Fracture Behavior of Crumb Rubber-Filled Elastomers

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ABSTRACT: The fracture behavior of a crumb rubber-filled elastomer was observed in optical micrographs. It was found that the failure started from the surface of the unfilled samples. The failure, however, started from a cavity around a crumb in the crumb-filled samples. This paper suggests that the failure mechanism in the crumb-filled elastomers (NR, NBR) was based on the microscopic observation of highly strained samples. This paper also considers the failure behavior of two-component systems: NR/NBR, SBR/NR, and NR/SBR. © 1999 John Wiley & Sons, Inc. J Appl Polym Sci 74: 3137–3144, 1999

Key words: fracture behavior; crumb rubber-filled elastomer; failure mechanism; microscopic observation

INTRODUCTION

The failure behavior of an elastomer is well known, and many research workers have done extensive work on the failure behavior of an elastomer.[1–5] However, the failure mechanism is not well understood. The failure behavior of the unfilled elastomer was reported by Choi and Roland,[2] who claimed that fracture mechanics analysis enables determination of the size of intrinsic flaws in rubber. They reported that although the failure properties of natural rubber do not parallel the magnitude of its intrinsic defects, the barrier performance may be quite sensitive to the flaw.

The inorganic reinforcing material, such as carbon black, improves fracture resistance and other mechanical properties because the carbon black affects the resistance of the rubber to crack growth.[6] Goldberg and Lauser[7] reported observations of fracture during stretching of NR and SBR loaded with carbon black. However, the mechanical properties decrease by adding an organic filler such as scrap or crumb rubber.[8–11] Kim[9] compared the effect of inorganic fillers and organic fillers on mechanical properties. Although the reinforcing effect of carbon black on the mechanical performance is well known, it is not obvious how crumb rubber affects the mechanical performance of its filled elastomer.

The purpose of this study is to investigate the failure mechanism of the crumb-filled rubber using microscopic observation. From the results, we tried to understand the failure mechanism of the crumb-filled rubbers. Our study also extended to the failure behavior of blended system.

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EXPERIMENTAL

Materials

The elastomers used were NR (SMR 100) and NBR (AN content 35%; manufactured by Kumho, KNB 35L) and SBR1500 (manufactured by Kumho). The particle size of the crumb rubber used in this study was 1–2 mm. Crumb rubber was obtained from used truck tires by ambient grinding.

Table I Components of the Rubber Sheet Used in This Study

NR sheet	
NR	100
Stearic acid	3
Zinc oxide	5
Sulfur	2.5
MTBS	0.6
Carbon black	50
NBR sheet	
NBR	100
Stearic acid	1
Zinc oxide	3
Sulfur	1.5
CBS	0.7
Carbon black	40
SBR sheet	
SBR	100
Stearic acid	1
Zinc oxide	0
Sulfur	1.75
CBS	1.0
Carbon black	50

Sample Preparation

The components of the rubber compounds are summarized in Table I. For compounding, a two-roll mill was used. Curing of the rubber mixture was carried out by compression molding, using a hot press at 150°C for 30 min. Then the vulcanized rubber sheet was cut 1 day after the curing process. A Dumbbell 3 shape specimen was prepared for the test. The values of Moony viscosity at 100°C was 41.60 poise for NR, 72.5 poise for NBR, and 76.9 poise for SBR compounds.[12]

Test Methods

Tensile properties were measured using a universal tensile tester (Instron) with 500 N of load cell and 500 mm/min of head speed. Fracture behavior of the sample was observed by using an optical microscope (Leica) that was connected to the image analyzer. We used an extender for observing the rubber samples under highly strained conditions. The schematic figure of the observation system of this study is shown in Figure 1.

RESULTS AND DISCUSSION

Table II shows the change in the tensile properties of the rubber samples of three different sample-preparing techniques. According to the experimental results, the mechanical performance of rubber compounds was reduced by the addition of crumb rubber. The reason for this can be explained by interfacial phenomena between the rubber matrix and the crumb rubber.

