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Erosion of unfilled elastomers by solid particle impact

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The response has been studied of eight unfilled elastomers (four natural rubber compounds, epoxidized natural rubber ENR50, butyl rubber, polybutadiene and polyurethane) to erosion by 150 μm silica sand at an impact velocity of 48 m sec^{-1}. All were tested at an impact angle of 30°, close to the impact conditions occurring in pipe bends, while two were also tested at 90°. Wide variations in erosion rate were observed between different rubbers. These differences did not correlate systematically with the nature of the base elastomer, glass transition temperature or mechanical properties such as hardness, tensile strength or ultimate tensile elongation, nor with resistance to abrasive wear. Good correlation was, however, found with rebound resilience. A high resilience tended to imply high erosion resistance. The erosion rate was found empirically to be proportional to the quantity (1 − fractional resilience) raised to the power 1.4. Different surface morphologies were found in specimens of high and low resilience after erosion at 30°. Finely spaced transverse ridges formed on high-resilience rubbers, whereas surface features on low-resilience rubbers showed no directionality. Preliminary conclusions are drawn about possible mechanisms of material removal.

1. Introduction

Erosion by solid particle impact is an important process of wear in powder transport, gas turbine compressors and pulverized coal combustion. While suitable choice of metallic alloys can provide relatively little reduction of this type of wear, the use of hard ceramic materials can offer significant gains; tiles of alumina and other very hard materials are, for example, commonly used to protect pipe bends in the transport of pulverized coal [1]. Wear can also be reduced by the use of elastomers, either as coatings or as bulk materials; Agarwal *et al.* [2], for example, found that synthetic rubber pipe bends used for pneumatic conveying of sand lasted above five times as long as mild steel bends under the same conditions. Other investigators have also compared the erosion behaviour of rubbers with steels; Uetz [3] found that when subjected to normal impact of silica particles rubber eroded much less than steels, but that as the impact angle decreased the volumetric wear rate rose rapidly, reaching nearly ten times that of mild steel at glancing incidence.

Despite the potential advantages of using elastomeric coatings or components to resist erosive wear, relatively little research has been devoted to identifying the properties desirable in a rubber for these applications. Agarwal *et al.* [2] compared the behaviour of pipe bends in an unspecified synthetic rubber with those in a natural rubber, and found that the latter exhibited more rapid erosion, but it is unclear what properties of the rubbers were responsible for this difference. Abu-Isa and Jaynes [4] examined the resistance of a natural rubber (NR), a styrene–butadiene rubber (SBR) and an ethylene–propylene–diene rubber (EPDM) to erosion by sand particles at normal incidence. They concluded, in apparent contradiction to earlier results [2], that NR had the highest resistance to erosion, followed by SBR and then by EPDM, but because the three compounds tested contained varying amounts of carbon black filler (NR unfilled, SBR 33 wt %, EPDM 58 wt %) it is unclear whether the observed erosion rates reflect true differences between the base elastomers, or whether they might be largely due to the different filler contents.

Some attempts have been made to correlate the resistance of thermoplastics [5] and rubbers [6] to solid particle erosion with other, more fundamental, properties, but no useful correlations have emerged for rubbers. Marei and Izvozchikov [7] carried out a series of erosion experiments at glancing incidence, and suggested that for unfilled elastomers the difference between the test temperature and the glass transition temperature (T_g) was important; low erosion rates were associated with a large difference between the testing temperature and T_g. They also found that fillers led to decreased erosion resistance, in agreement with the observations of Morris and Oser [6]. The latter workers suggested that softness,

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resilience and stored energy at break all correlate slightly with erosion resistance at 45° incidence.

The aim of the present work was to investigate the resistance to erosion by solid particle impact of unfilled rubbers with a wide range of mechanical properties, and to explore the correlation between erosion rate and mechanical properties. Erosion testing was carried out with irregularly shaped particles of silica sand, because silica is a common abrasive contaminant in practical applications. Most tests were conducted at an impact angle of 30°, close to the conditions of impact likely to occur in practice in pipeline bends [1, 8].

2. Experimental methods

Samples of unfilled rubbers were provided by the Malaysian Rubber Producers Research Association, Brickendonbury, Hertford, Herfordshire (MRPRA). The compositions and curing conditions of these materials are listed in Table I. The elastomers chosen were four natural rubber compounds (NR), epoxidized natural rubber (ENR50), butyl rubber (IIR) and polybutadiene (BR). A proprietary polyurethane abrasion-resistant coating (PU) was also tested. These materials provided a wide range of mechanical properties. Hardness, elastic modulus, resilience, elongation at break, tensile strength and glass transition temperatures were measured for all the materials, and are listed in Table II.

