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Study on the tribological characteristics of plant oil-based bio-lubricant with automotive liner-piston ring materials

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ABSTRACT

The development of bio-lubricant is an immerging area of research considering the rapid depletion of petroleum reserve and environmental concern. This study aims to develop non-edible jatropha oil-based bio-lubricant and investigate the tribological properties considering commonly used piston ring-cylinder liner materials of stainless steel and cast iron due to their interaction under lubricated conditions in an internal combustion engine. The bio-lubricant was prepared by blending different percentages of vegetable oil with commercial lubricants. The tribological test was carried out using a Reo-Bicerihigh-frequency reciprocating rig (HFRR) for the duration of 6 h under standard operating conditions. Different properties of bio-lubricants were measured before and after the HFRR test using various analytical instruments. The morphology of the worn material surfaces was examined via Hitachi S-4700 FE-SEM cold field emission high resolution scanning electron microscopy (SEM). The result showed that addition of vegetable oil lubricant up to 7.5% concentration can be compared with commercial lubricant in case of wear rate and coefficient of wear as weight loss reduced significantly. Minimum change in viscosity was observed at the addition of 7.5% bio-lubricant. Surface morphology analysis confirmed less damage of metal surface when tribological analysis were performed at mixed lubricated condition.

1. Introduction

Lubricants are made of mineral oil and appropriate additives, such as artificial colours, and antioxidants, to reduce friction between the moving mechanical components [1]. One of the critically important characteristics of lubricants is that they are not completely used throughout their lifetime compared with other petroleum derivatives. Disposal of lubricant residues thus requires much responsibility owing to its resistance to biodegradation [2]. About 12 million tonnes of lubricant waste have been reported to be exposed to environment each year [3]. These lubricants are also not compatible with the environment as these seriously affect the soil and waterways [4]. Thus, recent stringent regulatory government legislation aims to reduce their use due to environmental degradation caused by irresponsible disposal of mineral oil-based lubricants [5]. As such, research into environmentally friendly biodegradable lubricants has increased over the past few years [2,6,7]. One such lubricant includes bio-lubricant derived from renewable sources such as vegetable oils or fats [1,6].

Vegetable oil and fat-based lubricants are promising alternative to mineral lubricants because they are renewable, non-toxic, biodegradable, possess high flash point, low volatility, and high viscosity, etc. [8–10]. Furthermore, the presence of polar ester groups along with long-chain fatty acids demonstrated greater lubricity than that of mineral and synthetic lubricants [11,12]. The polar fatty acid carboxylic group sticks to the metal surface and forms a thin lubricating film that reduces friction and wear, minimising metal-to-metal contacts [13,14]. In general, bio-lubricant is produced by means of polyhydrolyte transesterification, for example trimethylolpropane (TMP) or glycol, and vegetable [15,16].

Jatropha oil has excellent lubricant properties compared to the mineral oils. Study showed that jatropha oil produces only 10%–20% wear

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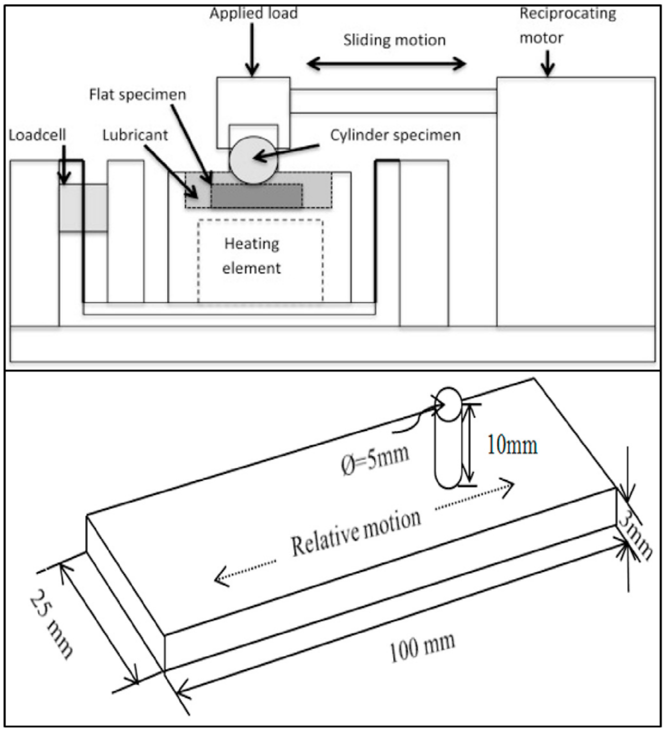

