J. Rubb. Res., **7(2)**, 115–126

Cyclic Crack Growth Measurement Using Split-tear Test-piece

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A cyclic crack growth machine using the split-tear test-piece was developed to avoid forking at the tip of the tear normally encountered with the conventional test-pieces especially those prepared from black-filled vulcanisates A small strain was applied in simple extension and cyclic stressing was applied in the transverse direction so that the crack grew in the direction of the applied strain. The experimental results agreed with those results published by Lake et al. *when cyclic crack growth rate (dc/dN) was plotted against tearing energy. Thus the experimental results provided further experimental evidence that tearing energy was a measure of true crack growth resistance independent of test-piece geometry. It was found also that there was no problem of forking for both unfilled and black-filled vulcanisates. By applying different strains, the effect of anisotropy was investigated. It was found that the tearing energy decreased as the applied strain was increased.*

Key words: cyclic; crack growth; split; tear; test-piece; strain; resistance; unfilled; black-filled; vulcanisates; anisotropy

Rubber products like tyres, rubber mountings and v-belts are susceptible to failure associated with crack growth under cyclic or repeated stressing. Small-scale crack growth can occur in rubbers, as in other materials, at energies below those required for catastrophic tearing. The crack growth resistance of the rubber products plays an important role in determining their service life. High crack growth resistance is desired to minimise premature failure associated with dynamic induced cracking, thus it will prolong the service life of the rubber. In view of its practical importance, intensive research on crack growth resistance of vulcanised rubber has been conducted in the fifties and sixties[1–3]. This area of work is still receiving close attention even to date with the aid of finite element analysis[4,5].

The most common test-pieces either to determine the tearing energy or the crack growth resistance of the vulcanised rubber are trouser tear, pure shear, parallel strips with an edge cut and angled type as shown in *Figure 1*. The tearing energy theory developed by Rivlin and Thomas[6] has been used successfully in various types of fracture of rubber-like materials such as tearing, fatigue, abrasion, cutting by sharp object and cyclic crack growth. Thus tearing energy gives a true measure of the strength of the rubber and independent of the test-piece geometry.

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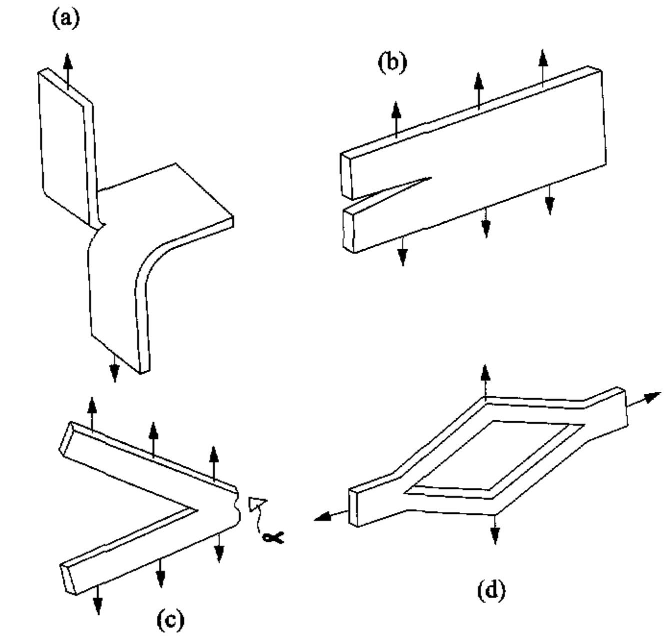
In conventional tearing measurement, the magnitude of tearing energy is not only affected by the rate and temperature of the test, but also by the types of failure namely steady (smooth), stick-slip and knotty tearing [9] In steady tearing, the crack grows along the intended path with little fluctuations of the tearing force against rate In contrast, with the stick-slip tearing, the tear does not propagate continuously, but rather arrests and reinitiates at fairly regular intervals Thus this would result in more pronounced fluctuations of the tearing force with the rate of propagation In the case of knotty tearing, the crack also does not propagate continuously but tends to deviate sideways almost at right angles to the intended path, and it requires higher tearing energy for the tear to propagate than that produced either by stick-slip tearing or steady tearing Almost all non-strain-crystallizing unfilled (gum) vulcanisates produce steady tear In contrast strain-crystallizing gum vulcanisates produce stick-slip tearing Knotty tear only occurs with filled vulcanisates containing reinforcing fillers, with the exception of natural rubber latex film which could also produce knotty tear[9]

