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INVESTIGATION OF PALM FATTY ACID DISTILLATE OIL AS AN ALTERNATIVE TO PETROCHEMICAL-BASED LUBRICANTS

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ABSTRACT

The development and application of new sources of lubricant/hydraulic oils for industrial use are rapidly increasing. This study investigated the lubricant and hydraulic properties of palm fatty acid distillate (PFAD) as a new, environmental-friendly and renewable source of lubricant and hydraulic oil in different loads and in a standard industrial manufacturing condition. A four-ball tribotester, digital microscope, charge-coupled device (CCD) camera and viscosity meter were used for the investigation. The experiments were done at constant speed (1200 rpm), temperature (75°C) and at running time (60 min), and under five different loading means, 200, 300, 392, 500 and 600 N. The main physical properties of PFAD: anti-wear, anti-friction, flash temperature parameter, the coefficient of friction, wear scar diameter, viscosity and extreme pressure condition, were measured and the results obtained were compared to the physical properties of mineral lubricant/hydraulic oil. The results show that the PFAD oil has more lubricant abilities with regard to friction and wear than the commercial engine and hydraulic oils at various loadings.

Keywords: palm fatty acid distillate, four-ball tribotester, wear scar diameter, friction, flash temperature parameter.

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INTRODUCTION

Oil and its derivatives are the main sources of energy and lubricant applications in industries. Environmental pollution has increased in recent years due to the global growth of industrial factories and vehicles. As reported by Deshimaru *et al.* (1973) and Sudo *et al.* (1965), mineral oils can pollute the earth through combustion and can also pollute the air, drinking water supplies and the seas. It also has negative effect on fishes, plants and other aquatic beings. A large percentage of lubricants are derivatives of mineral oils and they play an important role in vehicles and industrial manufacturing. Scientists are attempting to find a suitable substitute for petroleum in different areas. Vegetable oils are alternative sources that can replace mineral oils. These oils have an inherent ability to reduce friction. Friction and wear normally occur between two moving parts and some parameters, such as sliding speed and loads, can have an influence on them. Lubricants have the main responsibility of reducing wear and friction in a mechanical system and can be classified in two categories: engine lubricants and non-engine lubricants. Lubricant film plays a major role in controlling wear and friction under the boundary lubrication condition (Castro *et al.*, 2005). Vegetable oils are renewable, cheap, non-toxic, environmental-friendly and clean (Adhvaryu *et al.*, 2005). In recent decades, investigations were undertaken on some vegetable oils such as palm oil, sunflower oil, soya-

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bean oil and castor oil to make hydraulic liquid and lubricant oils (Wan Nik *et al.,* 2005a, b; 2007; Masjuki and Maleque, 1997). Research has been carried out on the physical and chemical properties of vegetable oils and some of these studies confirmed that mineral oil can be replaced with vegetable oils (Cheenkachorn *et al.,* 2006; Gawrilow, 2003; Aluyor *et al.,* 2010; Adhvaryu *et al.,* 2006; Goshokouh *et al.,* 2013).

There are several studies on the use of vegetable oil in lubricant application. The tribological behaviours of jatropha oil, *e.g.* wear scar, coefficient of friction and viscosity, were investigated following the ASTM Standards; this study compared pure jatropha oil with jatropha oil mixed with additive materials in a lubricant base (Liaquat *et al.,* 2012). Palm fatty acid distillate (PFAD) oil from the vegetable oils family was compared with mineral oil with regard to tribological properties, such as anti-wear, anti-friction, viscosity index and flash parameter point, using a four-ball tribotester under different temperatures (Golshokouh *et al.,* 2013). In other studies, refined, bleached and deodorised (RBD) palm stearin was studied using a four-ball tribotester at different loads (starting with a load of 40 kg and increasing to 60 kg with gradual increments of 10 kg) with a constant speed and also at different speeds (800, 1000, 1200 and 1400 rpm) with constant load. The RBD palm stearin results were simultaneously compared with additive-free paraffinic mineral oil and the results showed that the lubricant ability of RBD palm stearin in terms of friction reduction under test wear loads and sliding speeds was better than of additive-free paraffinic mineral oil (Tiong *et al*., 2012). The effect of temperature on the tribological behaviours of RBD palm stearin was investigated using a four-ball tribotester machine at a constant load and speed, and for evaluation, the results were compared with those of additive-free paraffinic mineral oil (Ing *et al*., 2012; Chiong Ing *et al*., 2012). The lubricant ability of palm oil was evaluated in a cold strain extrusion process and the results were compared with those of additive-free paraffinic mineral oil (Syahrullail *et al*., 2011). As yet, there are no reported research studies on the use of PFAD in lubricant and hydraulic applications.

The main sources of PFAD come from Southeast Asia and countries such as Thailand, Malaysia and Indonesia. Malaysia produces 41% of all palm oil products in the world, producing 17.73 million tonnes of crude palm oil in 2008 and exporting 2.34 million tonnes that year (MPOB, 2002). Lubrication ability of oils plays an essential role in prevention of or reduction of friction and wear between contact parts. Engine and hydraulic oils which have high lubrication ability are able to control corrosion, increase the thermal and oxidative stability, decrease the temperature fluidity, keep hydrolytic stability and viscosity for film maintenance.

The purpose of this study was to investigate and evaluate the tribological properties, *e.g.* wear scar, coefficient of friction, viscosity, flash temperature parameter and extreme pressure conditions of PFAD, at different loads (200, 300, 392, 500 and 600 N) and in the ASTM condition for lubricant and hydraulic applications. Each experiment was repeated four times for each load. To evaluate the experiments, all results were compared with commercial engine and hydraulic oils.

MATERIALS AND METHODS

A four-ball tribotester was used to determine friction torque and wear scar diameter. This machine was first described by Boerlage (1933). There were three balls in the middle part of four-ball tribotester and one ball was on the top part of this machine.

