A Comparative Experimental Analysis of Tribological Properties Between Commercial Mineral Oil and Neat Castor Oil using Taguchi Method in Boundary Lubrication Regime

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A B S T R A C T

The present work aims to carry out a comparative experimental analysis of tribological properties of 372cSt mineral oil and 229cSt castor oil. The antiwear and extreme pressure properties of both the oils have been analysed according to ASTM G 99 and ASTM D-2783 standards. The surfaces of the balls and pins after tribo tests have been analysed using Scanning Electron Microscope (SEM) images. The present test results predict that the antiwear and extreme pressure properties in case of the selected commercially available mineral oil are better than neat castor oil. Both coefficient of friction and frictional force increased by 16-42 % and 16-35 % respectively in case of neat castor oil as compared with that of the mineral oil. The load carrying capacity in case of mineral oil has been found to be 250 kg while in case of castor oil it has been found to be 126 kg. SEM images show a higher plastic deformation in case of castor oil as compared to the mineral oil. Both mineral oil and castor oil showed surface deteriorations and increase in roughness after 40 hrs of intermittent running during scuffing test. Thus, the present investigation indicates that the tribological properties of neat castor are inferior to that of mineral oil although close observation of the results shows that both AW and EP properties of neat castor oil are much closer to that of commercial mineral oil. Thus, the present work would help in formulating castor oil based new bio lubricants with better anti wear and extreme pressure properties.

1. INTRODUCTION

Lubrication is one of the most important factors in all process plants. With the increase in higher production rate the usage of lubricants has also increased during the past few years. Mineral oil has been used for a long time but now with the increase in environmental issues researchers are trying to develop eco-friendly lubricants, among which vegetable oils are of real interest because of their biodegradability, higher lubricity, suitably lower coefficient of friction and

frictional force, lower volatility, ease of availability and lesser cost. But the main question is, whether the vegetable oils can be used in their pure form or they need to be blended with other lubricants or addition of micro or nano-additivants. In almost all the investigations that have been reported [1,2] the vegetable oils have been blended with other lubricants or with different additives [3-5] and experiments have been carried out for the blended mixture. Jayadas [6] compared the tribological properties between coconut oil (both neat and additivated) and two stroke engine oil and observed a considerable reduction in wear in case of additive based coconut as compared to the two stroke oil. Bekal et al. [7] studied the tribological behaviour of neat pongamia oil, a blend of pongamia oil with mineral oil and neat mineral oil and predicted that the best results were obtained using the neat pongamia oil both as fuel and lubricant. The experiments were carried out with an objective of using pongamia oil as an alternative to mineral oil in IC engines. Ossia et al. [8] investigated the lubricity properties of eicosavoic acid in castor oil and the results were compared with those of zinc dialkyl dithiophosphate (ZDTP) and octadecanoic acid and found the former to have better tribological properties than the later additives. The increase in the use of vegetable oils as potential cutting fluids has been reported by many investigators. Elmunafi et al. [9] investigated the performance of minimum quantity lubrication using castor oil and predicted better performance of castor oil in terms of tool life. Results of eminent researchers [10,11,12,14] predict the superior performance of vegetable oils in both boundary and hydrodynamic regimes. This superior anti wear behaviour of vegetable oil is due to the strong film formation tendency of vegetable oils with lubricated surfaces which is the result of the amphiphilic nature [13,14]. Sanchez et al. [15] characterized many formulation based on castor oil and other biogenic thickeners and compared them with traditional lithium grease. They predicted that castor oil provided lower co-efficient of friction as compared with the traditional lithium based grease.

The present work investigates the tribological properties of commercially available mineral oil and neat castor oil. No additives have been added to the castor oil. The main objective of the present work is to find the tribo-efficiency of neat castor oil with respect to commercially available mineral oil. The present work would help in developing new biodegradable castor oil lubricants.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

2.1 Base oils

Commercial mineral oil (MCO) and neat castor oil (NCO) have been chosen. Mineral oil with viscosity of 372cSt is selected as very commonly used lubricant oil in heavy gear boxes in process plants. Castor oil has been chosen as it is biodegradable, non-edible and is easily available. Both these oils were procured from local vendors in Chennai, India.

2.2 Pin material

EN24 is a common gear-material. It has been used in untreated state (24 HRc) as pin material for pin-on-disc tribometer. The pins were of 10 mm diameter and 30 mm in length.

2.3 Antiwear test

A pin-on-disc (Make: Magnum, Model No. TE-POD-165LE) tribometer has been used to analyse the antiwear property of both mineral oil and castor oil. EN31 disc (hardness 58-60 HRc) is used as disk material. In order to maintain thin /boundary lubrication [16], oil was supplied dropwise at a rate of one drop per five seconds. Tests were conducted under different loads and velocity (rpm). All the samples were cleaned with acetone before and after the experiments. Each test was performed five times and an average value of the test result has been shown.

2.4 Extreme pressure test

In order to investigate the extreme pressure properties of the lubricant oils a four ball tester (Make: DUCOM, Model: TR-30L) has been used according to ASTM D 2783 standards. The test was conducted for approximate 10-15 seconds with a spindle speed of about 1770 rpm. Steel balls of AISI 52100 of diameter 12.7 mm, grade EP 25 and hardness 64-66 HRc have been used for the tests. All steel balls were thoroughly cleaned and dried before and after the experiments with industrial cleaner and degreaser.

2.5 Scuffing test

In order to compare the scuffing resistivity of MCO and NCO, in-house scuffing equipment was fabricated. A 1Hp 440v AC power motor is used to supply power to the test-rig and the speed is controlled using the variable frequency controller. The motor and the driving shaft are connected with the help of couplings. A weight hanger is provided on the driven shaft. The idle gear set was greased for smooth operation. It had to be ensured that the idle set does not wear out sooner than the test pair. After ensuring proper lubrication in all the bearings and the gear set, the test pair was given drop lubrication for boundary lubrication. This condition was monitored and assured every time the machine was operated. After arranging the drop lubrication, the ac drive controller was powered on from the three phase power supply. The experiments were conducted at 140 KN, 40 hours. The tooth flanks were inspected after every regular interval (40-45 minutes) for scuffing marks.