Fig. 1. Schematic presentation of HFRR and the dimensions of the plate and pin [7].

when compared with pure lubricant SAE 40 [17]. Other study showed that addition of 5%–10% concentration of jatropha oil with mineral oil significantly reduce COF and wear rate [18]. It has kinetic viscosity 52.76 at 30 °C and 4.7 to 7 at 100°C. Besides, 15W 40 provides good frictional properties. It prevents slippages and premature wear in joint engine lubricant and transmission system. Study reveals that 15W 40 provides less friction and wear and produces less changes in the geometric shape of the surface [19]. It has viscosity 119 at 40 °C and 15.4 at 100 °C.

A recent literature survey shows a continued interest in edible and non-edible oil-based bio-lubricants. Gul et al. [20] studied the tribological characteristics of cotton oil-based TMP ester blends with commercial lubricants. Tests were carried out in high-frequency reciprocating-rig with engine cylinder-liner and piston-ring combination. They reported that the addition of 10% cotton oil-based TMP ester in the blend showed the lowest friction and wear as compared to SAE-40. Attia et al. [15] studied ethylene glycol di-esters (EGDEs) as bio-lubricant that was produced by transesterification of FAMEs from sunflower, soybean, and jatropha and waste oils and ethylene glycol. The physicochemical characteristics such as density, thermal stability, viscosity index, shear rate etc. of those lubricants were determined using standard test method, thermogravimetric analysis, etc. Results show that all the tested bio-lubricant has sufficient chemical and rheological characteristics to be used as industrial commercialised lubricants. Zulkifli et al. [7] studied the partial substitution potential of palm oil-based TMP ester as an engine lubricant since TMP ester has high lubrication properties, such as flash point temperature and viscosity index etc. They studied the lubrication characteristics of different TMP samples in different regimes. In the boundary lubrication regime, at 3% addition of palm oil-based TMP ester in conventional lubricant shows the best wear reduction characteristics with maximum reduction of wear scar diameter and 30% reduction in coefficient of friction. As such, earlier studies show that very limited work has been done on jatropha oil-based bio-lubricant. As such, this study focuses on the formulation of lubricant using non-edible jatropha oil which was then blended with a commercial SAE 15W40 lubricant at different percentages to examine the tribological behavior on materials used in automotive IC engine.

Table 1
Specifications and test condition for Reo-Biceri high-frequency reciprocating rig.

Test parameter	Conditions
Sliding direction	Longitudinal
Sliding Distance/Rev	80.0 mm
Dead Load Weight Applied	10.2 kg
Density	7.8 g/cm^3
Arm length	0.226 m
Contact Area	6.0 mm^2
Operating hour	6.0 h
Temperature	80°C
Speed	150 rpm
Velocity	0.20 m/s

Table 2
Specifications of tested materials.

Metals	Density (gm/cm^3)	Hardness (MPa)
Cast iron	6.96	1863
Stainless steel	7.54	2599

Table 3
Lubricant sample compositions.

Samples	Lubricant compositions
BL0	Commercial lubricant as SAE 15W40 grade
BL2.5	2.5% addition of BL with SAE 15W40 grade
BL5	5% addition of BL with SAE 15W40 grade
BL7.5	7.5% addition of BL with SAE 15W40 grade
BL10	10% addition of BL with SAE 15W40 grade

Table 4
Viscosity and viscosity index (VI) of as received bio-lubricant sample.

Lubricant samples	Viscosity (cSt)		VI
	at 40°C	at 100°C	
BL0	98.0	13.1	141.5
BL2.5	92.3	13.2	143.2
BL5	79.2	12.2	150.7
BL7.5	72.0	11.6	154.5
BL10	64.3	10.6	157.7

2. Methodology

2.1. *High-frequency reciprocating wear and friction testing*

In this investigation, the wear and friction test was carried out using the pin on disc method using a high-frequency reciprocating rig (HFRR) where the cast iron was used as a plate while the pin was taken from the stainless steel. The schematic presentation of HFRR and the dimensions of the plate and pin are shown in Fig. 1, while the specification and operating condition are tabulated in Table 1.