A small thermocouple was also embedded at the bottom of the ball pot to measure the oil temperature (*Figure 1*). There was a heater inside the ball pot responsible for regulating the temperature.

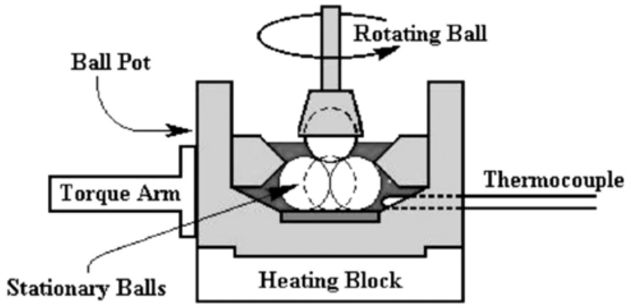

Figure 1. Schematic diagram of four ball wear geometry.

Furthermore, an acquisition software, charge-coupled device (CCD) camera and a microscope to measure wear scar diameter and to observe ball corrosion were also used.

Balls Model

This experiment used chrome alloy steel balls made of AISI Standard steel No: E-52100 based on ANSI standard: B3.12 (Specification for Metal Balls) (Institute). The diameter of each ball was 12.7 mm. All balls had an extra polish (EP) grade of 25 and a hardness of 64 to 66 Hrc. For each new test, four new balls were used, and before each experiment, all balls were cleaned with acetone and wiped with a fresh, lint-free industrial wipe.

Experimental Oils

PFAD is a by-product of physical refining of crude palm oil and is normally composed of 93 wt% free fatty acids, and the rest is composed of triglycerides, diglycerides (DG), monoglycerides (MG) and traces of impurities. All chemicals, including 99% methanol (MeOH), 98% sulphuric acid (H_2SO_4) and 99% sodium hydroxide (NaOH), were commercial grade (Chongkhong *et al*., 2007). *Table 1* shows the ingredients of the free fatty acid. This study also used high quality engine mineral oil and hydraulic mineral oil. *Figure 2* shows PFAD at room temperature.

Experimental Conditions

These tests were performed at various loads (200, 300, 392, 500 and 600 N). Other test parameters such as speed, time and temperature were constant; they were used based on standard test method for wear preventive characteristics of lubricating fluids (Four-Ball Method) D4172-94(2010)(Standard 2010). The experimental conditions for ASTM method were temperature (75 ± 2)°C, speed (1200 ± 60) rpm and time (60 ± 1) min, (Ahmed *et al*., 2002). To reduce the percentage of error caused by the operator and machine, five tests were run with each oil sample and, if the coefficient of friction, wear scar diameters and viscosity showed a relative error above 10%, additional experiments were run until at least three of the results agreed within 10%.

TABLE 1. INGREDIENT OF FREE FATTY ACID

Palmitoleic acid	0.2%
Ecosenoic	0.2%
Ecosanoic	0.3%
Linolenic	0.3%
Tetracosenoic	0.6%
Myristic	1.0%
Stearic	3.8%
Linoleic	7.7%
Oleic	33.3%
Palmitic	45.6%

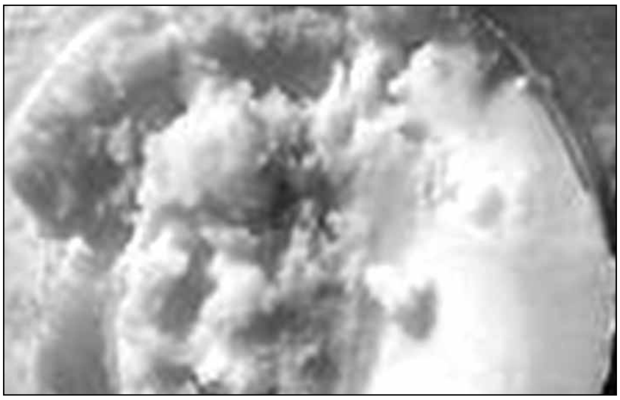

Figure 2. Palm fatty acid distillate at room temperature.

Experimental Procedure

In this research, the test loads which were expected to influence the friction, wear, viscosity, flash temperature parameter and characteristics of the lubricant, were evaluated. The four-ball tribotester was set up in current load, speed, temperature and time before the start of the experiment. Prior to the beginning of the experiment, all parts and balls were cleaned with acetone and wiped. This was repeated after the completion of each test. A clean ball was installed at the end of the spindle motor. Three clean balls were placed in the ball pot and the lock ring was inserted around the three balls and in the ball pot. The lock nut around the ball pot was locked using a wrench with 68 Nm torque. The three balls in the ball pot in the wear test were evaluated, and the average diameter of the circular scar formed on the ball was measured. Around 10 ml of experimental oil was added to the cup and the cup assembly components were installed into the frictionless disc in the four-ball tribotester. The load test was applied and to reach the desired temperature, the lubricant oil was heated. The heater was turned off and the oil cup assembly was removed from the four-ball tribotester 1 hr after the start of the experiment. The oil was drained and the upper parts of the balls were cleaned with a tissue. The test balls were placed on a microscope for microscopic evaluation and the wear scars on the ball specimens were measured.

Viscosity

There are several methods for measuring oil viscosity. Rotational viscometer and capillary viscometer are two of the most commonly used devices to measure viscosity in engineering application. In this research, viscosity was measured using rotary viscosity meter, which spins inside a container of the liquid and viscosity was measured as the resistance to rotation and torque.

Flash Temperature Parameter

Flash temperature parameter (FTP) is a limiting factor in mechanical performance, such as cutting and forming tools. The FTP values were calculated for PFAD oil, engine oil and hydraulic oil in the experimental condition of this study using Equation (1).

$$F = \frac{W}{d^{1.4}} \qquad (1)$$

where *W* is the load in kilogrammes and *d* is the wear scar diameter (WSD) in millimetres (Piekoszewski *et al*., 2001; Bhattacharya *et al*., 1990; Lane, 1957.)

