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Cavitation in Bonded Natural Rubber Cylinders Repeatedly Loaded in Tension

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This investigation describes cavitation behaviour in bonded rubber cylinders subjected to different loading schedules in tension. Three natural rubber vulcanisates have been studied. The effect of carbon black on cavitation behaviour is examined. It is shown that repeated cycling can alter the cavitation failure stress when compared to that of a single cycle. Some practical consequences of this finding are discussed together with the mechanism of cavitation.

For rubber bonded between rigid plates and subjected to a tensile force, the resulting triaxial tension may lead to negative hydrostatic forces sufficient to cause internal rupture or cavitation in the rubber. This phenomenon was first reported by Busse[1]; other workers[2-11] have subsequently investigated cavitation behaviour further. The presence of cavitation can have important practical implications in determining design limits for any rubber component, which may experience negative hydrostatic or inflation forces since the onset of cavitation can normally be considered as a maximum working limit. While cavitation will result in permanent damage to the rubber and thus reduce the performance of a component, such failure is not normally catastrophic in nature but tends to produce a progressive accumulation of damage especially during cyclic deformations. The behaviour of cavitation failure under cyclic condition, has received very little study, despite its having considerable practical importance, *e.g.* in rubber seismic isolation bearings. The present investigation has studied cavitation behaviour in three natural rubber vulcanisates subjected to different repeated loading schedules in tension.

EXPERIMENTAL

The cavitation studies were all conducted on single layer natural rubber bonded discs (diameter 50 mm) pulled in tension using a proprietary bonding adhesive system *(Chemlok 205/220)*[12]. A typical test piece assembly for connection to a tensile test machine is shown in *Figure 1*. Three natural rubber compounds were investigated. The rubber compound formulation and press cure conditions with relevant physical properties are given in *Table 1*.

Test pieces were manufactured by inserting two 50 mm diameter metal discs into a suitable transfer mould with sufficient vulcanisate to fill the mould cavity and hot curing under pressure in a press to 95% of full cure. Each metal disc was 20 mm in thickness, sufficient to ensure no significant bending occurred during testing. Before applying the bonding adhesive, the metal discs were degreased by cleaning in trichloroethane and shot blasted to ensure good bond strength.

The thickness of the rubber discs was varied to give a shape factor, S[=radius/(2 ×

