EVALUATION OF LOCAL OILS AS COLD ROLLING LUBRICANTS FOR STEEL

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ABSTRACT

Potentials of some local fatty oils (ground-oils) as lubricants for cold rolling of low carbon mild steel were evaluated from friction coefficients derived using an established plane-strain compression test that closely simulates the rolling theory. Values of friction coefficient estimated quantitatively under each oil lubrication condition using the slip-line field theory and the equation of the pressure required to deform an ideal plastic metal by flat punch indicate that palm oil has the best overall performance, followed by groundnut, shea butter, palm kernel and cottonseed oils. The measured values of friction coefficient fall within the established range in cold rolling of steel.

INTRODUCTION

In most metalworking operations, lubricants are an accepted necessity. Of all the purposes of metalworking lubricants (1), the most common is that of reducing friction. Friction is, with some significant exception, an unwanted factor with a number of undesirable side effects; in general, it raises the forces and power requirements, subjects the deformation tool to higher pressure, renders deformation less uniform within the workpiece, raises the temperature of the interface and may set limits to the maximum obtainable deformation. Accordingly, any lubricant so developed for metalworking operations in general and cold rolling of steel in particular, must be able to reduce these frictional effects to the barest minimum possible.

Based on the recognized need for direct measurement of the local coefficient of friction for assessing the effectiveness of lubricants in metalworking operations, various experimental techniques to determine the friction coefficient and how it affects deformation processing have been developed. Among the procedure described in the literature for lubricity test is the ring compression test (2-7) that was rated as excellent for its past success in correlating results with real performance (7,8). The ring compression test is widely applicable to evaluate lubricants, because this method is easily used with only the measurement of the change in geometry of a ring and without measurement of the mechanical properties of the metal. Besides the ease of implementation, extensive theoretical evaluations of the deformation involved in the ring compression test have also been developed (9,10,11).

Because of the great economic importance of metal rolling process, much impetus has been given to basic research in the determination of the friction coefficient under this metalworking operation. Using a pair of pressure-sensitive pins mounted in a roll, one normal and the other inclined to the interface, Rooyen and Backofen (12) determined, among others, the friction coefficient over the contact are in cold rolling under various lubrication conditions. For different conditions of lubrication, friction coefficient was found to vary below a certain maximum with both reduction and location in the interface.

The similarity in the overall deformation existing between a metal in strip rolling and in plane strain compression has led to the extensive use of plane strain compression test for grading lubricants through the determination of the friction coefficient in metalworking operations. The plane strain compression test was first successfully applied in a comprehensive strip rolling research by Ford (13) who verified experimentally that its use would permit acceptable accurate calculations to be made of roll separating force and torque for a variety of rolling conditions. The method itself has been thoroughly investigated experimentally by Watts and Ford (14), theoretically by Hill (15) and Green (16) and extensively applied by Sims (17). Guminski and Willis (18) used this technique as a quick sorting test for grading lubricants in the rolling of aluminum alloys. Based on the same analysis, Takahashi and Alexander (19), and Bailey and Singer (20) estimated quantitatively the friction coefficients under various lubrication conditions in metalworking operation both at room and elevated temperatures respectively, using a plane-strain compression test. Ford (21) had reported the plane-strain compression test to be very sensitive to frictional conditions.

Essentially, the plane-strain compression test consists of compressing a strip of material between two narrow dies with flat parallel faces; the dies being oriented with their length across strip. For greater accuracy, the strip must be considerably greater than the width of dies (22); for best result, however, the strip thickness should be no greater than the indenter (dies) width.

On the basis fo its successful implementations in the study of the frictional conditions produced by the various lubricants in metalworking operations, the plane-strain compression test was employed in this investigation to assess the potentials of local fatty oils (groundnut, shea butter, palm kernel, cottonseed and palm oils) as cold-rolling lubricants for mild steel.

EXPERIMENTAL TECHNIQUE

The original Watts-Ford plane strain compression test techniques used in conjunction with a 500 KN Denison hydraulic machine, was employed to obtain the plane-strain compression results. The assembly was fitted with a dial gauge in-

dicator which was actuated by the descending top press platen, the dial indicator being so arranged that the reduction in strip thickness and hence the thickness of materials between the dies could be determined as deformation progressed.

