Development of Novel Elastomeric Blends Containing Natural Rubber and Ultra-Low-Density Polyethylene

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ABSTRACT: This study sought to develop novel elastomeric compounds using natural rubber (NR) and ultra-low-density polyethylene (ULDPE). Blends were prepared by means of a two-roll mill for three ratios (70/30, 60/40, and 50/50 NR/ULDPE). Conventional vulcanization was performed in a compression mold. The physical and mechanical properties of the blend were determined according to ASTM standards. The results were compared with those obtained from NR blended with styrene-butadiene rubber (SBR). The morphological examinations with scanning electron microscopy indicated that ULDPE was compatible with NR; thus, the addition of a compatibilizer was not necessary. The cocontinuous phase was dominant in the NR/ULDPE blend containing 50 and 60 wt % NR. The tensile properties, tear resistance, and aging resistance of the NR/ULDPE blends were found to be superior to those of NR/SBR blends. On the other hand, the abrasion and flex cracking resistances of the NR/ULDPE blend were inferior to those exhibited by SBR blends but the Mooney viscosity and resilience of both blends fell in the same range. However, the addition of dicumyl peroxide appeared to have caused crosslinking of the ULDPE phase in the blend, which in turn increased the tensile properties and abrasion and aging resistance. The properties of the tertiary NR/SBR/ULDPE blend were investigated as well. © 2001 John Wiley & Sons, Inc. J Appl Polym Sci 82: 650–660, 2001

Key words: natural rubber; rubber blend; ultra-low-density polyethylene elastomer blend; styrene-butadiene rubber

INTRODUCTION

It is well established that elastomers do not exhibit all of the properties that are desired, and they are often blended with a second elastomer

during processing. Elastomer blends are used for many reasons such as lowering the compound cost, the product may be more easily fabricated in complex shapes during production, and the final performance can be beneficially modified. Natural rubber (NR) and styrene-butadiene rubber (SBR) have been blended for a long time for these reasons.[1–3] Blending SBR with NR can improve the tensile strength because NR crystallizes on stretching. At present, compounds are designed based on the rule of thumb that SBR requires less

sulfur and more accelerator than NR because of the lower unsaturation on SBR.

The process of NR blending has been widely studied. For example, blends of ethylene-vinyl acetate copolymer and NR were reported as good compatible blends that provide desirable mechanical properties.[4–11] Kim[12] investigated the mechanical properties of NR blended with styrene-ethylene/butylene-styrene grafted with maleic anhydride. The mechanical properties of this blend were not improved, and it required reinforcement with carbon and glass fibers to improve the mechanical properties. Recently, a study of elastomer blends based on NR for certain applications was performed.[13]

One of the new thermoplastic elastomers developed in the 1990s was the polyolefin elastomers (POE).[14] They are ethylene-octene (EO) copolymers developed from single-site INSITE metallocene catalyst technology, which are products of the Dow Chemical Company. The POEs contain typically over 20% by weight of octene comonomer and have densities of 0.880–0.864 g/mL. They are also called ultra-low-density polyethylene (ULDPE). They have a low propensity for chain scission because of the reduced frequency of tertiary hydrogen molecules. This also results in improved UV stability.[15] Compared to SBR, ULDPE shows minimal degradation, superior heat resistance, and higher ozone resistance because of its saturation. Systematic correlation of the EO copolymer composition, referred to as a density, with the crystallinity, morphology, and tensile behavior was reported by Hiltner and coworkers[16–20] who classified the EO copolymers into types I–IV. Type I copolymers with densities of less than 0.89 g/mL have no lamellae or spherulites. Fringed micellar or bundled crystals are inferred from the low degree of crystallinity, the low melting temperature (T_m), and the granular, nonlamellar morphology. Tensile deformation of the type I copolymer with density less than 0.88 g/mL (ULDPE) had elastomeric characteristics with a low initial modulus and macroscopic uniformity.

The superior properties of ULDPE to SBR and the more similar chemical composition of ULDPE than SBR compared to NR may contribute a higher aging and ozone resistance in the NR/ULDPE blend than the NR/SBR blend. Compatibility should be obtained from the NR/ULDPE blend as well. A new elastomeric blend, NR/ULDPE, is expected to reduce or eliminate some limitations

of the NR/SBR blend in terms of mechanical properties and processabilities. The objectives of the present study were to explore the processability of the NR/ULDPE blend and evaluate the physical and mechanical properties of this blend. Comparisons were made with NR/SBR blends. In this article we present the results of our studies on the unfilled vulcanized system. A comparison of the properties of a binary blend (NR/ULDPE) with those of a tertiary blend (NR/SBR/ULDPE) and the effects of crosslinking in the ULDPE on the properties are reported.

EXPERIMENTAL

Materials

The type of NR employed was STR5L-graded Standard Thai Natural Rubber. The ULDPE was Engage® 8150, a saturated EO copolymer containing 25% octene comonomer with a density of 0.868 g/mL. The SBR was general purpose grade petroFlex® 1502 with a styrene content of 23.5%. The compounding chemicals included activators (stearic acid and zinc oxide), antioxidant (Vulkanox PAN®), accelerator (Vulkacit CZ®), and vulcanizing agent (sulfur). Dicumyl peroxide (DCP) was analytical grade. All materials were used as received.

