

Friction of Rubber Lubricated by Aqueous Solutions of Different Acidity/Alkalinity

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Measurements made of water lubricated friction of vulcanised rubber sliding against glass, and against itself, show that the level of friction is sensitive to the acidity/alkalinity of the water. The friction of natural rubber was markedly less at pH values greater than nine. The effect is believed to be due to the presence of the non-rubbers in natural rubber; evidence points to the fatty acids as being the 'active' component. The effect is not observed for synthetic polyisoprene. The results have a bearing upon the action of water lubricated rubber articles.

Surface electrical character is thought to be a factor upon which lubricated friction depends; the mechanism could be electric double-layer support¹. By varying the pH of an electrolyte solution streaming through a natural rubber capillary the zeta potential was found to change². These results, together with measurements made on the lubrication of raw natural rubber by solutions of an acid salt, a neutral salt, and an alkaline salt³, suggest that by changing the pH of the lubricant solution (while keeping other parameters approximately constant) it may be possible to cause a change in the level of friction. This idea forms the basis of the work presented in this paper.

EXPERIMENTAL

A new apparatus was developed for the measurement of friction force, F , based upon earlier apparatus⁴. The improvements were traverse speed control, load arm stability (lower centre of gravity), purpose designed loading weights and a higher quality pivot bearing. Other features were a sturdier overall construction, use of a dual strain gauge rosette on the tangential force-leaf springs and a better

strain-gauge amplifier. Contact geometries are shown in *Figure 1*.

Track materials employed were soda glass, borosilicate glass, polymethylmethacrylate (PMMA), high density polyethylene (HDPE) and various rubber vulcanisates. The tracks were smooth-surfaced and flat. Rubber sliders were hemispherical, of diameter 16 mm–38 mm. The formulations of hot compression moulded vulcanised rubber samples are given in *Table 1*. The samples all had a glass-smooth surface finish.

All measurements were taken within a temperature range of 19°C–22°C in laboratory air of relative humidity 45%–60%. Before each measurement surfaces were cleaned. Time was allowed, typically 20 min, for surfaces to dry following the use of any solvent. Lubricant was applied before sliding contact was initiated. The direction of sliding was automatically reversed after a distance of 27 mm.

Lubricants used are listed in *Table 2*. In order to obtain different pH values, preliminary tests were made using a 0.001M potassium

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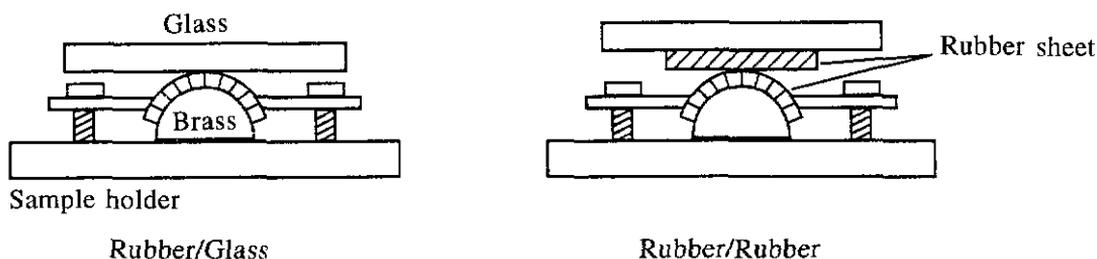


Figure 1. Contact geometries.

TABLE 1. FORMULATIONS OF RUBBER COMPOUNDS (PARTS BY WEIGHT)

Compound	Formulation								
	1	2	3	4	5	6	7	8	9
SMR L	100								
IR: <i>Cariflex 305</i>		100							
IR+: IR with acetone extract from NR added			100						
IR(st:low): IR containing 0.04% stearic acid				100					
IR(st:high): IR containing 0.27% stearic acid					100				
NR(E): NR, acetone extracted by Soxhlet when raw						100			
NR(E:st): NR(E) with 1% stearic acid							100		
DPNR: commercially deproteinised NR								100	
SKIM: NR with high non-rubber content									100
Dicumyl peroxide (<i>Dicup R</i>)	2	2	2	2	2	2	2	2	2

chloride (a neutral salt) solution, the pH of which was altered by the dropwise addition of 1M potassium hydroxide or 1M hydrochloric acid to produce solutions in the range pH 2 to pH 12. Subsequently, buffered solutions were employed, to give a more precisely controlled pH environment.

RESULTS

Preliminary

In the first series of tests, a 2 mm thick sheet of deproteinised natural rubber made by casting deproteinised (DP) latex against glass and allowing it to dry, was clamped firmly

TABLE 2. LIQUIDS TESTED AS LUBRICANTS

Concentration (M)	Compound	pH
0.001	Potassium chloride	7
	plus varying amounts of HCl	2 - 6
	plus varying amounts of KOH	8 - 12
	Buffer solutions	
0.1	Citric acid + sodium citrate	3.5
0.2	Sodium acetate + acetic acid	4.9
0.05	Potassium dihydrogen phosphate + NaOH	6.0
0.05	Potassium dihydrogen phosphate + NaOH	7.0
0.05	tris(hydroxymethyl) aminomethane + HCl	8.0
0.05	Borate + NaOH (0.1M in KCl)	9.0
0.05	Glycine + NaOH	10.3
0.051	Glycine + NaOH (0.051M in NaCl)	11.0
0.046	Glycine + NaOH (0.046M in NaCl)	12.3

over a brass hemisphere of radius 16.5 mm to form a slider and brought into contact with a soda glass track under a normal load of $W=0.98N$. Friction data were taken at sliding speeds of 0.11 mm/s and 0.43 mm/s. The findings are shown in *Figure 2*.

