J. Rubb. Res. Inst. Malaysia, 31(3), 236–250

Experiments on Friction of Raw Natural Rubber

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The static and sliding friction of various grades of raw natural rubber were investigated by sliding an unvulcanised rubber hemisphere against a Perspex plate and while measuring the sliding force, the interface was observed. The normal load, sliding velocity and surface roughness of the plate were varied. The level of friction was found to depend upon these variables and the state of mastication of the rubber. Sliding caused ridges of deformed rubber to be generated on hemispheres and surface cracks to grow into the rubber bulk. The friction-induced rate of crack growth could be accounted for in terms of tear energy of the rubber. Some aspects of wear, surface contamination and the effect of temperature were also investigated.

The frictional behaviour of unvulcanised natural rubber is important in various processes in rubber manufacture, such as extrusion, where whether the rubber grips or slips on a surface is relevant. It is recognised in the industry that the surface 'quality' of metallic parts plays a role, in operations such as milling and mixing. There appears, however, to be little published information; this paper discusses simple experiments carried out to improve understanding of physical factors involved when raw rubber slides on a hard substrate.

EXPERIMENTAL

Rubber samples were designated grades of Standard Malaysian Rubber (SMR) and ranged in hardness and Mooney viscosity, V_R , according to their state of mastication. They were compression moulded into hemispheres. The cavity mould surfaces were smoothened and brightened by polishing with paste and buffs. Mould times were 30–60 min at temperatures of 110°C–120°C. Hemispheres were left to cool in their moulds under pressure for 24 h, and they were easily removed without the need for release agents. Occasionally there were trapped air bubbles in the hemisphere surface, but usually there was enough free surface to carry out several friction tests per hemisphere (prestressing effects from previous runs were negligible). The hemispheres had a diameter $2R$ = 42 mm. Their Young's elastic modulus, E , was calculated from Hertz Equation[1] by measuring the contact radius against a Perspex plate under an applied load after 2 min dwell.

Friction Measurement

Apparatus was constructed for sliding a rubber hemisphere against a Perspex plate under conditions where the normal load and sliding speed could be varied and the sliding force measured while the interface was observed *(Figure 1)*. A balance spring gave the sliding force, F , under normal load W , the friction coefficient being $\mu = F/W$. The rubber was pulled over the Perspex by a variable speed electric motor acting through a three decade gearbox. With this arrangement it was possible to vary the normal

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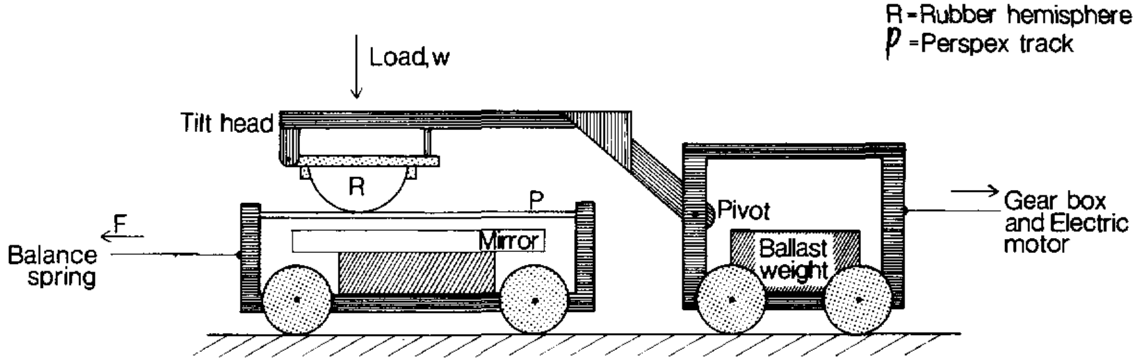

Figure 1. Diagram of friction apparatus.

load from 0.2N to 50N and the sliding speed from 10^{-4} mms^{-1} to 10^{2} mms^{-1}. Sliding speeds were measured with a scale and stopwatch. Allowance was made for the rolling resistance of the carriage supporting the Perspex track; this varied with increasing applied load from about $\mu = 0.03$ to 0.08.

The contact interface was viewed through a mirror at 45° to the horizontal placed under the Perspex track. This allowed the contact radius to be measured in order, for example, to determine the elastic modulus of the rubber, and physical events during sliding, such as wrinkling of the rubber surface could be followed.

In all tests, unless stated otherwise, the Perspex surface was cleaned with a paper tissue moistened with pure propan-2-ol (Analar grade) and allowed to dry. Rubber surfaces were friction tested as moulded without solvent cleaning.

RESULTS

Load Dependence

Experiments were carried out with SMR CV hemispheres (V_R = 60, *Table 1*); their surfaces were slightly uneven, presumably due to 'nerve' in the rubber, but they gave a reasonably uniform circular contact area when loaded against the Perspex track. The normal load was varied and the friction force measured for a constant sliding speed of 0.2 mms^{-1} It was always found that as the displacement between surfaces increased the initial circle of static contact became pinched in the direction of sliding into an oblong, slightly elliptical, contact patch as the rubber became deformed, a surface wrinkle developing into a ridge of protruding rubber *(Figure 2)*. The major axis of the ridge was approximately perpendicular to the direction of sliding. The friction was followed throughout this change. It increased to a high value at the formation of the tongue-like ridge and thereafter remained more or less constant. A plot of the friction-load data *(Figure 3)* indicates that for moderate contact pressures the friction coefficient varies inversely as the cube root of the normal load. In spite of a change in the contact

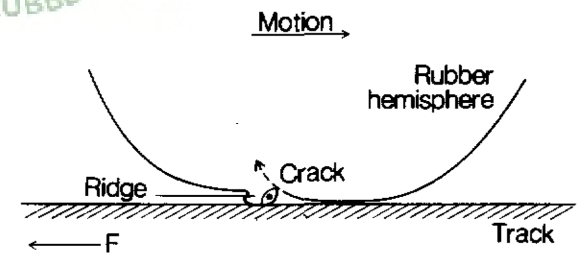

Figure 2. Sketch showing ridge formation and crack growth.