Scuffing and Seizure

Scuffing is a phenomenon that breaks down the oxide layers, physically or chemically, due to the local thermal expansion and plastic flow of asperities of the contact surfaces (Sheiretov, 1997). This surface failure creates a contact between the sliding surfaces without local surface melting (Piekoszewski *et al.*, 2001). In scuffing, factors, such as pressure, velocity and temperature, would influence the scuffing rate (Cavatorta, 2000). The limiting pressure of a seizure is calculated from Equation (2).

$$P(oz) = \frac{0.52P}{d^2} \qquad (2)$$

The average wear scar diameter *d* is calculated from the normal scar diameters measured on the stationary balls. *P* is the force, expressed in Newton and d in millimetres. Thus, the limiting pressure of a seizure, *P* (oz) is in N mm^{-2} (Piekoszewski *et al.*, 2001).

Coefficient of Friction

Equation (3) describes the coefficient of friction which is the ratio of the forces that are involved between bodies in the sliding surfaces,

$$F = \mu.N \qquad (3)$$

where μ is the coefficient of friction, *F* is force and *N* is normal force.

It is a dimensionless scalar value and plays a major role in determining transmission efficiency through the moving parts. The coefficients of friction in this investigation were calculated according to IP-239 Standards, as shown in Equation (4).

$$\mu = \frac{T\sqrt{6}}{3Wr} \qquad (4)$$

where μ is the coefficient of friction, *T* is the frictional torque (kg mm^{-1}), *W* is the applied load (kg) and *r* is the distance from the centre of the contact surface on the lower balls to the axis of rotation, which was determined to be 3.67 mm (Husnawan *et al.*, 2007; Thorp, 1975).

Wear Scar Test

In this study, wear was investigated following the ASTM conditions, method B (temperature, 75°C; load, 392 N; speed 1200 rpm; and time 60 min), and at different loads (200, 300, 392, 500 and 600 N). The wear scar diameter of the balls was measured using a CCD camera and scanning electron microscopy (SEM).

RESULTS AND DISCUSSION

The lubricant and hydraulic properties of PFAD oil were investigated with a four-ball tribotester in different loads. The tests present a good opportunity to discuss anti-friction and anti-wear ability and to compare PFAD oil with mineral oils.

Viscosity

Viscosity was used to recognise the primary properties of liquids and to describe the internal resistance of liquids or gas for flow. Viscosity has direct impact with liquid thickness. A thick layer of lubricant between contact parts can reduce friction and wear more than a thin layer in the same conditions. Liquids with higher viscosity can make a thicker oil layer between contact parts. However, increased viscosity sometimes shows that the oil has deteriorated by contamination or oxidation and decreased viscosity indicates a dilution of the oil. A viscosity index is used for measuring the variable temperatures of liquids in industrial applications, especially in the automotive industry.

A previous study about viscosity showed that lubricant oils with high viscosity have a much greater load carrying capacity and that there is a direct relationship between decreasing viscosity and increasing the load (Furey, 1962). The second definition of viscosity is resistance to flow where lubricant with zero viscosity cannot resist the flow and with minimum load. This condition causes the lubricant to start flowing away from the pressure point allowing for metal-to- metal contact (Igwe, 2004).

Figure 3 shows the viscosity of the experimental oils (PFAD, engine and hydraulic). According to the theory on the increased fluidly of liquid with an increase in temperature, this figure indicates that viscosity decreases when the temperature increases. At lower temperatures, the values of the viscosity of the engine oil and hydraulic oil were the same and higher than that of the PFAD oil, respectively. However, the temperature difference was less when increasing the temperature. PFAD had similar viscosity as hydraulic oil at 50°C. Furthermore, at higher temperatures, particularly at 90°C, 110°C and 120°C, the three experimental oils had almost the same viscosity. At all temperatures, engine oil had better viscosity than did hydraulic and PFAD oil. Normally, higher viscosity for fluids occurs because the anti-friction ability has better values, although large increases in viscosity causes the lubricant to begin to deteriorate with oxidation or contamination (Zuidema, 1959; Maleque *et al.*, 2000). It must be

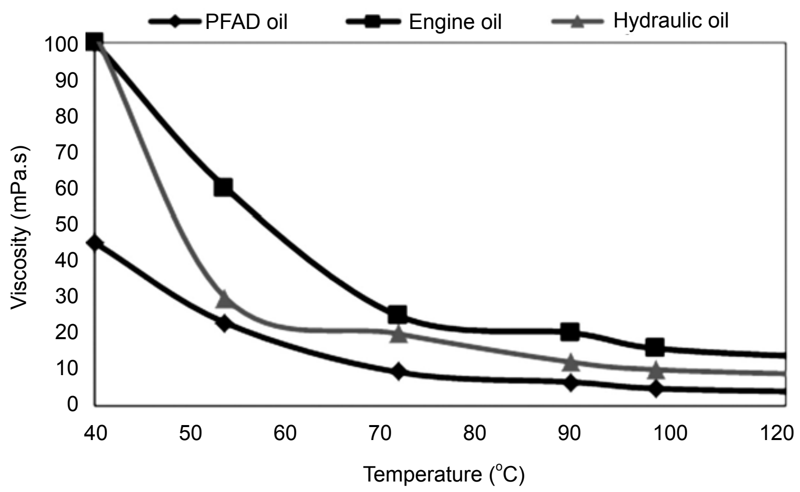

Figure 3. Kinematic viscosity measured for palm fatty acid distillate (PFAD), engine and hydraulic oils under different tested temperature.

noted that the engine and hydraulic oils used in this study were from commercial oils and contained additive materials to increase viscosity, but the PFAD oil was pure. The PFAD oil would have better a viscosity if it also had additives. Similarly, anti-wear and anti-friction could be further improved with additives in PFAD.