At first sight, there appears a general trend of reduction in friction with increasing pH, albeit with considerable scatter. However, when the tests were completed, the experiment was repeated on a different area of the glass track with a lubricant solution at pH 6.5. With increasing traversals, the friction coefficient ($\mu = F/W$) was seen to rise from $\mu = 0.10$ to $\mu = 0.45$. This suggested that the solution was conditioning the glass. By looking at the data with respect to the order in which the tests were made, it is noted that after exposure to a solution below pH 3 (points '4') the friction remains high even for a moderately high pH (points '5') whereas after exposure to a solution above pH 11 (points '7') the friction remains

low for solutions as low as pH 6.5 (points '9'). This conditioning of the glass is a known feature of such surface⁵. The irreproducibility, seen when using the same piece of glass, was not seen when using one piece for each pH value. This gave further evidence of the long term effects induced in glass by the action of acids and bases.

Tests on Vulcanised Rubber

To explore the pH effect more widely, tests were carried out using fully vulcanised compounds of natural rubber (SMR L) and a synthetic isoprene rubber (*Cariflex 305*). These hot compression moulded compounds will be referred to as NR and IR respectively. For each test the load and sliding speed were the same as before. Measurements were made with each rubber in contact with PMMA, and with rubber as both contacting surfaces, in the presence of solutions at pH 2 and pH 12. The results are shown in *Table 3*.

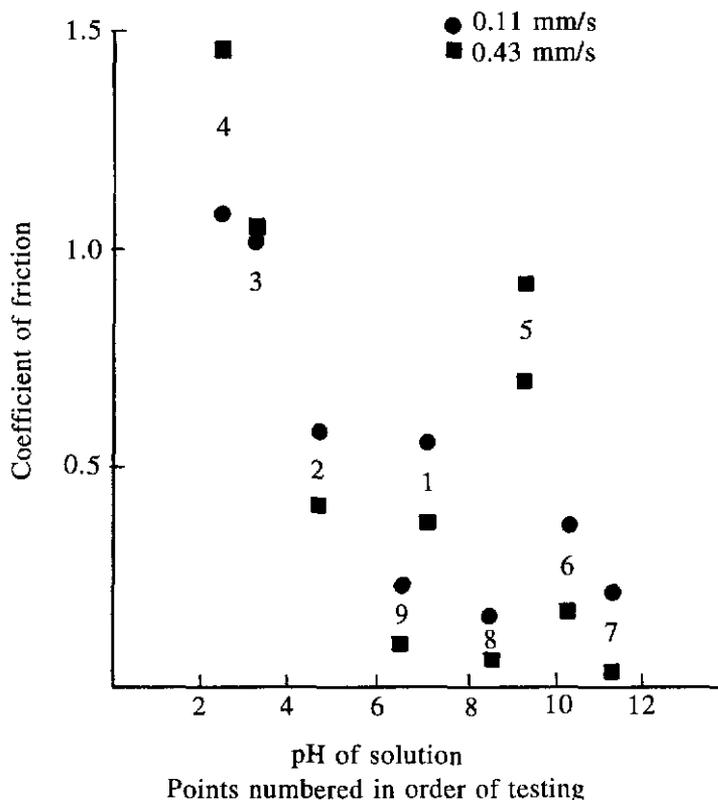


Figure 2. Friction of DP latex sheet in contact with soda glass and lubricated with solutions of strong electrolyte.

For IR no marked change in friction is seen between the extremes of pH, whether it is in contact with PMMA or itself. For NR, the friction in contact with PMMA drops by a

TABLE 3. NR AND IR LUBRICATION BY SOLUTIONS AT pH 2 AND pH 12

Contact pair	Friction coefficient	
	pH 2	pH 12
PMMA/IR	2.63	2.45 - 2.15
PMMA/NR	1.95 - 1.28	0.05 - 0.055
IR/IR	2.90 - 1.60	2.90 - 1.60
NR/NR	2.40 - 1.20	0.023 - 0.008

factor of around 40 from pH 2 to pH 12, and for contact with itself, by a factor of 100 or more. Reversibility of friction levels in the NR contacts was found to be immediate, and to operate after many reversals of solution pH. Since the two rubber compounds contain only the rubber itself and peroxide curing agent, these results suggest that the effect of friction reduction is due to the 'natural' non-rubber content of the NR.

The use of glass surfaces has been shown to bring with it the complications of acidic and alkaline surface modifications which are not quickly reversible. The investigation was

therefore continued using the rubber/rubber contact, which shows immediate reversibility. The symmetry of rubber/rubber contact is also attractive for understanding mechanisms.