The compression was carried out between the operative die surface of hardened mild steel, 6 mm emery paper and placed between the compression tables of the testing machine . Test on individual oil was conducted using a strip 42 mm wide, 0.8 mm thick and 200mm long of fully cold-rolled low carbon mild steel sheet.

Both the die and the strip were cleaned by cotton wool soaked in acetone before the first indentation. Oil under investigation was applied by dropping it on to the surface; great care being taken to avoid contaminating strip with grease from fingers. The die was lubricated before the first indentation only so that transferred metal particles remained on it to ensure that actual particles remained on it to ensure that actual rolling conditions, where there is the accumulation of metal debris in the lubricant circulated, was simulated.

The lubricated strip was inserted between the lubricated dies flat parallel faces, the dies being oriented with their length across the strip and centrally placed with respect to the loading axis. A procedure of incremental loading similar to that used by Watts and Ford (14) was adopted; each increment being chosen to give at least two percent reduction in thickness to ensure that the envelope of such incremental curves would be reached each time. The applied load to achieve the required deformation was held steady at that particular value for six seconds and then released. The platens were parted and the strip advanced so that the undeformed material was again between the tools.

The plane strain compression test data from the procedure described above were used to determine the friction coefficient under each oil lubrication condition from the slip-line field theory and the approximate analysis which may be summarized as follows. For slipping friction (i.e). $\tau = \mu p$ everywhere on the interface; τ is the shear stress at the interface, μ is the coefficient of friction and p is the normal stress at the interface).

$$\frac{\bar{P}}{2k} = \frac{\exp\left(\frac{\mu b}{b}\right) - 1}{\frac{\mu b}{t}} \qquad (1)$$

For combined friction (i.e. τ equals to either μ p or k whichever is less).

$$\frac{\bar{P}}{2k} = \left[\frac{(1+\alpha)^2 + 1}{4\mu} - 1\right] \Big/ \frac{\mu b}{t} \qquad (2)$$

where

α $\frac{\mu b}{t} \ln\sqrt{2\mu}$

k = yield shear stress of specimen

b = breadth of die

$\bar{P}$ = mean pressure over the die

t = thickness of material between dies

μ = coefficient of friction

Based on equations (1) and (2), a family pf curves may be constructed relating

$\frac{\bar{P}}{2k}, \frac{b}{t}$ and μ

For curve obtained with a particular lubricant, value of μ can be derived immediately for given experimental values of P/2K and b/t. However, the Takahashi-Alexander analysis was the procedure adopted in this investigation as schematically illustrated in Fig. 1. Using a thick paste of fine graphite powder and SAE 30 to give a substantially zero coefficient of friction, the basic yield-stress curve (Curve A Fig. 1) was obtained from the plot of mean pressure $\bar{P}$ against reduction r in plane-strain. With any other lubricant and surface condition, curve B which is the pressure/reduction curve, can be obtained. At any given reduction r, the values of $\bar{P}$ and 2k are defined from the two curves and hence ratio $\bar{P}$/2k. From the dial gauge indicator reading, the reduction r will define the thickness of material between the die and hence the current value of b/t at r. Substitution of these experimental values of $\bar{P}$/2k and b/t into equations (1) and (2), the friction coefficient under any lubrication condition can be determined immediately.

Using a single indentation technique from the plane strain test as proposed by Guminski and Willis (18) for assessing lubricants of different types for rolling aluminum, the coefficient of friction under each lubrication condition was determined from an equation which describes the pressure required to deform an ideal plastic material by a flat punch as derived by Tabor (23). Based on the pressure on the surface of the punch at the yield point, the equation predicting a hyperbolic relation between the deformation, Z, (shown schematically in Fig. 2) and the coefficient of friction, f, is expressed in the form:

$$Z = \frac{(h^2 [F_f - F_i])}{A Y b} \left(\frac{1}{f} - \frac{B}{2b}\right) \qquad (3)$$

where:

A = die surface area

b = width of die surface

F_f = final force value reached in the deformation

Fi_e = the initial force at the beginning of the deformation taken as the force required to reach the limit of elastic deformation

f = coefficient of friction

h = thickness of material between dies

Z = deformation.

