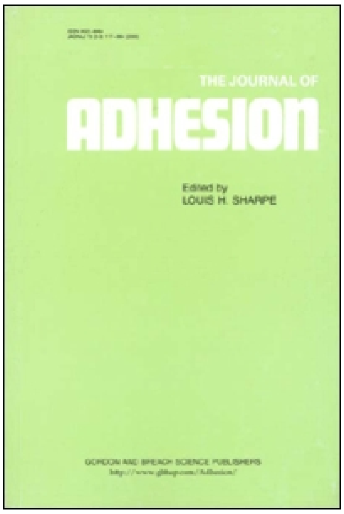

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Fatigue Failure of Rubber-to-Rubber Joints

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This paper presents an experimental investigation on fatigue failure of rubber-to-rubber similar and dissimilar joints made from natural rubber and EPDM. The effects of interlinking density, relative proportion of one matrix in the two-component joints, filler loading in the filled part of the joint and strain level on the fatigue life have been studied. Adhesion (peel strength) between similar and dissimilar rubber-to-rubber joints has also been investigated to attempt to determine a correlation between adhesion and fatigue failure.

KEY WORDS fatigue; fracture; rubber-to-rubber joints; adhesion; natural rubber; EPDM; peel strength.

INTRODUCTION

Rubber based composites are gaining increasing importance in a large number of applications. Thus, study of interfacial bond strength of such composites under both static and dynamic conditions is essential for maintaining acceptable product performance. So far, most investigations were carried out on rubber-to-metal or rubber-to-fabric composites due to their ease of fabrication. A few references are available on rubber-to-rubber joints. This is primarily due to lack of proper test methods, especially those employing dynamic test conditions. Our previous publications[1–2] described methods of measurement of adhesion and fatigue resistance of joints. Under static conditions, a modified peel test using a separator or perforator at the interface was used. Under dynamic conditions, a new test procedure was described to predict the fracture nucleation site(s) and the effect of joint angle on fatigue life (N) of the rubber-rubber, two-component specimens. We have also calculated the stresses, strain energy densities and stress distributions across the bondline of rubber-rubber joints by numerical method of finite element analysis (FEA) based on geometric and material non-linear mechanics and, finally, correlated the FEA data with the experimental photoelasticity and fringe patterns by generating a computer model in a graphics terminal.[3–5] However, there are still

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several unanswered questions in the previous publications; namely, the effect of interlinking density, filler loading, relative proportion of one component in a bi-rubber part, and strain level, on the fatigue life of rubber-rubber two-component joints. This paper attempts to quantify these aspects. These studies are important in the case of various rubber products such as tyres, belts, mounts, etc.

Gent, Lindley and Thomas[6] studied the cut-growth and fatigue behaviour of different rubbers and established a fundamental relationship between the cut-growth and the fatigue life of individual rubber matrices. For a tensile dumbell with a crack of length, c_o, and strain energy density, W, the number of cycles, (N), for a crack to grow from c_o to c is given by,

$$N=\frac{B}{(n-1)(2kW)^n}\left[\frac{1}{c_o^{n-1}}-\frac{1}{c^{n-1}}\right] \tag{1}$$

where B and n are the empirical constants and k is a function of the extension ratio. If the crack grows to many times its original length, the equation may be approximated to

$$N=\frac{B}{(n-1)(2kW)^n}\left[\frac{1}{c_o^{n-1}}\right] \tag{2}$$

This indicates that the fatigue life is decreased with an increase in W or c_o. Lake and Lindley[7-9] and Lindley and Thomas[10] studied the mechanical fatigue limit for both crystallizing natural rubber and non-crystallizing SBR. The fatigue failure of rubber and rubber blends has been reported earlier from this laboratory.[11-12]

EXPERIMENTAL

The compositions of various mixes based on NR and EPDM rubbers are given in Table I. Compounding and vulcanization were done following the usual procedure. The mechanical properties of both individual and two-component specimens were measured in a Zwick UTM 1445 as per ASTM D412-80.

Fabrication of the Fatigue Test Specimen

The rubber-rubber, two-component specimens were prepared in two stages. Compositions were so chosen that a relatively delayed acceleration effect was obtained. In the first stage of preparation, a thin, uniform, uncured sheet was prepared by pressing the rubber sheet under light pressure (2MPa) at a temperature of approximately 100°C between aluminium foils. The aluminium foils were then removed and the specimen was cut to the desired shape by a sharp cutting device. Two such sheets of uniform thickness (which may differ in their physical properties) were then joined and vulcanization was completed under controlled pressure (5MPa), temperature (150°C) and at the optimum cure time of the gum compound.