Blend Preparation

Elastomer blending and compounding were performed in a Yasuda Seiki® 191TM two-roll mill. The NR was masticated prior to blending with SBR and/or ULDPE, then the elastomers were mixed together until homogenization before adding the chemicals. The chemicals were added in the following order: activators (5 phr ZnO and 2 phr stearic acid), antioxidant (1 phr), accelerator (1.2 phr), and vulcanizing agent (2.5 phr). The chemical content was based on the NR and SBR content. Mixing DCP into the NR/ULDPE blends was classified as methods 1 and 2.

The setting temperatures of the two-roll mill were about 75 and 65°C for the front and back rolls, respectively. The front to back roll speed ratio was 1:1.23. Compounded elastomeric blends were left overnight at ambient temperature in a desiccator prior to compression molding. Compression molded sheets were prepared at 130 or 140°C under a pressure of 600 kg/cm² for 30 min

Table I   Sample Designation and Its Blend Composition

Sample	NR (wt %)	SBR (wt %)	ULDPE (wt %)	DCP (wt %)
S30	70	30	—	—
S40	60	40	—	—
S50	50	50	—	—
U30	70	—	30	—
U40	60	—	40	—
U50	50	—	50	—
S15U15	70	15	15	—
S20U20	60	20	20	—
S25U25	50	25	25	—
U30X	70	—	30	1
U40X	60	—	40	1
U50X	50	—	50	1

to produce 1 and 3 mm thick sheets for the mechanical and physical properties tests. The blend compositions and sample designations are listed in Table I.

Physical and Mechanical Properties

The physical and mechanical property testing methods are tabulated in Table II. Tensile testing was conducted at a tension speed of 500 mm/min. Tear resistance was investigated at a speed of 500 mm/min. The 7 mm thick specimens were employed for testing of flex cracking resistance as recommended in ASTM D813. Thermal aging was conducted according to two methods: ASTM D572 at 70°C for 7 days and ASTM D573 at 70°C for 3 days and 100°C for 2 days. The tensile testing before and after aging was carried out according to ASTM D412. The aging resistance is expressed as a percentage of the change in each tensile property (300% modulus, tensile strength, elongation at break), which was calculated as follows:

$$P = [(A - O)/O] \times 100$$

where P is the percentage change in the property, O is the original value, and A is the value after aging. Increases are indicated as positive and decreases as negative.

Blend Morphology

The fracture surfaces of tensile tested specimens were immersed in p-xylene in an ambient environment for 1–5 days and dried in a vacuum oven at room temperature for 1 day. Specimens were mounted on stubs and coated with 270 Å thick gold. The microscope analysis was done using a Jeol JSM5800LV.

## RESULTS AND DISCUSSION

Morphology

The fracture surfaces of specimens etched with p-xylene are shown in Figure 1(a–c). Uncrosslinked ULDPE was dissolved in p-xylene, which left holes on the surface. The 50/50 and 60/40 NR/ULDPE blends appeared to be cocontinuous while ULDPE became the dispersed phase in the 70/30 blend. A cocontinuous phase is quite common in general 50/50 blends (unfilled), including NR/SBR, NR/BR, NR/chloroprene, NR/ethylene-propylene-diene monomer, and NR/CIIR blends.[21] A cocontinuous phase implies that an interpenetrating polymer network exists. In conventional rubber-mixing techniques equal-volume fractions and equal viscosities of the compo-

**Table II   Physical and Mechanical Testing Methods**

Property	Standard Method	Equipment
Mooney viscosity, ML(1 + 4) at 100°C	ASTM D1646	Toyoseiki® OSK 10162
Hardness Shore A	ASTM D2240	Zwick® 7206
Resilience (vertical rebound)	ASTM D2632	Resiliometer
Abrasion resistance	ASTM D3389	TABER® 5131
Tensile properties	ASTM D412, die C	LLOYD® 1000S
Tear resistance	ASTM D624, die C	LLOYD® 1000S
Flex cracking resistance	ASTM D813	De Mattia Flexing Machine
Thermal aging resistance	ASTM D572	Tabai® gphh-200 Geer Oven and LLOYD® 1000S
	ASTM D573	Memmert® Air Oven and LLOYD® 1000S
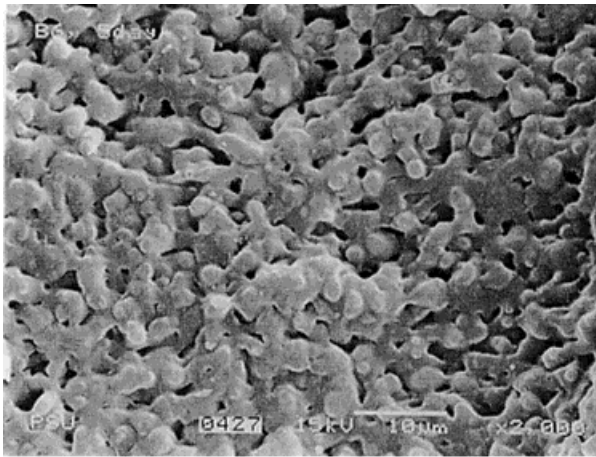
(a)
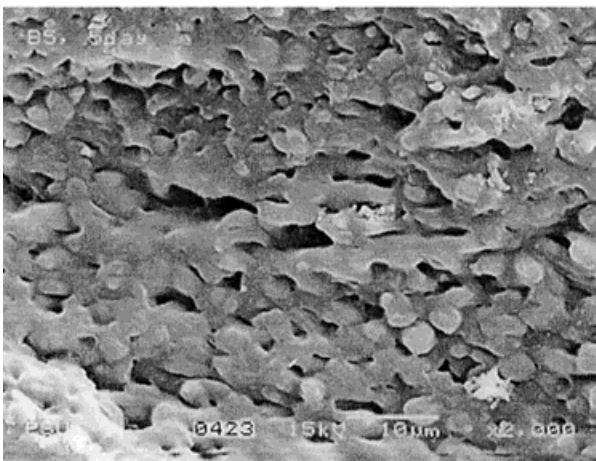
(b)
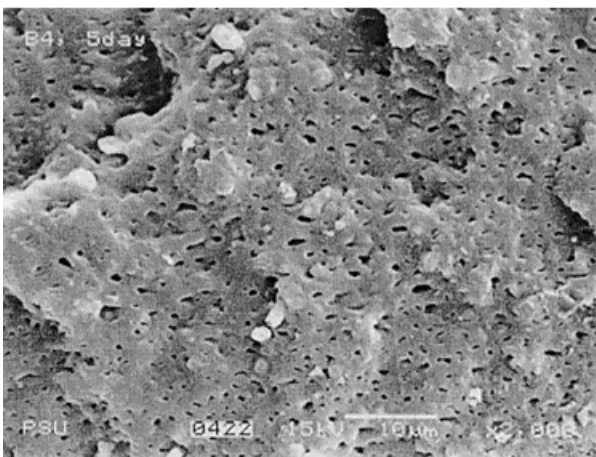
(c)