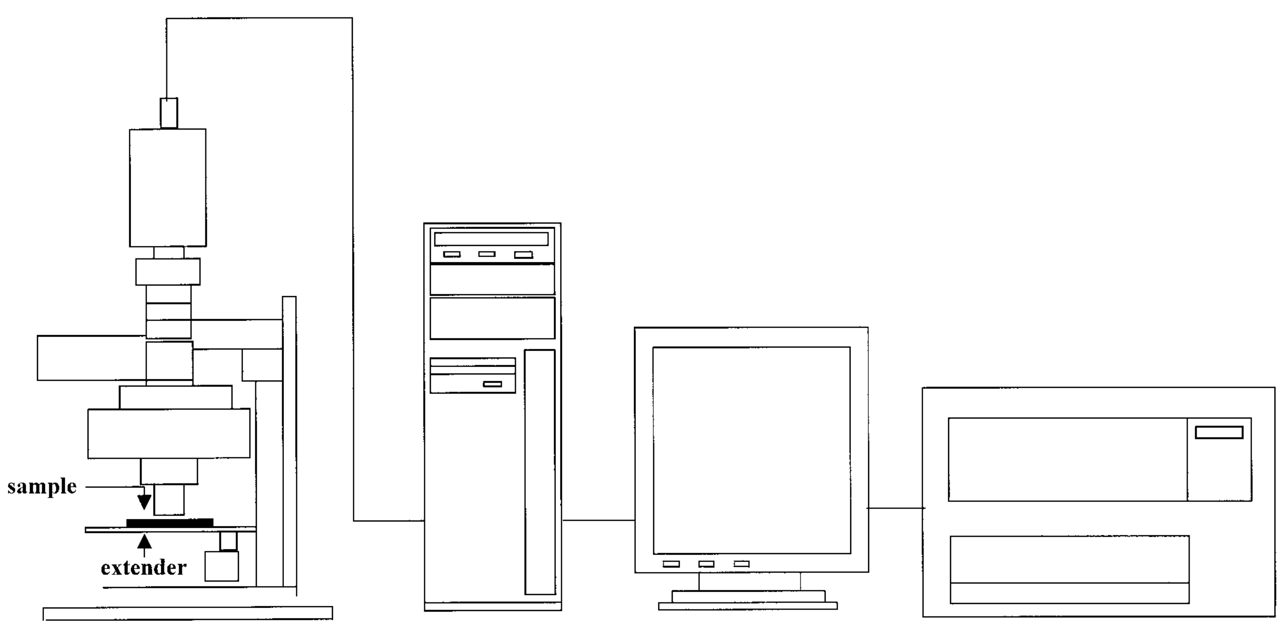

Figure 1 Schematic drawing of the observation system of this study.

Table II Mechanical Properties of Crumb Rubber-Filled Samples

Properties	NBR/C/ NBR	NBR + C/ NBR + C	NBR/ NBR	NR/C/ NR	NR + C/ NR + C	NR/ NR
Tensile strength (kg/cm^2)	167	110	302	163	140	207
Elongation at break (%)	439	352	585	486	458	563
Tear strength (kg/cm)	73	53	80	34	11	48

C, crumb rubber; NBR/C/NBR, crumb rubber was inserted between two NBR sheets pressed and vulcanized; NBR + C/ NBR + C, two NBR sheets filled with crumb rubber pressed and vulcanized; NBR/NBR, two NBR sheets pressed and vulcanized without crumb rubber.

We tried to determine the fracture behavior of elastomers by microscopic observation. It was noted that the failure behavior of the micrographs of the NR sample shown in Figure 2(a), when strained, started on the surface of the sample. The highly elongated sample developed striations, and a parabolic crack occurred on the surface area when strained to 200%. When more highly strained, the stress was concentrated at the end of the crack and resulted in a definite crack. However, the tear started in the cavity located around the crumb rubber of the crumb-filled NR, which is shown in Figure 2(b).