2.2. *Properties of materials, lubricants and additive*

In an automotive engine, tribological parts consist of the crankshaft, bearing, cylinder liner, piston and piston rings. In many applications cast iron and stainless steel are the meeting parts where lubricant plays a vital role to reduce wear and friction. One such example is the piston ring-liner arrangement. Commonly, the cylinder liner is made of cast iron, whereas the piston ring is made of stainless steel respectively. Hence, in this investigation cast iron was chosen as a cylinder material, whereas the stainless steel was chosen as a piston ring material. The mechanical properties of these materials are presented in Table 2.

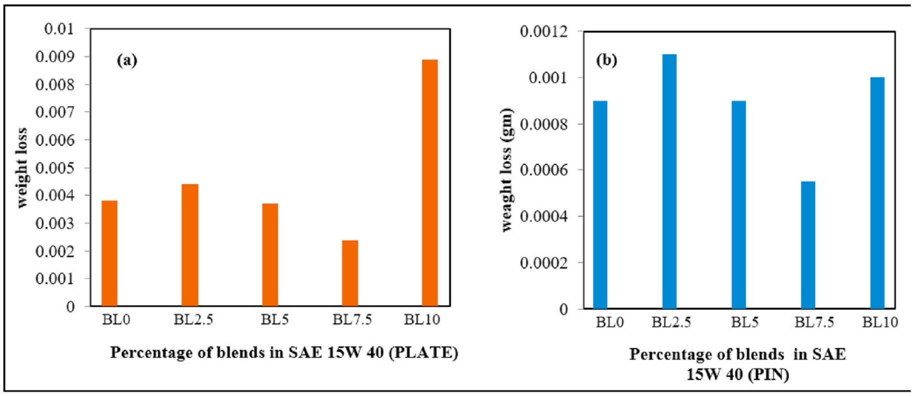

Fig. 2. Weight loss of (a) cast iron plate and (b) stainless steel after the operation of 6 h.

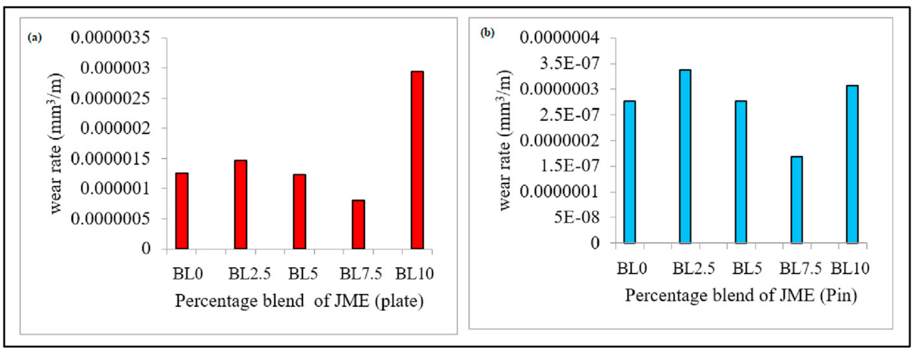

Fig. 3. Wear rate of (a) cast iron plate and (b) stainless steel after the operation of 6 h.

