CI methyl ester was produced at the Energy Laboratory, Department of Mechanical Engineering, University of Malaya using a transesterification process (Rahman, et al. (37)). Gas chromatography (Agilent model 6890, USA) was used to test the fatty acid composition and the result showed that CI fatty acid methyl ester contained 33.4%.

Table 2—Properties of Base Oil Used in This Study

<table>
<thead>
<tr>
<th>Base Oil</th>
<th>Density</th>
<th>Viscosity (cSt) at 40°C</th>
<th>Viscosity (cSt) at 100°C</th>
<th>Viscosity Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI TMP ester</td>
<td>0.912</td>
<td>60.83</td>
<td>10.21</td>
<td>156</td>
</tr>
<tr>
<td>Paraffin mineral oil</td>
<td>0.8283</td>
<td>14.85</td>
<td>3.47</td>
<td>110</td>
</tr>
<tr>
<td>Commercial lubricant</td>
<td>0.8549</td>
<td>102.29</td>
<td>14.93</td>
<td>142</td>
</tr>
</tbody>
</table>
saturated and 66.6% unsaturated fatty acids composition, shown in Table 3. A known amount of TMP and 200 g volume of CIME were placed into a 500-mL three-neck reactor and constantly stirred using a magnetic stirrer. The mixture was heated and maintained at a reaction temperature at 110°C for 2 h with a stirring speed of 600 rpm in the presence of a catalyst. Sodium methoxide (NaOCH3) was added at a fixed 2% w/w based on the total mass of reactants for the transesterification process. A vacuum was gradually applied to the system until a pressure of 1–1.5 mbar was reached. This pressure was maintained until completion of the reaction. Finally, the reaction mixture was cooled to room temperature and filtered to remove the catalyst and solid materials formed during the reaction. Paraffin mineral oil and a mineral-based commercial lubricant of SAE 15W-40 grade with an additive package were chosen for comparison.

**Apparatus**

For this research, a four-ball tribotester was used, which is a simple test rig that is widely used in the lubricant industry to help in research and development of new lubricants or greases. This machine consists of four balls; three fixed balls are held together firmly in an oil cup and one rotating ball bearing is held by a collet of an constant speed electric motor spindle at the top (Fig. 3). This oil cup was filled with the lubricant to be tested. Details of the four-ball tribotester are shown in Table 4. A 40 kg load was applied to the bottom three balls by weights on a load lever and different tests were performed by changing the operating temperature. An approximately 10 mL sample was used to cover the three lower balls to a depth of at least 3 mm. Friction torque was measured by the calibrated arm, which is connected to the spring of a friction recording device.

**Test Procedures**

To set up the experiment, four new steel balls and the oil cup were cleaned thoroughly first using toluene and then wiped using tissue until they are completely dry. Three steel balls were placed into the oil cup and then locked tightly together. One steel ball was held by the collet and then placed inside the machine. Lubricant was poured into the oil cup until it fully covered the three