When the crumb-filled NR sample was elongated, the cavity around the crumb deformed along the elongation direction and developed larger cavities, by absorbing smaller cavities. The failure mechanism of the crumb-filled and unfilled NR samples is shown schematically in Figure 3 based on observations. The highly strained region caused greater stress on the fracture surface of the sample and created a new surface by fracture. This stress was magnified at the edge of the cavity region around the crumb rubber, which led to further failure in the crumb-filled elastomer. Therefore, the fracture behavior of the crumb-filled elastomers began with the initiation of the fracture, followed by the propagation of the crack.

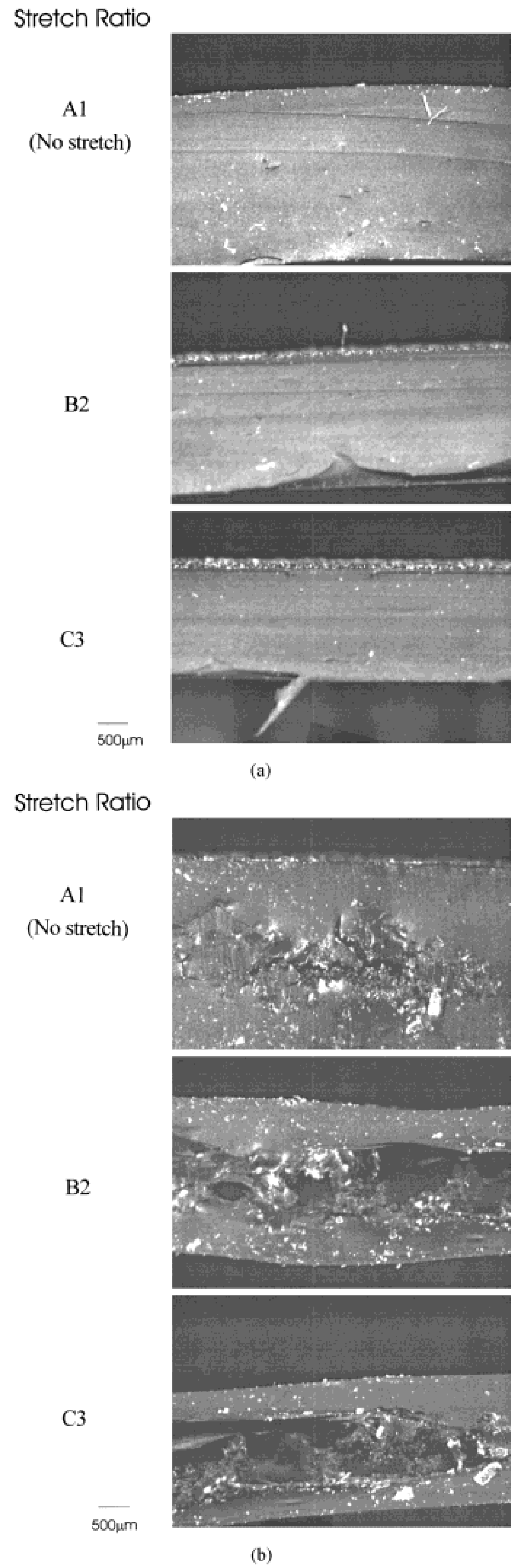

Figure 2 (a) Micrographs of the failure behavior of the NR with stretch ratio of A1 (No stretch), B2, and C3. (b) Micrographs of the failure behavior of the crumb-filled NR with stretch ratio of A1 (No stretch), B2, and C3.