Specifically, the single indentation technique involves the keeping of an applied load for a given reduction. The experimental values, F_f, A, h and Z from the indentation test and values of Y and F_i from tensile test were then substituted into equation (3) for immediate determination of the friction coefficient at that particular reduction under a given lubrication condition. For each oil under investigation, six indentations were made on each strip corresponding to 10, 20, 30, 40, 50 and 60 percent reduction, respectively.

The friction coefficients under various investigated local oils including dry condition, were determined both from the slip-line field theory and Tabor's equation. Eight interface frictional conditions were investigated using either single indentation technique or the slip-line field theory. The initial cross-head velocity of the hydraulic testing machine giving an average strain rate of 10/sec, was used in all experiments.

RESULTS

For high accuracy and speed, the solutions of equations (1), (2) and (3) yielding friction coefficients under various interface frictional conditions, were programmed on an Apple 2 Mini Basic Computer. Table 1 gives the values of friction coefficient obtained from the slip-line field theory and approximate analysis and Tabor's equation for various lubricating oils at various percentage reductions. In Table 2, the initial mean values of coefficient of friction obtained at room temperature in the present tests on mild steel strip specimens are compared with those on mild steel by Takahashi and Alexander (19) (Plane strain indentation tests), Whitton and Ford (21) (cold-rolling tests) and Male (24) (ring compression tests).

The plot of mean pressure $\bar{P}$ against percentage reduction under various investigated oils lubrication conditions for immediate determination of friction coefficients is given in Fig. 3. Variations of friction coefficients with percentage reduction and mean die pressure under investigated interface frictional conditions are plotted in Figs. 4 and 5, respectively.

DISCUSSION OF RESULTS

Many of the metalworking operations take place under plane-strain condition. Specifically, in cold rolling operation, plane strain is almost exactly realized because the elastic material adjacent to the plastic prevents lateral movement. Since the theory of the slip-line field has allowed the exact solution of several complex problems to be obtained in plane strain, the full application of this theory to assess the local oils as lubricants for the cold rolling of mild steel is therefore justified.

While the friction coefficient under graphite paste lubrication condition yield a fairly constant value of 0.001 using the slip-line theory, however, for all lubrication conditions, the friction coefficient decreases with increasing percentage reduction (Table 1, Fig. 4). With the exception of dry condition where the friction increases with increase in reduction, it can be seen that, in general, the friction coefficient is high at low reductions and falls at higher reductions with palm oil giving the smallest friction coefficient.

While these results confirm the earlier observation by the plot of the calculated and experimental coefficient of friction values versus deformation (25), they also re-affirm the claim that the coefficient of friction varies with pass reduction as observed by May, Nair and Hoffman (27).

As hypothesized by previous researches (21,27), the high coefficient of friction at low reduction can be attributed to the predominance of boundary lubrication, while on the other hand, the initial strip surface roughness which has to be modified by contact with the die and the work hardening capacity of the strip may also be contributing factors.

The decrease in friction coefficient with increasing reduction may be due to the increasing efficiency of hydrodynamic lubrication as suggested by May, Nair and Hoffman (27). The observed increase in the accumulated metallic debris with increasing reduction may presumably account for the decrease in friction coefficient at higher reductions, thus agreeing with the observations of Takahashi and Alexander (19) in the plane-strain compression test for quantitative estimation of the friction coefficient during metalworking. Moreover, it also confirms the observations that the presence of metallic debris clearly reduces friction as found by Guminski and Willis (18) for their intermediate lubricants in the cold rolling of aluminum.

The dependence of friction on mean die pressure was also observed as shown in Fig. 5. There is a rise in friction coefficient with reduction (Figs. 4 and 5) because steel shows a tendency to pressure-weld as previously observed by Schey (28). The suggestion of the accumulation of metallic debris that accounts for the increase in friction with increased die pressure under dry condition (19) seems applicable in the present investigation.