Flash Temperature Parameter Analysis

FTP is the lowest temperature at which a liquid can vaporise. It occurs with increased heat caused by friction between two rubbing surfaces (Piekoszewski *et al.*, 2001). FTP is a critical parameter for lubricant and hydraulic oil. At this temperature, the lubricant will start to evaporate. The lubricant layer between the contact surfaces will be decreased due to the evaporation of the lubricant, and as a result, the contact surfaces, become closer together. This phenomenon increases the possibility of contact between parts. *Figure 4* shows the FTP graph for PFAD, engine and hydraulic oil at different loads following the ASTM conditions. This figure also compares the values of FTP in these oils. *Figure 4* shows that all oils had an upward slope when the load was increased. This slope was less with hydraulic oil and more with PFAD oil. However, for PFAD oil, the downward trend was seen at a load of 600 N. The maximum FTP for PFAD oil was obtained at a test load of 500 N (51.02 kg) while for engine and hydraulic oil at 600 N (61.22 kg). The test results showed that the FTP was increased when

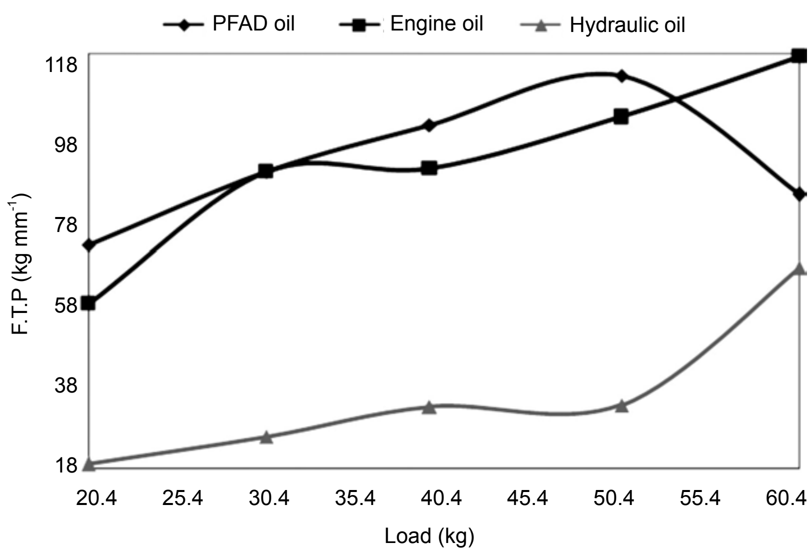

Figure 4. Flash temperature parameter on ball bearings lubricated with palm fatty acid distillate (PFAD), engine and hydraulic oils under different loads.

increasing the load of the PFAD oil and mineral lubricant oil. This increase can be explained with direct relationship between FTP and load, according to Equation (1). Furthermore, the results of these experiments showed that the reaction of PFAD oil versus the load for FTP with the average of 95.98°C was higher than the engine and hydraulic oils with 95.78°C and 36.29°C respectively. These results confirm that PFAD has higher resistance to evaporate versus an increase in the load than the engine and hydraulic mineral oil.

Effect of Load in Scuffing and Seizure

Scuffing was measured with the four-ball tribotester as a process leading to seizure when the load was increased. *Figure 5* shows the value of limiting pressure of seizure *P* (oz) and the loads of PFAD, engine and hydraulic oils. According to Equation (2), *P* (oz) has an inverse relationship with wear scar diameter, and the value of *P* (oz) decreases with the increase of the wear scar diameter and *vice versa*. There was a possibility that with an increase in the load, the scuffing occurred in the first few minutes of the experiment (Odi-owei, 1987). As shown in *Figure 5*, *P* (oz) increased when the loads of the experimental oils were increased. It can clearly be seen that the *P* (oz) value of PFAD was higher than that of hydraulic oil in all loads and was higher than that of engine oil at 200, 300, 400 and 500 N loads. However, the value of *P* (oz) for engine oil was not much different than that in PFAD oil, especially at 300 N. Furthermore, hydraulic oil had lower *P* (oz) values under different loads.

Effect of Load on the Coefficient of Friction and Friction Torque

The performance of PFAD as a lubricant was investigated using a four-ball tribotester under various loads. *Figure 6* shows the coefficient of friction of PFAD, engine and hydraulic oil at different loads following the ASTM conditions. It can be seen that the coefficient of friction increased when the load was increased. This effect was due to the decreased lubricant viscosity caused by the increased load (Clark *et al.,* 1984). The coefficient of friction for PFAD was lower compared to engine mineral oil and hydraulic mineral oil in all experimental loads. The fatty acid chain in vegetable oil makes a monolayer film of oil between the sliding surfaces, which prevents metal-to-metal contact (Sharma *et al.,* 2008). The stearic acid in PFAD is another resin that helps maintain the lubricant film and reduce friction between contact parts (Syahrullail *et al.*, 2011). However, the coefficient of friction of PFAD sharply increased at loads of 600 N. Hydraulic oil had the highest coefficient of friction under different loads, but the coefficients of friction of engine oil were similar to hydraulic oil at different loads. The lowest coefficient of friction was obtained at 200 N for PFAD oil and the highest was obtained at 600 N for hydraulic mineral oil with a lubricant base. The frictional torque data were recorded by the four-ball tribotester and transferred to a computer. The coefficient of friction was calculated using Equation (3), and the results are shown in *Figure 6*. The coefficient of friction for PFAD, engine and hydraulic oils increased with increasing loads when the oils were between specimen balls and when the four-ball tribotester was working. Other studies have confirmed that the fatty acid in vegetable oil can reduce the coefficient of friction and wear between contact parts (Masjuki and Maleque, 1997; Yunus *et al.,* 2004; Castro *et al.*, 2006).

