FRICITION AND WEAR CHARACTERISTICS OF WASTE VEGETABLE OIL CONTAMINATED LUBRICANTS

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ABSTRACT
In this paper, a four-ball tribotester was used with standard test method IP-239 to evaluate friction and wear characteristics of normal lubricant, additive added lubricant and waste vegetable oil (WVO) contaminated lubricants. The balls used in four-ball tribotester were based on carbon-chromium steel ball bearings. The results obtained to present friction and wear characteristics are coefficient of friction (μ), wear scar diameter (WSD), flash temperature parameter (FTP), viscosity index (VI) and total acid number (TAN). Each test was conducted for five different loads from 50 kg to 90 kg with an interval of 10 kg. The lubricant was contaminated with WVO from 1% to 5%. The normal lubricant (as sample A) was used for comparison purposes. The test results showed that WVO contaminated lubricants with suitable anti-wear additive can reduce wear and friction coefficient. The objective of this investigation is to develop a new lubricant based on waste palm oil (such as WVO).

Keywords: Four-ball tribotester , WVO, WSD

1. INTRODUCTION
As compared to other internal combustion engines, recent development of diesel engine has attracted the automotive manufacturers due to its high thermal efficiency and load carrying capacity (Sayem et al., 2011). However much attention has been also focused to the development of cleaner alternative fuels for reducing air pollution and for reducing the dependence on fossil fuels (Liaquat et al., 2010) due to rapid growth in the demand of transport fuel worldwide (Kalam et al., 2011). Regarding the conventional mineral oil based lubricants, it has been reported that these lubricants are developed based on fossil fuel (such as gasoline and diesel fuels). Therefore, these lubricants are not suitable for biodiesel fuelled engine as it degrades lube oil quality and increases engine wear rate as found by Masjuki & Maleque (1997). This happens due to mixing fuel with lubricant through the piston-cylinder friction zone. In order to bring improvements in stability and wear characteristics, biodegradable vegetable lubricants are commonly used worldwide (Husnawan et al., 2007). In this paper, waste palm oil (as WVO) contaminated lubricant has been developed as a biodegradable lubricant to be used for biodegradable fuelled engine such as biodiesel fuelled engines. Based on four ball tribotesting results, WVO contaminated lubricant with the presence of suitable anti-wear additive shows promising result as compared to conventional lubricant. This is mainly due to better thermal and oxidative properties of WVO consisting of long chain saturated fatty acids that leads to inferior cold flow behaviour (Zeman et al., 1995). The results of this investigation have given an indication for formulation of a new lubricant.

2. EXPERIMENTAL APPARATUS AND METHODS

2.1 Equipment
In this work, four-ball tribotester machine was used according to IP-239 standard test method. This machine is simple to use for testing friction and wear of lubricating oils. As shown in Figure 1, three balls are located in a cup below a fourth ball which is connected to a rotating shaft via a chuck. Different loads are applied to the balls by weights on load lever. The frictional torque exerted on the three lower balls can be measured by a calibrated arm, which is connected to the spring of a friction recording device. The extension of the spring in resisting the frictional torque is transmitted through a link mechanism, to a pen which records its travel on a drum at 1 revolution in 60-75s

![Figure 1 Schematic diagram of four-ball tribotester machine.](image)

2.2 Ball materials
The tested ball’s material was carbon-chromium steel (SKF), 12.7mm in diameter with a surface roughness of 0.1μm C.L.A. The chemical composition of ball material was obtained by Energy Dispersion X-Ray Spectrometer (EDS) and shown in Table 1. Before starting a test, all the balls were cleaned using spirit alcohol and dried with dry air. The four-ball tribotester machine was operated without any load for a period of 15 min, all the approximate parts of the machine were cleaned by solvent, dried with a clean soft lint-free cloth or clean dry air.
2.3 Lubricant samples

Three samples were explicitly prepared as follows: (1) Sample A - normal lubricant of SAE40 grade. It can be stated that sample A is the reference lubricant, (2) Sample B - consists of sample A with 0.5% Amine phosphate additive, and (3) Sample C - consists of sample A with 0.5% Octylated/butylated diphenylamine additive. It can be stated that sample B and sample C are prepared with two different types of anti-wear additives. Sample D and sample E can be referred to as base lubricants with respect to contaminated lubricant by WVO, from 1% to 5%. Details of lubricant compositions are shown in Table 2. The properties of anti-wear additives are given in Table 3.