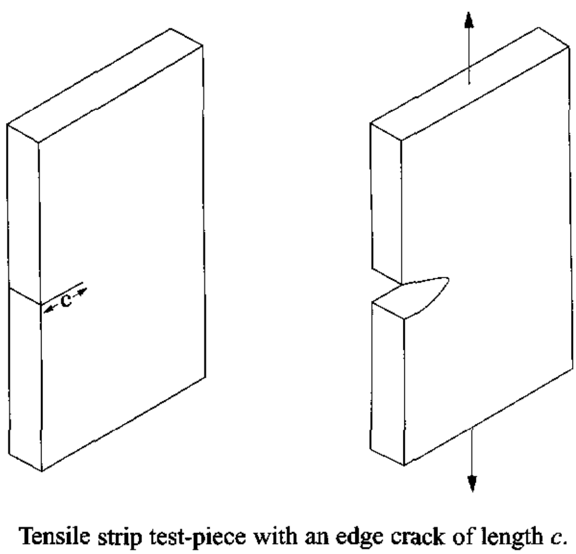
The occurrence of knotty tear is associated with the development of strength anisotropy around the tip of the tear[7,8] Azemi and Thomas[8] used the split tear test-piece to relate the anisotropy due to pre-straining with the tearing energy By giving different amounts of pre-straining on the split test-piece the effect of strength anisotropy on the development of knotty tear was investigated It was found that the energy to propagate a crack in the direction of pre-straining was substantially lower than that produced by the conventional trouser test-piece when knotty tear occurred Thus this result shows that when an advancing tear approaches the highly-oriented regions of local anisotropy around the tip of the tear, the tear splits along the direction of molecular orientation since the energy to propagate a tear in this direction is very low This is consistent with latest findings by Gent *et al*[4] who developed model cracks and used FEA to calculate the strain energy release rate to propagate tear both in the forward and sideways directions They found that a crack will turn or split sideways if the strength in that direction is about 40% less than that of the forward direction However, the phenomenon of forking or deviation of the crack tip from the intended tear path in cyclic crack growth has not been investigated as far as the authors are aware At first sight, the phenomenon of forking of the crack tip in cyclic crack growth could well be the same phenomenon as that of knotty tearing in conventional tear measurement Like knotty tear, forking occurs in vulcanisates containing an appreciable amount of reinforcing fillers When forking occurs at the crack tip, interpretation of the results is made difficult since the initial single crack tip branches into two or three new tips In order to circumvent this problem, split tear test-piece is preferred to other test-pieces Split-tear test piece as shown in *Figure 2* was originally introduced by Thomas[10] and later used by Azemi[8] to investigate the effect of strength anisotropy on the development of knotty tear

As far as the authors are aware, crack growth studies using split tear test-piece have not been published before Crack growth measurements using the split tear test-piece, provide further experimental evidence that tearing energy is a measure of true crack growth resistance independent of test-piece geometries Split-tear test-piece has a few advantages over other test-pieces, such as

- It reduces the problems of forking as experienced with other common test-pieces such as parallel tensile strip, pure shear and trouser-tear



Crack growth test pieces for which T can readily be calculated:
(a) 'trousers'; (b) 'pure shear'; (c) 'angled' and (d) 'split'.



Tensile strip test-piece with an edge crack of length c.

Figure 1. Types of test-piece geometries.