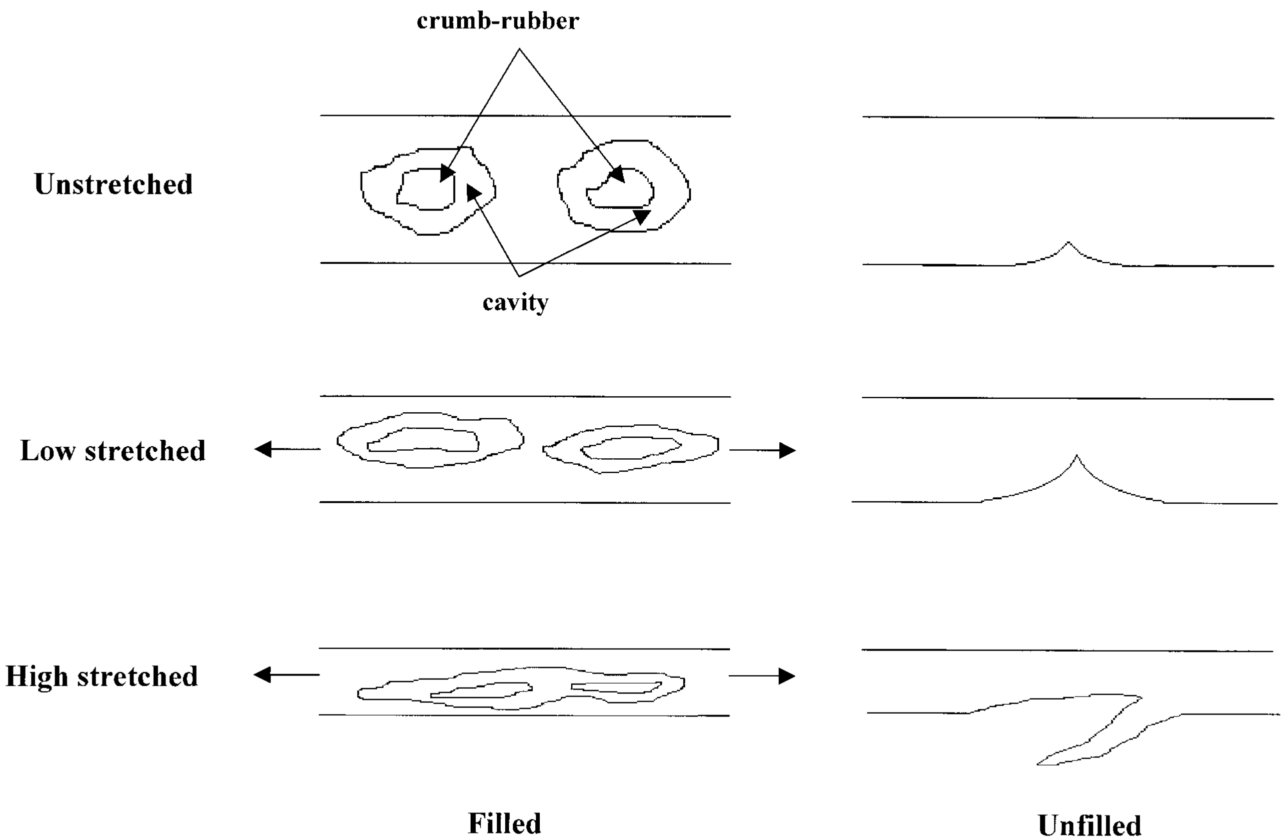

Figure 3 Failure mechanism of the crumb-filled NR and unfilled NR.

The values of tensile and elongation at the break decrease in both crumb-filled NR and filled NBR. Therefore, the failure behavior of the NBR compound was similar to the NR compound, which is shown in Figure 4.

From this result, we confirmed that the main cause of failure in crumb-filled elastomers is the tearing of the cavities that develop around the crumb, which are initiated by high stress exertion and result in a definite break.

Our next question deals with the accuracy of the failure mechanism in crumb-filled rubber samples. Therefore, we compared two samples. In the first sample, crumb rubber was inserted between two rubber sheets, pressed, and vulcanized in a hot press. The failure behavior is shown in

Table III Comparing Mechanical Properties of Samples Between Unfilled and Filled

Properties	NR	NBR	SBR	NR/NBR	NR/SBR	NR + C/ NBR + C	NR + C/ SBR + C
Tensile strength (kg/cm^2)	225	298	267	236	227	46	28
Elongation A break (%)	605	559	545	542	511	254	197
Tear strength (kg/cm)	51	87	87	59	70	27	16

C, crumb rubber.

