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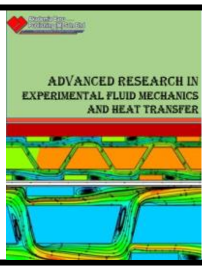

Application of Response Surface Methodology Experimental Design to Optimize Tribological Lubrication Characteristics

M. Mazwan Mahat[1,*], Farah Nabillah Kazwa[1], S. Kasolang[1] , Nurul Nadiah Mohd Kamaldin[1]

[1] School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia

ABSTRACT

Total Knee Replacement (TKR) has become a standard operation for patients with joint disorders. Despite the fact that the number of procedures is increasing all the time, the short service life of implants remains a persistent concern for researchers. Understanding lubrication may aid in explaining tribological processes that lead to replacements that last well into the third decade of service. Likewise, wear and friction in total knee replacement (TKR) components are among the most common causes of implant failure. As a result, this study will evaluate the feasibility of using the polymer Polylactic Acid (PLA) for cartilage replacement in Total Knee Replacement (TKR) using plant-based oils as lubricants. Furthermore, the modifier will be added to plant-based oils as an additive to make them analogous to human bodily fluids. The present paper is applying the Box-Behnken design to optimize the performance and mechanical responses of bio-lubricants toward Polylactic Acid (PLA) as a tibial insert for cartilage replacement in Total Knee Replacement (TKR). The main objective of this paper is to develop an optimized method for the selection of plant-based oil parameters using Response Surface Methodology (RSM). A three-level three-factor Box-Behnken design (BBD) was used to investigate the interactions between the essential factors comprising load (45 kg to 90 kg), speed (60 rpm, 90 rpm and 360 rpm), and concentration (0ml, 5ml and 10ml) of bio-lubricants to accomplish the indicated prospect of using polymer for cartilage replacement. Canola oil, castor oil, and sunflower seed oil are considered vegetable oils, whereas Hyaluronic Acid (HA) is the friction modifier. The parameters are used to create a Box-Behnken design for predicting lubricant anti-wear qualities stated in terms of coefficient of friction, wear rate and frictional force as determined by the pin-on-disk experimental procedure. As a result, the optimization using RSM successfully interpreted the experimental data, according to the analysis of variance, with coefficients of determination of R2 = 0.91 and adjusted R2 = 0.77. The Coefficient of Friction (CoF) and wear rate were investigated following tribological testing. Castor oil had a lower coefficient of friction than canola and sunflower seed oil, according to the findings. In terms of friction reduction, castor oil surpasses canola and sunflower seed oil.

Keywords:
Optimization; Polylactic Acid; Friction Coefficient; Plant Based Oil; Pin-on-Disc

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1. Introduction

Knee osteoarthritis (OA) is a chronic degenerative joint condition that manifests clinically as fluctuating joint pain, swelling, stiffness, and loss of mobility. The prevalence rises with age, and OA is a major source of disability. Worldwide, the frequency of OA among people aged 60 and above is estimated to be 18% of women and 10% of men. Approximately 80% of these people will have some

* *Corresponding author*
Email address: mazwan@uitm.edu.my

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degree of mobility restriction, and 1 in 4 will be limited in important everyday tasks [1]. Arthritis influences more women (23.5%) than men (18.1%); is more common in adults with mediocre health (40.5%) than in those with excellent health (15.4%) [2]. As people grow older, they are more likely to develop arthritis. When less intrusive therapies fail to resolve severe joint dysfunction and the joint may need to be replaced entirely with an artificial joint. Patients who have had joint replacement surgery may be able to resume their normal lives without discomfort. A common joint arthroplasty treatment is total knee replacement. However, after a few years, the artificial joint material particles wear away from the joint surface, producing osteolysis [3]. Ultrahigh-molecular-weight polyethylene, Co- Cr-Mo alloys, silica (SiO2), and silicon nitride (Si3N4) [4,5] are all popular materials used in joint replacement. They have all been proven to operate efficiently and are widely used in clinical settings. It has been shown, however, that the wear of UHMWPE and wear particles produced osteolysis and bone resorption. UHMWPE has a typical lifetime of around 10 years [6], and patients may require further surgery for joint replacement. As a result, this study urged for further research into polylactic acid (PLA) polymer, which might be used to replace current materials and broaden the usage of polymers in medical applications. As a result, polylactic acid (PLA) has been proposed as an alternative replacement material for the TKR device.