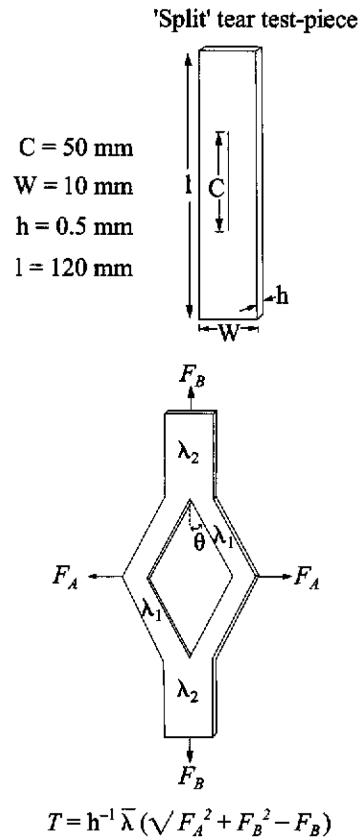


Figure 2. Schematic diagram of a split-tear test-piece.

- It can relate crack-growth propagation rate to the anisotropy introduced at different strain levels.

A prototype split-tear cyclic crack growth machine was developed to study the cyclic crack growth of both unfilled and black-filled vulcanisates. The main intention of this work is to see the suitability of split-tear test-piece to be used in cyclic crack-growth measurement, although it has been used successfully for the conventional tear test. The working principle of the machine will be discussed in the experimental part below.

EXPERIMENTAL

Gum and black-filled vulcanisates were prepared using mix formulations shown in *Table 1*.

Cure characteristics for gum and black-filled compounds were determined by using an oscillating disc Monsanto Rheometer MDR 2000 The results are given in the *Table 2*

Cyclic Crack Growth

The cyclic crack growth machine using the split-tear test-piece is as shown in *Figure 3* below The split-tear test-piece was prepared by stamping a die on a thin flat sheet of vulcanised rubber of uniform thickness The complete dimensions of the test-piece are given in *Figure 2* above The test-piece is clamped by a grip, and a dead load F_B is applied to the other end of the test-piece *via* a frictionless pulley, so that it is in a state of simple extension A dead load, F_4 which is attached to a straight cylindrical iron rod is applied on each side of the test-piece *via* a frictionless pulley in the transverse direction to F_B The total load, F_A is the sum of the dead load and the weight of the cylindrical rod The rod carrying the load F_A is designed to travel through a tubular (hollow) tube during motion to avoid the load from swinging This tubular tube is fitted with roller balls to minimise friction between the rod and the wall of the tube Each rod is attached to a horizontal bar driven by an electric motor *via* a

TABLE 1 FORMULATIONS FOR GUM AND FILLED COMPOUNDS

Ingredients	Gum	Filled
Natural Rubber[a]	100	100
Zinc Oxide	5	5
Stearic Acid	2	2
ISAF[b]	–	50
Aromatic Oil	–	4
6PPD[c]	2	2
Sulphur	2 5	2 5
CBS[a,d]	0 5	0 5

[a] SMR 5
[b] Carbon Black of N220 grade
[c] N-(1,3-dimethylbutyl)-N-phenyl-*p*-phenylenediamine
[d] N-cyclohexyl-2-benzothiazole sulphenamide

TABLE 2 CURING CHARACTERISTICS

	Gum	Filled
Rheological @ 150°C		
ML (lb)	0 96	2 66
MH (lb)	7 00	15 81
TS(2) (min)	1 00	3 00
TC(90) (min)	11 00	11 00
TC(95) (min)	13 00	13 00

metal shaft. As the shaft reaches its highest vertical height, the bar pushes the load F_A upwards and closes the cut in the test-piece. As the shaft moves downwards, the cut will open up. The cut reaches its maximum opening when the shaft reaches its maximum downward displacement. At this point, the load F_A on each side is left hanging. Sufficient gap about 15 mm (after this is called "gap") is left between the load FA and the upper surface of the tubular tube to accommodate the increase in length as the crack grows during repeated stressing. The load F_A would rest on the surface of the tubular tube when the distance of the gap equals the amount of crack growth. No correction was taken for the kinetic motion as the load F_A moves through this short distance (gap).

