

# Aging of Vulcanizates of Formulations for Rubber Seals

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**ABSTRACT:** Typical formulations based on NBR (acrylonitrile butadiene rubber), EPDM (ethylene propylene diene monomer rubber), and a NBR–CR (polychloroprene rubber) blend were studied for various properties under accelerated air aging conditions. The trend in tensile properties indicated the propensity of these formulations to oxidative degradation. The derivatives of these properties, such as their retention indices, strain energy, and Mooney–Rivlin constants also showed similar trends. Some of the observations correlate to shelf-aging data, but the time to rupture data derived from ultimate elongation values did not provide tangible conclusions. © 1998 John Wiley & Sons, Inc. *J Appl Polym Sci* 70: 985–994, 1998

**Key words:** technical rubber goods; NBR; EPDM; aging; technical properties

## INTRODUCTION

A rubber network could degrade due to causes such as thermal effects and oxidative effects. In general, small amounts of oxygen (3% by weight, for example) could cause greater influences on tensile properties and hardness. However, such effects are dependent upon the environmental conditions and the base polymers.<sup>1</sup>

Rubbers above their  $T_g$  (which is under ambient conditions in most of the rubber products) oxidize more rapidly than those in the glassy state due to the higher diffusion rate of oxygen. In such cases, mechanical properties (for example, tensile and tear) could be used to study the aging process.

It is well known that the properties of rubber continuously change with time (called aging<sup>2</sup>). To estimate the extent of change over a period of time, accelerated aging tests are practised. These are intended to accelerate only those parameters of the

environment that are destructive to the polymer under service conditions without introducing new ones. Such parameters could be temperature and air pressure.<sup>3</sup> The role of temperature is significant to the extent of reducing the strength of rubber vulcanizate to  $\frac{1}{3}$  of its value under ambient conditions.<sup>4</sup> An air oven method is suggested for better correlation with room temperature properties.<sup>5</sup> Oxidative degradation by excessive crosslinking is common among synthetic rubbers, such as NBR, EPDM, and CR.<sup>6</sup> The role of aging on the Mooney–Rivlin plots under nonequilibrium conditions has been reported.<sup>7</sup>

Stress relaxation in products like seals has a direct influence on the retention of the sealing force. The mechanism of tensile stress relaxation is well known.<sup>8</sup> This article reports mainly the work on effect of aging on the tensile properties, tensile stress relaxation, and rebound resilience of vulcanizates of NBR, EPDM, and NBR–CR.

## EXPERIMENTAL

The test mixes were prepared on a two-roll open mill of 150 × 300 mm size at a friction ratio of

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**Table I Compound Formulations (phr)**

Ingredient	N <sub>1</sub>	N <sub>2</sub>	N <sub>3</sub>	N <sub>4</sub>	EPDM	NC
NBR 34.50	100.0	100.0	100.0	100.0	0	50.0
Herlene 502	0	0	0	0	100	0
Neoprene W	0	0	0	0	0	50.0
Sulfur	0.5	0.2	1.0	0	1.2	0.3
Zinc oxide	5.0	5.0	5.0	4.0	5.0	3.0
LC MgO	0	0	0	0	0	4.0
Stearic acid	1.0	1.0	1.0	0.5	1.0	0
SP oil	0	1.0	0	0	0	0
CI resin	3.0	5.0	5.0	3.0	0	0
HAF	0	70.0	0	55.0	70.0	0
SRF	50.0	0	40.0	0	0	35.0
DOP-DBP	10.0	15.0	10.0	8.0	0	3.0
Naphthenic oil	0	0	0	0	20.0	0
Antioxidant A	0	0	1.0	1.0	0	1.0
Asbestos fiber pulp	20.0	0	0	0	0	0
MBT	0.5	1.0	2.5	0	1.5	0
TMTD	1.5	2.5	0	3.5	1.0	2.0

1 : 1.15. The standard procedure as per ASTM D 3182 was followed. Before final sheet-out, the mix was passed through tight nip 4 or 5 times. The mixes were tested for cure properties in an MDR 2000 after overnight maturation. Test vulcanizates were prepared in a single, daylight, electrically heated press in compression molding at a

temperature of  $150 \pm 1^\circ\text{C}$  with platen pressure being 10 MPa for  $t_{90} + 3$  min (for tensile slab) and  $t_{90} + 5$  min (resilience disc). Tensile properties were tested according to ASTM D 412 using die C, and rebound resilience was done as per BS 903 Part A8 using Dunlop Tripsometer at room temperature ( $27^\circ\text{C}$ ). Accelerated air aging was done on test specimens as per ASTM D 573 at preset temperatures of 70, 80, 90, 100, and  $105 \pm 1^\circ\text{C}$  for different durations, depending on the need. Tensile properties (with tensilegrams) and stress relaxation were obtained from UTM Zwick 1445.