2.6 Viscosity, fire and flash point tests

Viscosity, fire and flash points are important properties of any lubricant. In the present work viscosity was measured using a Redwood viscometer and fire and flash points were measured using Pensky martin closed cup method (castor oil) and Cleveland open cup method (mineral oil).

2.7 Design of experiments for pin-on-disc

Taguchi design of experiment technique enables us to model the experiments and analyse the influence of various parameters. In the present work, load and rpm have been considered as design parameters. The coefficient of friction and frictional force have been considered as outputs or responses. Three levels within the operating range of parameters have been selected for each of the factors. In the present work, L9 orthogonal array has been considered for experiments as shown in Table 1.

Table 1. L9 orthogonal array.

Experiment No.	Load (N)	RPM
I	140	500
II	140	800
III	140	1100
IV	150	500
V	150	800
VI	150	1100
VII	160	500
VIII	160	800
IX	160	1100

2.8 ANOVA analysis

The purpose of analysis of variance (ANOVA) is to predict the significant factors affecting the responses and thus, has been used in this work.

3. RESULTS

3.1 Analysis of Viscosity, Flash and Fire Points

Viscosity is an important factor in determining the formation of lubricant film. In the present work, the viscosity has been measured at 40 ^{0}C and 100 ^{0}C using Redwood viscometer. As observed from Table 2, the viscosity of neat castor oil is less than mineral oil but both flash and fire points in case of castor oil is higher than mineral oil.
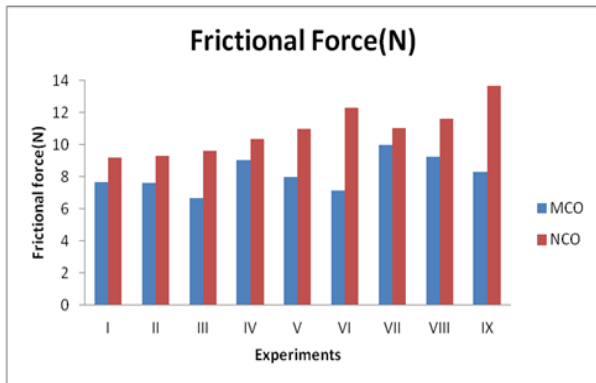
3.2 Antiwear test

The antiwear tests were carried out using a pin-on-disc tribometer. As observed from Fig. 1 and Fig. 2, both frictional force and coefficient of friction in case of mineral oil are less as compare to neat castor oil. Further, it can also be observed that the coefficient of friction and frictional force decreases with the increase in speed while in case of castor oil both coefficient of friction and frictional force increases with the increase in speed for each load (Fig. 2).

Table 2. Properties of mineral oil and castor oil.

Lubricants	Viscosity at 40 ^{0}C (cSt)	Viscosity at 100 ^{0}C (cSt)	Flash point ^{0}C	Fire Point ^{0}C	Viscosity Index
Mineral oil	372.31	47.17	210	220	187
Castor Oil	229.32	18.10	284	296	85

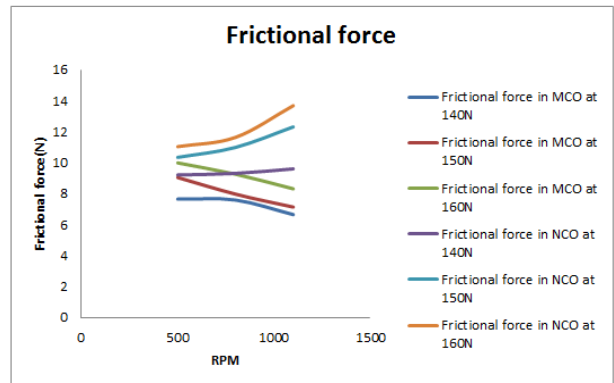**Table 3.** Coefficient of friction, frictional force and S/N ratio for MCO.
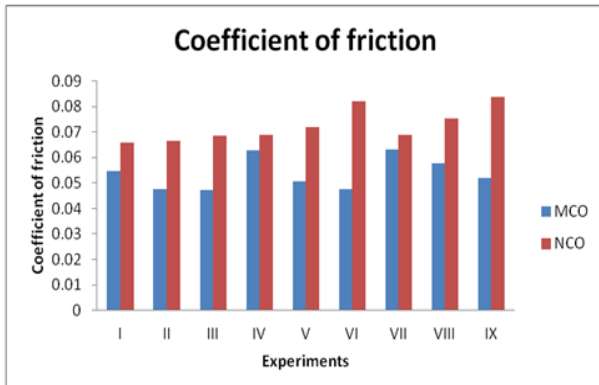
Experiment No.	Load (N)	RPM	Coefficient of friction	Frictional force (N)	S/N ratio for coefficient of friction	S/N ratio for frictional force
I	140	500	0.0546	7.65306	25.2561	-17.6767
II	140	800	0.0477	7.58950	26.4296	-17.6043
III	140	1100	0.0472	6.65402	26.5212	-16.4617
IV	150	500	0.0627	9.04590	24.0546	-19.1290
V	150	800	0.0505	7.97130	25.9342	-18.0306
VI	150	1100	0.0477	7.13687	26.4296	-17.0702
VII	160	500	0.0630	9.98930	24.0132	-19.9907
VIII	160	800	0.0578	9.26080	24.7614	-19.3330
IX	160	1100	0.0519	8.31480	25.6967	-18.3970
Mean (μ)					25.4551	-18.1881

Table 4. Coefficient of friction, frictional force and S/N ratio for NCO.

