

# Investigation of the Degradation Properties of Low Molecular Weight Natural Rubber Blends in Oven, Oxygen, Ozone, Water, and Some Organic Solvents

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**ABSTRACT:** Studies into how heat, oxygen, ozone, water, and some organic solvents affect the physico-mechanical properties of vulcanizates prepared from blends of natural rubber (NR) and low molecular weight natural rubber (LMWNR) were investigated. Various ratios of NR and LMWNR (100:0, 95:5, 90:10, 80:20, 50:50, 25:75, 10:90, 5:95, and 0:100 w/w) were mixed and labeled as mixes A to I. The physico-mechanical properties of all the vulcanizates before and after ageing in oven, oxygen, ozone, and water were measured and compared while the resistance of the vulcanizate in toluene, carbon tetrachloride, acetone, ethanol, cyclohexane, mineral oil, and brake fluid were determined in terms

of swelling and solubility measurements. From the unaged results, mix A with 100% NR has the best physico-mechanical properties. After degradation, mix C with 10% LMWNR showed the best ageing resistant. Similarly, mix D with 20% LMWNR showed more resistance in most of the solvents used, and this was closely followed by mix C. The results generally have proven that LMWNR is capable of improving the ageing properties and solvent resistance of NR. © 2011 Wiley Periodicals, Inc. *J Appl Polym Sci* 121: 78–85, 2011

**Key words:** ageing; blends; natural rubber; physico-mechanical; vulcanizates

## INTRODUCTION

Polymers are very important classes of industrial materials due to some of their properties that gave them special applications in various industrial sectors,<sup>1</sup> and natural rubber is an important polymeric material. Technological innovations in rubber processing are fast increasing and a great deal of commercial interest is being placed on rubbers or blend of rubbers that can combine improved processing characteristics with good ageing and solubility parameters. Several authors<sup>2–6</sup> have documented some of the inherent limitations of natural rubber (NR) as factors militating against its wider usage in some polymeric products. The quest on how to improve the limitation aspects of NR by scientists brought the idea of blending and compounding other polymers with NR, with the expectation of having a modified rubber that will gain wider commercial interest in usage and acceptability with improved processing characteristics that will enhance more innovations in rubber technology. It was in the light of this that Perera et al.<sup>2</sup> reported that some new generic family of polymers have lesser solubility prob-

lems and good ageing and processing characteristics. Akinlabi et al.<sup>1,4</sup> have also documented low molecular weight natural rubber (LMWNR) as a new family of polymers chemically derived from natural rubber by depolymerization of natural rubber latex (NRL) with nitrobenzene. This LMWNR has been found to be akin in properties with natural rubber, e.g., affinity for ingredients during compounding. It was thereafter further thought that the degrading pattern of blends of NR and LMWNR and the resistance of the blends in organic solvents is worth examining since elastomer degradation and ageing is a subject of great importance to technologists working with modified materials. This idea serves as the basis for this study. In addition, this study will provide more and useful information, data, uses, and applications about the newly blended material.

## EXPERIMENTAL

### Materials

Natural rubber latex from NIG 903 clone was obtained from the estates of the Rubber Research Institute of Nigeria (RRIN), Iyanomo, Benin City, while the crumb rubber conforming to technically specified rubber (TSR) 10 but usually denoted in Africa as standard African rubber (SAR) grade 10 was also obtained from the RRIN. The reagents and solvents used were of analytical grade, while the

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TABLE I  
Recipe for the Preparation of NR/LMWNR Blends

Compound component (phr)	Samples								
	A	B	C	D	E	F	G	H	I
Natural rubber	100	95	90	75	50	25	10	5	–
LMWNR (26,600 Mw)	–	5	10	25	50	75	90	95	100
Carbon black (N330)	40	40	40	40	40	40	40	40	40
Zinc oxide (ZnO)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Sulphur	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Stearic acid	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
MBTS	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Flectol H	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0

LMWNR = Low molecular weight natural rubber, MBTS = Dibenzothiazyl disulphide, Flectol H = Polymerized 1,2-dihydro-2,2,4-trimethyl quinolene.

rubber compounding chemicals were of commercial grade.