The opening and closing of the cut contributes to cyclic crack growth. The crack will grow in the direction of F_B. The rate of opening and closing of the cut (its frequency) can be regulated by choosing the desired motor speed.

The crack length can be measured with an eye-piece lens scale after a certain number of cycles. It is necessary to plot crack length measured in the unstrained state, c_o, *versus* number of cycles, N, at each tearing energy value. From the slope of the straight line, crack-growth cycle (dc/dN) can be obtained as shown in *Figures 4a* and *4b*. The tearing energy for the split-tear test-piece can be computed using the equation[10] given below:

$$T = \lambda\ [(F_A^2 + F_B^2)^{1/2} - F_A] / t \qquad \dots 1$$

where λ = average extension ratio in simple extension regions A and B.
t = average nominal thickness of the test-piece
T = tearing energy.

By varying loads F_A and F_B, series of tearing energy values can be obtained from which a plot of tearing energy *versus* dc/dN can be produced.

In the development of this machine, constant load is preferred to constant strain as the variables since the latter is susceptible to stress-relaxation and the former is susceptible to creep. It is more convenient to measure the increase in length than to measure the decay in the load.

Cyclic crack-growth measurement was also conducted by using parallel strip test-piece containing an edge crack. A crack about 0.5 mm depth was introduced by a sharp razor blade. The stress-strain measurement was done on the sample (without any crack inserted) to determine the stored strain energy density by manual integration of the stress-strain curve. The test-piece was cycled to a maximum 50% strain and relaxed to zero strain by using the DeMattia crack growth machine. The rate of growth of dc/dN was approximated by $\Delta c/\Delta N$ where Δc is the change in cut length measured over an interval of ΔN cycles. The corresponding T value was taken as that at the average cut length in the interval N. The tearing energy T is given by the equation[3] below:

$$T = 2kcW \qquad \dots 2$$

where c is the crack length, k is a function of extension ratio and W is the stored energy density of the test-piece without any crack inserted.

RESULTS AND DISCUSSIONS

It is very appropriate to discuss the crack growth characteristics of unfilled NR first before discussing the black-filled system. In

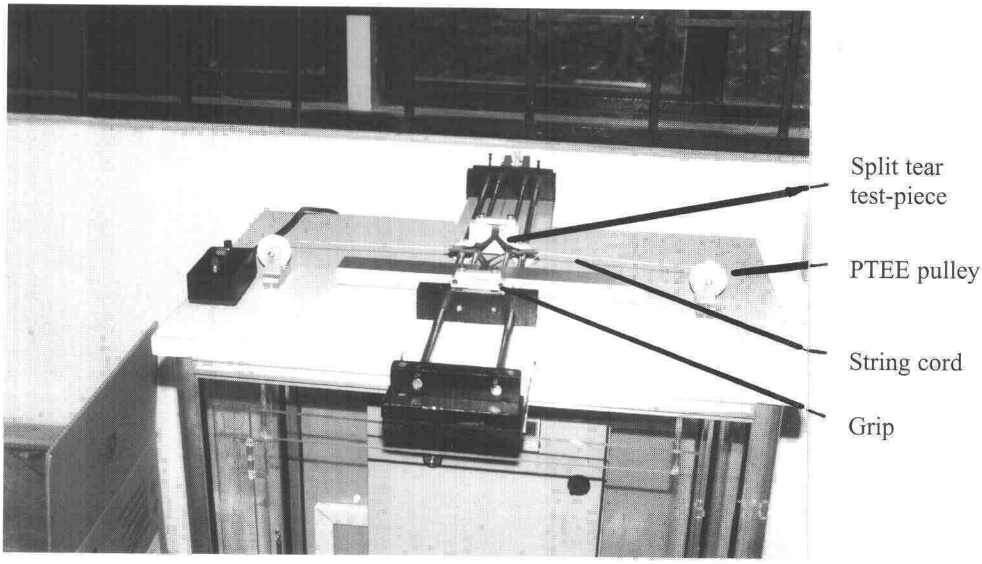


Figure 3a. Cyclic crack growth machine (Top view).