At reductions somewhat higher than those in the present tests, the tendency for friction to increase for all lubricants will be great since metal-to-metal contacts becomes greater with increasing pressure which leads to lubricants being squeezed out.

The friction values calculated from Tabor's equation (Equation (3)) are high compared to the value from slip-line field theory except for the dry condition where the coefficients from Tabor's equation are lower. The higher quantity of metallic debris obtained in the incremental loading in the slip-line field analysis as against single indentation for coefficient determination from Tabor's equation accounts for the lower coefficients. However, the reverse is the case under dry condition. Thus it goes to confirm the previous observations by Johnston and Atkinson (25) that different friction tests would give values for the coefficient of friction that would differ from one another, depending upon factors such as contact area, surface roughness, relative speed of surfaces and other features. In the present investigation, however, variations between the computed coefficients from both analyses are small although they are high at low reductions and low at high reductions.

It may be worthwhile noting that with incremental loading technique under dry condition, a maximum value of one was obtained as the friction coefficient using the combined friction (slipping and sticking) equation (equation (2)). It agrees with the observations of Bowden and Tabor (29) that value of friction coefficient between unlubricated steel surfaces is usually of the order of 1 to 1.5. The sticking effect thus contributes to the high value of friction coefficient because of the tendency of two similar metals to pressure weld under dry condition.

Excluding the dry condition where the value of mean coefficient of friction obtained in the present tests is higher than the value obtained from the rolling experiments of Whitton and Ford (21), there is general agreement with the plane strain indentation tests of Takahashi and Alexander (19) and ring compression tests of Male (24) as summarized in Table 3.

CONCLUSION

The vaunted excellence of fatty oil lubricants in lowering the coefficient of friction in metalworking operations has been demonstrated from the data obtained from the present tests. The potentials of the undiluted locally produced fatty oils as cold rolling lubricants for steel have been quantitatively established. The leading role the Nigerian palm oil has been displaying as one of the best lubricant for the cold rolling of steel as reported by Neckervis and Evans (30) is again confirmed in the present investigation. Based on its mean coefficient of friction of 0.061, the undiluted palm oil has proved to be a better lubricant than any other investigated locally produced oils including SAE 30 - an industrial lubricant. Furthermore, on the basis of the mean friction coefficient obtained from the present tests (Table 3) performance of each local oil as possible lubricant for cold rolling of steel listed in order of decreasing effectiveness is palm oil, groundnut oil, shea butter oil, palm kernel oil and cottonseed oil. It is interesting to observe that the undiluted locally produced fatty oils perform better than the

SAE 30.

While it is uneconomical to use undiluted fatty lubricants in metalworking operations, it is worthwhile to investigate the blending of these local oils with mineral oils in order to produce cheaper and more efficient lubricants for metalworking operations. The author earnestly hopes that these preliminary results will encourage such further progress.

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APPENDIX A

NOTATION

A - - die surface area

b - breadth of die

F_f - final force value reached in the deformation

F_i - the initial force at the beginning of the deformation taken as the force required to reach the unit of elastic deformation.

f, - coefficient of friction

h,t - thickness of material between dies

k,Y - yield shear stress of specimen

p - normal stress at the interface

P - mean pressure over the die

r - reduction

z - deformation

τ - shear stress at the interface.

Table 2 - Comparison of Friction Coefficient Values Obtained by Various Workers for Mild Steel Tested Under Various Lubrication Conditionat Room Temperature

LUBRICANT	COEFFICIENT OF FRICTION	PROCESS	REFERENCE
Dry Cottonseed oil Shea butter oil Palm oil Groundnut oil Palm Kernel oil SAE 30	0.189 - 0.240 0.155 - 0.060 0.127 - 0.047 0.101 - 0.025 0.114 - 0.037 0.130 - 0.051 0.174 - 0.067	Plane Strain Test	Present Work
Dry Paraffin SAE 10 Paraffin + 5% Oleate	0.25 - 0.17 0.23 - 0.14 0.12 - 0.04 0.10 - 0.02	Plane Strain Test	Takahashi and Alexander (19)
Dry 68/615 graphite Paraffin + Stearic Acid Paraffin 615 Graphite Camphor Paraffin + Sodium Oleate Paraffin + Lauric Acid	0.085 0.072 0.075 0.060 0.047 0.038 0.049 0.054	Rolling Test	Whitton and Ford (21)
Dry Lanolin	0.26 0.02 - 0.03	Ring Test	Male (24)

