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Tribological Characterisation of Biofluid using Four Ball Experiment

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ABSTRACT

This project study about the tribological characterisation of biofluid that used plant-based oil which namely sunflower oil and olive oil that been blends with hyaluronic acid as an additive. Plant-based oil is a type fluid that not be harmful to human and the hyaluronic acid helps the based fluid in absorption shock and distribution of forces. This project aims to measure the performance of this biofluid acts as an artificial synovial fluid in term of its coefficient of friction, frictional torque and the wear scar diameter produced. There are three different composition volumes of hyaluronic acid going to be used which are 0%, 5% and 10% in the fluid sample. This sample of biofluid going to be tested by using four ball tribological testing under one of the conditions which was wear preventive condition to obtain the coefficient of friction and frictional torque for the biofluid while by using the 3D Surface Measurement Systems was to measure the wear scar diameter produced at the ball bearings. The result that been acquired for this study which are the average coefficient of friction and frictional torque were directly proportional to the volume composition of additives. However, for the average wear scar diameter, it depends on the suitability of volume additives been added. Pure Sunflower oil has lowest coefficient of friction which is 0.065940. While, for average wear scar diameter, Olive oil with 10% hyaluronic acid recorded the lowest value which is 0.64828mm. It shows that pure plant-based oil having the best lubricant ability which is producing lower coefficient of friction and frictional torque compared to it going to be blend with hyaluronic acid. This result of this project might give benefits to the medical engineering nowadays that related to the case that need the usage of artificial synovial fluid.

1. Introduction

Synovial fluid is one of the main biofluid in human body. It contains physiologic serum, hyaluronic acid, proteins which are albumin and globulin and also lipids [1]. Synovial liquid is created as a ultrafiltrate of blood plasma and is fundamentally made out of hyaluronan, lubricin, proteinase, collagenases and prostaglandins. This fluid help to ensure the smoothness of our joint motion in the body and could absorb shock. According to the medical dictionary, synovial fluid is a clear thixotropic fluid that serves as a lubricant in joints. At sub-atmospheric pressures of about 50 µm, the fluid forms

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a thin microscopic layer of fluid on the surface of cartilage, filling all joint empty spaces [2]. In addition, synovial fluid also acts as natural lubrication in human body that could reduce friction in any movement of our body joint such as knee and hip. However, composition of synovial fluid could increase if the people adopt the healthy diet which is by taking the food that contains a lot of good nutrients. Synovial fluid producing a layer of membrane between the fluid and inner articular cartilage. This membrane plays it important responsibility to manage the joint movement in our body and pressure of the cartilage [3,4]. The membrane layer or film also could be destructed when extreme pressure such as high force and temperature been applied to this synovial fluid. However, Osteoarthritis affects to the failure of the synovial fluid in human joint to maintain its functions in human joint such as knee caused by smaller volume of the synovial fluid been degenerating in the joint such in Figure 1 [5]. As a result, Osteoarthritis causes the patients suffering in musculoskeletal disorders, pain and mobility limitations, lowering the patient's independence and overall quality of life. In Osteoarthritis, hyaluronic acid is easily broken down, resulting of decreasing the effectiveness in the viscous and elastic characteristics of synovial fluid [6]. Therefore, the synovial fluid for the human that suffering this type of disease has lower viscosity compared to the normal viscosity that resulting in reducing the volume composition [7]. From Figure 1, it clearly could be seen that the volume of synovial for healthy joint is greater than the person that facing Osteoarthritis. This type of disease usually attacked to the group of older people.

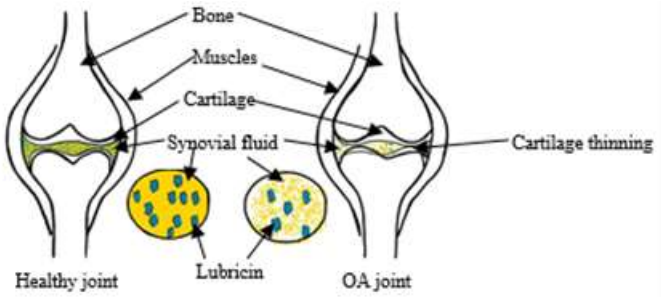


Fig. 1. Comparison volume of synovial fluid

From the observation, many medical industries nowadays were treating this type of disease by injecting the high volume of hyaluronic acid into the articular cartilage that only helps to reduce the pain [8,9]. However, some of the patients who suffering this type of disease was having allergies with the high concentration of hyaluronic acid. This going to make the patient facing another type of disease in their body such as pseudogout [10,11]. Due to the high price of the high concentration of hyaluronic acid in the global market, the medical industry is looking forward the new ways to overcome this problem [12]. Other than the hyaluronic acid, the combination of alginic sodium acid and lambda-carrageenan could be use as the additives because it gives the smaller value coefficient of friction and been tested by using pin on disc experiment comparing with the one type of additive only [13]. Since there are many demands in the medical sector to help implement the artificial synovial fluid, immediate research and work needs to be run to achieve the objective. Unfortunately, there is still a smaller number of researchers that study regarding the usage of plant-based oil as biofluid for replacement of the synovial fluid in human body joint. In order to produce the artificial synovial fluid, the biofluid with the less viscosity need to be used to produce less friction between the biofluid and the articular cartilage in human joint. This type of biofluid could be replaced by using the plant-based oil that having lower viscosity such as olive and sunflower oil as a based medium and it going to blend with suitable additives such as hyaluronic acid that could produce the membrane layer at the cartilage. Furthermore, the pure plant-based oil is not containing any harmful substances and suits with human body [14]. The presence of suitable additives leads to the success of artificial

synovial fluid caused it could increase the viscosity of the biofluid until achieve the best viscosity that reliable to the actual synovial fluid. In past review states that the increasing viscosity going to decrease the shear rate of the biofluid [15,16].

