Electron Beam (EB) Radiation Curing—A Unique Technique to Introduce Mixed Crosslinks in Cured Rubber Matrix to Improve Quality and Productivity

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ABSTRACT: Effect of electron beam (EB) pretreatment on tire components has been investigated. The technique proved to be incredibly useful for reducing curing time of thick rubber products in the press and enhancing or retaining the properties required by a tire. This unique technique can be use to incorporate mixed crosslink in rubber products. Investigations were performed both on experimental compounds and industrial compounds. Experimental compound study was limited to development of theoretical data, effect of particular ingredients on EB radiation curing, and evaluating optimum dose required for obtaining optimum properties and reduction in cure time. The same sequence of study was followed on the compounds of tire components obtained from a reputed tire manufacturer. Components of tire such as inner liner and tread were irradiated with optimum doses selected in line with the study conducted on the experimental and industrial compounds. These components were then used to build the green tire. Properties of compound and tire as a whole were checked and are reported in detail in the article. © 2011 Wiley Periodicals, Inc. J Appl Polym Sci 122: 3227–3236, 2011

Key words: electron beam; tire; inner liner; tread; endurance

INTRODUCTION

Electron Beam radiation technology is the present day technique in polymer processing. The technique is mainly used for crosslinking of PE and PVC cables and curing i.e., polymerization of coatings and adhesives. Utilization of EB radiation in rubber has not gained much popularity as that of EB crosslinking of plastics. But significant studies on elastomer curing and modification by EB radiation have been conducted on the same. A large volume of studies on EB curing of different rubbers are available in literature. Almost all the rubbers have been tried to crosslink with EB radiation. NR and SBR found to increase their green strength and tack on irradiation. These rubbers are most commonly used in the rubber industries, especially in tire industries. So the initial and large amount works are reported in these rubbers. An SBR tank pad for U. S army, with very high ozone resistance and good mechanical properties was prepared using EB radiation by Basfar and Silverman.[1–3] Initially they tried a complete cure by radiation and then with partial cure by sulfur and then postcure by EB radiation. The properties of EB cured or posttreated samples were found to be better compared with that of completely sulfur cured normal tank pad compound and even better than gamma radiation cured analogous sample. They even succeeded to make a polybutadiene rubber alternate for the SBR compound. A different kind of study on NR was done by Madani and Badawy.[4] They studied the solvent penetration characteristics NR upon EB irradiation. They employed a step crosslinking method for the study. It has been found that the filler polymer interaction increased and the maximum amount of solvent penetration decreased with increase in radiation. Fluorocarbon rubbers are the next most important family of rubbers which has been subjected to extensive study to find out the effect of radiation.[5,6] The dynamic mechanical properties were analyzed by the investigators in one study. The influence of EB radiation on nitrile rubber vulcanizates with varying amount of sulfur has been investigated.[7] The authors have also shown the mechanism of radiation induced crosslinking in nitrile rubber. The effect of mixed crosslink system on the properties of NBR has also been studied. Better strength and moduli were found in the irradiated sample compared with the sulfur cured control sample. The crosslinking effect of

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chloroprene in the presence of poly functional monomers has been reported. The sensitizing effect of the polyfunctional monomers has been the topic of study.[8] Many rubbers have been modified using EB. This is done by grafting. Literature has examples of work done on modification of EPDM,[9] nitrile, silicon,[10] etc. Chain modification improves many of the properties, processing behavior, curing, and reclaiming. Chemical chain modification is a tedious process compared with the fast EB technology. Silicone rubber was also tried to cure using EB radiation.[11] The properties were analyzed. It should be noted that the study involved the commercial cable insulation silicon compounds. The results obtained in such a way that every insulation compound formulation designated for peroxide vulcanization could be used for radiation vulcanization as well. The dose selected was 50 kGy. An excellent review on how different types of rubber behave on application of radiation and how their properties are affected is presented by Bohm and Tveekrem.[12] They have covered in their review about all general purpose rubbers like NR, SBR, etc; and some special purpose rubbers. The change in the mechanical properties and their aged properties with radiation has been deliberately explained.[12] EB curing of blends of Butyl rubber and Natural rubber has been reported to provide better mechanical properties.[13] The Butyl rubber has been reported to degrade upon irradiation. The structural changes in Butyl during gamma irradiation have been vastly studied.[14] EB helps to form covalent bonds between phases of blends. That may be the reason for scissoring effect of Butyl faded in the blend with NR.