Table 1 - Coefficients of Friction Obtained From Slip-Line Field Theory (μ) and Tabor's Equation (f) Under Various Lubrication Conditions for Various Amounts of Deformation

LUBRICATING OIL	PALM OIL		GROUNDNUT OIL		SHEA BUTTER OIL		PAKM KERNEL OIL		COTTON-SEED OIL		SAE 30		DRY CONDITION	
REDUCTION PERCENT	μ	f	μ	f	μ	f	μ	f	μ	f	μ	f	μ	f
5	0.101		0.114		0.127		0.130		0.155		0.114		0.189	
10	0.091	0.163	0.107	0.168	0.117	0.117	0.130	0.174	0.147	0.179	0.166	0.188	0.191	0.188
15	0.081		0.099		0.114		0.125		0.134		0.151		0.194	
20	0.078	0.114	0.095	0.120	0.103	0.123	0.113	0.126	0.126	0.135	0.140	0.149	0.196	0.150
25	0.075		0.093		0.099		0.113		0.121		0.137		0.200	
30	0.071	0.080	0.086	0.087	0.092	0.098	0.106	0.107	0.115	0.116	0.131	0.136	0.220	0.136
35	0.061		0.078		0.082		0.096		0.109		0.120		0.214	
40	0.051	0.054	0.072	0.074	0.079	0.084	0.090	0.092	0.101	0.102	0.111	0.112	0.221	0.115
45	0.041		0.068		0.072		0.083		0.096		0.102		0.231	
50	0.030	0.032	0.061	0.065	0.067	0.072	0.079	0.080	0.086	0.090	0.096	0.096	0.240	0.137
55	0.028		0.052		0.060		0.067		0.076		0.084		0.238	
60	0.025	0.027	0.037	0.042	0.047	0.059	0.051	0.060	0.060	0.065	0.067	0.073	0.242	0.207

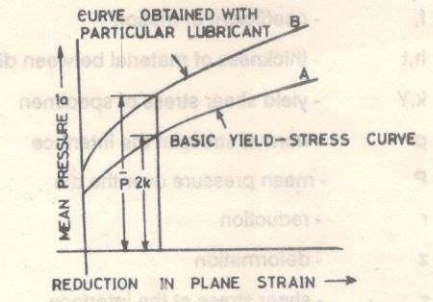


FIG. 1. Procedure adopted for the evaluation of $\bar{p}$ and 2k values from the plot of mean die pressure against reduction

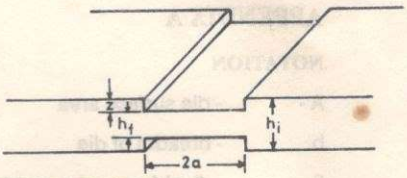


FIG. 2. Metal strip after deformation.