Sunflower seed oil is the non-unstable oil crushed from seeds of sunflower (Helianthus annuus) [17]. Sunflower oil regularly contains 69 percent linoleic acid, 20 percent oleic acid and 11 percent saturated fatty acids, but a variety of strategies have been used to present an advanced range of sunflower oils with increased oleic acid, stearic acid, linoleic acid, palmitic acid and low saturated acid [18,19]. It also viewed as plentiful in minerals like magnesium, iron, copper, calcium, zinc, sodium, potassium, phosphorus, selenium and manganese [20]. These fundamental unsaturated fats are pivotal in cell film development and for support of body formative exercises [21,22]. In research, it was found that the sunflower oil facing the transition phase to form the double crystal phase when it been applied by the pressure in the range of 440 to 500 MPa in duration of 170 hours [23]. On the other hand, graphene reinforced sunflower oil in the form of nanoparticle produced better surface metrology compared to others lubricating fluid [24].

Other than sunflower oil, it founds that pure olive oil also could acts as the based-fluid in producing an artificial synovial fluid. Olive oil is the oil gotten from the product of the olive tree (olea europaea sativa) without having been exposed to control or any treatment [25,26]. Olive oil piece is principally shaped by fatty substances and different a few mixtures in little amounts. Olive oil for the most part comprises of triacylglycerols (98-almost 100%). Triacylglycerols (TGA) are an assorted gathering of glycerol esters with various unsaturated fats [27]. Among the glyceride division, olive oil shows a high content of unsaturated fats and especially, a raised extent of monounsaturated unsaturated fats (MUFA). Unsaturated acids ultimately depend on 85% of its synthesis, because of its high satisfied in oleic acid (C18:1), which could run between 70-85% and other unsaturated fats as linoleic or palmitoleic acid [28]. In a study, by usage of olive oil diet give beneficial in medical therapy which is to forestall osteoarthritis illness to safeguard the articular ligament and afterward the whole joint [29]. The unsaponifiable fraction from the olive oil also reducing joint pain while improving the mobility of the patients that experienced Osteoarthritis [30]. Hydroxytyrosol in extra virgin olive oil is a powerful antioxidant that can influence specific signal transduction in chondrocytes that preventing from the inflammation and cartilage degradation [31].

In this study, the sunflower oil and olive oil been blends with hyaluronic acid and tests were carried out using a Fourball Tribotester and 3D Surface Measurement Systems (Alicona). Thus, the purpose of this study is to investigate the tribological properties which are the coefficient of friction, friction and also the wear scar diameter of the solution of biofluid.

2. Methodology

2.1 Apparatus and Procedure

For this research, Fourball Tribotester been used by following the standard of the ASTM D4172 which a test method to study about the wear preventive characteristics of lubricating fluid. Figure 3 shows the machine of Fourball Tribotester that being used while Figure 2 shows the schematic diagram for the position of all four ball that been used which is 3 balls were located at the bottom in the ball pot and another one ball was located at the top at the spindle [32].

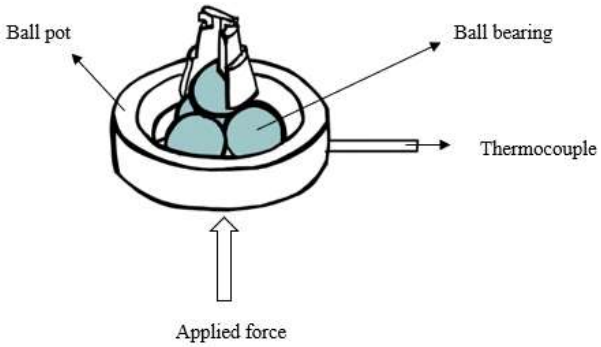


Fig. 2. Schematic diagram of Fourball Tribotester

The ball pot has been tightened through torque wrench of 50 lb-ft. In this study, a new set of four ball been used for every sample that going to be tested and it will soak in the N-Heptane to ensure the cleanliness of every balls. The ball pot containing 10ml of the sample fluid which will drown the balls at the bottom and it will be pressed by a ball at the top with force around 40kg (392.2N) and rotating at speed of 1200rpm. In addition, the sample fluid will be heating up to 75°C and this experiment going to run in 60 minutes.

Fig. 3. Fourball Tribotester machine

shows the specifications of balls that been used in this study [33]. Other that Fourball Tribotester, 3D Surface Measurement System (Alicona) with the usage of the optic IFM G4 10x also been used in this research in order to measure the wear scar diameter that being produced at the three balls at the bottom. By using this system, the surface of wear scar be seen clearly in term of its surface characteristics in 3-dimension view.

Table 1
Specification of balls [33]

Item	Specification
Material	Chrome alloy steel (AISI E-52100)
Diameter (mm)	12.7
Extra polish (EP) grade	25
Rockwell hardness (HRC)	64 - 66
Chemical composition	A high carbon, chromium containing low alloy steel that is through hardening

Figure 4 shows the Alicona System been used in this research. When use the system, must be ensure that usage of suitable optic such as in this study IFM G4 10x been use and the specimen was clean from any droplets of the test lubricant. Other than that, every optic has their range values of vertical resolution that must be set up in order to get clear sight of the surface that need to be observed. In addition, the position of the microscope needs to be adjusted until the suitable distance between the specimen and the microscope. The brightness and contrast setting also plays the important role to get clear view of sight of the wear scar when using 3D Surface Measurement System.

