TRIBOLOGICAL CHARACTERISATION OF BIO LUBRICANT FROM CUCURBITA PEPO L. SEED OIL

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This is to certify that the dissertation entitled, "TRIBOLOGICAL CHARACTERISATION OF BIO LUBRICANT FROM CUCURBITA PEPO L. SEED OIL" submitted by Mr. Ikramul Hossain Mondal to Assam Science and Technology University, Assam, is a record of bona fide Project work carried out by him under my/our supervision and guidance and is worthy of consideration for the award of the degree of Master of Technology in Energy Engineering.

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The foregoing dissertation submitted by Mr. Ikramul Hossain Mondal (000715220) is hereby approved as a creditable study carried out and presented in a manner satisfactory to warrant its acceptance as a pre-requisite to the degree for which it has been submitted. It is understood that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein but approve only for the purpose for which it is submitted.

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ABSTRACT

In recent years Bio-lubricants much desired in numerous applications in machineries due to their renewable characteristics, which have high biodegradable nature and produce fewer pollutants compared to mineral-based lubricants. Thus, in this paper, the effect of bio-lubricant (Cucurbita Pepo L. seed oil) on tribological behaviour in pin on disc tester is studied and compared with commercially available lubricant SAE20W40. Tests were conducted at different loads of 10 N, 50 N, 100 N, 150 N and 200 N at a constant speed of 3 m/s for 60 minutes to evaluate the behaviour of coefficient of friction (COF) and wear at a temperature of 28°C and 100°C. Results showed that the COF decreases whereas, the wear increases with the increase in temperature and load. Cucurbita pepo L. seed oil (CPO) resulted in a lower wear rate in comparison to commercial SAE20W40. Wear scares on the surface lubricated with CPO show a smoother surface compared to the pin lubricated with SAE20W40 at both lower temperature (28°C) and higher temperature (100°C). This shows that CPO has better lubricity than SAE20W40. The present work indicates that CPO can be a potential alternative to mineral-based lubricant SAE20W40 for higher-temperature workplaces.

Keywords: Wear, Coefficient of friction, Cucurbita pepo L., Pin-on-disc

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Ikramul Hossain Mondal

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LIST OF ABBREVIATIONS

Abbreviation	Description
COF	Coefficient of Friction
CPO	Cucurbita Pepo L. seed oil
SAE	Society of Automotive Engineers
VI	Viscosity Index

CHAPTER 1: INTRODUCTION

In ancient times people used vegetable oil and animal fat as friction and wear reducing agents by applying them in between the contact surfaces. With the advancement of human civilisation people mainly depends on machines for most of the work. To increase the life of the machine the friction and wear must be decreased between the moving surfaces. There are many ways to decrease friction and wear, lubrication is one of them. So, there is a need for continuous deployment of lubricating oil so that the life of machines can be improved.

After using petroleum-based lubricants which are used all over the world are thrown into the environment because of their decrease in lubricating properties [1]. These petroleum-based minerals cause many environmental pollutions like soil and air pollution due to some degree of toxicity and their highly flammable characteristics [2]. Nearly 12 million metric tons of petroleum-based lubricant waste are disposed to the environment per year. The pollution occurred due to this lubricant is harmful to animals, humans and plants. It causes many respiratory illnesses and diseases in living organisms [3]. Therefore, it is necessary to take some steps to reduce the dependence on petroleum-based lubricants and overcome the high consumption of petroleum-based lubricants [4]. Due to the rapid development of industries, there is a high demand for lubricants, especially bio-lubricants. This demand is motivated by environmental problems that highlight the bad effects of pollution and the need of limiting it [5]. To meet this demand and to make environment-friendly lubricants and many researchers are looking into an alternative to mineral-based lubes. Mineral-based lubricants can be substituted by bio-lubricants, not because of their environment-friendly properties, but also has better lubricating properties such as high viscosity index (VI), high lubricity and low volatility [3], [6].

Bio-lubricants are mostly extracted from oil seeds. India is a major oilseed producer in the world. About 10 million tons of vegetable oils are produced from oil seeds in India per annum. There are many vegetable oils available in India which are extracted from different types of vegetable and fruit seeds. Due to the high oil yield and easy availability, Cucurbita pepo L. (pumpkin) seed was considered for the extraction of oil for this experiment. Bikash *et al.*, (2018) [7] reported that Cucurbita pepo L. seed has an oil content of 48% which is higher compared to many other bio-oils. In addition, pumpkin seeds are a good source of minerals like N, P, Na, Ca, Cu, Zn, Mg, K, and Fe which are vital for our well-being [8].

The Society of Automatic Engineers (SAE) has established a numerical code system for grading engine oil according to the viscosity characteristics known as SAE J300. The original viscosity grades were all mono grades like SAE 30. All the oils' viscosity decreases when heated. So, to get the right film thickness at operating temperature the oils were manufactured as thick oil. But in the cold weather, it would be difficult to start the engine as the oil was too thick to crack. However, oil additive Technology was introduced that allowed oil to thin more slowly, this allowed selection of thinner oil to start with. Thus, a multigrade system is introduced, the first grade shows the low-temperature characteristics (W denoting winter) whereas the later grades denote the high temperature characteristics. So, "SAE 20W-40" is a product that acts like an SAE 20 at cold temperature and as an "SAE 40" at 100° C. Higher viscosity means higher the SAE code. So, a larger SAE number means thicker lubricants. It is also observed that SAE20W50 gives better performance than the SAE20W40. But manual of the two-wheeler recommends SAE20W40 because SAE20W50 has more viscosity improver, which will cause some cold starting issues at winter due to their high viscosity [9]. This is why the Cucurbita pepo L. seed oil is compared with SAE20W40 engine oil.

For the past few decades, Al alloy has gained the interest of many researchers who studied its tribological behaviour [10]. The studies were carried out mostly on a pin-on-disk tribotester using Al-Mg-Si as pin material. Aluminium has a low density and it has high environmental corrosion resistance. Components which are made from pure aluminium are relatively soft, durable, lightweight, ductile, and malleable. Baruah and Borah (2021) [11] studied the abrasive wear behaviour of the cast Al-Mg-Si alloy with and without Sn added to the alloy. For this experiment, the Al-Mg-Si alloy is chosen as pin material. The wear test was done using a pin with flat contact surface against a plane High carbon alloy steel EN31 disc.

In this paper, the effect of bio-lubricant (Cucurbita Pepo L. seed oil) on friction and wear behaviour in pin-on-disc tester is studied and compared with commercially available lubricant SAE20W40. Tests were conducted at different loads of 10 N, 50 N, 100 N, 150 N and 200 N at a constant speed of 3 m/s for 60 minutes to evaluate the behaviour of coefficient of friction (COF) and wear at a temperature of 28°C and 100°C.

CHAPTER 2: REVIEW OF LITERATURE

It was observed by many authors that wear and friction depends on conditions such that normal load [12], [13], geometry [14], [15], contact surface roughness [16], sliding speed [17], type of material, temperature [18], [19], relative humidity [20], lubrication [21][9], viscosity [9] and vibration [22]. Tribological tests are mainly done on pin-on-disc, four ball testers, block on-ring abrasive wear test etc. Mainly factors like applied load, sliding speed, sliding distance and temperature are changed during tribological testing to study the wear rate and coefficients of friction. Among those factors normal load and sliding speed are the two major factors which effects the COF and wear rate significantly [17].

Bio-lubricant is interpreted as a lubricant obtained from natural raw materials both vegetable and animal oils, renewable and non-toxic to humans and other living things, as well as environmentally friendly [23]. Bikash *et al.*, (2017) [7] studied the physicochemical properties of Cucurbita pepo L. seed oil and compared it with other biodiesel products along with Petroleum diesel and found out that its properties are comparable to petroleum diesel. The oil content of C. pepo L. seed is found to be around 48% which is higher than the Soybean and Jatropha seed [7]. Some of the vegetable oil can be used as Bio-lubricant i.e., castor oil [24], Karanja [25], [26], Neem [27], Rice Bran [28], Rapeseed [29], Castor [30], Linseed[31], Mahua [32], Palm oil [5], [33], sunflower oil [34], coconut [35], soybean [36], olive and canola [37], pumpkin seed [1]. Choudhury *et al.*, (2021) [1] studied the tribological properties of Cucurbita pepo L. Oil (CPO) and compared with Commercially available oil SAE 20W40 and other vegetable oils. They suggest that CPO can be a potential alternative to petroleum-based mineral oil. Researchers from Malaysia Nuraliza *et al.*, (2015) [5] found that palm oil has better fiction reduction properties (Co-efficient of friction) and higher resistance (anti-wear properties) at low and high speed compared to mineral-based oil. Studies regarding the wear behavior of Al-Si have mainly been carried out by varying the reinforcement volume fraction. The common parameters varied for studying the wear behavior of Al-Sic are applied load or pressure, sliding speed and temperature.

Trivedi and Bhatt (2017) [38] showed that variation of load play a vital role to characterise the behaviour of frictional force and wear. Authors used various load range to study tribological behaviour. Result of their experiment shows that viscosity and variation of load plays a vital role to characterize the behaviour of frictional force and wear. Authors found that high weight loss with incremental load and SAE20W40 and SAE20W50 have better performance compared to SAE10W30. Chowdhury *et al.*, (2011) [17] studied the effect of Speed and load on friction and wear. The experiments were performed with normal load 10N-20N, Speed 500-2500 rpm and relative humidity 70%. Results showed that the friction coefficient decreases with the increase in sliding speed and load for aluminium. They also found that wear rate increases with increase in sliding speed and normal load. Nuruzzaman *et al.*, (2012) [39] studied friction coefficient of Al sliding against different pin materials. Experiments were performed at normal load 5 N, 7.5 N and 10 N, sliding velocity 0.5,0.75 and 1 m/s and relative humidity 70%. They found out that, coefficient of friction increases for certain duration of time and after that it remains constant for rest of the experiment. Mozgovoy *et al.*, (2014) [40] studied the effect of temperature on friction and wear. The tribological test were performed using sliding friction and wear tester under normal load of 31N, sliding speed 0.2 ms-1 and temperature 40°C-800°C. They found out that friction and wear decreases with increase in temperature up to 600°C but on further increase in temperature the friction and wear increases due to thermal softening of the specimen and increased adhesion. Kalam *et al.*, (2011) [41] studied the friction and wear characteristics of normal lubricant, additive added lubricant and waste vegetable oil (WVO) contaminated lubricants. Tests were conducted in a four-ball tester for different loads (50 kg to 90 kg), contamination in WVO was 1% to 5%. Husnawan *et al.*, (2007) [2] find out that WVO contaminated lubricants with suitable anti-wear additive can reduce wear and friction coefficient. The authors studied the development of a fiction force model for mineral oil basestock containing palm olein, and antiwear amine phosphate as additive, tested on a four-ball tribotester. The model was developed using terms of wear load, speed and operating time. Their study shows that, palm oil itself indeed is a good antiwear lubricant compared to mineral oil basestock and adding additives can increase its lubricating property further. Nuraliza *et al.*, (2015) [5] used a load of 10 N, 50 N and 100 N for the wear test. Some of the researchers used a high load range to study the wear behavior. Straffelini *et al.*, (2004) [42] selected a load range of 100-800N to study the wear behavior of Al-Sic in a wide load range. To the study of effect of load on tribological behaviour, the sliding speed was kept constant within the range of 0-3m/s. Some of the researchers studied the effect of sliding speed on the wear behavior [43].

Researchers find out that the coefficient of friction decreases with increase in sliding speed and normal load [5], [17]. Coefficient of friction also decreases monotonically as the temperature increases because it forms a protective debris bed [40], [44]. Chowdhury *et al.,* (2011) [17] found that the wear rates increase with the increase in applied load and Sliding speed. Mozgovoy *et al.,* (2014) [40] found out that the specific wear rate decreases with increase in temperature (400°C and 600°C) but on further increase in temperature (800°C) the specific wear rate increased due to thermal softening and adhesion.

CHAPTER 3: METHODOLOGY

A pin-on-disc machine with a data application system was used to collect the friction force and wear behaviour of the aluminium alloy pin lubricated with Cucurbita pepo L. seed oil (CPO) and SAE20W40. To compare the tribological behaviour of CPO and SAE20W40 the experiment was performed at different normal load conditions with a constant speed and fixed sliding distance. This paper follows the ASTM G99-95a entitled " Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus".

3.1 Materials Preparation

The rotating disc and pin were made from different materials. Pin material Al-Mg-Si alloy and disc material is high carbon alloy steel EN31. The composition (wt.%) of the pin specimen is shown in Table 3.1.

Table 3. 1 Al-Mg-Si alloy material Composition (wt.%) [4]

Elements	**Alloy**
Mg	0.89
Si	0.35
Fe	0.25
Cu	0.05
Mn	0.12
Al	Balance

For this experiment, cylindrical-shaped pins with a length of 30 mm and a diameter of 10 mm were prepared as shown in Fig. 3.1. The hardness of the pin specimen was 81 HV and the Ra roughness of the test surface was 0.45±0.05 um. Before every test, 1000 grit size (SiC) emery paper was used to polish the contact surfaces of the pin specimen and then cleaned with acetone.

