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Assessment of the relationship between lubricating oil viscosity and surface-attached adhesion rate via regression modelling

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Abstract

This study used a regression model, experimental data from a viscosity measurement device, and a computational technique to investigate the relationship between lubricant viscosity and surface-attached adhesion rates. Three types of used lubricants were identified and evaluated using viscosity and surface adhesion measuring instruments using three different sizes of steel balls, namely 3 mm, 3.5 mm, and 4 mm. The experimental results were then analysed using a simple linear regression model with parameter estimation. At a significance level of 0.05, the results revealed that the lubricant viscosity and the rate of surface adhesion were linearly correlated. The results of this research could be utilized by industry to control the usage of lubricating oil in industrial parts, make judgments about changing or analysing the quality of the heat-reducing lubricant at the interface between mechanical components, and so on. To maintain lubrication efficiency and increase the service life of industrial parts. As a result of fulfilling this desired goal, the regression equations generated during this study can be used to estimate surface-attached adhesion rates in other circumstances. The viscosity range utilised in this case study corresponds to the normal viscosity of the unused lubricant. The surface-attached adhesion rate can thus be accurately selected by manufacturers, and the lubrication effectiveness can also be monitored. This is another indirect waste reduction in the manufacturing chain.

Keywords: Viscosity, Surface-attached adhesion, Regression model, Lubricant

Introduction

In modern times, various machinery, engines, and mechanical parts are employed in the manufacturing process that drives the economies of middle-income emerging nations like Thailand. The machines, engines, and mechanical parts use oil lubrication. Because of the properties of the lubricant, mechanical parts function better, last longer, and need fewer replacements. It also helps to increase their useful lives and reduce internal temperatures between them. The lubricant is required to be capable of measuring and testing the appropriate value using testing machines in accordance with international standards.

The measurement and assessment of engine oil viscosity is vital for increasing oil quality. It can be developed for higher quality and efficiency or differently to increase novelty in the production of the petroleum industry. For example, an effective experimental and testing method relies on experiments and calculation techniques to accurately estimate the quality of various grades of lubricants in accordance with international standards. This includes assessing and restoring waste lubricants to proper operating condition [1]. This can be done through various methods such as additive additives, extraction, adsorption, distillation of used lubricant, and oil recycling with solvents [2–4]. It also leads to the development of machines and engines that work more efficiently and is beneficial to the design of parts and equipment for machines and engines.

Used lubricating oil, if improperly disposed of, will pollute the environment and lubricating oil that is not at the end of its useful life but replaces it prematurely will result in direct cost. If, on the other hand, the lubricant deteriorates but the user does not replace it, it may have a detrimental impact on the machine or mechanical parts, resulting in indirect cost. The identification of lubricant deterioration in maintenance engineering is centred on the primary observation, which is the colour of the lubricant. In comparison to ready-to-use oil of the same quality, used oil is darker. Also, the deterioration is seen in the operating noise of the mechanical parts. Good lubricants, for example, will not cause excessive friction or vibration [5]. There is no noise from the surface friction of the machine elements. If there is a sound, it is assumed that the mechanical parts are rubbing against the skin due to friction. There is no lubricant wrapping between the contact surfaces, which may result in gritty lubrication and negatively influence maintenance [6]. In this situation, it may relate to lubricant deterioration in viscosity and surface adhesion qualities. Either way, the above observations are only indicative of the lost properties of the oil in order to plan proper replacement and reduce unnecessary losses.