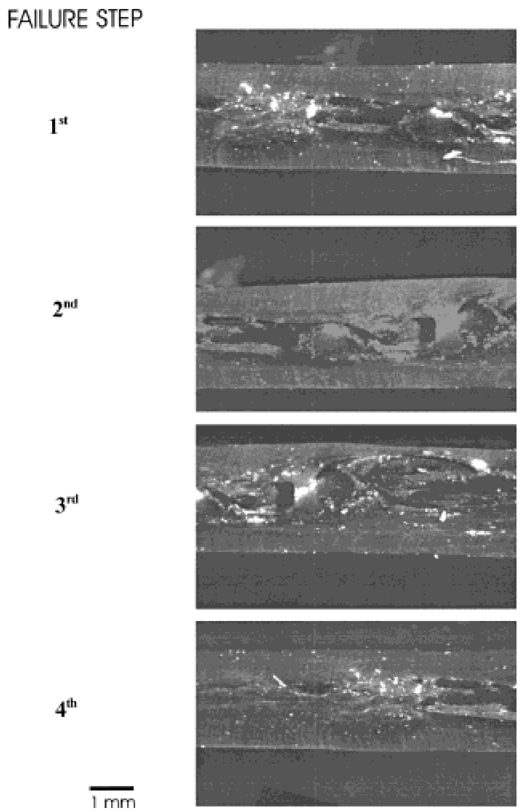

Figure 4 Micrographs of the failure behavior of the crumb inserted between two NBR sheets with failure step 1st, 2nd, 3rd, and 4th.

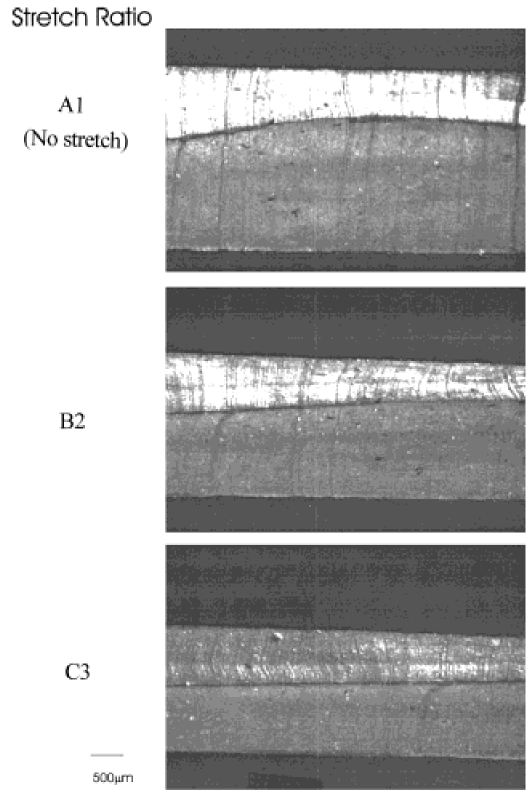

Figure 6 Micrographs of the failure behavior of the NR/NBR with stretch ratio of A1 (No stretch), B2, and C3.