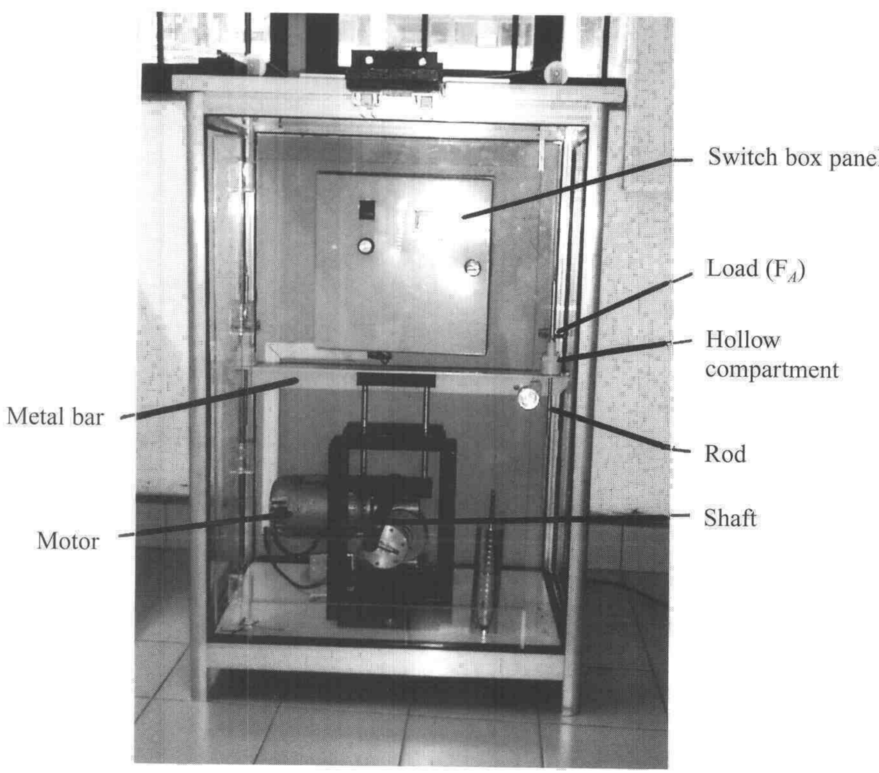


Figure 3b. Cyclic crack growth machine (Front view).

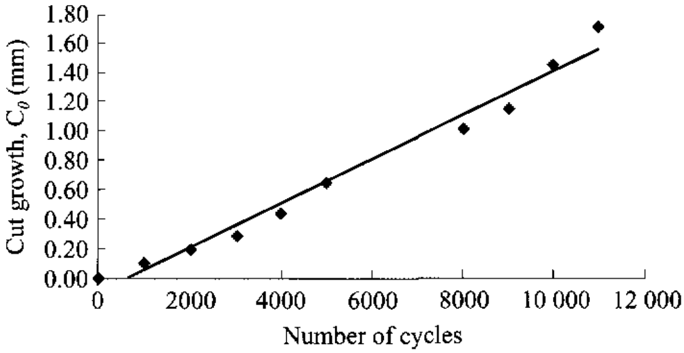


Figure 4a. Crack length vs *number of cycles for unfilled vulcanisate using split-tear test-piece.*