According to previous studies, lubrication effectiveness is dependent on a number of variables, including viscosity, surface adhesion, temperature, film thickness, etc. Additionally, each of the aforementioned factors is significantly related. In which Arif et al. [7] investigated the effect of surface contact and came to the conclusion that the surface adhesion rate considerably influenced the tribological efficiency directly. This indicates that one of the variable affecting lubrication is the rate of surface adherence. This is consistent with the hypotheses advanced by Yoshizawa et al. [8] and Adams et al. [9], who investigated the effects of surface adhesion on friction and lubrication. Regarding the issue of viscosity, it immediately influences the film thickness [10, 11] or even negatively impacts inadequate lubrication. Concerning viscosity, it has an immediate impact on film thickness [10, 11] and can even negatively impact inadequate lubrication. According to research conducted in 1991 by Sorab and Vanarsdale [12], the link between pressure and temperature and how it impacts lubricant viscosity was directly correlated with Lowrie and Sargent [13]. More recently, Van Leeuwen [14] offered the estimation of the lubricant's pressure-viscosity coefficient and the possibility of measuring viscosity using a number of experimental techniques or experimental calculations. Later, this result was also consistent with Yu et al. [15]. For greater reliability, the observed behaviour of lubrication-related variables has been applied to statistical principles, such as the application of statistical theory to assess wear rates proposed by Singh et al. [16]. The analysis of response surface methodology results in the identification of optimal parameters for precisely controlling the wear and friction properties of the appropriate lubricant. Even the application of a regression model describing the absolute viscosity of oil vs temperature, offered by Toro-Vazquez and Infante-Guerrero [17], gave a reliable heuristic. In recent years, a number of researchers have put proposed approaches to investigating viscosity prediction using the concepts of regression equations. According to the findings of these investigations [4, 18, 19], the viscosity can be precisely and reliably predicted using the regression approach using experimental data. Soon after, Mujtaba et al. [20] used a regression model to build an empirical link for estimating density and viscosity. The conclusion that the regression model fits precisely with the estimation model remains unaltered.

However, no studies have been conducted to look into the effect of the viscosity factor on the surface adhesion rate of lubricants. These two variables had a direct impact on lubrication efficiency, whereas surface adhesion had an influence on film thickness [10, 21–23]. With such significance, the goal of this research was to investigate the effect of the used lubricant viscosity on workpiece surface adhesion. According to the assumption, viscosity has a variable effect on the deterioration of the lubricant and the ageing of mechanical parts. The rate of adherence of oil to the workpiece surface influences the emergence of an oil film [24]. If the rate of oil film-making is slower than the ideal adhesion rate, the surface wear resistance of that part will decrease. In other contexts, surface-attached adhesion rates can be estimated using the regression equations created from the experimental data in this work. The range of viscosities employed here is consistent with the typical viscosity of the unused lubricant. On the assumption of precise knowledge of surface adhesion rates, the obtained relationship model is helpful for choosing the lubrication condition. In the production chain, this is yet another indirect waste reduction.

Methods and experimental work

Preparation method of experimental study

The main equipment utilised in the experiment included three types of used mixed-grade lubricants (Type A, Type B, and Type C), a digital weighing scale, a timer, a video recording device, a glass test tube with a distance bar, and three types of steel balls (3 mm, 3.5 mm, and 4 mm). Figure 1a depicts an example of some steel ball weighing steps. Every weighing requires the balance to be reset to zero, and an example of this process is given in Fig. 1b.

Measurement of lubricant viscosity and rate of surface-attached adhesion

In an experiment that continues from Fig. 1b, a steel ball is dropped into a cylindrical glass test tube travelling vertically through the lubricant in the centre of the orifice glass test tube. The video recording device captured the whole travel of the steel ball to the bottom of the glass test tube in detail. The period of time of this motion is related to the beginning of the release of the steel ball touching to the lubricant surface and finishing when the steel ball reaches the bottom of the glass test tube. To ensure that the observed velocity was constant, the point of initiation of the recording was moved as far away from the surface of the lubricant in the glass test tube as possible. The initial speed recording depth for this operation was 100 mm vertically from

