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EVALUATION OF OLIVE OIL AS LUBRICANT WITH THE HELP OF FOUR-BALL TESTER

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ABSTRACT

This paper presents a statistical evaluation of the experimental data obtained after a tribological study on extravirgin olive oil, in order to point out the lubricating behavior of this vegetal oil. The resulted mathematical models underlined the influence of the sliding speed and the load on the wear scar and the friction coefficient. Tests were done on a four-ball machine (SR EN ISO 20623:2004). The authors also studied the influence of the temperature and shear speed on the dynamic viscosity of this olive oil.

Keywords: lubricant, biodegradable, olive oil, wear, viscosity, shear rate.

1. Introduction

The main objective of a lubricant is to reduce frection an wear. But also, it is responsible for heat evacuation [1]. Taking into account their nature, there are mineral, synthetical, vegetal or animal lubricants. Untill the XIX-th century, the manufacturing process of lubricants has been based on vegetal and animal recources. In southern country, the olive and corn poppyoils were used meanwhile in northern country the rapeseed oil was used [2]. These oils have a high degree of biodegradability even today. But when the mankind has discovered that oil could be processed for having lubricants and fuels at acceptable costs, the importance of vegetal resources had been reduced, but these petroleum-based lubricants has a strogly negative impact on the environment.

Thousands of years, this oil was used for cooking, cosmetics and soap, but also as fuel for lamps. Olive oil has been the most characteristic fat used in the Mediterranean region; it is obtained from the fruit of several cultivators of olive tree (Olea europaea L). Each one of these cultivars exhibits specific physical and biochemical characteristics, providing oils with different compositions and performances [3], [4]. The olive oil is a mixture of tri-, di- and mono-glicerides, being an important source of fat acids and natural antioxidants (polyphenols and tocopherols). This oil contains saturated, unsaturated and poly-unsaturated fat acids, especially as esters with glicerol, these representing over 98% of the olive oil [5]. The concentrations of fat acids volatile substances in the olive oil are influenced by several factors, such as: the degree of maturation of the olive fruits, the storage conditions, the equipment and manufacturing process involved in getting the oil, and also the climate and the soil the plants have been cultivated in. [6], [7], [8].

The physico-chemical characteristics of the olive oil are: refraction index 1.4677–1.4705; the mass fraction of water and volatile substances 0.2%, the mass fraction of the impurities other than those from the fats (mass sediment) 0.1%, saponification index = 184-196 mg KOH/g, iodine index = 75-94 g I_2/100g, mass fraction of non-saponifiable substances max 15%, relative density at 20ºC = 0.910 - 0.916; 20 mmol oxigen activ/kg [9].

2. Experimental Details

The tribological study was done with the help of a four-ball machine that exists in the oil laboratory LubriTest of „Dunarea de Jos" University of Galati and it may do tests under the procedure of SR EN ISO 20623:2004 (fig. 1). This machine has the main elements: electric engine (1), machine body (2), loading system (3), electric pannel for tunning and monitorization (4) and support (5). The four ball machine provide a sliding motion on the four balls (fig. 2) and it has a vertical shaft este whicih ends with an assembly (1), allowing for mounting and fixing the mobile ball (2). This mobile ball is acting on the other balls, fixed into a cup with the help of a thread piece (4) and a conical element (5) [10]. The load is done through the action of a lever (3), see Fig. 1. One end of the lever is acting on the cup containing the fixed balls and the other e the othe diversend could be charged with known weights.

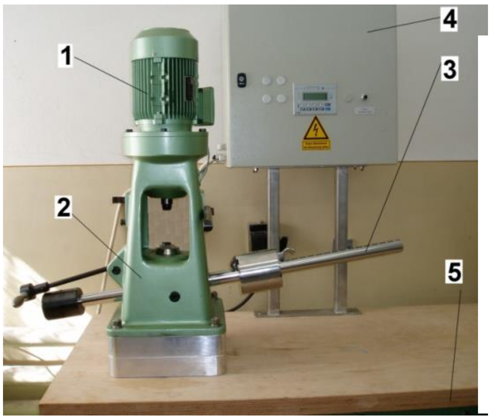

Fig. 1. The four ball machine from the oil laboratory LubriTest (without the testing system)