Fatigue to Failure Test

Fatigue-to-failure tests were carried out on thin strips of single rubber and on rubber-rubber joints normally 12 mm wide, approximately 1.5 mm thick and of

TABLE I
Formulations and characterization of the mixes

Ingredients	I	II	III	IV
NR(RMA-1X)	100	100	—	—
Mitsui EPT-3045	—	—	100	100
ZnO	5	5	5	5
Stearic Acid	2.5	2.5	1	1
N-330(HAF)	—	40	—	40
CBS[a]	0.6	0.6	—	—
TMTD[b]	—	—	1.5	1.5
MBT[c]	—	—	1.0	1.0
ZDEC[d]	—	—	0.6	0.6
Sulfur	2.5	2.5	1.5	1.5
RESULTS				
Scorch Time, min.	4.5	3.0	3.7	3.0
Optimum cure time, min.	14	12.7	14.7	12.5
Modulus at 300% elongation, MPa	2.4	9.6	1.01	4.6
Elongation at break, %	1050	660	320	670
Tensile strength, MPa	21.3	26.7	1.4	18.4
Hardness, Shore A	33	58	47	64

[a] CBS: Cyclohexyl Benzothiazyl Sulphenamide.
[b] TMTD: Tetramethyl Thiauram Disulfide.
[c] MBT: Mercaptobenzthiazole.
[d] ZDEC: Zinc Diethylditiocarbamate.

length of almost six times the width. The dimensions of the test specimen are shown in Figure 1(a). The test piece was then deformed in simple tension by repeated cycling in a fixed maximum extended length. The tests were carried out at a frequency of 10 cycles/minute with the test pieces being relaxed to zero stress in each cycle. The strain energy per unit volume of the bi-rubber part test specimen

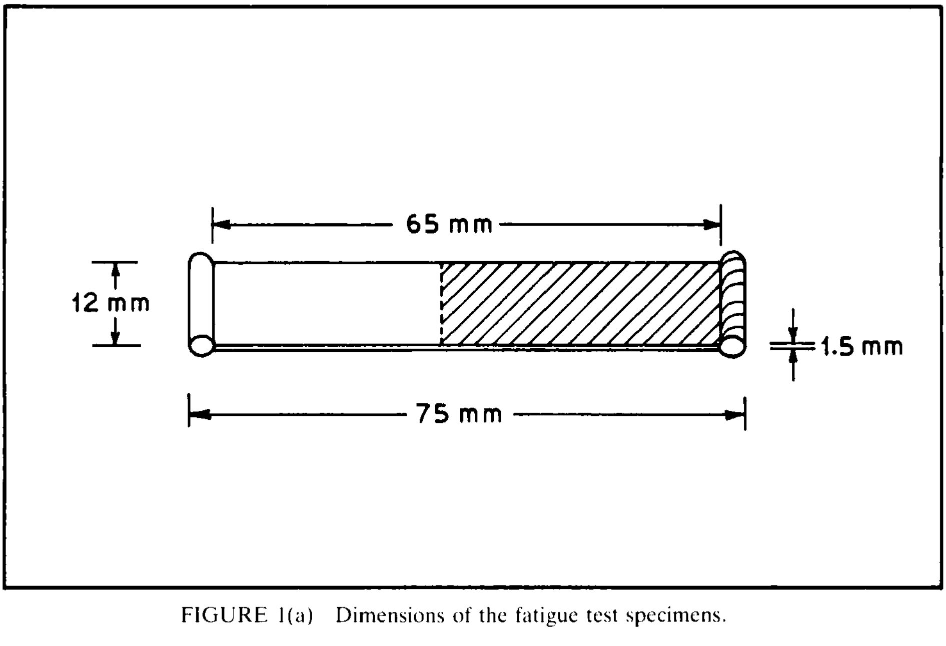

FIGURE 1(a) Dimensions of the fatigue test specimens.

was determined as a function of strain by numerical integration of the area under the stress-strain curve. Engineering stress and strain were measured, *i.e.* the stress was measured as the load divided by the original cross-sectional area and the strain as the increase in gauge length divided by the original gauge length. The volume fraction of the filled matrix in the rubber-rubber, two-component specimens was also varied as shown in Figure 1(b) in the lengthwise direction.