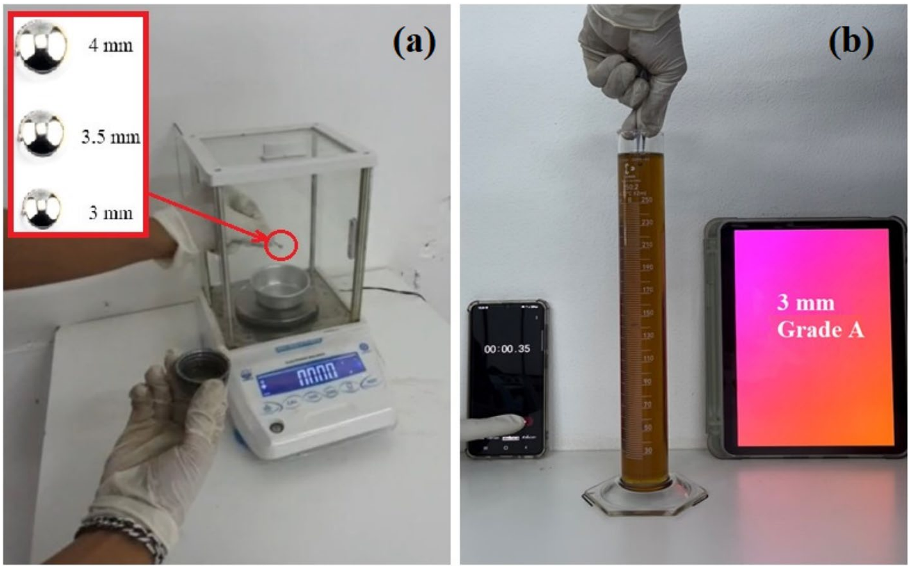

Fig. 1 Equipment preparation and experimental setup. **a** Steel ball weighing. **b** Pre-experiment preparation

the lubricant surface. Every time the experiment is done, the iron ball must be dipped to sink into the entire skin and then allowed to fall down according to independent gravity in order to be free from the impact of the steel ball and the surface on top of the lubricant. Additionally, for the highest possible accuracy of the measurement data, the motion recording was separated into three intervals from the starting point to the final position of the motion. This was done to determine the difference between the speeds of each motion interval. In this experiment, the video recording device and stopwatch were put at the suitable positions in this experiment, the video and time of the experiment could be clearly viewed, and each instance was repeated three times.

Following the experiment and collecting of the experimental results, the experimental data will be input into the calculation using the method shown in the diagram in Fig. 2. The calculation part was divided into two sections, namely the lubricant viscosity calculation section and the rate of surface-attached adhesion mensuration section. Both of these parts use data from the experiment, such as the pre-test weight of the steel ball, the post-test weight of the steel ball, the speed of movement of the steel ball, and the volume of the steel ball. Usually, the surface roughness of the steel ball and the mass loss of the lubricating coating affect the surface adhesion rate measurement accuracy. However, for this work, the surface roughness assumptions for steel balls are almost constant. The experiment employed a brand-new steel ball that had never been used before and was replicated in all instances with the same size steel ball in order that the steel ball's surface roughness was the same across all of the experiments. It is reliable that there will be no difference in the measurement of the lubricant film residual rate caused by the change in surface roughness of the steel balls. By employing the identical steel ball in each trial, it also produced an equivalent compensation for the mass loss of the lubricant film in each case. The lubricant viscosity can be calculated using the equations for the relationship between the speed of movement of the steel ball through the viscous lubricant shown in Eqs. (1) and