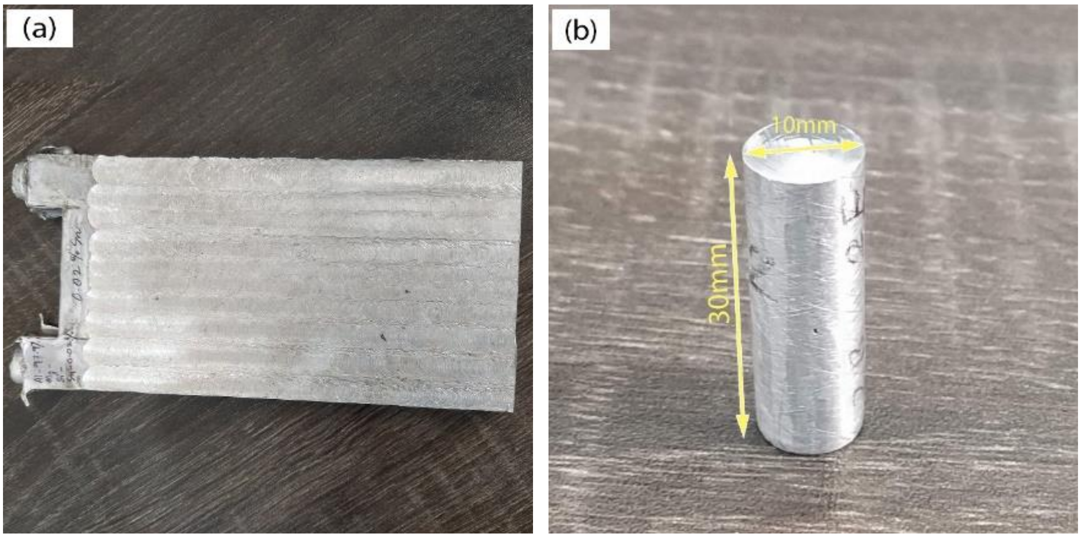

Fig. 3. 1 (a) Cast Al-Mg-Si alloy (b) Pin specimen

The EN31 is an excellent high carbon alloy steel which has a high degree of hardness with compressive strength and abrasive resistance. The diameter of the disc was 80 mm with a thickness of 10 mm as shown in Fig. 3.2.

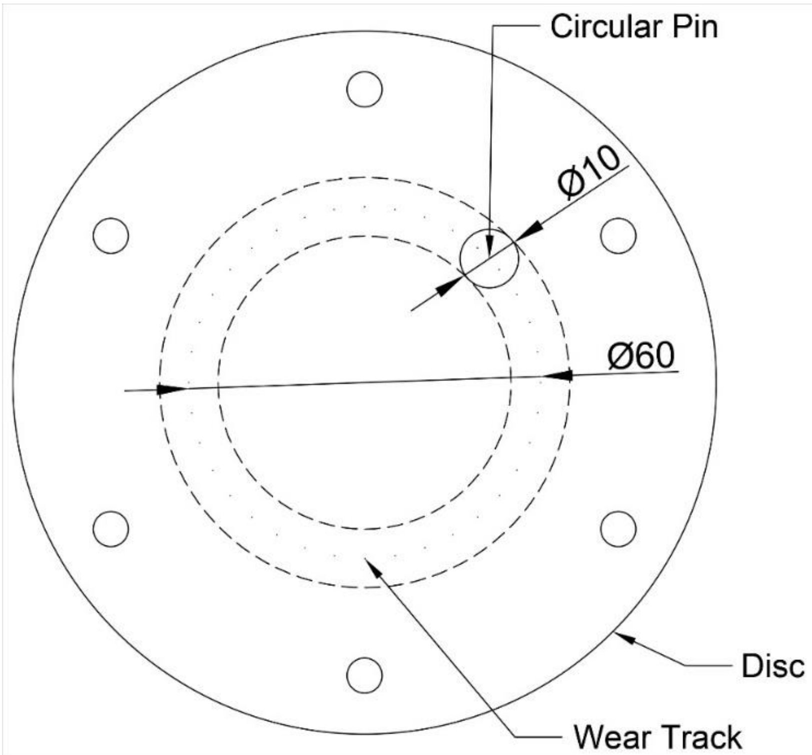

Fig. 3. 2 Schematic diagram of the plain disc with wear track diameter

3.2 Lubricant

Cucurbita Pepo L. Seed was purchased from a nearby shop in Guwahati, Assam, India. The seeds were cleaned from vegetables and washed off the external materials. The seeds were sun-dried for seven successive days and grinded into fine powders. The Soxhlet extraction method was used to extract the oil from the powdered seed [1]. The powdered seed of Cucurbita Pepo L was placed inside a thimble of Soxhlet extractor. A spherical bottom flask containing N-hexene (40-60°C) as an extractor solvent was placed at the lower end of the Soxhlet. When the solvent remaining in Soxhlet become colourless than the N-hexene extract was collected from the flask. The N-hexene extract so obtained was evaporated under low pressure in a rotatory vacuum evaporator (Make: IKA-RV-3V, Germany) to obtain the lubricant. Fig. 3.3(a) shows the Soxhlet extractor and Fig. 3.3 (b) the rotatory vacuum evaporator.

The oil yield of Cucurbita pepo L. seed is expressed in eqn. 3.1.

$$\left(\text{Yield of Cucurbita pepo L. seed} = \frac{\text{mass of CPO}}{\text{Mass of the sample}}\right) \times 100\% \qquad (3.1)$$

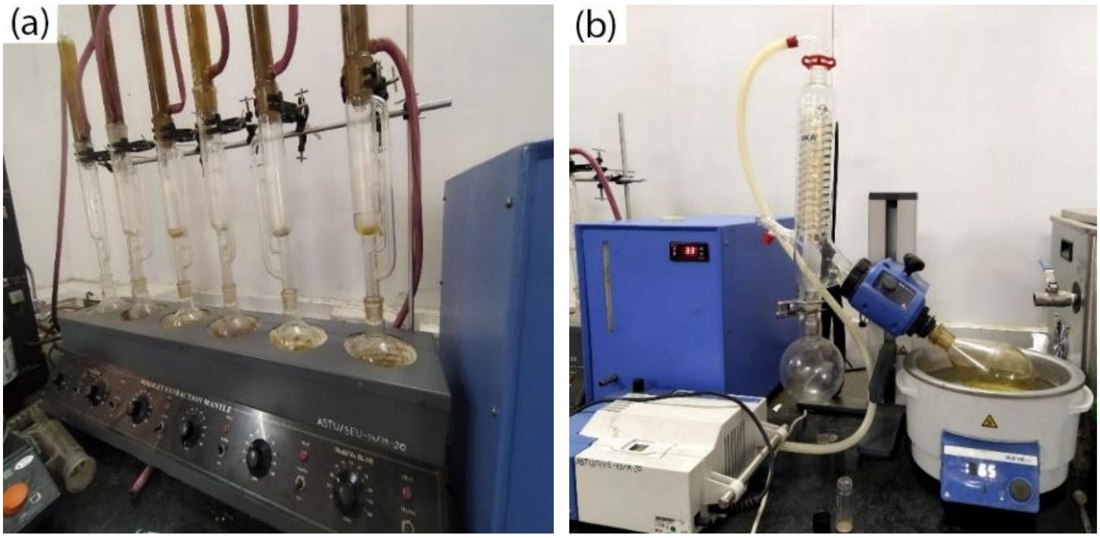

Fig. 3. 3 (a) Soxhlet extractor and (b) Rotatory vacuum evaporator

3.3 Wear Test Set-up

The tribological tests were performed on a pin-on-disc tribometer (Make: Ducom and model: CR 20-HTVT) at temperature (~28°C and 100°C) and humidity of (~65%). Fig. 3.4 shows the wear test setup and Fig. 3.5 shows the schematic diagram of the pin-on-disc machine. Before each test, the pin and disc were cleaned with Acetone to remove any metal fragments and oil from the contact surfaces. The disk was inserted into the holding device carefully and then clamped into the machine with the help of screws. The pin specimen was inserted into the pin holder and adjusted in such a way that it makes proper contact with the disc surface. The contact area between the pin and disc was examined so that it meets proper contact conditions. The lubricant was applied between the contact surfaces of the specimens. Lubrication was done at an interval of 5 minutes and approximately 2 ml of lubricant was used for each test.

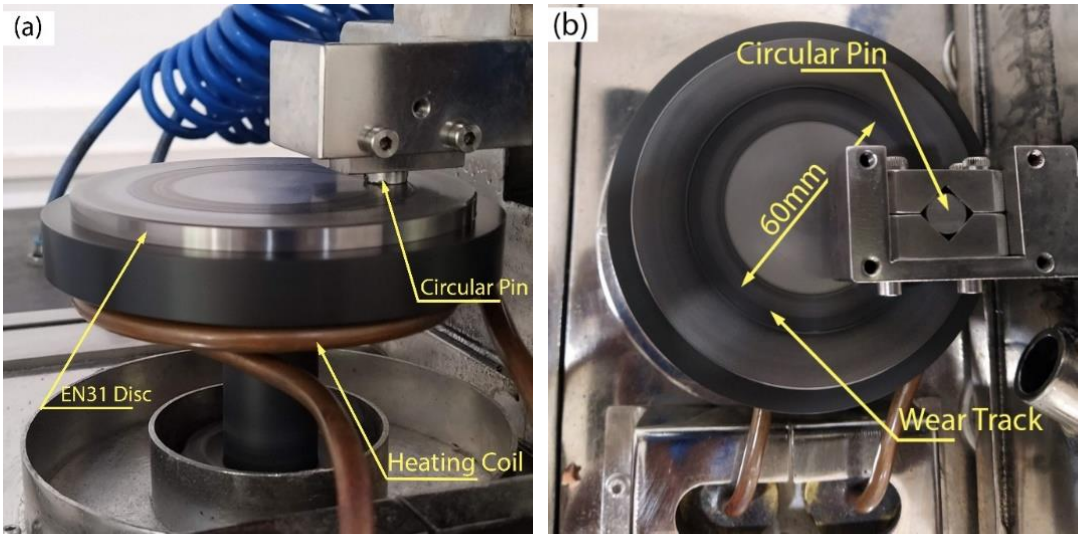

Fig. 3. 4 Wear test Set-up (a) Front view (b) Top View

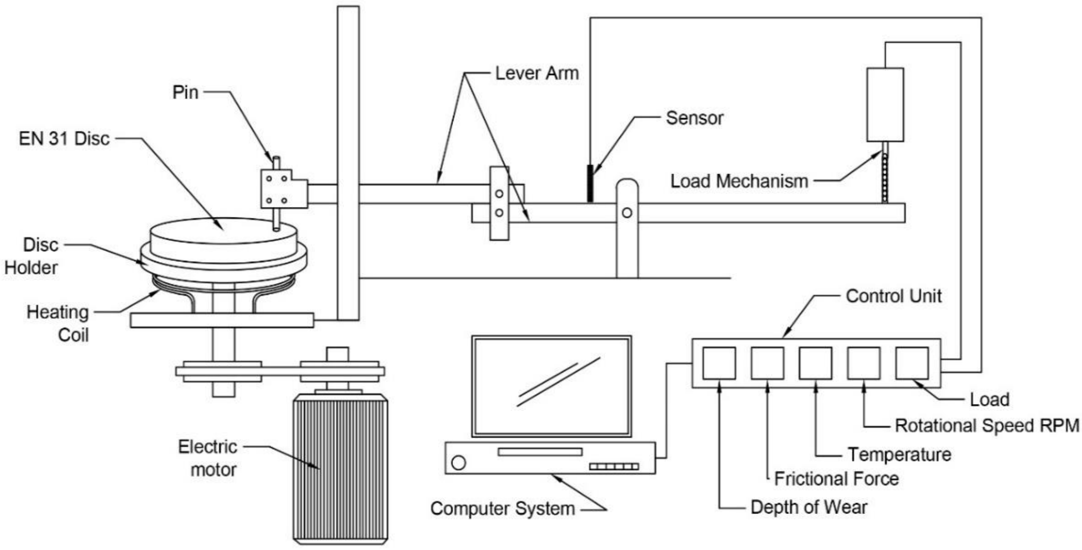

Fig. 3. 5 Schematic diagram of Pin-on-disc machine

Friction force was measured from the controller and wear can be expressed as weight loss in grams. To measure the weight loss of the specimen, the weight of the specimen was taken before and after each experiment with an electronic weighing scale with an accuracy of 0.0001g. The win Ducom software was used to record the data and display the results. In this paper, COF and wear of Al alloy lubricated with CPO was studied with different loads and compared with Commercially available petroleum-based oil SAE20W40.

The parameters used in this experiment are shown in Table 3.2. Wear track diameter of the disc set to 60mm. The proper load was given to the system lever which presses down the pin against the disc. The present experiment was done on five different loads 10 N, 50 N, 100 N, 150 N and 200 N with a constant speed of 3m/s. The rotational speed of the machine was set to 955 rpm, which makes a sliding distance of 10800 m, on running the test continuously for 60 minutes. The Ducom instrumentation and data acquisition were used to measure friction force and wear for all the test lubricants. The surface of the worn specimen was cleaned gently with acetone and observed using a microscope. Since the hardness of the EN31 disc was far higher than the Al alloy pin, so the wear volume is very small. So, the wear properties of the disc were not studied.

Table 3. 2 Test parameters used in this experiment

Test parameters	**Areal contact tests**
Temperature	28°C and 100°C
Load	10 N, 50 N, 100 N, 150 N, 200 N
Wear track diameter	60 mm
Duration	60 min
Speed	3 m/s
RPM	955
Sliding distance	10800 m

CHAPTER 4: RESULT AND DISCUSSION

4.1 Rheological properties of CPO

Fig. 4.1 (a) shows the bio-lubricant which was extracted from Cucurbita pepo L. seed and Fig. 4.1 (b) shows the mineral-based commercial oil SAE20W40. The yield of the bio-lubricant Cucurbita pepo L. seed oil (CPO) was found to be 13.5% which is similar to the yield of 12% reported by Shahangir *et al.*, (2015) [8].

