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Rubber Friction Dependence on Roughness and Surface Energy

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When a smooth surfaced rubber sphere slides on glass relative motion between surfaces may be only due to 'waves of detachment' (Schallamach waves) crossing the contact region. Remarkably enough, the observed friction scarcely depends on sliding speed, temperature or rubber type of similar hardness, despite rubber being a viscoelastic material. This is in sharp contrast to the 'classical results' of Grosch. His friction data for a wide range of speeds and temperatures showed a pronounced maximum in the friction with increasing rate, a characteristic to be expected if viscoelastic processes are involved. New measurements are helping to resolve the paradox. Schallamach waves act as a stress relieving mechanism which prevents a substantial rise in friction with rate.

If smooth surfaced rubber samples are deliberately roughened with abrasive, then the friction varies with speed and temperature in a manner more in accord with Grosch's data. Apparently, surface roughness is important to an overtly viscoelastic response. It also seems to suppress the generation of Schallamach waves, and cause the track surface energy to be reflected in the level of friction.

It is difficult to predict the likely level of friction of rubber components in engineering practice. Model experiments must often be carried out and sometimes full-scale tests are the only acceptable way, such as in tyre skid resistance. Many factors contribute to the friction of a rubber surface, and the topology of the track may matter as much as the rubber. Grosch[1] suggested ideas for prediction when he found, at least in his laboratory tests, that the frictional behaviour of different rubber vulcanisates could be anticipated according to their viscoelastic properties. In general it is observed that the frictional force F for a given load W rises with increasing sliding speed[2]. Grosch showed that there was a characteristic peak to the friction of a particular rubber and beyond that the friction fell with increasing speed. The effect of temperature could also be related through the WLF[3] shift factor a_T so that under certain circumstances Grosch was able to obtain his classical 'master curves' of friction coefficient μ $(=F/W)$ against reduced rate $lg\ a_TV$. In this notation V is the sliding speed and $lg\ a_T = -8.86\ (T - Tg - 50)\ /\ (51.5 + T - Tg)$, where T is the test temperature and Tg is the glass transition temperature of the particular rubber under test. The master curves were subsequently employed to predict, for example, tyre tread skid performance and have enjoyed a considerable measure of success.

The discovery of Schallamach waves[4] initiated new investigations into friction mechanics with a view to predicting the level of rubber friction in terms of viscoelastic and surface properties. It soon emerged that under circumstances where Schallamach waves were generated the sliding friction was surprisingly invariant with speed[5,6], with vulcanisate[7] and with temperature[8]. Apparently the rubber was not behaving in a viscoelastic manner. How can this be explained and how does it affect friction prediction?

It is now appreciated that Schallamach waves arise as an elastic instability in the rubber[4,5,9] and consequently the level of friction is determined by its elastic modulus[10]. One of these

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studies[9] agreed that in general the sliding friction was constant with speed and temperature; in sharp contrast to Grosch's data.

More recently this apparent contradiction was investigated in a systematic way by repeating the experiments of Grosch using the same rubber compound, pad dimensions and wavy glass[11]. It was still not possible to reproduce the Grosch data. In this latest study smooth rubber surfaces were employed, in common with many earlier studies. At the time of the study it came to light[12] that in his earlier work Grosch[1] had used rubber samples deliberately roughened in order to avoid complications due to surface oxidation. A few experiments were carried out at room temperature[11] in which rubber samples were deliberately roughened but surprisingly there was only a modest fall in friction. This made it difficult to rationalise with the earlier Grosch data. However, because the effect of roughness was only studied at room temperature, we decided to mount a more complete examination of the friction of surface roughened rubber samples over a broad range of temperatures.

In this paper we report measurements of the friction of smooth and roughened rubber samples against wavy glass. These will show how, with changing surface roughness, the master curve changes towards that obtained by Grosch. We also note that with rough surfaces, not only is there a more pronounced viscoelastic behaviour but also a response to track surface energy.

EXPERIMENTAL

The investigation consists of three distinct experiments. A 'deep freeze' apparatus[8,11] was used for the friction of rubber on wavy glass, with varied temperature and sliding speed. A cantilever apparatus was used for the frictional shear strength of rubber against a flat track, with varied speed and normal load. A simple rolling apparatus was employed to examine the variation in peel energy with speed.

Friction of Flat Rubber Against Wavy Glass

The experiments were carried out inside a deep freeze cabinet, covering temperatures from −45°C to +60°C; with dry ice to take it below −35°C and electric light bulbs to heat it above room temperature. The temperature could be maintained to ±2°C using a mercury contact thermometer installed through the lid.

The wavy glass track was supported on a turntable driven by an electrically powered hydraulic motor *via* a five speed gearbox. Speeds from 0.01 mm per second to 10 mm per second were used. The rubber pad was attached to the end of a lever arm on which a chosen load was applied to press it down on the wavy grass track *(Figure 1a)*. The normal load was 57 N unless otherwise stated. The tangential force between the rubber and the glass was measured using a load cell transducer fixed to the other end of the lever arm. Full details of the apparatus have been given previously[8,11].