### Methods

Production and characterization of LMWNR samples

Low molecular weight natural rubber was prepared using the method described previously.<sup>4</sup>

### Compounding of the mixes

Recipes used for preparing mixes A to J are given in Table I. Mixing was carried out using a laboratory two-roll mill in accordance to the method described by the American Society for Testing and Materials (ASTM)-D-3184-80.<sup>7</sup>

### Cure characteristics

The cure characteristics of the mixes were measured at 170°C using an oscillating disk rheometer (ALPHA ODR 2000) in accordance to ISO 3417 method as contained in the Standard African Rubber (SAR) manual No. 2.<sup>8</sup> The respective cure times as measured by  $t_{90}$ , scorch times, torque, and cure rates were read directly from the rheometer and recorded.

### Measurement of the Mooney viscosity

The Mooney viscosity of the sample was determined using the shearing disc viscometer model type Wallace MK III, according to ISO 289 as contained in the SAR manual No. 2.<sup>8</sup> The results were read directly from the Mooney viscometer, recorded, and expressed in terms of ML (1 + 4) at 100°C.

### Mechanical properties

The test specimens were molded in an electrically heated hydraulic press (TECHNO LOIRE) at 160°C for 5 min as predetermined from the rheometer. Tensile properties of the vulcanizates were measured

with a Mosanto Tensile Tester Model (1/M) at a crosshead speed of 500 mm/min using a dumbbell test specimen (type II) as contained in ASTM D-412-87 (method A) and as in the SAR manual no. 2.<sup>8</sup> Thereafter, the tensile strength at break, modulus, and elongation at break were then calculated.

### Compression set measurement

Wallace compression set machine (model/ref. no. C2; Hz 50) was used. Compression set was designed to evaluate the extent by which the specimen fails to return to its original thickness when subjected to standard compression load (1N) for a given period of time (24 h) at a given temperature (100°C). The difference between the original thickness and the recovered thickness was expressed as a percentage of the original thickness. This was expressed mathematically as:

$$\text{Compression set}(\%) = \frac{(t_o - t_r)100}{t_o} \quad (1)$$

where  $t_o$  = initial thickness and  $t_r$  = recovered thickness.

### Hardness test

The hardness test of rubber is the relative resistance of a surface to indentation by an indicator of a specified dimension under a specified load. The hardness of the vulcanizate was determined by adopting the standard dead load method described in BS 903, Part A26.<sup>9</sup> The standard dead load method of the measurement covers rubbers in the range of 30–85 international rubber hardness degrees (IRHD).

### Abrasion resistance

Wallace Akron abrasion tester was used in accordance with the SAR manual no. 2.<sup>8</sup> The angle between

the test specimen and the wheel was adjusted to an angle of 15°. The abrasion was carried out for four 1000 revolutions and the material loss for each run was noted. The specimen was reweighed between each test run. From the mean of the five runs, the volume of rubber loss per 1000 revolutions of the abrasive wheel was calculated.

The result was expressed as:

$$\text{Abrasion resistance index} = \frac{[S]100}{T} \quad (2)$$

where  $S$  = volume loss per 1000 revolutions of abrasive wheel, calculated from the mean of five runs on standard rubber,  $T$  = volume loss per 1000 revolutions of abrasive wheel, calculated from the mean of five runs on the sample rubber.

**Crosslink density.** The chemical crosslinking density ( $\rho RT/M_c$ ) was calculated from the shear modulus ( $G$ ), while the molecular mass between crosslinks was calculated using the Flory-Rhener equation<sup>10</sup>:

$$\ln(1 - V_2) + V_2 + \chi V_2^2 + \rho V_1 V_2^{1/3}/M_c = 0 \quad (3)$$

where  $\rho$  is the density of the rubber hydrocarbon,  $V_1$  is the molar volume of the solvent,  $V_2$  is the volume fraction of rubber in the swollen sample,  $M_c$  is the molecular weight between crosslinking, and  $\chi$  is the polar solvent interaction parameter given as ( $\chi = 0.44 + 0.18V_2$ ).

$$\text{Crosslinking densities}(\rho/M_c) = G/RT \quad (4)$$

#### Thermal ageing

Thermal aging was carried out in a thermostated air circulated multicell-ageing oven (Prolific Engineers, India) on the various test samples at 50, 60, 70, 80, 90, and 100°C for 110 h. The extent of thermal ageing was determined as the change in the physico-mechanical properties of the fresh (unaged) and oven-aged samples.