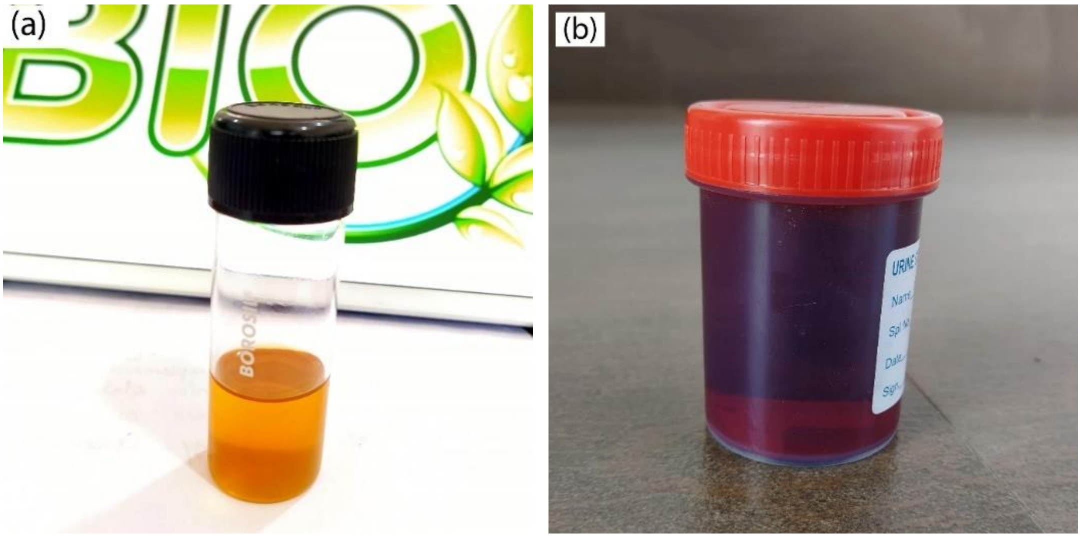

Fig. 4. 1 (a) Cucurbita pepo L. seed oil (CPO) and (b) SAE20W40 Engine oil

The rheological properties of the investigated oils are listed in Table 4.1. The viscosity of CPO was found as 54.17 mm^2/s at 40°C and 11.36 mm^2/s at 100°C whereas, the viscosity of SAE20W40 was found as 121.88 mm^2/s at 40°C and 14.2 mm^2/s at 100°C. It is observed that the viscosity of CPO is comparable with commercial SAE20W40 lubricants at 100°C. However, the viscosity of CPO is observed lower than the viscosity of SAE20W40 at 40°C. From Table 4.1 it is clear that there is a slight variation in viscosity of CPO at higher temperatures compared to that of commercially available oil SAE20W40. If the viscosity of the oil lies between 5-10 mm^2/s at 100°C, then it can be used in industrial applications [45].

Table 4. 1 Rheological Properties of CPO and SAE 20W40

Oil Type	Kinematic Viscosity (mm^2/s) at 40°C	Kinematic Viscosity (mm^2/s) at 100°C	Viscosity Index
Cucurbita pepo L. seed oil (CPO)	54.17	11.36	180
SAE 20W40	121.88	14.2	116

The viscosity index of CPO was found to be 180 whereas, the viscosity index of SAE20W40 was found to be 116 which is significantly less than the bio-lubricant CPO. The viscosity index (VI) of an oil is the ability to resist change in viscosity with change in temperatures. So higher VI means a lesser change in viscosity with increasing temperature. The higher VI of CPO shows higher lubricating film stability at a higher temperature compared to the commercial lubricant SAE20W40.

4.2 Frictional Behaviour

Experiments were conducted to find out the frictional behaviour of Al alloy lubricated with CPO and compare with SAE20W40 engine oil at room temperature (28°C) and higher temperature (100°C).

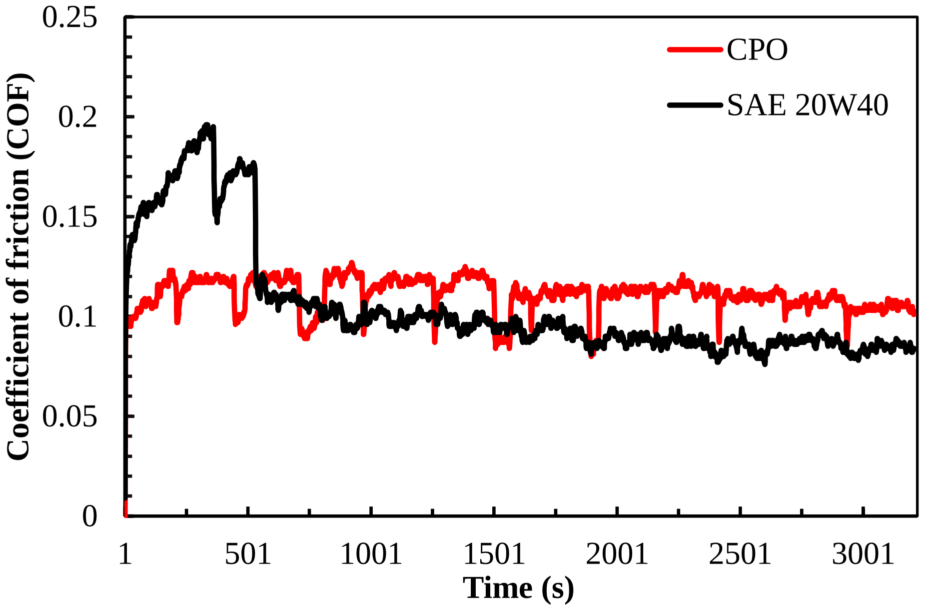

Fig. 4. 2 Variation of coefficient of friction with time for 10 N load at 28°C

Fig.4.2 shows the variation of friction with respect to time for 10 N load at room temperature (28°C). For load 10 N the maximum value of mean COF was recorded pin lubricated with CPO as 0.11 and minimum value of mean COF was recorded pin lubricated with SAE20W40 as 0.09 at room temperature (28 °C). From this graph it is seen that during initial run there is significant variation of COF but after some time the COF become steady state up to the end. This is because at initial condition the roughness of the sliding pair generates additional frictional force. At the same time at initial run the lubricating film can't be developed sufficiently thus by breaking up the deposit layer and clean metallic surface comes in contact which increases the bonding force between the contacting surfaces [9]. After a certain duration of rubbing the friction surface become smooth and the other parameters reach steady state condition and the variation of coefficient of friction stops and become constant for rest of the time for this experiment.

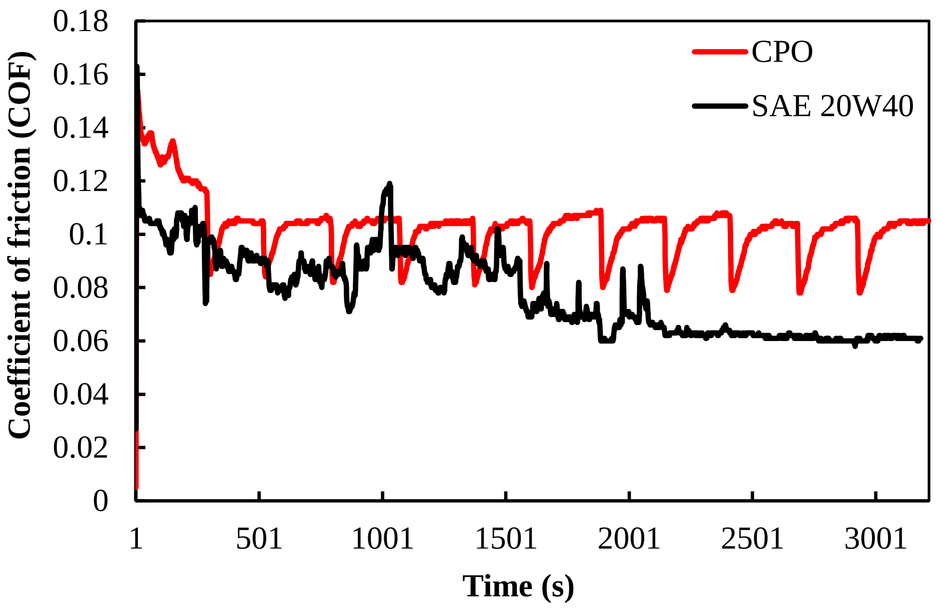

Fig. 4. 3 Variation of coefficient of friction with time for 50 N load at 28°C

Fig. 4.3 shows the variation of COF for 50 N load at room temperature (28°C). For the load 50 N the maximum mean value of COF is recorded for pin lubricated with CPO as 0.10 and the minimum mean value of COF is recorded as 0.07 for pin lubricated with SAE20W40. The curves in this graph also shows similar trend as shown by the curve in Fig. 4.2, first it varies initially then it follows steady state for rest of the time but in this case, it takes less time to become steady state then previous experiment.

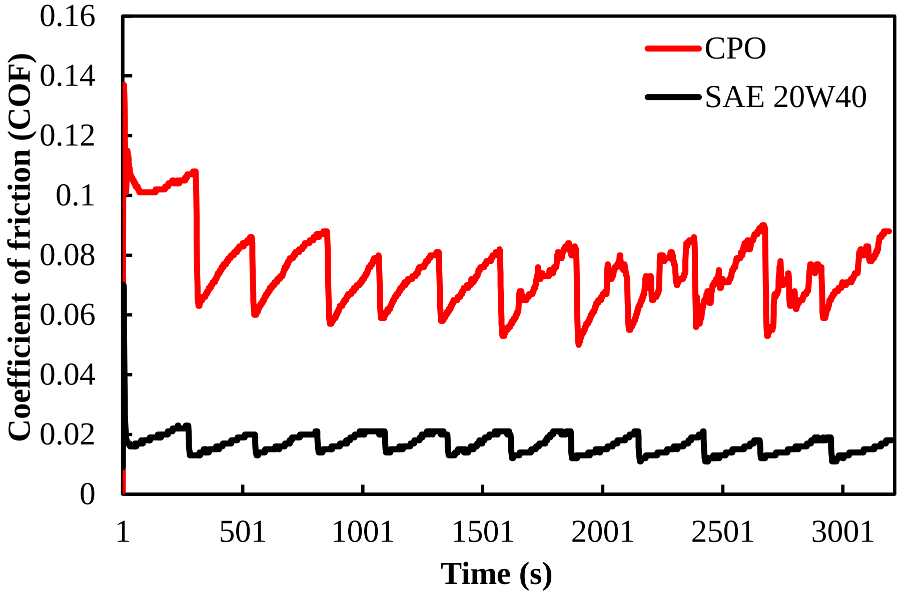

Fig. 4. 4 Variation of coefficient of friction with time for 100 N load at 28°C

Fig. 4.4 is drawn to show the variation of COF with duration of rubbing at 100 N load at room temperature (28°C). Then for load 100 N the maximum mean value of COF is 0.08 for CPO and minimum value of COF is 0.02 for pin lubricated with SAE20W40. The curves in this graph also shows similar trend as shown by the previous figures. First it varies for some time then it became constant for rest of the time, but in this case, it takes less time to become steady state then previous experiments.

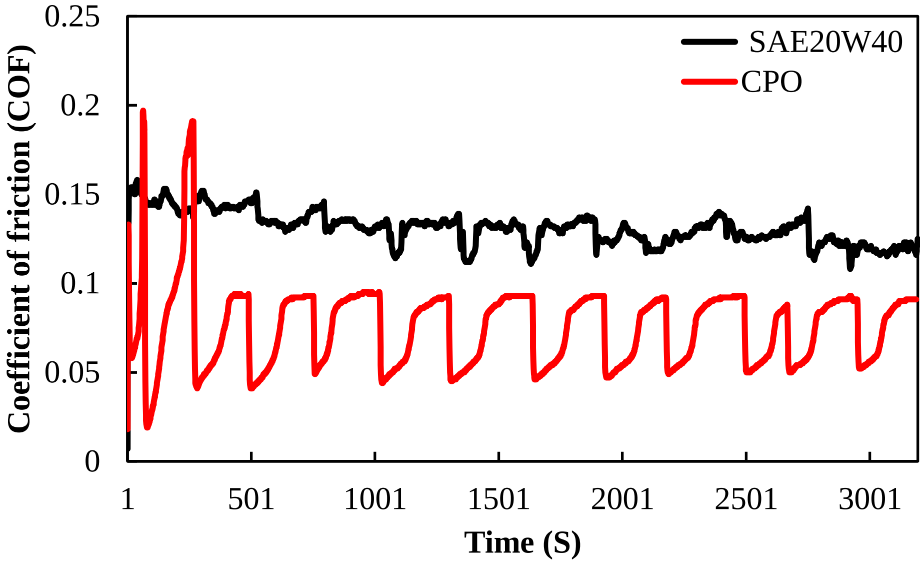

Fig. 4. 5 Variation of coefficient of friction with time for 150 N load at 28°C

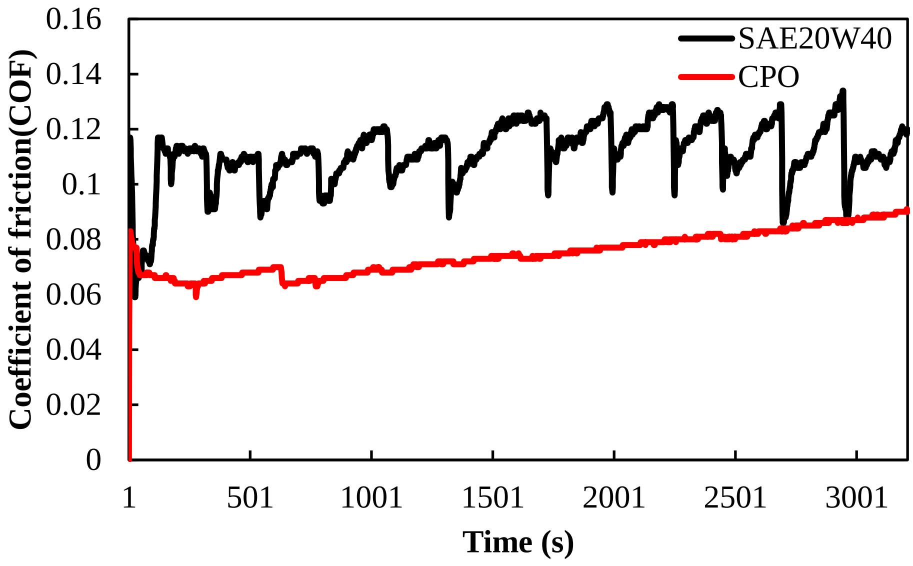

Fig. 4. 6 Variation of coefficient of friction with time for 200 N load at 28°C

Fig. 4.5 and Fig. 4.6 shows the friction variation for 150 N and 200 N respectively at room temperature (28°C). For load 150 N the mean value of coefficient of friction of was 0.075 and 0.13 for Cucurbita pepo L oil and SAE20W40 respectively at 28°C. In construct, the average COF value was 0.07 and 0.11 for a pin lubricated with CPO and engine oil respectively at normal load 200 N. From this graph it is seen that there is no significant variation of COF till the end of the experiment. For the normal load 150 N and 200 N the coefficient of friction of SAE20W40 was higher than the coefficient of friction of CPO.