Removal of Non-rubbers from NR

If the reduction in friction at high pH is due to non-rubbers, their removal should cause the effect to disappear. Two methods were used for removal:

- The rubber was soaked in a solution of a proteolytic enzyme. This was expected to remove the protein present in the surface of the rubber. Two proteases were selected, one of which is active in an alkaline medium, and the other which is active in an acidic medium. These were 0.25% superase in ammonia at pH 10, and 5% pepsin in hydrochloric acid at pH 2.
- The rubber was soaked in acetone. This was expected to remove fatty acids and most of the other non-rubbers, but not the proteins.

Pieces of rubber were immersed in solutions of both enzymes, in control solutions of ammonia and hydrochloric acid, and in acetone, and put in an oven at 35°C–37°C for 3 days. The rubbers were then removed from the liquids and dried in a vacuum desiccator for 2 days using concentrated sulphuric acid as desiccant, apart from the sample which had been soaked in acetone, which was dried in air for 2 days.

Friction measurements were made under a normal load of 0.5N at a sliding-speed of 0.4 mm/s over a track length of 25 mm, using solutions of acid at pH 2 and alkali at pH 12. The results (*Table 4*) suggest that the reduction in friction is caused by some component(s) of the acetone-extractable non-rubbers. This would appear to dissociate surface proteins

with the pH effect on friction for the vulcanisates tested here. The acetone extractable components responsible for the effect may be the fatty acids. Their content in NR was determined by gas-liquid chromatography of the methyl esters and the results are shown in *Table 5*.

TABLE 4. FRICTION AFTER SOAKING NR IN VARIOUS LIQUIDS

Treatment liquid	Friction coefficient	
	pH 2	pH 12
Superase in ammonia at pH 10	2.10 – 1.50	0.03
Ammonia at pH 10	2.75 – 1.90	0.03
Pepsin in HCl at pH 2	2.75	0.03
HCl at pH 2	2.55	0.05
Acetone	2.75 – 2.25	2.65

TABLE 5. FATTY ACID CONTENT OF NR

Fatty acid	Percentage by weight
Lauric	0.005
Myristic	0.005
Palmitic	0.055
Palmitoleic	0.013
Stearic	0.093
Oleic	0.100
Linoleic	0.161
Linolenic	0.008
Arachidic	0.030
Total	0.470

Friction Tests Using Aqueous Buffer Solutions as Lubricants

The previous experiments could be questioned because the lubricant solutions were not buffered. In the case of the alkaline solutions, the pH would gradually fall with absorption of atmospheric carbon dioxide. Therefore, to obtain a more stable, and more

precise, series of pH values for the lubricants, buffer solutions were made up in the range from pH 3.5 – pH 12.25, according to standard preparations^{6,7} as shown in *Table 2*. The exact pH values were measured using a meter. With these solutions, it was found that the pH value at which the friction reduction effect occurs in NR, is between 8 and 9.

Friction of Various Rubber Compounds over the Range of pH

By friction testing a range of standard grade and laboratory-modified rubbers, it was hoped to obtain further insight into which of the non-rubbers is responsible for the pH effect. The samples used are listed in *Table 1*. The cure system for each compound was 2% dicumyl peroxide. IR+ was made by Soxhlet acetone extracting NR, then milling the extract into the same mass of IR.

The amounts of stearic acid added to the mix when milling *Compounds 4* and *5* were 0.1% and 0.5%, values which correspond to the stearic acid content of NR and to the total fatty acid content of NR, as given in *Table 5*. After vulcanisation, the surfaces of these compounds had bloomed. Acetone-wiping removed the bloom from the surface of the rubber and fatty acid methyl ester chromatography (FAME) analysis confirmed the presence of fatty acid in the bulk of the rubber. The values given for stearic acid content (0.04% and 0.27%) are therefore those found for the acetone-wiped rubber samples, *i.e.* residual stearic acid contained in the bulk of the rubber.

The large amount of acetone extracted raw NR (about 400g) needed for making *Samples 6* and *7* was obtained by hot extraction in a Soxhlet apparatus for 2 days. After the extraction was complete, acetone was removed from the rubber bulk by drying in a vacuum oven at 40°C for 2 days.

Deproteinised natural rubber (DPNR) is produced by the deproteinisation of natural rubber latex by a proteolytic enzyme⁸. The principles behind this deproteinisation were the basis for the attempts to remove surface proteins (*see above*). The fatty acid content of the rubber is not affected by this process.

Skim rubber is obtained by skimming the liquid surface of the acidified latex serum to collect unflocculated particles and is a by-product of the latex coagulation process by which regular NR is produced. It contains a high proportion of non-rubbers. This is illustrated by comparing its nitrogen content (which includes protein) with that of other rubbers. For Skim this is 2.45%, for SMR L 0.33%, and for DPNR 0.09%. The fatty acid content of Skim is also high, around 2.50% compared with 0.45%–0.90% for NR and DPNR.

The friction measurements were all made using 2 mm thick sheets of the test rubber clamped firmly over a hemisphere of IR, of diameter 37.5 mm. This was slid against a flat surface of the same test rubber. The sliding speed was 0.4 mm/s, the normal load was 0.5N and the track length was 25 mm. Both surfaces were wiped with acetone to remove any contamination and were left for one minute to dry before testing.