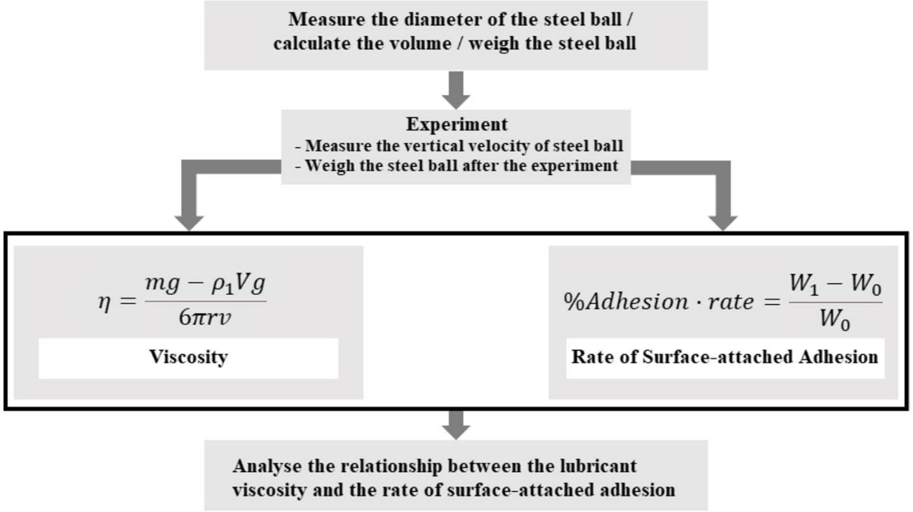

Fig. 2 Schematic diagrams illustrating the experimental procedures and calculations

(2). Meanwhile, the adhesion rate on the workpiece surface is determined from the percentage of the residual rate of the lubricant film coated on the steel ball surface, as stated in Eq. (3). It is a calculated approach applied to the percentage water absorption specified by Ramlee et al. [25].

$$\rho_1 Vg - \eta 6\pi rv = mg \tag{1}$$

$$\eta = \frac{mg - \rho_1 Vg}{6\pi rv} \tag{2}$$

$$\%Adhesion \cdot rate = \frac{W_1 - W_0}{W_0} \tag{3}$$

where

η, viscosity (N s/m^2)
ρ_1, lubricant density (kg/m^3)
V, volume immersed in the lubricant (m^3)
r, radius of the steel ball (m)
v, tip velocity of the steel ball (m/s)
m, mass (kg)
g, acceleration due to gravity (m/s^2)
W_0, weight of the steel ball before the experiment (kg)
W_1, weight of the steel ball after the experiment (kg)

Simple linear regression model

Parameter estimation of a simple linear regression model

A simple linear regression model, as described in Eq. (4), was utilised in this work to assess the association between lubricant Viscosity and rate of surface-attached adhesion. The values of parameters β_0 and β_1 were determined by estimating the outcomes using the least square method. This is because it is an impartial estimate with the lowest variance. As well, it implies that it is certified for accuracy and precision. The fundamental concept behind this estimation approach is to try to calculate the parameters for the regression line in such a way that the uncontrollable causal error in repeated experiments is minimised.

$$\widehat{Y} = \widehat{\beta}_0 + \widehat{\beta}_1 x \tag{4}$$

where

x, variable of viscosity (N s/m^2)

$\widehat{Y}$, variable of rate of surface-attached adhesion (%)

β_0, Y-intercept

β_1, slope

Simple linear regression model analysis requirements

Simple linear regression analysis necessitates data that is assumed to be normal and independent of the distribution error. Due to the mean being 0 and the variance being σ^2, each data set is normally distributed and independent, with a mean of $\beta_0 + \beta_1 x_i$ and a variance of σ^2.

Lack-of-Fit test

The Lack-of-Fit test of the model is crucial to increase confidence in the conclusions of the investigation of the relationship between lubricant viscosity and the rate of surface-attached adhesion. This examines whether the variation in the rate of surface-attached adhesion can be attributed to the viscosity of the lubricant, but it does not imply that a straightforward linear regression model is the most appropriate one for the data. It is required to assess the Lack-of-Fit of the regression model to the fictitious data because the parameter estimates of this regression model cannot know the genuine model of the data.