Figure 1   Scanning electron microscopy micrographs of the NR/ULDPE blends after etching with *p*-xylene: (a) U50 (50/50), (b) U40 (60/40), and (c) U30 (70/30).

nents favor cocontinuity.[22] Generally, the NR/SBR blend showed relatively good homogeneity. Homogeneity is favored by similarity in polymer viscosities and solubility parameters, as well as by the presence of polar groups. The blending between NR and SBR is homogeneous because they are nonpolar and have rather similar solubility parameters [(16.7 and 17.5) $\times$ 10^3 $(J/m^3)^{1/2}$, respectively].[13] In the present study the NR/SBR blends were vulcanized; therefore, phase separation was not observed because of the crosslinking in both elastomers. In Figure 1(a–c) the phase distribution appears to be uniform without a noticeable gross-phase segregation. This suggested compatibility of the blend and implied no compatibilizer was necessary; the compatibility was homogeneous on a macroscopic scale but not on a segmental level. Furthermore, the mechanical properties of the NR/ULDPE blend also pointed to compatibility as described later. The morphology of the compatible elastomer blends is dependent upon the mixing procedure and rheological properties of the blend components, as well as thermodynamic considerations.[21] The compatibility in this new blend may be attributed to similarity in the microstructure and the nonpolarity of NR and ULDPE. The ULDPE is closer to NR's chemical structure than SBR's because ULDPE consists of only carbon and hydrogen while SBR contains a benzene ring in its structure.

Crosslinking in ULDPE was caused by the addition of DCP. The etched specimen of the blend containing 50% ULDPE with 1% DCP is shown in Figure 2. It appears that *p*-xylene could not dissolve the ULDPE, there were no holes, and only a rough texture due to the solvent attack was visi-
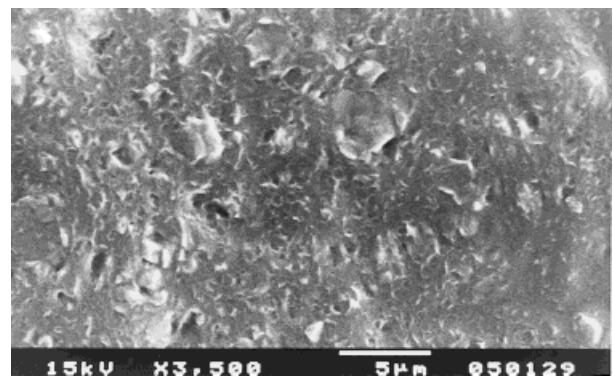

Figure 2   A scanning electron microscopy micrograph of the 50/50 NR/ULDPE blend containing dicumyl peroxide after etching with *p*-xylene.

Table III   Physical Properties of Parent Elastomers and Elastomer Blends

Sample	Mooney Viscosity[a]	Hardness (Shore A)	Resilience (%)	Abrasion Resistance[b]
NR	72.0	45	73	0.0744
SBR	49.3	48	59	0.1164
ULDPE	49.5	70	60	0.1556
S30	56.0	47	60	0.1186
S40	54.4	47	54	0.0991
S50	53.4	48	58	0.1549
U30	51.1	51	60	0.7712
U40	51.0	53	61	1.0677
U50	51.1	54	57	1.1541
S15U15	—	49	56	0.2818
S20U20	—	50	57	0.5851
S25U25	—	51	57	0.6663
U40X-1	—	57	59	0.7245
U50X-1	—	60	60	0.6297
U40X-2	—	57	60	0.6839
U50X-2	—	60	57	0.6892

X-1 and X-2, adding dicumyl peroxide by using methods 1 and 2, respectively.
[a] ML(1 + 4) at 100°C.
[b] Weight loss (g)/3000 cycles.

ble. The etched surface of the U50X specimen in Figure 2 looks similar to those of crosslinked NR, SBR, and NR/SBR blends. This morphology verified that DCP gave rise to crosslinking in ULDPE. The presence of crosslinking in ULDPE was confirmed by a swelling test. Without DCP the neat ULDPE was completely dissolved in *p*-xylene. In contrast, swollen ULDPE was obtained from ULDPE containing DCP.