The rubber pads were made from a natural rubber (NR) specimen whose rate of crystallisation had been considerably decreased by an isomerisation process which reduces the *cis*-double bond content of the rubber by about one-half. This material is subsequently referred to as isomerised natural rubber (INR), see *Table 1*. This compound is very similar to the rubber *Type E* used by Grosch[1], and has the advantage of crystallising slowly at low temperatures, which helps to minimise complications in the frictional behaviour of NR. Its glass transition temperature was measured by differential scanning calorimetry (DSC) and is −72°C ± 1°C. Its hardness was measured using an indentation hardness meter (reading accuracy ±2) and the mean of many readings was 43.3 IRHD at 20°C. This corresponds to a Young's modulus of 1.72 MPa. The rubber pads were 10 mm thick and had a sliding area of 645 mm^2. For rough rubber the pads were roughened by rubbing with 180 grade emery paper (Tri-M-ite). This was done by hand in a controlled manner using both circular (swirling) and linear motion. The surface roughness was measured with a Talysurf 10. Smooth rubber gave 0.23 μm CLA (±0.17 μm) after cleaning; 0.34 μm CLA (±0.22 μm) before the bloom was removed. The roughened rubber had roughnesses of 4 μm CLA (±0.2 μm). There was an intermediate pad with a roughness of

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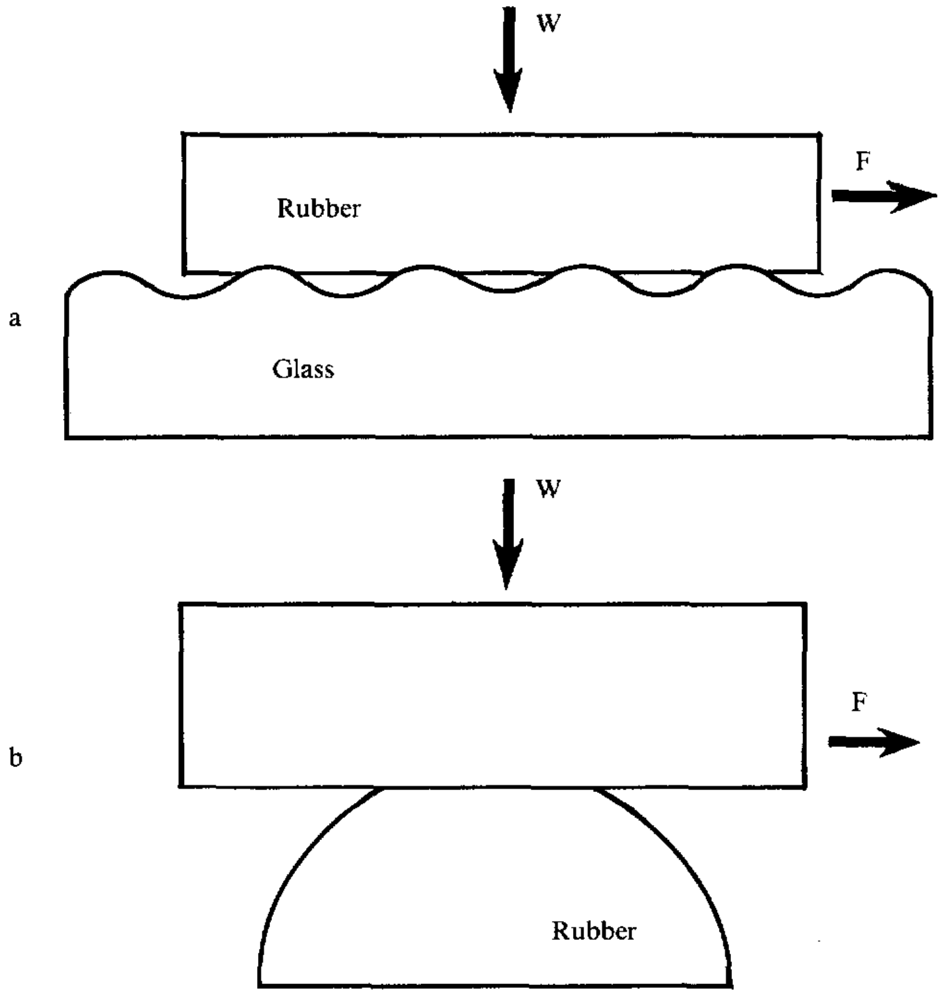

Figure 1. Contact geometries.

1.5 μm CLA (±0.9 μm). It is noted that most of the roughness measurements were distributed reasonably closely to the mean. The glass surface is made up of gentle adjacent individual bumps and gives a roughness value of 125 μm CLA.

Just before friction tests were carried out the rubber was cleaned with a variety of solvents to remove bloom and dust. The solvents were acetone, isopropanol and 10% acetylacetone in isopropanol. The glass was cleaned with acetone followed by isopropanol.

Friction of Rubber Hemisphere Against Flat Rigid Track

The apparatus consisted of a rubber hemisphere fixed to the stage of a microscope which was driven by an electric motor *via* a gear box. The travel distance available was 27 mm. Sliding speeds between 0.0019 mm per second and 17 mm per second could be achieved. The rigid track was part of a balanced arm and rested under an applied load on the rubber hemisphere *(Figure 1b)*. When transparent, the

TABLE 1. RUBBER COMPOUND FORMULATIONS (PARTS BY WEIGHT)

Compound	INR	NR
NR (SMR L)		100
INR (59% trans)	100	
Stearic acid	1	2
Zinc oxide	5	5
Sulphur	1.45	2.5
N-isopropyl-N-phenyl-p-p-phenylenediamine (Nonox ZA)		1
N-tert-butylbenzothiazole-2-sulphenamide		0.5
N-cyclohexylbenzothiazole-2-sulphenamide (Santocure CBS)	0.4	
Poly-2,2,4-trimethyl-1, 2-dihydroquinoline	1	
Cure time/temperature (min/°C)	35/140	40/140
Hardness (IRHD)	43.3	42.5
Young's modulus (MPa)	1.72	1.65
Glass transition temperature	−72	−69

IRHD = International Rubber Hardness Degrees

contact area could be viewed through it from above, using a low power microscope and normally incident illumination for good optical contrast.

The contact area could be measured using a scale in the microscope eyepiece and for static contact it was generally found to agree well with the Hertz theory[13]. For the sake of consistency the Hertzian area was used in all calculations. It was not possible to measure the area accurately when the rubber was moving. The traction force applied by the rubber on the rigid surface in the driven direction (horizontal) was detected by a cantilever arrangement *(Figure 2)* on the balanced arm. The bending of the leaf springs under an applied force was measured by a four arm strain gauge bridge, the output of which was amplified and recorded on a chart recorder.