Erosion tests were carried out with silica sand with a mean particle size of 150 μm, in the apparatus shown in Fig. 1. The silica particles were picked up by a swirling air flow from the hopper, and accelerated down the vertical cylindrical nozzle, 4.8 mm inside diameter and 300 mm long, with a constant differential pressure of 0.1 bar maintained between the ends of the nozzle. The velocity of the particles leaving the nozzle was measured to be 48 m sec^{-1} by the double rotating disc method [9]. All experiments were performed at this impact velocity.

The rubber specimens were cut from moulded plaques 5 to 10 mm thick (except for the polyurethane PU which was only 2 mm thick) into coupons 10 mm × 20 mm, which were then fixed with pressure-sensitive adhesive to steel backing plates. The specimen holder in the erosion apparatus could be set at any angle to the particle stream. Most experiments were performed with an impact angle (i.e. angle between the plane of the specimen surface and the impact direction) of 30°, although some tests were also made at normal incidence.

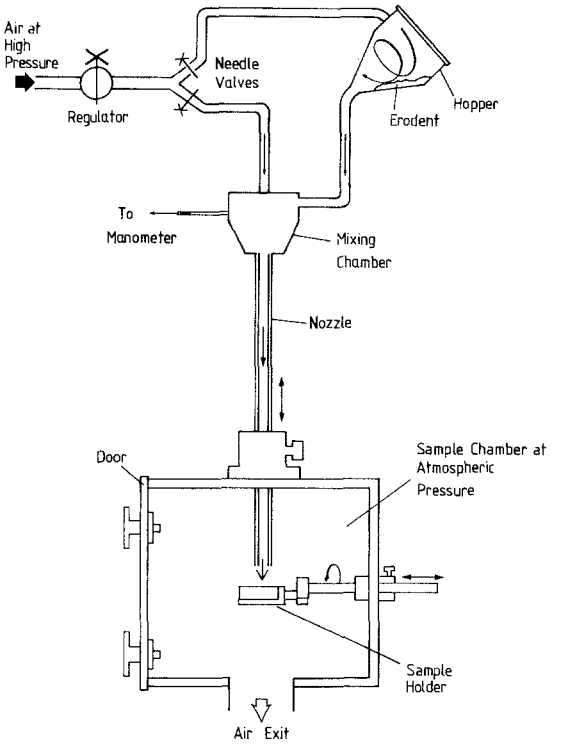

Figure 1 Apparatus used for erosion testing. Silica particles are fed from the hopper and mixed with the main air stream at the top of the cylindrical nozzle. They are accelerated downwards, striking the specimen at an angle determined by the orientation of the sample holder.

The wear rate was determined by weighing the specimens, still attached to their backing plates, after erosion by each increment (usually 200 g) of sand. A mean rate of erosion was then determined from a cumulative plot of mass loss against mass of sand. Before each weighing, loose silica particles were removed from the specimen by an air blast.

3. Results

Fig. 2 shows typical results of erosion experiments for four rubbers. All four had similar elastic modulus (see Table II), but considerably different strength and resilience. None of these four materials, at an impact angle of 30°, showed significant "incubation" behaviour; the mass loss in each case was linearly propor-

TABLE I Compositions of rubber tested

Designation	Base rubber	Additive (p.p.h.* base rubber)										Cure	
		ZnO	Stearic acid	Flectol H	Sulphur	MOR	CBS	MBT	TMTD	Dicumyl peroxide	Nonox ZA	Time (min)	Temp. (°C)
NR1	Natural	5	2	2	0.8	–	0.2	–	–	–	–	60	140
NR2	Natural	5	2	2	4.2	–	1.0	–	–	–	–	35	140
												10	100
NR3	Natural	–	–	2	–	–	–	–	–	2.7	–	then	
												90	150
NR4	Natural	5	2	–	1.7	–	0.4	–	–	–	1	40	140
ENR50	Epoxidized Natural ENR50	5	2	2	1.2	1.2	–	–	–	–	–	20	150
BR	Butadiene	3.5	2.5	2	1.7	–	0.5	–	–	–	–	50	150
IIR	Butyl	5	1	2	2	–	–	1	1	–	–	90	150
PU	Polyurethane	Sprayed coating of proprietary formulation											

*p.p.h. = parts per hundred.