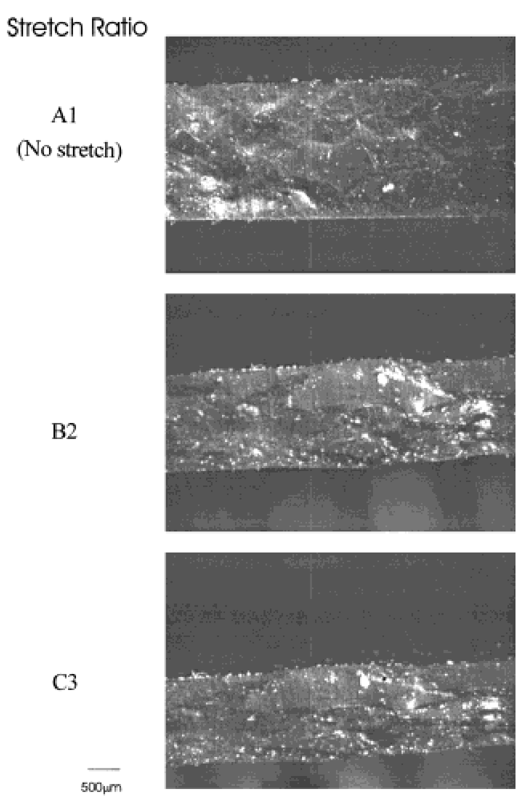

Figure 5 Micrographs of the failure behavior of the NBR sheets filled crumb rubber with stretch ratio of A1 (No stretch), B2, and C3.

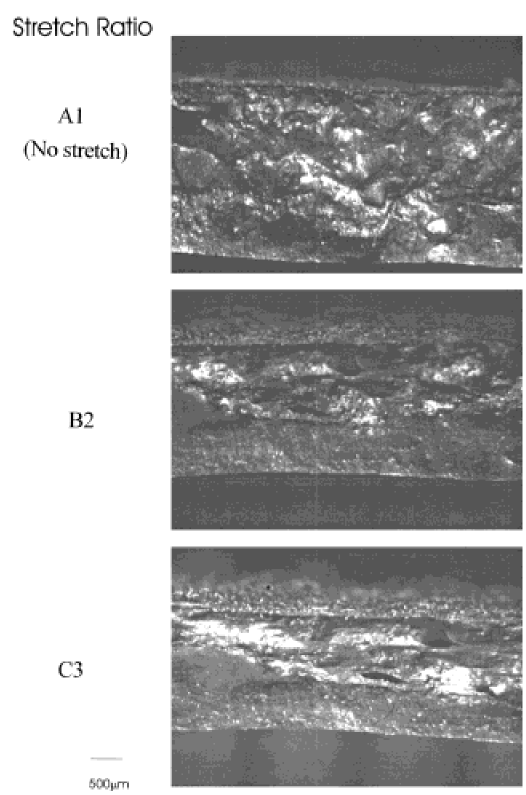

Figure 7 Micrographs of the failure behavior of crumb-filled NR/NBR with stretch ratio of A1 (No stretch), B2, and C3.

Figure 4. Second, we made two rubber compound sheets filled with crumb rubber, pressed, and vulcanized in a hot press.

The micrographs of the failure behavior under strain of the second sample are shown in Figure 5. The mechanical properties of the second sample, which proved to be inferior to those of the previous sample, are summarized in Table II. The explanation is that the applied stress on the surface of the first sample was higher than that on the second sample when stretched, because the first sample had no cavity on the surface of the sample. This led to the second sample breaking more easily than the first.

Therefore, we confirmed that the cavity led to the failure of the rubber compound. Next, we considered the failure behavior of NR/NBR double-layer rubber sheet, which was made by pressing an NR compound sheet onto a NBR compound sheet. The mechanical properties of the double rubber compound sheets, which are summarized in Table III, were significantly reduced by the addition of crumb rubber.

Figures 6 and 7 show the failure behavior of unfilled and crumb-filled NR/NBR compound