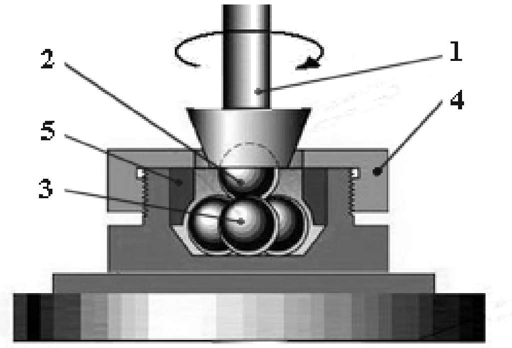

Fig. 2. Main elements of the testing area [10]

In order to measure the friction force, the authors designed and put into practice a system containing a tensometric bridge (connecting the machine body and the arm of the cup housing the fixed balls); its signal is processes by a data acquisition system type Scout 55 and then transmitted to a computer. The data acquisition and their processing are done with the help of the program CATMAN® EXPRESS 4.5. The values of the friction force are then used for calculating the friction moment and the friction coefficient.

The diameters of the four balls have the value of 12.7 mm (1/2"). The balls were delivered by SKF and they are made of ballbearing steel (Table 1), with a special treatment, having a high accuracy of the diameter (±0.0005 mm), high value of hardness and a fine quality of the surface texture (*Ra* = 0.02 ... 0.03 μm).

Table 1. Chemical composition (wt%) and the hardness of the steel balls (type SKF)

Material	C	Cr	Mn	Si	S	P	VHN
Steel grade EN31	1.0	1.3	0.5	0.35	0.05	0.05	805

For this study, the four ball machine was used for measuring the following parameters:

- diameters of the wear scars generated on the fixed balls,
- friction force and moment generated due to the movement of the mobile ball acting on the fixed balls,
- friction coefficient.

These parameters reflect the tribological behavior of the studied oil.

The test parameters were:

- loading force – 140 N, 200 N and 260 N;
- the angular speed of the main axle of the four ball machine - 800 rev/min and 1200 rev/min; the corresponding sliding speed for these angular speeds are 0.307 m/s and 0.461 m/s, respectively;
- test duration - 60 minutes.

Taguchi method was used for statistically analyzing the experimental data and for studying the dependence between input parameters, (sliding speedand load of the tribotester) and and output ones (diameter of wear scar and the friction coefficient. The authors also used intruments type DOE (Design of Experiments) and general notions os statistics of a dedicated software, Minitab Statistical Software [11], [12], [13].

The structure of the testing program includes the following steps in order to make the data acquisition and interpretation by statistical methods:

- identification of input parameters of the test program;
- study on the simultaneous influence of two independent input variables on an output one, using a dispersion analysis or a variance analysis (ANOVA) and the determination of the regression equation;
- calculation of the difference between the measured data and the theoretical ones, corresponding to each experiment (rezidues) [16], [14].

Applying a linear regression, a linear model was obtained that could express a relation between the input parameters characterizing the tribological process (load, alising speed) and the output parameters (diameter of the wear scar and friction coefficient). The regression using the method of least squares is the most used method for modeling [11], [14].

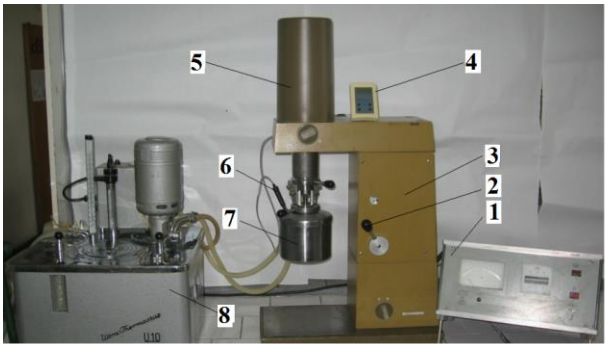

Fig. 3. Rheotest 2

In order to determine the variation of dynamic viscosity with temperature and shear speed, the equipment Rheotest 2 was used (Fig. 3). The equipment Rheotest2 is made of: 1

– commanding and measuring module, 2 – speed switchă, 3 – body, 4 – electronic thermometer, 5 – engine, 6 – thermometer support, 7 – enclosure for the cylinders, 8 – thermostate bath. The oil temperature varies between 30ºC and 90ºC, by a step of 10ºC, the tests being done for three shear speeds: 6 s^{-1}, 18 s^{-1} and 50s^{-1}.

3. Experimental Results

Table 2 presents the experimetal program and the input parameters involved in the friction process (the sliding speed and the normal load) and the output ones (the average diameters of the worn track and the friction coefficient).