It is generally known that healthy synovial joints have a great load-carrying capacity and lubricating function with exceptionally low friction coefficients and minimal wear rates throughout their lives. To understand the effects of friction and wear, Joseph *et al.,* [7] stated that researchers must also understand the interactions between the materials and the fluid present between the two moving surfaces. Lubricants are particularly essential in minimizing wear in a mechanical system so that it can run for a long length of time. As a result, experimental research is necessary to assess the impact and implications of what may be occurring to the cartilage.

2. Methodology

2.1 Materials and Preliminary Processing of Lubricants

The selection of a suitable materials for the disc and pins that would be acceptable for the human body was the preliminary step in this project. The disc was created using SOLIDWORKS software. Following that, choose the best lubricants that fulfil the knee condition criterion, which incorporates other factors such as material, load, speed, and concentration. Following that, the sample preparation technique is followed by the experiment method, and ultimately, the findings are obtained and reported.

2.2 Optimization Study

The optimization was carried out utilizing the Minitab programme V 21.1 and the Box-Behnken design (BBD). The three most essential elements were chosen as independent variables (factors), each with two minimum and maximum levels that shows in Table 1. The responses for the combination of the independent variables were Coefficient of Friction (CoF) and wear rate. The independent factors impact on the physical and mechanical qualities of the human body were studied under these settings.

Table 1
Optimization factors

Factor	Unit	Type	Minimum	Maximum
Speed	RPM	Numeric	60	360
Load	kg	Numeric	45	90
Concentration	ml	Numeric	0	10

2.3 Preparation of Experimental Setup

The standard pin used in this experiment is made of SS316L stainless steel and measures 8 mm in diameter and 25 mm in length. Stainless-steel pin being cut into 25 mm using an abrasive cutter, and pin being polished to a mirror-like finish. A single pin was used for each test. Before each successive test, the pin was cleaned with acetone and wiped dry with a clean lint-free industrial wipe.

A 3D printer was used to create polylactic acid (PLA) discs using the specifications stated in Table 2. The SOLIDWORK application was used to compute the dimensions of the disc. The disc model infill density and placement were adjusted using Ultimate Cura in the STL file. The plastic filament was heated to 185 degrees Celsius before the printing process began. The bedroom temperature has been set at 45 degrees Celsius. The printing may begin as soon as it reaches the preheat setting. The nozzle temperature must be 200 degrees Celsius and 60 degrees Celsius [8] during PLA printing to allow melted filaments to flow out of the nozzle and stick to the 3D printer.

Table 2
Material properties for PLA disc

Material	Poisson Ratio	Young Modulus (N/mm2)	Yield Strength (MPa)
Polylactic Acid (PLA)	0.36	3500	70

2.4 Preparation for Bio Lubricants

Castor oil, canola oil, and sunflower seed oil are the lubricants utilized in this research. Vegetable oils are preferred because they are biodegradable and non-toxic, making them suitable for use in medicine and the environment. Furthermore, it has been demonstrated that vegetable oils have high flash points, a high viscosity index, and low volatility [9]. The biggest drawback of using vegetable oil is its low thermal and oxidative stability [10]. The use of modifiers such as friction modifiers (FMs) has been shown to greatly reduce friction.

In this work, hyaluronic acid (HA) was employed as a modifier. Castor oil, canola oil and sunflower seed oil were chosen for this study because of their refined form and oleic acid concentration, which appears to help with friction reduction. The chemical composition of the lubricating oil is shown in Table 3.

Table 3
Composition of Bio lubricants oil

Fatty acid percentage	Castor oil	Canola oil	Sunflower seed oil
Linoleic acid (%)	4-5	6-14	44-75
Oleic acid (%)	3-4	50-65	14-43

A pin-on-disc tester was used to assess the tribological properties of the manufactured lubricant. PLA discs ranging in hardness from 104 to 118R [11] are used. The roughness of the pin was maintained between 0.2 and 0.3 m. The rotating speed of the disc at room temperature was 60, 90, and 360 rpm (walking, cycling, and running), and the usual weight was 45, 67.5, and 90 kg. All of the samples were cleaned with acetone and dried before to the testing. To maintain border lubrication, oil was dropped at the interface at a rate of 0.6 ml/s. This investigation is being carried out in order to obtain more trustworthy data for this study. The Coefficient of Friction and Wear Rate were investigated using a Pin-on-Disc machine. A sensor sensed the friction between the sample and the disc when a pin made tangential contact with a spinning PLA disc. At a room temperature of 28 degrees Celsius, the test lasted 1800 seconds, or 30 minutes.