Testing was carried out in the same way for each sample, beginning with the solution at pH 12.3. With the surfaces stationary and held slightly apart, approximately 1 ml of the solution was introduced to the gap using a dropping-pipette. Motion was initiated at the same time as the surfaces were brought together under the contact load. When a stable friction value was reached, the motion was halted, the surfaces separated slightly, and the solution withdrawn using a dropping-pipette. The solution with the next lowest pH was then

introduced and the same procedure followed as above to obtain a friction measurement. This was repeated with each solution down to pH 3.5, then for increasing solution pH back to pH 12.3.

The friction data for NR and IR are compared in *Figure 3*. The NR shows low friction when lubricated by buffer solutions greater than pH 9. However, if the NR is acetone extracted the friction is high through the entire pH range. When the non-rubber material extracted from the NR is mixed into IR, then there is a fall in friction above pH 9.

In *Figure 3* the friction of IR at each pH is given as a vertical line, rather than as the single-point value used for all other compounds. This is because in aqueous lubricated contact, IR almost always gave a discontinuous 'stickslip' friction, rather than the steady force seen in most other cases. The line length records the limits of the observed stickslip.

A comparison (*Figure 4*) of DPNR and SKIM suggested that if any surface protein were present it was ineffective in reducing the friction. The addition of stearic acid (*Figure 5*) to IR or to acetone extracted NR brought reduced friction under alkaline conditions. However, it was not as effective as the naturally occurring materials in NR (compare *Figures 3, 4 and 5*).

All the data support the view that, for vulcanised rubber, it is fatty acids above a certain concentration that cause the friction reduction at high pH.

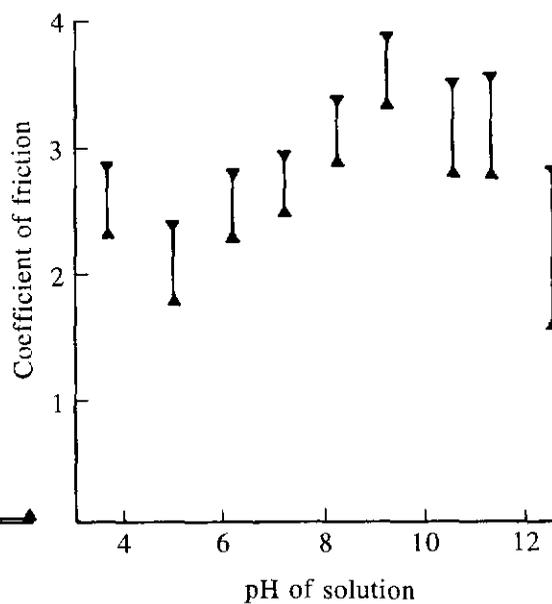
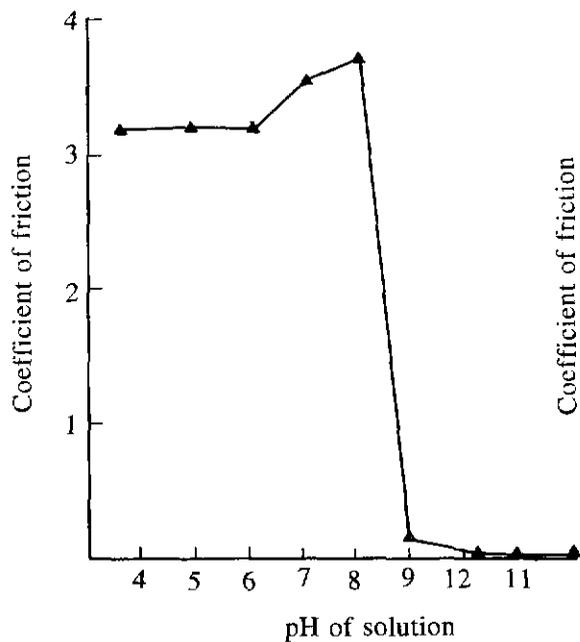
For IR containing 0.27% stearic acid, defined in *Table 1* as IR (st:high), the friction trend followed a single line (*Figure 5*), but for NR acetone extracted but 1% stearic acid added, defined in *Table 1* as NR (E:st) the level of friction found for decreasing solution

pH was below that found subsequently for increasing solution pH. It was thought that this could be a result of inadequate cleaning of the surface prior to testing, leaving traces of bloomed stearic acid on the surface. At the high friction suffered in pH 3.5 solution, it seemed possible that bloom could be scrubbed from the contact area, thus giving a more representative series of results for the portion of the graph for increasing solution pH. Further tests using more carefully acetone-wiped samples of NR(E:st) gave a single trend line, which followed the same values as the previous trend for increasing solution pH. This illustrated the importance of care in preparing the test samples for these measurements.