Tables 3 and 4 present the values obtained for the diameters of the wear scars as average of the values recorded for a set of fixed balls, for the olive oil used as lubricant.

As concerning the dispersion of the experimental data, the authors take into account a simultaneous analysis of the independent variables, obtaining information referring to the influence of each factor, but also information on how they interact, thus expressing a synergic effect.

Table 2. Experimental results when lubricating the four-ball tribotester with the olive oil

Test number	Test parameters		Output test parameters	
	Speed [m/s]	Load [N]	The average diameter of the worn tack [mm]	The friction coefficient
1	0.307	140	0.4567	0.1042
2	0.307	200	0.4965	0.1077
3	0.307	260	0.5324	0.1003
4	0.461	140	0.4352	0.0952
5	0.461	200	0.5418	0.1113
6	0.461	260	0.5738	0.0919

Table 3. Analysis of the experimental data obtained for the average diameter of the wear scar, using the olive oil as lubricant

Parameter	DF	Seq SS	Adj SS	Seq MS	F	P	P%
Sliding speed [m/s]	1	0.0007085	0.0007085	0.0007085	1.01	0.421	5.03
Load [N]	2	0.0119946	0.0119946	0.0059973	8.53	0.105	85.02
Error	2	0.0014056	0.0014056	0.0007028			
Total	5	0.0141088					
S = 0.0265108, R-Sq = 90.05%							

In order to determine the influence of the input parameters of the tribosystem and the relevant interactions, for the average diameter of the wear scars and the friction coefficient, the weight, P%, was calculated from Tables 3 and 4. Thus, it results that the parameter having a significant influence upon the average diameter of the wear scars is the load (85.02%), the sliding speed having a much lower influence (5.03%). As concerning the friction coefficient, a greater influence is given by the load (70.59%). The sliding speed influences less the friction coefficient (11.27%). These conclusions are valid for the studied ranges for the input parameters. The authors do not recommend the extrapolation outside the tested ranges for the output parameters.

The codes for parameters in Tables 3 and 4 are: DF - degrees of freedom, Adj SS – ajusted sum of squares (the sum of adjusted standard deviations); MS – the mean square (is an ANOVA expression of the sample dispersion); F – F ratio ANOVA; R-Sq - correlation coefficient, S - the sample standard deviation.

Table 4. Values of the friction coefficient when testing the olive oil as a lubricant in the four-ball tribotester

Parameter	DF	Seq SS	Adj SS	Seq MS	F	P	P%
Speed [m/s]	1	0.0000308	0.0000308	0.0000308	1.24	0.381	11.27
Load [N]	2	0.0001932	0.0001932	0.0000966	3.89	0.204	70.59
Error	2	0.0000497	0.0000497	0.0000248			
Total	5	0.0002737					
S = 0.00498264, R-Sq = 81.86%							

The equations of the average diameter of the wear scar and of the friction coefficient, as obtained as linear regressions, ($D_{ws,\ olive}$) and (Cof), for the olive oil used as lubricant, have the following forms:

$$D_{ws,olive} = 0.273291 + 0.141126 \cdot v + 8.92917 \cdot 10^{-4} \cdot F \ [mm] \quad (1)$$

$$Cof = 0.118871 - 0.0294372 \cdot v - 2.91667 \cdot 10 \cdot F \quad (2)$$

where v is the the sliding speed [m/s] and F is the load [N] on the four ball tribotester. Figures 4 and 5 present the residue probability diagrams for a confidence level of 95%, for the output data $D_{ws,\ olive}$ and Cof, as a difference of between the theoretical and experimental response of each tests.

The graphical representations in Figures 4 and 5 point out that the average values of wear scars, $D_{ws,olive}$, and the friction coefficient, Cof, as obtained from the tests, are within the recommended confidence space.

Using the linear regression equations (1) and (2) established by ANOVA variance, defining the values for the average diameter of the wear scars, D_{ws}, and for the friction coefficient, Cof, a comparing analysis was done. Thus, Tables 5 and 6, present the values obtained for the average diameter of the wear scars ($D_{ws,olive}$) and for the friction coefficient (Cof), as experimentally obtained, but also the predicted values, as given by the regression model and the errors calculated as differences between the experimental and theoretical values.