3. Results

3.1 Viscosity Fitting

The viscosity of the samples in this investigation was measured using a Canon CT-500 kinematic viscometer at temperatures of 40 and 100 °C in three concentrations of modifier with based oil of 0 ml, 5 ml, and 10 ml. The ASTM D2272 standard was used to calculate the viscosity index (VI).

Figure 2 depicts the results of the viscosity test (ASTM D445). It looks on the experimental measurement of different HA concentrations exposed to kinematic viscosity at 40°C and 100°C. As the temperature rises, the kinematic viscosity decreases [12]. As the concentration of HA increases, so does the kinematic viscosity. This is because, as concentrations increase, HA tends to agglomerate and form larger, asymmetric particles, which limit the flow of oil layers between them [13]. As the amount of HA in the lubricant grows, the molecules are driven to the liquid surface and form a cohesive force between them, resulting in higher lubricant surface tension. This action causes Van der Waals forces to form by closing the gaps between molecules.

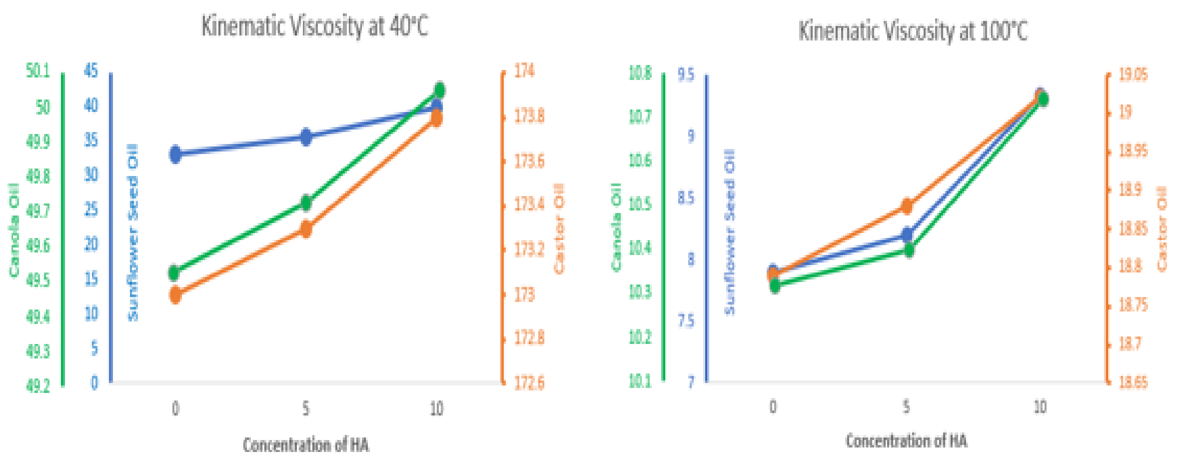

Fig.2. Kinematic Viscosity of lubricants at 40^{O}C and 100^{O}C

Figure 3 depicts the viscosity index (VI) against lubricants with modifier. According to the graph, the VI of castor oil is 6.23% greater than the VI of canola and sunflower seed oil. This is due to the fact that castor oil has a higher molecular weight than canola and sunflower oil. A higher viscosity index (VI) promotes more stable viscosity across a wider temperature range (independent to temperature).