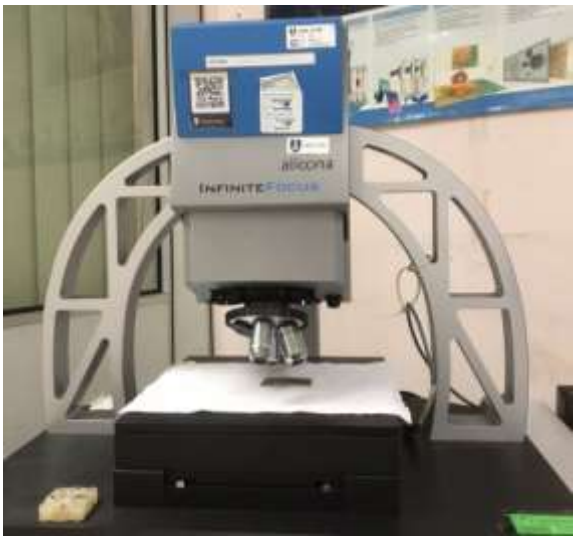


Fig. 4. 3D surface measurement system

2.2 Test Lubricant

There were 2 types of lubricants from the plant-based oil which are sunflower seed oil and olive oil as the medium-based oil. Figure 5 shows the test lubricants used in this research. Nowadays, the plant-based oils are well-known in Malaysia for food industrial only. These types of oil going to blends with the additives which is hyaluronic acid with three different volume composition and the total volume of the biofluid was 10 ml that will put inside the ball pot.

Fig. 5. Pure olive oil and sunflower seed oil

The tests for different samples of biofluid were labelled from Sample 1 until Sample 12 as shown in the **Error! Reference source not found.**. Based on the ingredients in these two types of plant-based oil, it was containing almost the same nutrient especially fat. It was found that the monounsaturated fat, polyunsaturated fat, saturated fat and also trans fatty acid in both Olive oil and Sunflower Seed oil. In order to ensure all of the nutrients were there, the plant-based oil that been used was not exceed its expiry date. All of the sample of both oil and hyaluronic acid had been measure of its volume by using different syringe. It caused the more accurate volume going to be use and followed all of the blending composition as the scope of work in this study. The usage of different syringe for three different fluids which are Olive oil, Sunflower oil and hyaluronic acid was to prevent the mixing of unwanted blending. The blending process was done by using a glass beaker in the fume hood. Three volume compositions are 0%, 5% and 10% of hyaluronic acid.

Table 2
Test lubricant's labels

Test (run)	Sample	Type of lubricants
1st	1	Olive oil + 0% ml HA
2nd	2	
1st	3	Olive oil + 5% ml HA
2nd	4	
1st	5	Olive oil + 10% ml HA
2nd	6	
1st	7	Sunflower oil + 0% ml HA
2nd	8	
1st	9	Sunflower oil + 5% ml HA
2nd	10	
1st	11	Sunflower oil + 10% ml HA
2nd	12	

2.4 Frictional Torque and Coefficient of Friction

The data for the frictional torque was get from the Fourball Tribotester machine directly. This data increasing rapidly in early few minutes before it going to be in a steady state condition. Based on the IP-239, the coefficient of friction calculated as in Eq. (1).

$$\mu=(T\sqrt{6})/3Wr \quad (1)$$

This method of calculation also been used by other researchers [34,35]. However, in this research, both values of frictional torque and the friction coefficient were calculated automatically by the system of the Fourball Tribotester machine.

2.5 Wear Scar Diameter

With the help of 3D Surface Measurement System, every scar that been produced after the wear preventive test had been done going to be measured. By using the high resolution and optical microscope which is IFM G4 10x, the surface characteristics such as diameter was captured. In addition, the vertical resolution of the microscope also been set up to 500 nm to obtain a clear sight of the wear scar characteristics. Every three balls at the bottom in every test had been measured. Nonetheless, the average of the diameters been calculated to reduce the error value.

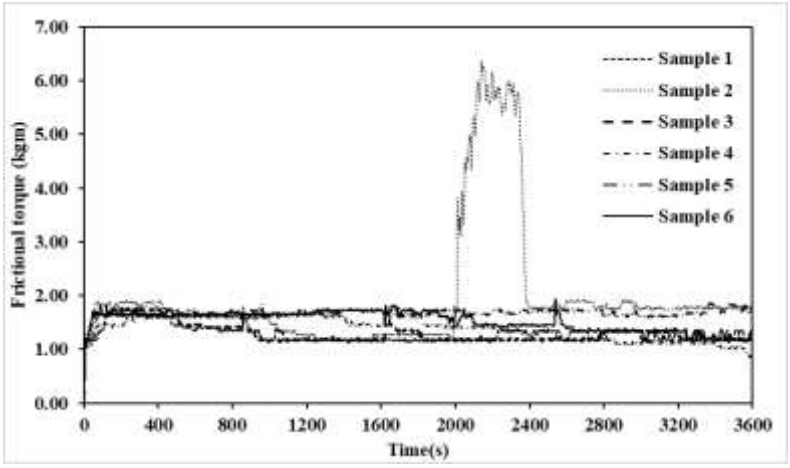
3. Results

The results that been obtained for all the test lubricants were discussed in term of it effect to the frictional torque, coefficient of friction and wear scar diameter produced. Olive oil and sunflower oil were blended with three volume compositions of hyaluronic acid and the total volume for all test lubricants was constant which is 10ml and heated to 75°C. It going to be tested with applied load of 40kg and rotating at speed of 1200RPM for 3600 seconds. This result going to identify whether the test lubricants suitable after going to blend with hyaluronic acid.