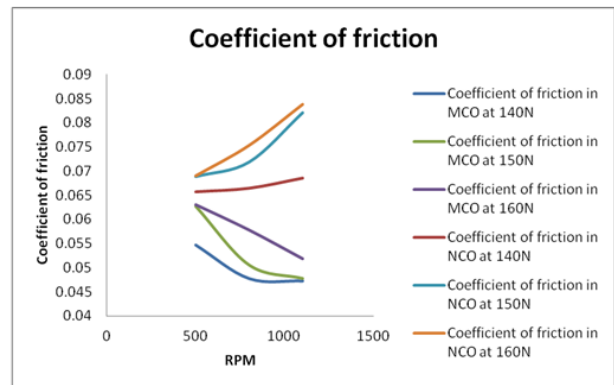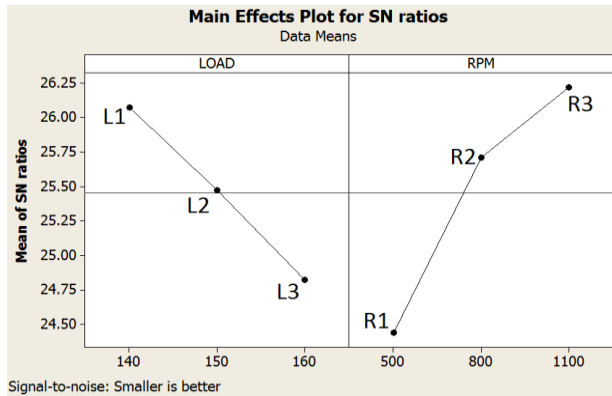| Experiment No.	Load (N)	RPM	Coefficient of friction	Frictional force (N)	S/N ratio for coefficient of friction	S/N ratio for frictional force
I	140	500	0.06570	9.2102	23.6487	-19.2854
II	140	800	0.06646	9.3080	23.5488	-19.3771
III	140	1100	0.06859	9.6031	23.2748	-19.6483
IV	150	500	0.06892	10.3436	23.2331	-20.2934
V	150	800	0.07192	10.9866	22.8630	-20.8173
VI	150	1100	0.07910	12.3123	22.0365	-21.8068
VII	160	500	0.06895	11.0366	23.2293	-20.8567
VIII	160	800	0.07530	11.6352	22.4641	-21.3155
IX	160	1100	0.08381	13.6811	21.5341	-22.7224
Mean (μ)					22.8702	-20.6803

a)

a)

b)

b)

Fig. 1. a) Frictional force; b) Co-efficient of friction.

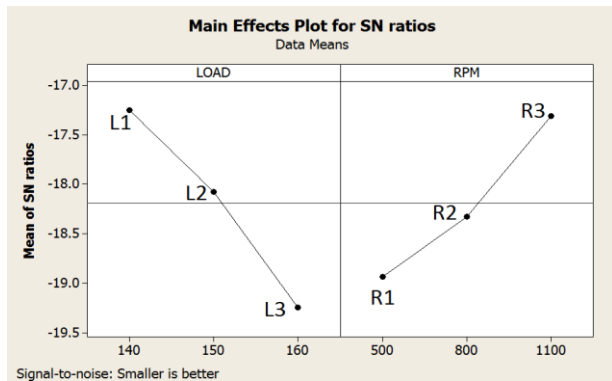**Fig. 2.** a) Frictional force Vs RPM; b) Coefficient of friction Vs RPM.

As stated earlier, three levels L9 orthogonal array has been considered for experimentations. The experimental values along with the design matrix are shown in Table 3 and Table 4. The S/N ratio is calculated based on quality of characteristics. The objective function of this investigation is to minimise the coefficient of friction and frictional force between two interacting surfaces. Thus, the smaller (the best) S/N ratio is indicative according to the formula:

$$\frac{S}{N} \text{ratio}(\eta) = -10\log_{10}\frac{1}{n}\sum_{i=1}^{n} y^2 \qquad (1)$$
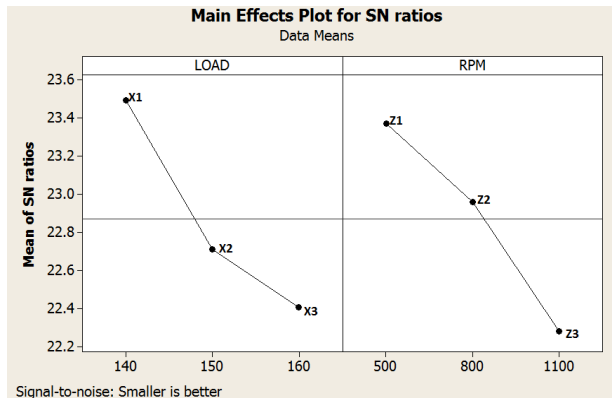
where n – no. of experiments, y - no. of response value. Minitab 16.2.4 software was used to estimate the parameters shown in the present work.
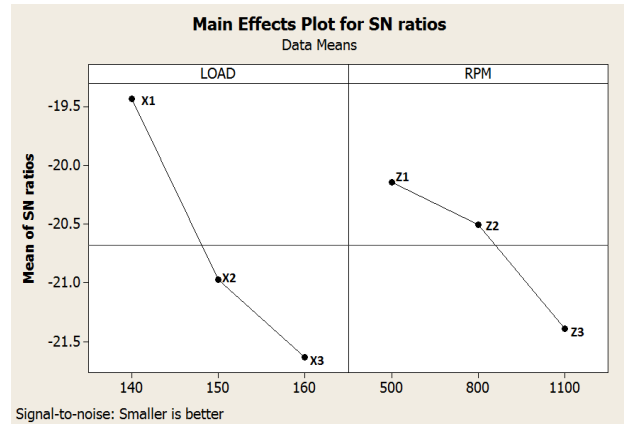

a)

b)

c)

d)

Fig. 3. Factor effect diagram for a) coefficient of friction in case of mineral; b) frictional force in case of MCO; c) coefficient of friction in case of castor oil; d) frictional force in case of NCO.

As observed from Fig. 3, the optimum level setting of parameters are L1-R3 for co-efficient of friction and frictional force in case of mineral oil and X1-Z1 for coefficient of friction and frictional force in case of castor oil.

The predicted S/N ratio (η') using the optimal levels of control parameters can be calculated as:

$$\eta' = \eta_m + \sum_{i=1}^{p} \eta_i - \eta_m \qquad (2)$$

where: η_m - total mean of S/N Ratio; η_i - mean of S/N Ratio at the optimum level; p - is the number of main parameters that significantly affect the performance.