#### Oxygen ageing

This was carried out following the ASTM-D-518 method B<sup>11</sup> in an oxygen chamber maintained at a constant concentration on the various test samples at 40°C. The extent of oxygen ageing was determined as change in the physico-mechanical properties of the fresh (unaged) and oxygen-aged samples.

#### Ozone ageing

Ozone studies was under static conditions with a mast model 700-1 ozone test chamber on the various test samples at 40°C in accordance with ASTM-D-

518 method B.<sup>11</sup> Ozone concentration in the chamber was adjusted to 50 parts per hundred million (pphm). The extent of ozone ageing was determined as change in the physico-mechanical properties of the fresh (unaged) and ozone-aged samples.

#### Water ageing

This was performed by dipping the various test samples in distilled water maintained at 30°C for 30 days as contained in ASTM-D471-66.<sup>12</sup> The extent of water ageing was determined as change in the physico-mechanical properties of the fresh (unaged) and water-aged samples.

**Solvent resistances.** The resistance of the vulcanizates in toluene, carbon tetrachloride, acetone, ethanol, cyclohexane, mineral oil, and brake fluid were determined by using the methods described by De and De<sup>13</sup> with slight modification and reported as percentage swelling and solubility. In a typical swelling experiment, three different shapes of the cured sample (triangle, square, and rhombus) were cut from the 1-mm thickness mold and weighed before submerging each samples in its respective solvent in airtight bottles maintained at the specified various temperature(s) for 72 h. Experiments were carried out in triplicate. At the end of the swelling, the samples were removed from the solvent, carefully blotted to remove excess liquid on the surface, and the weights immediately taken. Thereafter, samples were further dried to a constant weight. The percentage increases in the weight of the samples were calculated as the swelling while the percentage loss in weight after drying to a constant weight was calculated as the solubility.

$$\% \text{Swelling} = \left( \frac{W_2 - W_1}{W_2} \right) \times 100 \quad (5)$$

$$\% \text{Solubility} = \left( \frac{W_1 - W_3}{W_1} \right) \times 100 \quad (6)$$

where  $W_1$  is the initial weight of the sample,  $W_2$  is the weight after swelling, and  $W_3$  is the weight after drying to a constant weight.

## RESULTS AND DISCUSSION

The results presented in Table II gave the physico-mechanical properties of the vulcanizates compounded with the recipe in Table I. The tensile strength varies from 24.8 MPa for mix A to 9.6 MPa for mix I, which shows a decrease of about 61.3% in the value of tensile result, suggesting that LMWNR has a low tensile strength. The tensile results gradually reduce from mix A to mix I, as the concentration of the LMWNR is increasing, which further confirms that the LMWNR is acting as a softener.

TABLE II  
Physico-Mechanical Properties of the Rubber Blends

Physico-mechanical properties	Mixes								
	A	B	C	D	E	F	G	H	I
Tensile Strength (MPa)	24.8	24.3	23.6	22.4	21	18.9	13.9	11.1	9.6
Modulus @ 50% (MPa)	2	1.8	1.8	1.7	1.5	1.4	1.2	1.2	1.1
Modulus @ 100% (MPa)	5.4	5	5	5	4.8	4.6	4.5	4.1	3.4
Modulus @ 300% (MPa)	8.0	7.9	7.7	7.7	7.4	7.1	6.8	6.5	5.7
Elongation at Break (%)	880	889	912	918	923	923	900	894	699
Shear modulus (G)	0.424	0.435	0.439	0.441	0.443	0.441	0.439	0.431	0.428
Crosslink Density $\times 10^{-4}$	1.6	1.6	1.6	1.5	1.5	1.5	1.4	1.4	1.4
M Mass between crosslink	5.5	5.6	5.6	5.6	5.4	5.4	5.3	5.2	5.1
Volume fraction of rubber( $V_2$ )	0.8	0.8	0.8	0.7	0.7	0.7	0.7	0.7	0.8
Hardness (IRHD)	58	58	56	55	52	50	48	46	42
Compression set	42	42	42	43	43	43	43	43	43
Abrasion resistance	61	61	60	58	56	56	52	49	46
Mooney viscosity	80	78	77	76	73	70	65	63	59