The rubber vulcanisate used was sulphur cured NR *(Table 1)*. Its glass transition temperature was measured by DSC to be −69°C. Its modulus, deduced from measurements in IRHD was 1.65 MPa. The rubber hemispheres were either smooth or deliberately roughened by hand with 180 grade emery paper (Tri-M-ite). The roughnesses correspond to those of the pads above for smooth and fully roughened rubber respectively.

If there appeared to be bloom on the hemisphere it was cleaned once with 10% acetylacetone in isopropanol before being used for experiments. Before each experiment (a change in surface or speed) both surfaces were cleaned with isopropanol and allowed to dry for at least 20 minutes.

Adhesion of Rubber to Different Flat Tracks

Rolling experiments were completed for the NR vulcanisates on a series of flat tracks as used for friction experiments in friction of rubber hemisphere against flat rigid track. A sheet of 2 mm thick rubber was stuck around a 'Perspex' roller, total weight 0.5 N and radius 35.5 mm. The rubber roller thus formed was rested gently at the top of the sloping rigid track and released, the time between two fixed points being recorded[14]. Both surfaces were cleaned with isopropanol and allowed to dry for 20 min before each roll.

RESULTS

Friction of Flat Rubber Against Wavy Glass

Figure 3 shows the results as a coefficient of friction against reduced rate, using the Williams-Landel-Ferry equation[1,3,5,11] with a standard reference temperature of $Tg + 50°C$. Starting with the smooth rubber (0.2 μm CLA) good agreement is seen with a previous study[11] under identical conditions. The friction varies little with speed and temperature. For the slightly rough rubber (1.49 μm CLA) (a smooth sample that became worn) the friction characteristic shows more variation with rate, rising from $\mu = 0.5$ at low rates to a peak of around $\mu = 2.4$ and then falling again. The roughened rubber (4.1 μm CLA) gives even lower (as low as 0.3) friction coefficients at low rates. However the coefficient rises steeply to a plateau and where $l_g a_T V$ is above 1, $\mu = 2.5$ in the absence of stick-slip motion.

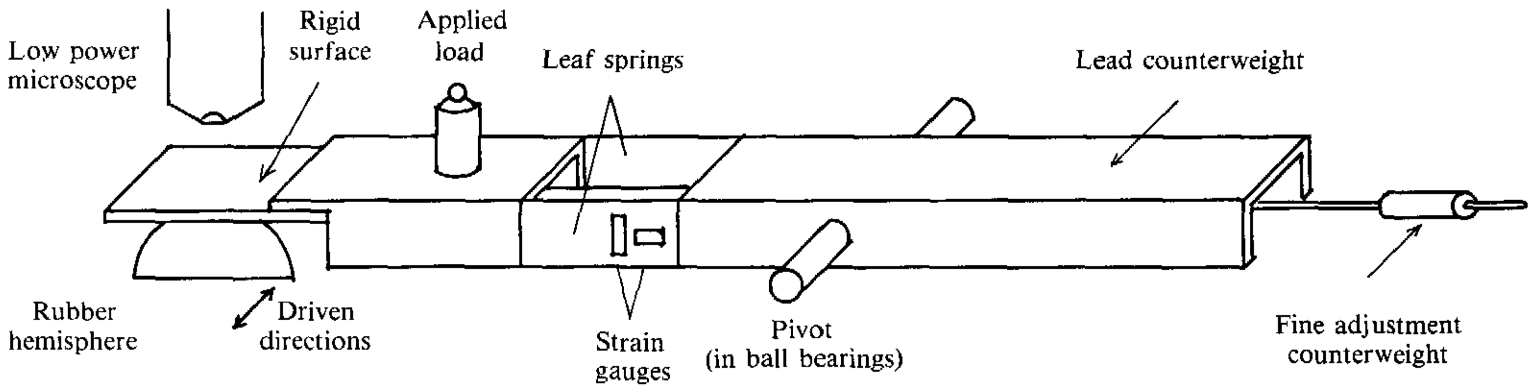

Figure 2. Apparatus for measuring interfacial shear strength.

