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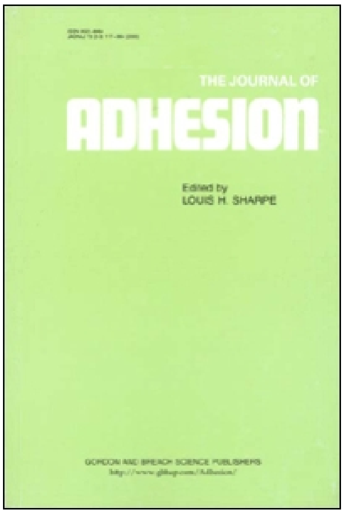

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Rubber-Ice Adhesion and Friction

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Rubber-Ice Adhesion and Friction

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The adhesion of smooth surfaced rubber rolling and sliding on polished ice has been investigated by an optical study of the contact interface. At low temperatures there was good adhesion and the measured high level of sliding friction could be predicted fairly accurately. Near to the melting point of ice, however, adhesion was lost and the friction was very low. This appears due to changed surface properties of the ice. The influence of ice surface frost and increasing age were investigated: both reduced the friction. Different rubber compounds sliding on polished ice were compared. At 0°C all showed the same very low friction, but with decreasing temperature the more soft and resilient the compound the higher the friction. Over the temperature range −20 to 0°C, which is of considerable practical importance, it is the ice behaviour rather than that of the rubber that sets the general level of friction. Even so, there are noticeable differences from one rubber compound to another which bear upon the performance of "winter" tyres.

INTRODUCTION

To further understanding of tyre grip on icy roads,[1,2] laboratory equipment has been developed to study the contact interface formed between rubber and ice.[3] Experiments were performed with smooth surfaced cylinders and spheres of rubber rolling and sliding on polished ice (Figure 1). By using a transparent rubber compound physical events in the contact region were observed.

RUBBER ROLLING ON ICE

The rolling velocity of a rubber cylinder (2% dicumyl peroxide cured cis-polyisoprene) on an inclined ice track was measured at different temperatures. When rolling on "cold" ice ($< -15°C$) rubber was observed to continuously

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adhere at the leading edge of the contact band and peel away at the trailing edge (Figure 1). For a cylinder of mass *m* and axial length *l*, equating the loss in mechanical potential energy with the work done in peeling the rubber off the ice when the track is raised to an angle θ gives

$$mg \sin \theta / 1 = \Delta\gamma \tag{1}$$

where $\Delta\gamma$ represents the energy difference in peeling and adhering.[4] The work done in peeling depends upon the rubber's viscoelasticity,[5,6] so $\Delta\gamma$ can be expected to increase with rolling velocity, v, but decrease with rising temperature. Measurements (Figure 2) showed this to be so. For comparison, rolling was also carried out on dry smooth glass. The pattern of results showed that the grip to ice became lost as its melting point was approached. The rubber cylinder rolled on *wet* glass showed a similar lack of grip to that on ice at −2°C.

RUBBER SLIDING ON ICE

A rubber hemisphere lens (2% peroxide cis-polyisoprene) was loaded against ice (Figure 1). The friction force between surfaces was measured and the contact area viewed through a low power microscope.[3] Observations were restricted to low sliding speeds to avoid frictional melting. Measurements on a freshly prepared ice track (Figure 3) showed a marked decline in friction as the ice melting point was approached.