The modulus at 50% elongation (M50), 100% elongation (M100), and 300% elongation (M300) were found to be highest with mix A and reduced gradually to mix I. The result of the elongation at break also follows the trend observed in the modulus results. The observable trend in the tensile properties could have arisen because of the fact that LMWNR on its own is a bit soft (even it got sticky on the rollers during compounding) and this might have gradually softened the natural rubber as well, thereby reducing the tensile strength in relation to the quantity of LMWNR present in the blend.

The crosslinking density result was calculated from the volume fraction of the rubber in the swollen gel ( $V_2$ ) by using the Flory-Rhener equation shown above as eq. (3). The crosslinking density results were found to be nearly of the same magnitude from mix A to mix I, so also was the results of the volume fraction of rubber in the vulcanizates. These suggest that the LMWNR has acted as a plasticizer enhancing the incorporation of the compounding ingredients into the rubber matrix and permitting uniform distribution of the materials across the vulcanizates. This uniform distribution of the materials can also make the rubber interface to become rich with a higher degree of crosslinking throughout the interfacial region. The results of the molecular mass between crosslinks were observed to decrease from mix A to mix I. This could have probably been due to the higher molecular mass and higher percentage of NR present in mix A than in mix I. As the percentage of NR reduces, the molecular mass between the crosslink also reduces. The results of the hardness, compression set, abrasion resistance, and Mooney viscosities of vulcanizates reduce from mix A to mix I. This gave an indication that NR has a higher hardness, compression set, abrasion resistance, and Mooney viscosities values more than the LMWNR. This trend should be expected by mere looking at the physical texture of the LMWNR. The

LMWNR was found to be a soft material, even sticking on the rollers. One would not have expected such a soft and sticky material to impact any reinforcing characteristics on the vulcanizate, rather, the values of the hardness, Mooney viscosity, and abrasion resistance are supposed to be higher in vulcanizates having more natural rubber. Nevertheless, the physico-mechanical properties of all the vulcanizates from mix A to I are still within the accepted range for NR compounds, suggesting that such vulcanizates will find uses in some rubber products, where high tensile strength, high hardness, high abrasion, and high Mooney viscosity values are not of desirable importance like in mats, shoe soles, etc.

The results presented in Table III gave the thermal ageing values in terms of percentages. The results of the physico-mechanical properties of the vulcanizates after ageing at 100°C for 48 h were compared with their unaged results and are presented in Table III. The thermal ageing was carried out at 40, 50, 60, 70, 80, 90, and 100°C but the ageing results at 40, 50, and 60°C do not show any significant change, whereas slight changes were observed at temperatures of 70, 80, and 90°C. The ageing results at 100°C was used for this discussion because it shows clearly the thermal ageing effects more than the other temperatures of 40, 50, 60, 70, 80, and 90°C. The ageing results were calculated using the expression below:

$$\text{Extent of aging} = [(O - a)/O] \times 100 \quad (7)$$

where  $O$  is the original value for the fresh sample and  $a$  is the value after aging.

From the thermal ageing results in Table III, it will be observed from the extent of ageing that mix C gave the least percentage with a value of 6.4%, signifying a good thermal ageing resistant vulcanizate while mix A gave the highest percentage with a value of 12.2%, signifying mix A as having low thermal ageing