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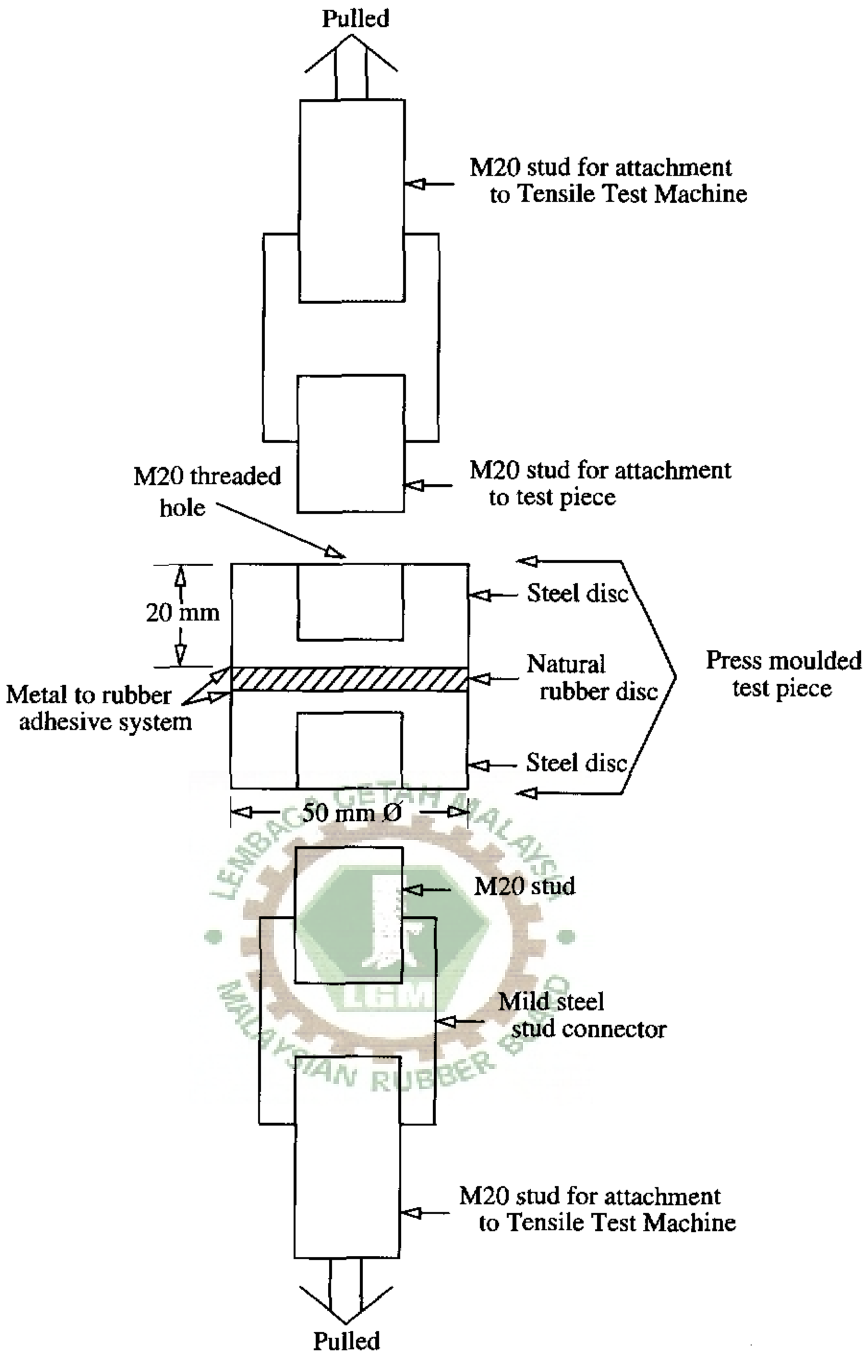

Figure 1. A typical test piece assembly.

TABLE 1. FORMULATIONS AND PHYSICAL PROPERTIES: SMR L 100, 100; ZINC OXIDE, 5; STEARIC ACID, 2; SULPHUR, 2.5; CBS, 0.6; ANTIOXIDANT 2246, 2 PARTS P.H.R.

Vulcanisate Number	1	2	3
N330, HAF black, parts p.h.r.	–	20	80
Dutrex 729	–	–	25
Press cures	37 min at 140°C	34 min at 140°C	33 min at 140°C
Physical properties			
Young's modulus (E_0[a], MN/m^2)	1.6	2.6	5.6
Tear strength[b], kN/m	8.0	12.0	26.3
Hardness (IRHD)[c]	43	55	67
Tensile elongation at break[d]	770	660	421

[a]E_0 to ± 0.1 MN/m^2
[b]Tear strength, trouser, to *ISO 34*
[c]Hardness to *ISO 48*
[d]Break to *ISO 37*

thickness)] of either 2.5 or 5. The test pieces were repeatedly pulled on a test machine at a crosshead speed of 2 mm/min. Load-extension graphs were obtained in each case. Internal rubber cracking or cavitation could be detected by deviations in the load-extension data and in some cases by associated audible cracking sounds.

Test pieces were loaded to a stress just in excess of the initial cavitation stress and subsequently cut into sections. Cavitation holes and cracks were observed in these test pieces across the central area of the cross-section. Cavities were not present at or near the free surface of the rubber where the negative hydrostatic pressure is less than at the centre of the test piece. Test pieces were also subjected to a stress a little less than the initial cavitation stress and subsequently cut into sections. No cavities were found in any of these test pieces.

To investigate the strength of the rubber-adhesive bond test pieces were pulled to catastrophic failure. The test pieces were found to fail catastrophically at a stress of about three times that of the initial cavitation stress. Delamination at the bond occurred just prior to the catastrophic failure stress. There was no delamination detected at a stress comparable to the cavitation stress.