Industrialization of the technique in rubber field has not gained attention in many areas of the world; especially in developing countries like India. But rubber industries; particularly tire sector in Japan and the U.S. are making use of the technology.[15] Their process line already comprises of the EB generator. A recent report says that 23 tire companies in Japan are making use EB accelerators for their radial tire production.[16] EB radiation could be used to cure thick or thin rubber products with or without curatives. Compared with crosslinking by other thermochemical means, electron beam process is very clean, requires less energy, permits greater processing speed and operates at ambient temperature. In rubber industry, this technique is mainly used to precure the rubber products and different components of a composite product before final curing. It can be seen in the literature; B. F. Goodrich Company was the first to vulcanize a tire with radiation. In 1957 Goodrich successfully vulcanized a whole tire with Cobalt 60 radiation. But the details of the process they adopted are not available.[17] The earliest work with EB was done by Hunt and Alliger for pretreatment of tire components, which in turn found to improve the green strength.[18,28] They were followed by many researchers and industrialists to try the effect of EB radiation on different components of tire. Study on calendered fabric showed that its gauge retention after curing was better, so the wastage of compound could be avoided. It helped to prevent ply movement during final curing also.[19] Halobutyl innerliner of tires is one of the most studied components. It is suggested that tires with irradiated inner liners retained their performance; i.e., their performance did not deteriorate despite irradiating the inner liner.[20] Literature shows that EB pretreatment can be effectively used in tire components such as fabric cord, steel wire or gum rubber components.[15,17] Reduction in curing time which in turn improves productivity has been the most preferred property by industrialists, which can only be obtained by EB pretreatment of tire tread stock before the assembly into the tire.[21] The technique could cure the thick tire tread more uniformly. On conventional heat curing the under tread will be under cured compared with the surface part, which comes in direct contact with the mold. Application of radiation on the under tread helps to partially cure it and reach optimum cure as that of surface of the tread upon heat curing. Tread for retreading also been tried to pretreat with EB radiation, which again increase the production rate and lowers the operating cost.[22] Seiberling has also shown that with radiation cured innerliner, tires can be cured without an airbag or bladder. In this method, the green tire is prepared in the usual manner. Then the green tire is subjected to a depth of 1/16 in. or more of electron beam radiation to cure the exposed inner surfaces. This process cures the innerliner and makes it resistant to the passage of steam or hot water. Therefore the green tire can be cured in a mold without an airbag or bladder.[23]

The present work involves study on experimental formulations based on Natural Rubber(NR), Styrene butadiene rubber(SBR) and Butadiene Rubber(BR) which are mainly used by tire industries. Work includes study on actual tread and innerliner collected from M/s CEAT Ltd to confirm that the experimental results repeat with industrial formulations. The uniqueness of the study is making the tire with irradiated components and analysis on the effect of radiation on final product (cured tire) properties. Experimental formulations were made based on NR, SBR, and BR as these are the main ingredients in tire component compounds. The study has been systematically done to see the effect of electron beam radiation for partial curing of rubber compound. The study aimed to increase the green strength of synthetic rubber and to increase cure rate to improve productivity. The properties, mainly green strength, tack, curing behavior and tensile properties of EB pretreated and sulfur cured

TABLE I
Experimental Compound Formulations

Ingredients	Mix no 1 (phr)	Mix no 2 (phr)	Mix no 3 (phr)	Mix no 4 (phr)	Mix no 5 (phr)	Mix no 6 (phr)
NR (RMA IV)	100	70	70	70	70	60
SBR (1502)	–	30	30	30	–	30
Cisamer (1220)	–	–	–	–	30	–
Reclaim	–	–	–	–	–	20
Zinc Oxide	5	5	5	5	5	5
Stearic acid	2	2	2	2	2	2
Antioxidant[a]	1	1	1	2	1	1
TDQ	1	1	1	2	1	1
FEF(N 550)	50	50	50	50	50(HAF)	50
Aromatic oil	7	7	7	7	7	7
Resin[b]	–	–	5	–	–	–
MOR	1.5	1.5	1.5	1.5	1.5	1.5
Sulfur	1.75	1.75	1.75	1.75	1.75	1.75

[a] 6PPD.
[b] Coumarone Indene resin.

compound were studied at various irradiation doses. The properties of the rubber compounds are expected to be superior as the compound ultimately i.e., after pretreatment with electron beam and final thermal curing would be composed of both C-C bonds and C-S bonds. Thus anticipated outcome of the study is fabricating superior quality tires with minimum cure time. The different mechanical properties were measured to see the effect of radiation on compounds which are having mixed crosslink.