<table>
<thead>
<tr>
<th>FAME Name</th>
<th>Structure</th>
<th>Molecular Weight</th>
<th>Formula</th>
<th>CIME (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methyl palmitate</td>
<td>16:00</td>
<td>270.45</td>
<td>CH₃(CH₂)₁₄CO₂CH₃</td>
<td>14.9</td>
</tr>
<tr>
<td>Methyl palmitoleate</td>
<td>16:01</td>
<td>268.43</td>
<td>CH₃(CH₂)₁₄CH=CH(CH₂)₂COOCH₃</td>
<td>0.2</td>
</tr>
<tr>
<td>Methyl stearate</td>
<td>18:00</td>
<td>298.5</td>
<td>CH₃(CH₂)₁₆CO₂CH₃</td>
<td>17.2</td>
</tr>
<tr>
<td>Methyl oleate</td>
<td>18:01</td>
<td>296.49</td>
<td>CH₃(CH₂)₁₄CH=CH(CH₂)₂CO₂CH₃</td>
<td>38.2</td>
</tr>
<tr>
<td>Methyl linoleate</td>
<td>18:02</td>
<td>294.47</td>
<td>CH₃(CH₂)₁₄(CH₃)CH=CH(CH₂)₂CO₂CH₃</td>
<td>27.6</td>
</tr>
<tr>
<td>Methyl linolenate</td>
<td>18:03</td>
<td>292.46</td>
<td>CH₃(CH₂)₁₄CH=CH(CH₂)₁₂CO₂CH₃</td>
<td>0.3</td>
</tr>
<tr>
<td>Methyl arachidate</td>
<td>20:00</td>
<td>326.56</td>
<td>CH₃(CH₂)₁₄COOCH₃</td>
<td>0.9</td>
</tr>
<tr>
<td>Methyl eicosenoate</td>
<td>20:01</td>
<td>324.54</td>
<td>CH₃(CH₂)₁₄CH=CHCOOCH₃</td>
<td>0.3</td>
</tr>
<tr>
<td>Methyl behenate</td>
<td>22:00</td>
<td>354.61</td>
<td>CH₃(CH₂)₁₄COOCH₃</td>
<td>0.3</td>
</tr>
<tr>
<td>Methyl lignocerate</td>
<td>24:00</td>
<td>382.66</td>
<td>CH₃(CH₂)₁₂COOCH₃</td>
<td>0.1</td>
</tr>
<tr>
<td>Saturated</td>
<td></td>
<td></td>
<td></td>
<td>33.4</td>
</tr>
<tr>
<td>Monounsaturated</td>
<td></td>
<td></td>
<td></td>
<td>38.7</td>
</tr>
<tr>
<td>Polyunsaturated</td>
<td></td>
<td></td>
<td></td>
<td>27.9</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>
balls. In this experiment, CI TMP ester was used as the lubricant first, followed by paraffin mineral oil and, finally, commercial lubricant. Details of steel ball and the conditions for the four-ball wear test are shown in Table 5. After each test, the three bottom balls were collected to evaluate the wear scar and determine the surface roughness average.

**Lubricant Properties Test**

Kinematic viscosity refers to the resistance of liquid to flow and is the ratio of dynamic viscosity to the density of the liquid. It is a prime parameter that affects the whole lubrication system, particularly at low temperature, when an increase in viscosity affects the fluidity of the lubricant, resulting in an increase in friction, wear, and heat (Albertson, et al. (39)). Kinematic viscosity is measured according to ASTM D445 standard (Standard, A. S. T. M. (40)). It can be seen from Table 2 that commercial lubricant possesses the highest kinematic viscosity of 102.29 and 14.93 mm²/s at 40 and 100 °C, respectively, and CI TMP ester shows an almost similar value of 60.83 and 10.21 mm²/s at 40 and 100 °C, respectively.

Viscosity index (VI) of the oil is a unitless number that indicates the effect of temperature changes on viscosity. It is an important parameter to define the oil quality. A high VI implies relatively little change in viscosity over a wide range of temperatures. In the case of automotive lubricant applications, it needs to reduce friction across a wide range of temperature conditions; for example, the engine is started from cold and up to 200 °C when it is running. The oil with the highest VI will remain stable and not vary much in viscosity over the temperature range. In this study, the viscosity index is determined based on the known viscosities between 40 and 100 °C using ASTM D2270 standard (Standard, A. S. T. M. (40)). It is seen from Table 2 that CI TMP ester possesses the highest VI of 156, which meets the commercial IC engine oil VI between 150 and 200, paraffin mineral oil shows a considerably lower VI of 110, and commercial lubricant shows a VI of 142.

The density of a lubricant is the relationship between the mass and volume, which indicates the lubricant’s composition and nature and is expressed in units of gm/cc. It plays a critical role in the functioning of a lubricant as well as in the performance of moving parts of a machine. The density of the lubricant was measured at 40 °C using ASTM D7042 standard (ASTM International (41)). The results in Table 2 show that the densities of CI TMP ester, paraffin mineral oil, and commercial oil at 40 °C are 0.9120, 0.8283, and 0.8549 gm/cc, respectively.

Table 6 shows the list of equipment used in this experiment for different lubricants.