RESULTS

Figure 2 shows the behaviour of a natural rubber vulcanisate containing no carbon black filler *(Compound 1)* repeatedly pulled in tension for 10 cycles to a constant maximum stress of 1.25 MN/m^2. Cavitation is indicated by the fluctuations in the stress on the first cycle. The initial or minimum cavitation stress (MICS) occurs at a value of 0.97 MN/m^2. It can be seen that no further cavitation occurs during the second or subsequent cycles.

A number of similar tests have been conducted which indicate that in the majority of cases cavitation only propagates during the first cycle. In the cases where further cavitation is present after the first cycle, small amounts

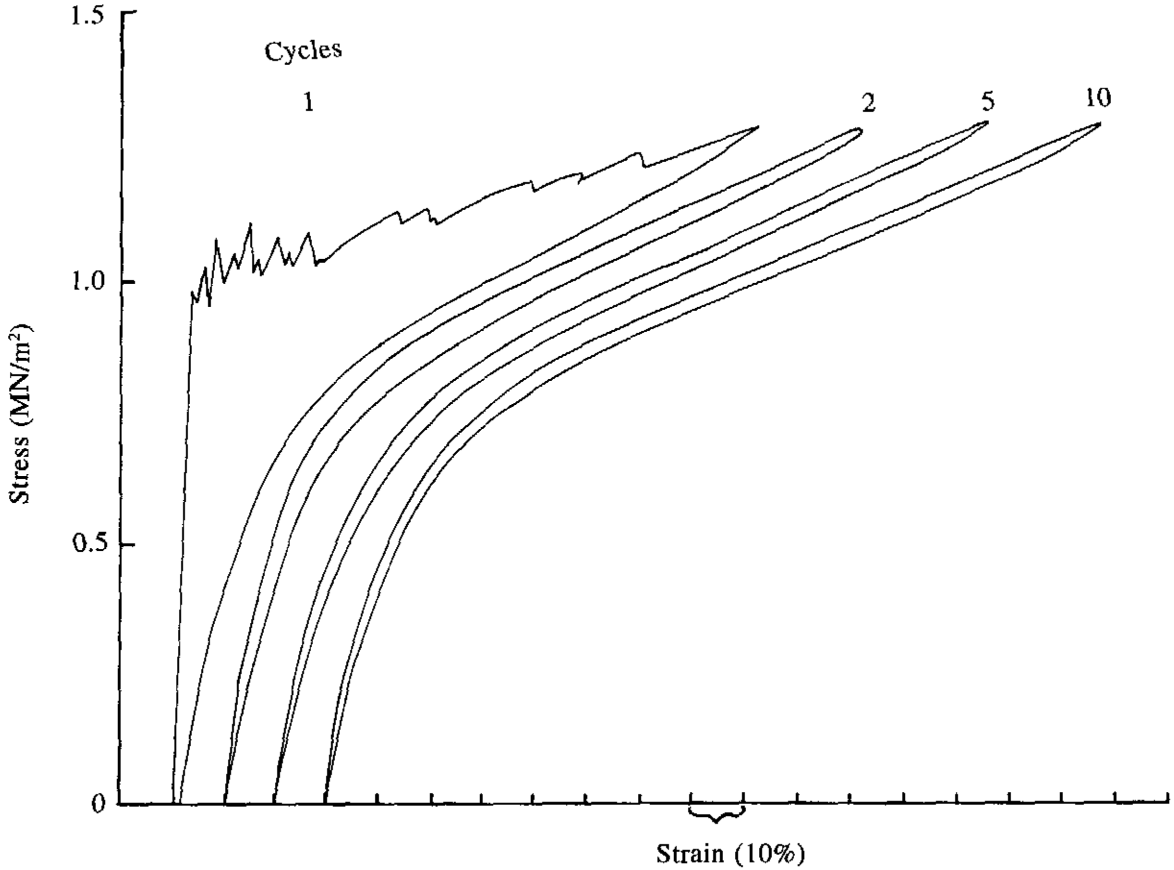

Figure 2. The effect of cavitation on the stress-strain behaviour of a natural rubber vulcanisate (Compound 1) *containing no carbon black filler. The testpiece has been repeatedly cycled ten times to a constant maximum stress of 1.25 MN/m^2. Cavitation damage occurs only on the first cycle as denoted by the fluctuations in the stress. The minimum cavitation stress is at 0.96 MN/m^2 (Shape Factor 2.5).*