From these figures it was observed that the curve become steady state at different time for different load conditions. The result shows that at normal load 10 N, 50 N, 100 N, 150, 200 N COF takes almost 600s, 300s, 275s, 250s and 150s respectively to become constant. That is higher the normal load, COF takes lesser time to stabilize [39]. There is a sudden drop and rise in coefficient of friction every 5 min because the lubrication was provided between the contact surface of the pin and disc at a time interval of 5 min.

Fig. 4.7 shows the frictional behaviour of Al alloy lubricated with CPO and SAE20W40 for different loads at room temperature (28°C). It is observed that in the case of CPO, the coefficient of friction (COF) decreases with an increase in normal load from 10 N to 200 N. These results strongly suggest that the COF is inversely proportional to the applied load. The COF decreases as the load increases because of changes in the shear rate [5]. The decline in COF may also occur due to the increased surface roughing and a large quantity of wear debris[17]. During friction, the top layer of the pin gets destroyed and forms wear debris. On applying a higher load this wear debris might break into smaller pieces and roll over between the contact surface of the pin and disc specimen thus reducing the instantaneous COF [46]. The maximum and minimum values of the COF in the case of CPO were recorded as 0.11 and 0.07 at 10 N and 200 N loads.

In the case of SAE20W40, it's observed that the COF initially decreases up to a certain limit of applied load (i.e. from 10 – 100 N) and then it increases. It may be because at lower load (i.e. from 10 – 100 N) COF decreases due to the development of wear debris and roll-over between contact surfaces. As the load increases the wear debris layer keeps increasing until it reaches critical thickness and breaks. As layer breaks, metal-to-metal contact occurs and COF increases for higher loads (150 N and 200 N) [40]. The increase in disc temperature, viscous damping of the friction surface, and higher adhesion due to micro-welding or deformation or hardening of the material might have some effect on the increase in the COF of SAE20W40 engine oil[17]. The lowest and highest values of the COF in the case of SAE20W40 were recorded as 0.09 and 0.13 at 10 N and 150 N loads.

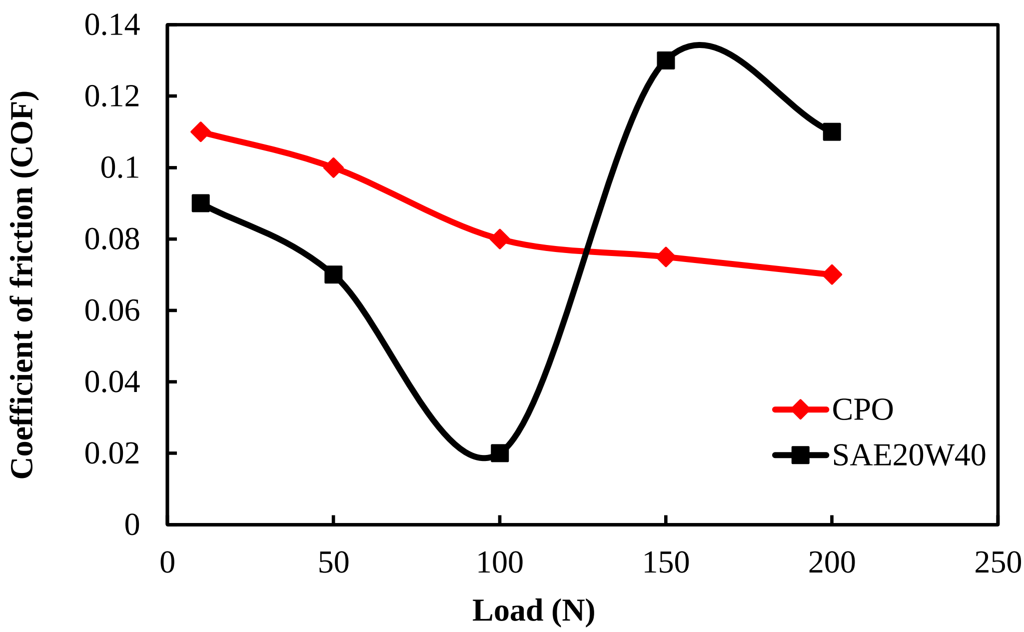

Fig. 4. 7 Variations of mean coefficient of friction with the increase in load for different Lubricants at 28°C

It is observed that SAE20W40 produced the lowest value of COF compared to CPO for lower loads (10 N, 50 N and 100 N). This is because when a lubricant (CPO) has lower viscosity it produces a thin lubricating film, which increases the possibility of direct surface contact between the moving parts and increases the friction force [5]. Whereas, the SAE20W40 produced the highest value of COF compared to CPO for higher loads (150 N and 200 N). This may be because SAE20W40 having a lower viscosity index may not be able to form a stable lubricating layer at a higher load which increases the chances of metal-to-metal contact which increases the adhesion strength and results in the increase in COF [1], [39].

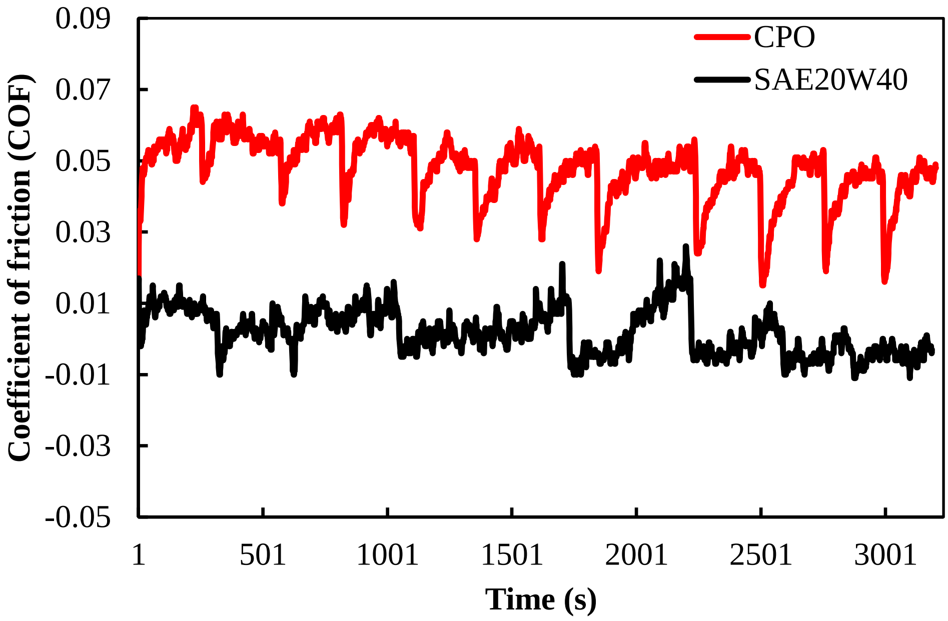

Fig. 4. 8 Variation of coefficient of friction with time for 10 N load at 100°C

Fig. 4.8 shows the variation of friction with respect to duration of experiment for 10 N load when the lower specimen (disc) was heated to 100°C. For load 10 Newton at 100°C the average coefficient of friction recorded 0.05 and 0.01 when the pain was lubricated with CPO and SAE20W40 engine oil respectively. From the figure it is clear that the coefficient of friction of CPO is higher than the coefficient of friction of SAE20W40 this is because the SAE20W40 engine oil has high viscosity then CPO so SAE20W40 produces thicker layer does by decreasing the coefficient of friction. In the this Fig. 4.8 sudden drop in coefficient of friction in every five minute is observed for both the lubricant because when the lubricating oil was given to the disc it formed a fresh lubricating layer thus reducing the coefficient of friction instantly.

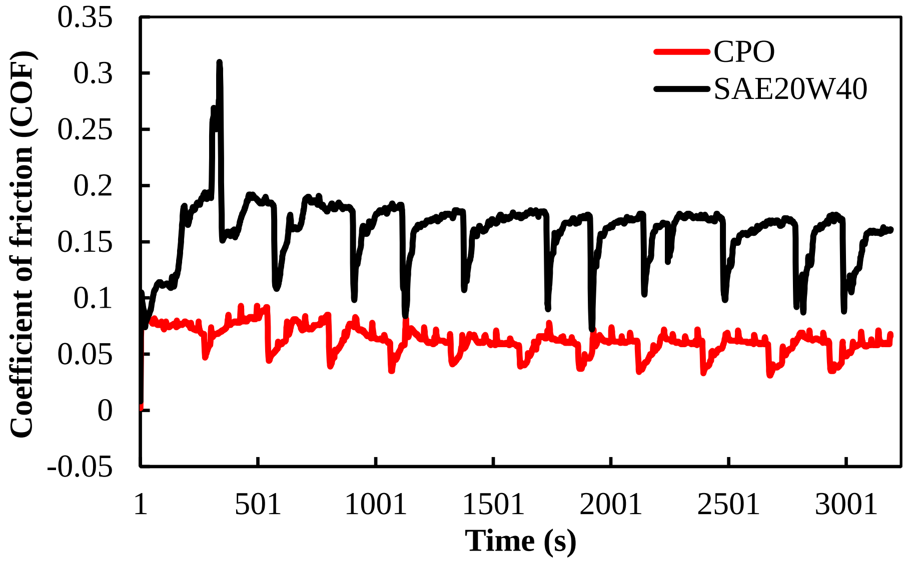

Fig. 4. 9 Variation of coefficient of friction with time for 50 N load at 100°C

Fig. 4.9 shows the effect of duration of rubbing on the COF for 50 N load at 100°C. The coefficient of friction of pin lubricated with CPO and SAE20W40 is 0.075 and 0.18. The coefficient of friction of pin lubricated with SAE20W40 is higher than the pin lubricated CPO. The curve in this graph shows a steady state flow of COF through the whole experiment, it shows decrease in coefficient of friction only during addition of lubricant, because of fresh lubricant layer formation.

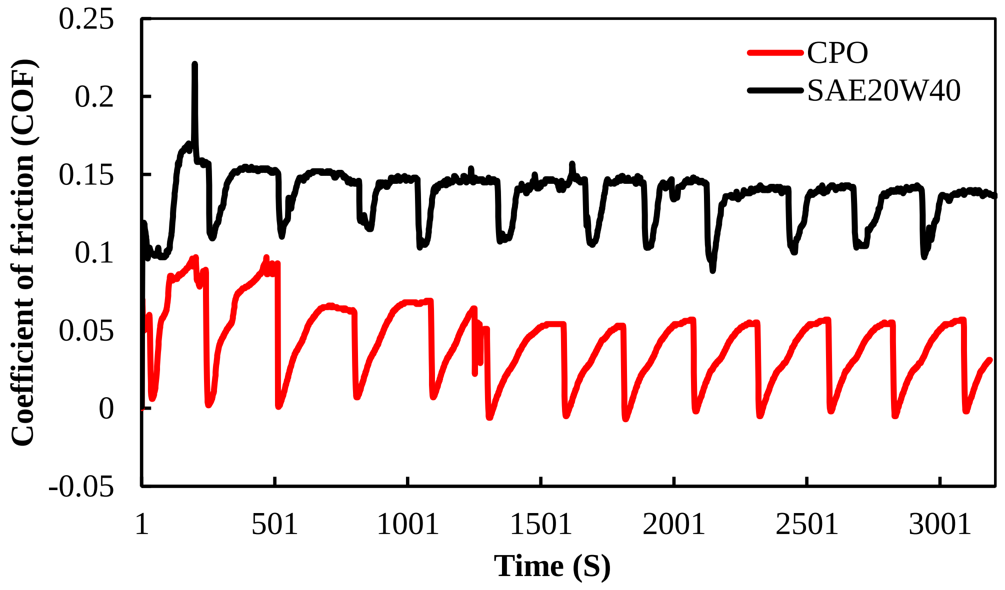

Fig. 4. 10 Variation of coefficient of friction with time for 100 N load at 100°C

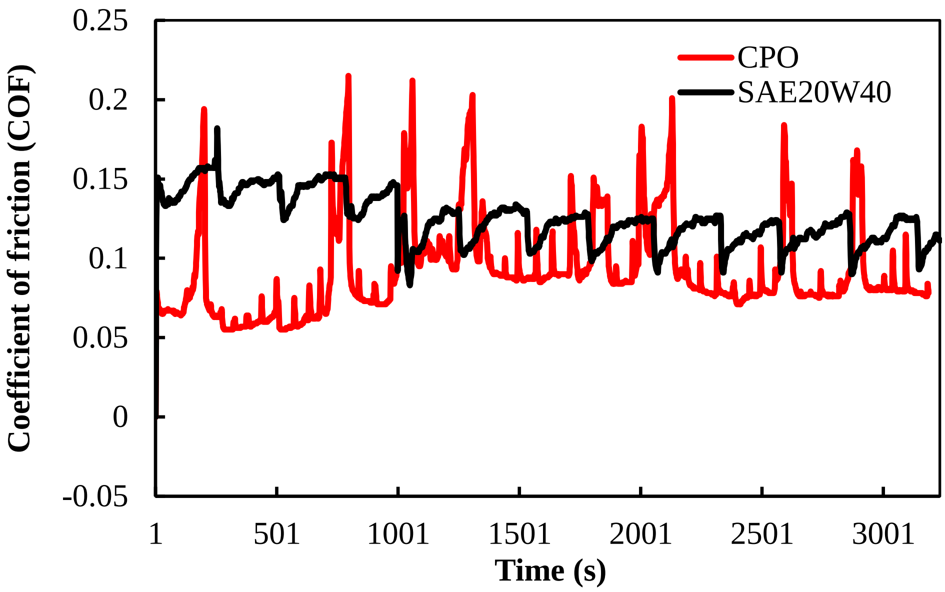

Fig. 4. 11 Variation of coefficient of friction with time for 150 N load at 100°C