**Table II Rheometric Data of Mixes N<sub>1</sub> to N<sub>4</sub> (MDR 2000)**

Mix Code	Temp (°C)	<i>ts</i> <sub>2</sub> (m:s)	<i>t</i> <sub>90</sub> (m:s)	<i>M</i> <sub>H</sub> (N m)	<i>E</i> <sub>a</sub> (KJ/mol)
N <sub>1</sub>	150	2:01	4:44	2.64	282.4
	160	1:12	2:45	2.59	
	170	0:49	1:39	2.41	
N <sub>2</sub>	150	2:37	6:56	1.88	216.7
	160	1:31	3:58	1.80	
	170	0:58	2:23	1.67	
N <sub>3</sub>	150	2:19	9:22	0.93	45.6
	160	1:26	7:11	0.93	
	170	0:58	5:47	0.86	
N <sub>4</sub>	150	3:20	15:56	1.66	188.7
	160	1:57	10:15	1.72	
	170	1:15	5:45	1.58	
EPDM	150	1:57	8:14	3.65	320.5
	160	1:12	6:59	3.88	
	170	0:51	4:51	3.71	
NC	150	2:01	11:19	2.44	173.6
	160	1:20	8:57	2.73	
	170	0:56	6:18	2.77	

## RESULTS AND DISCUSSION

The test formulations are given in Table I. Essential cure properties, which are given in Table II, are seen to be affected by the nature and level of the fillers and curing agents. Energy of activation (*E*<sub>a</sub>) was calculated from the following fitted equation:

$$\ln k = -E_a/RT \quad (1)$$

The purpose of asbestos in rubber formulation (N<sub>1</sub>) was reported to improve the flame retardancy of the vulcanizate<sup>9</sup>; but it results in a less-efficient curing system (high *E*<sub>a</sub>), and it may be attributed to the adsorption of the curatives onto

**Table III Tensile Stress–Strain Properties of N<sub>1</sub>**

Aging Schedule	M20 (MPa)	M100 (MPa)	M200 (MPa)	M300 (MPa)	Tensile Strength (MPa)	EB (%)
Unaged	NA	3.0	4.5	6.5	13.5	578
70°C, 72 h	NA	2.9	4.4	6.5	11.7	512
80°C, 72 h	1.5	3.3	5.2	NA	11.8	486
90°C, 72 h	1.9	3.7	5.7	NA	11.2	421
105°C, 72 h	NA	3.8	6.0	9.0	12.4	405
100°C, 144 h	2.3	4.7	7.2	NA	11.4	358
100°C, 168 h	1.8	4.2	6.9	NA	12.2	394
100°C, 264 h	2.0	4.8	7.4	NA	12.5	305
100°C, 288 h	2.2	5.1	8.2	NA	11.4	313

the asbestos pulp, thus inhibiting the vulcanization. Whereas N<sub>3</sub> appears to be more cure-efficient, meaning that the curing system of 1.0 phr of sulfur and 2.5 phr of MBT may be used in formulations of similar nature. In EPDM, a large  $E_a$  value implies that the ENB level needs to be increased from the present level of 4% for better cure efficiency.

## TECHNICAL PROPERTIES AND ROLE OF ACCELERATED AGING

### Tensile Stress–Strain Data

It is seen that tensile properties (Tables III–VII) and their derivatives provide useful information on the effect of aging, as follows.

1. The aging at moderate temperatures in the range of 70 to 105°C for duration up to 72 h does not affect the properties significantly.
2. Different durations (144 to 312 h) at 100°C show a distinct case of hardening due to oxidative degradation. The relative increase in M100 of N<sub>1</sub> is about 60%, while the decrease in elongation is about 50%. The relative increase in M100 (with respect to original (interchangeably used with unaged)) in other mixes (N<sub>2</sub> to EPDM) ranges from 110 to 200%. But in the case of elongation, it is around –30 to –60%. It is to emphasize the fact that the trends in both modulus and elongation indicate degradation in their own respects; but comparatively, the elongation properties merit

**Table IV Tensile Stress–Strain Properties of N<sub>2</sub>**

Aging Schedule	M20 (MPa)	M100 (MPa)	M200 (MPa)	M300 (MPa)	Tensile Strength (MPa)	EB (%)
Unaged	NA	2.4	5.2	8.2	16.0	600
70°C, 72 h	NA	2.6	5.5	8.8	15.9	555
105°C, 72 h	NA	4.3	8.9	13.8	17.8	426
100°C, 144 h	1.7	5.5	10.6	NA	19.0	460
100°C, 168 h	1.8	5.5	9.9	NA	18.1	430
100°C, 192 h	1.9	6.2	11.9	NA	17.1	340
100°C, 264 h	2.2	7.0	12.8	NA	19.1	383
100°C, 288 h	2.3	7.3	12.8	NA	14.9	267
100°C, 312 h	2.3	7.7	14.7	NA	21.0	337
100°C, 336 h	2.4	8.1	15.2	NA	15.7	230