Wear Scar Diameter Analysis

After the experiments, the wear scar on the surface of the test ball bearings, which were locked

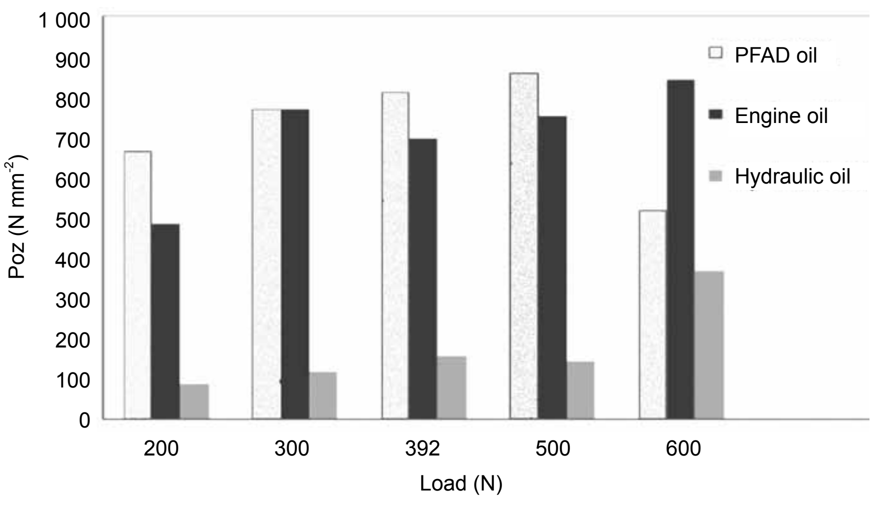

Figure 5. Value of limiting pressure of seizure for palm fatty acid distillate (PFAD), engine and hydraulic oils in 200, 300, 392, 500 and 600 N.

in the cup, were inspected with a CCD camera, and the diameters of the wear scars were measured and average values were calculated from the CCD camera images. The average of the wear scar diameter for PFAD, engine and hydraulic oils are shown in *Figure 7.* This figure clearly shows that at lower loads (200 and 300 N), the wear scar diameter on the ball specimens for PFAD oil was less than that for engine and hydraulic oils. At 400 N, the value of the wear scar diameter of PFAD was similar to that of engine oil and less than that of hydraulic oil. At higher loads (500 and 600 N), the wear scar diameter of PFAD was less than engine and hydraulic oils. This figure also indicates that the wear scar diameter increased when the load was increased. PFAD showed high lubricity in preventing metal-to-metal contact, as shown by a wear scar diameter value lower than hydraulic oil and the same as engine oil. However, at higher loads, the performance of PFAD decreased, as shown by the higher wear scar diameter value compared to engine mineral oil. The viscosity decreased when the load increased because there is a relationship between the viscosities of oil with molecular clusters and the hydrodynamic volume of the oil molecule. Increased load causes a decrease in the hydrodynamic volume leading to a weak molecules bond (Igwe, 2004).

Wear Worn Surface Characteristics

Due to the increased coefficient of friction, reduced viscosity and FTP with increased load, and the direct relationship between the coefficient of friction and corrosion, it is expected that the corro-

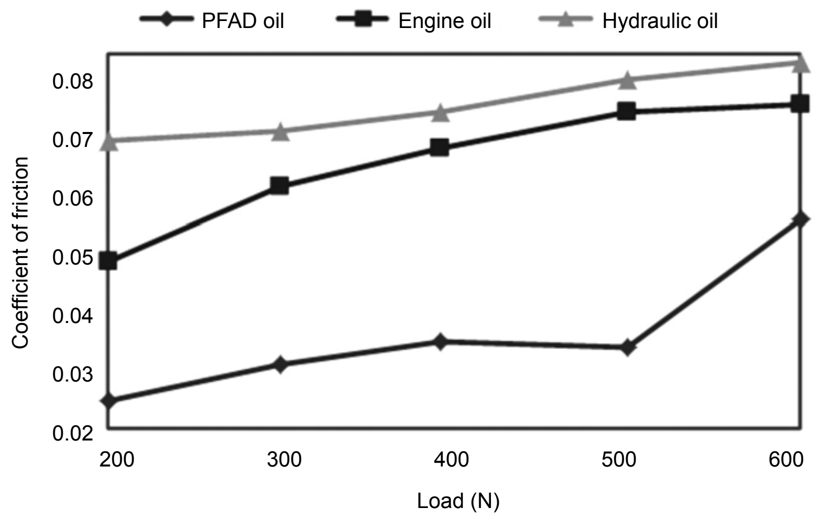

Figure 6. Effect of load on coefficient of friction for palm fatty acid distillate (PFAD), engine and hydraulic oils under 200, 300, 392, 500 and 600 N.

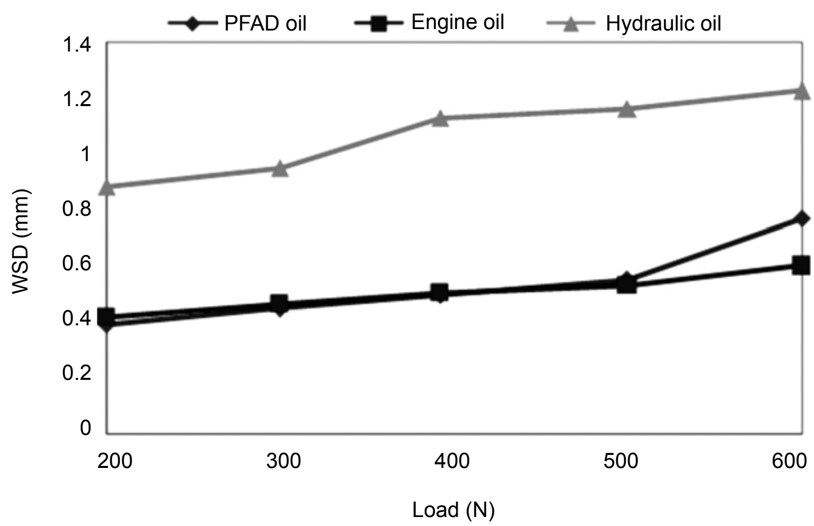

Figure 7. Effect of load on wear scar diameter (WSD) for palm fatty acid distillate (PFAD), engine and hydraulic oils in 200, 300, 392, 500 and 600 N.