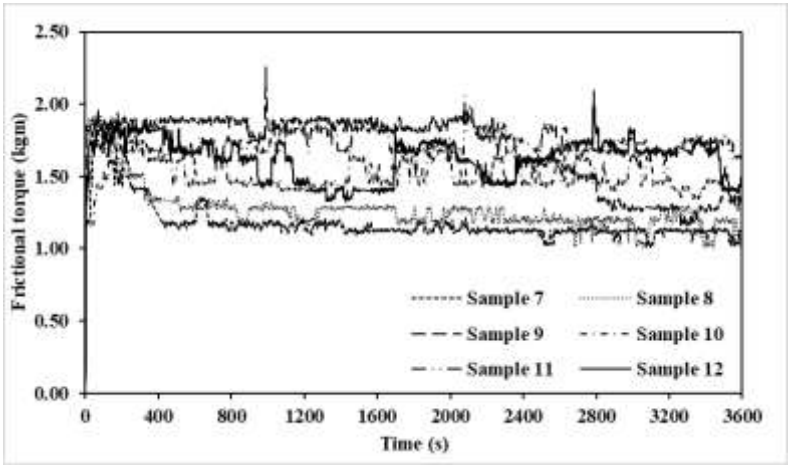
3.1 Viscosity Fitting

3.1.1 Effect on frictional torque

From the result of frictional torque, the value was increasing for a few seconds in the early stage of the Fourball Tribotester testing before it remains in a steady state condition. Frictional torque was the torque that been produce from the applied force which is about 392.2 N when the ball on the top in contact with three balls at the bottom. The result of frictional torque for every sample of test lubricant based on the medium-based oil has obtained as illustrated in Figure 6.



(a)



(b)

Fig. 6. (a) Fictional torque of olive oil (b) Frictional torque of sunflower oil

Graph of maximum, average frictional torque against the samples and also the percentage error had plotted as Figure 7 to Figure 9 below based on the overall result that been obtained.

The value for the result of frictional torque for every test had been plotted against test number. Figure 7 shows the maximum value of frictional torque obtained. Highest value for maximum frictional was found at Sample 2 which is 3.16kgm while lowest was recorded at Sample 7 which is 1.56kgm. It clearly seen that the maximum frictional torque was increasing after two tests be done from Sample 1 until Sample 12. However, for Sample 2, value of frictional torque was highest and out from the trendline of the graph. It shows that error occurred while conducting the test and it been clarified when the test had been done where the volume of test lubricant was very less compared to another sample.

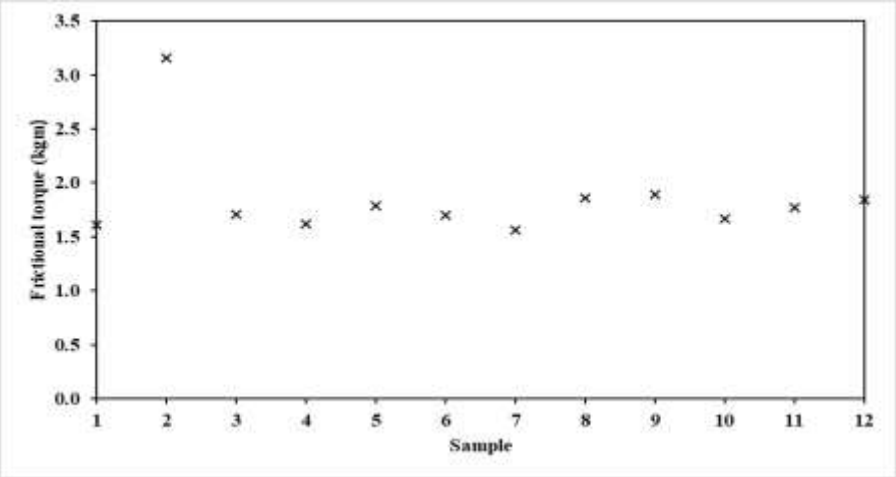


Fig. 7. Graph maximum frictional torque versus sample

For the average value of the frictional torque been plot such as Figure 8. It shows the same trend as the maximum frictional torque graph. From Figure 8, Sample 2 (Olive oil + 0%ml HA) was recorded highest value which is 1.96765620432916kgm while Sample 7 (Sunflower oil + 0%ml HA) was recorded the lowest average frictional torque which is 1.17495818727008kgm.

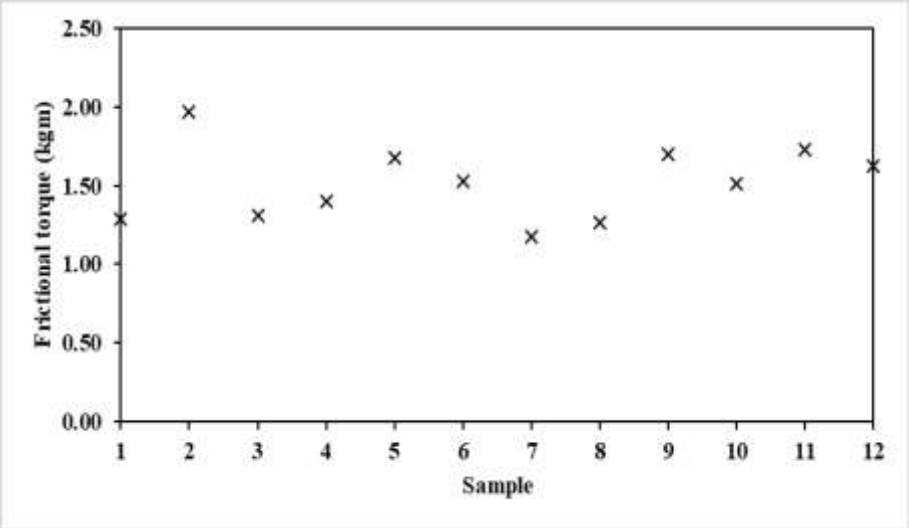


Fig. 8. Graph average frictional torque versus sample

The percentage of error between maximum and average frictional had been calculated and illustrated as Figure 9. This step been done in order to assist with deciding the connection between

what really occurred and what they expected to occur. Highest percentage error occurred for Sample 2 (60.6%) while lowest at Sample 11 (2.3%). All in all, lower frictional torque was obtained when use the pure plant-based oil (Olive oil and Sunflower oil) as test lubricants compared to when it going to blend with hyaluronic acid. This is due to the increasing of contact between metal-to-metal that resulting breakdown of the lubricant film along the motion process [36]. It occurred when the volume of fatty acid from the plant-based oil was decreasing.