The main idea behind the Lack-of-Fit test of the regression model on this data is to examine the discrepancy in the data generated by the regression model. If the discrepancy is large, the regression model under consideration is not suited to the data. When the component of the data error induced by the regression model (sum of square error; SSE) is considered, it is discovered that some disagreement exists with data that deviates from the mean or anticipated value of such data. It occurred throughout the data collection process. This amount of mistake is known as the experimental error, and it is written as the pure error sum of squares (SSPE). Therefore, the discrepancy of the data generated by each regression model is more or less, it does not depend on the amount of error from this experiment. However, it is dependent on another parameter, which is the regression approach departure from the mean or actual value of the data. This number of errors is commonly referred to as the model-data asymmetry error, and it is defined as the sum of squares of the model-data asymmetry error (Lack-of-Fit sum of square; SSLOF).

Table 1 Type A lubricant experimental results with various steel ball diameters

Diameter of steel ball (mm)	No	Viscosity (N s/m^2)	Rate of surface-attached adhesion (%)
3	1	0.067	8.56
	2	0.067	8.67
	3	0.066	8.16
3.5	1	0.065	7.76
	2	0.064	7.17
	3	0.064	7.22
4	1	0.062	6.23
	2	0.062	6.33
	3	0.062	6.15

Table 2 Type B lubricant experimental results with various steel ball diameters

Diameter of steel ball (mm)	No	Viscosity (N s/m^2)	Rate of surface-attached adhesion (%)
3	1	0.072	10.61
	2	0.072	10.49
	3	0.071	10.35
3.5	1	0.070	10.15
	2	0.070	10.05
	3	0.069	9.82
4	1	0.069	9.78
	2	0.068	9.64
	3	0.068	9.52

Results and discussion

Experimental results of lubricant viscosity and rate of surface-attached adhesion

The lubricant viscosity and rate of surface-attached adhesion derived from the trials described in the " Methods and experimental work" section are hypothetical experimental results based on the relationship between viscosity and surface adhesion rates. The experimental results could be classified according to the kind of lubrication, i.e., the experimental results of Type A lubricant are presented in Table 1, the experimental results of Type B lubricant are displayed in Table 2, and the experimental results of Type C are provided in Table 3. The experiment was performed three times in each case based on the findings of the three lubricants under the size of the steel ball in the three experimental sizes. Figure 3 depicts all of these measurement results. The results from the studies were shown as straight lines with varying slopes for each lubricant.

However, based on the lubricant viscosity test findings, Type A lubricant had the highest viscosity and Type C had the lowest viscosity. It is also interesting to note that Type A had the highest surface adhesion rate while Type C had the lowest. This is consistent with the assumption that the lubricant viscosity correlates to the rate of surface-attached adhesion.

Table 3 Type C lubricant experimental results with various steel ball diameters

Diameter of steel ball (mm)	No	Viscosity (N s/m^2)	Rate of surface-attached adhesion (%)
3	1	0.077	12.65
	2	0.077	12.54
	3	0.076	12.34
3.5	1	0.076	12.30
	2	0.075	11.92
	3	0.074	11.48
4	1	0.073	11.15
	2	0.073	11.08
	3	0.072	10.86

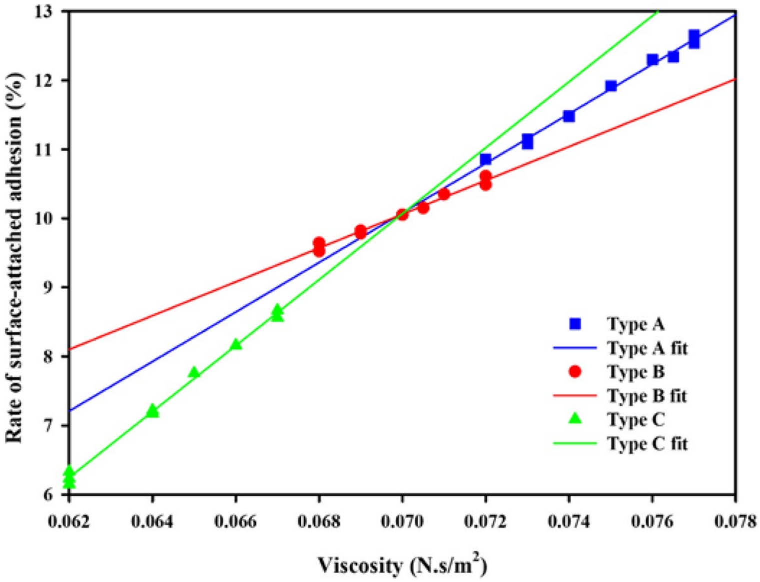

Fig. 3 Experimental data of lubricant viscosity and rate of surface-attached adhesion