**Friction Evaluation**

The coefficient of friction is a dimensionless number that describes the ratio between the friction force between two bodies and the normal force opposing them together. The coefficient of friction was calculated by multiplication of the mean friction torque and spring constant (IP-239 standard (42)). A load cell was used to measure the frictional torque in this experiment. The friction torque on the lower balls can be expressed as

\[
T = \mu \times \frac{3W \times r}{\sqrt{6}} \Rightarrow \mu = \frac{T \sqrt{6}}{3Wr},
\]

where \(\mu\) is the coefficient of friction, \(T\) is the frictional torque (kg-mm), \(W\) is the applied load \(k\) and \(r\) is the distance from the center of the contact surface on the lower balls to the axis of rotation, which was determined to be 3.67 mm.

**Flash Temperature Parameter**

The flash temperature parameter (FTP) was calculated for all experimental conditions. The FTP is a single number that is used to express the critical flash temperature at which a lubricant will fail under given conditions. For the conditions used in the four-ball test, the following relationship was used (Masjuki and Maleque (44); Lane (45)):

\[
FTP = \frac{W}{d^2},
\]

where \(W\) is the load (kg) and \(d\) is the mean wear scar diameter (mm).
**Wear Evaluation**

An optical microscope with a resolution of 0.01 mm (as per ASTM D4172) (ASTM Standard D4172-94 (43)) was used to calculate the wear scar diameter of the ball. The ball bearing was cleaned with toluene and wiped until dry using tissue first. Then, when the wear scar was found, the ball was placed on the stage (specimen platform) with the wear scar facing upwards. A suitable magnification lens was chosen and the focus was adjusted until a clear image was shown on the computer screen. The image was captured and saved by pressing the capture button. Next, using available software, the wear scar diameter was measured. All of these procedures were repeated for one bottom ball bearing from each test.

**Energy Saving**

The increasing demand for power has led us to consider the efficient use of energy and its conservation. This demonstrates other important uses of technology for reducing energy consumption and decreasing human impacts on climate change. Because friction is a major consumer of energy, it requires control or reduction to save energy. Energy conservation can be measured in a four-ball tribotester by using the equation of conservation of energy as follows:

\[
\text{TE} = \text{KE} + \text{PE} + \text{WE},
\]

where \( \text{KE} = 0, \text{PE} = 0, \) and \( \text{WE} = \mu \cdot mg \cdot d \).

\[
\Rightarrow \text{TE} = \frac{\mu mg d}{1000}.
\]

where \( \text{TE} \) is thermal energy (J), \( \mu \) is the coefficient of friction, \( m \) is the load applied (kg), \( d \) is the distance from the center of the contact surface on the lower balls (mm), and \( g \) is the gravitational acceleration \( (\text{ms}^{-2}) \).

**Measuring the Surface Roughness of the Ball**

A ball bearing from the experiment was then analyzed using a surface roughness tester contour measuring system to determine the surface roughness of the ball. This is a type of stylus profilometry instrument that can measure the surface roughness of round surfaces such as ball bearings. The stylus is placed directly above the wear on the ball and carefully adjusted until it slightly touches the wear. The computer program was set to surface roughness analysis and parameters such as the scale and sample size were adjusted. A graph is produced as the stylus moves slightly up and down the ball. Based on this graph, it will calculate the surface roughness average \( R_a \). All of these procedures were repeated for one bottom ball bearing from each test and all \( R_a \) values were recorded.

**RESULTS AND DISCUSSION**

**Coefficient of Friction Analysis**

The variation in coefficient of friction of the three types of lubricants under different operating conditions is shown in Fig. 4. It is seen that the COF is strongly related to the temperature and as the temperature increases, the COF decreases. This may be attributed to the high temperature due to lower viscosity, where the boundary layer becomes thinner and may break down completely or become less effective (Masjuki, et al. (46); Zulkifli, et al. (47)). The acceptable range of COF of a lubricant to be used for wide range of automotive applications is 0.05–0.14 (Alves, et al. (48); Arumugam and Sriram (49); Mobarak, et al. (50); Asadauskas, et al. (51); Bekal and Bhat (52); Jaina and Suhana (53)). Paraffin mineral oil shows the highest COF at each temperature compared to CI TMP ester and commercial lubricant. The COF recorded for CI TMP ester is the lowest throughout the experiment. This shows that the film provided by the CI TMP ester at the contact surface is more effective and has good lubricity, even at high temperature. This is probably due to
the presence of long-chain fatty acid in CI TMP ester, which allows monolayer film formation on the sliding surface and helps to improve boundary lubrication properties and prevent metal-to-metal contact (Masjuki and Maleque (54)). For the film formation by TMP ester, the polarity of TMP ester creates a strong affinity to the metal by one end of the molecule and allows a non-polar hydrocarbon to extend out and provide a barrier between surfaces (Canter (55)).