**TABLE III**  
**Physico-Mechanical Properties of the Rubber Blends After Ageing in Oven**

Physico-mechanical properties	Mixes								
	A	B	C	D	E	F	G	H	I
Tensile Strength (MPa)	12.2	10.3	8.1	5.4	7.3	11.2	13.6	14.4	10.3
Modulus @ 50% (MPa)	14.3	13.1	11.2	6.9	8.1	13	13.9	15.7	11.9
Modulus @ 100% (MPa)	13.6	13	12.1	6.6	7.9	13	13.7	14.9	11.4
Modulus @ 300% (MPa)	15.3	14.7	13.2	7.7	9.1	13.9	15.2	16.8	12.9
Elongation at Break (%)	10.3	10	9.5	5.9	7.1	9.2	11	12.3	9.7
Hardness (IRHD)	11.6	10.7	10	6.8	8.1	8.9	10.2	13.8	10.4
Compression set	9.9	9.9	9.3	7.1	8.7	9.9	10.7	12.1	8.9
Abrasion resistance	12.4	11.2	10.8	6.8	8.7	10	11	12.6	10.1
Mooney viscosity	14	13.2	11.8	7.9	9.3	10.9	13.8	15.2	12.8

resistant when compared with mix C. The ageing results of M50, M100, M300, elongation at break, hardness, compression, abrasion, and Mooney viscosity confirm that mix C has the least ageing percentages while mix A has the highest ageing percentages in the parameters measured. The lower the ageing percentage, the better the resistance to thermal ageing. Thus, the results have suggested that blending 90 parts of NR with 10 parts of LMWNR will improve the thermal ageing properties of the vulcanizate. The influence of LMWNR on the deterioration of the blends could be linked to the fact that when an unsaturated rubber is subjected to ageing, the hydrogen atom of  $\alpha$ -methylene carbon will be abstracted in the presence of oxygen, which will then initiate and oxidative reaction that can propagate autocatalytically and ends in chain scission, thereby affecting the formation of crosslinks. Since LMWNR has been documented as facilitating compounding and crosslinking of NR,<sup>1</sup> it can then be suggested that the LMWNR has facilitated formation of more crosslinks in the blends, thereby reducing the extent of the ageing of the vulcanizates. The results of this study is found to be in line with the work of Bhowmick and White,<sup>6</sup> but it is an improvement on their report, where thermal, UV, and sunlight ageing of NR/PE blends were investigated and found that thermal ageing caused tensile strength to deteriorate, especially at longer times.

Similar deteriorations were observed, but the presence of LMWNR reduced the extent of that deterioration. It is worth mentioning that during thermal ageing there was an initial slight increase in the tensile strength before degradation starts, which has been linked to continued crosslinking of the blend components by thermal ageing as a result of the fact that rubber vulcanizates are cured only at  $t_{90}$ , then the remaining 10% is kept as an allowance during service. Thus, thermal ageing completes this 10% curing, thereby resulting in the initial slight enhancement of the tensile strength.

Tables IV and V show the extent of oxygen and ozone degradation. The results were also presented in percentages as previously done for the thermal ageing using eq. (7) above. Looking at these results in Tables IV and V, it is clear that mix C in the two tables have the lowest percentage ageing values within the parameter measured viz-a-viz, TS, M50, M100, M300, EB, hardness, compression, abrasion, and Mooney viscosity while the highest percentage values were for mix A. It is scientifically believed that degradation reduces the life span of a material and also that thermal ageing, oxygen, and ozone deteriorates most materials which usually lead to shorter life span of materials. On the other hand, end users prefer materials that will have longer service life to justify the cost of purchase. The results

**TABLE IV**  
**Physico-Mechanical Properties of the Rubber Blends After Ageing in Oxygen**

Physico-mechanical properties	Mixes								
	A	B	C	D	E	F	G	H	I
Tensile Strength (MPa)	14.5	13.7	12.2	9.8	10.2	10.9	12.4	15.1	12.8
Modulus @ 50% (MPa)	16.3	15.1	14.3	12.0	12.6	13.0	14.8	16.6	14.1
Modulus @ 100% (MPa)	16.9	16.1	14.8	12.4	13.2	13.9	15.4	17.3	14.6
Modulus @ 300% (MPa)	17.5	16.7	15	13.2	13.8	14.6	16.0	18.2	15.4
Elongation at Break (%)	11.8	11.2	10.5	8.9	9.5	10.2	11.6	12.4	10.9
Hardness (IRHD)	12.4	11.8	10.9	9.2	10.1	10.8	12.1	13.0	11.3
Compression set	10.2	9.7	9.0	7.8	8.5	9.6	11.2	12.7	9.4
Abrasion resistance	13.6	12.8	11.4	9.3	10.0	10.9	12.5	14.4	12.0
Mooney viscosity	15.4	14.7	13.3	11.8	12.2	12.9	14.8	15.2	13.6