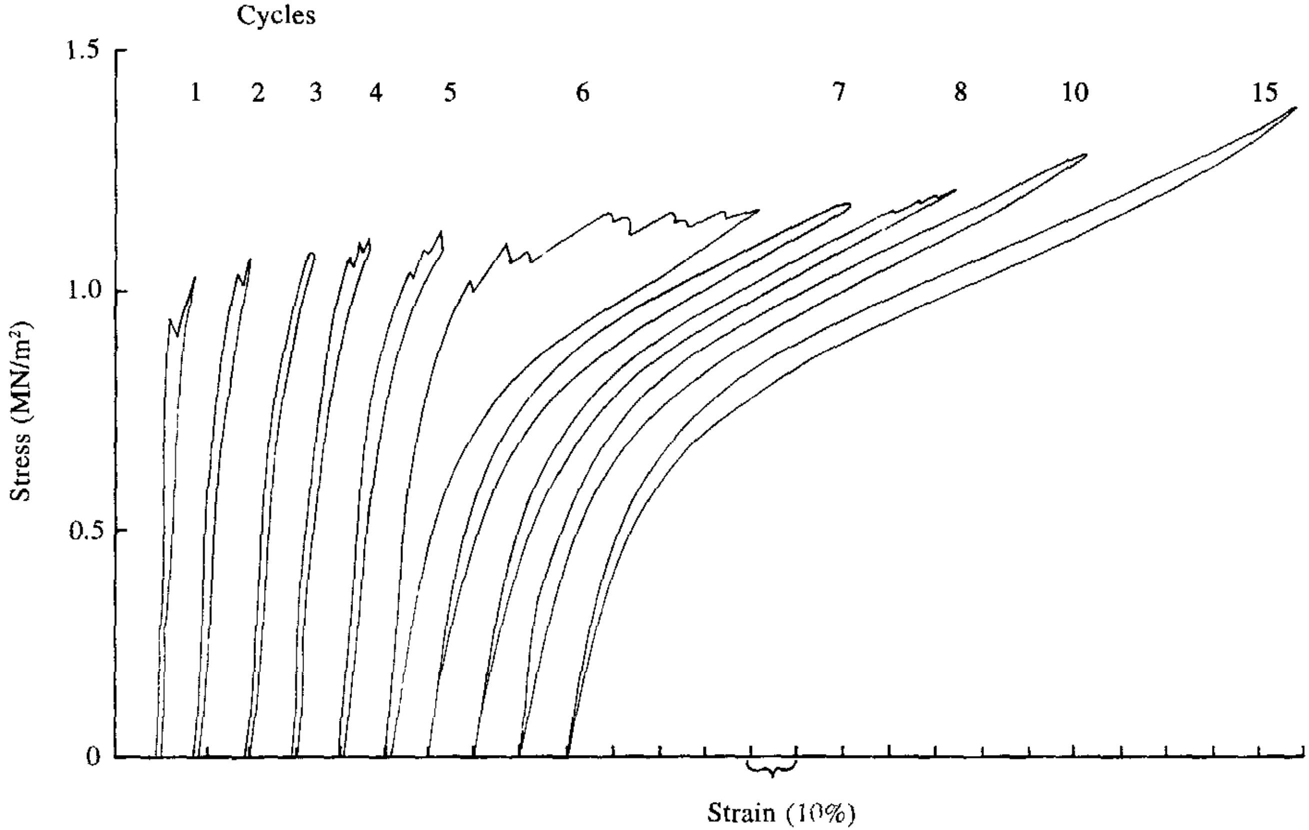

Figure 3. The effect of cavitation on the stress-strain behaviour of a natural rubber vulcanisate (Compound 1) *repeatedly cycled fifteen times with an incremental increase in the maximum stress per cycle of 0.025 MN/m^2. Cavitation damage only occurs between the first and eighth cycle.*