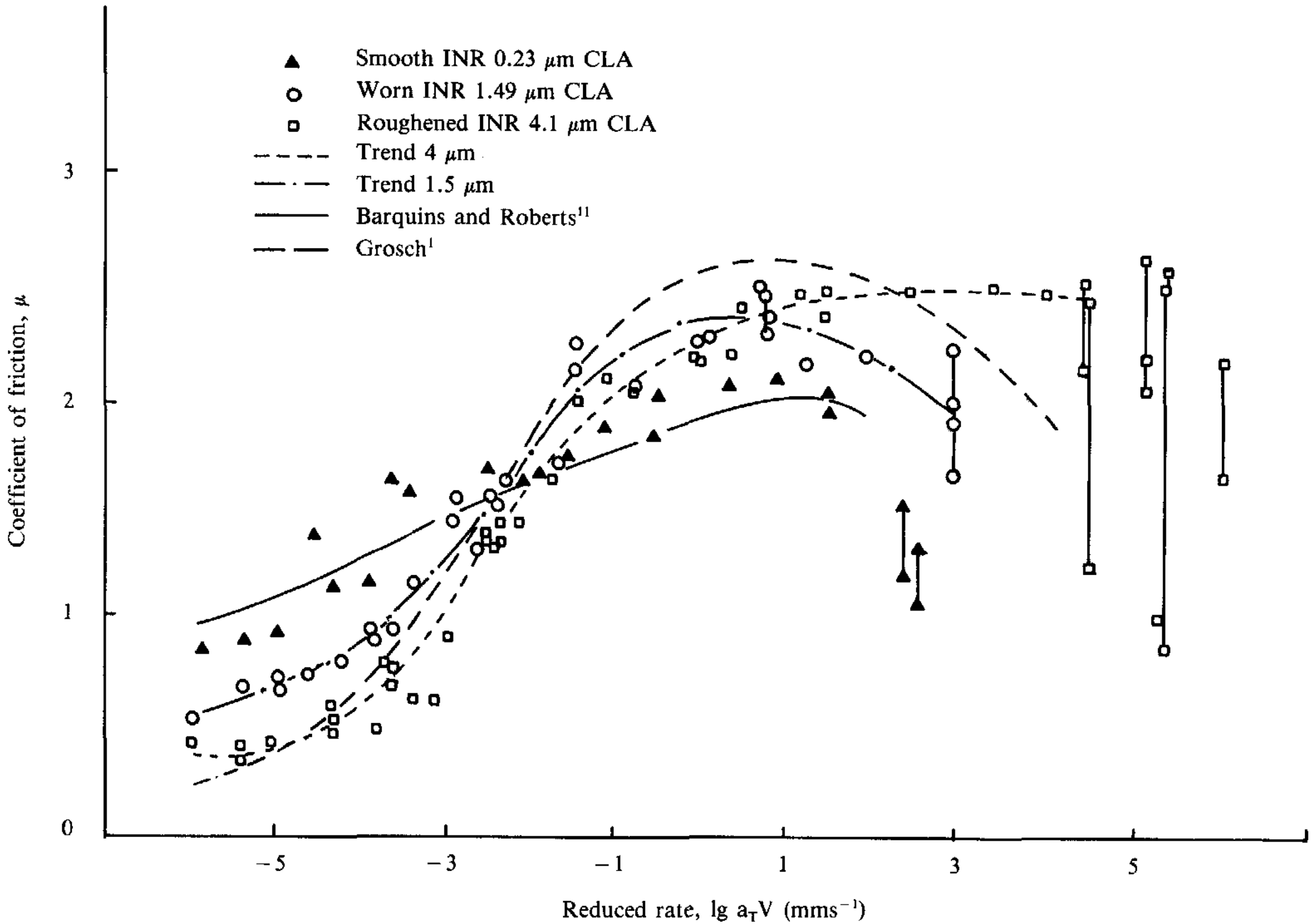

Figure 3. Friction of flat rubber against wavy glass.

Comparing the results obtained for three different levels of roughness reveals a clear pattern, the shape of the friction characteristic changing and becoming more rate sensitive with increased roughness.

Friction of Rubber Hemisphere Against Flat Rigid Track

Dependence on sliding speed. The variation of friction coefficient μ with speed, lgV, is shown in *Figure 4*. For smooth rubber against glass, well-defined Schallamach waves were observed over the whole range of speeds for which μ is constant. At lower speeds the waves diminish in size and frequency and the coefficient drops. Increasing the speed causes the waves to become stationary ridges[4] so that the relative motion is due to true sliding, and μ increases. The pattern is essentially the same for smooth rubber against polytetrafluoroethylene (PTFE) except that the interface adhesion is lower and so Schallamach waves do not occur until the speed is 0.2 mm per second. Below this speed true sliding probably occurs and the speed dependence of friction is obvious. At and above 0.2 mm per second the friction mechanism is dominated by the waves, and there is no difference in friction level between PTFE and glass.

For roughened rubber Schallamach waves were not observed, though individual asperity tips in contact with the glass plate were seen to 'twitch' from time to time. The friction coefficient showed a steady increase with speed. The contrast between this and smooth rubber suggests that the Schallamach waves are a stress relieving mechanism that limit the build up of friction with speed.

Dependence on track surface. Some measurements were carried out using six different tracks; these were smooth, flat and effectively rigid and had different surface energies. They were glass, nylon, polyethylene (PE), polypropylene (PP), polymethylmethacrylate (PMMA) and polytetrafluoroethylene (PTFE).

Figure 5 shows the friction of a smooth rubber hemisphere against these and is expressed as a shear strength τ (friction force/contact area) plotted against mean contact pressure P (normal load/contact area). Five of the surfaces give plots effectively coincident, and in these cases waves were observed if the track was transparent. Once again it is apparent that Schallamach waves act to mask differences, in this case differences between track surface energies. In the case of PTFE the friction was too low to produce waves and true sliding probably took place, except for the lowest load where a dual reading was obtained. There appeared to be two stable levels of friction and when plotted one agreed with the Schallamach wave motion associated with the first five tracks whilst the other agreed with the rest of the PTFE results. This bifurcation indicates that under these conditions the mechanism is close to the point at which true sliding ceases and waves begin. Barquins and Roberts[11] confirm that the production of waves is more likely at lower loads.

Figure 6 is the equivalent plot for roughened rubber, where Schallamach waves have not been observed. Here a wide range of friction levels is found for the six surfaces. For each, the friction increases with contact pressure producing a distinct line of data. The levels of friction appear to reflect the variation in levels of the surface energies of the tracks. Previously published measurements of rubber peel adhesion[14] show a similar pattern of behaviour. This prompted some rolling experiments to discover whether a link could be found between peel energy and the friction of roughened rubber.

Correlation with peel energy. Figure 7 shows the results of rolling experiments using the same rubber and tracks as for the friction measurements above. The data points for each track are reasonably consistent. The gradients of plots for different tracks are similar because they depend on the viscoelastic properties of the rubber. The most striking result is that these distinct lines of data fall in exactly the same order of level as the data for the shear strength of roughened rubber *(Figure 6)*. This is strong evidence for a link between the friction of roughened rubber and peeling adhesion, a link noticeably absent from the friction of smooth rubber.