NR/ULDPE Blends Versus NR/SBR Blends

Processability depends on the viscosity of the elastomer. The Mooney viscosities of ULDPE and SBR were in the same range and lower than that of NR (Table III). The NR/ULDPE blends seemed to flow slightly easier than the NR/SBR blends. This implied that the processability of both blends was insignificantly different.

The ULDPE displayed higher hardness than NR and SBR (Table III), which suggested a higher modulus. Keep in mind that the present study was a nonblack system. Because NR and SBR showed similar hardness, the hardness of NR/SBR blends fell in the same range as their parent elastomer. The NR/ULDPE blends were about 10% harder than NR/SBR blends. This was attributable to the higher hardness of ULDPE. The hardness of the new blends was closed to the

additivity line or the rule of mixture. The comparable viscosity and hardness properties of NR/SBR and NR/ULDPE blends were remarkable. There was also a resemblance in the resilience property of NR/SBR and NR/ULDPE blends. The resilience of ULDPE and SBR was similar (Table III); hence, both blends had similar rebounding characteristics.

One of the outstanding properties of unfilled NR is its high tensile strength due to strain-induced crystallization. On the other hand, SBR does not crystallize on stretching and requires reinforcement (i.e., carbon black or silica) to obtain good mechanical properties.[22] The NR/SBR compatible blend shows high tensile strength.[23] The stress–strain curves of NR and SBR in the present study are illustrated in Figure 3. The tensile characteristics of ULDPE are unique (Fig. 3). The initial modulus was higher than that of NR and SBR. Its tensile strength was between the NR and SBR values. The ULDPE could not crystallize on stretching due to irregularity in the chain structure. In general, ULDPE is a transparent, amorphous polymer, but it is able to partially crystallize. Based on DSC experiments, we observed that the melting range was very broad from 15 to 70°C and showed the highest peak T_m at 44°C. On the cooling scan the crystallization

temperature (T_c) was 34°C. The degree of crystallinity was very small at 9 and 6% for the T_m and T_c, respectively. Our results coincided with the study of Turek and coworkers[15] who reported T_m and T_c at 52 and 40°C, respectively. The rubber elasticity behavior of ULDPE was not as perfect as NR. The as-received ULDPE showed incomplete recovery after breaking. Permanent deformation appeared on tensile tested specimens as wrinkling along the gauge of the specimens, and a twofold increase in specimen length was noticed. Below 400% strain the ULDPE showed higher modulus than NR and SBR. The wrinkling on the tensile tested specimens was observed in the 50/50 NR/ULDPE blend as well.

The tensile properties of NR/ULDPE blends seemed to be synergistic. They were above the parent elastomers, or they at least agreed with the rule of mixture. The stress–strain behavior of 40% SBR (S40) and 40% ULDPE (U40) blends are shown in Figure 3. Strain-induced crystallization in the NR phase was discernible in these blends. The tensile properties of all the blends are tabulated in Table IV and demonstrated in Figure 4(a–c). The NR/ULDPE blends exhibited a higher 300% modulus and tensile strength (about 30%) than the NR/SBR blends. Their elongation at break was in about the same range. Comparing at the same composition, NR/ULDPE blends yielded better tensile properties than NR/SBR blends. This is the advantage of ULDPE, although it is uncrosslinked elastomer. We believe that the synergistic behavior of the NR/ULDPE was due to compatibility arising from the similarity in microstructure and nonpolarity of both materials, as well as the rubberlike characteristics of ULDPE.
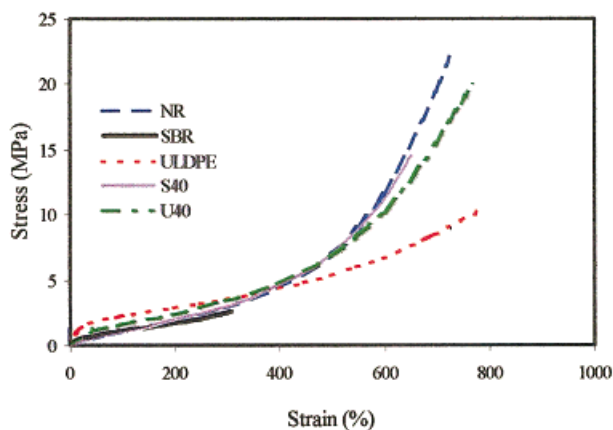
Table IV   Tensile Properties of Parent Elastomers and Elastomer Blends

Sample	$E_{300\%}$ (MPa)	σ_b (MPa)	ε_b (%)
NR	3.12	27.75	777
SBR	2.66	2.58	280
ULDPE	3.68	12.71	799
S30	2.83	17.75	739
S40	2.57	17.91	772
S50	2.74	15.68	736
U30	2.72	22.36	883
U40	3.43	23.43	821
U50	3.59	21.22	801
S15U15	3.23	18.57	682
S20U20	3.46	18.60	690
S25U25	3.12	15.63	676
U30X-1	3.51	28.25	808
U40X-1	3.56	28.29	827
U50X-1	3.92	18.30	673
U30X-2	3.50	25.80	773
U40X-2	3.42	23.74	766
U50X-2	3.79	16.38	617

The tear resistance was calculated from the force required for a tearing rupture per unit thickness of the test piece (ASTM D 624). In low hardness stocks the high gum strength polymers, such as NR, gave higher tear levels than low gum strength types, such as SBR.[24] Undoubtedly, the tear resistance of the unfilled SBR in the present study was much lower than that of NR (Table V). The tear resistance of ULDPE was in the same range as NR. Therefore, the tear resistance of NR/ULDPE blends was about 20% higher than that of NR/SBR blends, indicating the improved property in the new blend.