**TABLE V**  
**Physico-Mechanical Properties of the Rubber Blends After Ageing in Ozone**

Physico-mechanical properties	Mixes								
	A	B	C	D	E	F	G	H	I
Tensile Strength (MPa)	16.8	15.6	14.8	12.4	13.0	13.8	15.4	17.3	15.1
Modulus @ 50% (MPa)	18.5	17.8	16.6	14.4	15.1	15.8	17.2	19.8	16.9
Modulus @ 100% (MPa)	19.3	18.5	17.0	15.1	16.0	16.7	18.0	20.2	18.1
Modulus @ 300% (MPa)	20.9	20.2	19.3	17.0	17.8	18.7	20.3	22.1	19.7
Elongation at Break (%)	13.0	12.1	11.2	9.5	10.1	11.0	12.7	14.0	11.8
Hardness (IRHD)	13.5	12.8	11.9	9.9	10.7	11.8	13.8	15.3	12.4
Compression set	11.6	11.0	10.2	8.6	9.1	9.8	12.0	13.7	10.9
Abrasion resistance	14.8	14.1	13.1	11.0	11.6	12.3	14.0	15.7	13.5
Mooney viscosity	16.2	15.5	14.7	12.2	12.9	13.8	15.5	17.9	15.0

presented in Tables III–IV show improvements on the level of degradation of the vulcanizates, which is an indication for end users that they will derive more satisfaction from the materials compounded with such type of formulation from mix C. The results in Table VI gave the degradation pattern of the vulcanizates in water. The results were nearly of the same magnitude in all measured parameters, and this signifies that water uptake by the vulcanizates were negligible even after 30 days of ageing in water. The fact that the demand for rubbery materials of high temperature, oxygen, ozone, water, and weather resistance are increasing shows that blends of NR/LMWNR will find uses industrially. A study on accelerated ageing of rubber vulcanizates by Davies et al.<sup>5</sup> has shown that deterioration has effect on elongation at break, tensile strength, and modulus and this is also in line with our present study.

The swelling and solubility results in Table VII show that the vulcanizates from mix D gave the least swelling and solubility percentages while mix A gave the highest swelling and solubility percentages. The results in Table VII gave an indication that blending 80 parts of NR with 20 parts of LMWNR will surely improve swelling and solubility resistance of the material in the solvents used in the study. It was also observed that the vulcanizates were generally showing more affinities for toluene

and carbon tetrachloride. This was followed by acetone. Ethanol and cyclohexane penetrated almost at the same rate and followed acetone. Mineral oil followed cyclohexane while the vulcanizates showed the least resistance in brake fluid. Resistance of vulcanizates to solvents is usually enhanced by uniform distribution and dispersion of compounding ingredients in the rubber matrix, resulting from a well-crosslinked vulcanizate. Swelling of natural rubber has been documented by Baker et al.<sup>14</sup> to be influenced by various factors, such as crosslink type and density, amount, nature, and type of compounding ingredients and of elastomer. The swelling and solubility results have clearly signified that LMWNR facilitates crosslinking. It is also worth mentioning that swelling of the vulcanizates for longer periods (96 h and more) in toluene and carbon tetrachloride showed the vulcanizates from all the mixing schemes turning into slurry and the samples became difficult to weigh. This could have been responsible from prolonged penetrating power of the solvent by penetrating the vulcanizates through their segmental packing thereby weakening the resistance of the vulcanizate. It was also noticed that after swelling the samples for over 9 h in solvents and redried in a vacuum chamber, the weights recorded were lower than the original weight of the samples which can be due to some samples that might have possibly