**Table V Tensile Stress–Strain Properties of N<sub>3</sub>**

Aging Schedule	M20 (MPa)	M100 (MPa)	M200 (MPa)	M300 (MPa)	Tensile Strength (MPa)	EB (%)
Unaged	NA	1.14	1.7	2.5	12.4	1200
70°C, 72 h	NA	1.18	1.8	2.6	11.9	1205
105°C, 72 h	NA	1.50	2.6	4.1	11.2	765
100°C, 144 h	0.8	1.95	3.5	NA	13.0	780
100°C, 168 h	0.8	2.1	3.8	NA	14.5	910
100°C, 192 h	0.8	2.2	4.0	NA	12.7	630
100°C, 264 h	0.9	2.7	4.9	NA	14.3	NA
100°C, 288 h	1.0	3.0	5.6	NA	17.2	786

more attention than the rubber modulus. In that case, N<sub>3</sub> emerges to be the most suitable mix due to its little variation in elongation (about 33%).

- Closely related parameters are M20, strain energy, and time to rupture. Irrespective of the duration of aging (up to 336 h), N<sub>2</sub> continues to retain its original value of M20 around 2.0 MPa (Table VIII). To limit the increase in M20 within 4%, under all possible conditions of aging and, at the same time, possessing a high initial value, N<sub>2</sub> is a better choice. In general, retention of low strain moduli is a primary requirement for short fiber added formulations used for sealing purposes.<sup>10</sup> If that were the case in black loaded mixes also, then N<sub>2</sub> may be chosen under service conditions that are equivalent to the aging conditions given in Table VIII (144 to 336 h at 100°C).

#### Time to Rupture

Because the time to rupture data provide a scope for predicting failure times,<sup>11</sup> it was also ana-

lyzed. For a given strain rate at 500 mm/min, the time corresponding to the elongation at break was calculated. The representation of data is divided 2 ways: low intensity and high intensity of aging, as shown in Figures 1 and 2.

The data in Figure 1 indicate that EPDM shows a rising trend, while in N<sub>1</sub>, the trend is reversed (shown in the figure). For instance, the increase in the rupture time in EPDM is 14.5 s for a temperature rise of 25°C, while in N<sub>1</sub>, it is -10.2 s. This particular trend is absent in Figure 2, where N<sub>2</sub> shows a high rate of loss in rupture time. The overall trend in N<sub>2</sub> shows that for every 24 h of aging, the fall in fracture time is 3.4 s. Under normal circumstances, such poor aging performance of a formulation consisting of TMTD at 2.5, MBT at 1.0, and sulfur only at 0.2 phrs is unlikely because the residues of the accelerators have only a beneficial effect on the degradation. Besides, the M20 values showed the merit of N<sub>2</sub>. Secondly, the reversal in the trend, as noticed in Figure 1, is also uncommon because both sulfur-vulcanized EPDM and NBRs are known to undergo only oxidative hardening due to aging.

**Table VI Tensile Stress–Strain Properties of N<sub>4</sub>**

Aging Schedule	M20 (MPa)	M100 (MPa)	M200 (MPa)	M300 (MPa)	Tensile Strength (MPa)	EB (%)
Unaged	NA	2.2	4.4	7.1	17.6	745
70°C, 72 h	NA	2.2	4.0	6.3	17.7	648
105°C, 72 h	NA	3.2	6.7	10.7	20.0	642
100°C, 144 h	1.5	4.3	8.0	NA	20.6	630
100°C, 192 h	1.5	4.6	8.8	NA	19.1	521
100°C, 288 h	1.7	5.4	10.0	NA	21.5	578

**Table VII Tensile Stress–Strain Properties of EPDM**

Aging Schedule	M20 (MPa)	M100 (MPa)	M200 (MPa)	M300 (MPa)	Tensile Strength (MPa)	EB (%)
Unaged	NA	3.0	5.8	8.4	11.6	450
70°C, 72 h	NA	3.1	6.1	8.8	12.4	446
80°C, 72 h	1.5	4.5	7.8	NA	10.8	325
90°C, 72 h	1.5	4.5	8.1	NA	11.9	360
105°C, 72 h	NA	4.8	9.2	12.7	12.7	300
100°C, 144 h	NA	4.9	9.4	NA	12.5	292
100°C, 168 h	1.8	6.3	11.0	NA	13.0	272
100°C, 264 h	1.7	6.4	10.6	NA	12.5	306
100°C, 288 h	1.9	6.8	11.7	NA	14.1	283
100°C, 312 h	1.9	7.2	12.6	NA	13.5	240

Therefore, the representation of failure time in this way is unlikely to yield tangible conclusions.