Effect of Long-term Soaking of NR in Buffer Solutions

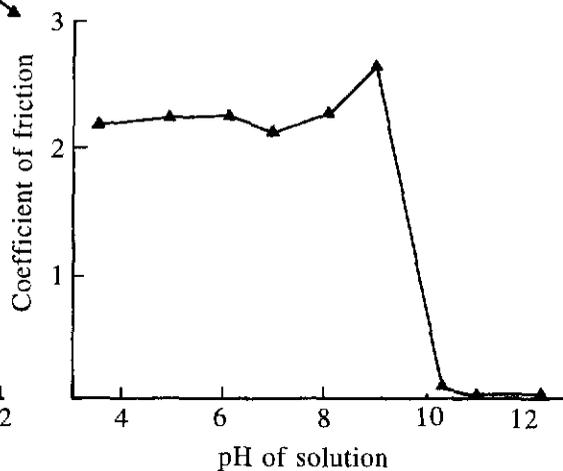
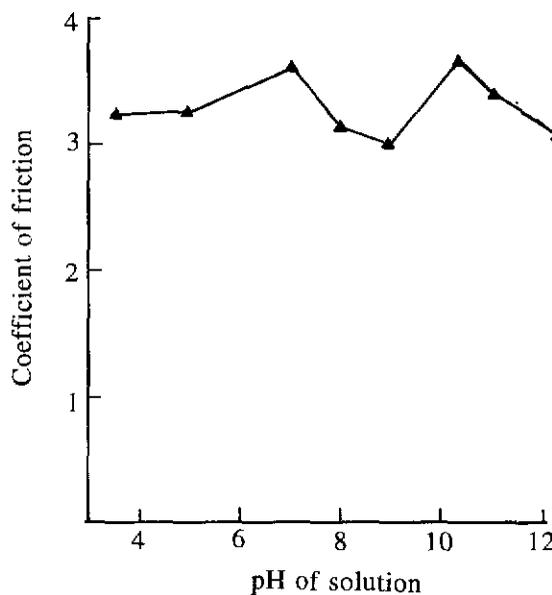
The idea for this work came from the following observation: a friction test was made to establish the persistence of the reduction in friction. An NR/NR contact was lubricated with pH 12.3 buffer and kept wet to compensate for evaporation; after 30 h of reciprocal sliding no increase in friction was seen. The liquid in the contact area was no longer clear, but cloudy. This liquid was drawn off and left in a capillary tube. A whitish-yellow solid settled out from the liquid after a few hours. This solid was found (by FAME analysis) to contain fatty acid as a large proportion of its mass. The inference drawn from this result was that the pH 12.3 solution could be solubilising fatty acid soaps from the rubber. The resulting soapy solution was then acting as a lubricant. To test this pieces of NR were soaked in solutions at pH values of 6.0, 7.0, 8.0, 9.0, 10.3 and 11.0.

After one week of soaking at room temperature, the rubber samples were vacuum-dried at room temperature over concentrated sulphuric acid. Drying to constant mass took one week. The mass of each sample was recorded before and after soaking and after



Friction of NR/NR contact lubricated with buffer solutions

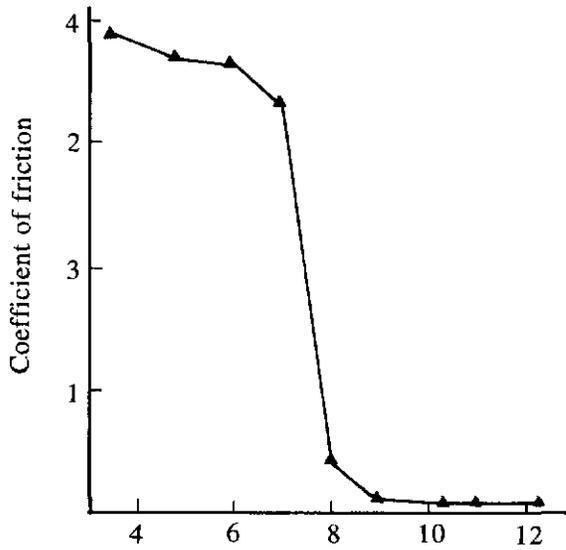
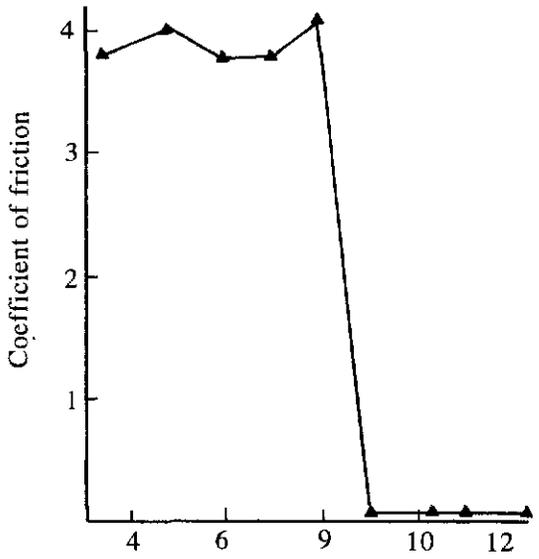
Friction of IR/IR contact lubricated with buffer solutions