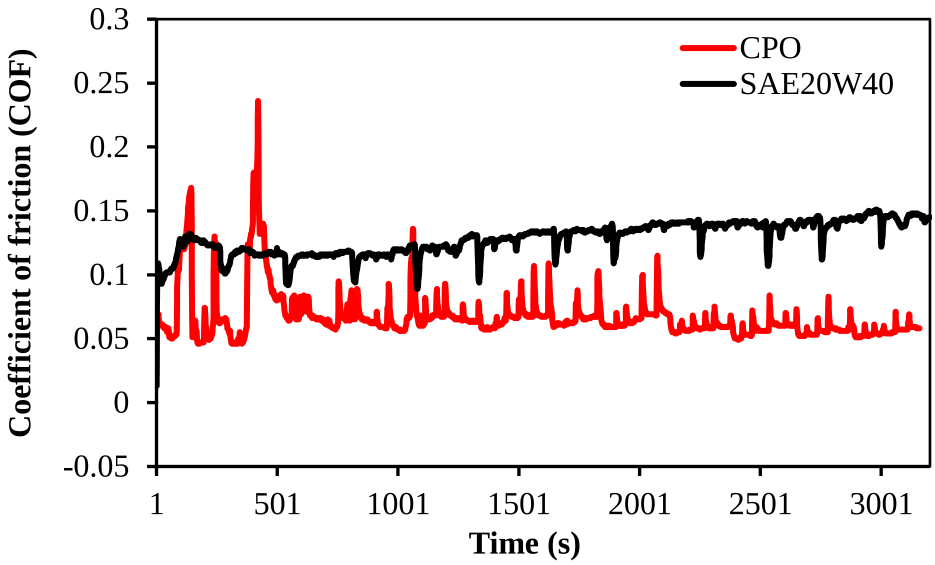

Fig. 4. 12 Variation of coefficient of friction with time for 200 N load at 100°C

Fig. 4.10, Fig. 4.11 and Fig. 4.12 show the friction variation for 100 N, 150 N and 200 N respectively at 100 °C. For load 100 N the average value of the coefficient of friction was 0.05 and 0.15 for CPO and SAE20W40 respectively at 100°C. The coefficient of friction value for 150 N load was 0.07 and 0.14 for CPO and SAE20W40 respectively. In construct, the average COF value was 0.06 and 0.13 for a pin lubricated with CPO and engine oil respectively at a normal load of 200 N. From this graph, it is clear that there is a variation in COF initially but after some time the curve becomes steady state till the end of experiments. For the normal load 100 N, 150 N and 200 N the coefficient of friction of SAE20W40 was slightly higher than the coefficient of friction of CPO.

Fig. 4.13 shows the frictional behaviour of Al alloy lubricated with CPO and SAE20W40 for different loads at 100°C. In the case of CPO, it is observed that the value of the COF remains similar for different loads. It may be because there is not sufficient change in the viscosity of the lubricant for different loads at 100°C due to its higher viscosity index. The maximum and minimum values of the COF in the case of CPO were recorded as 0.075 for both 50 N and 150 N load and 0.05 for both 10 N and 100 N load, respectively.

It is observed for SAE20W40, COF initially increases from 0.01 to 0.18 when the load increases from 10 N to 50 N. Further increasing the load to 100 N, the COF minorly decreases to 0.15 and remains almost uniform up to an increase in load to 200 N. This may be because at a lower load (10 N) a good lubrication layer formed between the contact surfaces of specimens, resulting in a lower value of COF [5]. But in the case of applied higher loads (50 N, 100 N, 150 N and 200 N), due to the increase in disc temperature, viscous damping of the friction surface and higher adhesion may result in the higher COF for SAE20W40 [17]. The maximum and minimum values of COF in the case of SAE20W40 were recorded as 0.18 and 0.01 at 50 N and 10 N loads, respectively.

It is observed that at a higher load, CPO with a higher viscosity index has a lower value of COF compared to SAE20W40 at 100°C. This indicates that CPO compared to the commercial-based lubricant SAE20W40 have higher lubricating film stability at higher temperature [1].

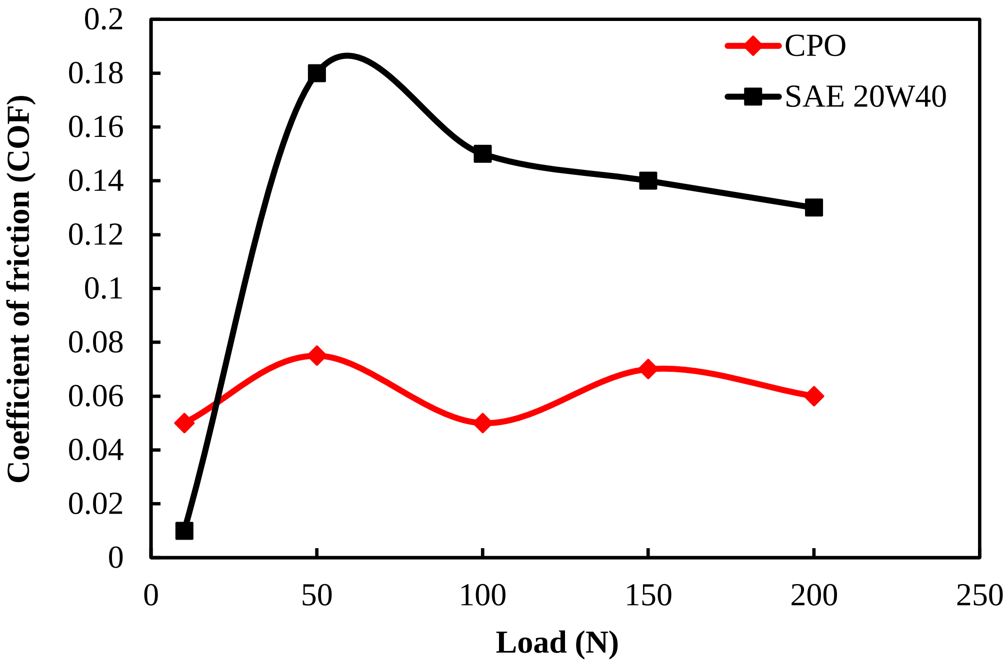

Fig. 4. 13 Variations of mean coefficient of friction with the increase in load for different Lubricants at 100°C

From Fig. 4.7 and Fig. 4.13, it is observed that for CPO, the average COF decreased with an increase in temperature. This may be due to the development of a compact wear debris layer on contact surfaces [40]. Pearson *et al.*, (2013) [47] also suggested that the COF decreases with a temperature rise may be because of the way that the oxide particles are sintered to form a protective wear debris bed. Whereas in the case of SAE20W40, it is observed that the average COF increased with an increase in temperature. It may be because of the thermal softening of the pin specimen and increased adhesion[40]. SAE20W40 has low viscosity index due to which the viscosity decreases with an increase in temperature and the lubricating layer becomes thinner which increases the chances of metal-to-metal contact thus increasing the COF [1].

4.3 Wear Behaviour

The variation of wear with time is shown for 10 N, 50 N and 100 N loads in Fig 4.14, Fig. 4.15 and Fig. 4.16 respectively at room temperature (28°C). When the lubricant is applied between the surface then a lube layer is formed, which prevents direct contact between the surface thus reducing the wear. In this experiment, heat is generated due to the rubbing of the pin and disc, which results in the elongation of the pin. The pin-on-disc testing machine measures the changes in the length of the specimen, normally due to wear the length of the pin decreases so the wear is shown as positive, but in this case decrease in length due to wear is less than the increase in length due to the heat generated. So, the overall length of the pin increases with time and the wear is shown as negative (-ve). So, the graph plotline having less negative value has a higher wear rate. From Fig. 4.14, Fig. 4.15, and Fig. 4.16 it can be seen that the wear rate is similar for pin lubricated with CPO and SAE20W40.

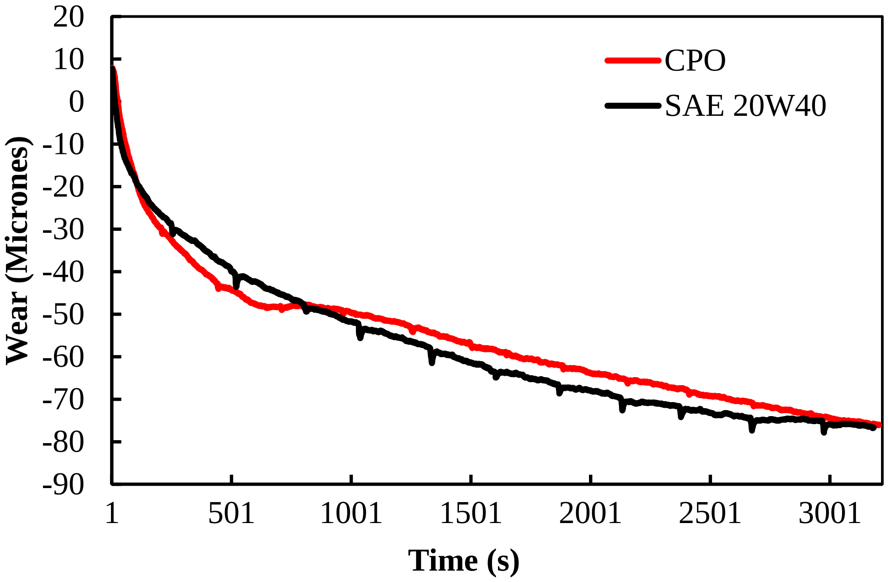

Fig. 4. 14 Variation of wear with time for 10 N load at room temperature (28°C)

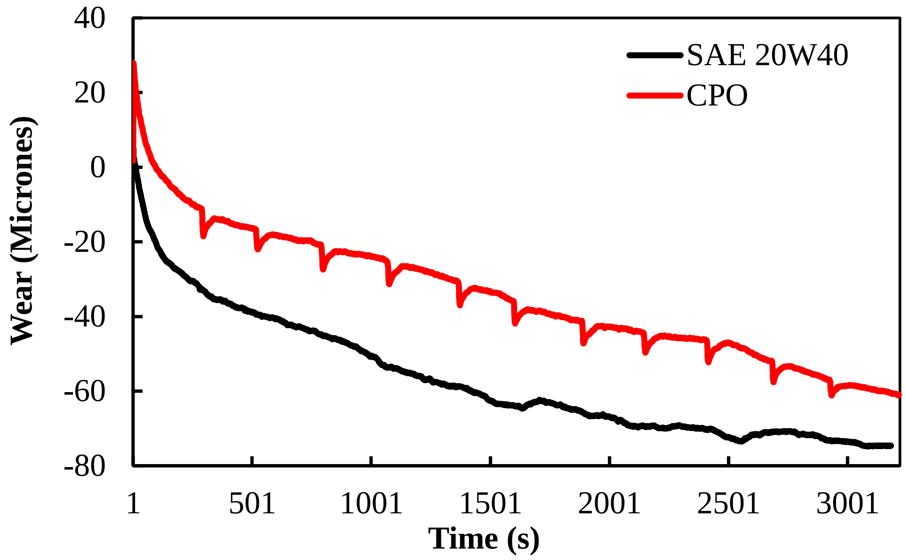

Fig. 4. 15 Variation of wear with time for 50 N load at room temperature (28°C)

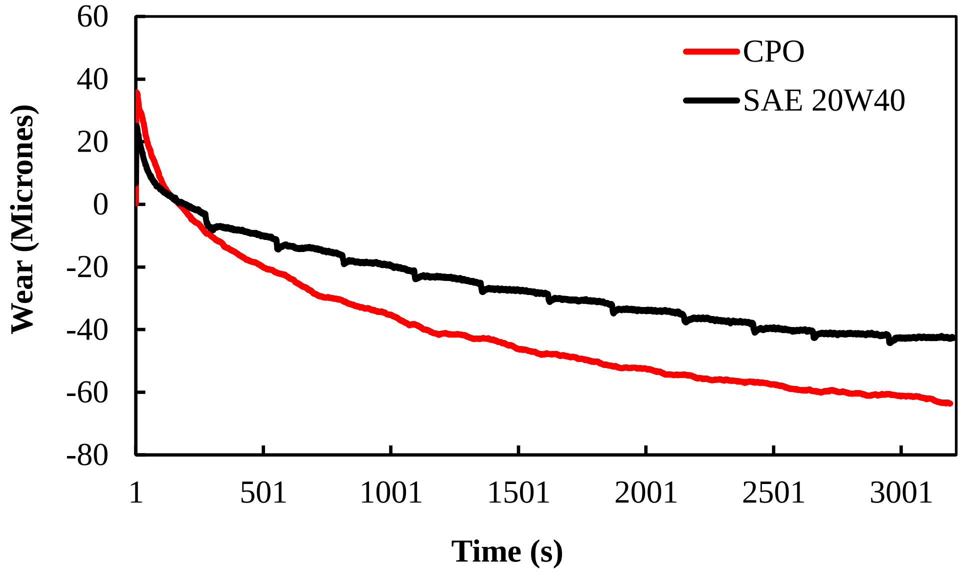

Fig. 4. 16 Variation of wear with time for 100 N load at room temperature (28°C)

The variation of instantaneous wear with time is shown in Fig. 4.17 and Fig. 4.18 for an applied load of 150 N and 200 N respectively at room temperature (28°C). Fig. 4.17 and Fig. 4.18 clearly show that the pin lubricated with SAE20W40 has a higher wear rate compared to the pin lubricated with CPO.