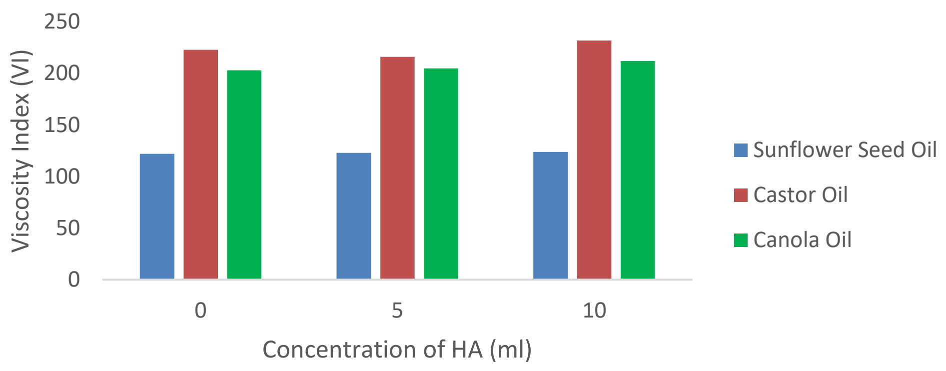

Fig. 3. Viscosity Index of Bio lubricants on Difference of HA concentration

3.2 Box Behnken Experimental Design

Three main independent parameters with significant factors are speed (rpm), load (kg), and concentration (ml). As a consequence of adjusting the values of the major chosen variables speed, load, and concentration at various levels, 15 formulas of various combinations were constructed using the optimization approach, as shown in Table 4. The anticipated and experimental results for the pin-on-disc test show that the percentage error ranges from 0.10 to 6.52. It clearly shows that they have a very high occurrence. The typical proportion of error ranges from 0.1 to 10%. There appear to be two cases with a percentage error of more than 5%. These four samples are shown running at high speeds (210 to 360 rpm), high loads (67.5 to 90 kg), and medium concentration (0 to 10 ml).

Table 4
BBD matrix with observed and predicted value of CoF

Run order	Coded variables			Real variables			Response		Error (%)
	Speed	Load	Sliding distance	Speed	Load	Concentration	Experimental	Predicted	
1	0	0	0	210	67.5	5	0.05133	0.068943	0.17
2	0	0	0	210	67.5	5	0.05674	0.068943	0.12
3	0	0	0	210	67.5	5	0.09876	0.068943	0.29
4	-1	1	0	60	90	5	0.08760	0.098367	0.10
5	1	-1	0	360	45	5	0.19876	0.187992	0.10
6	-1	0	-1	60	67.5	0	0.08765	0.087086	0.56
7	1	0	1	360	67.5	10	0.12340	0.123964	0.53
8	0	-1	-1	210	45	0	0.07654	0.070859	0.59
9	-1	-1	0	60	45	5	0.06578	0.072025	0.62
10	1	1	0	360	90	5	0.02342	0.017175	0.67
11	0	1	1	210	90	10	0.01243	0.018111	5.68
12	0	-1	1	210	45	10	0.08785	0.098054	1.02
13	1	0	-1	360	67.5	0	0.05423	0.70679	6.52
14	-1	0	1	60	67.5	10	0.08923	0.072781	1.14
15	0	1	-1	210	90	0	0.01653	0.006326	1.02

3.3 Effect of Independent Variables On Cof

To analyse the model's relevance and competence, an analysis of variance (ANOVA) is necessary. It is vital to assess the model significance and proficiency. When analysing the influence of parameters and the interaction of independent variables over CoF, it produces a highly effective result in ANOVA. Using various statistical parameters, the acquired data were fitted using the quadratic polynomial model shows in Eq. 1. The calculated regression model for CoF is shown below

$$\text{CoF} = -0.058 + 0.000322\ \text{speed} + 0.00368\ \text{load} + 0.00470\ \text{concentration} + 0.000001\ \text{speed}^2 - 0.00015\ \text{load}^2 - 0.000517\ \text{concentration}^2 - 0.000015\ \text{speed} * \text{load} + 0.000023\ \text{speed} * \text{concentration} - 0.000034\ \text{load} * \text{concentration} \quad (1)$$

The coefficient of determination (R^2) is a measure of fit as well as a ratio of explained variation to total variance. A decent model fit requires an R^2 of at least 0.8. The model robustness is evaluated by comparing the coefficient of determination R^2 and adjusted R^2 with an estimated difference of less than 0.15. The reported fit statistics show that the anticipated R^2 of 0.918 was in reasonable agreement with the adjusted R^2 of 0.772, with a difference of less than 0.2, indicating that the models were highly predictable. When the acceptable threshold value of R^2 is greater than or equal to 0.8, it becomes increasingly significant as it approaches 1.

3.4 Effect on The Factors of Their Interactions of Responses

Due to the initial contact with the tribopair, the surface roughness of the PLA disc creates a higher friction coefficient. When the applied stress increases however, micro-peaks on the surface of the film begin to deform dramatically, resulting in smoothening and, as a result, a low friction coefficient. A normal probability plot of residuals is also generated to test whether the population assumptions are normally distributed. Figure 4 exhibits a residual normal probability plot, which shows that the residuals are generally drawn along a straight line, confirming the assumption on the presumption of normality. It demonstrates that speed*load and speed*speed are the most significant types in the normal plot.