sion rate increases with the increasing load. *Figure 8* shows the representative wear scar from the bottom ball specimen of PFAD, engine and hydraulic mineral oils at 200 N loads following the ASTM conditions. This figure shows that the ball bearing surface wear scar was circular after experiments with PFAD oil and engine oil. A mild abrasion on the surface of PFAD and engine ball specimens and rough abrasions on the surface of hydraulic ball specimens were seen. For all the three oils, it is clear that the wear scar diameter increased with increasing loads. *Figure 9* shows the wear scar on the ball specimens at 300 N. In this figure, it can be observed that there were more wear scar lines on the hydraulic ball surface at 300 N than at 200 N, and the edge of the wear scar was slightly ragged and obscured by metal. Mild abrasions were observed on the PFAD and engine oil ball surfaces, and there was not much difference between the wear scars on the ball specimens for these oils at 300 and 200 N. *Figure 10* shows the wear scar on the ball surfaces of the experimental oils following the ASTM conditions (load 392 N). At this load, there was a circular rough abrasion and light pitting corrosion on the ball specimen of PFAD oil (*Figure 13a*) and engine oil. Furthermore, there were some deep grooves and some small pits on the hydraulic oil ball specimen (*Figure 13b*). In hydraulic oil, the wear scar was circular and the ball surface was ragged and was sometimes obscured by metal. *Figure 11* shows the wear scar for PFAD, engine and hydraulic oils at 500 N. In this figure, the wear scar of the PFAD and engine ball specimens was circular, and some shallow grooves on the PFAD ball surfaces and deep grooves on the engine ball surfaces were observed. Furthermore, on the PFAD and engine ball surfaces, abrasions were seen as the dominant wear mechanism. There were some deep grooves on the hydraulic ball surfaces, and was observed rough erosion between surfaces. *Figure 12* shows the test balls surfaces in different oils at load 600 N. These figure shows that the test ball surfaces of PFAD and engine oil were covered with rough erosion and deep scratches and grooves, and the test ball surface of hydraulic oil was worn with rough erosion and

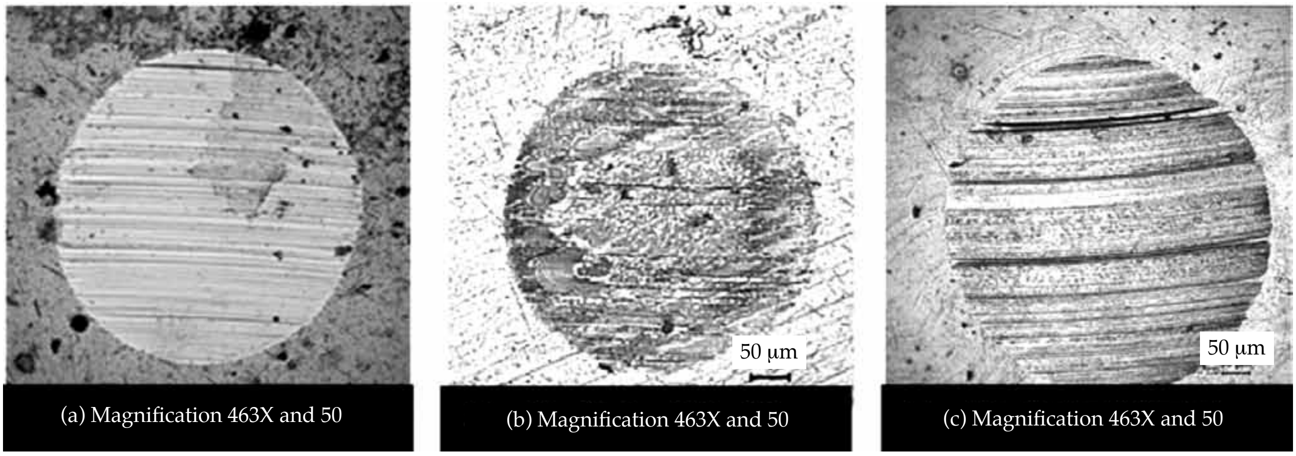

Figure 8. Optical micrographs of wear area on the balls surface and in 200 N (magnification 463X and 50 μm): (a) palm fatty acid distillate (PFAD) oil, (b) engine mineral oil, and (c) hydraulic mineral oil.

