

THE RHEOLOGICAL BEHAVIOR OF STRAIGHT AND BLENDED NATURAL OIL LUBRICANTS

M.I. Oseni ; A.O. Ette, and H. Iortyer
Department of Mechanical Engineering,
University of Agriculture, Makurdi, Nigeria

ABSTRACT

The rheological behavior of straight and blended natural oil lubricants was investigated. Mineral base transmission oil (EPSAE85W/140) was blended in various proportions with gmelina seed oil, rubber seed oil, palm oil and soy oil. The dynamic viscosity of the straight and blended natural oil samples was measured using Baird rotational viscometer and transformed into rheological properties such as viscosity, viscous shear stress and torque using formalized equations of state for oil lubricants. Rheograms obtained showed a viscosity drop with rise in temperature with the rate of decrease in viscosity of the oil blends with temperature directly proportional to the quantity of mineral oil in the blends. Viscous shear stress for the straight natural oils increased with rise in shear rate while torque obtained for the natural oils was lower than the torque obtained for the reference oil. The similarity observed in the values obtained for the rheological parameters investigated implies that the natural oils can be upgraded by processing with additives or blended with conventional mineral oil lubricants to reduce maintenance cost, improve lubrication performance and the environment.

Keywords: Rheology, oil, lubricants.

1.0 INTRODUCTION

Oil lubricants are classified into mineral oils, natural oils, synthetic oils and emulsions. Natural oils are regenerative and renewable through improved agricultural techniques. Mineral base oil lubricants for engineering mechanisms formulated from hydrocarbon mineral oils are expensive to process and use. Whole or partial substitution with natural oil by blending will not only reduce processing and use cost but also enhance downstream relevance of the botanical plants and encourage the upstream primary producers to expand their agricultural activities.

Erhan et. al. (2004) suggested that the polar functionality of natural oil structure provides a surface protection film with strong adsorption energy arising from greater lateral interaction between the polar heads and long hydrocarbon chains of the ester group. The coefficient of friction and wear rate are dependent on the strength of the fluid film and extent of adsorption on the metal surface. However, the cold flow behavior of natural oil derivatives poses a rheological challenge. Sharma et. al. (2004) suggested improvement in flow behavior by structural modification using anhydrides.

The rheology of oil lubricants indicates the flow and deformation characteristics of the lubricant during processing, transport and use. The rheology of the oil lubricant should maintain the integrity of interacting surfaces under

operating conditions of sliding speed, contact pressure, temperature and humidity, and atmospheric cleanliness.

Rheological behavior of oil lubricants is most relevant in the hydrodynamic and elastohydrodynamic lubrication regimes. Harris and Busby (1973), Spikes (1994), Taylor (2002) and Barnes et. al. (2001) among others, have studied various aspects of mineral oil lubricants rheology and have concluded that mineral oils have good wear and friction properties because of their inherent lubricity, adequate low temperature flow behavior and good oxidation property; but they are not environment friendly. Alakali et. al. (2003) and Satimehin et. al. (2003) worked on the rheology of palm oil and Canarium oil respectively with relevance to processing and transport and found their low temperature instability a major hindrance to processing. Similar conclusions were drawn by Adhavarya et. al. (2004), Sharma et. al. (2004) and Castro et. al. (2006) in their work on the oxidation and wear properties of soybean oil. They suggested the modification of the chemical or generic composition of the oil to improve its oxidation and wear properties. The rheology of a great variety of natural oils from tropical plants amenable to short rotation plantation deserve more research in order to reduce lubrication costs and down times of production equipment. The work seeks to investigate the rheological behavior of straight

and blended natural oils as alternative lubricants in current areas of application of mineral oil base lubricants.

This work focuses on the rheology of natural oil from palm fruits (*Elaes guineensis v. dura*), para rubber seeds (*Hevea brasiliensis*) and gmelina seeds (*Gmelina arborae*) among the variety of tropical oil seeds available. The choice was informed by the availability of palm oil, and abundance of rubber and gmelina plantations in the southern and middle belt parts of Nigeria. Rubber and gmelina trees are useful economic trees that provide logs for building and the electricity industry, and rubber for automobile and other industries. These oils contain phospholipids and sterols which dissolve in organic solvents and a region that is attracted to and soluble in water. Thus, they contain cells with both lipid soluble and water soluble regions that mark them out as biodegradable and environment friendly (Sharma et. al. 2005).