TABLE II Mechanical properties and erosion results

Designation	Hardness (Shore A)	Modulus at 100% strain (MPa)	T_g (°C)	Rebound resilience (%)*	Tensile strength (MPa)	Tensile elongation at break (%)	Erosion at 30° angle	Erosion at 90° angle	Abrasion rate (DIN) (mg)
NR1	29	0.35	−71	66	7.7	794	1.8×10^{-6}	–	–
NR2	48	1.08	−67	74	26.1	555	3.1×10^{-6}	–	677
NR3	37	0.66	−72	71	8.1	505	3.0×10^{-6}	–	287
NR4	36	0.60	−70	68	24.2	846	2.6×10^{-6}	0.24×10^{-6}	–
ENR50	41	0.77	−15	2	4.7	447	17×10^{-6}	–	–
BR	44	0.80	−111	82	1.6	223	1.2×10^{-6}	–	497
IIR	35	0.50	−74	5	1.8	312	11×10^{-6}	1.1×10^{-6}	–
PU	74	2.8	−89	55	21	500	3.9×10^{-6}	–	–

*Rebound resilience was measured with a 6.3 mm steel ball falling from 150 mm.

tional to the mass of abrasive striking the specimen, essentially from the start of the test. Some specimens, however, notably BR, showed a small mass gain at early stages of the test before steady linear wear became established. This incubation behaviour was more pronounced for normal impact. For each material, erosion testing was continued until steady-state conditions were attained, where the mass removed was linearly proportional to the mass of abrasive striking the sample. The slope of this linear region of the mass loss curve was then taken as a measure of the erosion suffered by the specimen. Values of erosion determined in this way are listed in Table II.

Subsidiary experiments were conducted to determine the effect of varying the flux of abrasive particles at constant velocity, by changing the particle feed rate. Most tests were conducted with a particle feed rate of 15 to 20 g min^{-1}; a sample of ENR50 was also tested at a mass flow rate of 5 g min^{-1}, and exhibited an erosion rate (mass removed per unit mass of silica particles) only 2% higher than that observed at a flow rate four times greater. This difference lies well within the experimental error associated with the erosion testing.

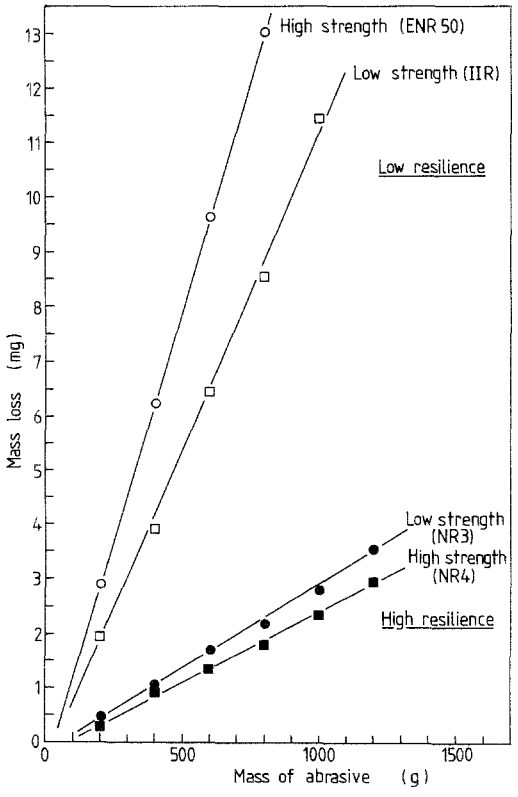

Figure 2 Plots of specimen mass loss against mass of abrasive striking the specimen, for four of the rubbers at a particle impact angle of 30°.

The bulk temperature rise in the rubber specimen during erosion testing was measured with a fine thermocouple embedded 2 mm beneath the surface of a sample of IIR, eroded at normal incidence. A maximum temperature rise of 2 K was registered at that location, about 1 min after the erosion testing had started. This temperature rise was then found to be maintained during the remainder of the test.