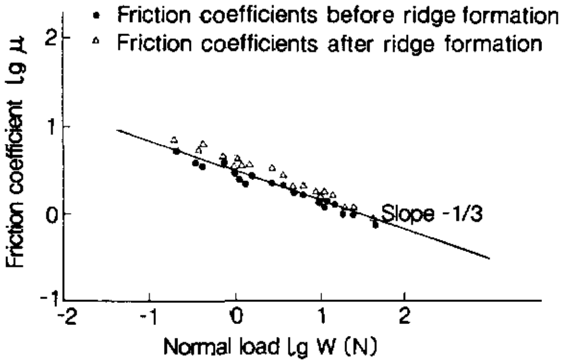

Figure 3. Friction dependence on load. Hemispheres of SMR CV slid on smooth Perspex track at 0.2 mms^{-1}, T = 24°C–26°C and RH = 60%–70%.

area from circular to oblong after ridge formation, the friction-load variation remains about the same. Linear regression analysis of the data points just before ridge formation gave a slope $m = -0.325$ with a correlation coefficient $r = 0.985$, and after formation $m = -0.392$ and $r = 0.983$.

One way to explain these findings is to assume that the frictional force F is proportional to the area A of rubber in contact with the Perspex, that is

$$F = As \qquad \ldots 1$$

where s is the proportionality constant, which appears as a interfacial shear strength. Then for a circular contact area of radius a, resulting from loading an elastic sphere on a rigid flat, Hertz theory[1] gives $F = \pi s\ (9WR/16E)^{2/3}$ and hence the coefficient of friction is

$$\mu = \pi s \left(\frac{9R}{16E}\right)^{\frac{2}{3}} W^{-\frac{1}{3}} \qquad \ldots 2$$

Even after ridge formation when the contact patch becomes oblong the friction coefficient is still not far from proportional to the cube root of the normal load, though the higher slope implies a transition towards Hertzian cylindrical contact ($\mu \propto w^{-\frac{1}{2}}$).

Interfacial Shear Strength

The effect of contact pressure on the interfacial shear strength of SMR-CV hemispheres sliding against smooth Perspex was examined. The shear strength, τ, was taken as the measured sliding friction force divided by the observed ridge contact area (oblong with major axis two to fifteen times minor). Experimental results (*Figure 4*) at a constant sliding speed show that the interfacial shear strength increases with the mean contact pressure ($P = W/A$). This data is similar in trend to that reported for various plastics[2,3] although the absolute magnitude of the shear strength of raw rubber is much less. Analysis of our rubber data suggests that the interfacial shear strength is linearly dependent on the contact pressure according to

$$\tau = \tau_0 + \alpha P \qquad \ldots 3$$

where for this particular data $\tau_0 = 0.15$ MPa and $\alpha = 0.92$ (correlation coefficient 0.96).

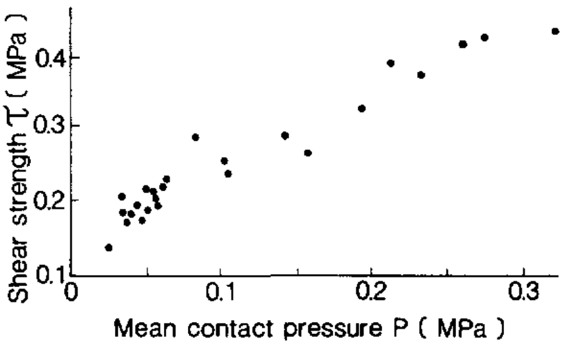

Figure 4. Effect of contact pressure on interfacial shear strength of SMR CV hemispheres slid on smooth Perspex track at 0.2 mms^{-1}, T = 24°C–26°C and RH = 60%–70%.

In the sliding of various plastics it has been suggested that shearing is confined to a narrow interfacial plane only some 10 nm thick, and that for a given strain rate the interfacial shear strength is an order of magnitude less than that of the bulk. In our raw rubber sliding experiments the test hemisphere rides on a ridge of rubber formed during sliding *(Figure 2)*, so that presumably both the interface and the subsurface to a depth of 1 mm or so are involved in shearing. The protrusion height, h , of the ridge could be directly observed and measured during and after sliding, so the corresponding strain rate in the ridge is of the order v/h. For the data of *Figure 4*, ridge protrusions were 1–2 mm, which suggests strain rates of 0.1–0.2 s^{-1}. The interfacial shear strength of raw rubber as obtained from friction measurement *(Figure 4)* may be compared with that of bulk strength derived from tensile stress measurement on extruded strands of the same rubber at a similar strain rate. Measurements with an elongational viscometer at 25°C gave strength of 0.35–0.48 MPa at strain rates of 0.026–0.045 s^{-1}, and hence are of the same magnitude as the interface. Further, the viscosity of the ridge material may be expected to be $\tau h/v$, and this viscosity can be compared with that obtained from capillary rheometer measurements. A rheometer test using only the barrel of the rheometer (barrel length/diameter ratio 21, barrel diameter = 9.5 mm) carried out on SMR CV at 30°C under lamina flow at a low strain rate of 10^{-3} s^{-1} gave η = 200 MPa s (2×10^9 Poise); low speed sliding friction measurements at 25°C for which the strain rate v/h was 1.9×10^{-3} s^{-1} (v = 0.0038 mms^{-1}) gave η = 171 MPa s. This suggests little difference between bulk strength and interfacial shear strength for raw rubber, in contrast to plastics[2,3] and may be explained on the basis that shearing is not constrained to a narrow interfacial plane.