In general, for elastomers that react with oxygen resulting in crosslinking, the accelerated aging tests would result in increases in tensile stress at a given elongation and decreases in ultimate elongation. For elastomers that react with oxygen resulting in chain scission, the accelerated aging tests would result in decreases in tensile stress at a given elongation and either increases or decreases in ultimate elongation, depending on the extent of degradation. The best system would be the one that gave the lowest change in properties in the accelerated aging tests. The new NR/ULDPE blend showed higher thermal aging resistance than the NR/SBR blend. The first test was carried out at 70°C for 7 days in the Geer oven. The two types of samples used were with

Figure 3 Stress–strain curves of NR, SBR, ULDPE, S40, and U40.

and without antioxidant. In both cases a smaller change in tensile properties was derived from the NR/ULDPE blend for all blend compositions [Fig. 5(a–c)]. A larger difference was obtained from samples without antioxidant. A change in the
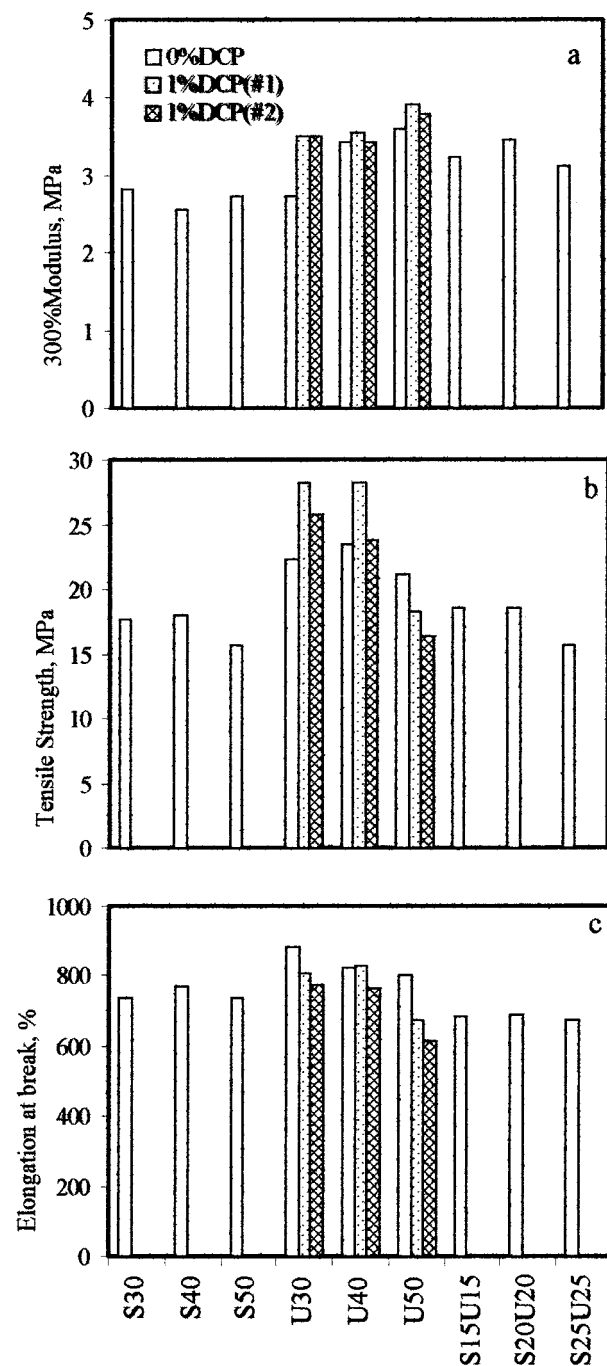
Table V   Tear Resistance of Parent Elastomers and Elastomer Blends

Sample	Tear Resistance (kN/m)
NR	29.1
SBR	7.7
ULDPE	27.0
S30	25.9
S40	20.7
S50	21.1
U30	32.0
U40	26.3
U50	26.4
S15U15	24.18
S20U20	22.16
S25U25	19.35

Figure 4 The tensile properties of the samples showing the effect of crosslinking in ULDPE: (a) 300% modulus, (b) tensile strength, and (c) elongation at break.

300% modulus equals 100% refers to the elongation at break after aging is lower than 300%. The NR/ULDPE blends still exhibited better oxidation resistance than NR/SBR blends under various aging conditions. Figure 6 illustrates the changes in tensile properties after thermal aging at 70°C for 3 days in the air oven, and Figure 7(a–c) illustrates the changes in tensile properties after thermal aging at 100°C for 2 days in the air oven. Both experiments employed nonantioxidant samples. Undoubtedly, saturation of ULDPE played an important role in the improved aging resistance. The heat resistance of ULDPE is higher than that of NR and SBR[14] and may impart better thermal aging. The mechanisms of degradation are beyond the scope of the present study.