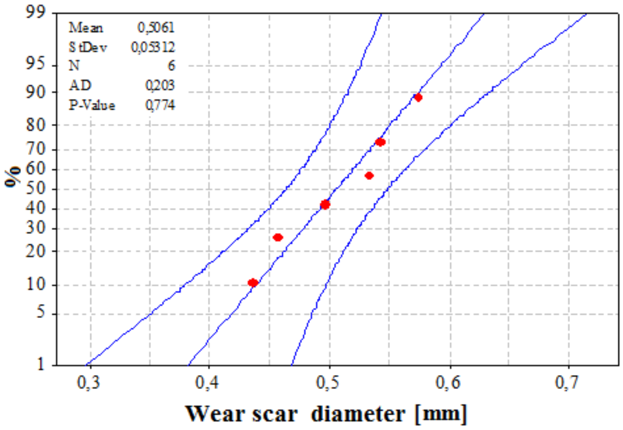

Fig. 4. Probability diagram of the residues for $D_{ws,\ olive}$

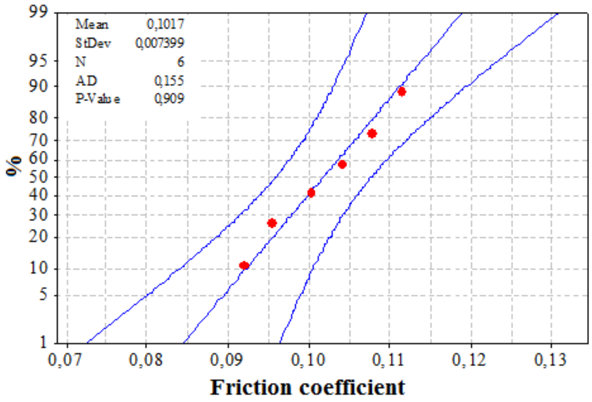

Fig. 5. Probability diagram of the residues for Cof

The prediction error given by the linear regression model for the average value of the wear scars was calculated with the help of the following relation:

$$\text{Erroro} = \frac{\left| D_{ws,\,measured} - D_{ws,\,calculated} \right|}{\max\left(D_{ws,\,measured}, D_{ws,\,calculated} \right)} \cdot 100 \quad [\%]\ [\%] \qquad (3)$$

Table 5. Values of the average diameter of the wear scars when using the olive oil as lubricant

Sliding speed [m/s]	**0.307**			**0.461**		
Load [N]	**140**	**200**	**260**	**140**	**200**	**260**
$D_{ws,\ measured}$ [mm]	0.4567	0.4965	0.5324	0.4352	0.5418	0.5738
$D_{ws,\ calculated}$ [mm]	0.441625	0.4952	0.5487751	0.463358	0.516933	0.570509
Error D_{ws} [%]	**3.3**	**0.26**	**-2.9**	**-6.47**	**4.59**	**0.57**

Table 6. The values of the friction coefficient on four-ball machine, obtained for tests done with the olive oil

Sliding speed [m/s]	**0.307**			**0.461**		
Load [N]	**140**	**200**	**260**	**140**	**200**	**260**
$Cof_{measured}$	0.104	0.1077	0.1003	0.0952	0.1113	0.0919
$Cof_{calculated}$	0.10575	0.104	0.10225	0.101217	0.099467	0.097717
Error *Cof* [%]	**-1.68**	**3.43**	**-1.94**	**-6.32**	**10.63**	**-6.31**

For a satisfactory statistical analysis, the value of the prediction error has to be less than 20% [14], [11]. Analyzing the values of prediction errors (Tables 5 and 6), one may notice these are between 0.26% and 10.63% and are less the values recommended by an acceptable tolerance in statistics [14], [11]. The average of the prediction errors for each equation is 3.02% for the equation describing the average diameter of the wear scars and 5.05% for the equation describing the friction coefficient.

Figure 6 presents the dependence of the dynamic viscosity with temperature, for the shear speeds of 6 s^{-1}, 18 s^{-1} and 50 s^{-1}. One may notice that the dynamic viscosity decreases when the temperature increases, this behavior being pointed out also in the works [15], [16], [17], for other vegetal oils. The temperature increase tends to intensify the intermolecular movement and to reduce the atraction forces among the oil molecules. The decrease of the dynamic viscosity with the temperature increase is influenced in a greater manner by the effect of reducing the atraction forces than the effect produced by intermoleculary movement in the oil [18].