### Strain Energy

The tensilegrams were cut and weighed as representing the strain energy. The retention values are expressed in terms of the value of aging at 100°C/144 h and are shown in Figure 3. This condition is likely to ensure complete absence of diffusion and a more open network structure, which will give a better picture of the relative merits of the formulations. Under identical conditions, the fall in retention is less rapid in N<sub>3</sub> than in N<sub>1</sub> (shown in the figure). In N<sub>2</sub>, the aging intensity was so high (264–288 h) that the retention falls below 50%. But a further increase of aging time by 48 h does not unduly affect the retention. That means, for products for which strain energy retention is very critical, N<sub>2</sub> may safely be used under conditions that would cause structure–property effects equal to 264 h at 100°C. N<sub>3</sub> is far superior up to 192 h of aging.

Even with the beneficial effect of residues from TMTD (tetramethyl thiuram disulfide), N<sub>1</sub> is less reliable compared to N<sub>3</sub> under identical conditions. In the case of other formulations, probably due to molecular complexity (EPDM) and lack of data (N<sub>4</sub>), similar conclusions could not be drawn.

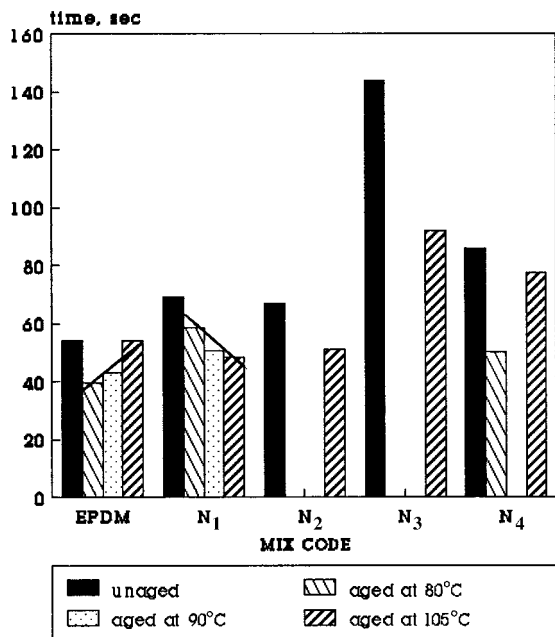
### Rebound Resilience

The following observations are made on the resilience data.

1. In general, low intensity of aging does not distinguish the formulations in respect to their retention values (Fig. 4). But a retention of 90+ is well assured in all mixes. In the case of high intensity, though the values of the percentage of retention spread between 75 and 110, relative merits of the formulations, as well as the aging schedule, are better seen in Figure 5. Resilience is an important parameter that completely reflects the structure. Therefore, the high

**Table VIII Modulus at 20% Elongation (M20) of N<sub>1</sub> to N<sub>4</sub> Formulations**

Mix Code	Air Aging at 100°C for Hours						
	144	168	192	264	288	312	336
N <sub>1</sub>	2.3	1.8	NA	2.0	2.2	NA	NA
N <sub>2</sub>	1.7	1.8	1.9	2.2	2.3	2.3	2.4
N <sub>3</sub>	0.8	0.8	0.8	0.9	1.0	NA	NA
N <sub>4</sub>	1.5	NA	1.5	NA	1.7	NA	NA
EPDM	NA	1.8	NA	1.7	1.9	1.2	NA



**Figure 1** Time to rupture (tension) versus Air aging for 72 h (Low intensity).

intensity of aging ensures that weak network modifications are almost absent and the property measured represents entirely the stable macromolecular feature of the vulcanizate. Aging intensity numbers (6) and (8) are seen to show a better picture than the rest.\* So, representing the retention according to aging intensity numbers (6) or (8) will give a good knowledge of the formulations.

- For service conditions in which retention of resilience is the criterion (which is required for low-temperature sealing), compound N<sub>1</sub> is less preferable [the percentage of retention is about 65 compared to 80 and above in other formulations for the intensity (8)], as shown in Figure 6. It is probably due to the presence of asbestos fiber pulp, which makes the molecular mobility more sluggish.