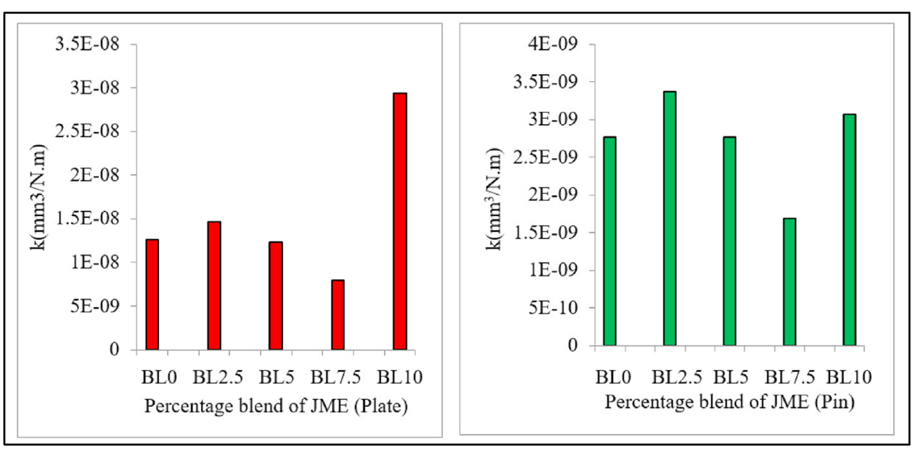

Fig. 4. Coefficient of wear (a) cast iron plate and (b) stainless steel after the operation of 6 h.

The bio-lubricant was formulated from the non-edible jatropha which was blended with a blending with a commercial SAE 15W40 lubricant at a different percentage of bio-lubricants between 2.5 and 10%. The bio-lubricant sample was homogenously mixed with the commercial lubricant using a mixture machine using an rpm of 250. The details of the lubricant samples are listed in Table 3, while the properties of lubricants before the test is presented in Table 4. The preparation procedures of the lubricants can be found in the earlier publications [21,22].

Before and after the wear and friction test using HFRR, the viscosity of the lubricants was measured using an automatic Anton Paar SVM-3000 apparatus at a temperature of 40 and 100°C. Before and after of the each experiment, the weight of each disc is measured by precision electronic balance and from the difference of the weights (before and after) the wear rate is measured. Besides the surface Morphology of the worn surface of the cast iron plate was tested using the Hitachi S-4700 FE-SEM cold field emission high resolution scanning electron microscopy (SEM).

3. Results and discussion

3.1. Wear rate analysis

Fig. 2(a) and (b) show the weight loss of cast iron plate and stainless steel pin respectively, while Fig. 3 illustrates the wear rate. Co-efficient of ware for cast iron plate and stainless steel pin is presented in Fig. 4. According to Fig. 2, throughout operation time (6 h) the loss of material from the cast iron plate (counter body) was much higher than the stainless steel pin. Besides, Fig. 2 depicts the variation of weight loss depending on the different percentage of BL in the commercial lubricant.

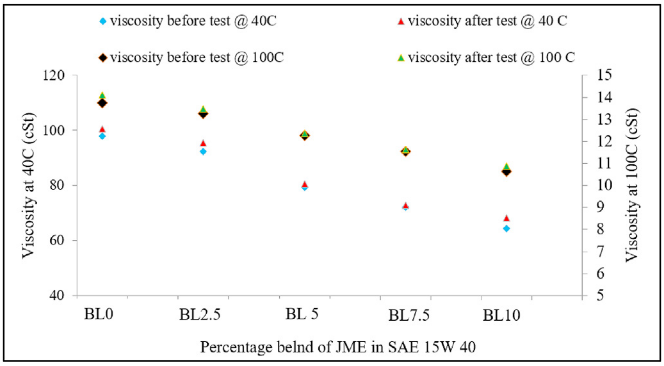

Fig. 5. Change in viscosities of different bio-lubricants before and after the test.

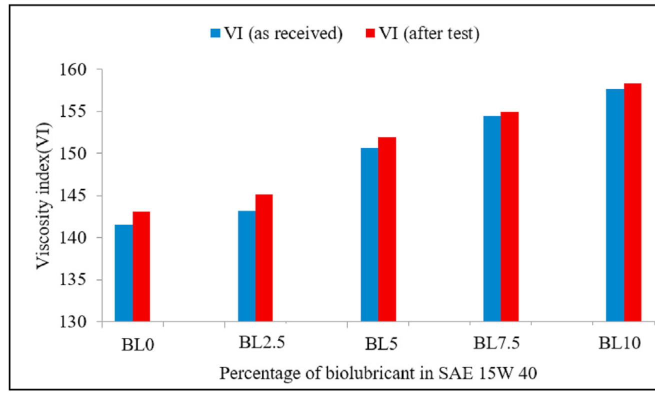

Fig. 6. Change in viscosity index of different bio-lubricants before and after the test.