Sample Preparation and Determination of Peel Strength

For determination of peel strength, sheets of approximately 3 mm thickness were prepared in an electrically heated hydraulic press. One side of the sheet was backed by cloth. Sheeting was done at 100°C between smooth aluminium foils. The aluminium foils were then carefully removed and the strips were allowed to come in contact. In between these two smooth similar and dissimilar elastomeric sheets a

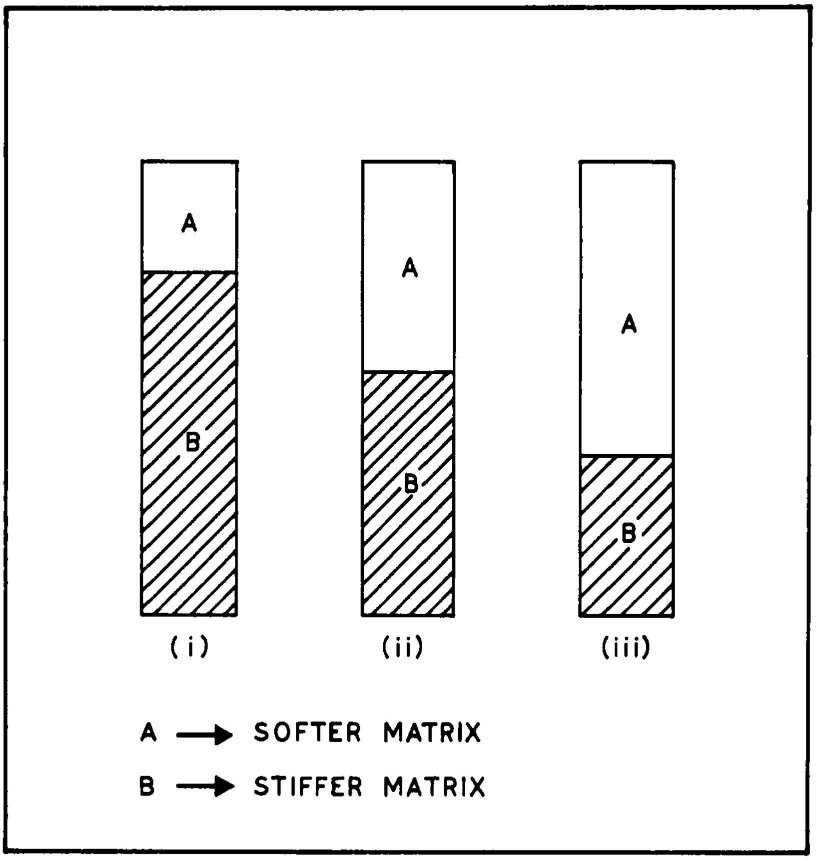

FIGURE 1(b) Specimens with different proportions of gum and filled rubbers. A—Gum rubber portion; B—Carbon black filled portion perforator sheet of thickness 0.3 mm was placed.[13] The force of separation of the two strips was measured in a Zwick machine (UTM 1445) using a T-peel geometry (Fig. 1c).

$$G_a = \frac{2F}{w - w'}$$

where, G_a = Fracture energy per unit area
F = Average force required for peeling
$w - w'$ = Effective width of the strip.[13]

Interlinking Density Concept

Different types of joints were prepared consisting of a fully crosslinked sheet of one elastomer bonded to an uncrosslinked sheet of either the same or a dissimilar rubber by joining them together and completing the crosslinking process. The crosslinking

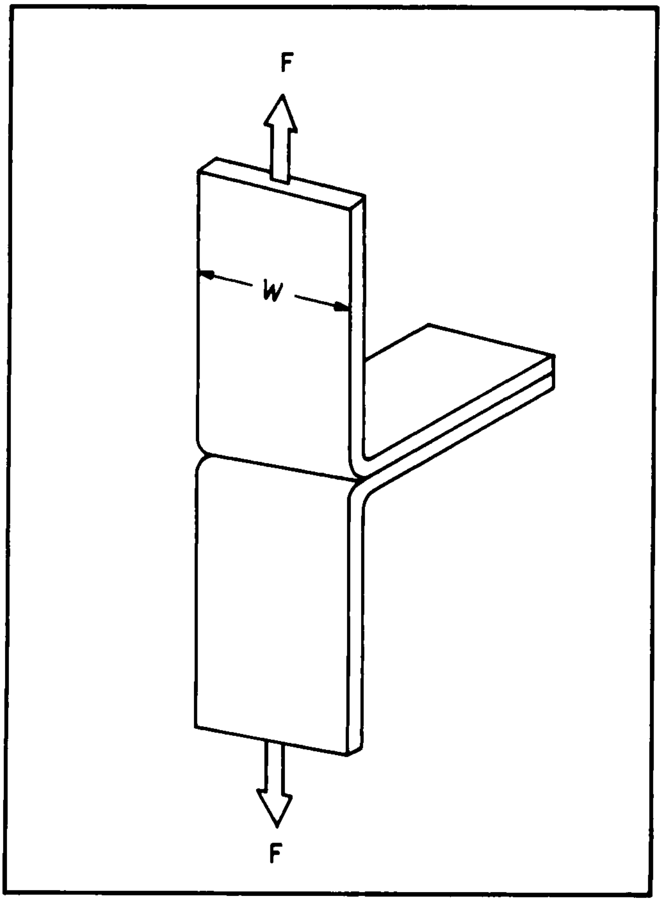

FIGURE 1(c) Measurement of 180° peel strength.

density, in terms of volume fraction of rubber for each sheet, was calculated by measuring the equilibrium degree of swelling in benzene following the same procedure as discussed elsewhere.[14] The interlinking density (ΔV_r) was calculated from the difference in the volume fraction of rubber.