So far the physical properties were similar for both blends, and the mechanical properties of the NR/ULDPE blend seemed to be better than those of the NR/SBR blend. However, ULDPE provided inferior abrasion and flex cracking resistance properties (Tables III, VI). The higher the ULDPE content, the lower the abrasion resistance. This resulted from the absence of crosslinking in the ULDPE. The neat ULDPE showed high abrasion resistance, similar to SBR. Keep in mind that the neat ULDPE specimen had no chemicals or filler. The chemicals in NR/ULDPE blends may have acted as stress concentrators and weakened the ULDPE in the blend. During testing the chemicals were rubbed out and the induced ULDPE rubbed out, too. We assumed that the crosslinking in ULDPE should improve this defect. The addition of 1% DCP improved the abrasion resistance up to 46% as illustrated in Table

III. The flex cracking resistance of the 60/40 NR/ULDPE blend was the best. We believed that the low flex cracking resistance of the new blend due to the uncrosslinked nature of ULDPE and crosslinking in the ULDPE may improve this property.
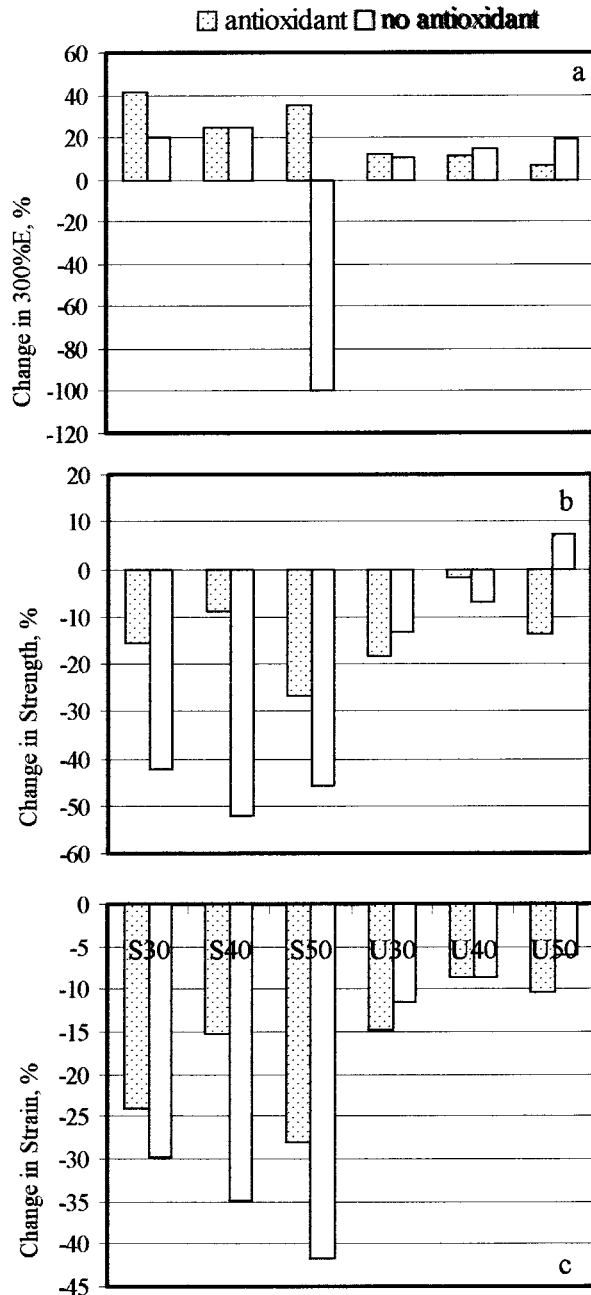

Figure 5 The percentage of change in the tensile properties of the samples after thermal aging at 70°C for 7 days in a Geer oven: (a) 300% modulus, (b) tensile strength, and (c) elongation at break.
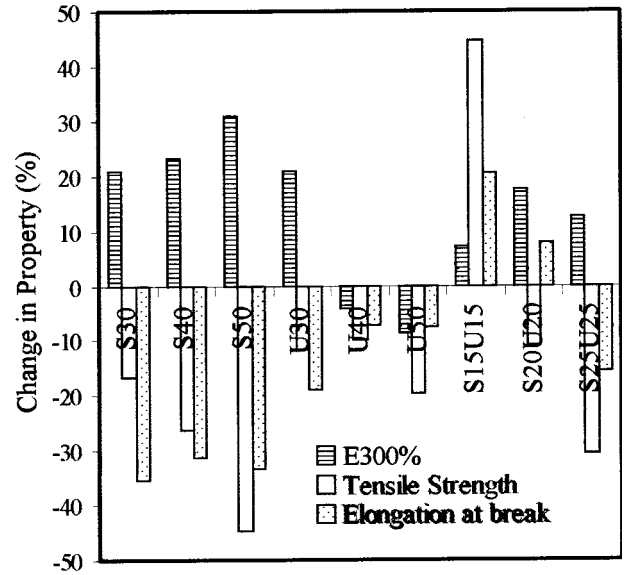

Figure 6 The percentage of change in the tensile properties of the samples without DCP after thermal aging at 70°C for 3 days in an air oven.

In this section we saw that the NR/ULDPE blend was better than the NR/SBR blend in terms of tensile properties, thermal aging resistance (oxidation resistance), and tear resistance. The Mooney viscosity, hardness, and resilience were similar. The abrasion and flex cracking resistance could be improved by crosslinking in the ULDPE. The 60/40 NR/ULDPE blend seemed to be the best one, based on the overall properties.

Binary NR/ULDPE Blends Versus Tertiary NR/ULDPE/SBR Blends

The hardness and resilience of the tertiary blends did not change significantly compared to the binary blends, and these values were close to the values of NR/SBR blends (Table III). The tertiary blends showed better abrasion resistance than binary blends but still lower than NR/SBR blends (Table III). Similar to the binary blend, the higher ULDPE content in the tertiary blend showed lower abrasion resistance. Regarding the same NR content, the tertiary blend contained less thermoplastic elastomer (ULDPE) or more vulcanized rubber than the binary blend. Therefore, an increase in abrasion resistance was derived from the tertiary blends.