The rubber specimens were examined by optical and scanning electron microscopy before and after erosion. The surface appearance of all the samples before erosion was similar, with fine irregularities typically on a scale of 1 to 2 μm. Specimens after erosion at 30° tended to show two distinct types of surface morphology, exemplified by the micrographs in Figs 3 and 4. The resilient rubbers NR1, NR2, NR3, NR4 and BR all showed similar features, as seen in Fig. 3a and at higher magnification in Fig. 4a. In these rubbers, ridges or waves were formed, running across the surface at right angles to the direction of impact of the silica particles. Large, somewhat globular, fragments of rubber remained attached to the crests of the ridges. The ridge spacing varied between the different materials, but was typically 15 to 30 μm. The rubbers with very low resilience (ENR50 and IIR) showed a different surface appearance, rough and irregular, with no signs of the ridges seen in the higher resilience materials (Figs 3b and 4b). Comparison of the two classes of rubber at high magnification (Fig. 4) showed more rounded features in the high resilience rubbers than in the low. Imaging in the back-scattered mode, giving atomic number contrast, revealed only a very few small ($\sim 10\,\mu$m) silica particles on the surfaces of the high-resilience rubbers, with rather more evident on the low-resilience materials. The polyurethane samples (PU), which had an intermediate resilience, exhibited less obvious surface ridges than the rubbers with higher resilience; they also showed fine angular surface features more similar to those of the lower resilience rubbers.

Only two materials were tested at normal incidence: NR4 and IIR. The erosion rates were in each case approximately one tenth of those exhibited at 30° impact angle. Little difference was seen between

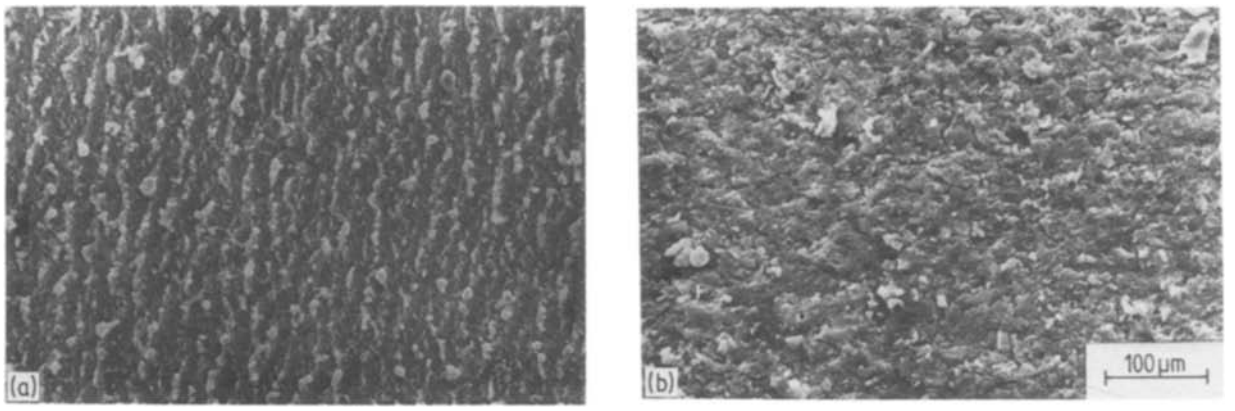

Figure 3 Scanning electron micrographs of the surface of rubber samples after erosion at 30° impact angle. (a) NR1, (b) ENR50.

surfaces of IIR eroded at 90° and at 30°, although the surface eroded at 90° appeared slightly rougher. Surface ripples were completely absent from samples of NR4 eroded at normal incidence, the specimens being much smoother than those eroded at 30°, but with numerous intersecting fissures on a scale of 5 to 30 μm. Some embedment of fine silica particles was evident in both rubbers.

4. Discussion

The substantial increase in erosion rate as the angle of incidence is reduced from 90° has previously been reported by Uetz [3] and Bulgin and Walters [10]. The latter suggested that it is the tangential component of the impact force which is largely responsible for erosion, and that this will vary approximately as the cosine of the angle of incidence.