2.0 THEORETICAL CONSIDERATIONS

Rheology is viscosity dependent and lubricant's flow is classified according to their viscosity sensitivity to shear rate, pressure and temperature. Rotational viscometers measure dynamic viscosity directly and are usually in the form of concentric cylinders, which rotate in the oil sample (Hutton, 1973).

A plane bearing model with an oil lubricant would generate a viscous shear stress due to oil viscosity (Fuller, 1984) thus,

$$\eta = \frac{\tau}{\Gamma} \quad (1)$$

where,

η = Dynamic viscosity
 τ = Viscous Shear stress
 Γ = Shear rate

For a shaft turning in a viscous medium, the shear rate can be obtained from

$$\Gamma = \frac{2\pi Nr}{C} \quad (2)$$

where, C = Diametrical clearance between bearing and journal

r = Shaft radius
 N = Shaft speed

Viscous shear stress can therefore be written as

$$\tau = \frac{2\pi n N \eta}{C} \quad (3)$$

The torque generated by the shaft is

$$T = \frac{4\pi^2 r^3 L N \eta}{C} \quad (4)$$

where,

L = Bearing length

Newtonian flow is characterized by equation (1) the Newtonian equation while non-Newtonian flows are subdivided into Bingham plastics, quasi-viscous flows, quasi-plastic flows and time-dependent flows. Quasi-viscous flows have non-linear relationship between shear stress and shear rate and are represented by the Ostwald – de Waele equation (Lewis, 1987).

$$\tau = K r^n \quad (5)$$

where,

K = Apparent viscosity;
 n = Flow behavior index

The flow can be pseudoplastic or dilatant. In pseudoplastic flow, the flow index is less than one ($n < 1$) and the curve from the origin is concave downwards at low shears and becomes linear at high shears. In dilatant flow, the flow index is greater than one ($n > 1$) and the curve is concave upward at low shears and becomes linear at high shears.

Hutton (1973) and Tabor (1982) related variation of viscosity with temperature with a variant of Arrhenius equation, which is based on the principle that flow will occur if a molecule has sufficient thermal energy to change its site relative to the neighboring molecules. Thus;

$$\eta = K \exp^{-Ea/RT} \quad (6)$$

where,

η = Measured viscosity
 K = Apparent viscosity at reference temperature
 T = Absolute temperature
 Ea = Activation energy
 R = Universal gas constant (8.3143 Jk⁻¹ mol⁻¹)

3.0 EXPERIMENTAL METHOD

The following materials were used for the rheological tests: Gmelina seed, rubber seed and palm oils, EPSAE85W/140 reference oil, Baird rotational viscometer (model LV8), thermometer, hot plate, aluminum cups and hot water bath. The gmelina and rubber oils were extracted from seeds obtained in plantations at Ugep near Calabar and Gboko in Benue State.

Palm oil and the reference oil were purchased in the open market in Markudi. The tests were carried out in the Food Chemistry Laboratory of the University of Agriculture, Makurdi. The oil samples generated for the tests are shown in Table 1. The samples were individually placed in the sample holder of the rotational viscometer. The spindles (sizes 1 and 4) were immersed to

the set points. The temperatures of the samples were normalized at 30 °C, 50 °C, 70 °C, 90 °C and 110 °C each using hot water in a beaker for 30 minutes before switching on the viscometer. Five spindle speeds (3rpm, 6rpm,12rpm,30rpm and 60rpm) were used to achieve five different shear rates and the viscosity was recorded. Torque was calculated using equation (4). Shear rate was determined from equation (2) using spindle speeds and instrument constants while viscous shear stress was obtained from equation (3) using measured viscosity data and instrument constants. Flow behavior index was calculated from equations (5) and (6). Results were statistically analyzed to establish strength of relationships.

4.0 RESULTS AND DISCUSSIONS

The results of the determination of the rheological behaviors of oil samples are shown in Figures 1-3 for five speeds and temperature ranges. Dynamic viscosity values were transformed to obtain viscous shear stress, shear rate, torque, activation energy, apparent viscosity and power law. Three relationships of interest included viscosity – temperature, shear stress - shear rate and frictional torque - shear rate.