Effect of Sliding Speed

The variation in friction with speed was investigated for various grades of SMR masticated to different extents. In all cases friction was found to increase with sliding speed. The results shown in *Figure 5* are typical: there was considerable scatter in the data. This may arise from imperfectly spherical and smooth surfaces; it may also reflect variability in the rubber surface composition, such as inhomogeneities and contaminants.

There was a tendency for masticated rubber samples (e.g. SMR L/V_R = 55, *Figure 5*) to stick firmly after a few minutes contact dwell, so leading to a large static friction. At very low speeds the rare event was witnessed of a rubber hemisphere sticking so firmly that its entire bulk became drawn before interfacial grip was lost Once any initially high adhesion had been overcome, interfacial slip ensued at all speeds for all rubber grades. At low speeds transfer of material from the rubber surface onto the Perspex track was seen as a smear film. Transfer was not obvious at higher speeds, unless there was marked stick-slip motion: then transfer occurred at each stick. At high speeds stick-slip motion was often present, giving rise to contact squeal, and occasionally there were flickering ripples in the contact zone similar to the Schallamach waves[4] generated by a peel process[5] with vulcanised rubber.

A comparison of friction levels with changing speeds under a fixed normal load is given in *Table 1* for the various SMR grades tested. Friction levels were all similar. However, there was discernable trend of increasing friction with decreasing Mooney viscosity (*i.e.* decreasing Young's modulus/increasing state of mastication), which may arise because under a fixed

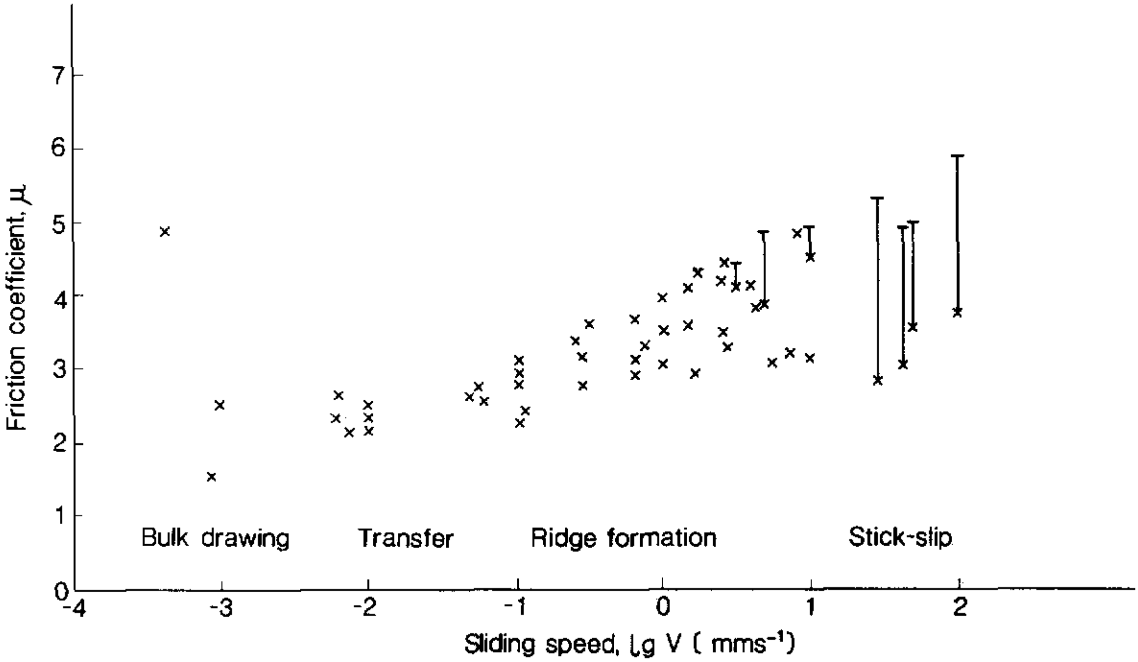

Figure 5. Variation in friction of masticated (V_R = 55) SMR L hemispheres with sliding speed on a smooth Perspex track under a normal load of 1.57N, T = 24°C–27°C, RH = 60%–70%.

TABLE 1. FRICTION COEFFICIENTS OF RAW SMR GRADES

Grade	V_R ± 2	E (MPa) ± 10%	Sliding speed, V (mms^{-1})			
			0.01	0.1	1	10
SMR CV	60	0.43	2.3±0.3	2.7±0.3	3.5±0.5	4.0±0.6
SMR CV (mast.)	35	0.14	2.5±0.4	2.9±0.3	3.6±0.4	4.1±0.5
SMR L	86	0.78	1.8±0.3	2.2±0.4	2.5±0.6	3.0±0.7
SMR L (mast.)	55	0.20	2.3±0.2	2.7±0.4	3.5±0.5	4.0±0.9
SMR L (mast.)	38	0.15	2.4±0.2	3.0±0.2	3.7±0.3	4.2±0.8
SMR 10	80	0.58	2.0±0.1	2.3±0.1	3.0±0.2	3.4±0.2
SMR 20 (mast.)	62	0.41	2.4±0.2	2.6±0.2	3.1±0.3	3.4±0.3

Raw rubber hemispheres (R = 21 mm) sliding on smooth Perspex track under 1.57 N load. Temp. 23°C–27°C, RH = 55%–80%, mast. = masticated. Friction coefficients quoted are the average of several tests, with an indication of maximum/minimum values.

load a softer rubber makes a greater area of contact with the track. Increasing the normal load decreased the friction coefficient throughout the speed range for all SMR grades in accordance with earlier load dependence findings.