On cold ice Schallamach waves of detachment[7] were seen to propagate

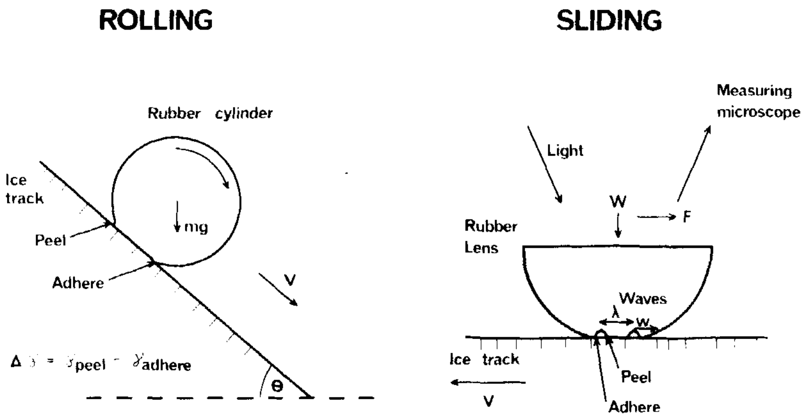

FIGURE 1 Arrangements made to study the rubber-ice interface for rolling (left) and sliding contact. The radius of the rubber cylinder was 18 mm and that of the hemisphere lens was 19 mm.

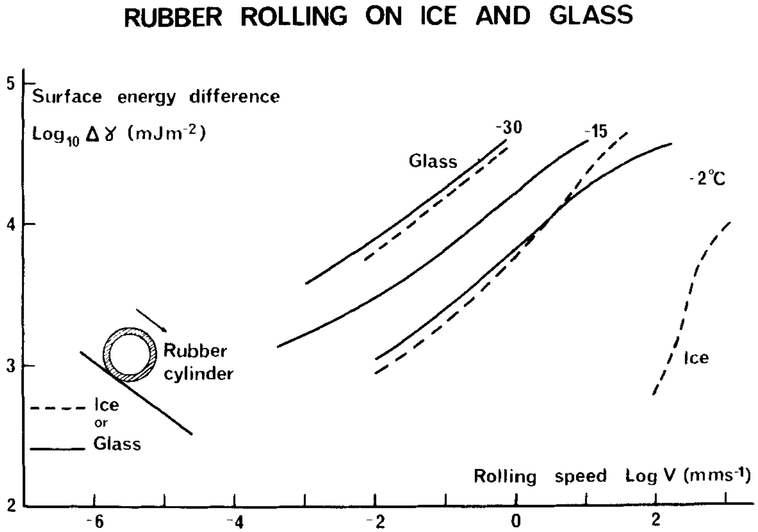

FIGURE 2 Variation found in rolling grip (expressed as $\Delta\gamma$) with temperature for a rubber cylinder on polished ice and on dry plate glass. (Experimental trend; scatter up to half decade on speed axis. Cylinder axial length 25 mm and mass up to 0.1 kg with steel core fitted.)

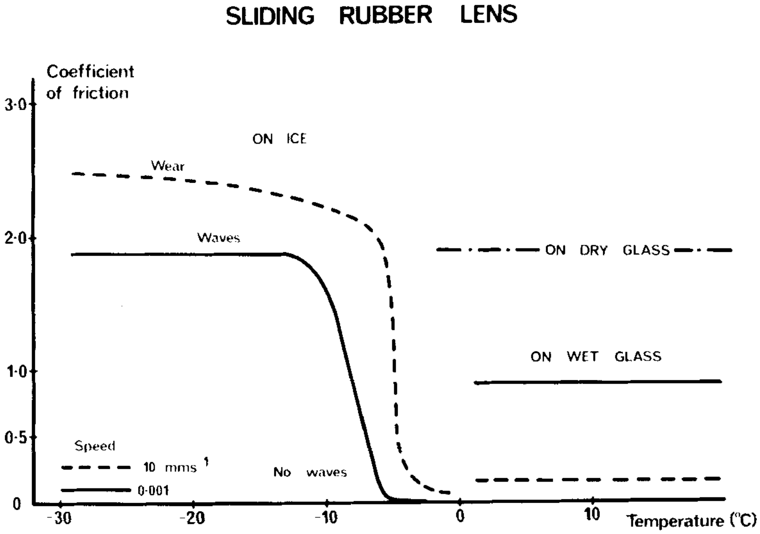

FIGURE 3 Friction coefficient (friction force/normal load) variation with temperature found when sliding rubber hemisphere lens on polished ice and on plate glass. (Experimental trend using new ice track; scatter up to 30% on friction axis—see Ref. 3. Normal load 2.2 N.)