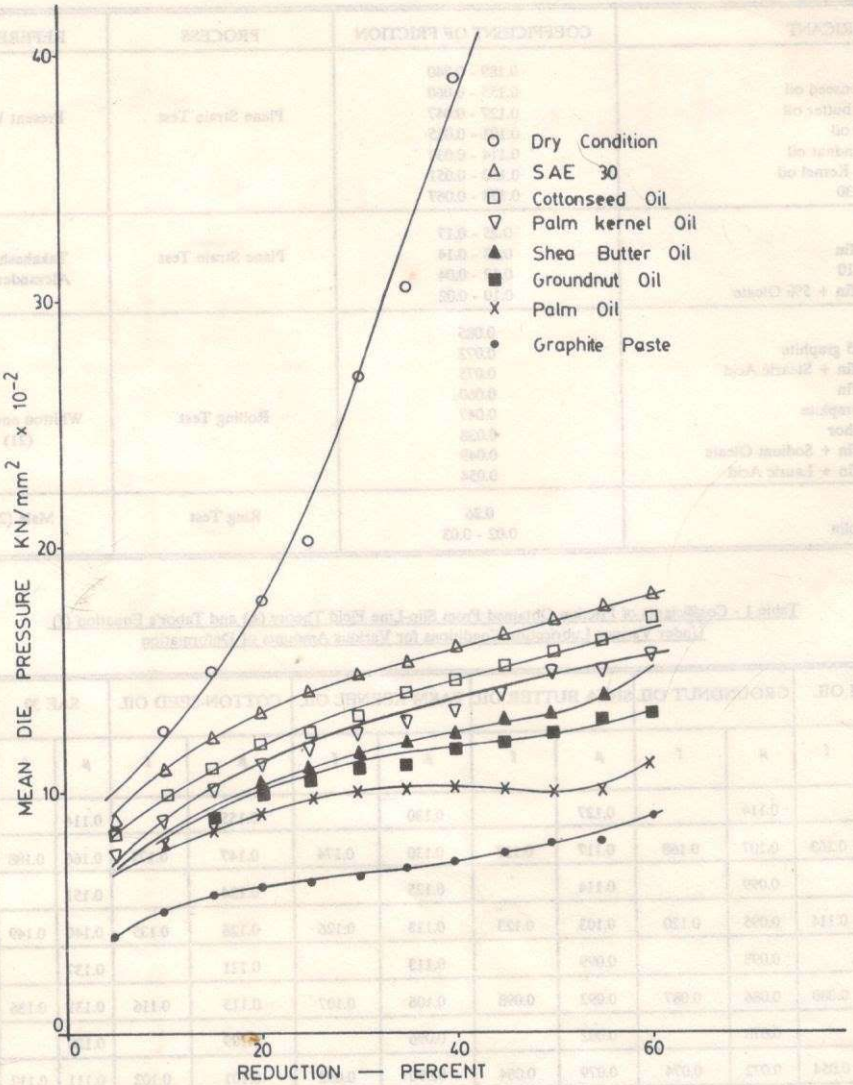


FIG. 3. Plot of mean die pressure against reduction under various lubrication conditions.