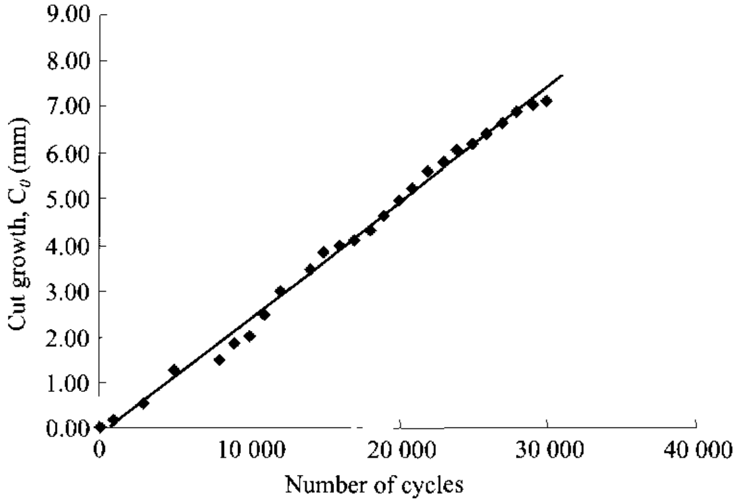


Figure 4b. Crack length vs *number of cycles for black-filled vulcanisate using split-tear test-piece.*

this investigation, the strain ranged from 25% to 60% to minimise marked effect of anisotropy. The results are presented in the form of crack growth per cycle *(dc/dN) versus* tearing energy *T* using log-log plot as shown in *Figure 5.*

The results obtained in this experiment are compared with those results published by Lake[11,12]. This comparison is very significant since crack growth measurement using split-tear test-pieces has not been published elsewhere before. It is very interesting to note that at low tearing energy about 0.9 kJm^{-2}, the results obtained from split-tear produced faster crack-growth rate (1×10^{-5} cms^{-1}) than the result (4×10^{-6} cms^{-1}) published by Lake. However,

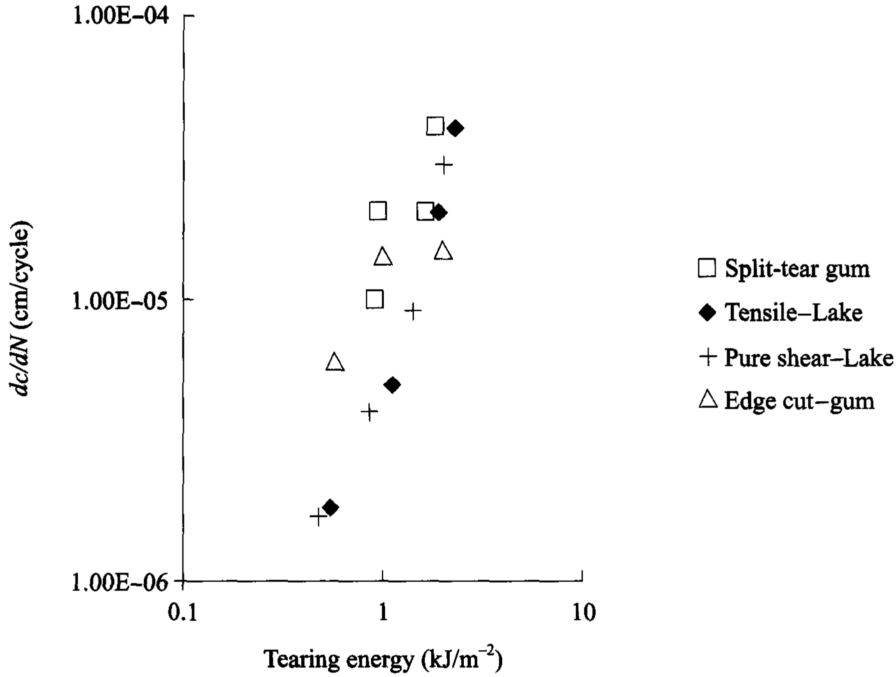


Figure 5. Comparison between split-tear and other test-piece, dc/dN vs *tearing energy,* T.