Rubber Surface Morphology

In general, all grades and viscosities of raw rubber showed the following surface transitions with increasing sliding speed: bulk drawing accompanied by material transfer onto track; ridge formation; slight scuffing under stick-slip motion *(Figure 5)*. Transfer was less distinct for unmasticated rubbers. Hemisphere rubber surfaces were studied visually after each friction test. The overall impression gained was that those of unmasticated rubber of high Mooney viscosity acquired several irregular ridges at intermediate sliding speeds (0.01–1 $mm s^{-1}$), whereas masticated rubbers deformed into a single smooth ridge.

Evidence of strain-induced crystallisation in the vicinity of the rubber interface was obtained during low-speed sliding under high normal loads ($>5N$). For example, with SMR CV (V_R = 60) when the contact area was viewed directly through the Perspex track during sliding a white hue was visible in drawn areas. Upon the release of stress (contact surfaces separated) the whiteness disappeared. When the hemisphere sample was cooled towards 0°C in a refrigerator the drawn region became white, so revealing unrelaxed strain, but the bulk showed no whiteness. Under a microscope unrelaxed strain in the contact surface could be readily seen in polarised light, strain being most intense in the drawn region. When masticated SMR CV (V_R = 35) was examined there was no whiteness in sliding contact, though cooling afterwards produced a faint whiteness on drawn ridges.

Crack-growth during Sliding

Sliding of raw rubber hemispheres over smooth Perspex tracks not only produced ridges of rubber raised above the spherical surface, but also wide cracks that penetrated beneath the surface. The formation of a ridge and crack is illustrated *(Figure 2)*. Prolonged sliding sometimes increased the crack depth, c , and a preliminary analysis of this phenomenon suggests that the crack-growth can be accounted for in terms of the tear energy of the raw rubber. This energy varies with Mooney viscosity and tear rate[6]. Assuming that the crack-opening in sliding is similar to the 'trousers' mode of tearing[7] and that the force opening the crack is the friction force, the tear energy is of the order[8]:

$$T = \frac{F}{l}\,(1 + \cos\theta) \qquad \ldots 4$$

where l is the length of the crack in the rubber surface approximately perpendicular to the direction of sliding

θ is the crack angle *(Figure 2)*, and if it is assumed that the crack propagates into the bulk at a steep angle to the surface, $T \approx F/l$.

Cracks in hemisphere surfaces were generally crescent-shaped, and were most deeply developed under a high normal load. After frictional sliding approximate values of l and c were measured with a ruler. The total time of sliding was known for each friction test, hence a crack-growth rate, $\Delta c/\Delta t$, could be found. This was needed to assess the relevant tear energy from independent measurements on the same grade and viscosity of rubber using a 'trousers' test-piece. Energy derived from the friction tests, F/l, compares favourably with energy from 'trousers' tests, T *(Table 2)*. In this comparison for all the

TABLE 2. FRICTION-INDUCED CRACK GROWTH

Grade	V_R	W (N)	V (mms^{-1})	F (N)	l (mm)	c (mm)	$\Delta c/\Delta t$ (mms^{-1})	T ($N mm^{-1}$)	F/l
SMR L	86	6.4	0.01	9.8	13	2	0.001	1.3	0.75
		6.4	1.3	8.8	9	1	0.016	1.8	0.98
		24.5	2.5	38.2	15	0.8	0.1	2.9	2.55
SMR L (mast.)	55	1.6	0.06	2.6	9	1.3	0.001	0.6	0.29
		1.6	5.7	2.9	6	1	0.06	1.1	0.49
SMR L (mast.)	38	1.6	0.56	5.9	12	1	0.01	0.5	0.49
		6.4	0.22	3.9	12	1	0.003	0.5	0.33
SMR CV	60	14.7	0.2	25.5	17	1.5	0.008	(0.9)	1.50
		44.1	0.2	41.1	27	2	0.04	(1.1)	1.52
SMR CV (mast.)	35	6.4	2.0	12.3	17	2	0.01	(0.5)	0.72
SMR 10	80	6.4	0.1	11.8	13	1.5	0.004	(1.4)	0.91

Raw rubber hemispheres (R = 21 mm) sliding on smooth Perspex track. Temp. 25°C–28°C, RH = 60%–80%, mast. = masticated. Quoted T values were derived from 'trousers' tear tests on SMR L. Measurements of F were accurate to ±0.15N and those of l and c to ±0.1 mm.

friction tests with SMR L the values of F/l were less than T. This may be because the crack angle was more shallow than assumed in *Equation 4* and an allowance should be made[8]. On the other hand friction tests with SMR CV gave values of F/l greater than the T values quoted for SMR L. This presumably reflects the fact that although SMR CV has a Mooney viscosity of 60 it is not masticated, so that with longer chain lengths its tear energy will be higher than that for SMR L masticated down to a comparable viscosity; and likewise the comparison of masticated CV (V_R = 35) with highly masticated SMR L (V_R = 38). These observations illustrate the general point that Mooney viscosity values are not a reliable guide to the physical properties of raw rubbers – the entire history of a material needs to be known[9].

Although further study is indicated, this preliminary evidence draws attention to the role that frictional forces can play in initiating cracks in raw rubber, and to how the crack-growth rate might be assessed quantitatively.

Wear

Attempts were made to follow interface events on prolonged sliding of raw rubber hemispheres against a smooth Perspex track. The objectives were to see whether the crack depth could be significantly increased and if eventually a wear fragment would become detached from the rubber surface. To prolong sliding, several passes were made over the same length of track, the track being cleaned between each pass.

At low sliding speeds ($\simeq$ 0.1 mms^{-1}) it was found that this procedure did not significantly increase the depth of the first formed crack. The first crack became blunted and further smaller cracks appeared on the ridge tongue surface.