RESULTS AND DISCUSSION

Effect of Degree of Interfacial Linking

The effect of degree of interfacial linking on the fatigue life of the bi-rubber parts is given in Figure 2. Interfacial linking is varied by varying the partial cure time[15] and also the amount of crosslinking agent, and assessed by the difference in the volume fraction of rubber in the two substrates. As the partial cure time or the amount of crosslinking agent used increases, the volume fraction of rubber increases. When two such sheets are joined, the interfacial linking decreases with the increase in partial cure time (Table II). In all cases, the fatigue life decreases with the decrease in interfacial linking. The decrease is very sharp for strong joints of natural rubber. EPDM/EPDM shows a low initial value because of the lower strength of EPDM and the dependence of failure life on interlinking density is less. The NR/EPDM joint shows still poorer fatigue life. The reduction in fatigue life may be explained as being due to increase in strain energy density of the samples and is predominantly due to the weak interface that acts as a crack in the samples. This is shown in equation (1). The strain energy density calculated from the area under the stress-strain curve decreases when the interlinking density is reduced due to lower dissipation of the supplied energy. This is again due to poor interdiffusion and adhesion in this system as explained below. Since the fracture of such joints starts from the weak interface, the crack after initiation faces little resistance toward propagation across the interface as the substrates continuously debond under lower forces.

In order to understand the interaction, the peel strength of various joints was determined. The results are reported in Figure 3. As usual, the peel strength increases as the interfacial linking increases. Interestingly, EPDM/EPDM joints show higher peel strength than NR/EPDM joints because of difference in cure rate of the latter two rubbers and also because of the difference in interdiffusion in these dissimilar rubbers. In order to suppress the interdiffusion effect on adhesion, a few joint samples were swollen in benzene and their peel strengths were also measured. The values of the work of detachment for swollen samples are found to be 100 times less than those of unswollen samples. Gent *et al.*[16] observed a similar dependence of peel strength on the degree of interlinking density under threshold conditions. Fatigue studies of swollen samples could not be performed under these conditions as these samples are very weak and break even under low forces. Hence, it is difficult to establish a relation between fatigue life and interfacial linking under conditions where dissipative processes are minimized. It is interesting to note that though the peel strength increases linearly with interlinking for all systems, the fatigue life does not. This indicates that there are other, complicating, factors involved in the fatigue process which must be considered for fatigue life prediction.