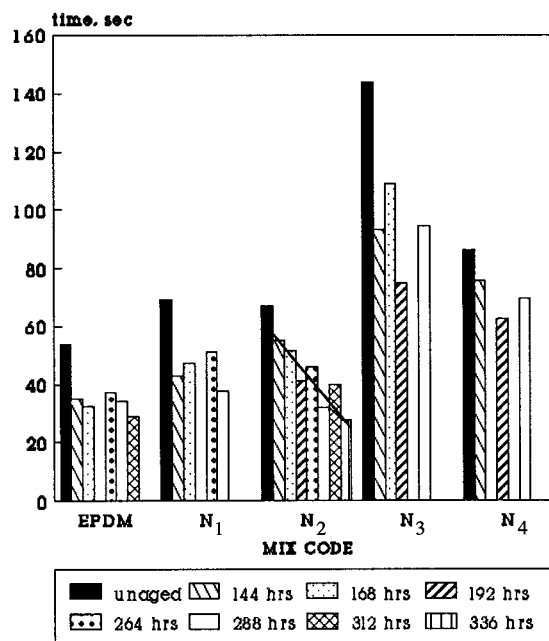
\* Aging schedule (intensity of aging):

(1) Unaged; (2) 70°C, 72 hours; (3) 80°C, 72 hours; (4) 90°C, 72 hours. (5) Step 1: aging as per (3). Step 2: Conditioning at 27°C for not less than 24 hours. Step 3: Aging at 100°C/120 hours. (6) Step 1: aging as per (4). Step 2: Conditioning at 27°C for not less than 24 hours. Step 3: aging at 100°C/120 hours. (7) Step 1: aging as per (5). Step 2: Conditioning at 27°C for not less than 24 hours. Step 3: aging at 100°C/120 hours. (8) Step 1: aging as per (6). Step 2: Conditioning at 27°C for not less than 24 hours. Step 3: aging at 100°C/120 hours.

## Stress Relaxation

The tensile stress for 50% elongation was recorded continuously for about 60 min. Since the extent of elongation does not affect the stress relaxation behavior appreciably,<sup>12</sup> elongation at 50% was arbitrarily chosen. The relaxation of EPDM, N<sub>1</sub>, N<sub>2</sub>, and N<sub>3</sub> as representative cases are shown in Figures 7 to 10. The following observations are made on the data.

- Sulfur and the accelerators at varying levels are expected to result in different random main chain modifications. The present observation concurs with the theory.<sup>8</sup>
- In the case of EPDM (Fig. 7), if the product performance demands a stress retention of only 0.87 of  $\sigma_o$  ( $\sigma_o = 2.02$  MPa), then formulations of a similar nature assure high reliability. This corresponds to the relaxation time of 2400 s. It is subject to the conditions that the structure-property effects are much less than what would have been caused due to degradation at 100°C for 192 h in the laboratory.
- Sulfur at only 0.2 phr is expected to cause more stable crosslinks that are less vulnerable to modifications. In order to confirm



**Figure 2** Time to rupture (tension) versus Air aging at 100°C (High intensity).

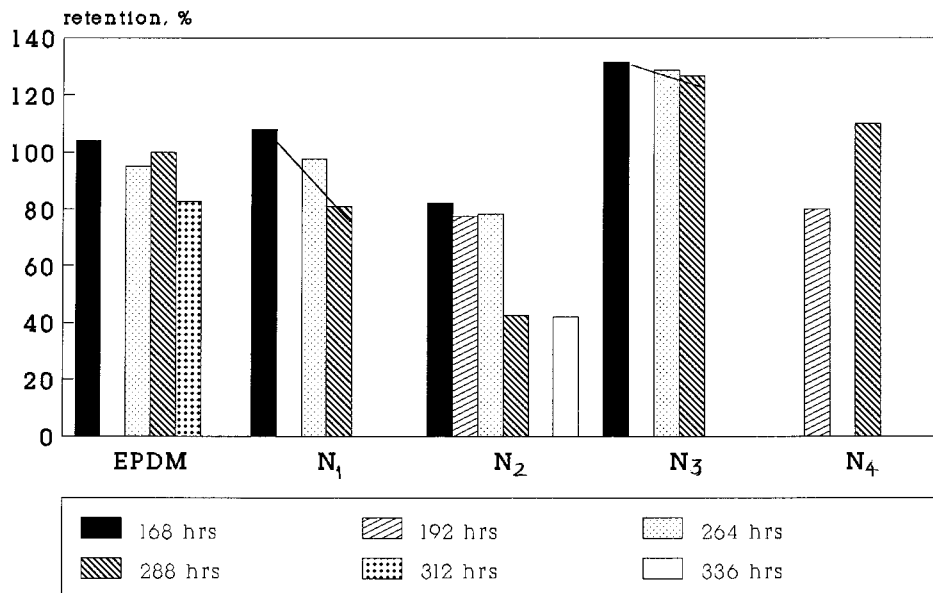


Figure 3 Strain energy retention; percentage normalized to aging at 100°C/144 h after samples were aged at 100°C.

this theory, the relaxation of N<sub>2</sub> is shown in Figure 8 for 3 different aging conditions. The relaxations occurred at almost equal rates. The observation is in conformity with the theory. This means that the tensile-stress relaxation does provide useful information in the follow-up of the aging process. Further, the plot of 192 h aging shows an asymptotic value,  $\sigma_t$ , of  $0.75\sigma_o$  at

$t = 420$  s. Similarly, the 288-h plot gives  $\sigma_t = 0.70\sigma_o$  at  $t = 450$  s; in the case of 312 h, it is  $0.67\sigma_o$  at  $t = 540$  s. The absolute values of  $\sigma_t$  are (for aging of 192, 288, and 312 h) 2.22, 1.83, and 1.48 (MPa), respectively. It shows that with the intensity of aging, (1) the residual stress value decreases and (2) the relaxation time correspondingly increases.