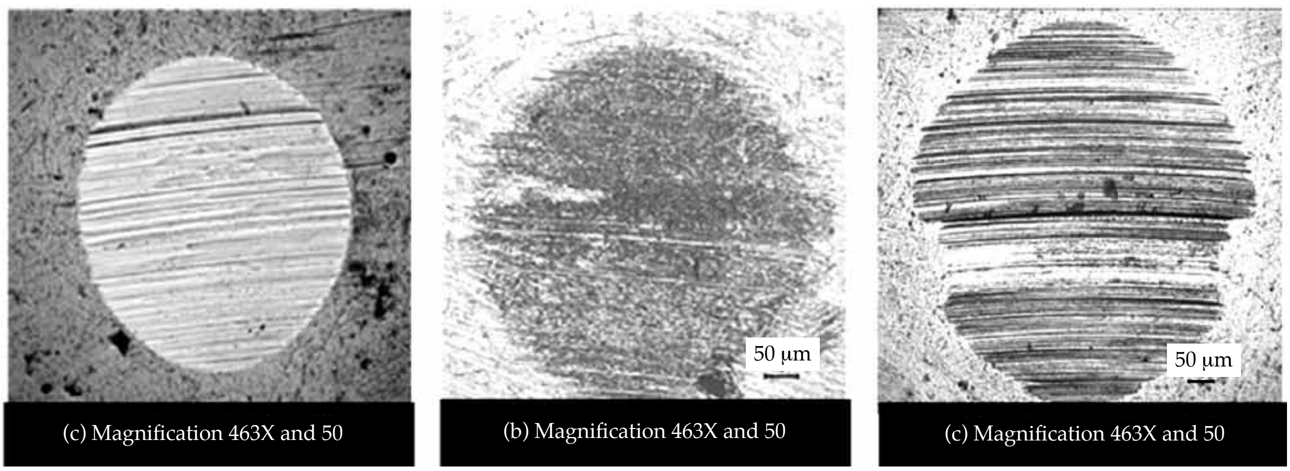

Figure 9. Optical micrographs of wear area on the balls surface and in 300 N (magnification 463X and 50 μm): (a) palm fatty acid distillate (PFAD) oil, (b) engine mineral oil, and (c) hydraulic mineral oil.

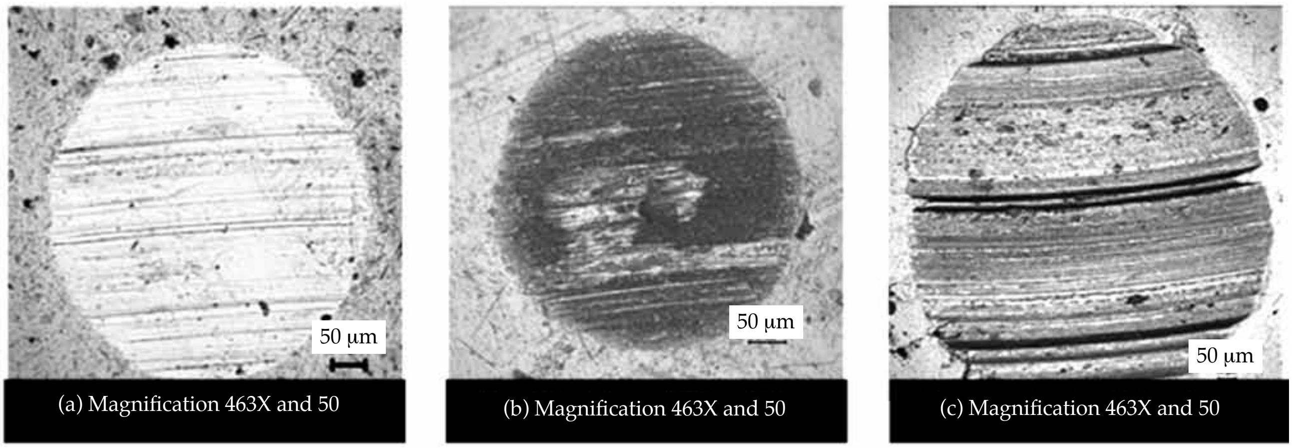

Figure 10. Optical micrographs of wear area on the balls surface and in 392 N (magnification 463X and 50 µm): (a) palm fatty acid distillate (PFAD) oil, (b) engine mineral oil, and (c) hydraulic mineral oil.

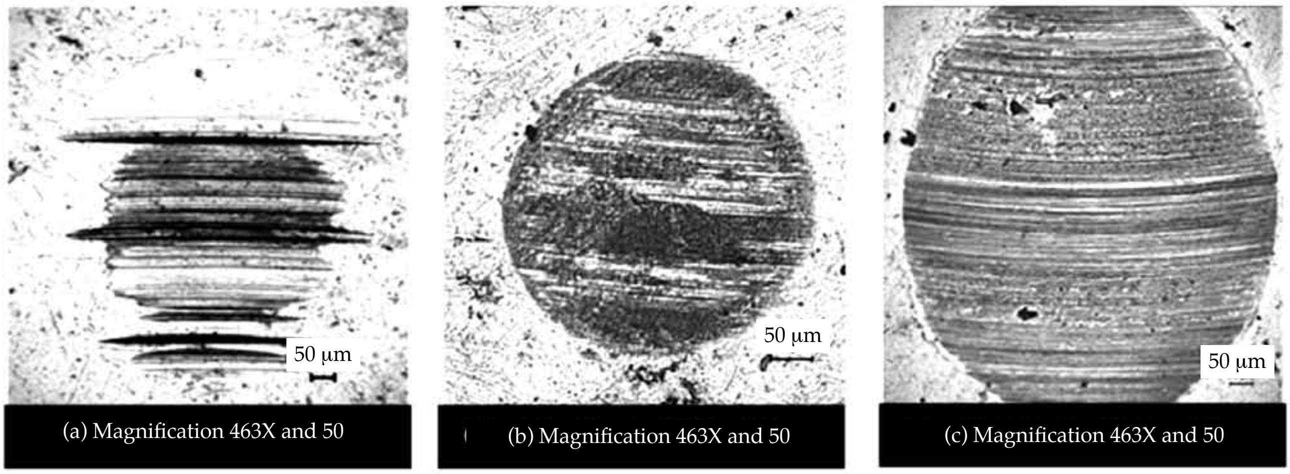

Figure 11. Optical micrographs of wear area on the balls surface and in 500 N (magnification 463X and 50 µm): (a) palm fatty acid distillate (PFAD), (b) engine mineral oil, and (c) hydraulic mineral oil.