at tearing energies between 1.5 kJm^{-2} – 1.8 kJm^{-2}, the crack-growth rates are comparable [(dc/dN = 4 × 10^{-5} cms^{-1} produced from split-tear; and dc/dN = 3.6 × 10^{-5} cms^{-1} – produced from pure shear (Lake)]. In the case of edge crack test-piece, close agreement was observed at tearing energy of about 2 kJm^{-2} where the current result matches the value produced by Lake. At tearing energy lower than 1.0 kJm^{-2} the agreement was not that close. This disagreement may be attributed to the differences between the gum mix formulation used by the authors here and that used by Lake. Lake[12] used 0.6 p.p.h.r. of CBS while the authors used 0.5 p.p.h.r. of CBS. Lake cured the rubber for 40 min at 140°C and the authors here cured the rubber for 15 min at 150°C. The low vulcanisation temperature and the high amount of CBS used by Lake would produce slightly higher modulus gum vulcanisate than that obtained by the current authors.

Nevertheless, the close agreement of crack-growth rate produced by split-tear and those of pure shear and edge crack test-piece at tearing energies 1.5 kJm^{-2} – 1.8 kJm^{-2} provides another experimental evidence to show that crack growth rate is independent of the test-piece geometry when results are expressed in terms of tearing energy. Thus the split-tear test-piece can be used both in conventional tear as well as in cyclic crack growth measurement.

Figure 6 shows the comparison between cyclic crack growth resistance of gum and black-filled vulcanisates where dc/dN is plotted against T using log-log plot. It is well established that black-filled vulcanisate produces higher tensile and tear strengths than unfilled vulcanisate. In the case of cyclic crack growth, black-filled vulcanisate produces slower crack growth rate than that of unfilled vulcanisate[13]. However, the results obtained here are in contrast with published results using the conventional test-piece geometries. For a given tearing energy, the black-filled vulcanisate produces about the same crack growth rate as that produced by unfilled vulcanisate. The discrepancy between split-tear and conventional test-pieces is associated with the anisotropy produced by pre-straining. Although, the tearing energy is the same but the amount of pre-straining is markedly higher in black-filled vulcanisate than unfilled vulcanisate because of the strain-amplification effect. The strain-amplification effect introduces higher level of anisotropy in black-filled than in unfilled vulcanisates. Consequently, the crack propagation rate of the black-filled vulcanisate appears to be similar with that of crack propagation rate of unfilled vulcanisate.

However, when the results are compared with those obtained from a tensile test-piece which contained an edge crack, the crack growth rate of black-filled vulcanisate is slower than dc/dN of unfilled vulcanisate. Thus the discrepancy in the results of black-filled vulcanisates between split-tear and tensile test-piece is associated with the effect of anisotropy. The split-tear introduces significant anisotropy because of the applied strain plus