Figure 1 shows that viscosities decrease with rise in temperature for mineral oil compounded with the natural oils. However, the rate of decrease in viscosity of the oil blends with temperature was directly proportional to the quantity of mineral oil in the blends. Thus, the higher the mineral oil proportion in the blend, the higher the viscosity of the blend at 30 °C. The change in viscosity with temperature varied slightly with the mineral oil content in the blend at temperatures above 30 °C because of the influence of the mineral oil on the temperature performance of the oil blends. Knowledge of the temperature performance of the oils is essential for selection of additives as well as preventing oils instability (Castro et. al. 2006). The same behavior was observed with rubber and palm oil. On the basis of viscosity- temperature coefficient, gmelina oil was superior to rubber and palm oil hence it is most amenable to upgrading.

In Figure 2, the effect of the various proportions of mineral oils in the blend was more distinct. Viscous shear stress increased with rise in shear rate for the oil samples. This increase was attributed to increase in molecular interaction and decrease in vibration of the molecules as shear rate increased (Pywell, 1973). The oils can therefore be referred to as shear rate thickening on the basis of flow index obtained which increased with increase in viscous shear stress and shear rate (Satimehin et. al. 2003). This is an

important characteristic in lubrication as it shows the ability of the lubricant to retain a hydrodynamic film at increasing shear rates. The higher the flow index, the higher the deviation of the fluid from Newtonian behavior. The rise in viscous shear stress with increase in shear rate was quite significant. Presence of natural oil in the blends lowered the viscous shear stress, but this was at the expense of increased free fatty acids from the natural oils and viscosity-temperature coefficient. The rise in viscous shear stress with increase in shear rate depicted the ability of the minimum oil film thickness to carry loads during actual service (Taylor, 2004). However, rise in operating temperature sets a limit to the permissible viscous shear stress at a given shear rate. Effect of blending was more pronounced at higher temperatures where the free fatty acids in the oil formed metallic soaps that improved the viscous shear stress. In Figure 2(b), sample S₇ stood out in the property and during hydrodynamic lubrication, it is likely to perform best because of its higher viscous shear stress.

Figure 3 shows rheograms for torque-shear rate. There was rise in torque with increase in shear rate for all oil blends. The proportion of natural oil in the blends was reflected by the rheograms in the figure. As shear rate increased, frictional torque rose due to pressure on the oil by the rigid boundaries (Alakali et. al. 2003 and Sharma et. al. 2004). This pressure which can increase viscosity by a factor of 10⁴-10⁶ between the surfaces carrying a pressure of 100 MN/m² increased frictional torque within the oil lubricant and the rigid boundaries (Pywell, 1973). While rise in temperature was a direct effect, the phenomenon is beneficial in hydrodynamic lubrication regime and formation of hydrodynamic oil film in lubrication. However, at high shear rates, centrifugal and boundary slippage effects are expected during actual service. Frictional torque was affected by oil lubricant viscosity and composition.

Correlation coefficients of selected rheological parameters (viscosity, viscous shear stress, torque and flow behavior) for natural oil blends at different temperatures and speeds are shown in Tables 2. In the table, various proportions of gmelina oil blended with reference mineral oil showed an inverse relationship with viscosity, viscous shear stress, friction stress and power law at 30 °C and 50 °C in varying degrees. At 70 °C and 90 °C, there was a reverse in trend as the relationship is direct, possibly because of realignment of the hydrocarbon structure to accommodate a low molecular weight material. At

the completion of the realignment, the reverse relationship continued at 110 °C. Rubber and palm oil showed similar relationships. Two-way test of significance of the difference in selected rheological parameters using Randomized Complete Block Design (RCBD) is shown in Table 3, at five speeds and three temperatures. The results were obtained at 95% and 99% confidence levels. The two-way test of significance of difference in viscosities of blended mineral oils at $F_{0.05}$ and $F_{0.01}$ showed that at 30°C, there was significant difference in viscosity among the proportions administered whereas at higher temperatures up to 110 °C difference was insignificant (Table 3). There was no difference in the effect the proportions had on each type of natural oil at all temperatures except 70 °C and speed of 6rpm.

The results imply that mineral oil-based lubricants predominantly in use because of their inherent lubricity and low cost can be substituted with natural oils that are biodegradable and environment friendly. The results have demonstrated the effect on rheology of whole or partial substitution of mineral oils with natural oils.