In both erosion rate and surface appearance after erosion, all the rubbers with high resilience (NR1, NR2, NR3, NR4 and BR) differed markedly from those with low resilience (ENR50 and IIR), while in both respects polyurethane exhibited intermediate behaviour. In Fig. 2, for example, the two high-resilience rubbers NR3 and NR4 exhibit similar erosion behaviour, despite their difference in tensile strength; similarly, the two low-resilience rubbers ENR50 and IIR show erosion rates some five times greater, which again appear to be little influenced by tensile strength. The lack of correlation between erosion behaviour and tensile strength is further illustrated in Fig. 5, for all the materials tested. Other investigators of elastomers have found correlation between solid particle erosion rates and glass transition temperatures [7], and between rates of erosion by cavitating liquids or by liquid-drop impingement and Shore A hardness [11]. Fig. 6 shows little evidence of any useful correlation between the erosion rates observed in the present work and the glass transition temperature, while Fig. 7 suggests that hardness is also of no value in predicting erosion resistance in these unfilled elastomers.

Data supplied by MRPRA on the susceptibilities of three materials (NR2, NR3 and BR) to abrasion, as measured by the DIN standard test, are also listed in Table II. They show poor correlation with the observed erosion rates, because the two natural rubbers NR2 and NR3 exhibit almost the same rate of erosion while differing by a factor of greater than two in abrasive wear resistance; the butadiene rubber (BR) has much better erosion resistance than the natural rubbers, but only indifferent abrasion resistance. It therefore seems unlikely that properties found to correlate with abrasion resistance, as reviewed, for example, by Evans and Lancaster [12], would be of value in predicting resistance to solid particle erosion.

Relatively good correlation is, however, found with the rebound resilience of the elastomers. Fig. 8 shows the observed erosion rates plotted against (1 − fractional resilience), for erosion tests at angles of 30° and 90°. The experimental points lie close to straight lines of slope 1.4 on this log–log plot, for both impact angles. This correlation between erosion rate and (1 − fractional resilience)$^{1.4}$ should be viewed cautiously, because the resilience was measured under

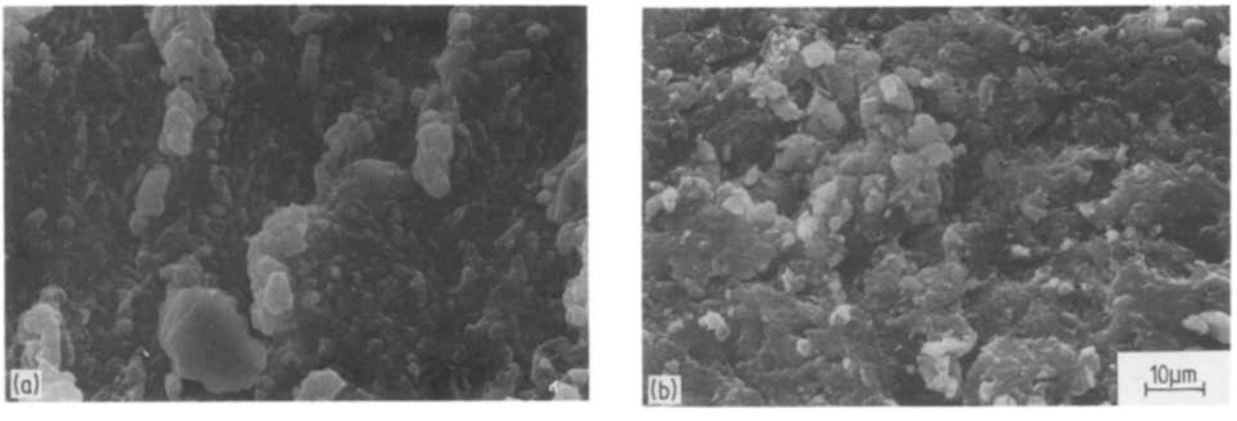

Figure 4 Micrographs at higher magnification of the samples shown in Fig. 3.

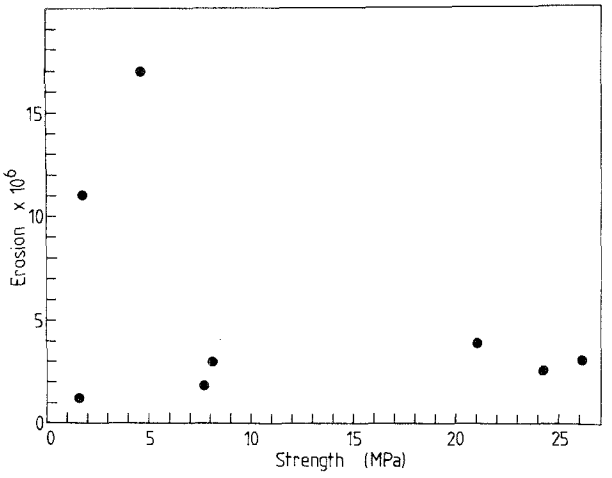

Figure 5 Erosion (mass lost per unit mass of erodent) plotted against tensile strength, for rubbers eroded at 30° impact angle.