Thus, from the above definition (Table 5):

Predicted value of coefficient of friction using MCO = 0.04552.

Predicted value of frictional force using MCO = 6.5855 (N).

Predicted value of coefficient of friction using NCO = 0.06316.

Predicted value of frictional force using NCO = 8.8203(N).

Table 5. Predicted and Experimental values for MCO and NCO.

Parameters	MCO		NCO	
	Predicted Value	Experimen. Value	Predicted Value	Experimen. Value
Coefficient of friction	0.04552	0.0472	0.06316	0.06570
Frictional force(N)	6.5855	6.65402	8.82033	9.2102

3.3 ANOVA analysis

The purpose of ANOVA analysis is to find the significant factors affecting coefficient of friction and frictional force. The ANOVA table is calculated as shown in Tables 6-9.

The p-value in case of load and RPM in both mineral and castor oil is very close to 0.05, hence, both load and rpm have roles to play in minimizing the coefficient of friction and frictional force. The higher R^2 value indicates that the selected model fits the data in

determining the frictional force at the interface of the two mating bodies in both MCO and NCO.

The normal probability plot shown in Fig. 4 is the result of testing of normality of the experimental results and it shows the predicted versus actual values for the design matrix. For any ANOVA analysis it is very much important that the normal probability plot should be closer to the mean line. As observed from Fig. 4 all the experimental values are much closer to the mean line.

Table 6. Results for ANOVA analysis for coefficient of friction using mineral oil.

Parameters	Degree of freedom	Sum of Squares (SS)	Mean Square (MS)	F	P	% contribution
Load	2	0.000089716	0.000044858	7.66	0.043	28.67
RPM*	2	0.000199709	0.000099854	17.06	0.011	63.83
Error	4	0.000023411	0.000005853			
Total	8	0.000312836				

*significant factor
S = 0.00241925   R-Sq = 92.52 %   R-Sq (adj) = 85.03 %

Table 7 Results for ANOVA analysis for frictional force using mineral oil.

Parameters	Degree of freedom	Sum of Squares (SS)	Mean Square (MS)	F	P	% contribution
Load*	2	5.4289	2.7144	33.17	0.003	58.39
RPM	2	3.5401	1.7700	21.63	0.007	38.08
Error	4	0.3274	0.0818			
Total	8	9.2963				

*significant factor
S = 0.286077   R-Sq = 96.48 %   R-Sq (adj) = 92.96 %

Table 8. Results for ANOVA analysis for coefficient of friction using castor oil.

Parameters	Degree of freedom	Sum of Squares (SS)	Mean Square (MS)	F	P	% contribution
Load	2	0.0001311	0.0000656	7.07	0.049	43.48
RPM*	2	0.0001333	0.0000667	7.19	0.047	44.21
Error	4	0.0000371	0.0000093			
Total	8	0.0003015				

*significant factor
S = 0.00336103   R-Sq = 87.70 %   R-Sq (adj) = 75.40 %

Table 9. Results for ANOVA analysis for frictional force using castor oil.

Parameters	Degree of freedom	Sum of Squares (SS)	Mean Square (MS)	F	P	% contribution
Load*	2	11.7321	5.8660	15.99	0.012	66.36
RPM	2	4.4778	2.2389	6.10	0.061	25.33
Error	4	1.4673	0.3668			
Total	8	17.6771				

*significant factor
S= 0.605659   R-Sq =91.70%   R-Sq(adj)=83.40%
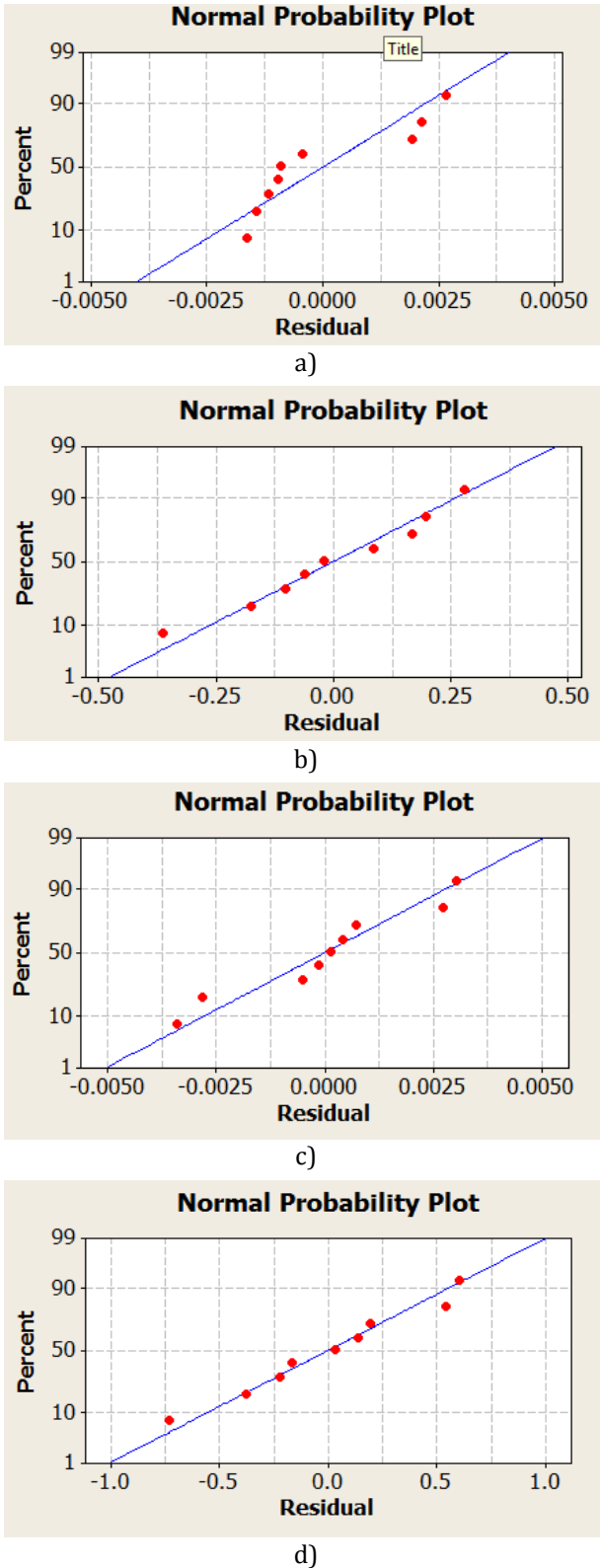
a)

b)

c)

d)

Fig. 4. Normal probability plot of a) coefficient of friction for MCO; b) frictional force for MCO; c) coefficient of friction for NCO; d) frictional force for NCO.