EXPERIMENTAL

Materials

Rubber and chemicals used for the study were obtained from standard chemical suppliers in India. The formulations are given in Table I. A 100% natural rubber (NR) based compound and blends of natural rubber with styrene butadiene rubber (SBR) and butadiene rubber (BR-Cisamer) were considered for the study. Tire industries mainly use compounds based on these three compositions. We used 100% Natural rubber compound and NR/BR blend for tread of truck tires and NR/SBR blends for tread of passenger car and radial tires. The ply and innerliner compounds are also usually based on these rubbers. Compound formulations with some special ingredients were also studied. This was to analyze the effect of these ingredients which are commonly used in tire compounding on EB irradiation. The special ingredients which were considered in the study were resin and reclaim rubber.

Sample preparation

Mixing of the rubber with other ingredients was done in a conventional laboratory two roll mill (15 cm × 33 cm) at 30 to 40°C according to ASTM D 15-70. Mixed compound was sheeted out to a thickness of 2.5 mm. This is to make sure that the beam should penetrate uniformly through the entire thickness. Then the sheets are cut into 6″ × 6″ slabs.

Irradiation of the sample

The sheeted rubber compound was subsequently irradiated in air at room temperature with an electron beam dose in the range of 0 to 10 Mrad using EB accelerator model ILU 6 at Bhabha Atomic Research Centre (BARC), Mumbai, India. The acceleration energy and beam current applied were 1.8 MeV and 1 mA, respectively. Dynamic irradiation technique was utilized at a conveyer speed of 0.9 m min^{-1}. A radiation dose of 1 Mrad was applied in a single pass. If the required dose was 4 Mrad, the sample was subjected to pass under the beam four times.

Tread and inner liner samples of tire size 4.50 : 10 collected from M/s CEAT Ltd. were subsequently irradiated in air at room temperature with an electron beam dose in the range of 0 to 15 Mrad at BARC. One set of tread and inner liner was exposed to 5 Mrad electron beam dose, denoted as A5 and two sets of tread and inner liner samples were irradiated at a dose of 7 Mrad (B7 and C7).

Curing/vulcanization

Irradiated rubber compound was cured in the form of slabs, using heat and pressure in a hydraulic press at 150°C and 15 MPa pressure. The optimum cure time of both normal and irradiated sample as were measured. Molding was done according to this cure time.

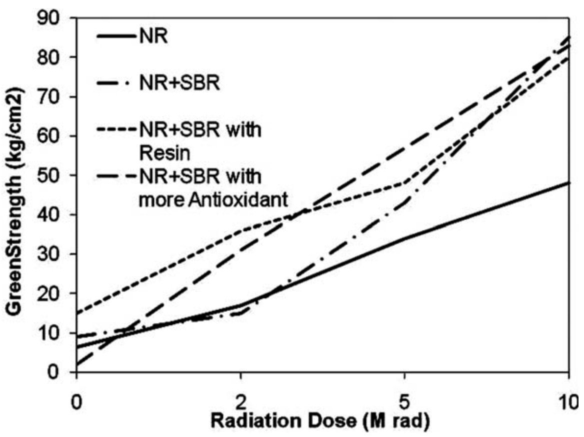

Figure 1 Green Strength of different compounds at different radiation doses.

Postexposure to EB radiation, the tread and proportionate inner liners of tire size 4.50 to 10 were sent to M/s CEAT Ltd. for tire building and curing.

Testing of mechanical properties

Mechanical properties like tensile strength, modulus, elongation at break, etc were measured at room temperature (25 ± 2°C) according to ASTM D-412-98 test method using dumbbell shaped test specimen which are punched out from molded sheet. The test were carried out in a Zwick Universal testing machine at a crosshead Speed of 500 mm per minute the standard deviation of tensile measurement is ±1 kg/cm^2.