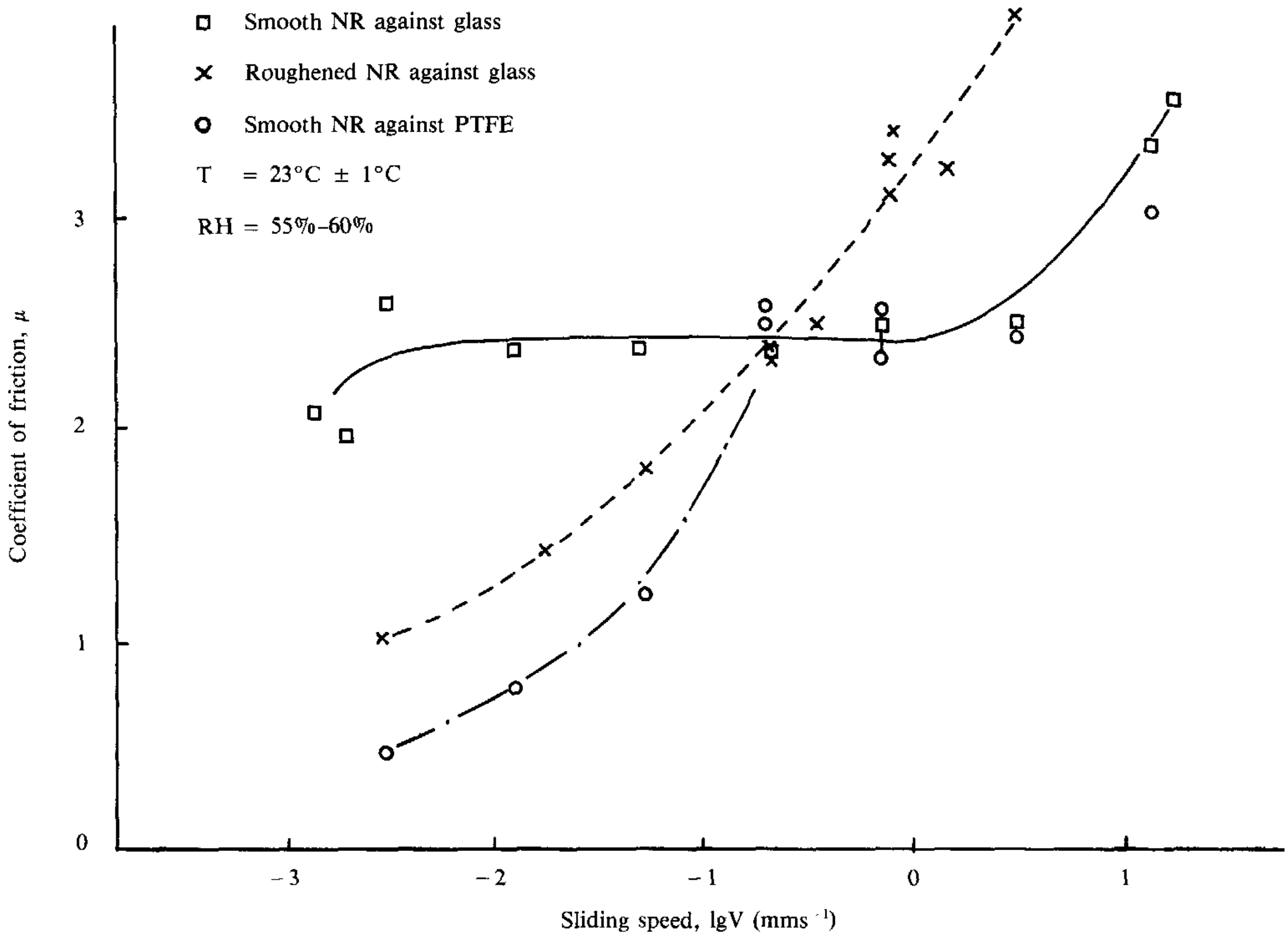

Figure 4. Speed dependence of smooth and roughened rubber.