The normal probability plot shown in Fig. 4 is the result of testing of normality of the experimental results and it shows the predicted versus actual values for the design matrix. For any ANOVA analysis it is very much important that the normal probability plot should be closer to the mean line. As observed from Fig. 4 all the experimental values are much closer to the mean line.

3.4 Regression Equations

The experimental values are fitted to the following regression equations and the usual statistics were used to determine the goodness of fit. From the statistical point of view it is important to determine the residuals for normality, independence and constant variance which have been shown above.

The regression equations for coefficient of friction and frictional force in case of MCO and NCO are as follows:
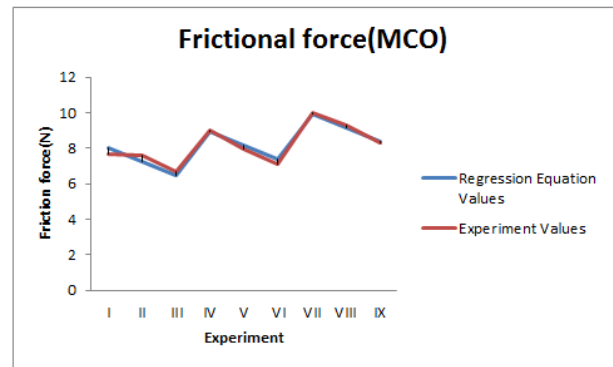
$$COF_{MCO} = 0.0106 + 0.000387 Load - 0.000019 rpm \quad (3)$$

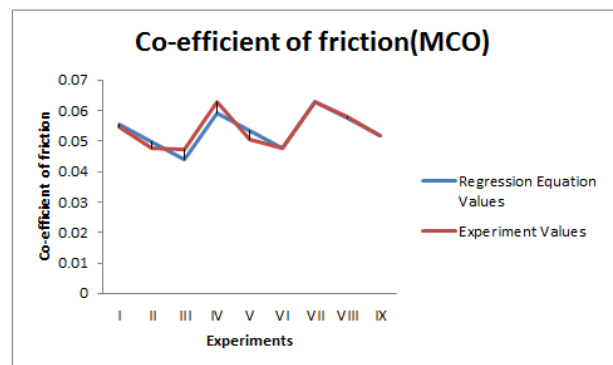$$COF_{NCO} = -0.0086 + 0.000455 Load + 0.000016 rpm \quad (4)$$

$$FF_{MCO} = -3.95 + 0.0945 Load - 0.00255 rpm \quad (5)$$

$$FF_{NCO} = -11.9 + 0.137 Load + 0.00278 rpm \quad (6)$$
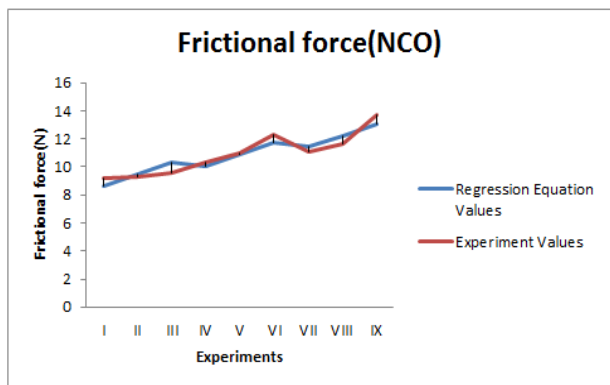
As observed from Fig. 5 both the experimental results and regression results were very close to each other.
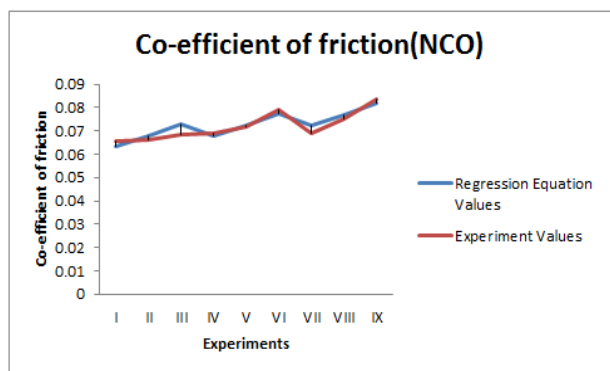

a)

b)

c)

d)

Fig. 5. Regression and experimental values in MCO and NCO.

Hence, the design of experiment model chosen for the work was appropriate. Since, the experimental values were nearly normally fitted (Fig. 4) in both NCO and MCO, a power transform was not generated using the Box-Cox plot or else the model had to be transformed to higher polynomial levels for accurate results.

3.5 Extreme pressure test

The load carrying capacity of the mineral oil and castor oil has been analysed using a four ball tester. As observed from Fig. 6, both pass and weld loads are higher in case of mineral oil as compared with neat castor oil. The lower pass load and weld load in case of castor oil may be due to the lower viscosity of castor oil, due to which the thickness of the lubricant film may have been thinner as compared to the mineral oil. The lower viscosity index in case of neat castor oil also signifies the instability of lubricant film.