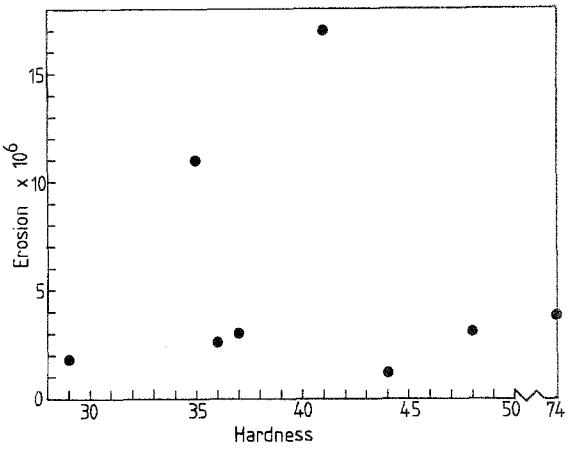

Figure 7 Erosion (mass lost per unit mass of erodent) plotted against Shore A hardness, for rubbers eroded at 30° impact angle.

impact conditions considerably different from those relevant to the erosion tests; the small size of the erosive particles, together with their higher impact velocity, will lead to impact strain rates some 10^3 times greater than those occurring in the measurement of rebound resilience. The correlation observed here is stronger than that found by Morris and Oser [6], whose study of unfilled rubbers was restricted to five vulcanizates all with resiliences greater than 40%.

For many rubbers there is an inverse correlation between T_g and resilience. IIR is an exception in having a low T_g and also low resilience. The fact that the correlation of erosion rate with T_g is poor for IIR, but that that with resilience is much better, suggests that the latter correlation may be more physically significant.

The quantity (1 − fractional resilience) represents the fraction of the initial energy of the impacting particle which is absorbed by the rubber and is therefore available, at least in principle, to cause permanent deformation or fracture, and hence erosion. It is therefore tempting to suggest that an energy-based model for the erosion of rubbers might be developed. It would clearly be useful in this context to explore the dependence of erosion rate on impact velocity, and also to examine the relationship between erosion rate and resilience for other elastomers.

An alternative approach would be to consider the effect of resilience on the tangential component of the impact force (and its duration), following the suggestion of Bulgin and Walters [10] that the tangential velocity component might be important.

The main features revealed by microscopic examination appear to differ between the groups of rubbers of high and low resilience. High-resilience rubbers formed distinctive surface ridges on erosion at 30°, similar to the features seen on abraded rubber surfaces [13] and possibly indicative of a similar cyclic crack growth mechanism caused by the tangential component of the impact force. Rounded particles of rubber form at the peaks of these ridges, and probably provide the source of material loss. Similar ridges, at right angles to the direction of particle impact, have also been remarked in the erosion of ductile metals by solid particles [14]. However, the similarity of the surface appearance need not imply that similar mechanisms of material removal are occurring [15].

The surfaces of the low-resilience specimens eroded at 30° are in contrast much more uniformly roughened, showing evidence of apparently loosely attached angular rubber fragments distributed over the surface, and numerous cracks and fissures. The occurrence of these cracks, which are not seen on the high-resilience rubbers, suggests that erosion may proceed by a catastrophic tearing process in these rubbers of lower resilience, perhaps because the impact stresses are higher.

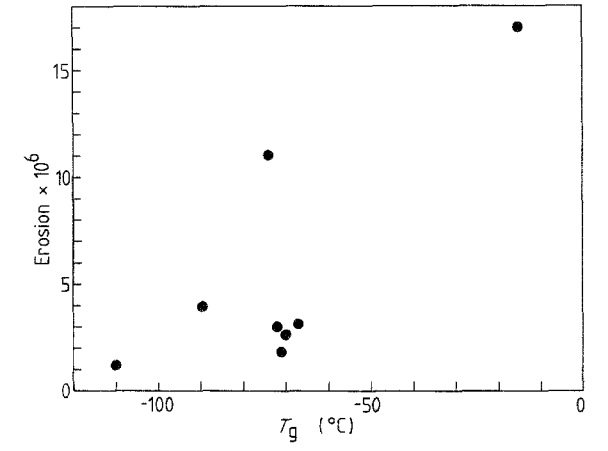

Figure 6 Erosion (mass lost per unit mass of erodent) plotted against glass transition temperature, for rubbers eroded at 30° impact angle.