The tongue itself became more drawn, particularly for well masticated rubber, but tended to stick to the underside of the rubber hemisphere rather than become detached. Sometimes the rubber surface rolled a little so that the original ridge came out of contact with successive passes over the track. New ridges and cracks initiated on adjacent rubber surface. The previous ridge became 'smudged' away to the exit of the contact area so that eventually layers of smudge built up at the exit. The layering of debris has its parallel in die extrusion if material is allowed to accumulate at the die exit.

At high sliding speeds ($\simeq 10\ mms^{-1}$) it was usually found that the hemisphere tilted sufficiently relative to the track so as to reduce the contact area to the tip of the tongue. This concentrated traction stresses with the result that a rubber fragment separated. Fragments separated more easily for unmasticated rubber, which was less tacky.

The wear process in these experiments resembles that of wear by roll formation[10]. One difference, however, is that the tackiness of raw rubber tends to inhibit the separation of a wear fragment, unlike vulcanised rubber where the fragment can be rolled in the contact zone.

Influence of Surface Roughness

The friction coefficients of SMR L hemispheres of 38, 55 and 86 Mooney viscosity were measured when slid on a Perspex track roughened (with silicon carbide paper) to 0.4 μm Centre Line Average (CLA). The measurements were compared with those on smooth Perspex and showed that the friction of unmasticated rubber (V_R = 86) was reduced on the roughened Perspex, whereas for well masticated rubber (V_R = 38) it tended to be increased. Stick-slip of the masticated samples blurred friction levels. However, by plotting the maximum observed friction (meaning the stick when stick-slip motion occurred) a clearer distinction in levels was obtained, this being more akin to an evaluation of adhesion (*Figure 6*). Although stick-slip was severe for samples of 38 Mooney, it was less for samples of 55 and almost absent for samples of 86 Mooney. At low speeds, samples of 38 Mooney sometimes adhered so well to the roughened Perspex that the hemisphere bulk became bodily stretched and pulled into two parts – leaving a separated blob of rubber on the track. Examination of the contact zone after sliding against roughened Perspex, showed that all hemisphere surfaces became deformed into a single ridge in the speed range 0.1 to $10\ mms^{-1}$. At higher speeds they appeared to be only lightly rubbed – less so than against smooth Perspex. On the coarsely rough track (50–100 μm) the gross asperities produced fine plough lines in rubber surfaces at lower speeds, ridge formation being somewhat suppressed. At higher speeds there were also plough lines, but sometimes a rubbed appearance developed more like the abrasion patterns seen on vulcanisates[11]. Stick-slip motion was less pronounced on roughened tracks, particularly so for the harder rubbers.

The effect of different degrees of Perspex track roughness was investigated systematically. At a sliding speed of $1\ mms^{-1}$ the most highly masticated rubber had the highest friction through the range of roughness examined (*Figure 7*), the static friction after 2 min dwell being distinctly greater than the average kinetic friction observed during continuous sliding. The static friction was increased on a slightly rough surface. A clear distinction between static and kinetic friction was not apparent for unmasticated rubber (V_R = 86), nor for a 2½% sulphur vulcanisate. The latter was the least frictional at all levels of roughness.

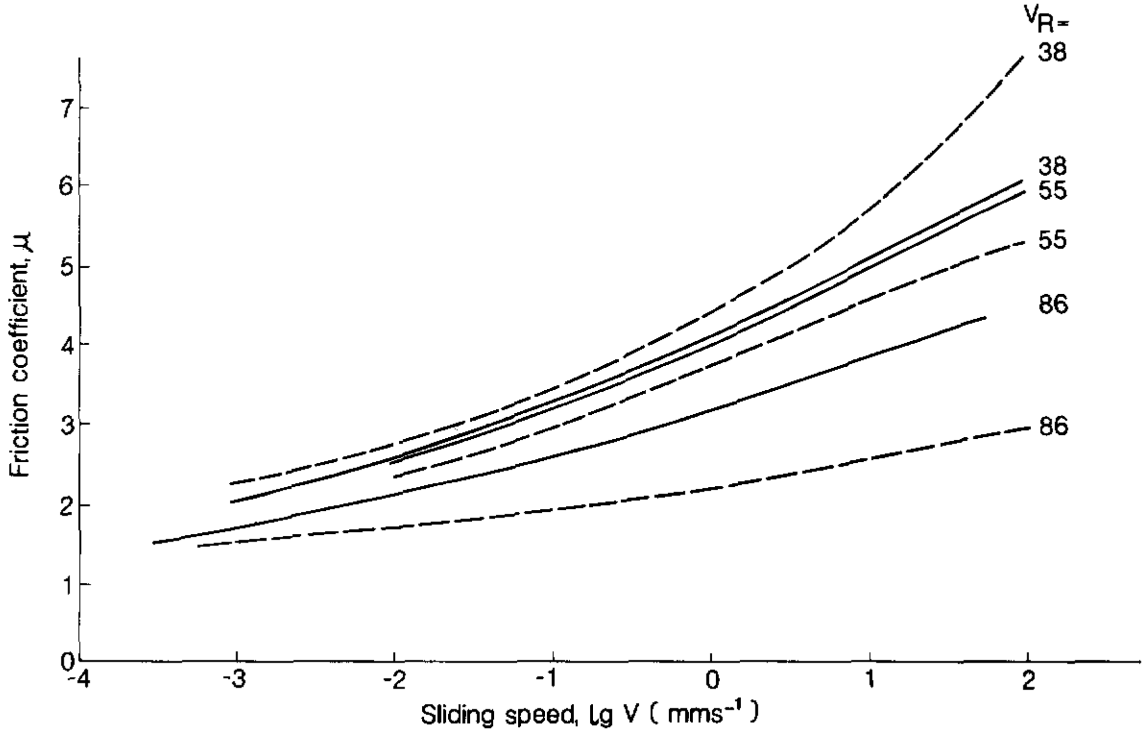

Figure 6. Effect of track roughening on friction. Trend lines of maximum observed friction were plotted for a normal load of 1.57N, T = 23°C–27°C, RH = 55%–75%.