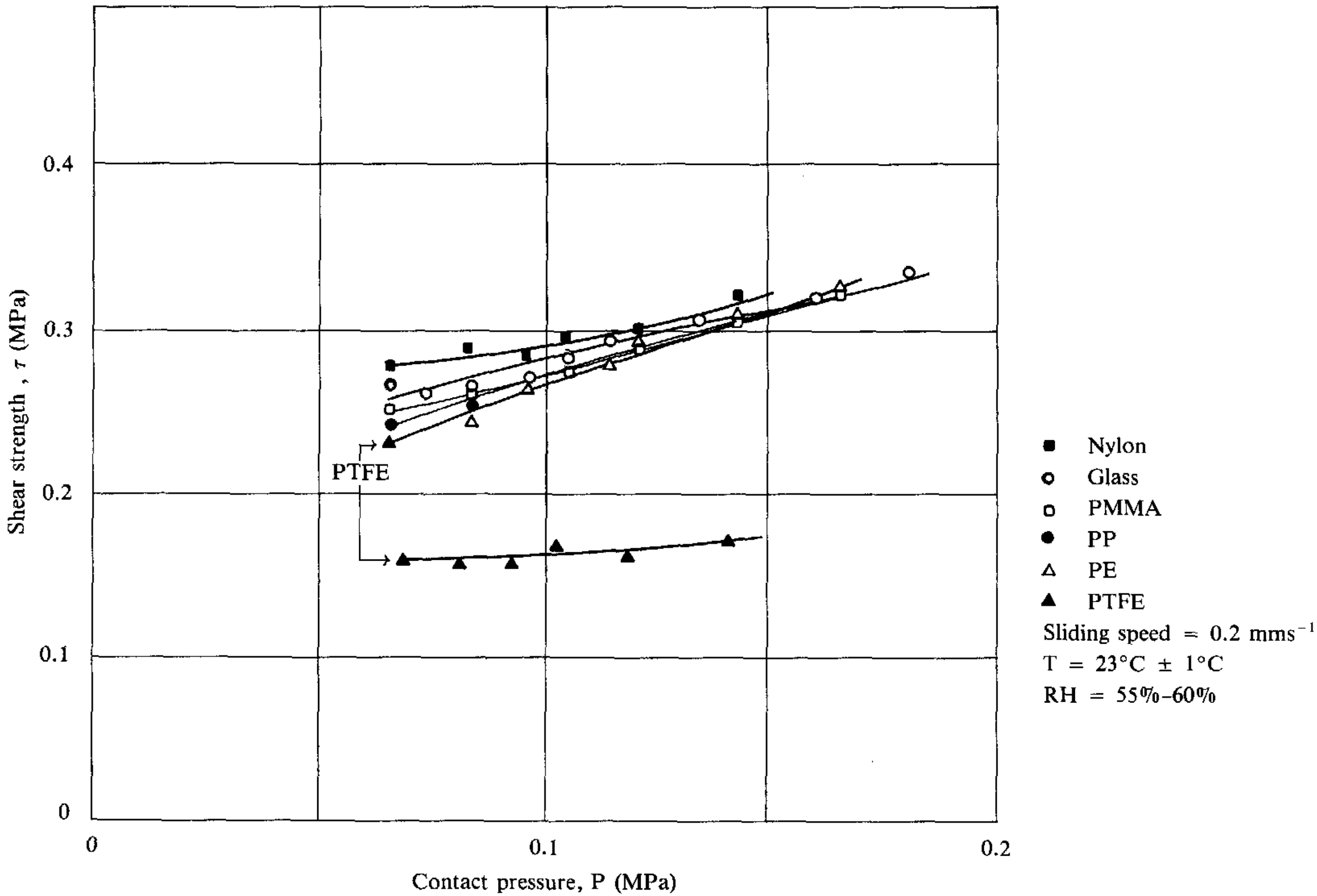

Figure 5. Smooth rubber against various substrates.

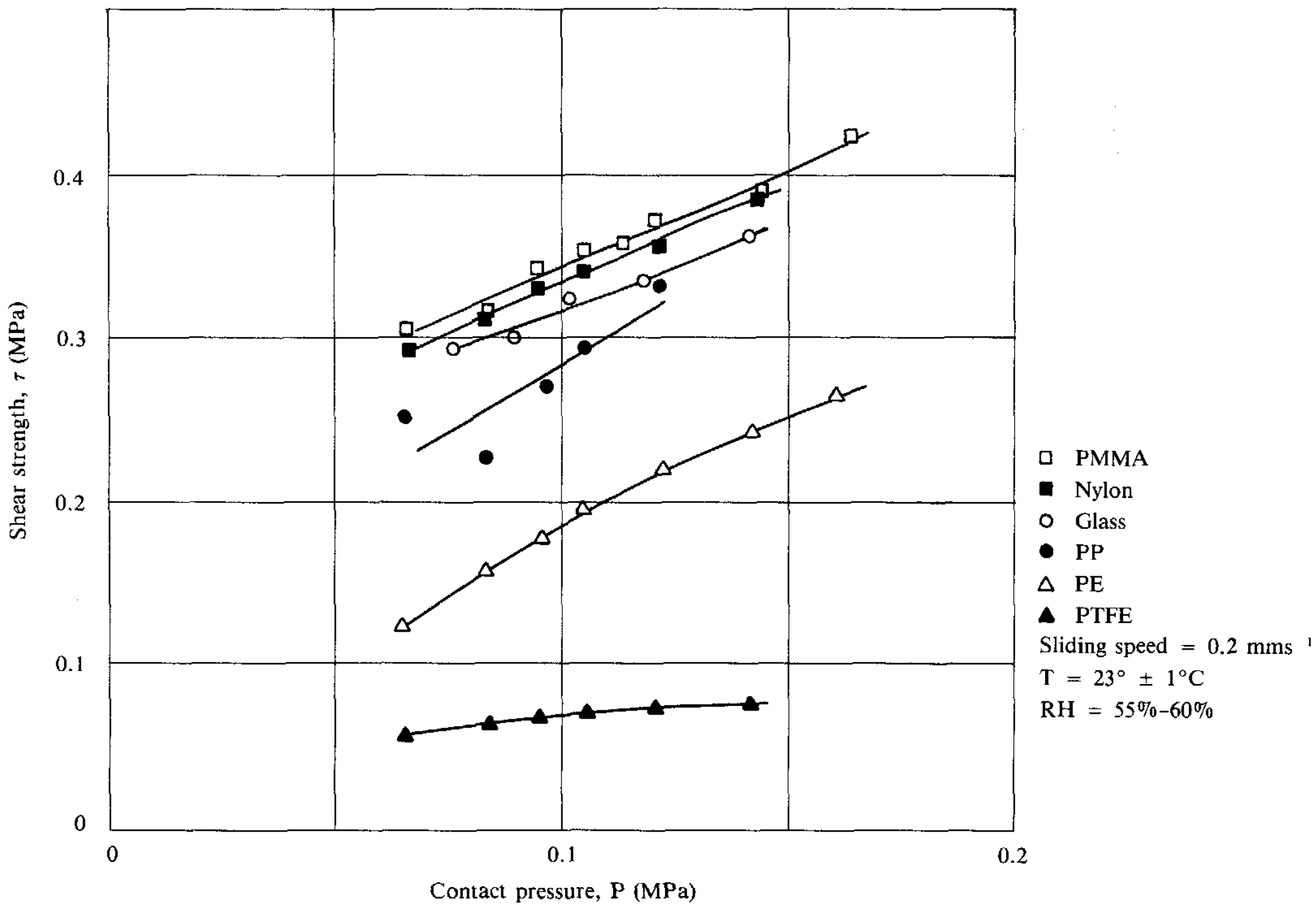

Figure 6. Roughened rubber against various substrates.