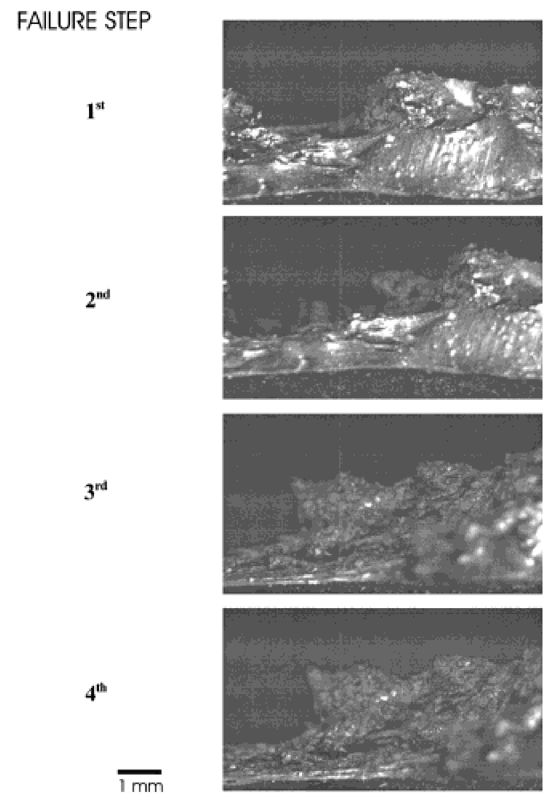

Figure 8 Schematic drawing of the failure behavior of the NR/NBR with failure step 1st, 2nd, 3rd, and 4th.

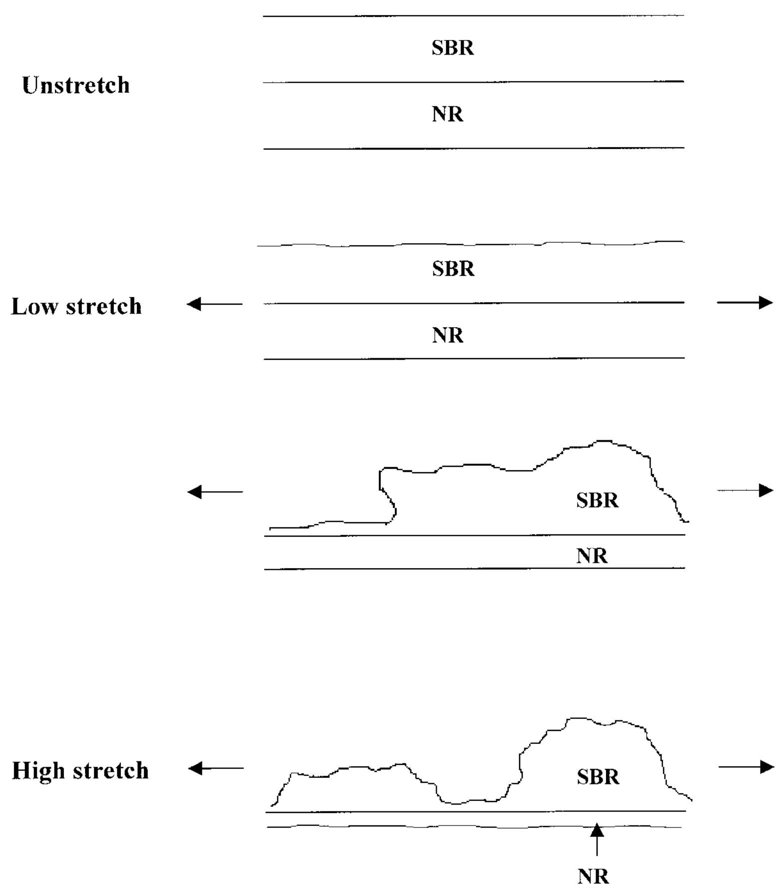

Figure 9 Schematic drawing of the failure behavior of crumb-filled NR/SBR.

sheets, respectively. In the unfilled NR/NBR system, an line of interface was clearly observed between the NR and the NBR compound sheet. When the sample was elongated, the NR bottom part in the micrographs was more deformed in the direction of the elongation than that of the NBR, which is shown in the micrographs.

In Figure 7 each crumb-filled NR and NBR sheet was pressed together and stretched. The bottom part (crumb-filled NR) remained unfractured, but the upper part (crumb-filled NBR) fractured under high strain, because of the fact that the value of elongation at breaking of NR is much higher than that of NBR (refer to Table III).

The behavior of NR/SBR was very similar to NR/NBR, which is shown in Figure 8. Figure 9 shows a schematical drawing of the failure behavior from the observations in Figure 8.

We also considered detailed information in the area of interface between crumb rubber and rubber matrix when the rubber was highly strained.