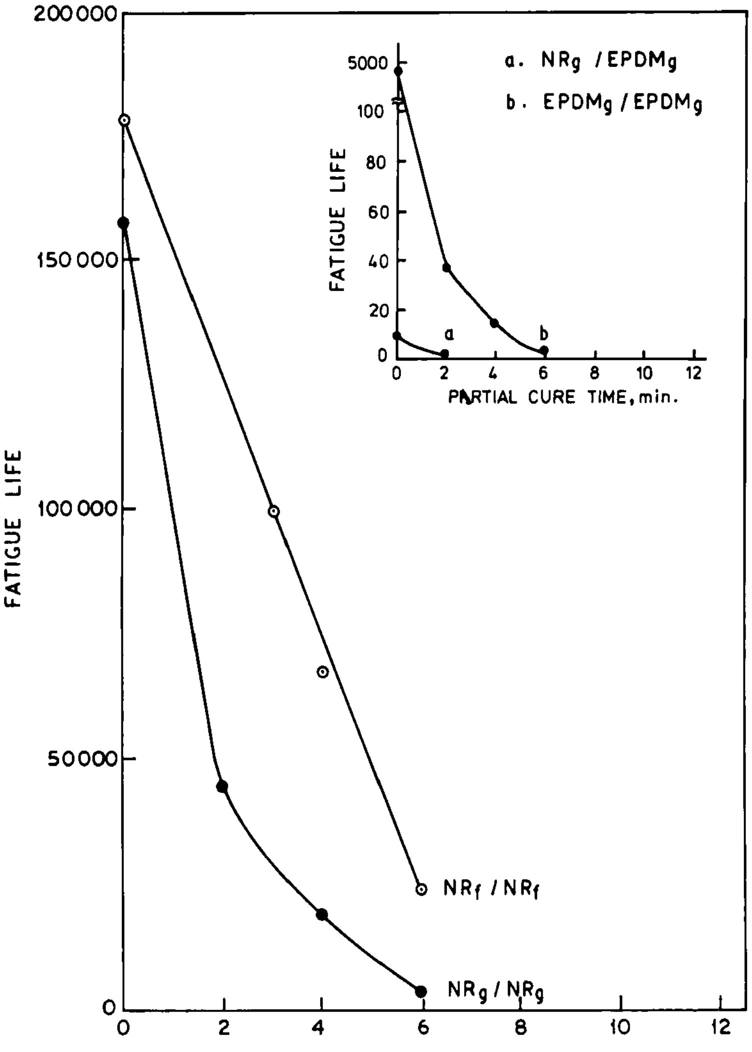

FIGURE 2 Effect of interfacial linking on the fatigue life of bi-rubber part joints. g—Gum rubber; f—Filled rubber

TABLE II
Interfacial linking between the rubber phases at various partial cure times

NR_g/NR_g		NR_f/NR_f		$NR_g/EPDM_g$		$EPDM_g/EPDM_g$	
Partial cure time (min)	ΔV_r	Partial cure time (min)	ΔV_r	Partial cure time (min)	ΔV_r	Partial cure time (min)	ΔV_r
2	0.209	2	0.219	2	0.175	2	0.206
4	0.141	4	0.149	4	0.107	4	0.115
6	0.066	6	0.059	6	0.032	6	0.056
8	0.021	8	0.027	8	—	8	0.029

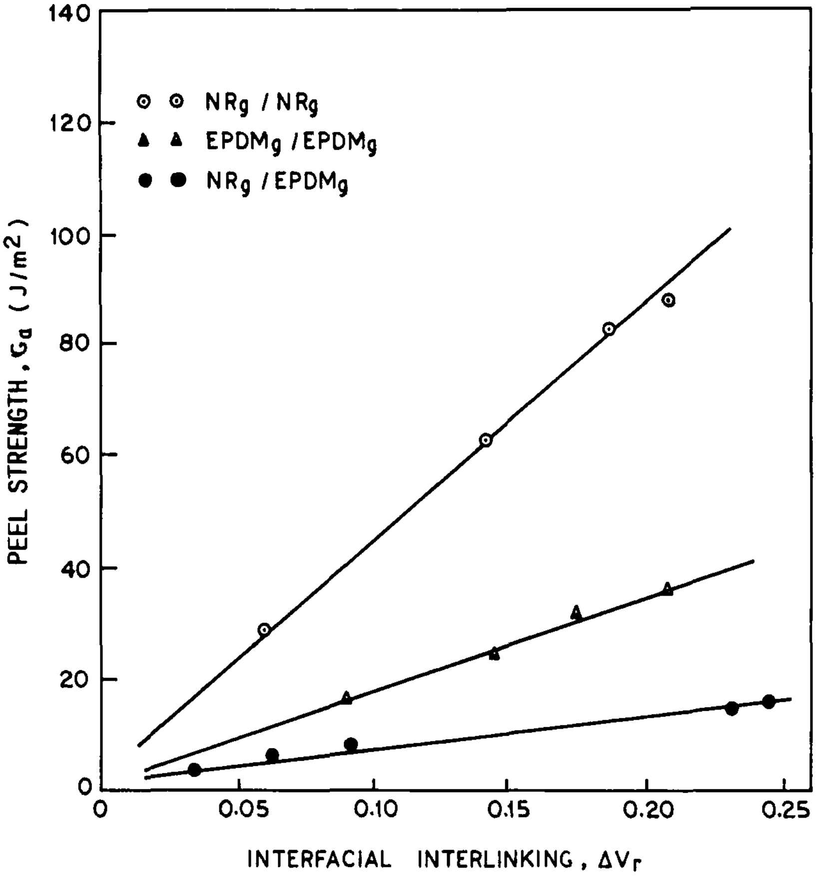

FIGURE 3 Plot of peel strength against the interfacial linking.

Effect of Volume Fraction of Filled Matrix in the Bi-rubber Specimen

The volume fraction of the filled portion in the total bi-rubber specimen was varied in the lengthwise direction as shown in Figure 1(b) in order to understand the effect of strain energy density. The results are plotted in Figure 4(a). It is interesting to note that as the filled portion in the total two-component specimen increases, the fatigue-to-failure of the bi-rubber part decreases progressively at any particular strain level (in this case 100% elongation is considered). This lower fatigue life of bi-rubber specimens having a higher filler content is attributed to higher stress generation at the same strain level at the interface (as calculated by FEM),[3] which is also clear from the stress-strain curve of these two component specimens as shown in Figure 4(b). Another interesting feature is that the failure initiation site in all cases is near the interfacial zone and near the edge of the joint, but ultimately propagation of the crack proceeds through the weaker gum matrix because of the lack of constraint ahead of the crack tip in the gum matrix. The strain energy per unit volume for each proportion of the bi-rubber specimen is plotted in the same