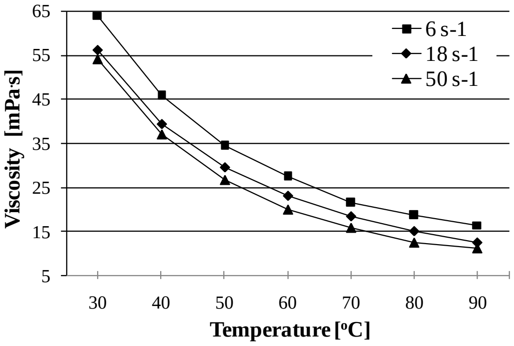

Fig. 6. The viscosity dependence on temperature for the tested olive oil, for three values of the shear speed

For the temperature range of 30ºC – 60ºC, a more accentuated decrease of the viscosity was noticed as compared to that obtained for the temperature range of 60ºC – 90ºC. For the olive oil, tested at the shear speed of 50 s^{-1}, in the temperature range of 30ºC – 60ºC, the decrease is of 63%, meanwhile, for the temperature range of 60ºC – 90ºC, the decrease is only with 44.4%. On the entire temperature range, for the shear speed of 6 s^{-1}, the percentage variation of the dynamic viscosity was 74.4%, but for the values of shear speed of 18 s^{-1} and 50 s^{-1}, it was 77.8% and 79.5%, respectively. The increase of the shear speed produces a more accentuated decrease of the dynamic viscosity with the oil temperature.

The variation of dynamic viscosity with temperature was put into the form of Pentru a Andrade equation [19], [20], [21], [22]:

$$\eta = A \cdot \exp^{\frac{B}{T}} \tag{4}$$

where T is the absolute temperature and A and B are constant of the material.

Applying a logarithm to equation (4), it results:

$$\ln \eta = \ln A + \frac{B}{T} \tag{5}$$

The last equation is used for making linear the equation (4). Applying the method of least squares to process the experimental data and considering that 1/T is a variable for temperature, the values presented in Table 6 are obtained.

Esteban et al. [21] recommend the Azian equation (6) [23], deriving from equation (5), this equation being useful when analysing the viscosity variation on large ranges of temperature.

$$\ln \eta = A + \frac{B}{T} + \frac{C}{T^2} \tag{6}$$

Comparing the correlation factors as determined after generating Andrade and Azian equations (Table 7), one may notice values closer to unit when using the Azian equation. The authors do not consider necessary to look polynimial function of higher order as the correlation coefficients are high enough, having values between 0.99967 and 0.99989. The

Azian equation approximates very well the experimental, putând fi utilizată pentru a determina variaţia vâscozităţii uleiurilor cu temperatura.

Table 7. Valorile parametrilor ecuaţiilor Andrade si Azian

Shear speed [s^{-1}]	**Type of equation**	**lnA/A**	**B**	**C**	**Correlation coefficient**
6	Andrade ($\ln \eta = \ln A + B/T$)	-4.20914	2516.723	-	0.99433
	Azian ($\ln \eta = A + B/T + C/T^2$	10.9162	-7520.305	$1.6591 \cdot 10^6$	0.99967
18	Andrade ($\ln \eta = \ln A + B/T$)	-5.01956	2726.198	-	0.99789
	Azian ($\ln \eta = A + B/T+C/T^2$)	4.98513	-3912.773	$1.0974 \cdot 10^6$	0.99989
50	Andrade ($\ln \eta = \ln A + B/T$)	-5.7936	2945.621	-	0.99531
	Azian ($\ln \eta = A+ B/T+C/T2$)	10.2145	-7677.311	$1.7559 \cdot 10^6$	0.99969

4. Conclusions

The authors used Taguchi method for a statistical analysis of the experimental results and for studying the dependence between input variables (sliding speed and trobotester load) and the output parameters (average diameter of the wear scars and the friction coeffiecient). For this porpuse, instruments like DOE (Design of Experiments) and general statistics were used, Minitab Statistical Software.

Taking into account this analysis, the parameter having a significant influence upon the value of the wear scar diameter is the load (85.02%) while the sliding speed has a lower influence (5.03%). As concerning the friction coefficient, the higher influence is given by the load, too (70.59%), the sliding speed having a share of only 11.27%.

The dynamic viscosity decreases with the increase in olive oil temperature vâscozitatea, the phenomenon being noticeble for all three tested shear speeds. For the temperature range of 30ºC – 60ºC, there was noticed a more accentuated decrease of the dynamic viscosity as comparedt obtained for the range of 60ºC – 90ºC.

The analysis of the viscosity dependence on temperature was done using Andrade and Azian equations, the results having very good correlation coefficients when using Azian equation; the authors pointed out that this one gave the best approximations for the experimental data.

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