Table 2 Lubricant sample compositions

<table>
<thead>
<tr>
<th>Samples</th>
<th>Lubricant composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Normal lubricant as SAE 40 grade</td>
</tr>
<tr>
<td>B</td>
<td>Sample A with 0.5% Amine phosphate additive</td>
</tr>
<tr>
<td>C</td>
<td>Sample A with 0.5% Octylated/butylated diphenylamine additive</td>
</tr>
<tr>
<td>D</td>
<td>Sample B with 1% to 5% waste palm oil (WVO) with base lubricant</td>
</tr>
<tr>
<td>E</td>
<td>Sample C with 1% to 5% waste palm oil (WVO) with base lubricant</td>
</tr>
</tbody>
</table>

Table 3 Properties of anti-wear additives

<table>
<thead>
<tr>
<th>Chemical description</th>
<th>Amine phosphate Octylated/butylated diphenylamine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treat level/range</td>
<td>0.1 – 1.0% 0.3 – 1.0%</td>
</tr>
<tr>
<td>Viscosity at 40°C</td>
<td>220 (mm²/s) 280 (mm²/s)</td>
</tr>
<tr>
<td>Melting point &lt;10°C</td>
<td>&lt;10°C</td>
</tr>
<tr>
<td>Density at 20°C (g/m³)</td>
<td>0.92 0.98</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>4.8% 4.5%</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>2.7% 4.5%</td>
</tr>
<tr>
<td>Flash point</td>
<td>135°C 185°C</td>
</tr>
<tr>
<td>Solubility limits at 5°C (wt. %)</td>
<td>3 5</td>
</tr>
<tr>
<td>• Mineral oil</td>
<td>&gt;5 5</td>
</tr>
<tr>
<td>• Ester</td>
<td>&lt;0.01 5</td>
</tr>
<tr>
<td>• water</td>
<td>&lt;0.01 &lt;0.01</td>
</tr>
</tbody>
</table>

2.4 Test methods

At the beginning of the experiment, lubricant sample is placed on the erected plate where three balls are held in position into a cup (at the end of the motor spindle) with the clamping ring and assembly secured by tightening the locknut. The fourth ball is then fitted on the upper balls chuck. Mounting disks are placed between the thrust bearing and the cup. The desired loads are then placed on the load lever to be tested at.

2.5 Friction evaluation

The coefficient of friction is calculated by multiplication of the mean friction torque and spring constant (Ducom, 2008). The frictional torque on the lower balls may be expressed as:

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

where, \( \mu \) = coefficient of friction, \( T \) = frictional torque in kg/mm, \( W \) = applied load in kg, \( r \) = distance from the center of the contact surfaces on the lower balls to the axis of rotation, which is 3.67 mm

2.6 Wear test

The test run was carried out at loads (50, 60, 70, 80 and 90 in kg) and at 1500 rev min⁻¹ with test duration of 60 minutes. The wear scar diameter (WSD) is measured and analyzed by “ducom software” with installed image acquisition system.

2.7 Flash Temperature Parameter (FTP)

The FTP indicates the potential for lubricant film to breakdown. High value of FTP indicates high performance of the lubricant. For conditions existing in the four-ball test, the following formula is used (IP-239, 1986).

\[ FTP = \frac{W}{d^{1.4}} \]

Where, \( W \) = load in kg, \( d \) = mean wear scar diameter in mm

2.8 Total acid number analysis

The total acid number is a measure for the total amount of both weak and strong organic acids present in the lubricant and is expressed in mgKOH/g, i.e., the amount in milligrams of potassium hydroxide required to neutralize one gram of lubricating oil.

2.9 Kinematics viscosity analysis

The ISL Automatic HOUILLON Viscometer is used to measure the viscosity of the lubricating oil using ASTM Method D-455 at 40°C. Before measuring the viscosity of the lube oil, the viscometer tubes are calibrated by standard sample lube oil. The lube oil is warmed to the desired temperature and allowed to flow through the calibrated region to be measured. The lube oil’s viscosity (in cSt) is the flow time (in second) multiplied by the apparatus constant.
3. RESULTS AND DISCUSSION

All the samples preparation and test are conducted at Engine Tribology Laboratory, Department of Mechanical Engineering, University of Malaya. All the test results can be discussed as follow:

3.1 Coefficient of Friction (COF) analysis

The COF versus applied loads on four-ball tester is shown in Figure 2. Sample A is the reference lubricant of SAE40 grade. Samples B and C are the anti-wear additive added lubricants with sample A. Figure 2 shows how the different types of anti-wear additive affects COF. It is found that sample C increases COF from 0.08 to 0.24 for increasing loads from 50 kg to 90 kg. However, the sample B shows lower COF than reference lubricant A. It is evident that the additive (0.5% Octylated/butylated diphenylamine based additive) in sample C has an adverse effect on COF with reference lubricant A. The lowest COF was found from sample B followed by sample A and sample C. Hence, Amine phosphate additive is effective in reducing friction and is consistent throughout the load range. This is because amine phosphate is an extreme pressure and anti-wear additive for industrial lubricants that can withstand higher loads.

3.2 Wear Scar Diameter (WSD) analysis

Figure 4 shows WSD for samples A, B and C and Figure 5 shows WSD for samples D and E. Referring to Figure 4, it is found that sample C produces higher level WSD followed by samples A and B. Sample B shows the best performance (a reduction of 20% of WSD as compared to sample A) which means that amine phosphate is effective in palm oil contaminated lubricant.