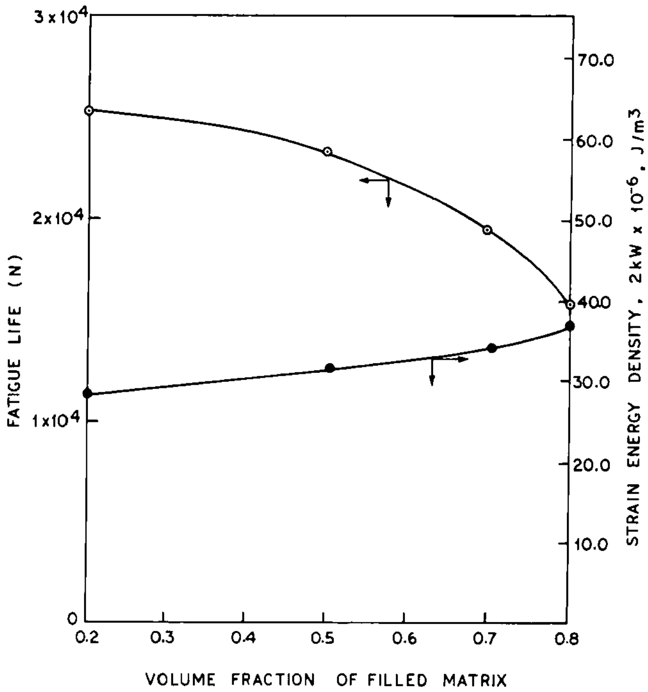

FIGURE 4(a) Plot of fatigue life against the volume fraction of filled matrix in the two-component joints.

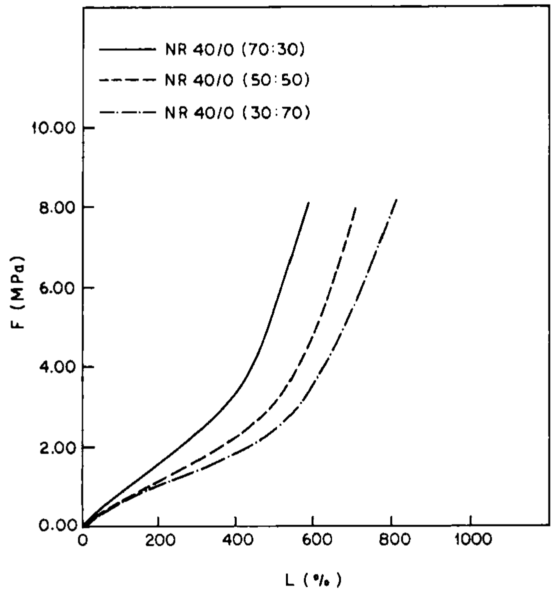

FIGURE 4(b) Stress-strain plot of two-component joints having different volume fraction of filled matrix.

——— NR filled 70%; NR gum 30% (by volume)

——— NR filled 50%; NR gum 50% (by volume)

——— NR filled 30%; NR gum 70% (by volume) figure [Figure 4(a)]. The value decreases gradually with the increase in filler content (by volume) in the two-component specimen at 100% elongation. An inverse relationship between fatigue life and strain energy density was established for single (filled and unfilled) rubbers[17–18] (equation 1). Following a similar approach, a value of $n \simeq 1.5$ has been found for $NR_{gum} - NR_{filled}$ two-component joints.

Effect of Filler Loading in the Filled Portion of the Bi-rubber Specimen

The increase in filler loading in the filled portion of the rubber-rubber joints increases the magnitude of the difference in modulus between the two phases at the interface and also may affect adhesion. The fatigue life for these specimens is plotted against the filler loading as shown in Figure 5. It is noticed that as the filler loading