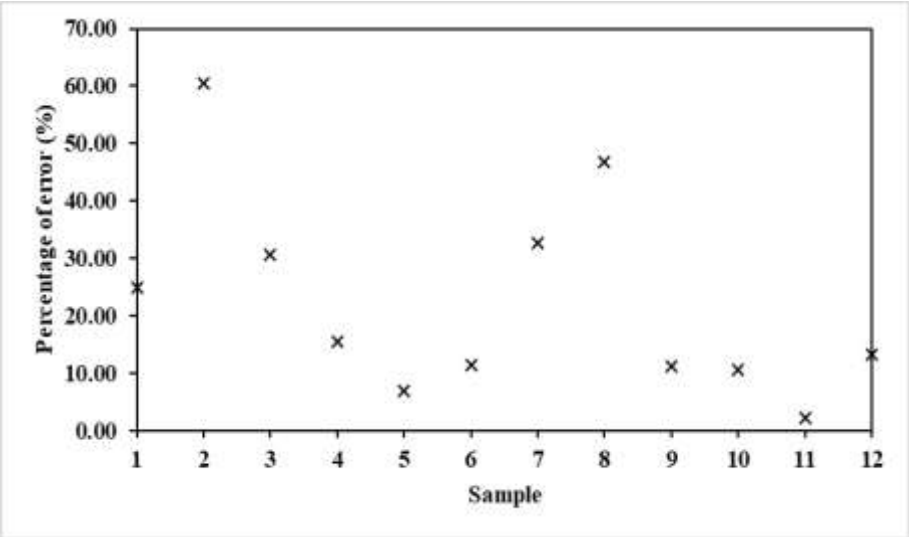
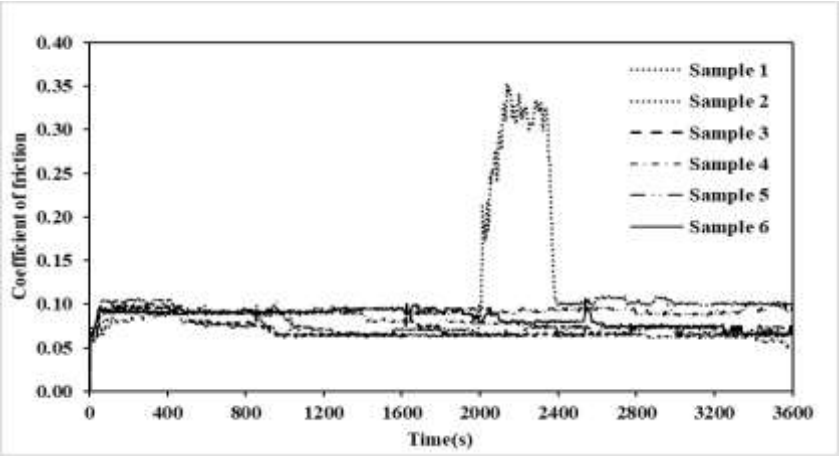


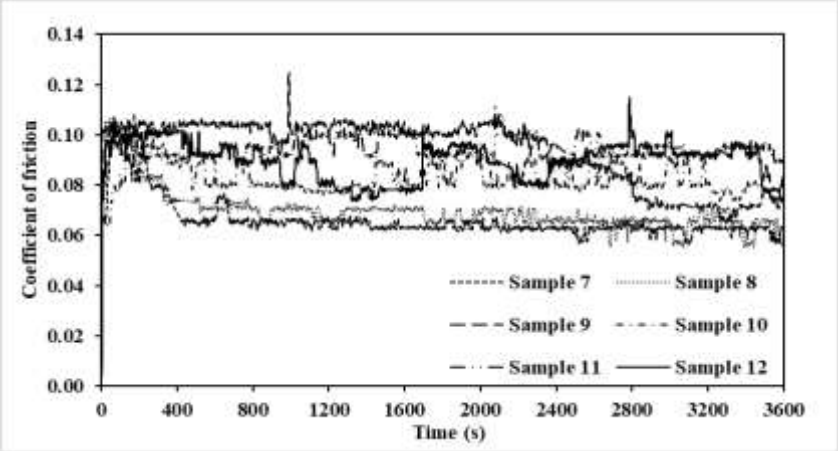
Fig. 9. Percentage error of frictional torque

3.2 Effect on Coefficient of Friction

The impact of coefficient of friction is very significant for the improvement of oils. The coefficient of friction assumes a significant part in the assurance of transmission efficiencies by means of moving parts. Less friction adds to higher proficiency of the lubricants. Therefore, in this study, the biofluid that having lower coefficient of friction is preferrable. Figure 10 shows the overall result obtained for two different types of the medium-based-oil.



(a)



(b)

Fig. 10. (a) COF of olive-based oil (b) COF of sunflower based oil

From the result obtained in Figure 10, analysing process of the data has been done and graph of maximum and average coefficient of friction and percentage error for every sample has been plot as illustrated in Figure 11 to Figure 13 below.

Graph for the coefficient of friction versus sample had been plotted and it was having the same trend as the graph for frictional torque. Sample 2 had been eliminated from the result obtained caused of the percentage error was above 70%. For the maximum coefficient of friction, Sample 8 and 9 recorded highest value (0.104), while Sample 1 and 7 recorded the lowest value which is 0.088 as illustrated in Figure 11.