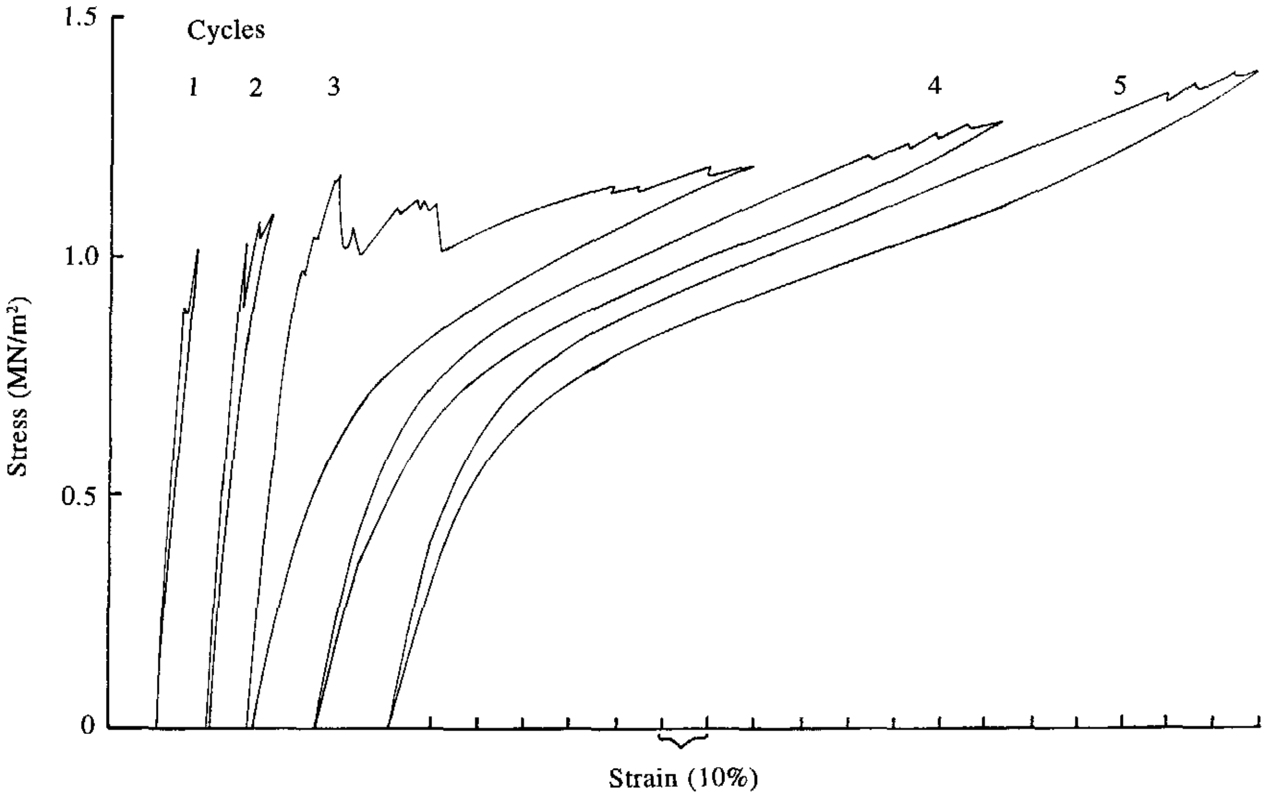

Figure 4. The effect of cavitation on the stress-strain behaviour of a natural rubber vulcanisate (Compound 1) *repeatedly cycled with an incremental increase in the maximum stress per cycle of 0.1 MN/m^2. Cavitation damage only occurs between the first and fifth cycle.*