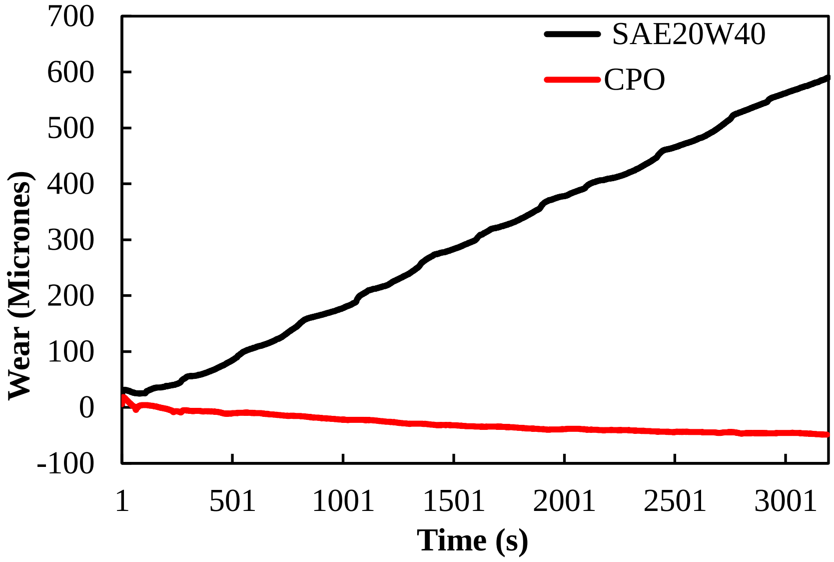

Fig. 4. 17 Variation of wear with time for 150 N load at room temperature (28°C)

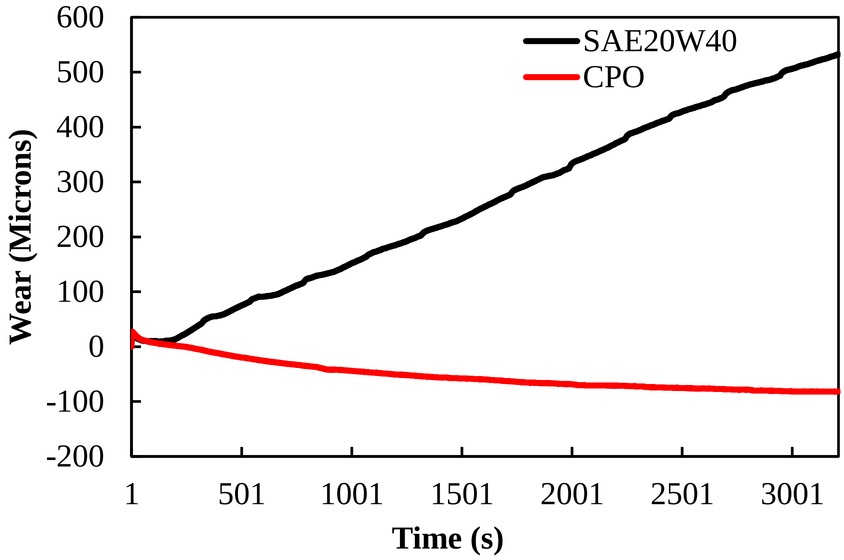

Fig. 4. 18 Variation of wear with time for 200 N load at room temperature (28°C)

From experimental data, it is clear that CPO and engine oil perform similarly at 10 N, 50 N and 100 N applied load, but in the case of the 150 N and 200 N applied load, the wear in pin lubricated with SAE20W40 increases drastically. It might be because of higher load conditions the lubricating film layer of SAE20W40 break down because it has lower VI which results in direct metal-to-metal contact increasing wear [1]. A good lubricant is expected to reduce the wear rate. In this study, at lower load, both the lubricant performs similarly but CPO performs better than mineral-based oil SAE20W40 in higher load conditions.

Fig. 4.19 Shows the variation of instantaneous wear (microns) during rubbing of pin and disc for 10 N load, 3m/s speed and at a temperature of 100°C. From the curve, it is clear that the wear for the pin lubricated with CPO was higher than the pin lubricated with SAE20W40 engine oil. The wear curve goes in a negative direction because the decrease in the length of the pin due to loss of metal from the contact surface is less than the increase in length due to heat.

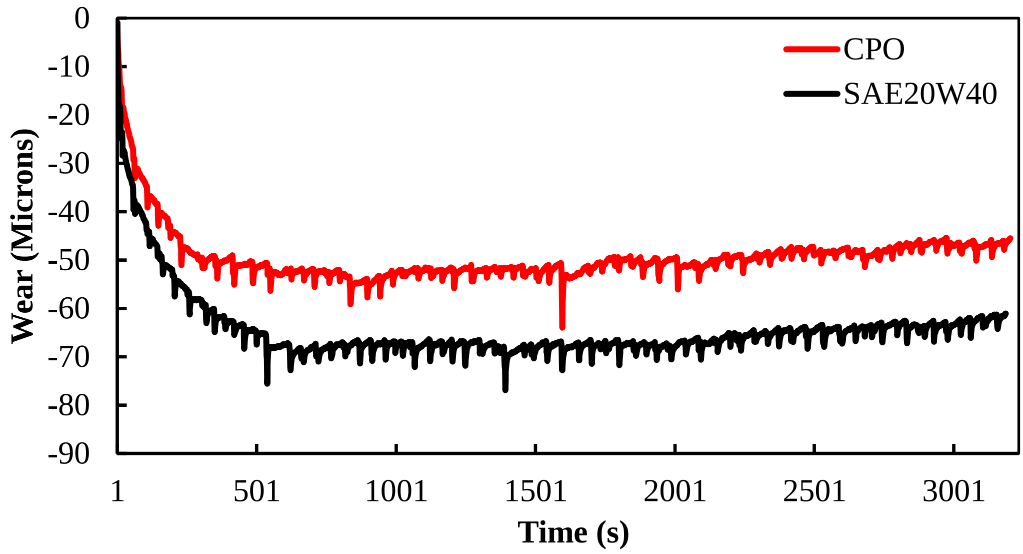

Fig. 4. 19 Variation of wear with time for 10 N load at 100°C

Fig. 4.20, Fig. 4.21, Fig. 4.22 and Fig. 4.23 show the variation of instantaneous wear (microns) concerning the duration of rubbing for 50 N, 100 N, 150 N and 200 N applied load at a higher temperature (100°C). Those results show that the wear rate of the pin lubricated with SAE20W40 was higher than the pin lubricated with CPO for the loads 50-200 N. The VI for CPO was higher than the SAE20W40 engine oil. So, with an increase in temperature, the change in viscosity for CPO is less compared to mineral-based oil. With the increase in temperature and load the mineral-based lubricant SAE20W40 gets thinner and metal-to-metal contact occurs and the wear gets increased gradually. But in the case of CPO which maintains a thicker lubricating layer compared to SAE20W40 because of higher VI even in higher temperatures and loads thus reducing the wear rate. It is seen that with the increase in loads the wear rate increases.

This is because with the increase in load increases the frictional heat generation and plastic deformation appear due to the thermal softening of the material [40]. Hence strength of the material decreases and the wear rate increases with an increase in load [17].

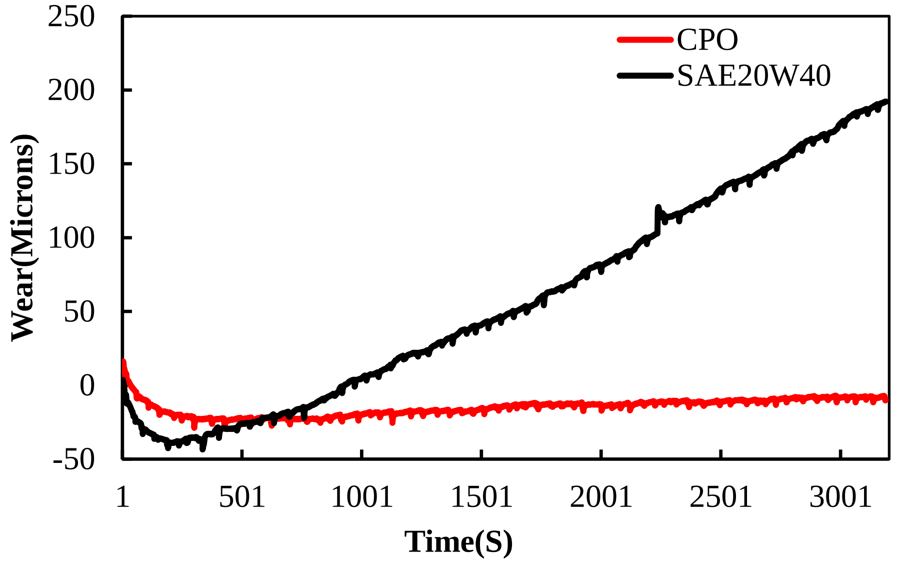

Fig. 4. 20 Variation of wear with time for 50 N load at 100°C

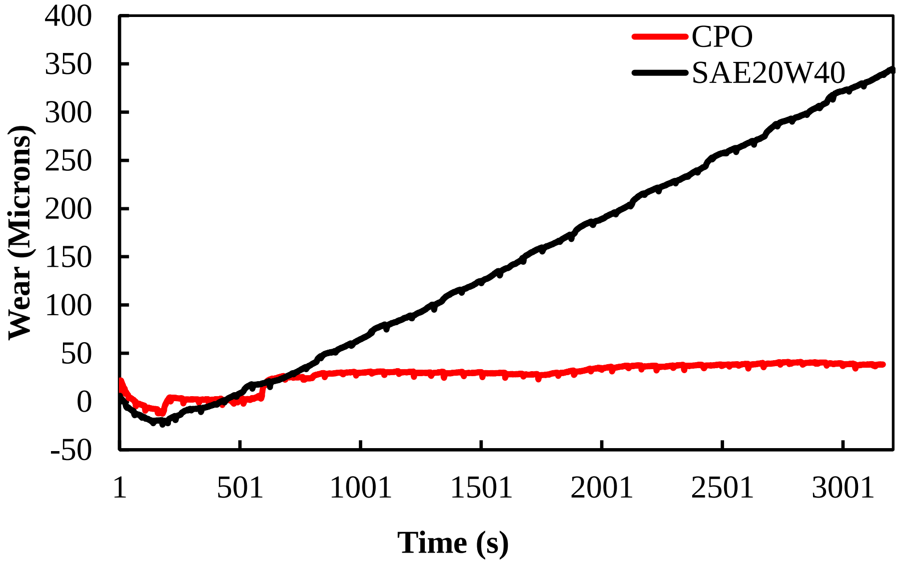

Fig. 4. 21 Variation of wear with time for 100 N load at 100°C

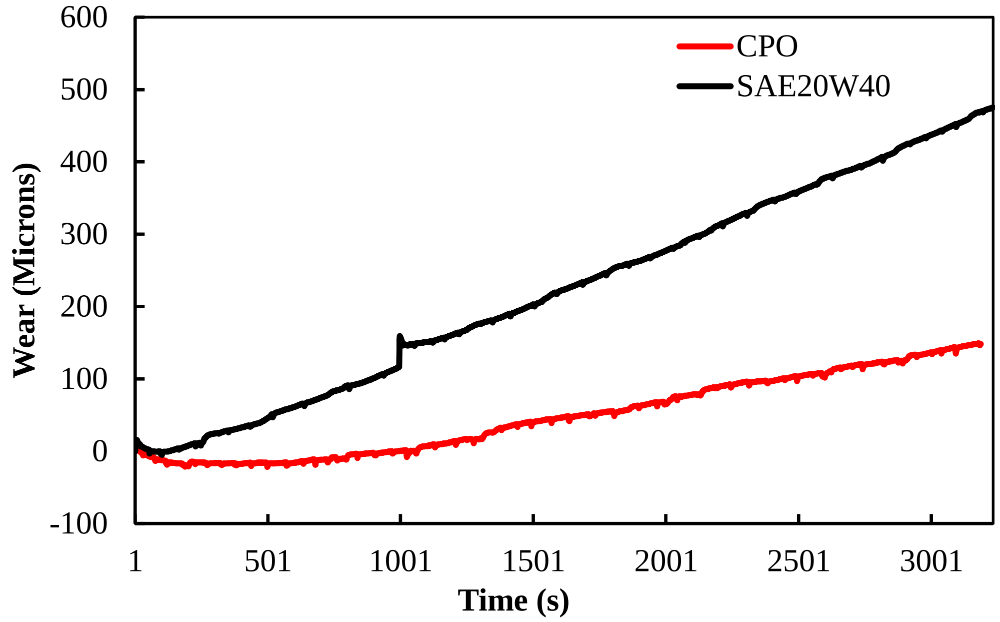

Fig. 4. 22 Variation of wear with time for 150 N load at 100°C

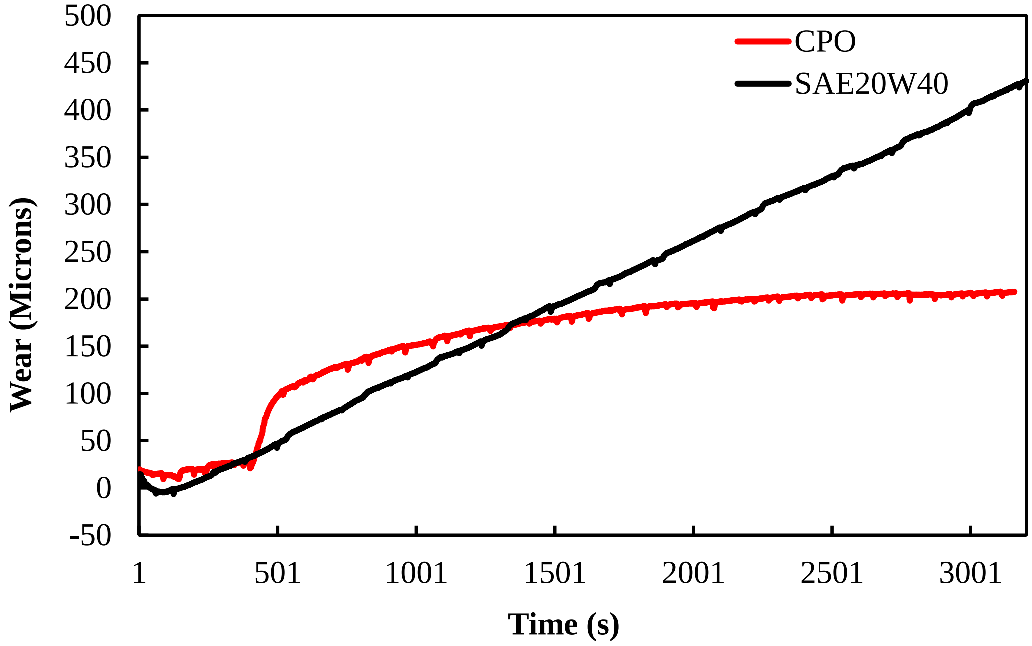

Fig. 4. 23 Variation of wear with time for 200 N load at 100°C

4.4 Weight loss of the Pin

The wear in this experiment is measured as weight loss in (g). Fig. 4.24 shows the comparison of weight loss of specimens lubricated with CPO and SAE 20W40 at a temperature of 28°C and 100°C under various loading conditions. When tested at room temperature (28°C) and loads (10 N, 50 N and 100 N), no significant difference in the wear resistance is observed when lubricated with CPO and SAE20W40. However, at higher loads (150 N and 200 N) a significant difference in the wear resistance is observed when lubricated with CPO and SAE20W40. At higher loads, the wear resistance is observed to improve when lubricated with CPO. Similarly, at high temperature (100°C) also CPO showed improved wear resistance when tested under 50 N, 100 N, 150 N and 200 N loads. At all conditions, it is seen that the wear rate increases with the increase in loads. This is because the increase in normal load increases the frictional heat generation at contact surfaces and plastic deformation appears due to thermal softening [40]. Hence strength of the material decreases and the wear rate increases [17].