Table 4 Analysis of variance results for experimental data of lubricant Type A

Source	DF	SS	MS	*F*	*P*
Regression	1	7.76316	7.76316	1813.19	0.000
Error	7	0.02997	0.00428		
Total	8	7.79313			

Analysis of variance of the experimental data

The linearization outcomes from the experimental data in Fig. 3 could be used to analyse the experimental variance of Type A, Type B, and Type C lubricants, as shown in Tables 4, 5, and 6, respectively. In each lubricant-type experiment, the *P*-value of the analysis of variance was equal to 0.000, which was less than 0.05. This established that

Table 5 Analysis of variance results for experimental data of lubricant Type B

Source	DF	SS	MS	*F*	*P*
Regression	1	1.15261	1.15261	426.93	0.000
Error	7	0.01890	0.00270		
Total	8	1.17150			

Table 6 Analysis of variance results for experimental data of lubricant Type C

Source	DF	SS	MS	*F*	*P*
Regression	1	3.73553	3.73553	917.27	0.000
Error	7	0.02851	0.00407		
Total	8	3.76403			

the lubricant viscosity and rate of surface-attached adhesion exhibited a significant linear relationship at the 95% confidence level.

Confidence analysis for parameters of a simple linear regression model

Another important aspect of the researcher is the results of the confidence analysis for the overall experimental parameters, which is an analysis of process variance of the lubricant-type sub-trials in the " Analysis of variance of the experimental data" section. However, the results of the confidence analysis for the parameters of the simple linear regression model from the entire experimental data were critical in this study to corroborate the experimental design. According to the confidence analysis in the 95% confidence interval of this regression line, the R-Sq value was 98.6%, while the R-Sq(adj) value was 98.5%, as shown in Fig. 4.

Simple linear regression equation analysis with experimental data

The *P*-value of the analysis of variance for the Lack-of-Fit test is displayed in Table 7, with a value of 0.001, based on the simple linear regression analysis with the experimental data using the approach described in the " Lack-of-Fit test" section. A *P*-value less than 0.05 suggests that the model-data asymmetry error is significantly very small, while the *P*-value for the regression line model is 0.000. Thus, at the 95% confidence level, this confirms a linear relationship between lubricant viscosity and the rate of surface-attached adhesion.

Analysis of decision coefficients

Based on the confidence analysis results for the parameters of the simple linear regression model illustrated in Fig. 4. Further in-depth investigation of decision-making under this regression model-based experimental validity analysis can be undertaken by analysing the discrepancies between Sq(adj) and R-Sq values. The accuracy of this regression-based decision-making is determined by the data which demonstrates how much of the variance in the response variable can be explained by the regression-based data. Therefore, it is necessary to consider the decision coefficient. However, the research discovered that the R-Sq value was 98.6% based on the 95% confidence interval analysis of