through the contact area. The waves have been identified as a peeling process[4,8,9] and their presence indicates good grip between surfaces. However, on cold ice at speeds greater than 10 mm/s the rubber wears, particles of rubber becoming detached and left as debris on the ice track. On "warm" ice ($> -10°C$) both waves and wear were absent. Significantly, when the rubber lens was slid slowly on water covered smooth glass the friction rose to a high level (Figure 3) and fragmented wet waves of detachment[10] were seen, implying that water was squeezed out of the contact zone. Ice about to melt was much more slippery than wet glass. This may be due to a thin aqueous film bound to the ice surface that, unlike water on glass, is not squeezed away and so provides very effective lubrication.

The friction of the rubber lens sliding on dry glass was also measured. At low speeds (0.001 to 1 mm s^{-1}) it was constant over the temperature range -30 to $+20°C$, and the same as on cold ice. The wave patterns arising on cold ice and glass were similar, looking much like photographs already published.[7–11]

Prediction of Sliding Friction

The wave pattern can be used to predict the sliding friction stress (friction force/contact area) F, of rubber on glass. When the rubber lens advances by detachment waves the work done in the contact area can be calculated[4] in terms of the rate-dependent energy and the expression, supported by experiments on glass,[8,9] is

$$F = \Delta\gamma \cdot \omega/\lambda V \tag{2}$$

where ω is the wave velocity, λ the wave spacing and V the sliding speed. At low speeds on cold ice the wave velocities and spacings were measured through the viewing microscope. Average values of ω and λ were taken midway across the contact for uniform propagation of waves. At the wave peel rates the relevant $\Delta\gamma$ values were determined from the ice rolling curves (Figure 2). Frictional stress values were calculated (Eq. 2) and compared (Table I) with

TABLE I

Wave observations and sliding friction on ice

Sliding speed V (mm s^{-1})	Wave spacing and velocity λ (mm)	ω(mm s^{-1})	Energy $\Delta\gamma$ (J m^{-2})	Sliding friction stress F(MPa) Theory	Experiment
At $-30°C$					
0.01	3.8 ± 0.7	0.46 ± 0.3	22	0.28	0.31 ± 0.04
0.1	2.1 ± 0.4	1.78 ± 0.7	33	0.27	0.26 ± 0.03
At $-20°C$					
0.01	4.4 ± 1.3	1.32 ± 0.3	12	0.37	0.25 ± 0.07
0.1	4.4 ± 1.5	3.8 ± 1.7	20	0.23	0.24 ± 0.02

those simultaneously measured. Agreement was good, so indicating that energy dissipated by wave peeling can account for the level of friction on cold ice.

Ice Near to Melting

After some minutes dwell in lightly loaded static contact at temperatures greater than −10°C the rubber lens made a circular mark in the ice. Below −20°C a mark was made faintly, only after hours dwell at high load. The surface of warm ice appeared to flow readily, although contact pressures were only modest ($\simeq 1$ bar). Other studies[12] of the deformation of ice by indentation indicate a change in flow properties at about −10°C.

The pull-off force to separate the rubber lens very slowly from both ice and glass was measured. Off both below −15°C force values were similar. Above −10°C whilst values off glass remained the same, those off ice fell to 1/10 or less. Below −15°C the rubber surface separated from the ice by peeling at the contact periphery, but above −10°C the surfaces literally "popped" apart, the separating force needed becoming smaller and smaller as the ice melting point was approached. The small force values suggested the presence of surface water. Ice near its melting point may be covered by a thin aqueous film because ionic impurities become frozen out, concentrate at the surface (and in grain boundaries) and thereby lower the melting point so forming a film of brine.[13] Our ice was made from once distilled water (total dissolved solids 25–30 gm^{-3}), so this type of surface melting is a possibility.