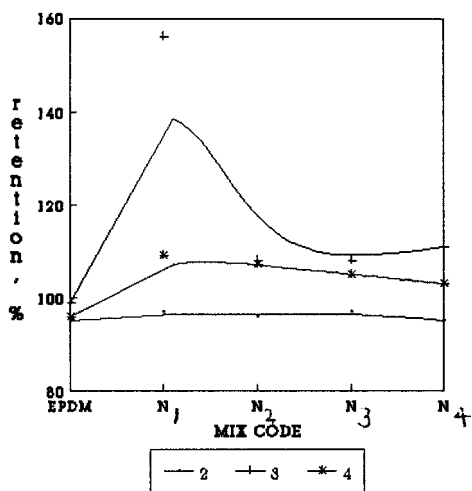


Figure 4 Rebound resilience—percentage of retention (reference to unaged); low intensity.

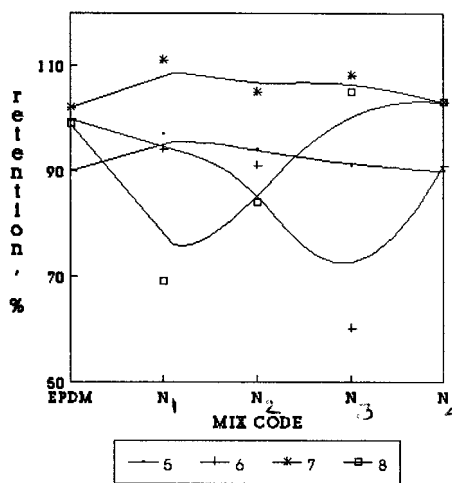
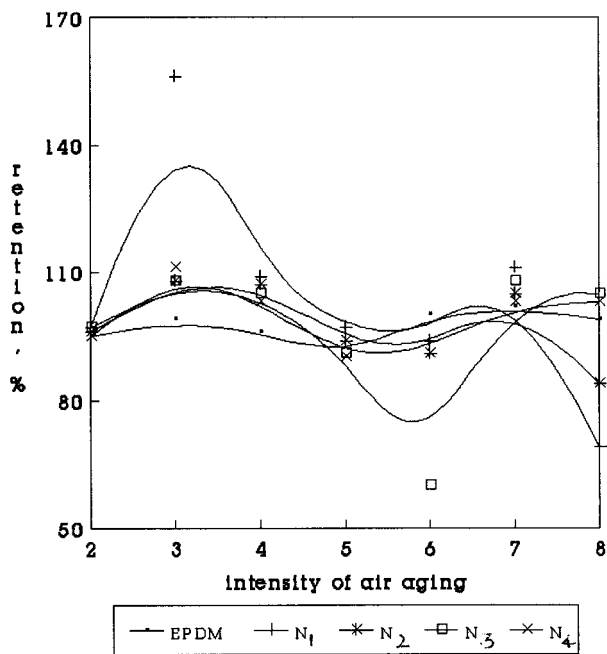
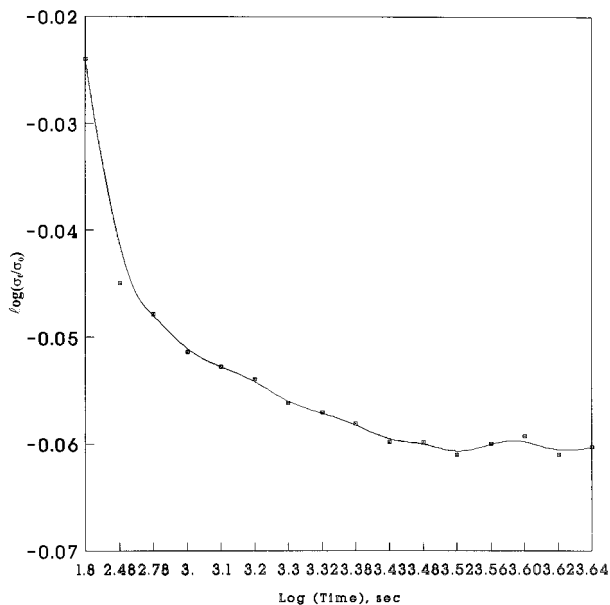


Figure 5 Rebound resilience—percentage of retention (reference to unaged); high intensity.