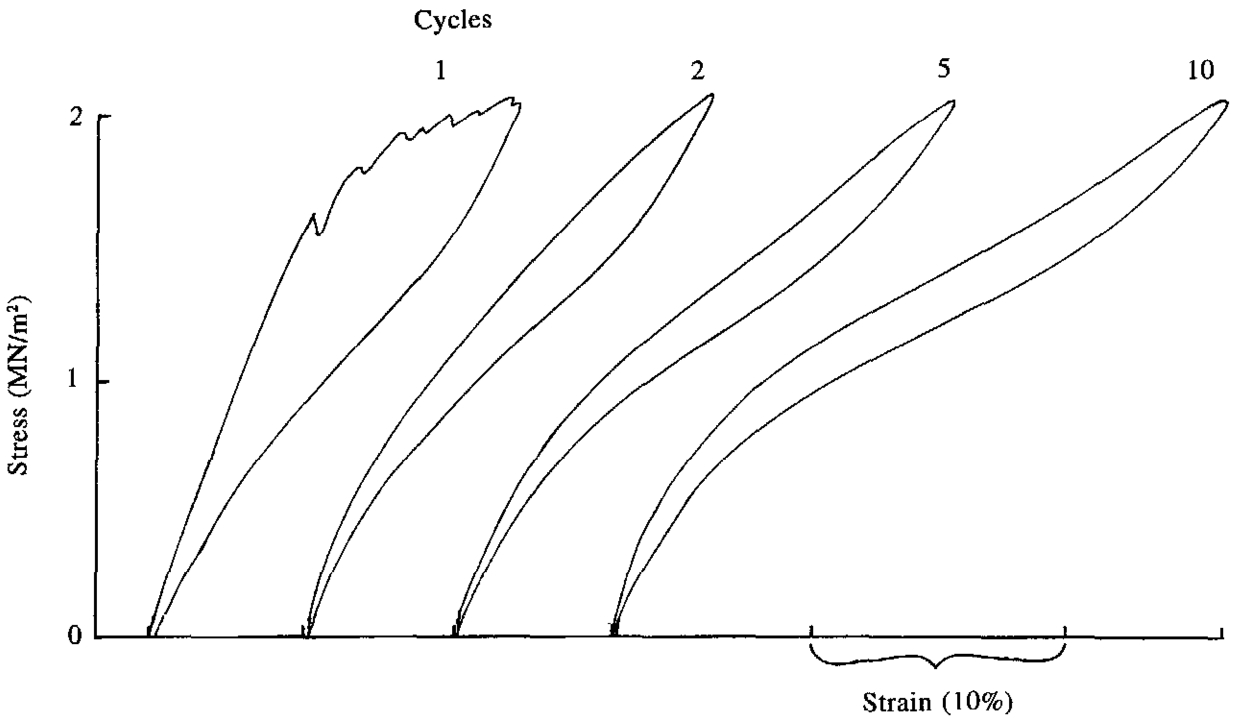

Figure 5. The effect of cavitation on the stress-strain behaviour of a natural rubber vulcanisate (Compound 2) *containing 20 p.p.h.r. HAF carbon black filler. The testpiece has been cycled ten times to a constant maximum stress of 2 MN/m². Cavitation damage only occurs on the first cycle. The initial cavitation takes place at a stress of 1.6 MN/m².*