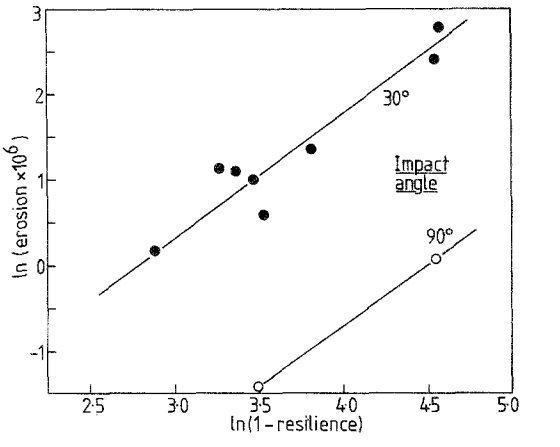

Figure 8 Log–log plot of erosion (mass lost per unit mass of erodent) against the quantity (1 − resilience), for rubbers eroded at 30° and 90°.

The results of the experiments at low particle fluxes are of interest in considering a suggestion made by Marei and Izvozchikov [7]. They proposed that when a grit particle strikes the surface, only low stresses are created, which are insufficient to tear off material; erosion results from local intensification of the stress, caused by subsequent impacts occurring on the same area before the stress due to earlier impact had been able to relax. If this model applied it would be expected that the rate of arrival of particles should influence the erosion rate. The insignificant difference between erosion rates observed for high and low particle fluxes suggests that this mechanism involving stress cumulation is unimportant.

It is instructive to estimate, from the erosion rates, the amount of rubber removed by each impinging particle. If the eroding particles are assumed for this purpose to be spheres of 150 μm diameter and of density 2.7 $Mg\,m^{-3}$, then the erosion rate of 17×10^{-6} observed for ENR50 at 30° impact angle corresponds to the removal of a spherical particle of rubber of 5.4 μm diameter by each impinging particle. Surface features of this order of size are seen in Fig. 4b, apparently loosely attached; these observations would be consistent with an erosion mechanism in which fragments of rubber become detached after only a small number of deformation cycles (impacts), rather than one involving failure after many cycles. A similar calculation for the high-resilience rubber NR1 (Fig. 4a) shows that the erosion rate is equivalent to the removal of a rubber particle of 2.5 μm diameter by each impact. Features on the sloping faces of the surface ridges are of this order of size, although the particles at the crests of the ridges, which are more vulnerable to removal, are rather larger. However, these particles appear at high magnification to consist of agglomerations of smaller particles, similar in size to those seen on the sloping faces. A mechanism may be tentatively proposed in which the smaller particles, formed by a small number of impacts, are swept up towards the crests of the ridges by successive impacts; they may be retained on the surface by adhesive forces until they are eventually removed as part of the larger rounded conglomerate particles. More detailed microscopical study of the evolution of the surface morphology, and of eroded debris, would be required to confirm this model.

5. Conclusions

The resistance of unfilled elastomers to erosion by solid particle impact depends strongly on impact angle, as has already been established, for example, by Uetz [3] and by Bulgin and Walters [10]. The rubbers studied in the present work exhibited wear rates at 30° impact angle some ten times higher than at normal incidence.

Wide variations in erosion rates were observed between different rubbers; these differences did not correlate systematically with the nature of the base elastomer, with glass transition temperature or with mechanical properties such as hardness (and hence modulus), tensile strength or ultimate tensile elongation, nor did they parallel resistance to abrasive wear. Good correlation was, however, found with rebound resilience, with a high resilience tending to imply high erosion resistance. Erosion rate was found empirically, for impact at 30° and at 90°, to be proportional to $(1 - \text{fractional resilience})^{1.4}$, a quantity related to the fraction of the kinetic energy of the erosive particles which is absorbed by the rubber.

The high-resilience rubbers eroded at 30° exhibited wave-like patterns running across the surface, perpendicular to the impact direction. In contrast, the low-resilience rubbers showed no directionality, but numerous particles of rubber on the surface. Only tentative suggestions about erosion mechanisms can be made from this evidence, although it appears likely that material is removed in small (typically 3 to 10 μm) fragments, and that only a small number of impacts is required to remove each fragment.

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