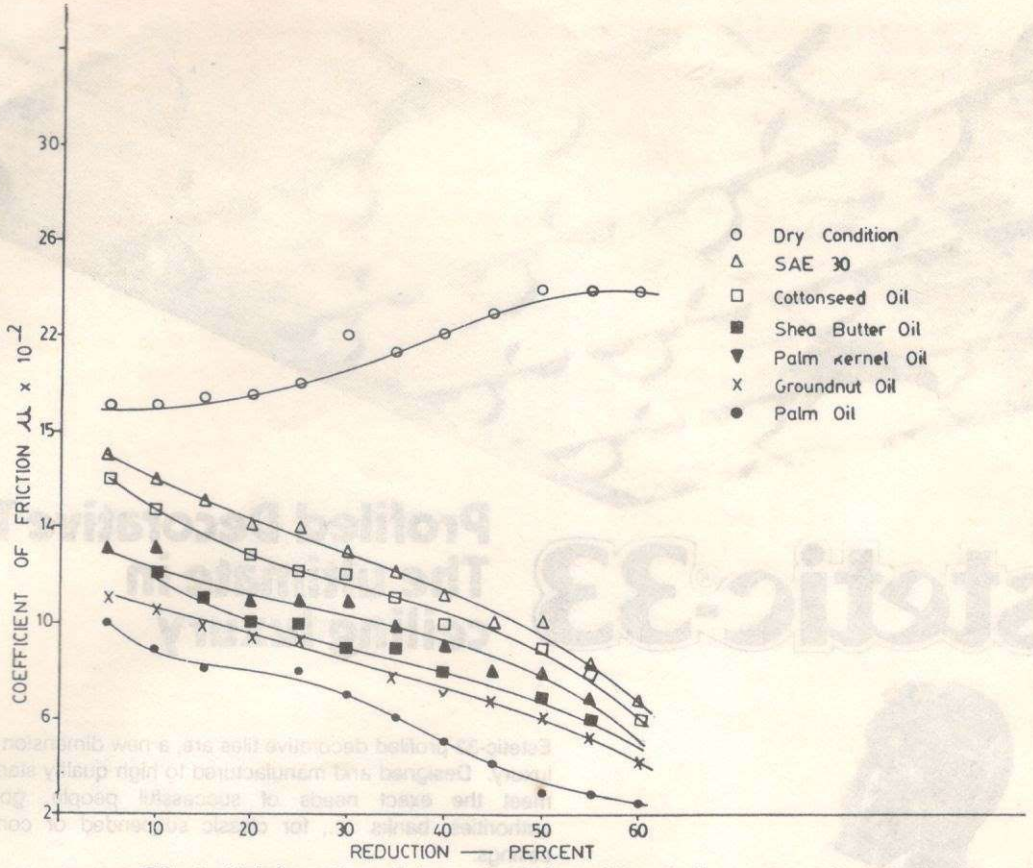


FIG. 4. Variation of coefficient of friction with reduction under various lubrication conditions.

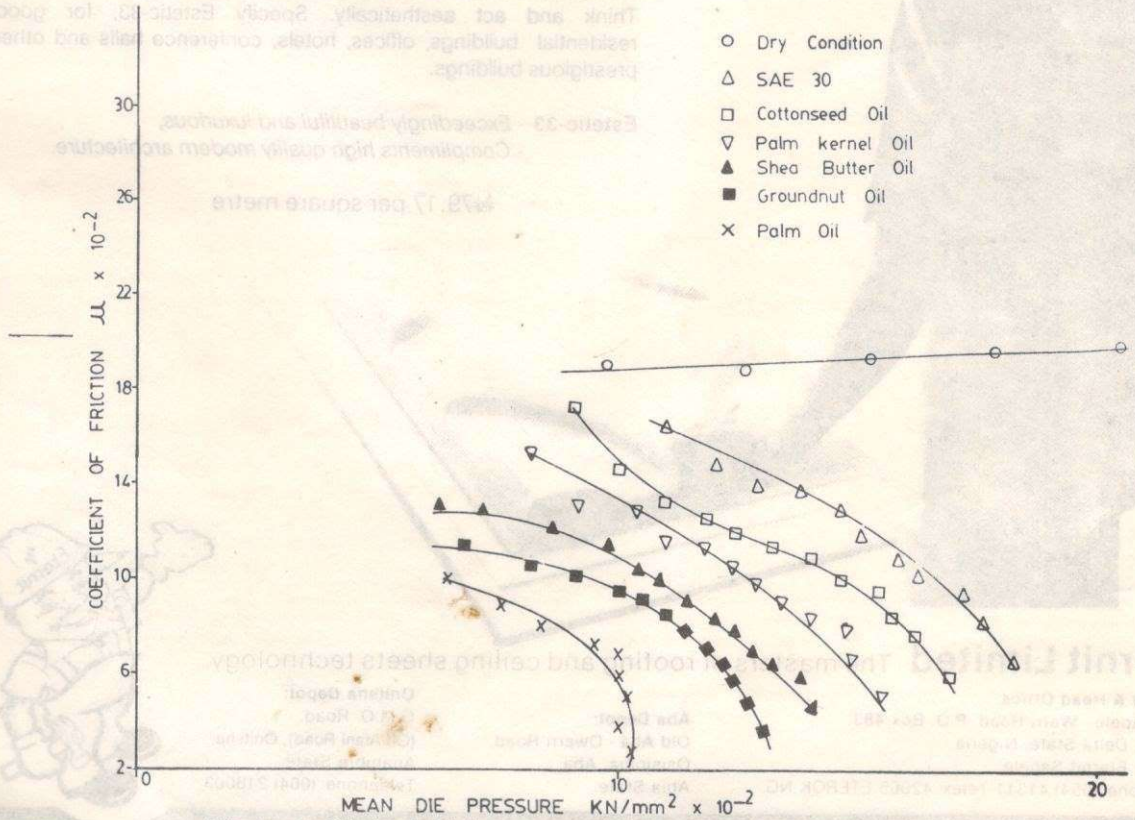


FIG. 5. Coefficient of friction plotted against mean die pressure under various lubrication conditions.