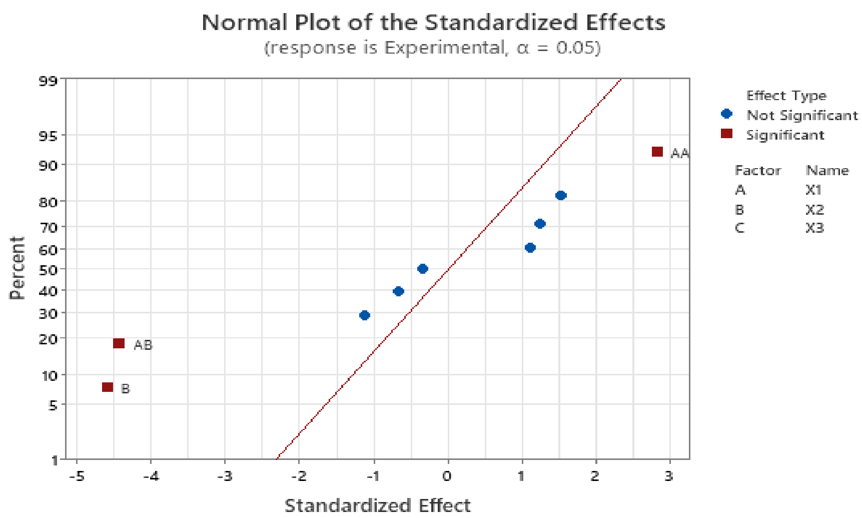

Fig. 4. Normal probability plot of the standardized effect on CoF

Figure 5 depict the response surface and contour plots of CoF as a function of the independent variables using Equation 1 of the constructed empirical model. These surfaces are generated by keeping one parameter constant while adjusting the others. The region with the optimal zone in the contour plot speed vs load is illustrated by the yellow region in Figure 5, which is speed at 150 to 360 rpm, load at 80 to 90 kg, and CoF at 0. 052120. There is always an optimal speed beyond which material quality and performance may suffer. When the temperature rises faster than the ideal rate, it may approach the melting point, resulting in strong adhesion between contact surfaces and, finally, an increase in friction [14].

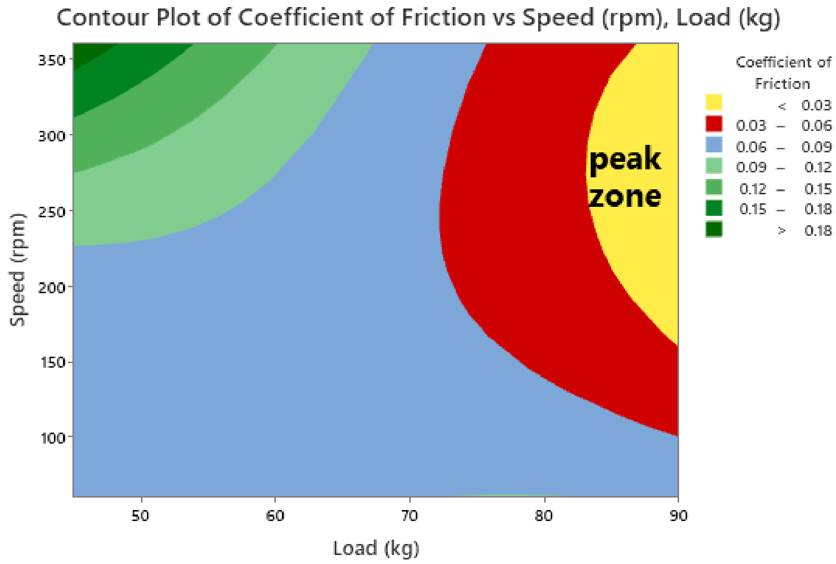

Fig. 5. Contour plot of CoF of Friction against speed and load

4. Conclusions

In summary, the experimental results show that castor oil with HA modifier has an adduct effect, synergy, and antagonism impact on tribological properties such as viscosity, friction, wear, reflection coefficient, and film thickness. As a result, it is expected that the contribution of this chapter would be advantageous not only to the defined lubricant outline, but also to the general academic and tribology community.

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