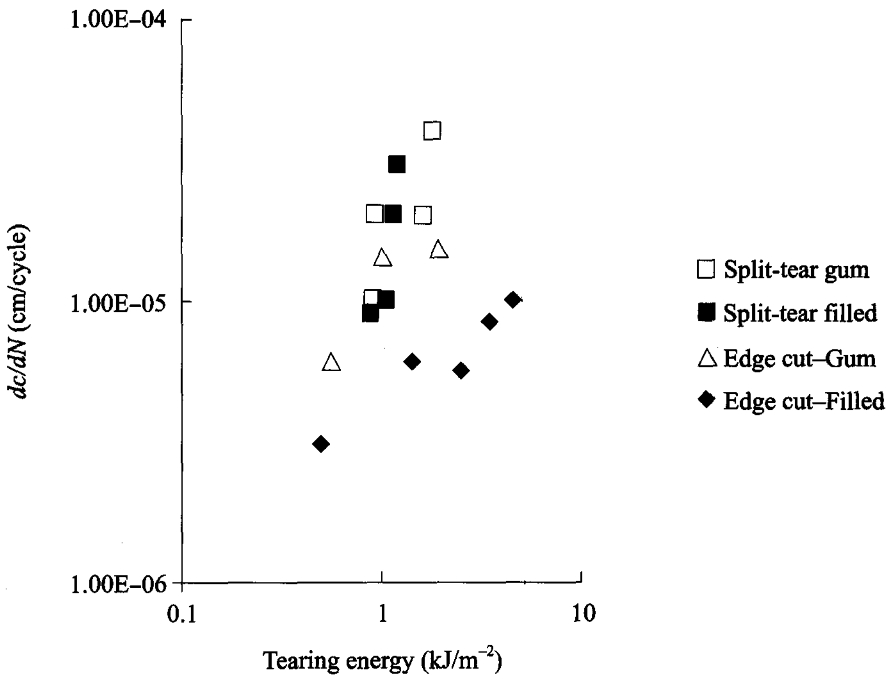


Figure 6. Comparison between crack growth rate of unfilled and black-filled vulcanisates.

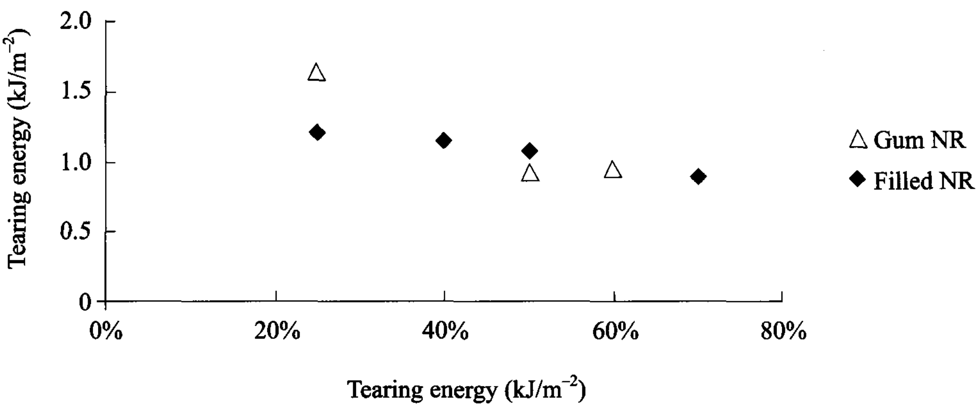


Figure 7. Tearing energy vs *applied strain.*

the strain-amplification effect contributed by the carbon black. Consequently *dc/dN* is faster since the anisotropy introduces sharper crack tip than that of the crack tip of the tensile test-piece as observed visually during the experiment. From visual observation, the torn surface of split-tear test-piece was smoother than an edge crack test-piece.

Finally the effect of anisotropy on the tearing energy measured at about the same crack-growth rate ($dc/dN = 2 \times 10^{-5}$ cm/s) is discussed. *Figure 7* shows the plot of tearing energy *versus* applied strain for unfilled and black-filled vulcanisates. The tearing energy decreases progressively as the applied strain increases. The tearing energy decreases by about 30% as the applied strain is increased from 20% to about 70%. This indicates that as the amount of anisotropy increases with the applied strain, the energy to propagate tearing in the direction of the applied strain decreases. Just like the phenomenon of knotty tear in conventional tear test using trouser test-piece, the problem of forking of black-filled vulcanisate in cyclic crack growth measurement observed in conventional test-pieces is also associated with the splitting of the crack tip in the direction of the applied strain since the energy to propagate crack in this direction is lower than the intended path. At high strain level, the tearing energy of black-filled vulcanisate is marginally higher than that of the unfilled vulcanisate.

CONCLUSION

Split-tear test-pieces were suitable for crack growth measurement since the results obtained were in good agreement with those published by Lake who used different test-piece geometries. It provided another experimental evidence that crack growth rate was independent of the test-piece geometry when results were expressed in terms of tearing energy.

Split-tear test-pieces eliminated forking of crack-tip of black-filled vulcanisates normally encountered by other types of test-pieces.

ACKNOWLEDGEMENT

This work forms part of the post-graduate study programme undertaken by Bijarimi at the Department of Polymer Technology, UiTM The authors also wish to thank the Dean of the Faculty of Applied Science for his encouragement and permission to publish this work

Date of receipt November 2003
Date of acceptance April 2004

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