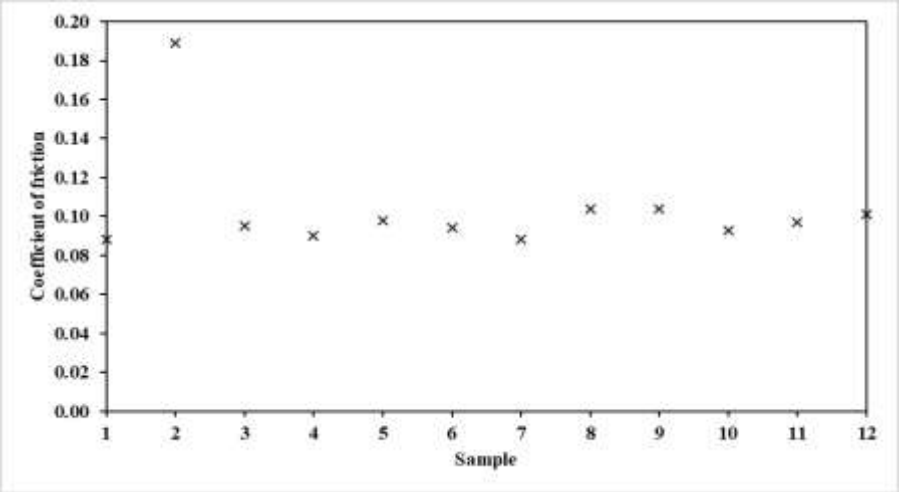


Fig. 11. Graph maximum coefficient of friction versus sample

However, for the average coefficient of friction for the test lubricants had been shown in Figure 12. It shows the differences with the highest maximum value of coefficient of friction. Sample 11 has the highest average coefficient of friction which is 0.094685 while Sample 7 has the lowest which is 0.065940.

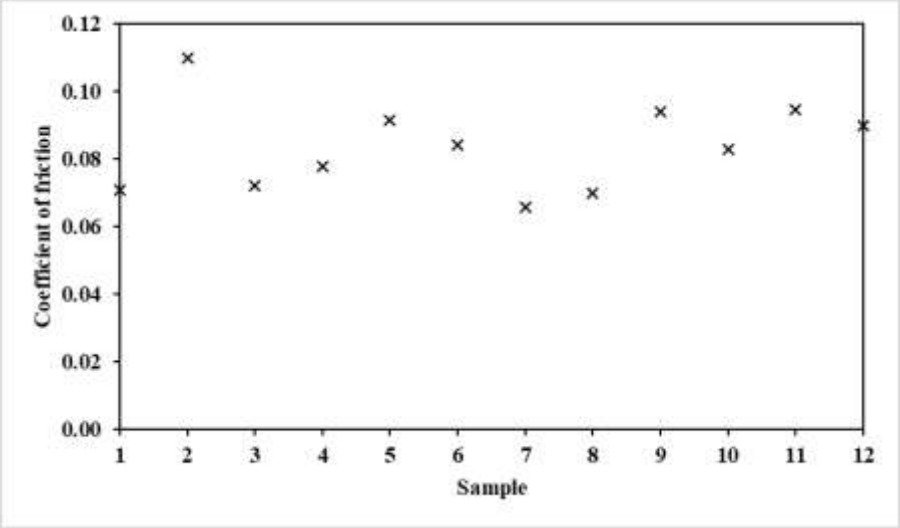


Fig. 12. Graph average coefficient of friction versus sample

For the percentage of error, Sample 2 was recorded the highest error which is 71.61% while Sample 11 recorded the lowest which is 2.44% as shown in Figure 13. From this observation, Olive oil and Sunflower oil without blends with hyaluronic acid were seen to give the lower coefficient of friction compared to other sample of test lubricants. It shows that pure plant-based oil gives better lubricity ability compared to when it going blends with hyaluronic acid. This happened because of the high volume of strong intermolecular structures such as fatty acid in the plant-based oil that make higher strength of lubricating film [37].

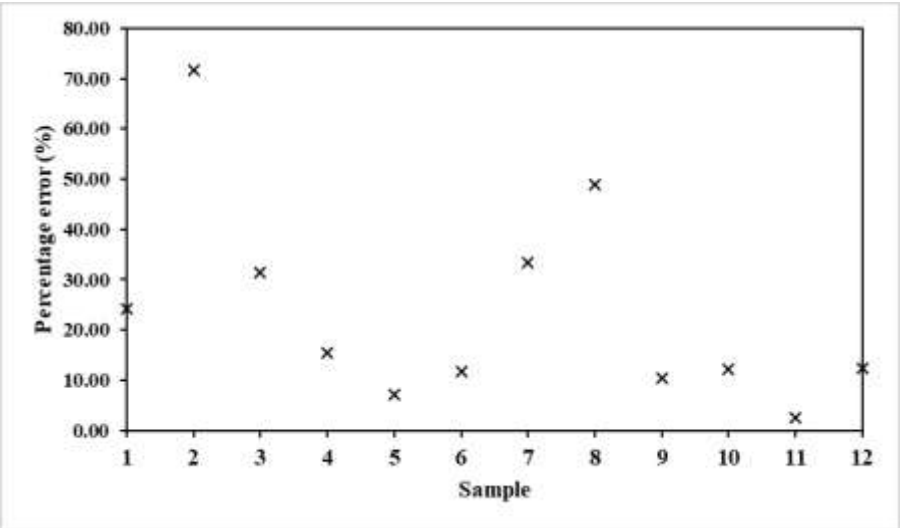


Fig. 13. Graph percentage error of coefficient of friction

3.3 Effect on Wear Scar Diameter

After done the Fourball Tribotester testing, three balls at the bottom were going to be investigate in term of it surface characteristic such as wear scar under the 3D Surface Measurement System. The wear preventive method demonstrates how well a lubricant could resists wear. The smaller the wear scar produced, the more effective the lubricant is. The area that having scar was captured by using high resolution and high magnifying microscope that caused a clear view of the wear scar been observed. The sample of biofluid that having the smaller average wear scar diameter is having the

high tendency to be the lubricant that good in ability to resist of wear scar. Based on the result of wear scar diameter for every ball at the bottom which has three, the average wear scar diameter for every sample of test lubricant was calculated as Eq. (2). From the result obtained, graph of average wear scar diameter had been plotted against the samples of test lubricant as Figure 14.