**Energy Consumption Analysis**

Figure 5 represents the energy consumption chart for different tested lubricants at different temperatures. Paraffin mineral oil shows the highest energy consumption compared to other lubricants. The lowest energy consumption has been achieved for CI TMP ester at every temperature. According to Sharma, et al. (56), the metal surface adsorbed the ester ends of the fatty acid chain. This allows monolayer film formation with the hydrocarbon end of fatty acids oriented away from the metal surface. The fatty acid chain thus offers a sliding surface that prevents direct metal-to-metal contact. The general trend for all of the lubricants is that as temperature decreases, energy consumption decreases. High temperature will cause lubricant viscosity to decrease, making it easier to form a full lubricant film between the ball bearings, thus resulting in the lowest consumption of energy (Foo and Hameed (57)).

**Wear Scar Diameter Analysis**

The wear scar diameter (WSD) results for the tested lubricants used in this experiment are shown in Fig. 6. It is seen from the figure that the WSD increases with increasing temperature. CI TMP ester shows a smaller wear scar than paraffin mineral oil and a larger wear scar than conventional lubricant. This is due to the presence of additives inside the commercial lubricant, which provide protection to the surface area of the ball bearing, and this explains the small WSD. Maleque, et al. (58) studied the effect of mechanical factors on the tribological properties of palm oil methyl ester–blended lubricant and found that at higher temperature, the film formed by the fatty acid chains seems to be less stable and causes comparatively higher wear compared to commercial lubricant. On the other hand, according to Kumar and Chauhan (59), the methyl ester shows better lubricity than the base oil due to its amphiphilic properties, which are provided by the long hydrocarbon chains of the fatty acid methyl ester. Due to this phenomenon, the fatty acid chain of the ester adsorbs to the metal surface and forms a protective layer on the surface and hence improves the lubricity.

**Flash Temperature Parameter Analysis**

The FTP is the critical temperature below which the lubricant can create a film and withstand without breakdown. According to Fig. 7, it is seen that commercial lubricant has the highest flash temperature, whereas the lowest FTP is found for paraffin mineral oil. In general, as the temperature increases, the flash temperature of both tested lubricants decreases. This can be explained due to the higher temperature degradation of the tested lubricants that occurs and thus the rubbing surfaces come closer to each other and increase the surface contact (Shahabuddin, et al. (23)). A higher FTP indicates good lubricating properties and less possibility of lubricant film breakdown. In this regard, CI TMP ester has better lubricating performance compared to paraffin mineral oil. This may be explained due to the WSD of worn specimens and viscosity parameter of the lubricant samples. CI

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**Fig. 5—Energy consumption chart for different lubricants.**

**Fig. 6—Effects of temperature on the wear scar diameter of different lubricants.**

**Fig. 7—Effects of temperature on the flash temperature parameter of different lubricants.**
TMP ester has a higher viscosity, which results in a smaller WSD compared to paraffin mineral oil and thus increases the flash temperature (Masjuki and Maleque (54)).