The tensile properties of the tertiary blends became worse than those of the binary blends (Table IV). Although the 300% modulus was sim-

ilar, the tensile strength and elongation at break were lower [Fig. 4(a–c)]. Compared to NR/SBR blends, the tertiary blends were not better and the elongation at break seemed to be lower as well.

The tear resistance of the tertiary blends appeared to be lower than that of the binary blends, and the resistance decreased as the NR content
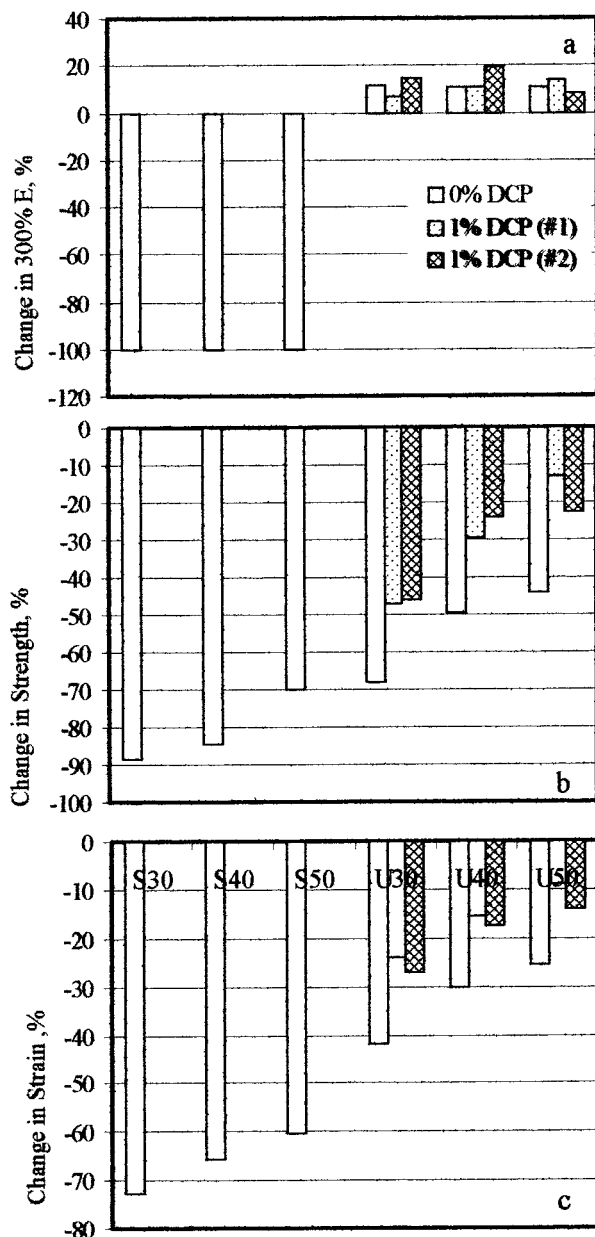
Table VI Flex Cracking Resistance of Elastomer Blends

Sample	No. Cycles	Results
S30	100,000	No crack observed
S40	100,000	No crack observed
S50	100,000	No crack observed
U30	85,000	Tiny crack observed
U40	100,000	No crack observed
U50	65,000	Tiny crack observed

decreased (Table V). The thermal aging resistance (oxidation resistance) of the binary blends (NR/ULDPE) was superior to the tertiary blend (Fig. 6). The inferior properties of the tertiary blend may have come from thermal degradation during processing that required a longer blending time, causing a decrease in the molecular weight. It should be noted that the tertiary blend containing 60% NR seemed to be the best among the blends in terms of tensile properties and aging resistance. Nonetheless, the tertiary blends showed no improvement compared to the binary blend.

Effect of Crosslinking in ULDPE: NR/ULDPE Versus NR/xULDPE Blends

Slightly chemically crosslinked ULDPE was prepared by adding 1% DCP. The occurrence of crosslinks was examined by the swelling test. The as-received ULDPE was dissolved in p-xylene. The ULDPE containing 1% DCP (xULDPE) swelled in p-xylene. Some of the physical properties of NR/xULDPE blends were slightly changed from the NR/ULDPE blends (Table III). The hardness was slightly increased and the resilience was insignificantly changed compared to the blends without DCP. In contrast, adding DCP significantly improved the abrasion resistance (about 46%). The tensile behavior of blends containing DCP was similar to those without DCP. The chemical crosslinks influenced the tensile strength and elongation at break (Table IV, Fig. 4). The strength increased approximately 20%, while the elongation at break decreased approximately 10%. The modulus at 300% strain tended to be higher. The large effect of the chemical crosslinks also appeared in the oxidation resistance. A smaller change in the tensile strength and elongation at break after thermal aging was obtained [Fig. 7(b,c)]. Compared to NR/SBR

Figure 7 The percentage of change in the tensile properties of the samples without DCP after thermal aging at 100°C for 2 days in an air oven: (a) 300% modulus, (b) tensile strength, and (c) elongation at break.

blends, the NR/*x*ULDPE blends exhibited much higher aging resistance. The changes in the 300% modulus depended on the method of mixing [Fig. 7(a)]. Adding DCP by method 1 provided better properties than method 2 experimentally, and the 40/60 NR/*x*ULDPE blend was the best blend in the present study.