Friction of NR(E)/NR(E) contact lubricated with buffer solutions

Friction of IR+/IR+ contact lubricated with buffer solutions

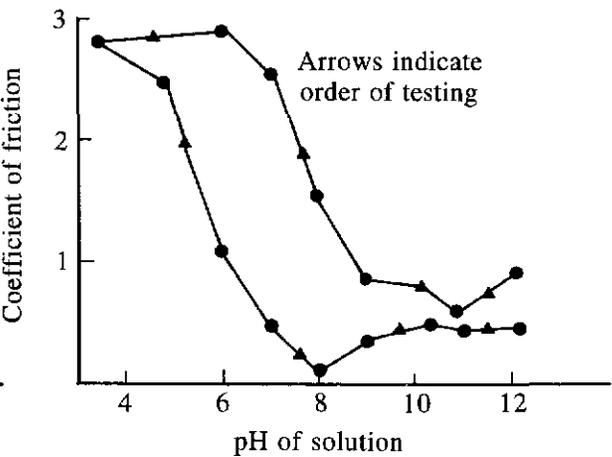
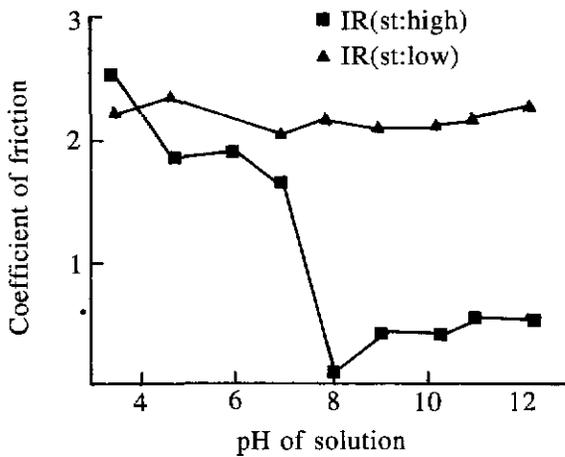
Figure 3. Friction of NR and IR.



Friction of DPNR/DPNR contact lubricated with buffer solutions

Friction of Skim/Skim contact lubricated with buffer solutions

Figure 4. Friction of DPNR and skim rubber.



Friction of IR(st:high)/IR(st:high) and IR(st:low)/IR(st:low) contacts lubricated with buffer solutions

Friction of NR(E:st)/NR(E:st) contact lubricated with buffer solutions

Figure 5. Friction of IR and NR.

drying. These data are shown in *Table 6*. It would seem, at first sight, that the mass reached after soaking then drying is not compatible with the initial mass and the mass after soaking. For all samples a reduction in mass is seen. However, if a piece of NR, as moulded, is put into a vacuum desiccator under the same conditions as above, and left for a week, a mass loss of around 1.3% is recorded. This is due to the removal of the volatile residual components of the curatives in the rubber and is recognisable by the loss of the characteristic smell of this type of vulcanised rubber after vacuum-desiccation. In all cases the mass change between the soaked and dried samples is around 2%. Once the 1.3% of the mass lost through volatiles has been accounted for a mass change of 0.7% remains to be explained.

This amount is a typical value for the water uptake of NR during such a period of soaking. The solutions remaining after one week of soaking were tested for fatty acid soaps. The results are shown in *Table 7*. At a solution pH of 8 and below, no significant amount of fatty acid is removed. At a solution pH of 9 and above, an amount of fatty acid is removed which is related to the solution pH; the higher the pH, the greater is the amount of fatty acid removed.

The pieces of rubber which had been soaked for one week and dried were friction-tested using solutions over the range of pH. The method of testing was as previously. For the samples soaked in solutions at pH 6.0, 7.0 and 8.0, the effect of friction reduction was the

TABLE 6. NR SOAKED IN BUFFER SOLUTIONS

Solution pH	Initial mass (1)	Mass after soaking (2)	% Mass change	Mass after drying	% Mass change from (1)	% Mass change from (2)
6	5.3181	5.3427	+0.46	5.2308	-1.64	-2.09
7	5.5003	5.5180	+0.32	5.4081	-1.68	-1.99
8	5.3211	5.3414	+0.38	5.2288	-1.73	-2.11
9	5.6867	5.6686	-0.34	5.5596	-2.25	-1.92
10.3	5.8137	5.7878	-0.45	5.6739	-2.40	-1.97
11	5.3185	5.2924	-0.49	5.1897	-2.42	-1.94

TABLE 7. FATTY ACID CONTENT OF BUFFER SOLUTIONS AFTER ONE WEEK OF NR SOAK

Fatty acid	6	7	8	9	10.3	11
Lauric	0	0	0	0.003	0	0
Myristic	0	0	0	0.001	0.002	0.002
Palmitic	0.001	0	0.001	0.030	0.037	0.042
Palmitoleic	0.001	0	0.001	0.002	0.004	0.005
Stearic	0.001	0	0.001	0.053	0.100	0.105
Oleic	0.002	0	0	0.045	0.107	0.126
Linoleic	0.001	0	0.001	0.094	0.162	0.246
Linolenic	0	0	0	0.007	0.011	0.019
Totals	0.006	0	0.004	0.235	0.423	0.545