The crumb rubber in the rubber matrix was deformed when the sample was elongated. We observed that the crumb rubber was pulled out

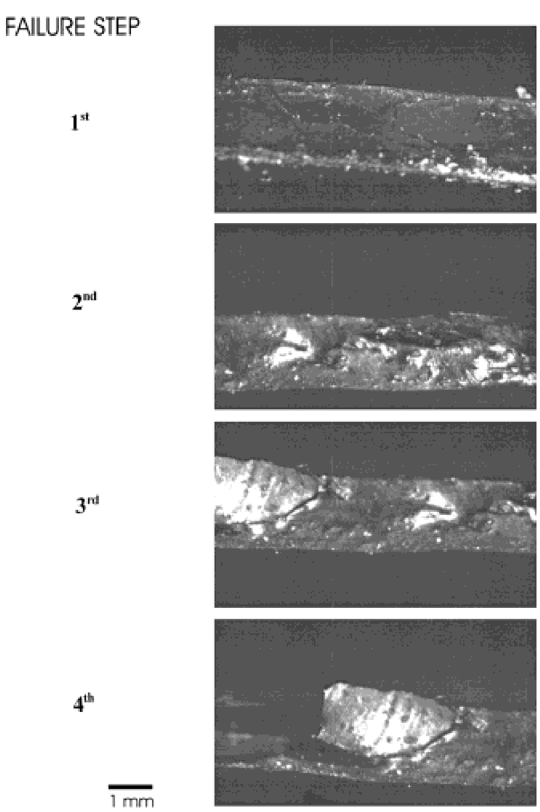

Figure 10 Micrographs of the failure behavior of the crumb rubber sample under stress with failure step 1st, 2nd, 3rd, and 4th.

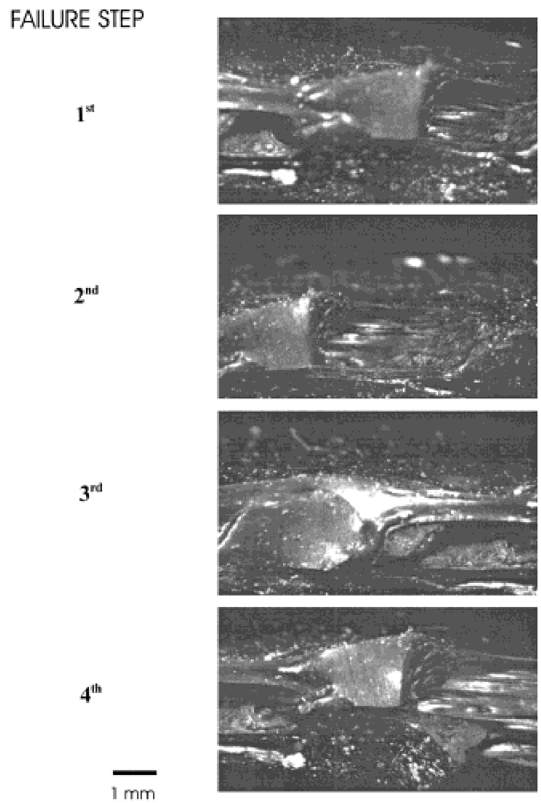

Figure 11 Micrographs of the highly deformed crumb-filled rubber sample with failure step 1st, 2nd, 3rd, and 4th.

when highly elongated. The schematic drawing is shown in Figure 10.

We also observed entanglement around the crumb rubber of the highly deformed crumb-filled rubber sample (Fig. 11).

CONCLUSIONS

1. The failure of the highly strained rubber started from the surface of the sample, but the actual failure started from cavities around the crumb rubber of the crumb-filled rubber.
2. Although there are smaller cavities in the crumb rubber-filled sample, it is the larger cavities around crumb rubbers, when they are highly elongated, that lead to the initiation of failure.
3. In the case of two attached rubber sheets, the sheet with lower tensile properties tore first, and the one with higher tensile properties sustained its properties longer.

4. The crumb rubber initiated the tearing of the rubber sheet because of the fact that the crumb rubber was pulled out when the sheet was highly elongated.

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