The rubber elasticity of EO copolymers was studied by Bensason and coworkers.[20] Their approach was that these elastomers followed the slip-link theory, and a physical network built on fringed micellar crystal junctions and entanglements was invoked to account for the elastomeric response. This concept was close to the one used for describing the elasticity of thermoplastic elastomers.[25] The presence of 1% DCP caused chemical crosslinking and produced stronger elastomers and negligibly interferred with the elastomeric response. Based on our observation, this *x*ULDPE showed stress–strain behavior similar to ULDPE. All secant moduli and the tensile strength of *x*ULDPE were higher, whereas the elongation at break was about the same. We believe that the improvement in abrasion resistance, tensile strength, and aging resistance of the NR/*x*ULDPE blend came from chemical crosslinks in the ULDPE, although DCP could induce crosslinking in NR.

CONCLUSIONS

The following conclusions may be drawn from this study:

1. Compared to the NR/SBR blend, the NR/ULDPE blend showed improved properties (tensile properties, tear resistance, and aging resistance) and limitations in the abrasion resistance and flex cracking resistance. The physical properties such as the Mooney viscosity, hardness, and resilience of both blends were in the same range.

2. Crosslinking in ULDPE improved the abrasion and aging resistance of the NR/ULDPE blend. It also increased the tensile strength of the blends containing 30 and 40% ULDPE. However, little change in the 300% modulus, elongation at break, hardness, and resilience of these blends was observed.

3. The NR/ULDPE blend was the compatible blend, similar to the NR/SBR blend. No compatibilizer, processing aids, and material modification were necessary.

4. A new blend from NR and ULDPE, which was comparable to the NR/SBR blend, was successfully formulated. The NR/ULDPE blend containing 40% crosslinked ULDPE (U50X-1) seemed to be the best blend among the present studied systems. The tertiary NR/SBR/ULDPE blend showed inferior properties to the binary NR/ULDPE blend.

It is known that carbon black and other reinforcing agents can cause significant changes in vulcanized rubber properties. Therefore, future work will be focused on the effect of carbon black on the physical and mechanical properties of this new blend, which will be compounded in an internal mixer. The DCP concentration in the blend will be determined as well.

REFERENCES

1. McDonel, E. T.; Baranwal, K. C.; Andries, J. C. In Polymer Blends; Paul, D. R., Newman, S., Eds.; Academic: New York, 1978; Vol. 2, Chap. 19.
2. Joseph, R.; George, K. E.; Francis, D. J. J Appl Polym Sci 1988, 35, 1003.
3. George, S. C.; Ninan, K. N.; Greonincks, G.; Thomas, S. J Appl Polym Sci 2000, 78, 1280.
4. Chu, M. S.; Meyers, R. R. J Appl Polym Sci 1987, 34, 1447.
5. Koshy, A. T.; Kuriakose, B.; Thomas, S. Polym Degrad Stabil 1992, 36, 137.
6. Koshy, A. T.; Kuriakose, B.; Thomas, S.; Varghese, S. Polymer 1993, 34, 3428.
7. Koshy, A. T.; Kuriakose, B.; Thomas, S.; Premalatha, C. K.; Varghese, S. J Appl Polym Sci 1993, 49, 901.
8. Koshy, A. T.; Kuriakose, B. Polym Plast Technol Eng 1994, 33, 149.
9. Jansen, P.; Amorim, M.; Gomes, A. S.; Soares, B. G. J Appl Polym Sci 1995, 58, 101.
10. Jansen, P.; Soares, B. G. Polym Degrad Stabil 1996, 52, 95.
11. Jansen, P.; Gomes, A. S.; Soares, B. G. J Appl Polym Sci 1996, 61, 591.

12. Kim, K. J Appl Polym Sci 1996, 61, 431.

13. Tinker, A. J.; Jones, K. P. Blends of Natural Rubber: Novel Techniques for Blending with Speciality Polymers; Chapman & Hall: London, 1998.

14. White, L. Eur Rubber J 1994, March, 16.

15. Turek, D. E.; Landes, B. G.; Winter, J. M.; Sehanobish, K.; Chum, S. ANTEC 95 SPE Conference Proceedings; 1995; Vol. 41, p 2270.

16. Minick, J.; Moet, A.; Hiltner, A.; Baer, E.; Chum, S. P. J Appl Polym Sci 1995, 58, 1371.

17. Bensason, S.; Minick, J.; Moet, A.; Chum, S.; Hiltner, A.; Baer, E. J Polym Sci B: Polym Phys 1996, 34, 1301.

18. Bensason, S.; Nazarenko, S.; Chum, S.; Hiltner, A.; Baer, E. Polymer 1997, 38, 3513.

19. Bensason, S.; Nazarenko, S.; Chum, S.; Hiltner, A.; Baer, E. Polymer 1997, 38, 3913.

20. Bensason, S.; Stepanov, E. V.; Chum, S.; Hiltner, A.; Baer, E. Macromolecules 1997, 30, 2436.

21. Hess, W. M.; Herd, C. R.; Vegvari, P. C. Rubber Chem Technol 1993, 66, 329.

22. Roland, C. M. In Handbook of Elastomers: New Developments and Technology; Bhowmick, A. K., Stephens, H. L., Eds.; Marcel Dekker: New York, 1988; Chap. 6.

23. Thavamani, P.; Khastgir, D. K.; Bhowmick, A. K. Plast Rubber Compos Process Applic 1993, 19, 245.

24. Jacques, J. E. In Rubber Technology and Manufacture; Blow, C. M., Ed.; Newnes–Butterworths: London, 1977; Chap. 9.

25. Legge, N. R.; Holden, G.; Schroeder, H. E. Thermoplastic Elastomers: A Comprehensive Review; Hanser: New York, 1987.