same as that found previously for NR, with a large drop in friction between a lubricant pH of 8.0 and 9.0. For the samples soaked in solutions at pH 9.0, 10.3 and 11.0, friction reduction was observed, but the drop in friction occurred between pH 9.0 and pH 10.3. Examples of these friction trends, for rubber soaked at pH 8.0 and pH 9.0, are shown in *Figure 6*. By comparing these with *Figure 3* for NR, it is seen that the level of friction at lower lubricant pH is different. For 'as moulded' rubber the friction (*Figure 3*) is $\mu = 3.2-3.6$, whereas for soaked rubber (*Figure 6*) it is $\mu = 2.3-2.6$. This is a feature introduced by soaking, which causes the hardness of the rubber to increase, and hence the friction to

decrease⁹. The removal of water-solubles from NR may account for the increase in hardness.

Since no fatty acids had been removed from the NR by soaking in solutions at pH 8.0 and below, such solutions were not used in further soaking tests. The NR samples which had been soaked at pH 9, and above, were immersed in fresh solutions at the same pH in which they had been previously soaked. They were left soaking at room temperature for a further week (2 weeks of total soaking). After the second week of soaking, the solutions were clear and did not foam when shaken. This contrasted strongly with the solutions resulting from one week of soaking, which were cloudy and

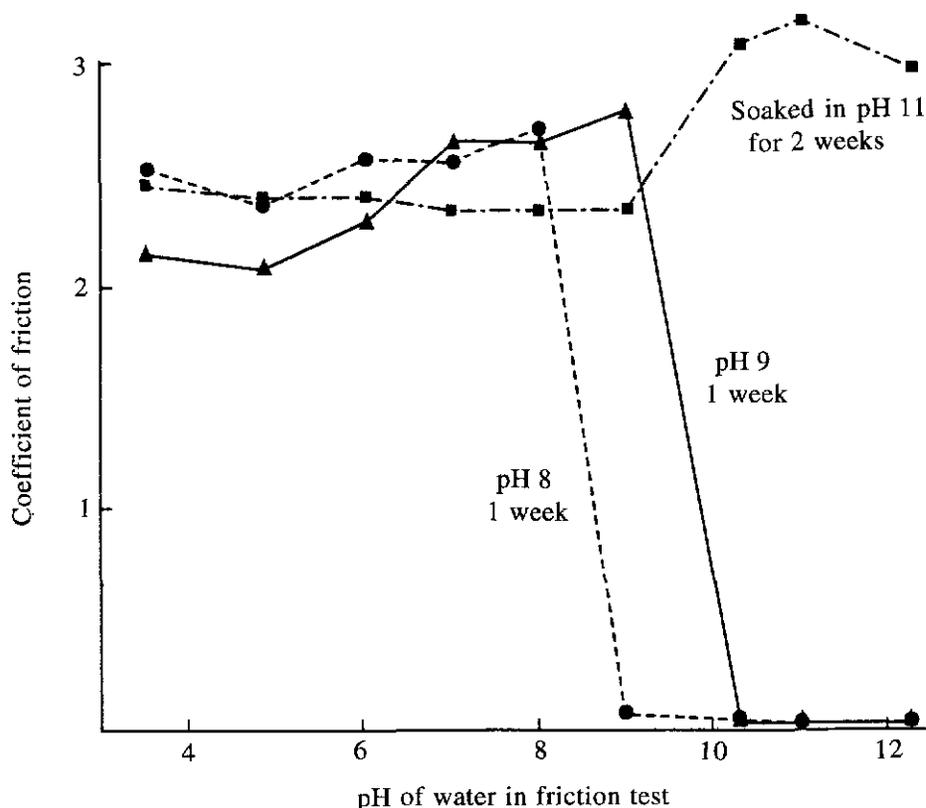


Figure 6. Friction of NR/NR contact after soaking in alkali.

foamed easily when shaken (indicating the presence of soaps). FAME analysis showed that the solutions contained fatty acid soaps, but in far smaller quantities than after the first week of soaking, as shown in *Table 8*.

After vacuum-desiccation of the soaked samples for one week, friction measurements were made using the solutions of various pH as lubricants. For the samples soaked at pH 9.0 and pH 10.3, there was no change in the friction trend from that found after soaking for one

week (*Figure 6*). The friction of the sample soaked at pH 11.0 for 2 weeks remained above $\mu = 2.3$ over the whole range of lubricant pH, as shown in *Figure 6*.

The amount of fatty acid remaining in the rubber samples after 2 weeks of soaking was found (*Table 9*). It was seen that the higher the pH at which the sample had been soaked, the smaller was the amount of fatty acid remaining in the sample, as expected.