As observed from Fig. 7, the plastic deformation in case of neat castor oil is much higher than the mineral oil. Though deep grooves are being

observed in both MCO and NCO but the surface in case of NCO has been observed to be more detoriated than MCO. This shows that the lubricant film in case of NCO was weaker as compared to MCO due to which plowing has occurred severely on the surface on NCO pins.
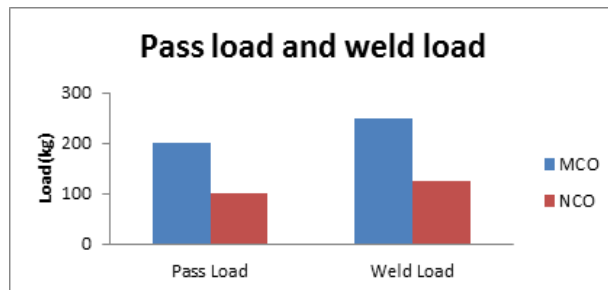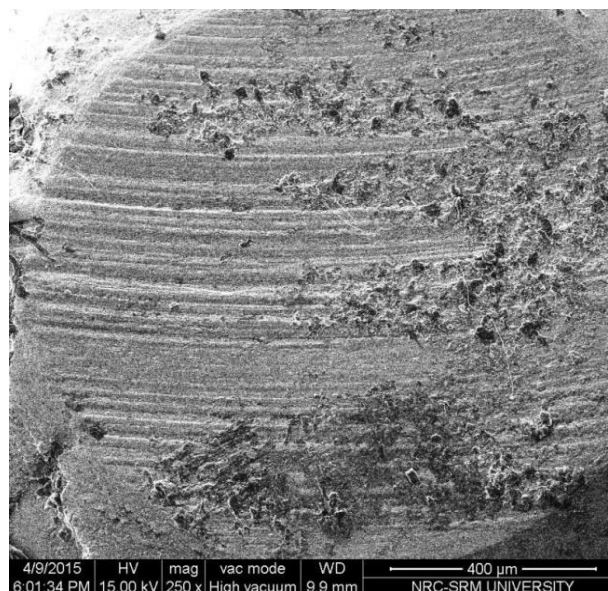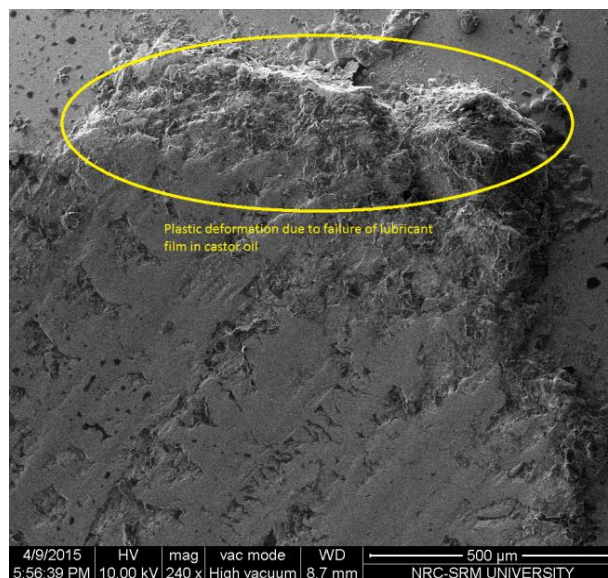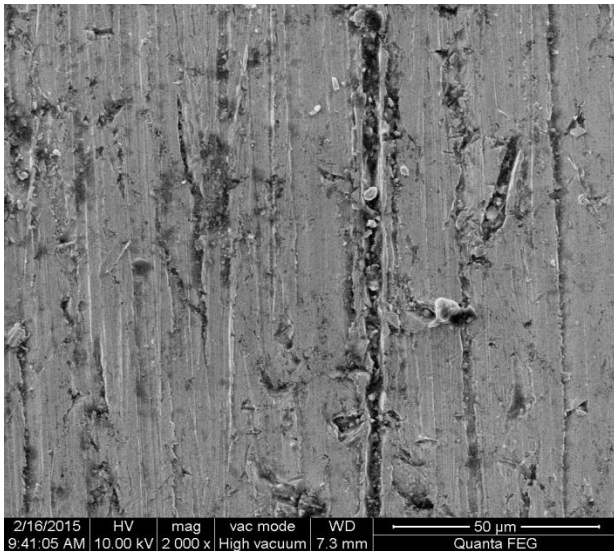

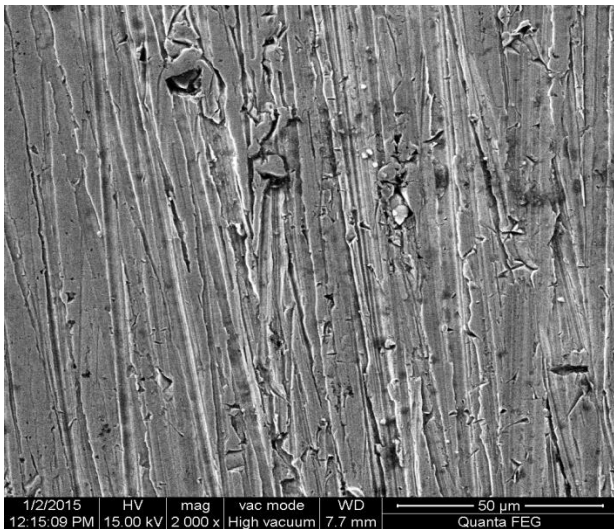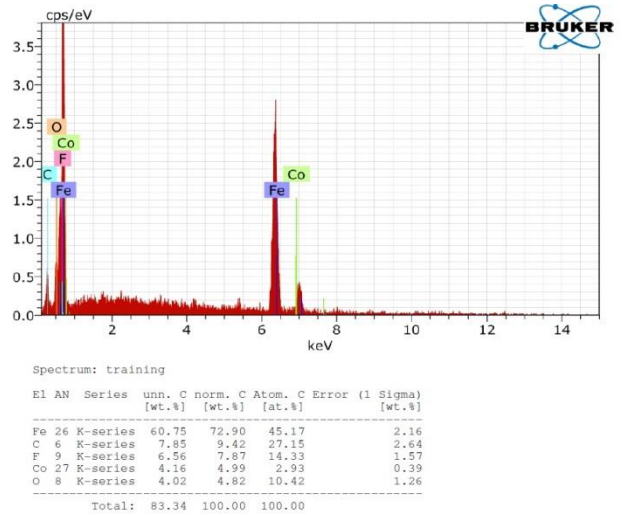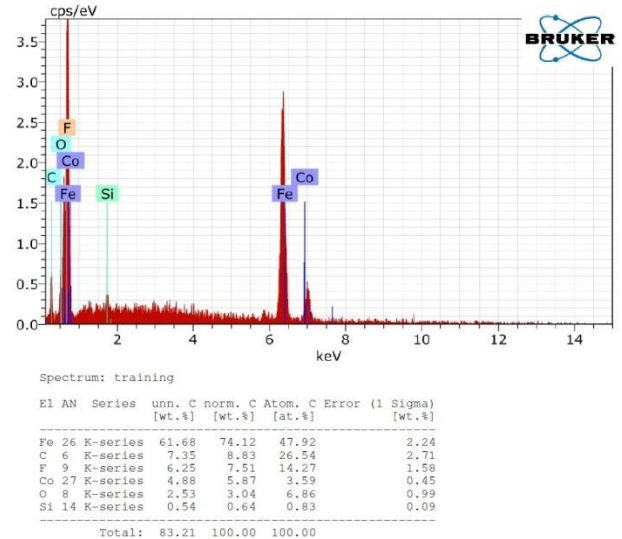**Fig. 6.** Pass and weld loads for MCO and NCO.