Surface Roughness Analysis

Surface roughness indicates the vertical deviation of a real surface from its ideal form. It is closely related to the wear and friction properties. The changes in surface roughness of the tested lubricants due to the effect of temperature have also been studied and the results are shown in Fig. 8. The $R_a$ is the lowest for commercial lubricant and highest for CI TMP ester throughout the experiment. For all three lubricants, the $R_a$ at 100°C is low compared to at 50°C for commercial lubricant and CI TMP ester. This is probably because with lubricant film formation, the density and viscosity of the lubricant decreases and thus it is easier for the fluid film to break down. This means that the hydrodynamic lubrication regime is dominant and metal-to-metal contact is reduced; therefore, there are fewer irregularities on the surface of the ball bearing. According to Bowden and Tabor (60), vegetable oil has a low coefficient of friction but the wear rate is high because of chemical attack on the surface by the fatty acids present in the vegetable oil. The soapy metallic film rubs away during sliding and produces a nonreactive detergent that increases wear.

![Fig. 8—Effects of temperature on the surface roughness average of different lubricants.](image)

![Fig. 9—SEM micrographs of worn surfaces from a stationary ball for different samples at 70°C.](image)
Scanning Electron Microscopy Analysis

Figure 9 illustrates the scanning electron microscopy (SEM) micrographs of the worn surfaces of the steel ball specimen for different lubricant samples. It can be seen that for the lubricant sample (Figs. 9a–9c) there is deep groove of loss of material created in the sliding direction of the rotating ball. This indicates that the wear for ordinary lubricants is abrasive wear (Sperring and Nowell (61)). For both CI TMP ester (Figs. 9d–9f) and paraffin oil (Figs. 9g–9i) samples it is observed that the rotation of top ball causes the contacting asperities to adhere to each other and creates grooves and pits. However, it seems that the sizes of the pits and grooves are much bigger than 20 \( \mu m \). Rabinowitz (62) mentioned that the size of the particles removed from the cavities larger than 20 \( \mu m \) results adhesive wear. Therefore, the wear mechanism for both CI TMP ester and paraffin oil is adhesive wear.

Furthermore, the appearance of the worn surfaces of the ordinary lubricant and CI TMP ester seems to present a black color and CI TMP ester is darker than ordinary lubricant. Again, the black color region of both worn surfaces shows severe wear compared to the non-black area. This is may be explained due to the occurrence of oxidative corrosion (Kumar and Chauhan (59)). Bhale, et al. (63) reported that different acids and inorganic oxides like \( Fe_2O_3 \) and \( Fe_3O_4 \) are produced during oxidation and increase corrosive wear and thus negatively affect lubricity. However, it is worth noting that the duration of oxidation is an influencing factor in producing lubricity as the amount of peroxides and acids formed vary with the variation of oxidation period (Wu, et al. (64)). It can also be observed that the sample of CI TMP ester has small pits and grooves compared to the paraffin mineral oil sample. This may be explained due to the long hydrocarbon chains of the fatty acid residue present in the CI TMP ester. Due to this phenomenon, a monolayer film is formed on the metal surface and enhances the lubricity (Sharma, et al. (56)).

CONCLUSIONS

This study investigates the tribological characteristics of CI-based TMP ester. Based on the experimental study, the following conclusions can be drawn:

- The experimental results show that as the temperature increases, the coefficient of friction decreases and wear increases for CI TMP ester. At all test temperatures, CI TMP ester has the lowest coefficient of friction compared to paraffin mineral oil and commercial lubricant. This is due to the fatty acid present in the CI TMP ester that creates a boundary film, thus increasing lubricity.
- CI TMP ester represents the best performance in terms of energy consumption at each temperature compared to commercial lubricant and paraffin mineral oil.
- In terms of wear, CI TMP ester shows a smaller wear scar and lower FTP than paraffin mineral oil and higher than conventional lubricant. This is because of the presence of additives inside commercial lubricant, which provide protection to the surface area of the ball bearing, and this explains the small WSD and low FTP. CI TMP ester has the highest worn surface roughness average (Ra) compared to the other two tested lubricants at all test temperatures.
- Deformation of the worn surfaces is higher for paraffin mineral oil and lower for commercial lubricant compared to CI TMP ester. The steel ball in commercial lubricant is subjected to abrasive wear and both CI TMP ester and paraffin mineral oil are subjected to adhesive wear.

The findings from this study contributed to the sustainable development of the biolubricant field. In addition, this study shows that CI TMP ester has a promising future to replace mineral oil-based lubricant because its performance is energy efficient, thus reducing energy dependence.

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