5.0 CONCLUSION

It was established that the straight and blended oils have similar rheological behavior (i.e. shear rate thickening and dilatant fluids). This behavior is highly predictable as proportion of natural oil in mineral oil increases or decreases. Choice of natural oil-mineral oil blend for any lubrication application should consider the prevailing lubrication model. Blending of natural oils with mineral oils improves the lubrication performance of the blended oils. All the natural oils were amenable to upgrading for better lubrication performance under boundary and hydrodynamic lubrication conditions. The straight oils can be used in transformers, gears, slides and rollers while the blends can successfully replace conventional oils in industrial gear boxes, trunnion journal bearings and hydraulic systems.

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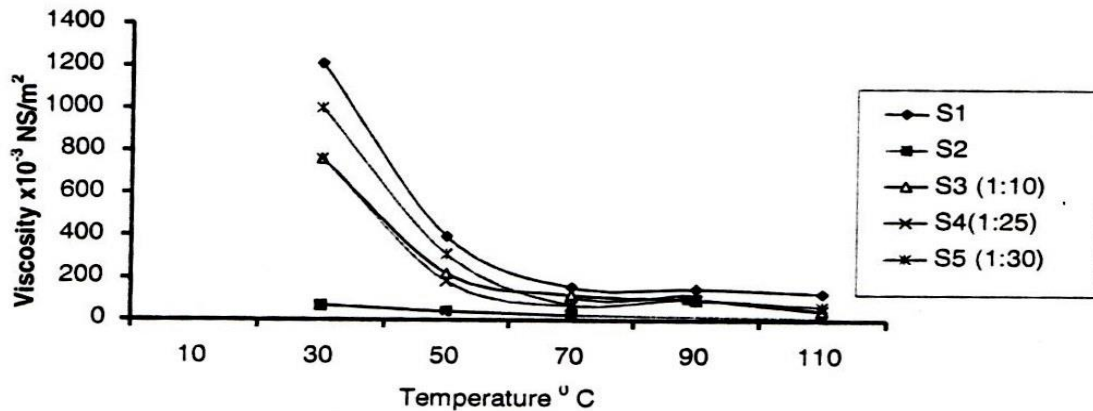
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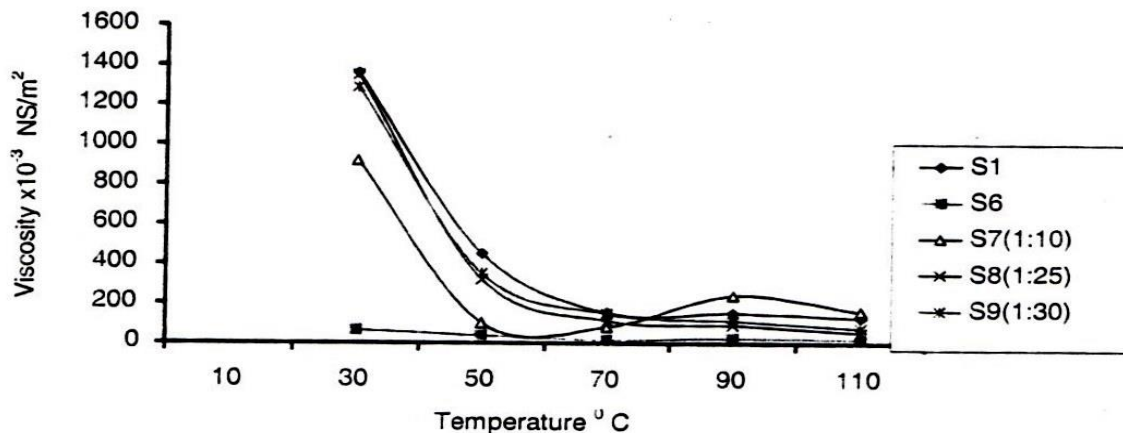
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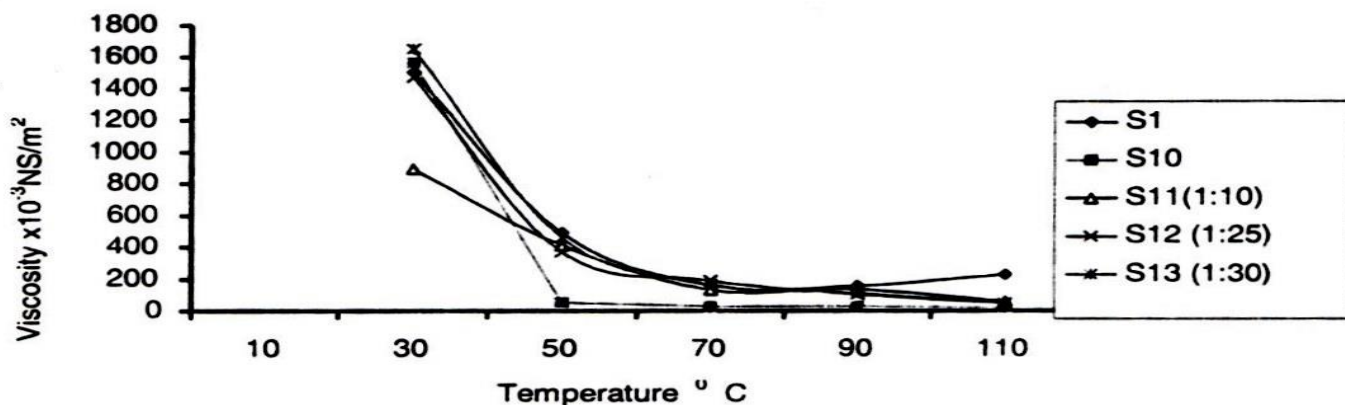