a)

b)

c)

d)

Fig. 7. SEM images of (i) balls after pass loads in four ball tester in a) MCO; b) NCO. (ii) Pins after testing (150N, 800 rpm) in c) MCO; d) NCO.

The EDS analysis as shown in Fig.8 the pin samples after the tribo tests shows that not much of elemental changes have been taken place.
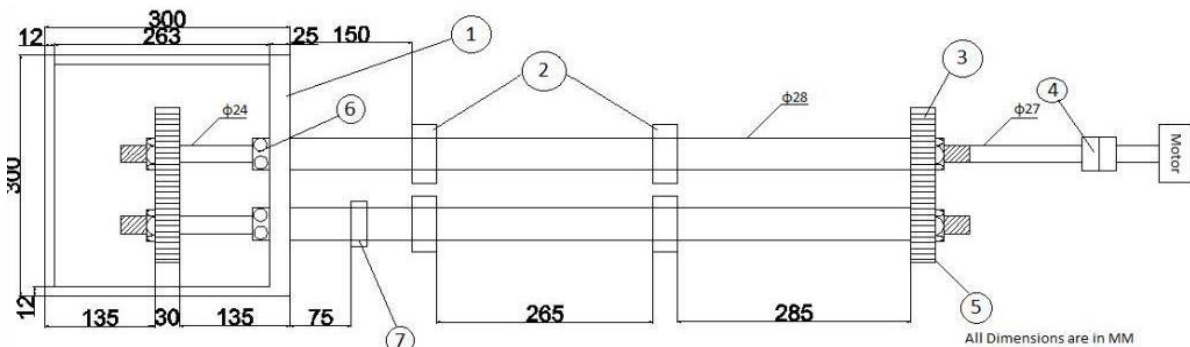

Spectrum: training

El	AN	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]
Fe	26	K-series	60.75	72.90	45.17	2.16
C	6	K-series	7.85	9.42	27.15	2.64
F	9	K-series	6.56	7.87	14.33	1.57
Co	27	K-series	4.16	4.99	2.93	0.39
O	8	K-series	4.02	4.82	10.42	1.26
		Total:	83.34	100.00	100.00	

a)

Spectrum: training

El	AN	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]
Fe	26	K-series	61.68	74.12	47.92	2.24
C	6	K-series	7.35	8.83	26.54	2.71
F	9	K-series	6.25	7.51	14.27	1.58
Co	27	K-series	4.88	5.87	3.59	0.45
O	8	K-series	2.53	3.04	6.86	0.99
Si	14	K-series	0.54	0.64	0.83	0.09
		Total:	83.21	100.00	100.00	

b)

Fig. 8. EDS analysis of the pins after test a) MCO; b) NCO.

3.6 Determination of scuffing resistivity

In order to compare the scuffing resistivity of MCO and NCO, in-house scuffing equipment (Fig. 9) was fabricated according to the details shown in Table 10.

(1) Test Gear Box; (2) Journal Bearings; (3) Slave Gear; (4) Coupling; (5) Pinion; (6) Ball Bearing; (7) Weight Hanger

Fig. 9. Inhouse built equipment for testing scuffing resistivity of oil.

Table 10. Test Gear Design [17].

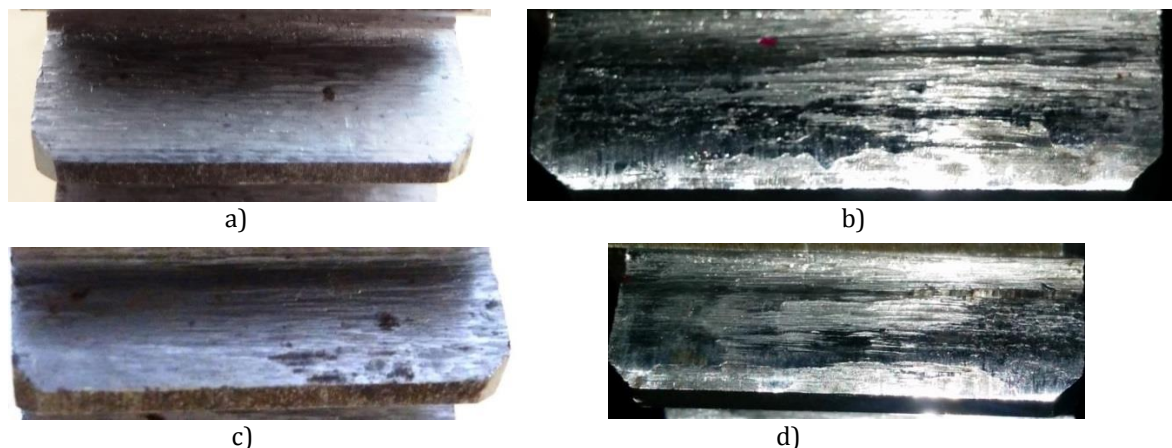| Dimension	Symbol	Units	Pinon	Gear
Number of Teeth	z	number	20	30
Pitch circle Diameter	d_p	mm	72.570	108.857
Base Circle Diameter	d_b	mm	68.194	102.293
Tip Diameter	d_t	Mm	82.042	116.713
Pressure Angle	α_n	Deg	20	20
Center Distance	a	mm	91.5	91.5

a)

b)

c)

d)