It can be seen that the lowest weight loss was obtained while BL7.5 was added with the commercial lubricant, a further increment of BL by 2.5% (BL10) increase the weight loss considerably. Likewise, Figs. 3 and 4 showed a similar result. As observed in Figs. 3 and 4 the wear rate and co-efficient wear of cast iron plate are much higher than that of stainless steel.

Accordingly, the rate of wear and coefficient of wear was lowest using BL7.5 for both cast iron plate and stainless-steel plate while the highest value was for 10% lubricant. Another important fact is that the addition 2.5% BL imposed an adverse effect on the lubricant properties and an addition of 5% BL does not help to improve the lubricant stability significantly. The coefficient of wear is the end-result of weight loss and wear rate or wear volume. The co-efficient of wear depends on the hardness of the material which is inversely proportional to the rate of wear or co-efficient of wear [23]. Thereby, the co-efficient of wear of cast iron plate was much higher than stainless steel pin since stainless steel has a higher hardness value than that of the cast iron plate as presented in Table 4.

The wear rate also influences by the applied load, temperature, contact pressure and sliding distance. However, since all these parameters are kept constant thus hardness is only the variable which impacted the wear rate. In this study the potential of BL is tested which showed that the addition of a certain percentage (i.e. 7.5%) of BL act as an anti-wear additive, which consequently reduces the rate of wear from the interacting matting parts such that cylinder liner (made of cast iron) and piston ring (made of stainless steel). The reduction in wear rate by the addition of BL in engine oil can be explained by the presence of free fatty acid in the BL [24]. The free fatty acid produces a soap layer between the active end of the molecule of fatty acid and the firm surface through chemical adsorption. Consequently, a small percentage of BL in the commercial lubricant acts as an additive and thus plays as a wear-resistant of cast iron plate. This additive has a great affinity to the metal surface. A strong monolayer or coating is formed between the metal surfaces with the presence of BL added bio-lubricant. Thereby the rate of wear is reduced considerably [25].

Amiril Sahab Abdul Sani et al. [26] investigated the tribological performance of metal where jatropha oil has been used as biolubricant. In the experiment, it is seen that friction coefficient reduced at jatropha oil lubricant condition. Esters, fatty acids and polar structures of jatropha oil played a vital role to reduce the friction coefficient. A. Ruggiero et al. [27] evaluated the tribological performance of metal with jatropha oil based lubricant. They found in the experiment that the coefficient of friction reduces at higher velocity due to the presence of jatropha oil lubricant.

3.2. Viscosity analysis

Fig. 5 shows the change in viscosity at a temperature of both 40°C and 100°C after the test duration of 6 h while Fig. 6 illustrates the change in viscosity index after the test. Referring to Fig. 4, the viscosities after the test was increased for both temperatures. However, even though the viscosity was increased for all lubricants, the changes were minimal for BL 7.5 added bio-lubricant. It is important to take note that after the operation, the viscosity may increase or decrease. It is believed that in general the viscosity is decreased due to the dilution by lower viscosity oil or degradation of its viscous property with the presence of foreign material at an elevated temperature while the increase in viscosity is the consequence of oxidation or contamination. During the test, due to the oxidation, the sludge or insoluble product is formed resulting in the increases of the length of the molecular chain. Hence, the viscosity of the used lubricants is increased [28,29].

Along with viscosity, the viscosity index was also measured in this study. Viscosity index is the measure of the stability of lubricant without changing its viscosity at elevated temperature. A lubricant with low VI changes greatly in viscosity with temperature, while high viscosity indexed lubricant changes its viscosity relatively small for the same temperature [29]. The changes in VI after 6 h operation shows that higher concentration of BL possess higher viscosity index and this is because of the BL contains triglycerides that maintain stronger molecular bonding among the triglyceride molecules in the lubricant [30]. This phenomenon can also be explained as hydrogen bonding among the triglyceride molecule, which leads to increase the viscosity index after the test, VI of all lubricants, were increased however, the lowest increment was found for 7.5% BL added bio-lubricants, which is due to the lower oxidation of this lubricant.