It can be explained that the friction and wear resistance mechanism of anti-wear additive in palm oil contaminated lubricant causes from complex chemical transformation on the metal surface. The amine
phosphate has the general structure represented (below) by: R = mostly aliphatic groups (2-ethylhexyl, hexyl and n-octyl); amines have tert-alkyl group with 10–24 carbon atoms (Bowman et al., 1996). Figure 5 shows that sample D reduces WSD with maximum at 4% WVO. The breakdown of WVO (waste palm oil) molecule during tribo-chemical process results in the formation of fatty acids which can react with the phosphorus containing group from amine phosphate. This substance functions as effective friction modifiers and anti-wear agent in the presence of WVO. The long hydrocarbon chain of the fatty acid provide an excellent molecular barrier while, the polar group coordinate with iron to form a protective film on the metal surface. Above 4% WVO content, the film thickness might be broken due to increasing palm oil percentage.

Sample C (Figure 4) shows the WSD between 0.70 - 0.80 mm, which is 50% higher than sample B. This can be caused by the high friction in contact surfaces as a result of octylated/butylated diphenylamine additive. It can be realized that the octylated/butylated diphenylamine additive works as anti-oxidant rather than anti-wear agent when added with WVO (waste palm oil) contaminated lubricant. This additive and the palm oil neutralize each other at high temperature that causes adverse effect on the metal surface. A similar phenomenon was also reported by Maleque et al. (2000) and Adhvaryu et al. (2004).

### 3.3 Flash Temperature Parameter (FTP) analysis

From Figures 6 and 7, it can be said that amine phosphate based lubricant (samples B and D) show higher level of FTP value, which means higher lubricant stability. Meanwhile, samples C and E show lower FTP value that indicate easiness for lubricant film to breakdown. However, above 4% WVO (waste palm oil) contaminated lubricant, the FTP value drops as shown in Figure 7.

### 3.4 Total Acid Number (TAN) analysis

The TAN test results are shown in Figures 8 and 9. From to Figure 8, the lowest TAN value is found from sample B (1.60 mgKOH/g) followed by sample A (1.70 mgKOH/g) and sample C (2.30 mgKOH/g). Sample E produced higher level of TAN compared to sample D, as shown in Figure 9. It is evident that the octylated/butylated diphenylamine additive is not suitable in both the normal lubricant (sample A) and WVO (waste palm oil) contaminated lubricant (sample E). This is mainly due to the chemical properties of octylated/butylated diphenylamine additive that does not suit with samples A and E. In addition, the amine phosphate anti-wear (sample D) additive does shows slightly higher TAN value (Figure 9) as compared to normal lubricant (sample A) when the percentage of WVO is increased. This is mainly due to the high fatty acid in WVO. However, the TAN value may also increase due to several causes such as (i) effect of oxygen in WVO, (ii) at higher temperature, the fatty acid molecules or other organic acids can be decomposed during operation.
3.5 Viscosity Index (VI) analysis
Viscosity is the property used for identification of individual grades of lube oil and for monitoring the changes occurring in the lube oil while in service. Higher viscosity indicates that the lubricant is being deteriorated by either oxidation or contamination, while a decrease usually indicates dilution by lower viscosity oil or by fuel (Maleque et al., 2000). Figures 10 and 11 show viscosity at 40 °C. From Figure 10, it can be seen that amine phosphate (sample B) increases viscosity. However, viscosity decreases with the same additive and palm oil (Figure 11), as compared to sample A. However, this change is within the useful range of lubricant. Sample D shows viscosity decrease from 120 cSt to 100 cSt as WVO content is increased from 1% to 5%, indicating suitability for machinery operations. Normally at 40 °C, the lower limit of engine oil should be 80 cSt and below this value indicates that the oil has degraded in quality. The applicable range of engine oil/lubricating oil at 40 °C and 100 °C are 80 cSt to 150 cSt and 12 cSt to 20 cSt, respectively. Samples C and E show higher decreasing trend as compared to samples B and D. Hence, sample C and E will increase component’s wear through degrading oil quality.

![Figure 10 Viscosity (at 40 °C) vs. loads for samples A, B and C.](image)

![Figure 11 Viscosity (at 40 °C) vs. percentage (%) of palm oil in samples D and E at constant 70 kg load.](image)

4. CONCLUSION
The following conclusions may be drawn from the present study:
1. Amine phosphate as anti-wear additive shows better result with normal lubricant (SAE grade 40), whereby it reduces COF, reduces WSD, increases FTP, reduces TAN value, and increases viscosity, as compared to octylated/butylated diphenylamine additive.
2. Combination of amine phosphate, normal lubricant and palm oil (up to 4%) show better results, whereby it reduces COF, reduces WSD, increases FTP, reduces TAN value, and reduces viscosity within the operating range, as compared to octylated/butylated diphenylamine additive.

Hence, it can be stated that waste palm oil can be used as lubricant substitute (maximum 4%) with normal lubricant and amine phosphate additive. However, palm oil based lubricant still shows higher TAN value, which will be further investigated.

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