Surface Contamination

In a particular set of sliding tests with hemispheres of SMR CV (V_R = 60) the presence of trace amounts of silicone spray release agent, picked up off the metal ballmould, was found to reduce the friction through the speed range studied (0.01–1 mms^{-1}) by about 25%–50% less than indicated in *Table 1.* Hence the friction of raw rubber appeared sensitive to contaminants. It could be argued that the absence of Schallamach waves may suggest the presence of a boundary lubricant film on all samples tested. In an attempt to resolve this the following experiments were carried out.

The friction of an 'as moulded' hemisphere surface was compared with that of the same surface after solvent cleaning (wiped with solvent-soaked paper tissue and allowed to dry). The results of friction tests with SMR CV (V_R = 60) cleaned in turn with acetone, toluene and aqueous detergent (teepol) suggest that there was no readily soluble surface contaminant present that might be acting as a boundary lubricant *(Table 3).* After the solvent wiping there were still no Schallamach waves, nor complete drawing of the rubber bulk with no interfacial slip.

In rubber processing talc is often employed to reduce tack, and it was clear from our tests that with sufficient talc 'contaminant' the sliding friction of raw rubber could be reduced to a low level *(Table 3).*

Effect of Temperature

The frictional properties of vulcanised rubber are known to be temperature

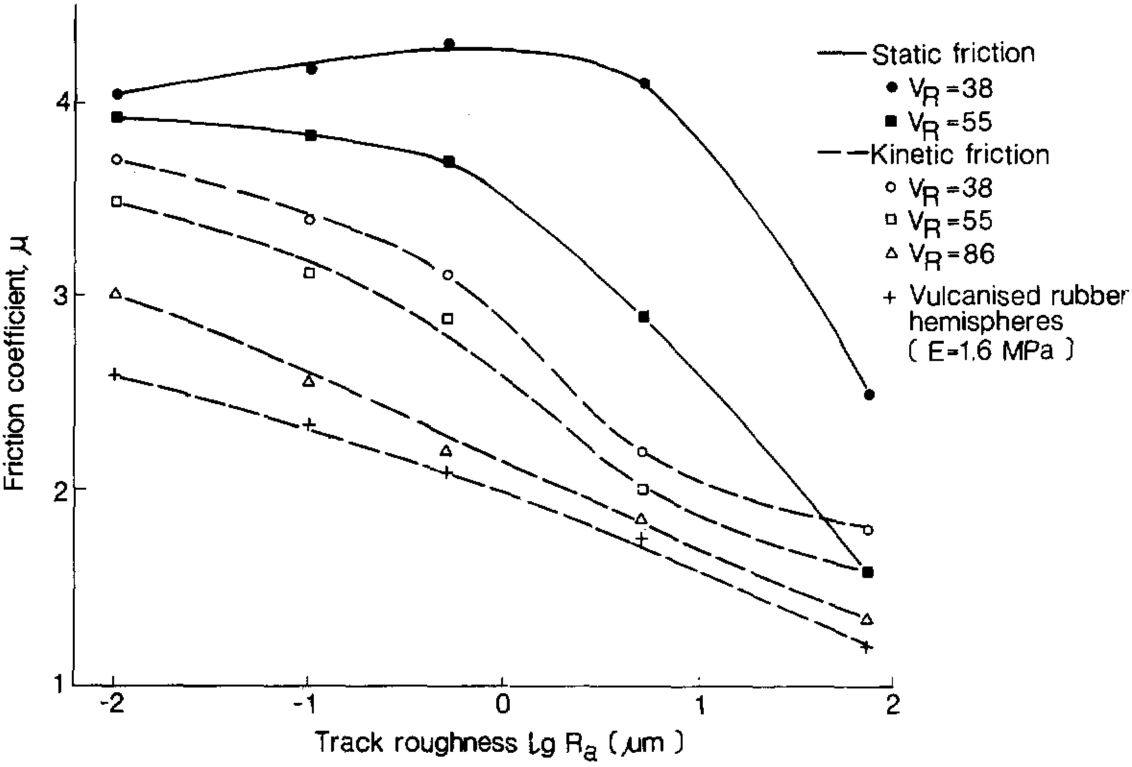

Figure 7. Friction of raw (SMR L) and sulphur vulcanised rubber hemispheres on Perspex tracks of different roughness. Speed 1 mms^{-1}, normal load 1.57 N, t = 25°C–29°C, RH = 60%–85%.

TABLE 3. FRICTION OF DRY RAW RUBBER

Surface condition	Friction coefficient, μ	Observations
Rubber 'as moulded'	3.1	Friction just after ridge formation
Rubber wiped with acetone	3.3	No colouration on wiped tissue
Rubber wiped with toluene	3.0	Brown colour on tissue
Rubber wiped with teepol/distilled water rinse	3.3	No obvious rubber surface changes
Talc, dusted on rubber only	1.7–2.4	Slight rubber ridge
Plenty of talc dusted on rubber and track	0.01	No damage to rubber

SMR CV hemisphere (R = 21 mm) sliding at 0.2 mms^{-1} on smooth Perspex track under 1.57 N load. Temp. 23°C–24°C, RH = 55%–65%. Friction coefficients quoted were average values; the scatter was about ±20%.

dependent[12], so simple apparatus modifications were made to study the effect on raw rubber. This enabled observations to be extended up to temperatures typically encountered in process machinery.