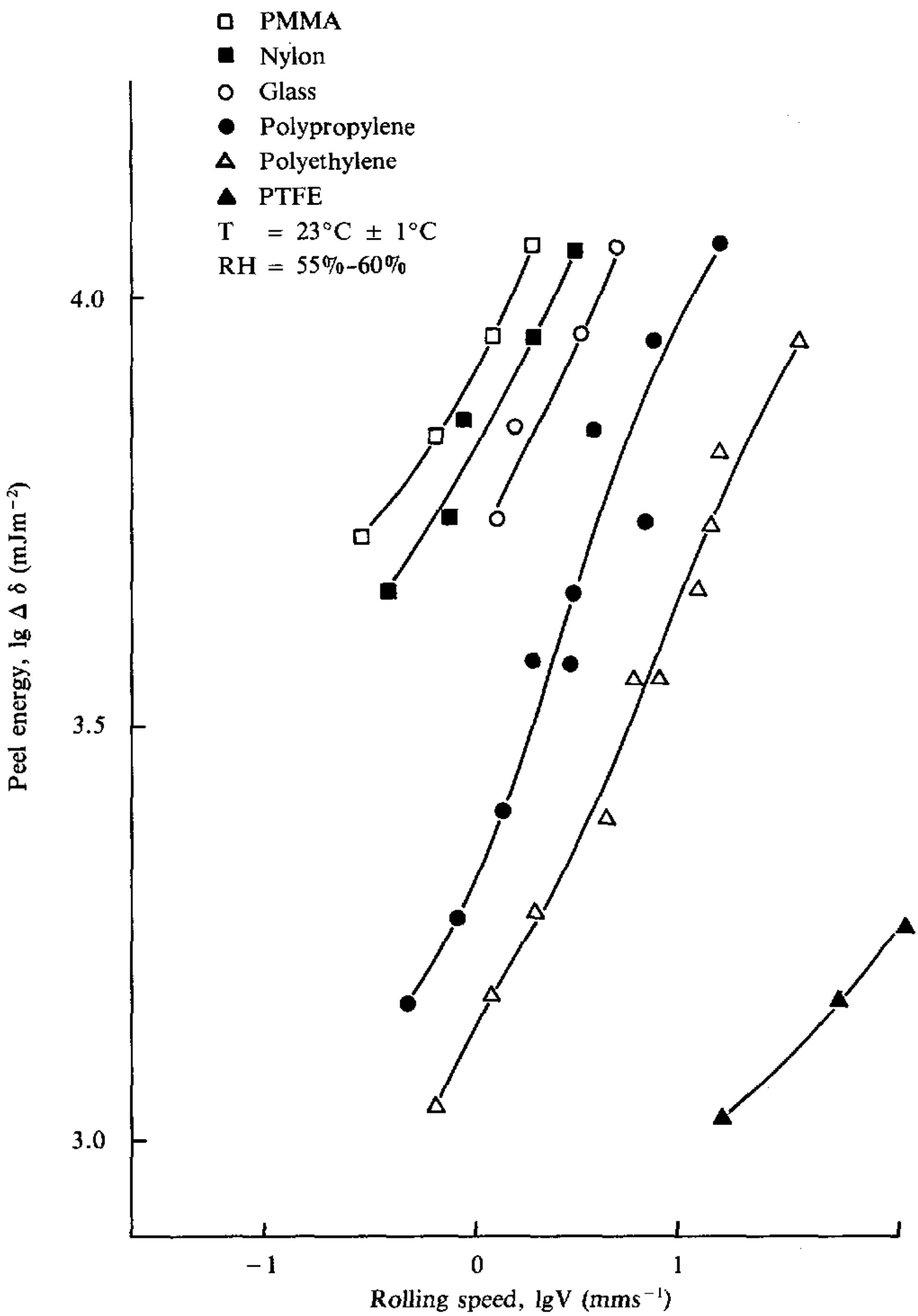

Figure 7. Variation in peel energy with speed obtained by rolling measurements. The peel energy, $\Delta\delta$, is given by mg sin θ/L where m is roller mass of axial length L, and θ is track angle[14].

DISCUSSION

These results for the friction of NR show a variation in the friction coefficient according to the roughness of the rubber. The wavy glass track or the hemispherical rubber slider ensure that the nominal contact area is well-defined. Schallamach waves do not appear to form on a roughened rubber surface and so what is observed may reflect the 'true' frictional nature of the contact pair. True sliding appears to take place though the mechanism for this awaits clarification. One possibility is that actual peeling takes place, on a microscopic scale, support for this idea coming from the link between frictional stress and track surface energy. However, the relationship between the sliding friction and rolling adhesion measurements may be more subtle. An effect of surface energy on rubber friction has been previously reported[15]. The coefficient of friction for a series of rigid indentors sliding on rubber was correlated with the contact angle for a liquid drop on the indentor. This correlation was made without invoking peeling.

Schallamach waves have been studied in detail[4–11] and a predictive criterion for the frictional force has been sought. Following many contact area observations the relationship $F = Yw/lV$ was suggested[7] where a rubber slab is pulled at a velocity V over a hard track by a tangential stress F. The waves move with a velocity w and their spacing apart is l. Y is the rate dependent surface energy. We find, however, that in the presence of waves F is independent of sliding speed, and also independent of the track surface energy. The waves appear to be part of a relaxation mechanism which responds to keep the friction at a level determined by elastic properties[10]. So the relationship predicts the product of the number and speed of the waves rather than the level of friction.