**TABLE VI**  
**Physico-Mechanical Properties of the Rubber Blends After Ageing in Water**

Physico-mechanical properties	Mixes								
	A	B	C	D	E	F	G	H	I
Tensile Strength (MPa)	4.7	3.9	3.4	2.2	2.8	3.5	4.1	4.9	3.8
Modulus @ 50% (MPa)	5.1	4.8	4.1	3	3.5	3.9	4.7	5.6	3.6
Modulus @ 100% (MPa)	6.5	6.1	5.4	4.5	4.9	5.3	5.9	6.6	5.2
Modulus @ 300% (MPa)	7.3	6.8	6.1	4.8	5.4	5.8	6.7	7.9	5.9
Elongation at Break (%)	4.9	4.0	3.2	2.4	2.9	3.1	4.1	5.3	3.3
Hardness (IRHD)	7.7	7.0	6.3	4.8	5.2	5.8	6.5	8.0	6.4
Compression set	6.2	5.7	5.1	3.5	4.0	4.6	5.7	7.2	5.8
Abrasion resistance	8.5	8.1	7.3	5.5	6.1	6.5	7.2	8.5	7.0
Mooney viscosity	9.1	8.0	7.2	5.6	6.3	6.9	7.6	8.9	7.1

**TABLE VII**  
**Swelling and Solubility Parameters of Blends of NR/LMWNR in Various Solvents**

Solvents	Mixes	W1	W2	W3	% swelling	% solubility
Toluene	A	0.3617	0.4379	0.3317	17.4	8.3
	B	0.3921	0.4719	0.3608	16.9	8.0
	C	0.3711	0.4445	0.3433	16.5	7.5
	D	0.3765	0.4424	0.3531	14.9	6.2
	E	0.3521	0.4162	0.3289	15.4	6.6
	F	0.3862	0.4581	0.3599	15.7	6.8
	G	0.3678	0.4384	0.3428	16.1	6.8
	H	0.3441	0.4121	0.3193	16.5	7.2
	I	0.3340	0.4004	0.3099	16.6	7.2
Carbon tetrachloride	A	0.4145	0.4995	0.3810	17.0	8.1
	B	0.3894	0.4652	0.3594	16.3	7.7
	C	0.4281	0.5072	0.3973	15.6	7.2
	D	0.4390	0.5110	0.4131	14.1	5.9
	E	0.4202	0.4926	0.3933	14.7	6.4
	F	0.4153	0.4897	0.3879	15.2	6.6
	G	0.4458	0.5301	0.4146	15.9	7.0
	H	0.4036	0.4822	0.3745	16.3	7.2
	I	0.4370	0.5221	0.4042	16.3	7.5
Acetone	A	0.3331	0.3951	0.3101	15.7	6.9
	B	0.3604	0.4250	0.3362	15.2	6.7
	C	0.3379	0.3952	0.3173	14.5	6.1
	D	0.3596	0.4143	0.3423	13.2	4.8
	E	0.3352	0.3880	0.3181	13.6	5.1
	F	0.3671	0.4268	0.3476	14.0	5.3
	G	0.3390	0.3956	0.3204	14.3	5.5
	H	0.3164	0.3713	0.2977	14.8	5.9
	I	0.3042	0.3575	0.2856	14.9	6.1
Ethanol	A	0.3549	0.3996	0.3368	11.2	5.1
	B	0.3175	0.3559	0.3026	10.8	4.7
	C	0.3384	0.3772	0.3235	10.3	4.4
	D	0.3811	0.4188	0.3667	9.0	3.8
	E	0.3422	0.3768	0.3285	9.2	4.0
	F	0.3663	0.4043	0.3513	9.4	4.1
	G	0.4254	0.4722	0.4067	9.9	4.4
	H	0.4637	0.5164	0.4424	10.2	4.6
	I	0.4441	0.4951	0.4237	10.3	4.6
Cyclohexane	A	0.3516	0.3946	0.3344	10.9	4.9
	B	0.3672	0.4107	0.3503	10.6	4.6
	C	0.3778	0.4203	0.3616	10.1	4.3
	D	0.3439	0.3771	0.3312	8.8	3.7
	E	0.3697	0.4067	0.3549	9.1	4.0
	F	0.3501	0.3869	0.3351	9.5	4.3
	G	0.3681	0.4081	0.3519	9.8	4.4
	H	0.3470	0.3859	0.3310	10.1	4.6
	I	0.3461	0.3862	0.3298	10.4	4.7
Mineral oil	A	0.3810	0.4128	0.3669	7.7	3.7
	B	0.3469	0.3746	0.3351	7.4	3.4
	C	0.3600	0.3867	0.3489	6.9	3.1
	D	0.3973	0.4235	0.3865	6.2	2.7
	E	0.3714	0.3973	0.3607	6.5	2.9
	F	0.3503	0.3754	0.3394	6.7	3.1
	G	0.3499	0.3763	0.3387	7.0	3.2
	H	0.3397	0.3664	0.3288	7.3	3.2
	I	0.3315	0.3576	0.3209	7.3	3.2
Brake fluid	A	0.4191	0.4444	0.4086	5.7	2.5
	B	0.3694	0.3909	0.3609	5.5	2.3
	C	0.3990	0.4213	0.3906	5.3	2.1
	D	0.3793	0.3984	0.3728	4.8	1.7
	E	0.3487	0.3667	0.3421	4.9	1.9
	F	0.3667	0.3864	0.3597	5.1	1.9
	G	0.3726	0.3927	0.3652	5.1	2.0
	H	0.3371	0.3559	0.3300	5.3	2.1
	I	0.3764	0.3974	0.3681	5.3	2.2