$$Average\ Wear\ Scar\ Diameter = (Diameter\ Ball\ 1 + Diameter\ Ball\ 2 + Diameter\ Ball\ 3)/3 \quad (2)$$

Figure 14 shows the average wear scar diameter produced for all test lubricants. This value was calculated for all three balls located at the bottom while conducting the wear preventive test using Fourball Tribotester. It shows the increasing trend through the test lubricants. However, for the test lubricant (Olive oil + 10%ml HA) found to be the lowest which is 0.64828mm. The highest wear scar produced was at the final test lubricant (Sunflower oil +10%ml HA) that recorded 0.75126mm. In this paper, there are no relationship between the coefficient of friction and wear scar diameter across. The wear scar diameter was an impression of the oxidation rate that happened during the investigation. All in all, as Sunflower oil being the based medium oil, the wear scar diameter produced was greater than olive oil. This is due the higher oxidation rate produced in Sunflower oil [38]. This is due the high content of oleic acid in Sunflower oil compared to Olive oil [39]. Oxidation process occurred going to made the balls more brittle. In addition, the hyaluronic acid also experienced the same process which is been oxidated [40].

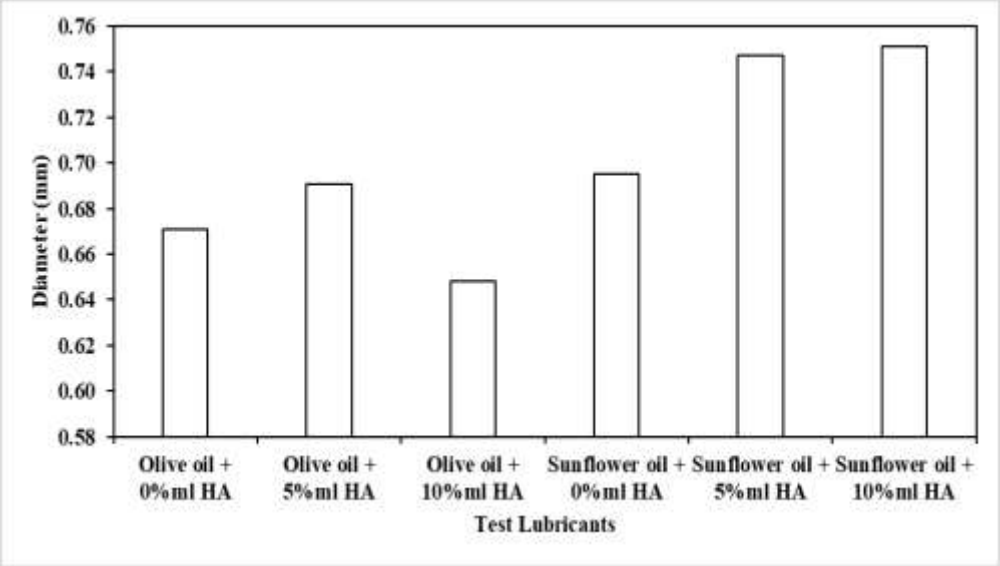


Fig. 14. Average wear scar diameter of sample

3.4 Comparison of Result

A comparison with other researcher had been done in order to compare result that been get in this study. This researcher had study about the effect of palm fatty acid distillate as the additives on the commercial metal forming oil as medium-based oil [41]. The additive was blend with the oil in different mass volume. The researcher also had done the tribological test by using Fourball Tribotester following standard of ASTM D4172. It studies the effect of test lubricants on the average coefficient of friction and average wear scar diameter. The samples of the test lubricant of the researcher from S1 until S7 that having different percentage mass volume composition of the medium-based oil and the palm fatty acid distillate as the additives. The percentage mass volume of palm fatty acid distillate added were varies for every sample which are 5%, 10%, 15%, 20% and 25%.

In addition, the researcher also studies the tribological characteristics of the pure commercial metal forming oil without the help of palm fatty acid as additive and also the pure 100% of additive only which are S1 and S7 respectively. This is because, these type of test lubricants had been set up to be the benchmark of the study in their research. All of the standard for run the wear preventive test by using Fourball Tribotester that been used by this researcher also same with present study which are 40kg of applied force with 75°C of sample of biofluid temperature and it going to rotating at the speed of 1200 RPM. The purpose of these researcher's study was to help in optimization of lubrication by implemented of the usage vegetable oil in the industrial sector.

Figure 15 shows the result of other researcher in term of its average coefficient of friction and been compared with COF of this present study. From the figure, it be seen that the higher mass volume of palm fatty acid having the tendency to reduce the coefficient of friction. However, it depends on its suitability on the mass volume of additive that going to be blends with. The mass volume of the additive also has the important role in order to reduce the coefficient of friction. This is because S2 recorded the highest coefficient of friction compared to other test that having higher mass volume of the additives. This shows that the 5 percent of volume mass of additives is not suitable when be blends with the medium-based oil. While the lowest coefficient of friction found on S5. In addition, the value of COF also increasing when the mass volume of additive greater than 20 percent.