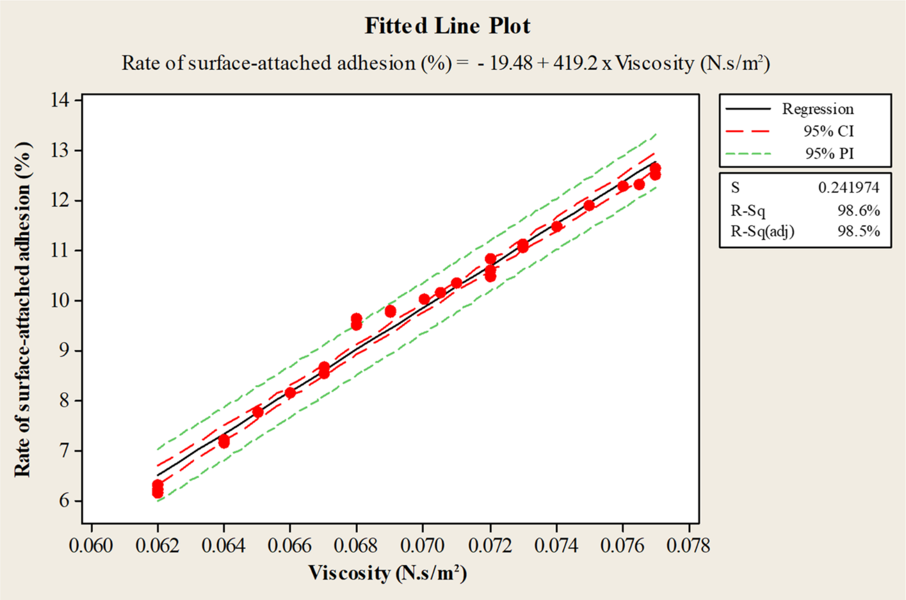

Fig. 4 Confidence interval plot of the regression line

Table 7 Analysis of variance results of the testing Lack-of-Fit to the experimental data

Source	DF	SS	MS	*F*	*P*
Regression	1	101.79	101.79	1738.47	0.000
Error	25	1.46	0.06		
LOF	15	1.35	0.09	8.15	0.001
PE	10	0.11	0.01		
Total	26	103.25			

this regression line. This suggests that the variation in the rate of surface-attached adhesion data of 100% can be explained by a linear relationship with the lubricant viscosity of 98.6%, whereas the R-Sq(adj) value is close to R-Sq. That means there is enough data to analyse the experimental outcomes.

Conclusions

At the significance level of 0.05, it is possible to conclude that there is a linear relationship between lubricant viscosity and the rate of surface-attached adhesion. This was corroborated by the findings of the *P* value of the experimental analysis of variance for each oil, which was less than 0.05, proving the linear relationship between lubricant viscosity and the rate of surface-attached adhesion. The analytical results of R-Sq were 98.6% under the 95% confidence interval analysis of this regression line, whereas R-Sq(adj) was 98.5%. It demonstrates that the R-Sq value and the R-Sq(adj) value differ slightly. This signifies that enough data was obtained in this work to analyse the results. However, the error from the Lack-of-Fit test was significantly small, with the *P*-value of the regression line model equal to 0.000. This again supports the hypothesis at the 95% confidence level that there is a linear relationship between the lubricant viscosity and the rate of surface-attached adhesion. Accordingly, the findings of this study could potentially be used as a source of data to support the hypothesis that the rate of surface-attached adhesion and lubricant viscosity are correlated. This information helps the industry manage the use of oil in lubricating industrial parts, making decisions about replacement or evaluating the quality of the lubricant to see if it is still usable or has degraded. To maintain lubrication efficiency and increase the service life of industrial parts. However, the lubricant viscosity range studied in this work is the lubricant viscosity range that is still close to typical operating circumstances. But when lubricant viscosity is the only factor taken into account, too low or too high a lubricant viscosity would result in subpar lubrication performance.

Abbreviations

SSE	Sum of square error
SSPE	Pure error sum of squares
LOF	Lack-of-Fit
SSLOF	Lack-of-Fit sum of square
R-Sq	R-squared
R-Sq(adj)	Adjusted R-squared

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Author's contributions
TJ conceptualised, investigated, determined methodology, designed a data management plan, supervised, reviewed, analysed, and visualised the data, and was a major contribution to the article.

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Availability of data and materials
The datasets are available from the corresponding author on reasonable request.

Declarations

Competing interests
The author declares no competing interests.

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