(a) Mineral oil (S₁) blended with gmelina oil (S₂) at 6rpm



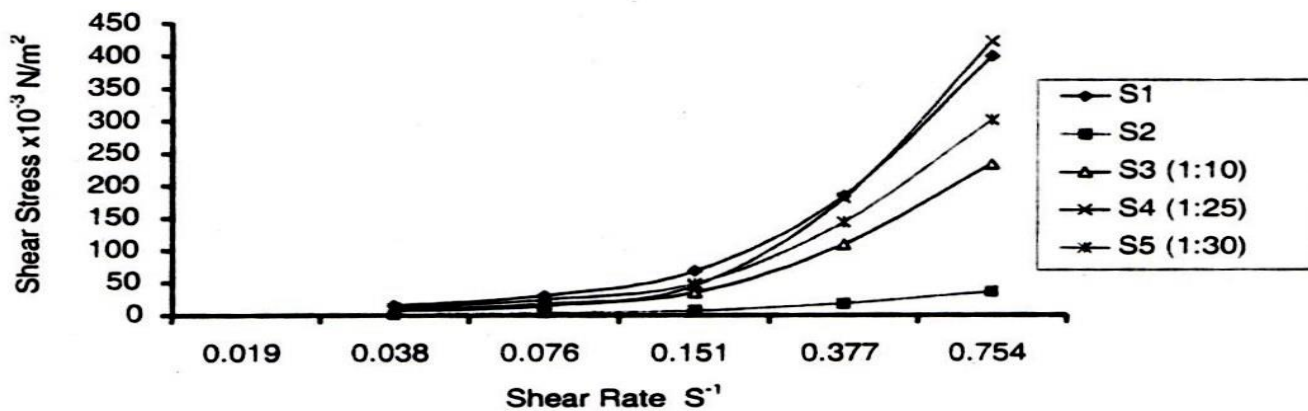
(b) Mineral oil (S₁) blended with rubber oil (S₅) at 12rpm

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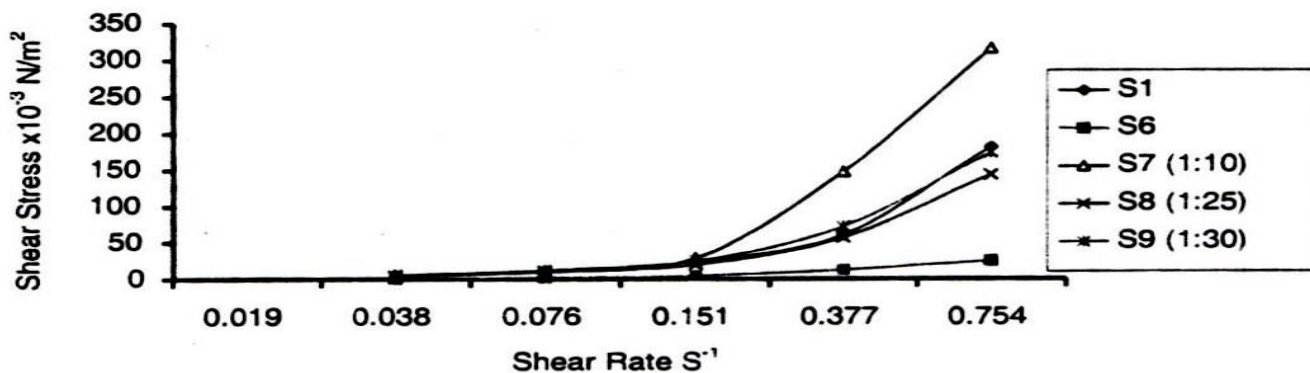