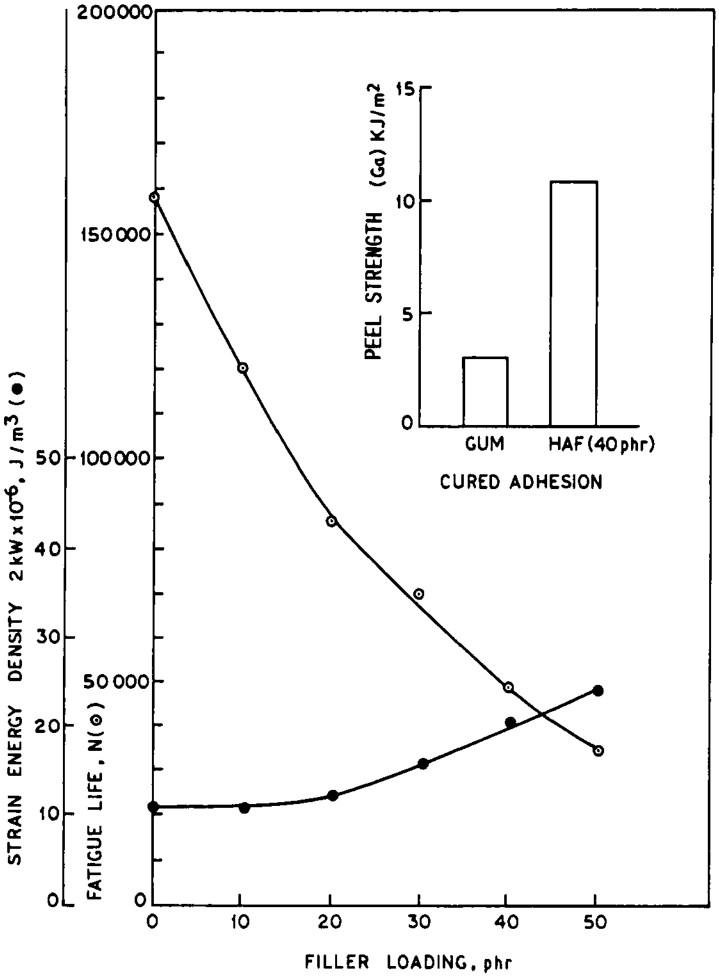

FIGURE 5 Plot of strain energy density and fatigue life against filler loading in the two-component joints.

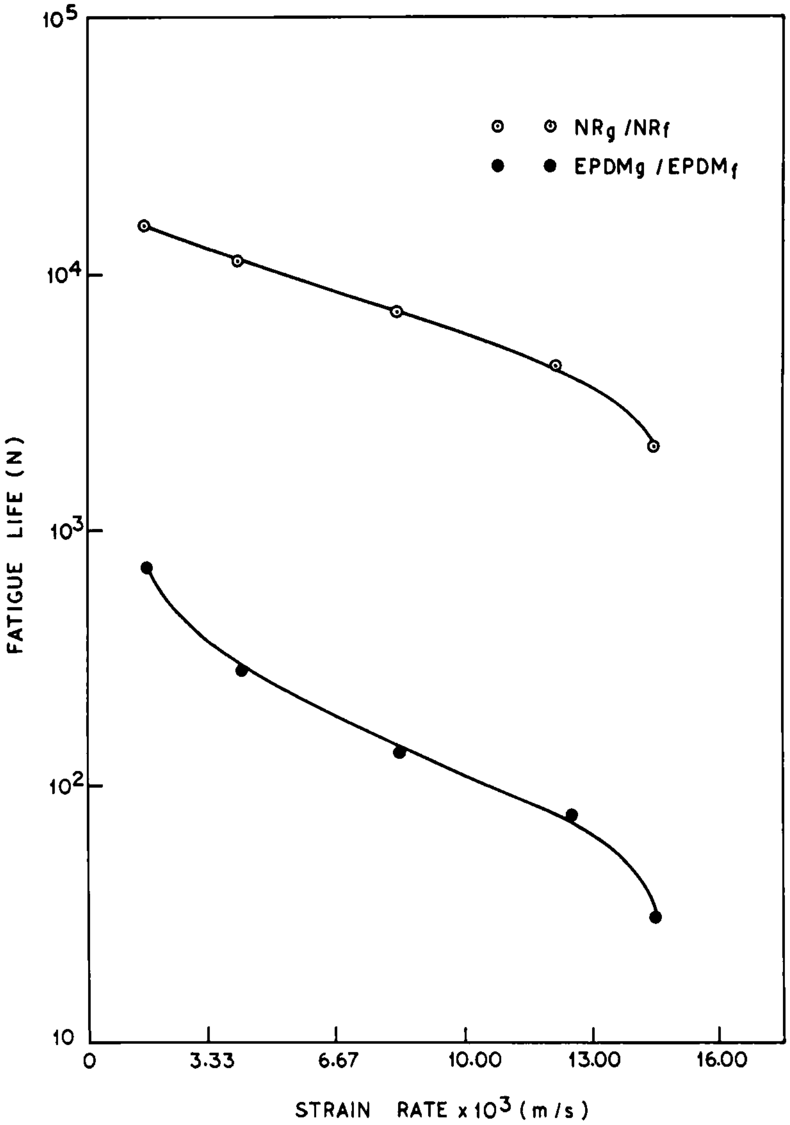

FIGURE 6 Plot of fatigue life (N) against the strain rate of different two-component joints. g—Gum rubber; f—Filled rubber

in the filled portion of the two-component specimen increases, the increasing difference in modulus value reduces the fatigue life. This may be due to higher stress concentration near the interface and higher strain energy density at that elongation. The theoretical calculation based on finite element analysis (FEA),[3-4] and the experimental findings from photoelastic experiments,[5] substantiate the hypothesis of higher stress concentration site(s) near the interface.