Fig. 10. Gear tooth profile using (i) mineral oil, a) before the experiment; b) after 40 hrs of intermittent running, (ii) using castor oil, c) before experiment; d) after 40 hrs of intermittent running.
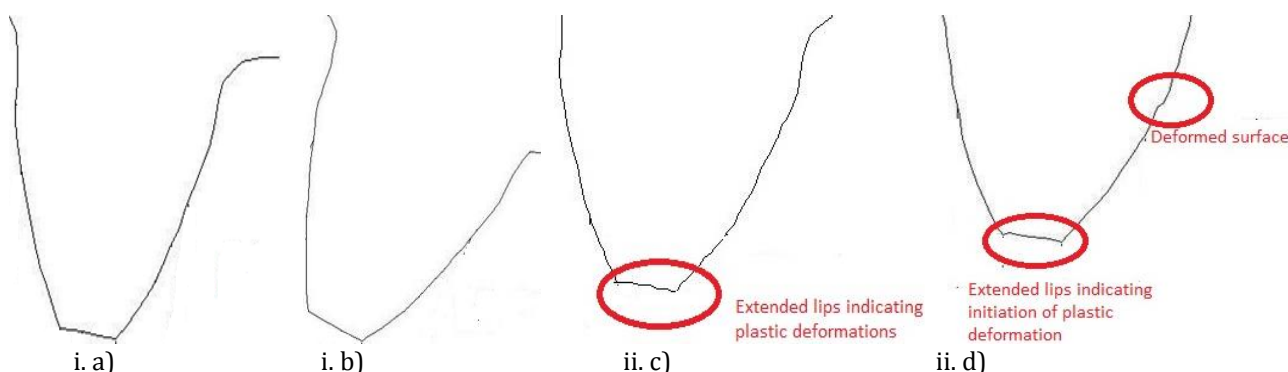

i. a) i. b) ii. c) ii. d)

Fig. 11. Gear tooth profile (i) before the experiment – a) MCO; b) NCO; (ii) after 40 hrs of intermittent running – c) MCO; d) NCO.

Table 11. Surface roughness

Samples	Roughness before test (µm)	Roughness after test (µm)	Percentage increase (%)
MCO	1.547	2.613	40.91
NCO	1.117	3.429	67.42

It was observed (Fig. 10 and Fig. 11) that the tooth of the gears in both MCO and NCO were deformed after 40 hrs of intermittent running. Extended lips were observed on the tips of the teeth in both NCO and MCO. These extended lip formations, which are types of gear failures, occur generally due to the plastic deformations which result due to failure of lubricating films. Furthermore, the increase in roughness values (Table 11) also showed that the lubricant film was less stable in case of NCO as compared to MCO.

4. DISCUSSIONS

As observed from the above results, COF in case of mineral oil has followed a decreasing trend with the increase in sliding speed while in case of NCO it is opposite. One of the main reasons for higher COF is the lubricant film breakage. According to Zhu et al. [18] a lubricant film may break due to: low speed, low viscosity, heavy load and roughness. Thus, the low viscosity (as compared to MCO), heavy load and roughness

(roughness increased due to metal to metal contact due to film breakage) may be the reasons for NCO lubricant film breakage which inturn increased the COF. Furthermore, at high speeds, the lubricating oil is dragged to the inlet of the contact and the lubricating film thickness varies according to the viscosity [19]. It is an important point to note that MCO follows the classical Stribeck curve while it is not follwed in case of NCO. The friction graphs thus show that MCO attained elasto hydrodynamic lubrication (EHL) phase from boundary or mixed regime.The mineral oil would have formed stable lubricating film and thus, the COF of MCO has been observed to be lower than NCO in all the experiments .Due to the presence of various additives in MCO the load bearing capacity of MCO is higher than NCO.

The following has been observed from the present work:

1. Viscosity and viscosity index of neat castor oil is lower than that of mineral oil.

2. Coefficient of friction and frictional force is higher is case of neat castor oil as compared with mineral oil.

3. Load carrying capacity of neat castor oil is lesser than that of mineral oil.

4. SEM images showed higher plastic deformation on the ball surfaces in case of neat castor oil as compared with that of mineral oil. Thus, it can be predicted that film formed in case of neat castor oil is weaker as compared with that of mineral oil.

5. The teeth profile in both mineral oil and castor oil has shown detoriation after 40 hrs of running condition.

6. The increase in surface roughness on the teeth of gears is higher in case of castor oil as compared with that of mineral oil.

7. Plastic deformations has been observed (Fig. 11) on the tip of the tooth of the gears in both mineral and castor oil but a slight deformation near the pitch line has been observed in case of castor oil.

8. From ANOVA analysis it has been observed that RPM is the significant factor while determining the coefficient of friction and the normal load is the significant factor while determining frictional force.

9. The results obtained from experiments and regression analysis are very close to each other and hence, the Taguchi L9 orthogonal array of design of experiment can be used in analysing the tribological behaviour of mineral and neat castor oil.

5. CONCLUSION

As observed from the present work the tribological properties of neat castor oil are inferior to the mineral oil, although from close observation of the results we find that the values in both the cases are much closer to each other. The commercial mineral oil contained additives and thus, performed better as compared to the neat castor oil. Hence, more detailed research work would be carried out using various types of additives in castor oil to get a good fomulation of castor oil which may replace mineral oil in many applications,thus, reducing the impact on environment. The results of the future research would be reported in future articles.

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