The maximum tangential force required to initiate sliding (the static friction) was recorded. On ice below −20°C it was the same as the low speed kinetic friction. At −7°C the static friction, although half that on cold ice, was 10–20% higher than the kinetic friction. This suggests some breakdown in interface structure when sheared. On ice near to melting (> -4°C) static and kinetic frictions were indistinguishable and of very low value, the rubber lens appearing to glide over the ice, which again suggested surface water, though it was not visible.

Although above −10°C with rising temperature there was a marked fall in friction for a constant sliding speed, if the speed was increased the friction increased (Figure 3) and portions or fragments of Schallamach waves were sometimes generated. At constant low speed sliding the fall in friction with rising temperature may simply reflect the more ready yield of the ice surface. Easy shear in the ice surface layers obviates the need for waves to be generated in the rubber interface during displacement. If sliding is rapid, however, the rate at which surface ice can flow may be insufficient to accommodate the rate of displacement, so wave fragments are generated and the friction is higher.

An attempt was made to explain the tangential force necessary to produce low speed sliding in terms of the yield of the ice surface. Using published data[12] for the *bulk* mechanical creep of pure ice at a contact pressure appropriate to the present experiments, the friction force was calculated but found to be much higher than that observed. This suggested that the surface layers of the ice are mechanically much weaker than the bulk. The calculation, together with the indentation, pull-off and static/kinetic friction observations, point to an ice surface that might be described as mobile, liquid-like and disordered. We note in other investigations[14 18] that a quasi-liquid state has been inferred, even from experiments using pure ice. Thus the low adhesion and friction of rubber on ice near its melting point would appear to be largely due to the nature of the ice surface.

Frosted Ice

Adhesion and friction levels were compared for ice freshly polished with a rubber pad to a glazed finish (0.03 μm C.L.A., by stylus instrument) and on the same ice after it had become frosty. On well polished ice at $-30°C$ the friction coefficient for a sliding speed of 10 mm s^{-1} was 1.8 ± 0.2, there being some stickslip—an indication of good adhesion. At the other extreme, on ice covered with much hoar frost the coefficient was reduced to 0.5 ± 0.05 and stickslip was absent. Intermediate levels of frost accumulation resulted in intermediate levels of friction.

It was found that at temperatures of $-30°C$ a polished ice track would remain so only for a few hours, despite being in a closed deep freeze cabinet.[3] As soon as small frost crystals began to form on the ice the friction became less. Looked at another way, traces of frost may account for observed friction variation and mask the response due to rubber properties. For this reason all results published here are for an ice track characterized as being well polished so that meaningful comparisons can be made between different rubber compounds in the search for improved rubber grip to ice. It entailed continuous monitoring to assess ice surface finish. This could be done fairly simply by viewing the ice through a low power microscope using oblique illumination so that small frost particles could be readily seen, as they formed. In this way, whenever indicated, the ice track was repolished and this helped to reduce scatter in the friction data.

Age of Ice Track

Data taken for a freshly cast and well polished ice track was compared with that for a polished track after 10 months use. It showed that for the same rubber compound (2% peroxide cis-polyisoprene) and operating conditions the friction level was lower on the old track (Figure 4).

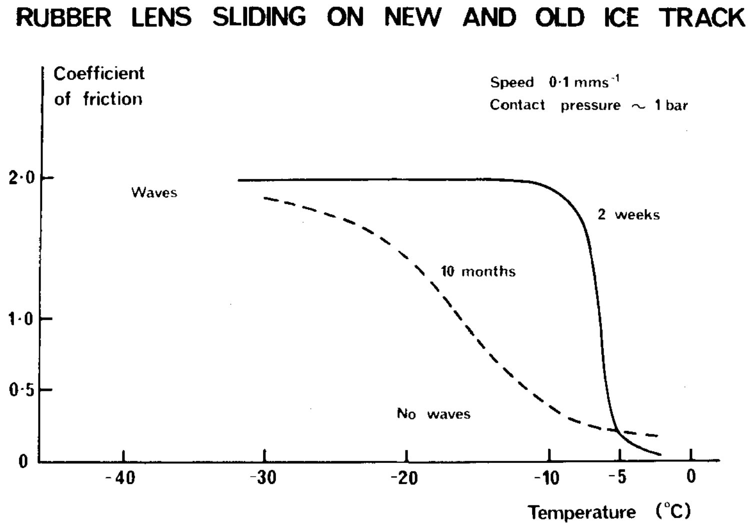

FIGURE 4 Friction comparison made for rubber hemisphere lens sliding on new and old (10 months) polished ice tracks. (Experimental trend; friction scatter on old ice up to 40%. Normal load 2.2 N, speed 0.1 mm s^{-1}.)