Tests on unvulcanized compounds

Some properties like green strength and tack compounds were measured on the compound before the thermal curing. The tensile strength of an uncured rubber compound is known to be green strength. The test was done adhering to ISO 9026.

Tack of the compound was measured using an instrument known as Tel-Tak tackmeter of Monsanto. The mixed rubber compound was sheeted out from two roll mill at 1.5 mm thickness and then cut into slab of 6″ × 6″ size. This slab is placed over a square woven cotton cloth and press in between a sheet of cellophane on both top and bottom in a mold at 100°C for 3 min. After cooling a specimen of size 2″ × 0.25″ was cut from the sheet. Two such specimens are then mounted on the upper and lower clamps of the instrument in a perpendicular way. Then the specimens are pressed against each other under a load of 0.22 kg for 2 min before they are pulled apart at a speed of 25 mm/min. Tel-Tak measures the maximum force required to separate a contact area of 0.25″ × 0.25″ between two identical rubber specimens. The method of testing is mentioned by Brown in Handbook of Polymer Testing.[24]

The cure characteristics of both irradiated and unirradiated sheets were determined according to ASTM D 2084 at 150°C using Monsanto Rheometer (R-100). The cure characteristics obtained from rheograph are scorch time; T_{s2}, optimum cure time; T_{90}, minimum torque; ML and maximum torque; MH. T_{s2} is measured as the time required for the minimum torque to raise by 2 units. T_{90} is the time required by the compound to achieve optimum cure. In general for rubber compounds 90% cure is considered to be optimum and at which the compound attains the required state of cure.

Gel content of the irradiated samples was determined according to ASTM D 3616 by toluene extraction for 24 h. The samples were extracted, in toluene for 24 h and the extracted samples were dried to constant weight. The gel content was calculated as

$$\text{Gel content } (\%) = W_2/W_1 \times 100$$

where, W_1 is the weight of the sample before extraction and W_2 is the weight of the dried sample after extraction.

Tests on vulcanized compound

Mechanical properties, hardness, abrasion and ageing were done according to respective ASTM standards. Ageing of the samples was done for 72 h at 70°C.

Apparent crosslink density by equilibrium swelling method

Equilibrium swelling studies were performed on standard specimen cut from sheets.[7,25] Previously weighed samples were allowed to swell in toluene

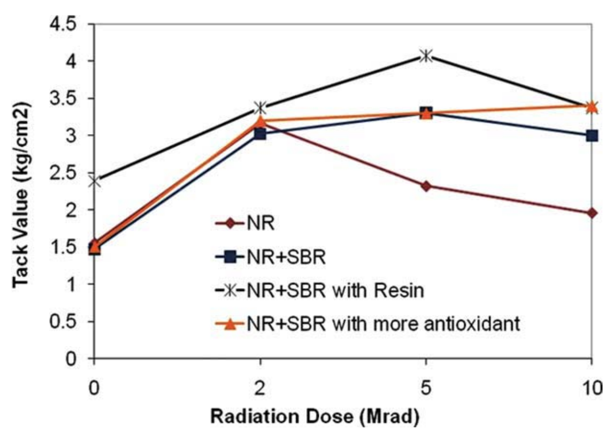

Figure 2 Tack of different compounds at different radiation doses. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

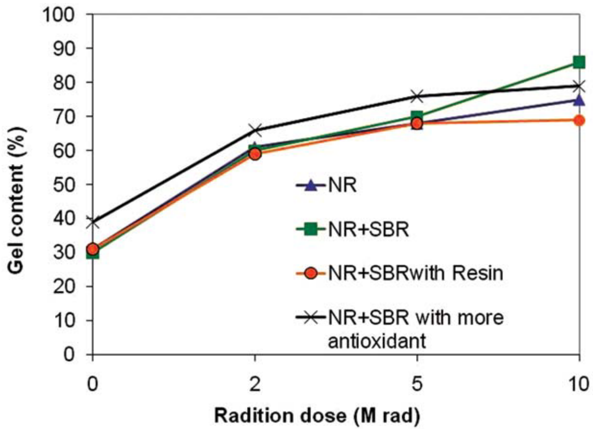

Figure 3 Gel content of different compounds at different radiation doses. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

at 40°C up to 3 d for equilibrium swelling. The samples were then removed, weighed, and dried to a constant weight in an oven at 70°C for 6 h. The volume fraction of the rubber in the swollen gel (v_r) was determined using the following relation:

$$\nu_r = (D_s - F_f A_w)\rho_r^{-1}/(D_s - Ff\ A_w)\rho_r^{-1} + A_s\rho_s^{-1}$$

where v_r, volume fraction of rubber in the swollen gel; A_w, weight of the test specimen; D_s, deswollen weight of the specimen; F_f, weight fraction of the insoluble components; A_s, weight of the absorbed solvent; ρ_r, density of the rubber; ρ_s, density of the toluene.