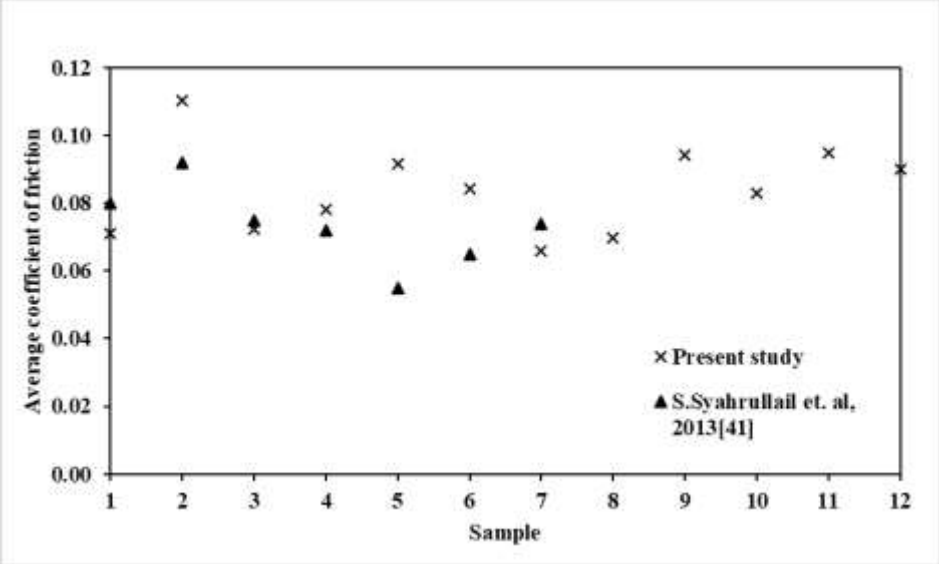


Fig. 15. Comparison average COF

Figure 16 shows the result of average wear scar diameter against the test lubricants of the researcher and compared with the result of this present study. It shows the continuous increment when the mass volume of palm fatty acid as additive increasing with the commercial metal forming oil as the based-medium. From the figure, the highest average wear scar diameter was found at the S7 which has the highest percentage of the additive. As a result, the additives palm fatty acid does not have the ability to produce biofluid that good wear preventive lubricant but good in reducing the coefficient of friction. From this result of the researcher, it shows the same trendline with this study of plant-based oil (Olive oil and Sunflower oil) with hyaluronic acid as additive. So, the plant-based oil was not suitable to be use in term of producing the lubricants with high wear preventive ability.

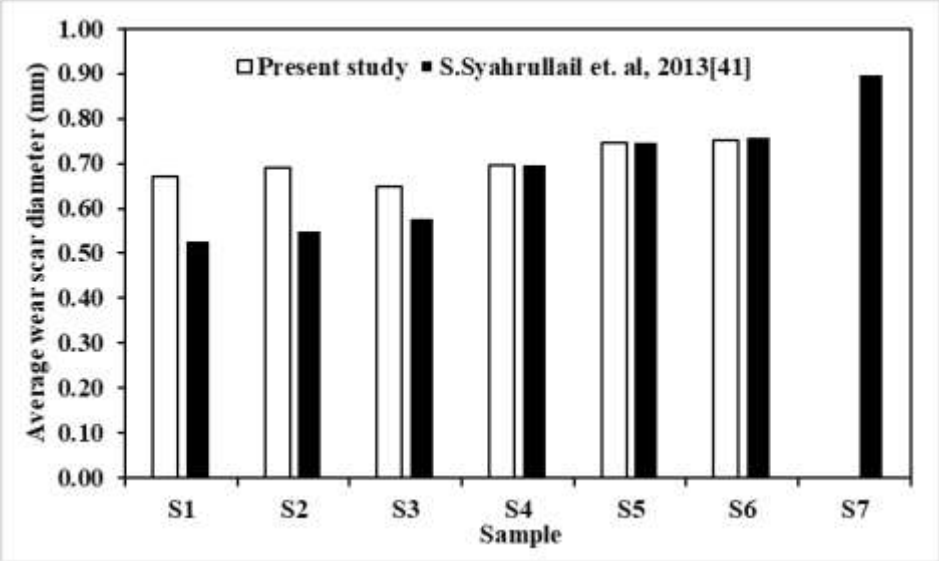


Fig. 16. Comparison average WSD

4. Conclusions

Based on all of the findings obtained in this study, the additive of hyaluronic acid was not suitable to blend with the plant-based oil which are Olive oil and Sunflower oil. This is due to the increasing of the coefficient of friction and producing larger wear scar diameter. Pure plant-based oil was having the better lubricant ability compared to it going to blends with hyaluronic acid. However, for the Olive oil, it is suitable to be blend with 10 percent volume composition of hyaluronic acid which produce smallest average wear scar diameter which is 0.64828mm that seen to be a lubricant that having higher preventive conditions. While, pure Sunflower oil which is Sample 7 producing the smallest average coefficient of friction and frictional torque which is 0.065940 and 1.17495818727008kgm respectively. All in all, with the aid of the hyaluronic acid, Olive oil as medium-based oil has better result in term of it tribological characteristics compared to Sunflower oil. It is clearly seen on the result where with the based- medium of Olive oil produce less frictional torque, coefficient of friction and also smaller wear scar diameter. This result of this study going to give the beneficial to the medical industry in order to produce the new artificial synovial fluid. Lastly, it is recommended that bovine serum albumin could be implemented as the additive as to produce the lubricants with better lubricity and wear preventive. This is due to characteristic of bovine serum that could reducing the friction and wear with the aid of oil-protein layer.

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