Although this investigation has revealed a change in the friction-rate characteristic with increased roughness, the results do not entirely agree with the appropriate 'master curve' reported by Grosch[1]. Further experiments were carried out, using roughened rubber against wavy glass as above, and they reveal changes in friction level with normal load. Grosch[1] stated that the coefficient of friction was substantially independent of load up to 0.55 kg per square centimetre, his highest experimental normal pressure. This pressure corresponds to a normal load of 34.8 N, whereas the normal load used here to obtain the data in *Figure 3* was 57 N. Trend lines from further experiments show the change in friction coefficient with reduced rate *(Figure 8)* for loads of 3.7 N, 13.2 N and 57 N (repeat measurements). It would seem that the friction coefficient is not independent of load but that given the right combination of normal load and rubber roughness one might be able to reproduce Grosch's 'master curves.'

The contrast between the behaviour of smooth and roughened rubber suggests a difference in friction mechanisms. It is clearly vital, when reporting on the friction of rubber, to specify the operating conditions and likely mechanism involved.

When looking for reference measurements appropriate to applications such as vehicle tyres or windscreen wipers, the rough rubber friction value should normally be used. This means that minor distinctions between different rubbers, tracks or surface treatments will affect the friction both as measured in the laboratory and in practice. On the other hand, reference measurements appropriate to rubber seals will probably call for the use of 'smooth rubber' friction values that are less dependent on rubber hysteresis or tracks surface energy, being mainly governed by the bulk elastic modulus of the rubber[10].

CONCLUSION

The main outcome of this investigation is a clear indication of the importance of rubber roughness to the sliding friction of rubber against a rigid track. With smooth rubber when waves are not present true sliding appears to take place. Increasing the sliding speed or the track surface energy increases the friction coefficient and may initiate the propagation of Schallamach waves. In the presence of waves, the friction coefficient is independent of sliding speed and track surface energy. Waves were not

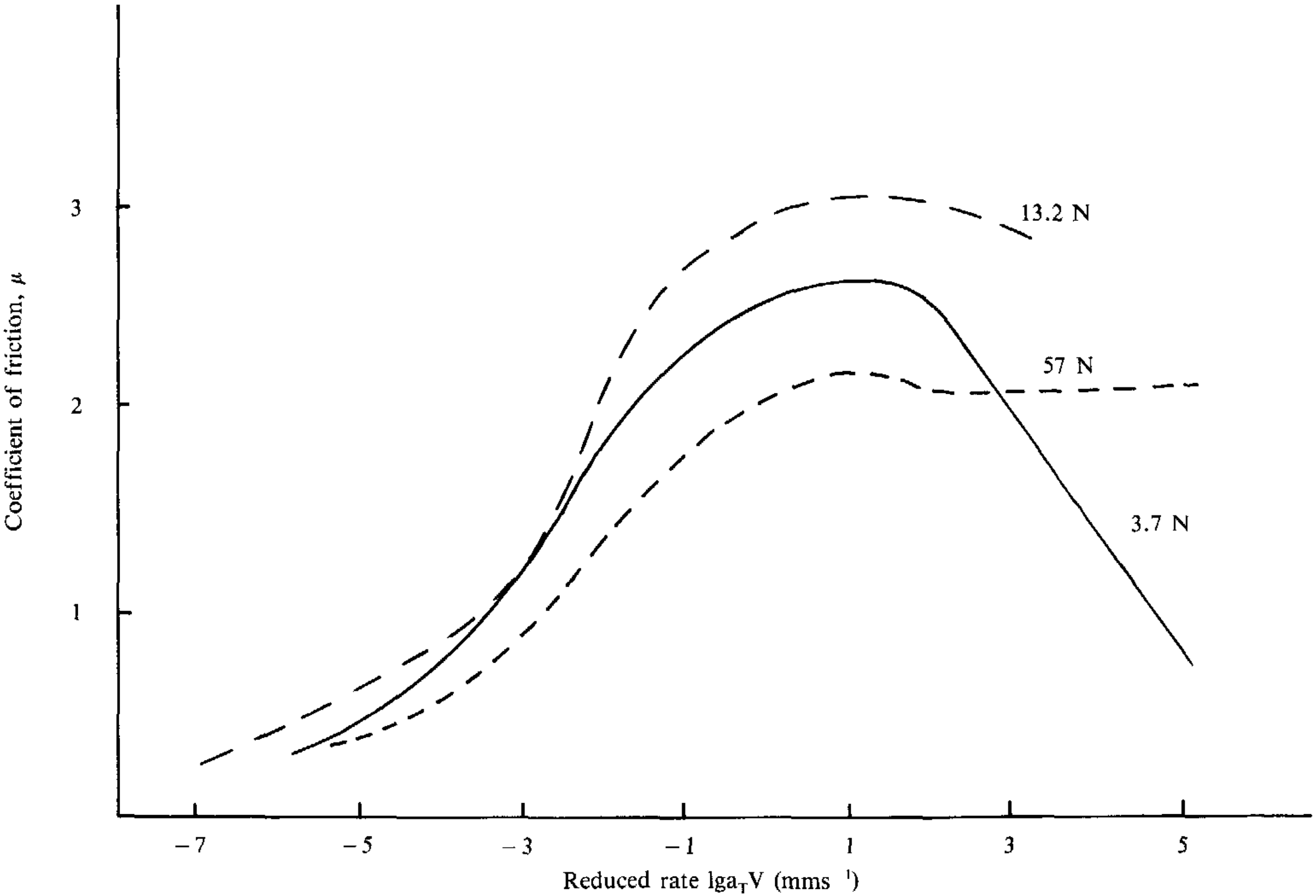

Figure 8. Friction of INR flat on wavy glass for different normal loads.

observed for roughened rubber. The friction of roughened rubber is strongly rate dependent and for the right combination of load and roughness Grosch's 'master curves' would not seem unlikely. The level of friction is seen to reflect the track surface energy, as measured by rolling experiments.

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