Adhesion/peel tests (ISO 9026)—Type a—180° peel

Rubber to rubber adhesion is measured in terms of green tack (strength) of the compound. Green tack between the compounded rubber is important in tire building operation, Belt construction, etc. Take two 1″ strip and prepare the test sample as detailed in Section 6 of ASTM D413. Strip the separating layer from the specimen at an angle of approximately 180° and continue the separation for a sufficient distance to indicate the adhesion value.

H-pull test (IS 4910-part 13)

Assessment of the adhesion between a rubber and the textile cord is made by measuring the force required to pull a single cord from the block of cured rubber. The adhesion measured is essentially a shearing force acting at the cord to rubber interface. The detailed of test method followed as per IS-4910 (Part 13)

Tests on vulcanized tire

The tires that were built from irradiated tread and proportionate inner liner of size 4.50 : 10 and subsequently cured were subjected to endurance test according to BIS 15627 at M/s CEAT Ltd.

Cut tire analysis study was performed by taking cured tire cross sections to find any defects in molding and to measure inner liner gauge and any distortion in carcass across the cross section.

RESULTS AND DISCUSSION

Study on experimental compounds

The gel content, green strength, and tack values of compounded sheets before and after irradiation are described with the help of Figures 1–3. The gel content increases with radiation dose as a result of radiation induced crosslinking which occurs through the formation of mainly carbon–carbon bonds.[7] The green strength which is a measure of form stability shows marked improvement after irradiation. A rubber compound with high green strength is always desirable as it helps to maintain orientation of

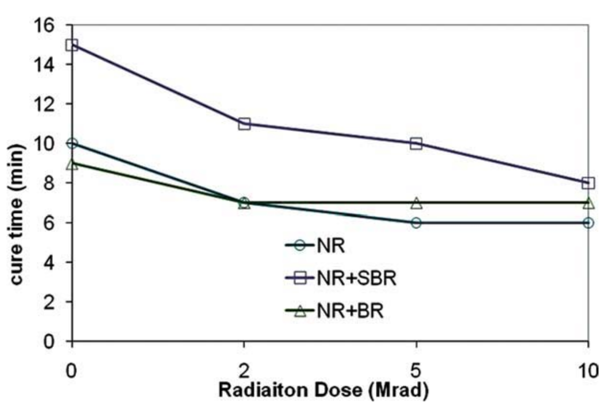

Figure 4 Cure time of different rubber compounds at different radiation doses. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

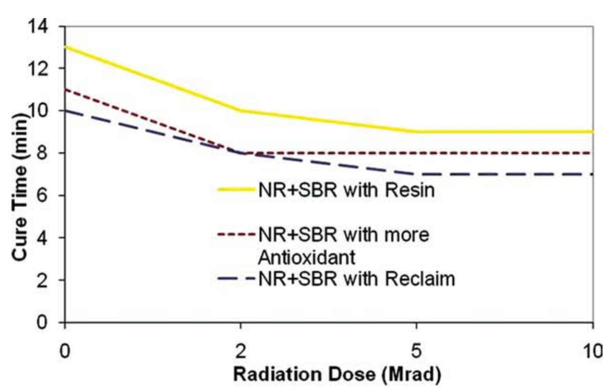

Figure 5 Cure time of NR+SBR blend with special ingredients at different radiation doses. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