In this exploratory study undue apparatus complications were avoided by simply sliding a rubber hemisphere sample against an electrically heated steel track open to the air. Upon contact with the track a temperature difference was set up across the sample. The technique employed was to allow a sufficiently long contact dwell-time so that the rubber sub-surface was up to temperature before sliding was started. The necessary dwell-time was estimated from heat conduction theory[13]. For a depth into the sub-surface of 2 mm (typical ridge height) and assuming one-dimensional heat flow, the theory indicated that a dwell-time of 5 min should be about sufficient. Estimates were checked experimentally with a thermocouple buried between rubber sheets, and found to be satisfactory.

A mild steel track polished to a smooth finish was put in place of the Perspex track in the friction apparatus *(Figure 1)*. An electric hot plate was in contact with the bottom-side of the steel track; the temperature of the top-side was monitored with a thermocouple. For friction measurements a rubber hemisphere (SMR CV) was brought into contact under a load of 3.73 N for 5 min dwell and then pulled. Results showed that the friction coefficient increased with sliding speed, as found for sliding on Perspex, but for a particular speed the coefficient was broadly the same at all temperatures from T = 23°C to 120°C. For example, at a speed of 0.2 mms^{-1} results at different temperatures all clustered around μ = 1, and at 20 mms^{-1} they were all around μ = 2, with low and high scatter points in both cases.

The area of contact made between the rubber hemisphere and steel track during sliding was estimated from the ridge dimensions (length and breadth) or, at higher temperatures when no ridge was formed, from the area of sheared rubber contact surface. The area data was used to calculate shear stresses (friction force/contact area). When the interfacial shear stress was plotted against sliding speed there was a fairly clear separation for each test temperature. Furthermore, it was found that individual data points could be transformed, more or less, into a single 'master-curve' by using the WLF equation[14] where for SMR CV the glass transition temperature T_g was taken to be −66°C[15]. The shear stress was multipled by T_s/T, where $T_s = T_g + 50$, since forces in polymer chains depend upon the absolute temperature. Scatter in the plot of the transformed data *(Figure 8)* may be due to the difficulty of measuring the contact area accurately, particularly so at

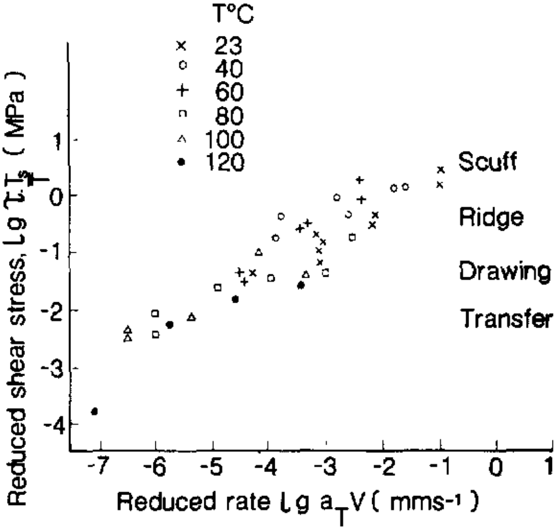

Figure 8. Effect of temperature and speed on interfacial shear stress for SMR CV hemisphere slid on steel track, RH = 60%–70%.

high stress values. Observations of the rubber surface indicated less deformation into a ridge with increasing sliding temperature, but more transfer. At high temperatures hemispheres tended to flatten to produce a large contact area, but the resistance to sliding was very low.

DISCUSSION

Fundamental Aspects

In common with vulcanised rubber, the surface friction of raw rubber was found to be both load- and velocity-dependent. For mean contact pressures around an atmosphere the friction coefficient for spherical contact varies inversely as the cube root of the normal load, a relationship already found for vulcanised rubber[16]. This supports the notion that the frictional force is proportional to the true area of contact, though this may be too simplistic because the interfacial shear strength appears from our experimental evidence to be contact pressure-dependent. Under a fixed normal load the friction coefficient doubles on increasing the sliding speed by four decades (0.001–10 mms^{-1}) at room temperature. This accords with some vulcanised rubber observations[17] and suggests a rate process.

In contrast with vulcanised rubber, during low-speed sliding (less than 1 mms^{-1}) a spherical surface of raw rubber became deformed into a protruding ridge whereas in the case of vulcanised rubber of the same geometry and surface smoothness Schallamach waves were generated in the contact zone. At higher sliding speeds (10–100 mms^{-1}) there was only slight scuffing of the raw rubber surface and a tendency to stick-slip motion with an occasional hint of Schallamach waves, all of which suggests that in the shorter time scale the raw rubber was behaving in a more elastic manner (as if lightly crosslinked).

Visual observations showed that during sliding it was possible to 'see' strain-induced crystallisation in the vicinity of the raw rubber interface, manifested as a whitening. After sliding a study of surface cracks allowed a bridge to be made between the friction and tear properties of a particular grade of rubber under test. This in turn led to an examination of the wear process.

The friction coefficient of raw rubber tended to decrease with increasing track roughness,except at long dwell-time and for highly masticated rubber. The sliding results obtained here may be compared with earlier rolling measurements[18] where a greater tendency to higher adhesion at intermediate substrate roughnesses was observed. The higher adhesion in rolling may reflect the absence of an applied interfacial shear stress. Rolling with raw rubber (V_R = 40) produced extensive bulk drawing of the rubber in a direction approximately normal to the contact interface when rolling speeds were 0.1 mms^{-1} or less. The contact dwell-time was about 100 s. In the present sliding experiments extensive bulk drawing occurred only at speeds below 0.001 mms^{-1}, the dwell-time being about 10 000 s, and the drawing direction was tangential to the contact interface. The difference may be partly because drawing during sliding requires higher adhesion and partly due to a difference in specimen geometry (solid hemisphere compared to sheet wound around cylindrical former). Another factor may be environmental: rolling was carried out at a lower temperature (22°C) and humidity (55% RH), and these can influence the level of ahesion[19].