TABLE 8. FATTY ACID CONTENT OF BUFFER SOLUTIONS AFTER SECOND WEEK OF NR SOAK

Fatty acid	Solution pH		
	9	10.2	11
Lauric	0.003	0	0
Myristic	0.002	0.002	0.002
Palmitic	0.006	0.003	0.001
Palmitoleic	0.002	0.002	0.001
Stearic	0.015	0.005	0.001
Oleic	0.007	0.007	0.002
Linoleic	0.012	0.016	0.007
Linolenic	0.001	0.001	0.001
Totals	0.048	0.036	0.015

TABLE 9. FATTY ACID CONTENT OF NR AFTER TWO WEEKS SOAKING IN BUFFER SOLUTIONS

Fatty acid	Solution pH		
	9	10.3	11
Myristic	0.015	0.007	0.009
Palmitic	0.027	0.024	0.021
Palmitoleic	0.014	0.017	0.015
Stearic	0.068	0.065	0.060
Oleic	0.089	0.063	0.048
Linoleic	0.160	0.100	0.090
Linolenic	0.008	0.006	0.005
Totals	0.381	0.282	0.248

Contact Angle of Buffer Solutions on NR and IR

It is known that the presence of any surfactant material in a liquid will reduce the interfacial contact angle when a drop of the liquid is placed on a surface. With this in mind, contact angles were found between drops of aqueous buffer solutions and a rubber surface. Each drop had a volume of 19.2 mm³. The base diameter observed between the drop and the rubber was averaged over two perpendicular directions (to allow for asymmetry) after 20 min equilibration time. The average of 10 such drops was used to find a value for the contact angle. The results are shown in Figure 7.

It is seen that the solution pH has no effect on the contact angle with IR. However, with

NR the contact angle is around 90° at pH 8.0 and below but around 65° at pH 9.0 and above. This suggested a possible influence of fatty acid soaps on the contact angle. Using IR, contact angles were measured for SDS solutions at concentrations of 0.001M, 0.005M and 0.01M. The values obtained were 78°±4°, 39°±4°, and 47°±4° respectively, illustrating that surfactant can lower contact angles on rubber, and that there is an effect of surfactant concentration on the contact angle. The contact angle of a solution of fatty acids leached from NR at pH 10.3 was found to give a contact angle of 46°±4° on IR.

Comment on Practical Utility

The study reported here relates to the lubricated behaviour of unfilled rubber compounds of simple formulation. Whether

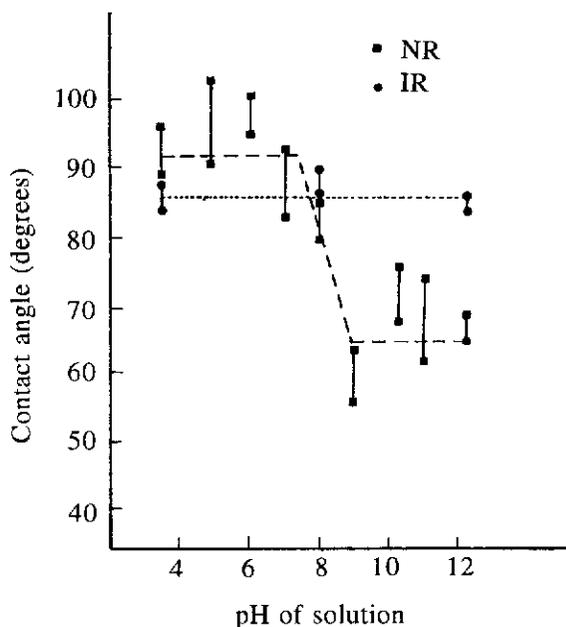


Figure 7. Contact angles of buffer solutions on NR and IR.

the present findings would be borne out in fully formulated rubber article is the subject of ongoing research. The preliminary indications are that they might, albeit on a reduced scale of effect. In practical situations an influencing factor is wear, which causes an increase in surface roughness and apparently a considerably reduced pH effect, although it can persist for certain combinations of contact surfaces. It is hoped to publish the details in a future communication.

CONCLUSION

Using a contact-pair of rubber and glass, it appears that the modification of glass surfaces by solutions at different pH is a long-term effect. This can obscure any coherent trend in the variation of friction of a rubber/glass contact lubricated by solutions at different pH, unless a separate piece of glass is used with each different solution. By using separate pieces of glass, a reduction in friction was seen as the pH of the lubricating solution was increased. Removing portions of the non-rubbers from NR, and adding selected components to IR, suggested that it was the fatty acids in the vulcanised NR which reduced the friction at high pH for rubber/rubber contact.

Soaking NR test samples in buffer solutions showed that solutions at pH 8.0 and below cause no removal of fatty acids from the rubber, and in friction tests high values are given. The solutions at pH 9.0 and above cause fatty acids to be removed, as well as giving low values in friction tests.

Prolonged soaking of NR in a solution at pH 11.0 gave a sample which showed no friction reduction at all. The rubber still contained 0.25% by weight of fatty acids, which is about a half of the original fatty acid content. This indicates a level of fatty acid

content in the rubber below which no friction reduction is obtained, even at the highest pH. This compares well with the results for IR with added stearic acid, where low friction was seen with a bulk concentration of 0.27% in IR(st:high), but not with a bulk concentration of 0.04% in IR(st:low).

The sample soaked at pH 10.3 for two weeks had a residual fatty acid concentration of 0.28% and yet still gave low friction when lubricated with a solution at pH 10.3 and above. This suggests that the bulk concentration at which the friction reduction comes into operation is over a narrow range, at around 0.25% by weight of the rubber.

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