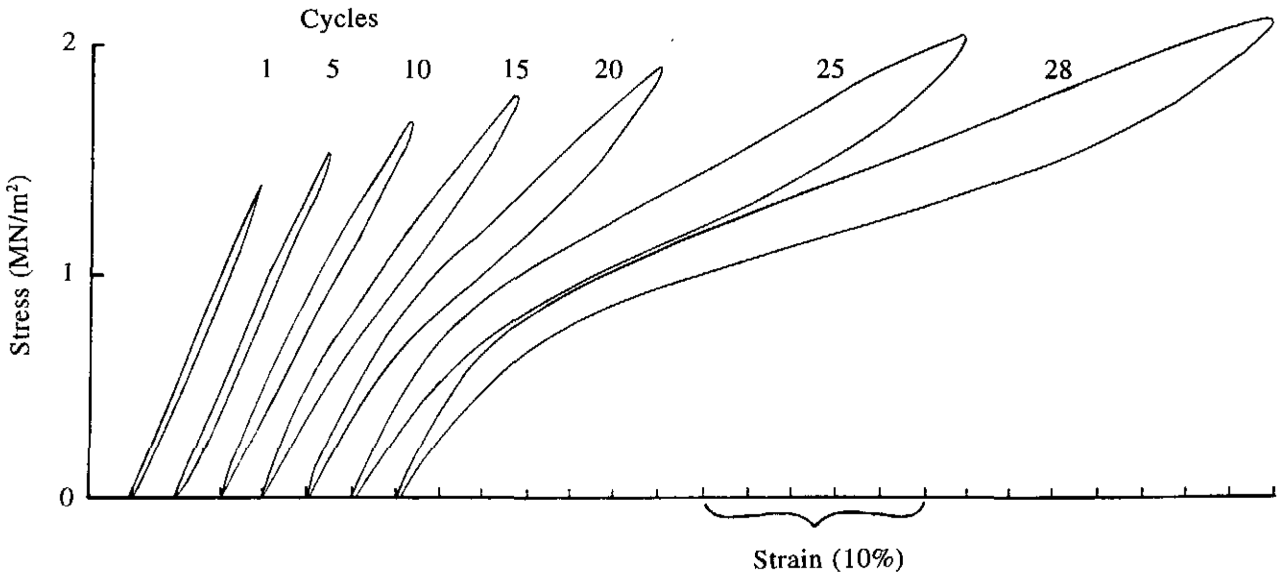

Figure 6. The stress-strain behaviour of a natural rubber vulcanisate (Compound 2) *repeatedly cycled twenty-eight times with an incremental increase in the maximum stress per cycle of 0.025 MN/m². No cavitation damage is present despite the testpiece being subjected to a higher stress (2.1 MN/m²) than that of the initial cavitation stress (1.6 MN/m²) for a single cycle as shown in* Figure 4.

of cavitation were detected, by load fluctuations, just prior to the point of maximum stress on the second and occasionally the third cycle. No further cavitation was detected during the fourth and subsequent cycles.

Cavitation studies have also been conducted on the same vulcanisate subjected to an incremental increase in the maximum stress per cycle. The results of such a test is shown in *Figure 3* for a stress increment of 0.025 MN/m^2 (50 N load) over 15 cycles. It can be seen that cavitation tends to occur on most of the cycles up to a maximum cavitation stress (MACS) of 1.17 MN/m^2 (the eighth cycle), with no cavitation detectable on subseqüent cycles. The amount of cavitation per cycle does not appear to remain constant but tends to be greatest at a particular value of stress (some 1.1 MN/m^2 for *Compound 1*), with progressively less cavitation occurring in the region of the minimum and maximum cavitation stress. The value of the MACS does, however, appear to depend on the number of cycles applied to the vulcanisate. Such behaviour is indicated by comparing *Figure 3* with *Figure 4* where cavitation occurs during the first five cycles only and produces a MACS value of 1.38 MN/m^2.

Figure 5 shows the results of a natural rubber vulcanisate containing carbon black filler *(Compound 2)* repeatedly pulled for 10 cycles to a maximum stress of 2 MN/m^2. Cavitation only propagates during the first cycle. The vulcanisate has a MICS value of 1.6 MN/m^2 and continues to cavitate up to the maximum applied stress. *Figure 6* shows the behaviour of the same compound over 28 cycles with an increase in the maximum stress per cycle (0.025 MN/m^2). The first cycle has a maximum stress (1.4 MN/m^2) a little below that of the MICS value (1.6 MN/m^2). No cavitation was detected on any of the cycles or observed after subsequent sectioning and microscopic examination. Some results of similar tests for each vulcanisate subjected to various loading schedules are given in *Table 2*. Where cavitation was prevented by repeated loading the test pieces were subjected to a stress at least 50% greater than the MICS value and in some cases almost to catastrophic failure.

DISCUSSION

Cavities consist of an initial nucleation site with crack growth occurring through the rubber which emanates from this site. When a cavity develops, cracks typically propagate rapidly around the nucleation site and then stop. A succession of such cavity formations and associated crack growth produces multiple sharp falls in the stress-strain behaviour of a test piece such as those seen on the first cycle in *Figure 2*. Such stress-strain deviations may be used as unambiguous indicators of internal rubber cracking. The presence of internal cracking in the rubber is referred to here as cavitation damage. Examination of sectioned test pieces indicates that the number of sharp falls observed in a stress-strain plot approximately corresponds to the number of cavities present. Where no such stress-strain deviations were measured no cavities were observed under microscopic examination.