There are reports in the literature to the effect that ionic "impurities" in ice can weaken it mechanically.[13,19] The conductivity of the once distilled water used to make a new ice track was 2×10^{-4} S m^{-1}. The surface of the ten month old track was skimmed with a clean razor blade, the ice shavings collected and when melted the conductivity was measured to be 140×10^{-4} S m^{-1}. The increase suggests a concentration of ionic impurities at the ice track surface. This may be due to impurity diffusion from the ice bulk, to a concentration effect as the ice sublimes (new track 30 mm thick but after 10 months only 3 mm) and to deposition of material from the surrounding atmosphere. Chemical analysis showed a small increase in alkalinity (7%) together with increased sodium (~60 ×) and chloride (20 ×) content. Thus the inference from these results would appear to be that as an ice track ages ionic impurities become concentrated at the ice surface, which leads to a mechanical weakening of the surface layers and hence a fall in friction.

Effect of Glass Transition Temperature

Peroxide cured hemisphere lenses of silicone, cis-polyisoprene and acrylonitrilebutadiene rubber were slid on polished ice (about $\frac{1}{2}$ yr old) and friction levels compared (Figure 5). Their glass transition temperatures were measured by differential scanning calorimetry to be, respectively, −133, −67

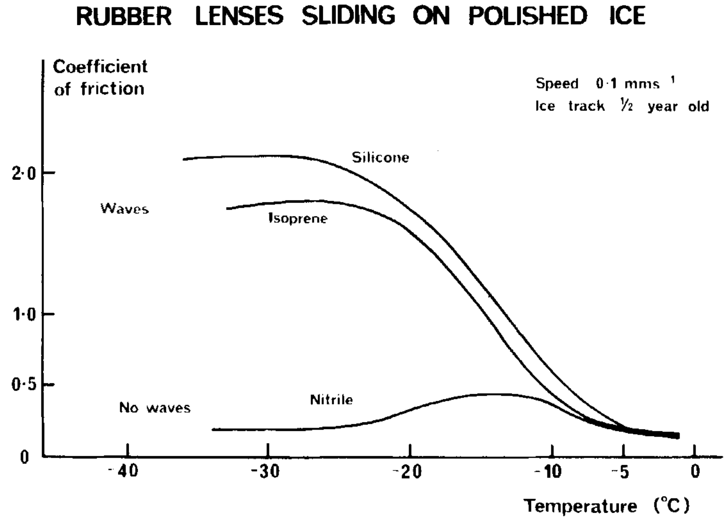

FIGURE 5 Smoothed friction data (scatter up to 40%) obtained for different rubbery polymers sliding on polished ice ($\frac{1}{2}$ yr old) at a speed of 0.1 mm s^{-1}. (Silicone type GE RTV 602; Isoprene type Cariflex 305/92% cis; Nitrile type Polysar Krynac 801/38.5% wt ACN. Normal load 2.2 N.)

and −25°C. Near to 0°C all the rubber compounds showed about the same low friction, which reflects the slipperiness of the ice surface. At lower temperatures the more resilient the compound the higher the friction (resilience increases as the glass transition temperature decreases). High friction was usually accompanied by the appearance of Schallamach waves.

Below −30°C the friction of the isoprene rubber began to decline a little. This is probably a result of hardening and loss in resilience as the glass transition is approached. In consequence it is more difficult for the rubber to come into extensive intimate contact with the ice, particularly at high speed where contact duration is short, so the friction falls.