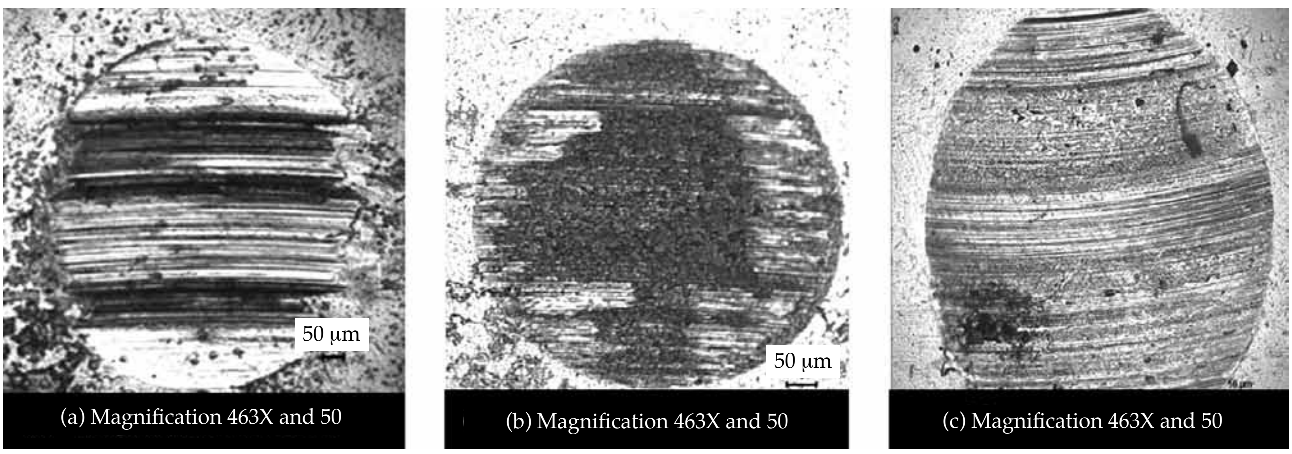

Figure 12. Optical micrographs of wear area on the balls surface and in 600 N (magnification 463X and 50 µm): (a) palm fatty acid distillate (PFAD) oil, (b) engine mineral oil, and (c) hydraulic mineral oil.

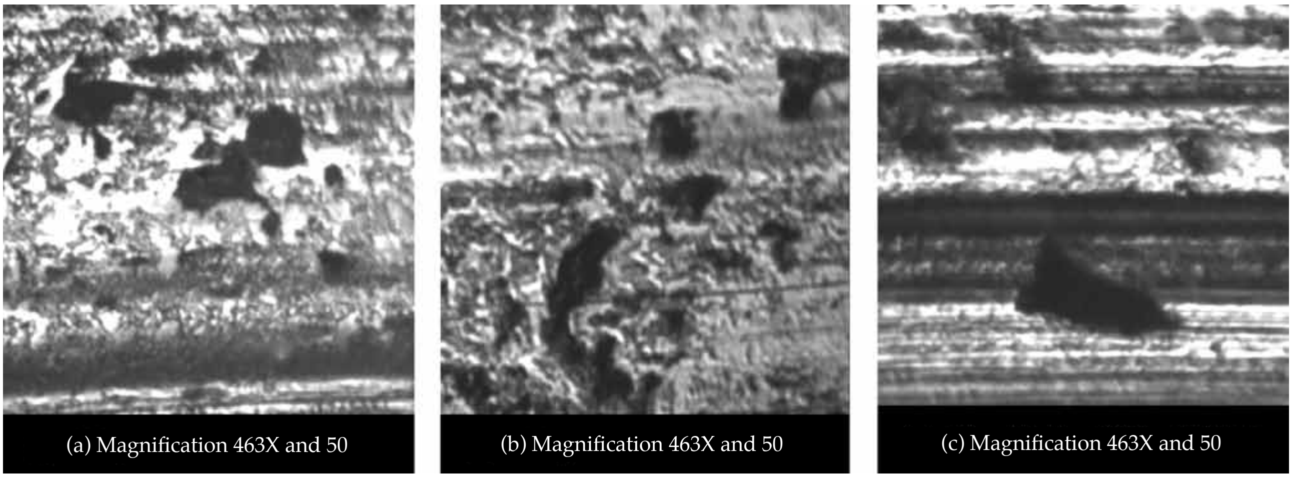

Figure 13. The pitting corrosion on ball specimen. (a) Palm fatty acid distillate (PFAD) ball specimen in 392 N, (b) hydraulic ball specimen in 400 N and (c) hydraulic ball specimen in 600 N.

corrosion with small pits (*Figure 13c*). Furthermore, fusion of metal between contact surface parts was observed in engine oil and hydraulic oil. A previous study about vegetable oils showed that stearic acid has a good affinity to be absorbed into the steel surfaces. This contact between acid molecules and steel surfaces is caused by the chemically polymerised molecules in the contact parts. This great affinity has an important role in reducing friction and wear in contact parts (Farooq, 2011). The results of this study showed that in all test oils, the wear scars on ball specimens increased when the load increased. Due to the similar and better efficacy of PFAD oil to reduce wear scars in industrial application, it can be concluded that the PFAD oil from the vegetable oils family can be a viable alternative to mineral lubricant oil. It should be noted that PFAD oil in this experiment was pure, but that there were anti-wear additives to reduce adhesive wear in the engine oil and hydraulic oil; these additives have a very important role in wear protection properties (Wan *et al.*, 1997).

CONCLUSION

This investigation was performed under different applied loads and working temperatures for PFAD, engine and hydraulic oils using a four-ball tribotester. Findings of this research showed that the coefficient of friction and wear scar diameter increased with increasing load. Also, FTP increased as the load increased on all test oils in this study. However, the amount of viscosity for the engine oil was higher than PFAD oil but overall, PFAD oil as a bio-oil had better anti-friction and anti-wear ability and better tribological characteristics compared to engine and hydraulic oils. The results of this research confirms that PFAD oil is indeed a potential source of lubricant oil and can be considered a viable replacement for engine and hydraulic oils.

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