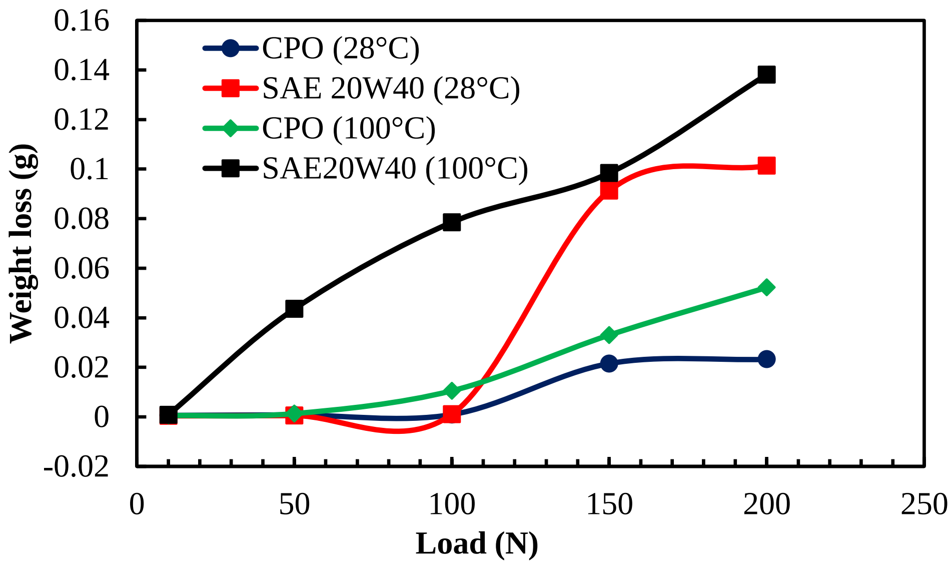

Fig. 4. 24 Increment in weight loss with an increase in loads for different lubricants

Considering the effect of temperature on wear rate, it is seen that the wear rate increases with an increase in temperature. This may be because of increased adhesion of contact surfaces and thermal softening of the specimen. These changes in wear mechanisms are explained by [40]. Moreover, the viscosity index of CPO is observed to be higher than SAE20W40, resulting in higher stability of CPO tribo films at a higher temperature [1]. Hence, at a higher temperature, a significant improvement in wear resistance is observed when lubricated with CPO than SAE20W40.

4.5 Examination of the worn Surface

The microscopic images of worn surfaces for pin lubricated with CPO and SAE20W40 are shown in Fig. 4.25-4.28 at various loads and temperatures. It can be observed from the microscopic image in Fig. 4.25-4.28 that a lot of parallel, continuous and deep plunging groups exist on the wear surface of the pinned specimen. From Fig. 4.25 and Fig. 4.26 it is clear that the surface of the specimen becomes smoother as the load increases (from 10 N to 200 N) for the pin lubricated with CPO and SAE20W40 at 28°C. This may have occurred due to the increased surface roughing and the top layer of the pin gets destroyed and forms wear debris. On applying a higher load this wear debris might break into smaller pieces and roll over between the contact surface of the pin and disc specimen and making the surface smooth [46].

From Fig. 4.27 and Fig. 4.28, it is observed that there is no significant effect of load on surface roughness of pin lubricated with CPO in comparison to SAE20W40 at 100°C. Some cracks and removal of materials from the contact surface of the pin specimen are observed when lubricated with CPO for loads 10 N and 50 N at 100°C. In the case of SAE20W40, the surface roughness of the pin remains almost similar for a lower applied load (10 N, 50 N and 100 N), but as the load increases (150 N and 200 N) the surface becomes rough. This may be because with increases in load adhesion force increases and micro-welding occurs which results in a rough surface[17]. It is observed that the wear scares in the surface lubricated with CPO show a smoother surface compared to the pin lubricated with SAE20W40 at both temperatures of 28°C and 100°C. The greater the wear scares the worse the lubricity[5]. This indicates that CPO has better lubricity compared to mineral-based SAE20W40.

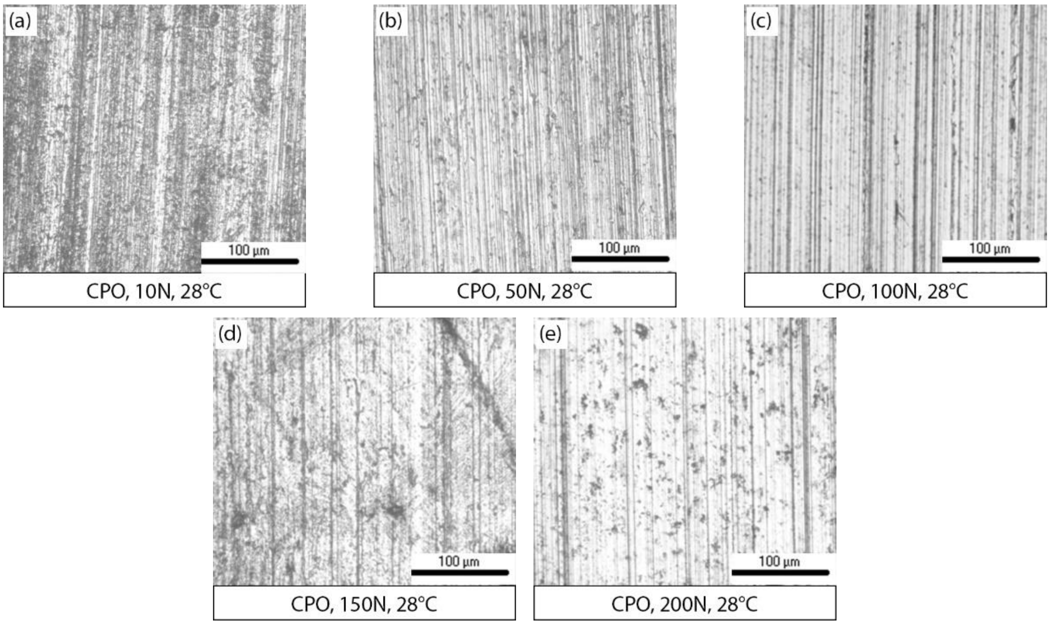

Fig. 4. 25 Optical microscopic images of worn surfaces of pin Lubricated with CPO at different loads at 28°C

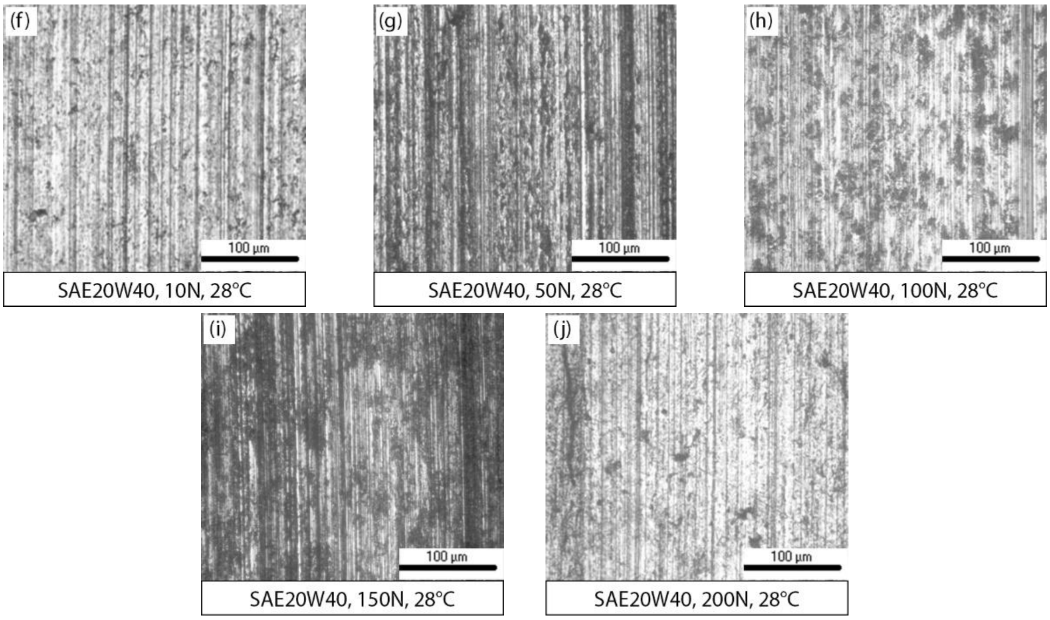

Fig. 4. 26 Optical microscopic images of worn surfaces of pin Lubricated with SAE20W40 at different loads at 28°C

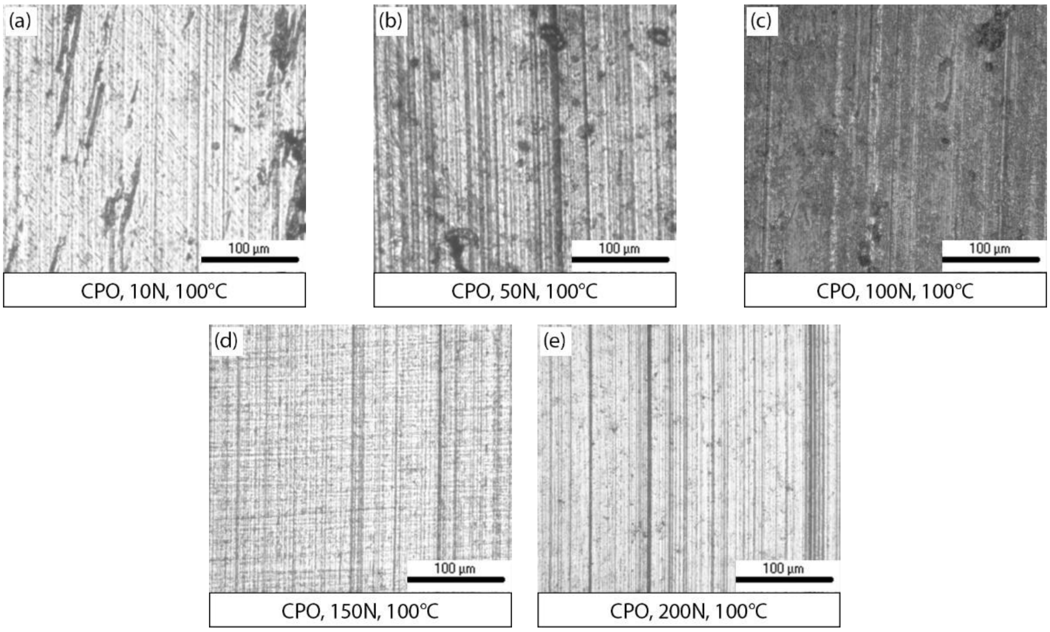

Fig. 4. 27 Optical microscopic images of worn surfaces of pin Lubricated with CPO at different loads at 100°C

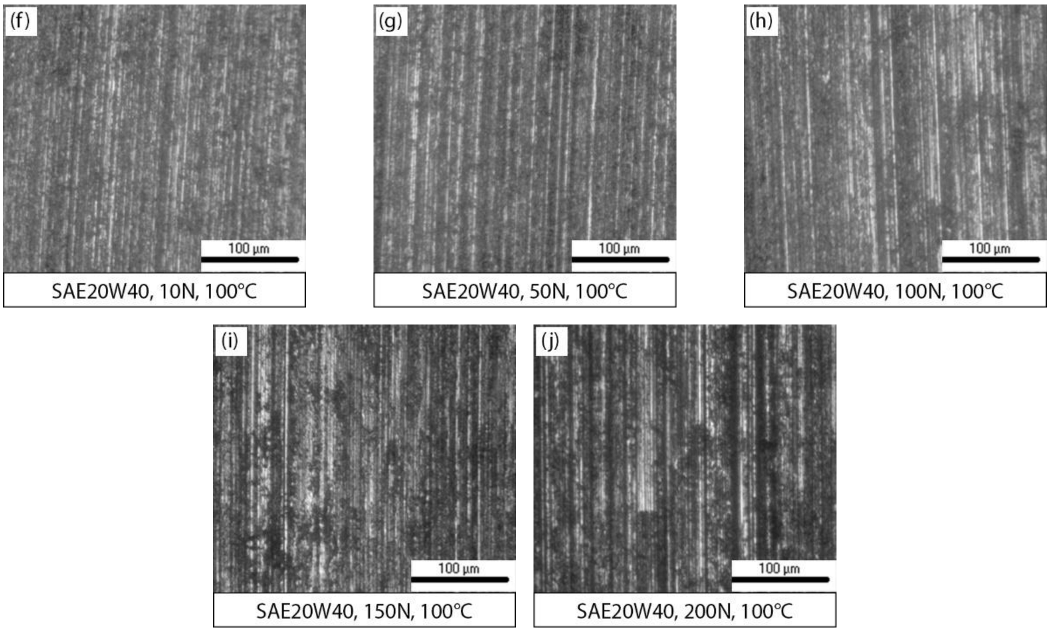

Fig. 4. 28 Optical microscopic images of worn surfaces of pin Lubricated with SAE20W40 at different loads at 100°C

CHAPTER 5: SUMMARY AND CONCLUSION

Based on the results that were obtained from this experiment, it can be said the applied load and temperature influence tribological properties (friction and wear). The following conclusions could be drawn.