On the other hand, when the peel strengths are measured between the elastomers studied, there is a many-fold increase in peel strength in the carbon black loaded sample as compared with the gum rubber-to-gum rubber joints. The results are shown in the same figure (Figure 5). The higher strength of the filled rubber matrix at, or in the vicinity of, the interface is achieved due to higher rubber-filler interaction and reinforcement. The same observation was made for fatigue strength of filled NR rubber-to-filled NR rubber joints. The higher peel strength seems to be offset by the higher strain energy density, resulting in lower fatigue life.

Effect of Strain Rate

The fatigue life of rubber-rubber joints is plotted against the various strain rates of testing as shown in Figure 6. It is observed that the higher the strain rate, the shorter is the fatigue life of all types of two-component specimens. This may be due to greater degree of stress accumulation at the interface at the higher strain level and higher energy input. However, the magnitude depends upon the type of material joined and its strength property. The natural rubber gum and filled bi-rubber specimen shows much higher fatigue resistance than the EPDM gum-filled, two-component specimen. On the other hand, the bi-rubber specimen of NR gum and filled EPDM or vice-versa shows a very poor fatigue life as compared with their individual gum and filled specimens. This may be due to poor interfacial interaction and poor properties of the boundary layer in the vicinity of the interface.

The effect of strain rate on peel strength, however, is different. For example, in the case of EPDM-EPDM joints shown in Figure 7 it is observed that joint strength increases with the increase in rate of testing. High peel strength may be related to the low dissipation of energy at the interface at a high rate of testing. At the higher rate the coiled elastomer molecules do not have sufficient time to uncoil, and breaking of these coiled molecules needs a higher amount of energy and hence the peel strength is high. The opposite is true for a low rate of testing. Hence, there is no similarity in behaviour between fatigue resistance and peel strength in this case.

CONCLUSIONS

1. The decrease in interlinking density at or near the interface decreases the fatigue life and peel strength. Among the NR and EPDM similar and dissimilar joints, the NR-EPDM shows the lowest peel strength.

2. The higher the proportion of the filled matrix in the bi-rubber specimen, the shorter is the fatigue life of the joints.

3. The higher the filler loading (carbon black) in the filled portion of the gum-filled composite, the lower is the fatigue life of the composite.

4. The higher the strain rate, the shorter is the fatigue life of the rubber-rubber joints studied here. On the other hand, the higher the strain rate, the higher is the peel strength of the joints.

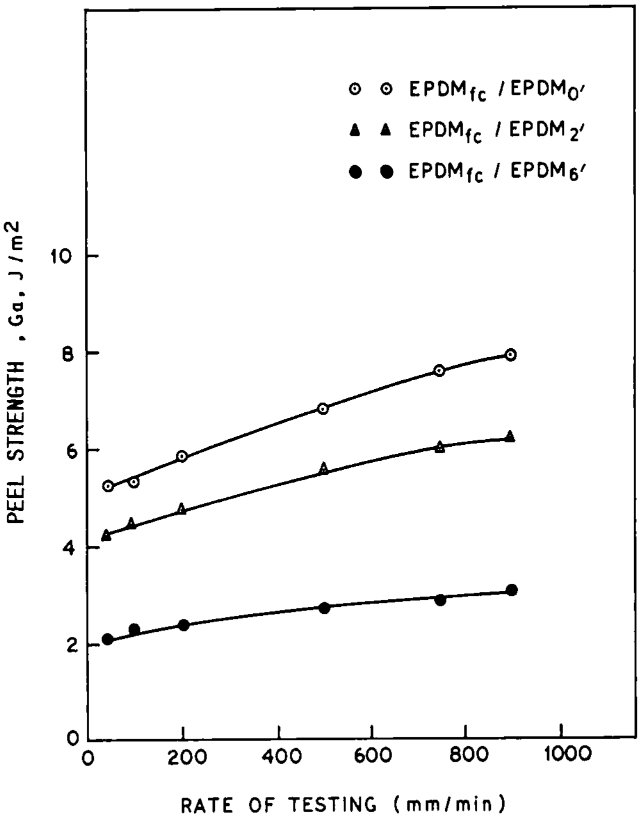

FIGURE 7 Plot of peel strength against the rate of peeling. fc—Fully cured; 0', 2', 6'—Partial cure time

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