3.3. Morphology analysis

The worn surface of the cast iron plate after 6 h operation of bench test is shown in Fig. 7 using scanning electron microscopy (SEM) test. After the test, the presence of grove parallel to wear direction is observed. The surface which was lubricated with BL10 is found to be more grooves, pits, cracks and more metal transfer from the surface of the cast iron plate. Whereas, these phenomena are less while the plate was lubricated with 5% and 7.5% BL. The iron debris because of initial wear of the cast iron plate is likely to be the source of abrasive wear. The large ploughing grooves and wedge-like agglomerates are found on the surface of the plate [25]. The size of wear scar in the addition of 5% and 7.5% BL were significantly lower compared to those of others. Thus, this can be concluded that the addition/dilution of BL in commercial lubricant can enhance the properties of the lubricant but up-to a certain level (i.e. 7.5%) and above that the inferiority is observed.

4. Conclusion

In this study, non-edible jatropha based bio-lubricant is developed and tested considering different tribological properties. Results showed that bio-lubricant has the potential to partially substitute the commercial

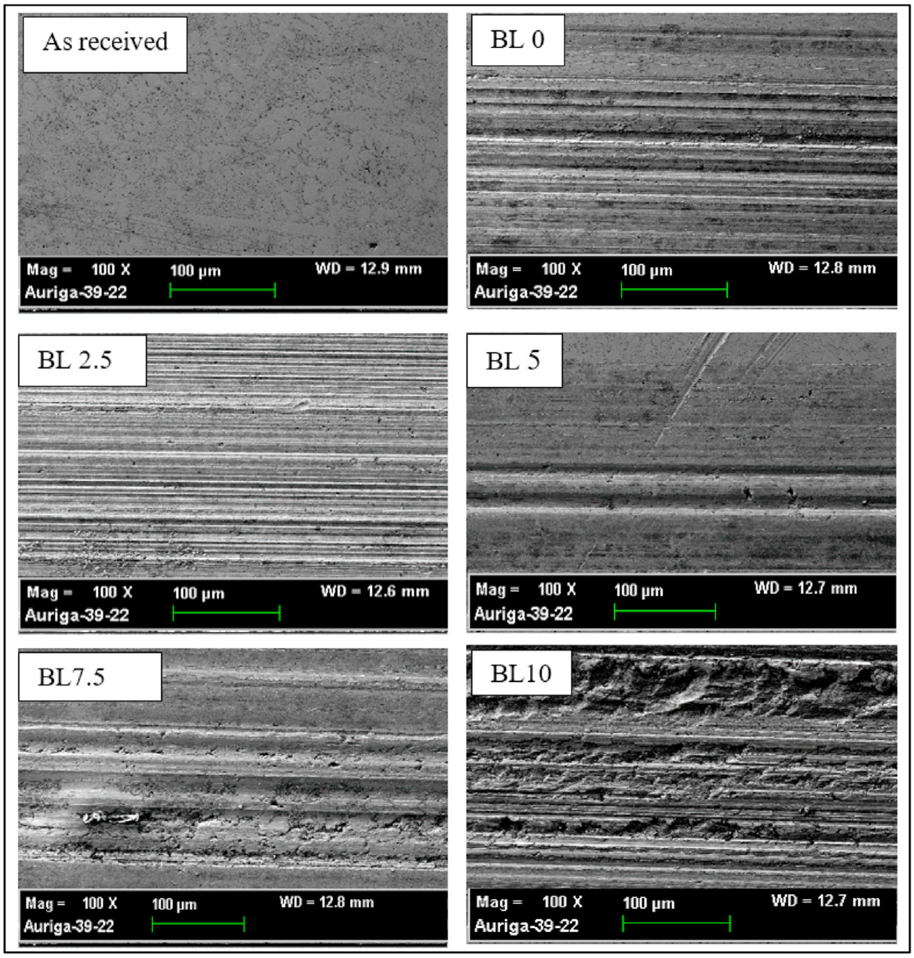

Fig. 7. SEM microstructure of cast iron plate after the operation of Biceri wear machine.

lubricant which will, in turn, reduce the dependency on the mineral lubricant, and help to reduce the harmful environmental impact. Besides, viscosity of the lubricant increases with the increase of temperature. However, for the addition of 7.5% bio-lubricant the viscosity was minimum. Addition of bio-lubricant reduces the effect of grooves, pits and cracks on the surface on the metal.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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