1) It is observed that the COF decreases as the load increases.
2) The wear rate increases with the increase in loads and temperature.
3) The wear rate is less for pin lubricated with CPO compared to SAE20W40.
4) The wear scars in the surface lubricated with CPO show a smoother surface compared to the pin lubricated with SAE20W40 at both temperatures of 28°C and 100°C. This shows that CPO has better lubricity than SAE20W40.
5) The present work thus indicates that CPO can be a potential alternative to mineral-based lubricant SAE20W40 for higher-temperature workplaces.

BIBLIOGRAPHY

[1] N. D. Choudhury, N. Saha, S. Bhaumik, and R. Kataki, "Production and evaluation of physicochemical, rheological, and tribological properties of Cucurbita pepo L. seed oil," *Biomass Conversion and Biorefinery 2021*, pp. 1–14, Jan. 2021, doi: 10.1007/S13399-020-01236-5.

[2] M. Husnawan, M. G. Saifullah, and H. H. Masjuki, "Development of friction force model for mineral oil basestock containing palm olein and antiwear additive," *Tribology International*, vol. 40, no. 1, pp. 74–81, Jan. 2007, doi: 10.1016/J.TRIBOINT.2006.02.062.

[3] J. McNutt and Q. S. He, "Development of biolubricants from vegetable oils via chemical modification," *Journal of Industrial and Engineering Chemistry*, vol. 36, pp. 1–12, Apr. 2016, doi: 10.1016/J.JIEC.2016.02.008.

[4] A. M. Liaquat, M. A. Kalam, H. H. Masjuki, and M. H. Jayed, "Potential emissions reduction in road transport sector using biofuel in developing countries," *Atmospheric Environment*, vol. 44, no. 32, pp. 3869–3877, Oct. 2010, doi: 10.1016/J.ATMOSENV.2010.07.003.

[5] N. Nuraliza, S. Syahrullail, and M. H. Faizal, "Tribological properties of aluminum lubricated with palm olein at different load using pin-on-disk machine," *Jurnal Tribologi*, vol. 9, pp. 45–59, 2016.

[6] N. H. Jayadas and K. P. Nair, "Coconut oil as base oil for industrial lubricants-evaluation and modification of thermal, oxidative and low temperature properties," *Tribology International*, vol. 39, no. 9, pp. 873–878, Sep. 2006, doi: 10.1016/J.TRIBOINT.2005.06.006.

[7] B. Bikash, N. D. Choudhury, D. K. Bora, and K. Kalita, "Physicochemical Assessment of Pumpkin (L.) Seed Oil as a Viable Feedstock for Biodiesel Production," pp. 19–28, 2018, doi: 10.1007/978-981-10-6107-3_2.

[8] A. H. Shahangir, "Nutritional and Lipid Composition Analysis of Pumpkin Seed (Cucurbita maxima Linn.)," *Journal of Nutrition & Food Sciences*, vol. 05, no. 04, 2015, doi: 10.4172/2155-9600.1000374.

[9] H. K. Trivedi and D. v. Bhatt, “Effect of lubricating oil on tribological behaviour in pin on disc test rig,” *Tribology in Industry*, vol. 39, no. 1, pp. 90–99, 2017, doi: 10.24874/TI.2017.39.01.10.

[10] V. Aleksandar and R. Aleksandar, “Tribological Behaviour of Al-Based Mmcs and Their Application in Automotive Industry,” *Tribology in industry*, vol. 26, 2004.

[11] M. Baruah and A. Borah, “On the enhancement of wear resistance of Al-Mg-Si alloy via micro-alloying Sn,” *Sādhanā*, vol. 46, no. 3, Sep. 2021, doi: 10.1007/S12046-021-01655-8.

[12] S. Kar, B. B. Sahu, H. Kousaka, J. G. Han, and M. Hori, “Study of the effect of normal load on friction coefficient and wear properties of CNx thin films,” *AIP Advances*, vol. 10, no. 6, p. 065214, Jun. 2020, doi: 10.1063/5.0009783.

[13] I. Srinivasula Reddy and V. Kaliveeran, “Dry sliding friction and wear of Al 6061 and Al 6082 alloys under different normal loads,” *Materials Today: Proceedings*, vol. 27, pp. 2631–2634, Jan. 2020, doi: 10.1016/J.MATPR.2019.11.080.

[14] T. Mishra, M. de Rooij, and D. J. Schipper, “The effect of asperity geometry on the wear behaviour in sliding of an elliptical asperity,” *Wear*, vol. 470–471, p. 203615, Apr. 2021, doi: 10.1016/J.WEAR.2021.203615.

[15] S. Ding, J. Xu, P. Liu, Z. Shi, O. Yang, and Y. Hu, “Geometric influence on friction and wear performance of cast iron with a micro-dimpled surface,” *Results in Engineering*, vol. 9, p. 100211, Mar. 2021, doi: 10.1016/J.RINENG.2021.100211.

[16] Y. Zhou, H. Zhu, W. Zhang, X. Zuo, Y. Li, and J. Yang, “Influence of surface roughness on the friction property of textured surface Introduction,” *Advances in Mechanical Engineering*, 2015, doi: 10.1177/1687814014568500.

[17] M. A. Chowdhury, M. K. Khalil, D. M. Nuruzzaman, and M. L. Rahaman, “The Effect of Sliding Speed and Normal Load on Friction and Wear Property of Aluminum,” *International journal of Mechanical and Mechatronics Engineering*, vol. 11, no. 01, 2011, Accessed: May 29, 2022, doi=10.1.1.369.1903

[18] A. Pauschitz, M. Roy, and F. Franek, “Mechanisms of sliding wear of metals and alloys at elevated temperatures,” *Tribology International*, vol. 41, no. 7, pp. 584–602, Jul. 2008, doi: 10.1016/J.TRIBOINT.2007.10.003.

[19] F. E. Kennedy, Y. Lu, and I. Baker, “Contact temperatures and their influence on wear during pin-on-disk tribotesting,” *Tribology International*, vol. 82, no. PB, pp. 534–542, Feb. 2015, doi: 10.1016/J.TRIBOINT.2013.10.022.

[20] Z. Chen, X. He, C. Xiao, and S. H. Kim, “Effect of humidity on friction and Wear-A critical review,” *Lubricants*, vol. 6, no. 3, 2018, doi: 10.3390/LUBRICANTS6030074.

[21] M. Wahyudi, R. Ismail, and J. Jamari, “Friction and Wear Analysis of UHMWPE Material Using Pin-on-Disc Tester with Lubricant and Non-Lubricant,” *Journal of Physics: Conference Series*, vol. 1569, no. 3, Jul. 2020, doi: 10.1088/1742-6596/1569/3/032057.

[22] A. Shanaghi, A. R. Souri, V. Chaturvedi, U. Pandel, and A. Sharma, “Effect of mechanical vibrations on the wear behavior of AZ91 Mg alloy ,” *Material Science and Engineering*, 2018, doi: 10.1088/1757-899X/314/1/012030.

[23] B. L. A. Prabhavathi Devi, T. V. K. Reddy, and M. F. Mohd Yusoff, “Ionic Liquids in the Production of Biodiesel and Other Oleochemicals,” *Ionic Liquids in Lipid Processing and Analysis: Opportunities and Challenges*, pp. 373–401, Feb. 2016, doi: 10.1016/B978-1-63067-047-4.00012-X.

[24] M. Shahabuddin, H. H. Masjuki, M. A. Kalam, M. M. K. Bhuiya, and H. Mehat, “Comparative tribological investigation of bio-lubricant formulated from a non-edible oil source (Jatropha oil),” *Industrial Crops and Products*, vol. 47, pp. 323–330, May 2013, doi: 10.1016/J.INDCROP.2013.03.026.

[25] U. C. Sharma, G. Anand, S. Krishna, P. Kuchhal, N. S. Krishna, and S. Sachan, “Rheology of Karanja (Pongamia) Oil Based Biolubricant,” pp. 203–208, 2017, doi: 10.1007/978-3-319-47257-7_18.

[26] A. Vasishth, P. Kuchhal, and G. Anand, “Study of Rheological Properties of Industrial Lubricants,” *Conference Papers in Science*, vol. 2014, pp. 1–5, May 2014, doi: 10.1155/2014/324615.

[27] C. Sharma, G. Shyam Sundar, H. K. Babu, S. M. Sitale, and S. B. S, "Experimental Study on The Use of Neem Oil as Lubricant in IC Engine," *International Research Journal of Engineering and Technology*, 2017.

[28] E. Sneha, R. B. Akhil, A. Krishna, S. Rani, and S. A. Kumar, "Formulation of bio-lubricant based on modified rice bran oil with stearic acid as an anti-wear additive," *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, vol. 235, no. 9, pp. 1950–1957, Sep. 2021, doi: 10.1177/1350650120977381.

[29] X. Wu, X. Zhang, S. Yang, H. Chen, and D. Wang, "Study of epoxidized rapeseed oil used as a potential biodegradable lubricant," *JAOCS, Journal of the American Oil Chemists' Society*, vol. 77, no. 5, pp. 561–563, 2000, doi: 10.1007/S11746-000-0089-2.

[30] I. N. Dibal, P. C. Okonkwo, and I. Haruna, "Production of biolubricant from castor oil," *Society of Petroleum Engineers - Nigeria Annual International Conference and Exhibition 2017*, pp. 1297–1304, 2017, doi: 10.2118/189183-MS.

[31] S. Dixit, S. Kanakraj, and A. Rehman, "Linseed oil as a potential resource for bio-diesel: A review," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 7, pp. 4415–4421, Sep. 2012, doi: 10.1016/J.RSER.2012.04.042.

[32] A. N. Annisa and W. Widayat, "A Review of Bio-lubricant Production from Vegetable Oils Using Esterification Transesterification Process," *MATEC Web of Conferences*, vol. 156, Mar. 2018, doi: 10.1051/MATECCONF/201815606007.

[33] A. E. Atabani *et al.*, "Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production," *Renewable and Sustainable Energy Reviews*, vol. 18, pp. 211–245, Feb. 2013, doi: 10.1016/J.RSER.2012.10.013.

[34] J. D. Leao *et al.*, "New formulations of sunflower based bio-lubricants with high oleic acid content - VOSOLUB project," *OCL - Oilseeds and fats, Crops and Lipids*, vol. 2016, 2016, doi: 10.1051/OCL/2016033.

[35] N. H. Jayadas and K. P. Nair, “Coconut oil as bio lubricant- study of the anti-wear properties using quantum chemical calculations and tribological tests,” *Proceedings of the World Tribology Congress III - 2005*, pp. 513–514, 2005, doi: 10.1115/WTC2005-63786.

[36] A. Z. Syahir *et al.*, “A review on bio-based lubricants and their applications,” *Journal of Cleaner Production*, vol. 168, pp. 997–1016, Dec. 2017, doi: 10.1016/J.JCLEPRO.2017.09.106.

[37] “Editorial Board,” *Applied Catalysis B: Environmental*, vol. 142–143, p. CO2, Oct. 2013, doi: 10.1016/S0926-3373(13)00477-3.

[38] H. K. Trivedi and D. v. Bhatt, “Effect of lubricating oil on tribological behaviour in pin on disc test rig,” *Tribology in Industry*, vol. 39, no. 1, pp. 90–99, 2017, doi: 10.24874/TI.2017.39.01.10.

[39] D. Muhammad Nuruzzaman and M. Asaduzzaman Chowdhury, “Effect of Load and Sliding Velocity on Friction Coefficient of Aluminum Sliding Against Different Pin Materials,” *American Journal of Materials Science*, vol. 2, no. 1, pp. 26–31, Feb. 2012, doi: 10.5923/J.MATERIALS.20120201.05.

[40] S. Mozgovoy, J. Hardell, L. Deng, M. Oldenburg, and B. Prakash, “Effect of temperature on friction and wear of prehardened tool steel during sliding against 22MnB5 steel,” *Tribology - Materials, Surfaces and Interfaces*, vol. 8, no. 2, pp. 65–73, Jun. 2014, doi: 10.1179/1751584X13Y.0000000056.

[41] M.A. Kalam, H.H. Masjuki, and A.M. Liaquat, “Friction and wear characteristics of waste vegetable oil contaminated lubricants,” *International Journal Of Mechanical And Material Engineering*, 2011.

[42] G. Straffelini, M. Pellizzari, and A. Molinari, “Influence of load and temperature on the dry sliding behaviour of Al-based metal-matrix-composites against friction material,” *Wear*, vol. 256, no. 7–8, pp. 754–763, Apr. 2004, doi: 10.1016/S0043-1648(03)00529-5.

[43] M. Prasanna Kumar and S. B. Kanakuppi Sadashivappa, “Dry Sliding Wear Behaviour of Garnet Particles Reinforced Zinc-Aluminium Alloy Metal Matrix Composites,” *Metarial Science*, 2006.

[44] S. R. Pearson, P. H. Shipway, J. O. Abere, and R. A. A. Hewitt, “The effect of temperature on wear and friction of a high strength steel in fretting,” *Wear*, vol. 303, no. 1–2, pp. 622–631, Jun. 2013, doi: 10.1016/J.WEAR.2013.03.048.

[45] M. Gul, H. H. Masjuki, M. A. Kalam, N. W. M. Zulkifli, and M. A. Mujtaba, “A Review: Role of Fatty Acids Composition in Characterizing Potential Feedstock for Sustainable Green Lubricants by Advance Transesterification Process and its Global as Well as Pakistani Prospective,” *BioEnergy Research 2019 13:1*, vol. 13, no. 1, pp. 1–22, Oct. 2019, doi: 10.1007/S12155-019-10040-7.

[46] H. Shi, S. Du, C. Sun, C. Song, Z. Yang, and Y. Zhang, “Behavior of Wear Debris and Its Action Mechanism on the Tribological Properties of Medium-Carbon Steel with Magnetic Field,” *Materials (Basel)*, vol. 12, no. 1, Dec. 2018, doi: 10.3390/MA12010045.

[47] S. R. Pearson, P. H. Shipway, J. O. Abere, and R. A. A. Hewitt, “The effect of temperature on wear and friction of a high strength steel in fretting,” *Wear*, vol. 303, no. 1–2, pp. 622–631, Jun. 2013, doi: 10.1016/J.WEAR.2013.03.048.