(c) Mineral oil (S₁) blended with palm oil (S₁₀) at 30rpm

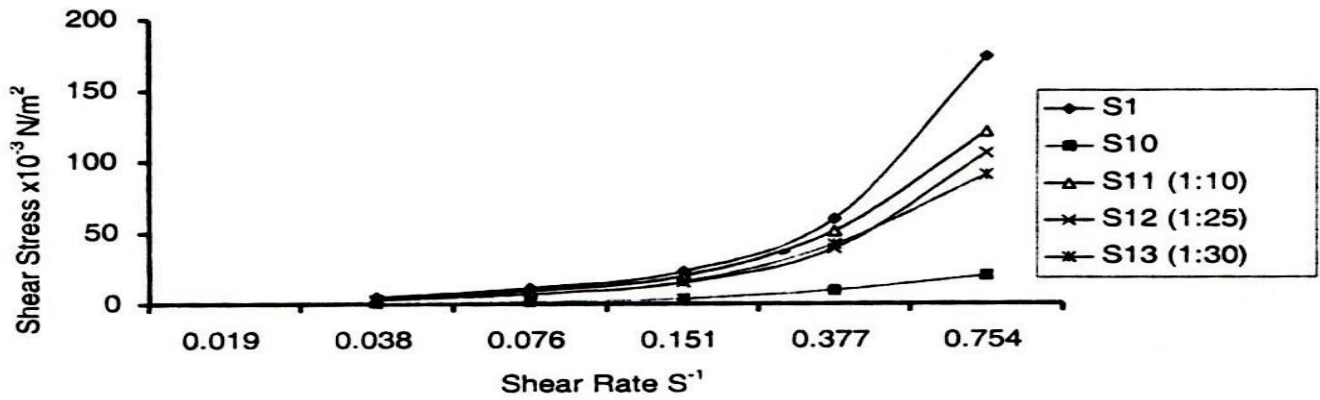
Figure 1 Dependence of viscosity on temperature for blended mineral oils