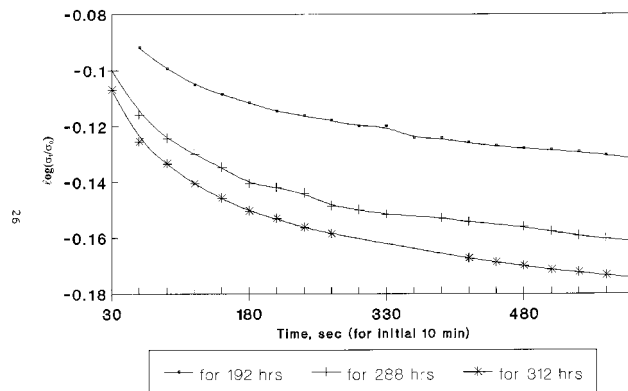


**Figure 6** Resilience-intensity of aging versus the percentage of retention (reference to unaged).

It means that, for meaningful analysis of such relaxation behavior, it is essential to consider both the stress and the time at which the relaxation process is complete.

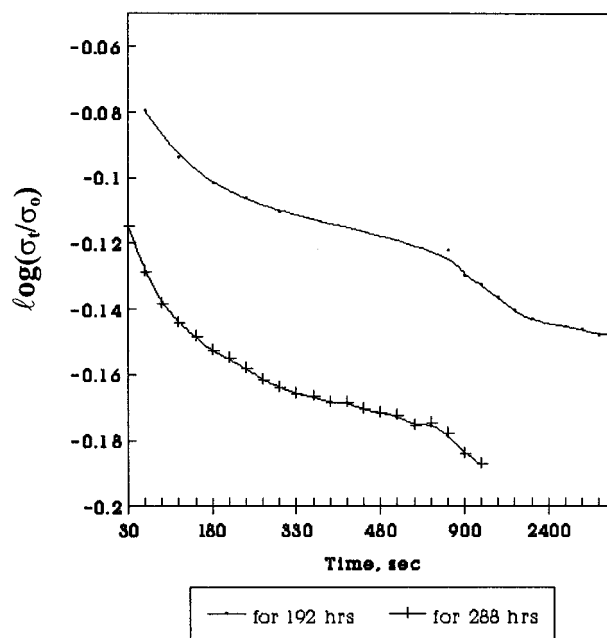


**Figure 7** Stress relaxation EPDM 50% elongation at room temperature (after the specimen was aged at 100°C for 192 h).



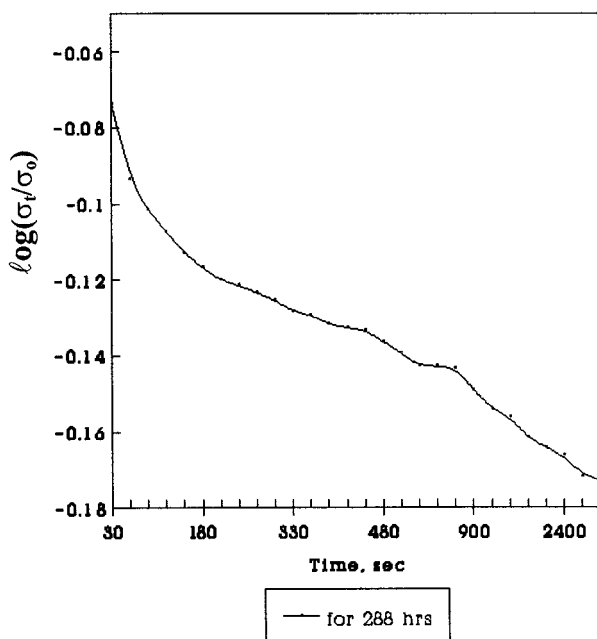
**Figure 8** Stress relaxation-N<sub>2</sub> 50% elongation at room temperature (after specimen was aged at 100°C).

4. Sulfur at 0.5 phr and the presence of pulp are likely to alter the network behavior to the aging process. The secondary relaxation, which is distinctly present in Fig. 9, even after aging for 288 h, illustrates that tensile stress relaxation tests are equally useful compared to compression tests.
5. In the same way, 1.0 phr of sulfur (N<sub>3</sub>) (Fig. 10) is expected to cause greater crosslink modifications, leading to secondary network



**Figure 9** Stress relaxation-N<sub>1</sub> 50% elongation at room temperature (after specimen was aged at 100°C).





**Figure 10** Stress relaxation— $N_3$  50% elongation at room temperature (after specimen was aged at  $100^\circ\text{C}$ ).

relaxation. The current observation (beyond 10 min) is an example for this phenomenon.