This investigation of cavitation behaviour indicates that a cavitation stress band is present for each vulcanisate. The amount of cavitation damage occurring within each stress band is not constant. The maximum amount of cavitation damage tends to occur at a value of stress which is approximately half way between that of the minimum and maximum cavitation stress value. Cavitation damage tends to become progressively less as the lower and upper cavitation stress limits are approached. For a particular vulcanisate, the cavitation stress limits are not necessarily constant, but may be altered depending upon the cycle

TABLE 2. CAVITATION STRESS BANDS FOR THREE NR VULCANISATES SUBJECTED TO DIFFERENT TENSILE LOADING SCHEDULES

Vulc. no.	Shape factor	Maximum stress (1st cycle) MN/m²	Incremental stress per cycle	No. of cycles < MICS	Minimum cavitation stress (MICS) MN/m²	Maximum cavitation stress (MICS) MN/m²
1	2.5	1.25	Constant	None	0.97	–
1	2.5	To failure	–	None	0.94	1.40
1	2.5	1.0	+0.1	None	0.94	1.38
1	2.5	1.0	+0.5	None	0.95	1.25
1	2.5	1.0	+.025	None	0.93	1.17
1	2.5	0.8	+.05	3	0.95	1.10
1	2.5	0.8	+.025	5	0.93	1.07
1	2.5	0.8	+.01	17	0.97	1.05
1	2.5	0.8	+.002	25	0.85	0.85
1	2.5	0.8	+.0005	100	None	None
2	2.5	To failure	–	None	1.6	1.8
2	2.5	1.2	+0.1	5	1.7	1.8
2	2.5	1.2	+.05	10	1.7	1.7
2	2.5	1.2	+.025	20	None	None
2	5	To failure	–	None	1.8	2.4
2	5	1.4	+0.1	4	1.8	2.3
2	5	1.4	+.05	12	2.0	2.2
2	5	1.4	+.025	28	2.1	2.2
2	5	1.4	+.01	70	None	None
3	2.5	3.2	Constant	None	2.6	3.2
3	2.5	2.5	+0.1	1	None	None
3	2.5	2.5	+.025	4	None	None

loading schedule, or amount of work, applied to the vulcanisate. With sufficient cyclic loadings, initially at a stress below that of the minimum cavitation stress, cavitation damage can be completely prevented as illustrated by comparing *Figures 5* and *6*. The number of such loading cycles required to prevent cavitation damage tends to vary depending upon the type of vulcanisate. A natural rubber vulcanisate containing no carbon black filler requires a greater number of cyclic loadings to prevent cavitation than a vulcanisate containing carbon black filler (see *Table 2*). A greater quantity of carbon black filler tends to reduce the number of cycles required to prevent cavitation.

The phenomenon of cavitation would appear to be associated with the long chain molecular network structure in natural rubber. The action of repeatedly loading the rubber in the manner described here appears to be capable of producing a sufficiently progressive rearrangement of the molecular network to reduce or prevent cavitation. Repeated loading may allow chain entanglements to move or slip and crosslinks to break and recombine such that local stress concentrations are reduced in a progressive manner within the heterogeneous rubber network tending to form a more homogeneously stressed structure thus reducing the risk of cavitation.

The observation that cavitation damage can be prevented with sufficient cyclic loadings applied below the MICS value is of particular interest where components may be repeatedly highly stressed for a small number of cycles. One such condition is found in rubber seismic isolation bearings which may typically experience a small number of large shear deformations in the event of an earthquake. The rubber in a seismic bearing can experience sufficient negative hydrostatic stresses, due to tilting of the reinforcing layers, to produce cavitation failure. The presence of cavitation damage in such a component can, therefore, be influenced by the cyclic loading history of the bearing. Sufficient repeated shear deformations, or scragging, of a bearing to a little less than the MICS value prior to installation should reduce or prevent cavitation damage. Since the majority of seismic compounds contain substantial quantities of carbon black filler the number of deformations, or scragging cycles required to prevent cavitation is likely to be quite small (see *Table 2*). If a seismic bearing should experience a small number of shear deformations, less than the MICS value, in service in the event of an earthquake as could occur in minor tremours just before say a peak tremor such a condition would also be expected to be beneficial in reducing the risk of cavitation damage.

CONCLUSION

Repeated loading can alter the cavitation failure stress when compared to that of a single loading. An increase in the number of loadings applied to a vulcanisate, initially at a lower stress than that of the cavitation stress, tends to reduce the amount of cavitation damage present. A sufficient number of such loadings can completely prevent cavitation damage.

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