The friction of the nitrile rubber is at a lowish level at all temperatures. The shallow peak at −14°C presumably arises due to ice slipperiness limiting the friction at higher temperatures and rubber properties limiting it at lower temperatures as the glass transition is reached. Below −30°C the acrylonitrilebutadiene is no longer rubbery and the friction level is more akin to that of a plastic polymer sliding on a hard surface.

Effect of Crosslink Density

The number of crosslinks in a rubber network can be increased by using more curing agent in the rubber compound. An increase in crosslink density has the effect of increasing the glass transition temperature and the compound hardness. Natural rubber hemisphere lenses were prepared by curing with 0.5 and 8% dicumyl peroxide. The glass transition temperatures (by differential scanning calorimetry) of each were, respectively, −72 and −64°C. The hardness (by IRHD meter, Ref. 20) of each gave a measure of their Youngs modulus. At −2°C the modulus of the 0.5% peroxide compound was 1.1 MPa and at −30°C it was 1.4 MPa; the corresponding values for the 8% peroxide were 5.2 and 6.0 MPa.

Each was slid on polished ice and the friction measured (Figure 6). Near to 0°C the friction level of both was low and Schallamach waves were absent. At lower temperatures the friction was much higher and waves appeared. Even so, through the temperature range (and at other speeds) the 0.5% peroxide gave the higher friction. It would appear that, in addition to resilience, compound softness benefits the grip to ice, probably because the softer rubber can come into more extensive intimate contact with the ice.

TYRE GRIP ON ICE

The grip of rubber to ice near its melting point appears largely to depend upon the surface properties of the ice. In temperate climates (rarely below −10°C) tyre tread patterns to promote mechanical grip on ice are likely to be as

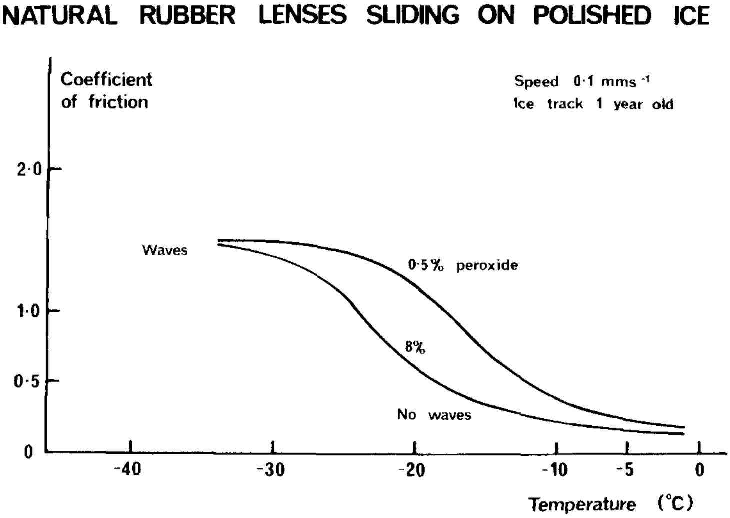

FIGURE 6 Smoothed friction data (scatter up to 50%) obtained for hemisphere lenses of pale crepe natural rubber crosslinked with 0.5 and 8% dicumyl peroxide (polished ice, 1 yr old; speed 0.1 mm s^{-1}; normal load 2.2 N).

important as the intrinsic friction of the rubber. Even so, numerous tyre trials do show differences in skid resistance when one tread rubber is compared with another. The differences are only 10–20% but of significance in vehicle handling. We cannot yet fully explain these differences, for example why treads made from natural rubber give superior grip, but clearly this is the aim of continuing investigations in order to optimise rubber compounding.

CONCLUSION

Understanding of rubber-ice friction has been furthered by taking a direct look at events in the contact region. The main feature to emerge is that of the weakness of an ice surface above −10°C. This appears, at least for simple contact geometries, to determine the general level of adhesion and friction rather than the properties of the rubber slider. Even so, there are noticeable differences from one rubber compound to another and these differences are of practical significance.

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