(a) Mineral oil (S₁) blended with gmelina oil (S₂) at 50° C

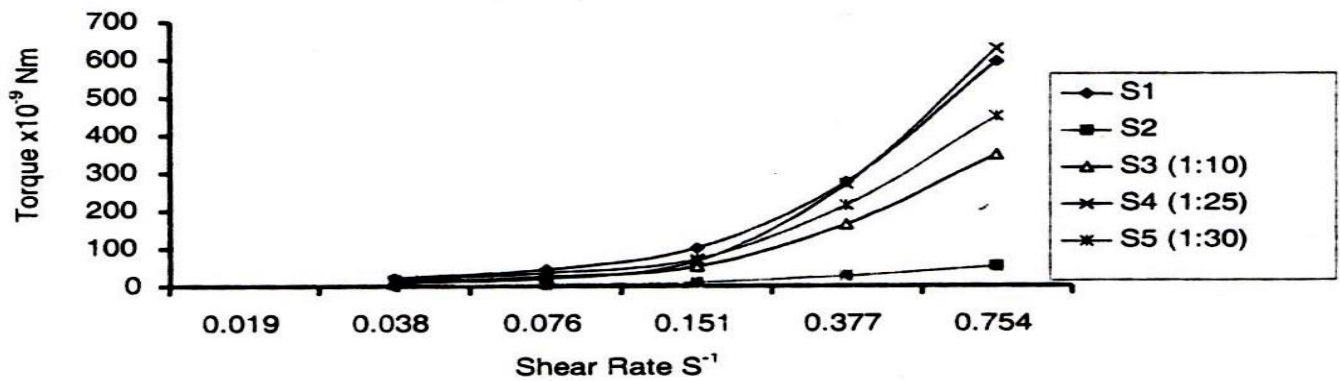


(b) Mineral oil (S₁) blended with rubber oil (S₆) at 70° C

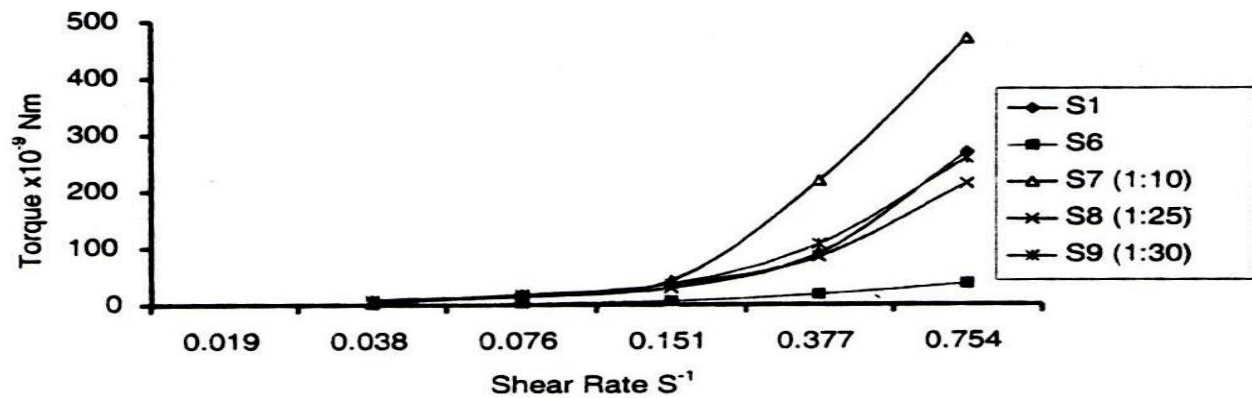


(c) Mineral oil (S_1) blended with palm oil (S_{10}) at 90°C

Figure 2 Dependence of shear stress on shear rate for blended mineral oils

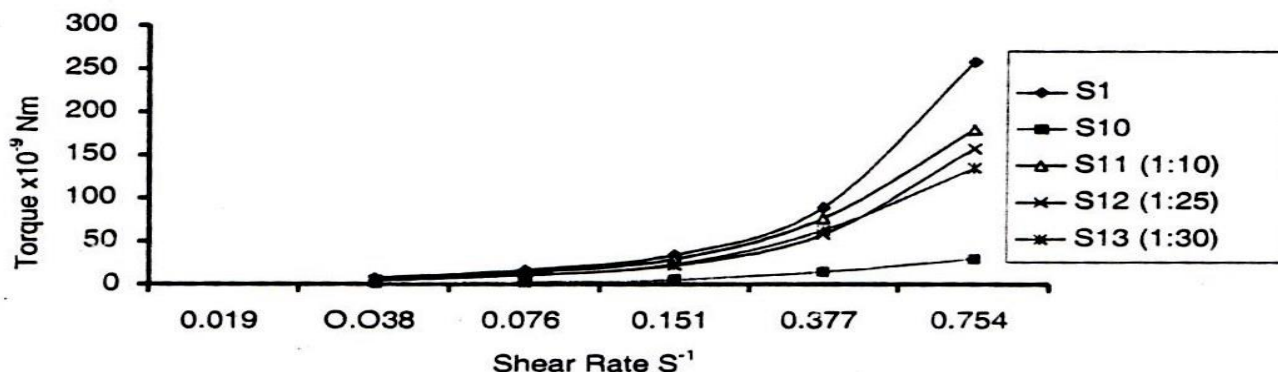


(a) Mineral oil (S_1) blended with gmelina oil (S_2) at 50°C



(b) Mineral oil (S_1) blended with rubber oil (S_6) at 70°C

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(c) Mineral oil (S₁) blended with palm oil (S₁₀) at 90° C