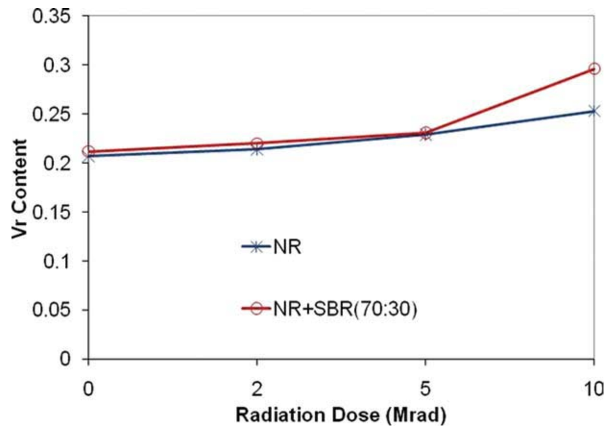

Figure 6 Vr content of NR and NR+SBR blend at different doses of radiation. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

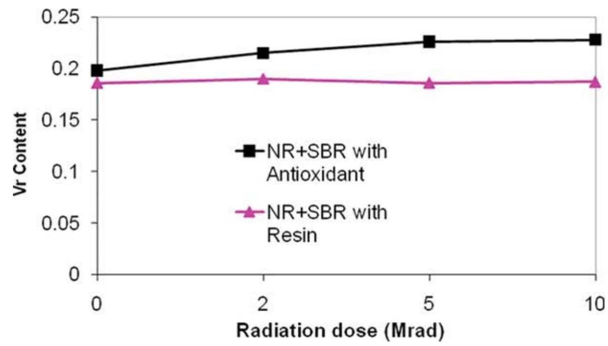

Figure 7 Vr content of NR+SBR blend with special ingredients at different doses of radiation. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

reinforcement material (cords) during final molding. Adequate green strength is essential to prevent the creep and distortion of an uncured assembled product before final molding.

One important finding is the increase in tack value at low radiation dose followed by a decrease at higher dose. Since tack is influenced by green strength of the rubber stock, an increase in green strength with radiation dose is considered to be the reason for initial increase in tack.[26] Although the tack value decreases at higher doses but the value is still higher than that of controlled sample. The reduction in tack value at higher doses may be attributed to the reduction in polymer chain mobility due to radiation precuring leading to limited interdiffusion of molecular segments across the interface. Basically tack is a physical phenomena and is governed by flow of material and physical adhesion whereas the green strength is the effect of physical and chemical crosslinks. Tack is an important property which decides how strongly individual rubber components can hold each other before molding of a composite like tire. The compound which contains more quantity of antioxidant did not show the same trend in tack like other compounds. Antioxidant in the compound reduces the surface crosslinking by oxidation so more chains are available in this case for interdiffusion.[27] That accounts for the change in the behavior of tack for the compound with higher amount of antioxidant. The increase in tack and green strength both at optimum dose rate of radiation occur.

It is observed that, $Tc_{90,}$ decreases with the increase in radiation dose for both NR and NR/SBR blends (Figs. 4 and 5). This lowering in Tc_{90} values indicates a faster curing rate which can allow a reduction in curing cycle or a faster manufacturing throughput.

Volume fraction of rubber content in the sample increases with increase in radiation dose. This indicates that the crosslink density of the sample

TABLE II
Mechanical Properties of Samples Based on Different Rubbers at Different Doses

Radiation dose (Mrad)	Tensile strength (kg/cm^2)	Elongation at break (%)	100% Modulus (kg/cm^2)	300% Modulus (kg/cm^2)	Hardness (shore A)
Natural rubber based sample (mix no.1)					
0	216	540	18	65	61
2	220	520	22	106	62
5	232	500	23	118	62
10	220	480	23	120	63
NR + SBR (70 : 30) based sample (mix no.2)					
0	217	530	26	117	62
2	231	520	28	125	63
5	245	500	30	130	64
10	221	470	32	132	64
NR + BR (70 : 30) based sample (mix no.5)					
0	256	600	28	114	64
2	209	500	21	107	61
5	209	450	27	133	61
10	232	500	25	140	62

TABLE III
Mechanical Properties NR + SBR Blend with Special Ingredients at Different Doses