The effect of temperature on the sliding friction coefficient was not systematic, unlike vulcanised rubber. The reason appears to be that the extent of the contact area made between raw rubber and a hot track was variable. It was found, however, that the interfacial shear stress was temperature-dependent and all the data could be assembled into a 'master-curve' on a reduced-rate plot. Such a plot describes the frictional behaviour over a wide range of speed and temperature, and also maps the raw rubber's surface deformation as a result of sliding. After sliding against the steel plate at room temperature the rubber contact zone appeared white in the drawn region. At sliding temperatures of 40°C and 60°C whitening was revealed by cooling rubbed samples in a refrigerator. At temperatures of 80°C or more there was no whitening upon cooling.

Technological Matters

Studies have shown that as die extrudate rates are increased a change from continuous to stick-slip motion occurs. The transition is usually at a higher rate for a softer rubber. In our sliding friction experiments it was observed that with increasing speed a transition to stick-slip motion was reached, generally at a higher speed for a softer rubber. Specifically, when SMR L was extruded at 100°C (die diameter = 1.27 mm, die length/diameter ratio = 20) stick-slip occurred for material of 89 Mooney at rates greater than 40 mms^{-1}, and for 60 Mooney at greater than 160 mms^{-1}; when SMR L hemispheres of 86 and 55 Mooney were slid against smooth Perspex at 25°C stick-slip began at about 1 mms^{-1} and 3 mms^{-1}, respectively. These sliding speeds transformed by the WLF shift factor[14] to 100°C became 108 mms^{-1} and 324 mms^{-1}. It is interesting to note that despite the very different circumstances existing in the extrusion and friction tests the stick-slip transition rates for each rubber were comparable after they had been transformed to the same temperature.

Examination of rubber hemisphere surfaces after frictional sliding usually showed that unmasticated rubber of high Mooney viscosity became irregularly deformed into several small ridges, but masticated rubber deformed into one large smooth-surfaced ridge. These trends are seen on die extrudates: SMR CV and masticated SMR 20 are known[20] to give smooth-surfaced extrudates at low rates, whereas unmasticated SMR 10 does not — its surface tends to be irregular, presumably due to 'nerve'.

Another outcome of investigating the surface morphology of rubber hemispheres is an appreciation of the role that friction forces can play in producing tear cracks in raw rubber. Such cracks may relate, for example, to the tiny multiple ridges and surface cracks sometimes found on highly masticated rubber after die extrusion at a very low rate. They may also relate to the milling of highly masticated rubber when surface cracks are seen perpendicular to the sheet-out direction.

The friction experiments indicate that at 25°C the most highly masticated rubbers have the highest stiction against a rough track, the trend being exaggerated at long contact dwell-time. This presumably reflects their ability to flow and come into a high degree of intimate contact with a rough track, resulting in higher adhesion[18]. This ability is likely to improve with increasing temperature. It has been observed[21] that roughening the rotor in a Mooney-type viscometer can increase the shear stress at 100°C. Some exploratory studies[22] with a capillary rheometer suggest that there is a region of intermediate extrusion rate over which the friction of a die with a roughened internal wall can be markedly greater than that for a smooth die. The absolute rates at which this occurs depends on rubber type, and all the indications are that it also depends on temperature. At high extrusion rates when complete slip between die wall and rubber occurs there is no noticeable difference between smooth and rough dies. Apparently some stiction between wall and rubber is required to show the roughness effect. These die extrusion observations might be rationalised in terms of the ability of a rubber to flow at a particular temperature to produce a high area of interfacial contact with the rough wall in the contact dwell-time available.

Raw rubber may either stick to the metal parts of processing machinery and be deformed, or it may slip. Prior indication of which would be helpful. In the present study the observed values of friction of the various SMR grades tested were about the same for a given sliding speed. Most measurements of friction are subject to considerable scatter, and raw rubber is no exception. Sometimes our data was reproducible to within ±10%, but more often it was poorer than this and on occasions barely within a factor of two. Surface contamination may partly be responsible. For these reasons a raw rubber 'friction index' may not be a satisfactory indication of its processability, but it is evident that friction studies increase understanding of the physical phenomena underlying processing behaviour.

CONCLUSION

The friction of raw natural rubber at higher sliding speeds resembles that of lightly crosslinked rubber. At lower speeds it behaves in a more viscous manner with bulk deformation and material transfer to the track. In general, the coefficient of friction of hemisphere samples at room temperature increases with sliding speed, but decreases with normal load and surface roughness. An exception is highly masticated rubber that shows greatest stiction on a slightly rough track. The friction coefficients of various SMR grades at a given sliding speed on a smooth track are all similar, though there is a discernable increase in coefficient with increasing state of mastication. The interfacial shear strength appears to depend in a linear manner upon the applied contact pressure. Surface cracks produced by frictional sliding can be approximately accounted for in terms of the tear energy of the raw rubber. Although the friction coefficient is not systematically temperature dependent, the interfacial shear stress can be rate-temperature transformed. Some insight into the technological process behaviour of raw rubber was gained from the elementary experiments on friction.

ACKNOWLEDGEMENT

The authors thank Dr A. Kadir for raw rubber tear energy measurements, Dr K.N.G. Fuller (MRPRA) for surface roughness measurements and Encik A. Majid and Mr N. Srikaran for experimental assistance.

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Kuala Lumpur *February 1983*

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