Figure 3 Dependence of torque on shear rate for blended mineral oils

TABLE 1 : STRAIGHT AND BLENDED OIL SAMPLES FOR RHEOLOGICAL TESTS

Sample	Description	Proportion
S ₁	EPSAE85W/140 oil	-
S ₂	Gmelina seed oil	-
S ₃	Gmelina seed oil : EPSAE85W/140	1 : 10
S ₄	Gmelina oil seed : EPSAE85W/140	1 : 25
S ₅	Gmelina oil seed : EPSAE85W/140	1 : 30
S ₆	Rubber seed oil	-
S ₇	Rubber seed oil : EPSAE85W/140	1 : 10
S ₈	Rubber seed oil : EPSAE85W/140	1 : 25
S ₉	Rubber seed oil : EPSAE85W/140	1 : 30
S ₁₀	Palm oil	-
S ₁₁	Palm oil: EPSAE85W/140	1 : 10
S ₁₂	Palm oil: EPSAE85W/140	1 : 25
S ₁₃	Palm oil: EPSAE85W/140	1 : 30

TABLE 2: CORRELATION OF SELECTED RHEOLOGICAL PARAMETERS WITH PROPORTION OF GMELINA OIL IN BLENDED MINERAL OIL SAMPLES (S₃ – S₅)

Temperature °C	Speed rpm	r _η	r _τ	r _{TR}	r _n
30	3	-0.72	-0.72	-0.72	-0.71
30	6	-0.58	-0.58	-0.58	-0.56
30	12	-0.42	-0.42	-0.42	-0.33
30	30	-0.42	-0.42	-0.42	-0.45
30	60	-0.55	-0.55	-0.55	-0.54
50	3	-0.31	-0.31	-0.31	-0.74
50	6	-0.32	-0.32	-0.32	-0.56
50	12	-0.99	-0.99	-0.99	-0.42
50	30	-0.80	-0.80	-0.80	-0.38
50	60	-0.71	-0.71	-0.71	-0.53
70	3	0.97	0.97	0.97	-0.74
70	6	0.98	0.98	0.98	-0.56
70	12	0.99	0.99	0.99	-0.43
70	30	0.99	0.99	0.99	-0.37
70	60	1	1	1	-0.52
90	3	-0.17	-0.17	-0.17	-0.73
90	6	0.64	0.64	0.64	-0.56
90	12	0.88	0.88	0.88	-0.4
90	30	0.57	0.57	0.57	-0.37
90	60	0.58	0.58	0.58	-0.53
110	3	-0.6	-0.6	-0.6	-0.77
110	6	-0.74	-0.74	-0.74	-0.59
110	12	-0.57	-0.57	-0.57	-0.52
110	30	-0.76	-0.76	-0.76	-0.37
110	60	-0.75	-0.75	-0.75	-0.5

r_η = Correlation Coefficients for Viscosity r_{TR} = Correlation Coefficients for Frictional Torque
 r_τ = Correlation Coefficients for Viscous Shear Stress r_n = Correlation Coefficients for Flow Behavior

TABLE 3: TWO-WAY TEST OF SIGNIFICANCE OF THE DIFFERENCE IN VISCOSITY (η) OF BLENDED MINERAL OILS USING RANDOMIZED COMPLETE BLOCK DESIGN

Temperature °C	Speed rpm	Oil Type			Blending Ratio		
		F _{cal}	F _{0.05}	F _{0.01}	F _{cal}	F _{0.05}	F _{0.01}
30	3	8.93	5.14	10.9	3.95	4.76	9.78
30	6	7.48	5.14	10.9	1.14	4.76	9.78
30	12	6.87	5.14	10.9	0.98	4.76	9.78
30	30	5.94	5.14	10.9	1.19	4.76	9.78
30	60	5.82	5.14	10.9	1.19	4.76	9.78
70	3	0.96	5.14	10.9	3.73	4.76	9.78
70	6	0.48	5.14	10.9	5.39	4.76	9.78
70	12	0.61	5.14	10.9	4.03	4.76	9.78
70	30	0.75	5.14	10.9	1.14	4.76	9.78
70	60	0.4	5.14	10.9	1.16	4.76	9.78
110	3	0.36	5.14	10.9	2.2	4.76	9.78
110	6	0.72	5.14	10.9	2.06	4.76	9.78
110	12	0.89	5.14	10.9	1.58	4.76	9.78
110	30	0.92	5.14	10.9	1.32	4.76	9.78
110	60	0.9	5.14	10.9	1.23	4.76	9.78