### Mooney–Rivlin Constants

The Mooney–Rivlin equation is useful in establishing a structure–property relationship.<sup>7</sup> It is normally represented as follows:

$$\sigma/[2(\lambda - \lambda^{-2})] \text{ versus } 1/\lambda.$$

In this plot on extrapolating to  $1/\lambda = 0$ , a value of  $C_1$  is obtained, and the slope is denoted as  $C_2$ . By comparison with the theory of elasticity, it is proposed that  $C_1 = 0.5 NRT$ , where  $N$  is the

crosslink density,  $R$  is a gas constant, and  $T$  is the absolute temperature. In practice, the constant  $C_1$  has proved to be a useful measure of the crosslink density. There is a linear dependence of  $C_1$  on the concentration of sulfur. In many cases, an extrapolation to  $C_1$  is not allowed since, in the absence of chemical crosslinks, the physical entanglements also contribute to  $C_1$ .  $C_2$  decreases as the chain cross section increases, that is, as the polymer chain becomes stiffer and the conformational entropy of the network chains decreases. Such experiments are used to corroborate the idea that  $C_2$  reflects the concentration of physical, more unstable crosslinks (such as entanglements, filler–filler, and filler–polymer interactions).

With available data, tensile strength alone does not seem to give a clear picture of the aging process, but it is expected to provide useful derivatives in the form of Mooney–Rivlin plots.<sup>7</sup>

The initial shear modulus  $G$ , ( $G = 2(C_1 + C_2)$ ), calculated from these plots, are given in Tables IX and X. The sum of the constants in the form of  $G$  are reported here because such a method ensures better reproducibility.<sup>12</sup> The abrupt increase in its value is prevalent in all cases (Table X) after aging at  $100^\circ\text{C}/144$  h. But after that, it is seen that  $N_2$  continues to maintain its  $G$  value around 4 MPa. The  $G$  values of  $N_1$  and  $N_2$  are comparable. Further, as concluded in the case of M20, the mix  $N_2$  is a clear winner of all the test formulations. As is seen from both M20 &  $G$  values, these values did not change appreciably for  $N_2$  while aging beyond 192 h at  $100^\circ\text{C}$ . This leads to conclude (1) that in conditions in which M20 &  $G$  are the criteria, vulcanizates like  $N_2$  can serve quite a length of time; and (2) follow-up of low strain moduli, such as M20, indicates the aging process in the right direction.

**Table IX** Mooney–Rivlin Constants ( $C_1 + C_2$ )<sup>a</sup>

Mix Code	Aged for 72 h				
	Unaged	At $70^\circ\text{C}$	At $80^\circ\text{C}$	At $90^\circ\text{C}$	At $105^\circ\text{C}$
$N_1$	1.04	1.06	1.70	NA	NA
$N_2$	0.27	0.13	NA	NA	0.09
$N_3$	0.42	0.42	NA	NA	0.35
$N_4$	0.20	0.42	1.47	NA	0.05
EPDM	0.43	0.90	1.58	1.60	0.70

<sup>a</sup> MPa (constant duration).

**Table X Mooney–Rivlin Constants ( $C_1 + C_2$ )<sup>a</sup>**

Mix Code	Unaged (Original)	Aged at 100°C for h						
		144	168	192	264	288	312	336
$N_1$	1.04	2.74	2.05	NA <sup>b</sup>	2.27	2.54	NA	NA
$N_2$	0.27	1.86	1.97	2.02	2.33	2.55	2.43	2.45
$N_3$	0.42	0.88	0.96	0.93	NA	0.87	NA	NA
$N_4$	0.20	1.59	NA	1.63	NA	1.80	NA	NA
EPDM	0.43	0.69	1.80	1.54	NA	1.87	1.93	NA

<sup>a</sup> MPa (constant temperature).<sup>b</sup> NA means that data was not available.

As observed in the case of mechanical properties, it is seen from the Table IX that the aging in the range of 70 to 105°C for a duration up to 72 h did not affect the sum ( $C_1 + C_2$ ) appreciably.

## NOMENCLATURE

NBR 34.50	acrylonitrile butadiene rubber, 34% ACN; ML (1 + 4) 100°C = 50
Herlene 502	ethylene propylene diene rubber, E/P ratio = 67/33; ML (1 + 4) 125°C = 54; ENB, % = 4
Neoprene W	polychloroprene rubber, W grade, Mercaptan-modified; ML (2.5') 100°C = 45 to 54
N774	SRF (semireinforcing furnace carbon black)
N330	HAF (high-abrasion furnace carbon black)
SP oil	styrenated phenol oil (antioxidant)
CI resin	coumarone indene resin (tackifier)
DOP/DBP	dioctyl phthalate (or) dibutyl phthalate
Antioxidant A	mixed alkyl aryl- <i>p</i> -phenylene diamine
$\sigma_o$	tensile stress at time, $t = 0$
$\sigma_t$	tensile stress at time, $t = t$

$$\text{Retention of property} = \frac{\text{value of property after aging}}{\text{value of property before aging}}$$

$$\% \text{ Change in property} = \frac{\% \text{ retention of property} - 100}{100}$$

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