gone into solution, and this accounts for the solubility percentages.

### CONCLUSIONS

This work has proved and found low molecular weight natural rubber as being compatible with NR. It also shows LMWNR as having a positive influence in reducing the degradation rates of vulcanizates under thermal, oxygen, ozone, and water ageing. For vulcanizates with best thermal ageing, oxygen, ozone, and water ageing, formulation with 90 part NR and 10 parts LMWNR is recommended while for vulcanizates of good resistance to solvents, formulation with 80 part NR and 20 parts LMWNR is recommended. Toluene and carbon tetrachloride were found penetrating all the vulcanizates more and faster than acetone, ethanol, cyclohexane, mineral oil, and brake fluid. Finally, for materials where high tensile strength is not compulsory, blends of 90 parts of NR and 10 parts of LMWNR is recommended for longer service life.

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### References

1. Okieimen, F. E.; Akinlabi, A. K. *J Appl Polym Sci* 85, 2002, 1070.
2. Perera, M. O.; Bradbury, J. H. *Epoxidized Natural Rubber*; Australian National University, Chemistry Department, Canberra, Australia, 1992; A.C.T. 2600, pp 1–12.
3. United Nations Office for Project Development. *Development of the applications of liquid natural rubber (UNIDO—project final report Abidjan, 1989.*
4. Akinlabi, A. K.; Okieimen, F. E.; Aigbodion, A. I. *Polym Adv Technol* 16, 2005, 1.
5. Davies, K. M.; Lloyd, D. G. In *Development in Polymer Stabilisation*; Scott, G. Ed. Applied Science: London, 1981; Vol.4.
6. Bhowmick, A. K.; White, J. R. *J Mater Sci* 37, 2002, 5141.
7. ASTM, *Annual Book of ASTM Standards, Section 9, Vol 09, 1989*, p 851.
8. Professional Association of Natural Rubber in Africa (ANRA). *Standard African Rubber SAR Manual No. 2, Specification and Test Methods Abidjan; 1998.*
9. BS-903. *Determination of Natural Rubber Hardness, Part A26, England, 1995.*
10. Flory, P.; Rhener J. *J Chem Phys* 11, 1943, 521.
11. ASTM, *Oxygen and Ozone Test Methods—B, 1989, ASTM-D-518.*
12. ASTM, *Water Ageing Test Methods, 1986, D471-66.*
13. De, P. P.; De, S. K.; Alex, K. *J Polym Sci C* 27, 1989, 361.
14. Baker, C. L. S.; Gelling, I. R.; Newell, R. *Rubb Chem Technol* 58, 1985, 67.