Radiation dose (Mrad)	Tensile strength (kg/cm^2)	Elongation at break (%)	100% Modulus (kg/cm^2)	300 % Modiulus (kg/cm^2)	Hardness (shore A)
NR + SBR (70 : 30) with resin (mix no. 3)					
0	207	560	24	98	62
2	165	475	27	110	62
5	189	450	34	132	62
10	171	450	25	100	62
NR + SBR (70 : 30) with more dosage of antioxidant (mix no. 4)					
0	211	525	27	113	63
2	207	500	35	125	61
5	202	475	30	131	62
10	201	450	29	140	62
NR + SBR (60 : 30) with reclaim (mix no. 6)					
0	195	600	25	103	62
2	187	483	33	127	62
5	174	416	26	109	65
10	165	400	25	115	61

increases with increase in radiation dose. The trend was almost followed by all the samples (Figs. 6 and 7). This clearly indicates the increase in cross-link density due to formation of C-C crosslinks upon irradiation. Reduction in elongation values and increase in modulus values of the irradiated samples also indicates the same. Tensile strength values showed a maximum at 10 Mrad dosage for NR and NR/SBR blend (Table II). Formulation with reclaim rubber showed not much improvement in properties or reduction in cure time. Resin or antioxidant (more in quantity) in the formulation does not have any worse effect on the properties of the irradiated samples (Table III).

Study on industrial tread and innerliner compounds

In normal bag O matic curing process, tire gets cured by the steam and this high pressure steam is supplied through the bag. Since the rubber is a poor thermal conductor, there is always a chance that the thick portion under the tread gets under cured while the outer surface gets completely cured. If we still keep the temperature for curing inner side of thick tread then outer surface gets over cured. Here we apply this electron beam curing technique. We partially irradiated the inner portion of tread and outer plies so that after final curing process whole tire will be cured homogenously.

In this study we collected raw materials, mainly tread, ply, and inner liner of tire of size 4.50 to 10 from CEAT Ltd. Radiation dose range was 0 to 15 Mrad. Samples were identified as CTR-CEAT tread, CIL-CEAT inner liner. Mechanical properties of the irradiated and unirradiated samples are listed in Tables IV. There were only nominal difference in tensile strength and elongation at break values of irradiated and unirradiated samples.

Rheometric study of the irradiated tread was done on a 5-mm thick sample sliced from the irradiated surface. Cure time of tread compound showed a dramatic decrease with increase in radiation dosage where as inner liner compound almost did not show a change in cure time (Fig. 8). The green strength of the later increased considerably. This can in turn help to increase the tack and reduce the squeeze out of innerliner compound through the carcass on curing. This ultimately leads to gauge retention which results in material saving and cost reduction.

TABLE IV
Properties of Unirradiated and Irradiated Tread and Inner Liner Compounds

Properties	CIL 0 Mrad	CTR 0 Mrad	CIL 5 Mrad	CTR 5 Mrad	CIL 10 Mrad	CTR 10 Mrad	CIL 15 Mrad	CTR 15 Mrad
Green strength (kg/cm^2)	46	–	91	–	135	––	138	–
Tensile strength (kg/cm^2)	199	241	200	190	200	186	195	111
Elongation at break (%)	475	600	445	407	440	400	415	320
300% Modulus (kg/cm^2)	124	92	135	131	136	140	143	112
Hardness (°A)	65	62	66	64	65	66	65	66
Abrasion resistance Index	–	238	–	206	–	192	–	–

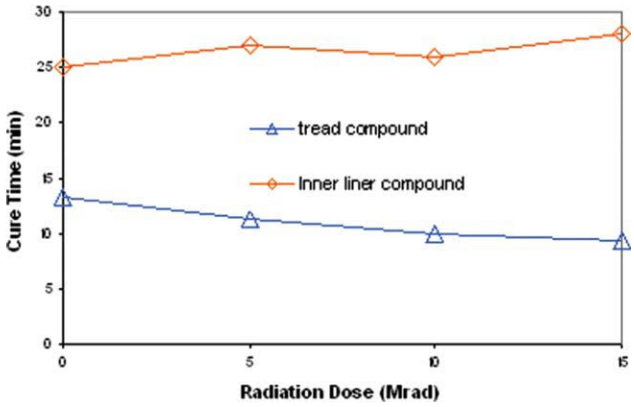

Figure 8 Cure time of tread and inner liner compound at different doses of radiation. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The gel content of the uncured tread sample was studied to evaluate the extent of curing upon radiation. Gel content was measured for each sample of thickness 2 mm sliced from the radiation exposed tread surface as well as non exposed surface. Gel content values indicate an uniform cure upto 6 mm distance from the radiated surface (Table V). After that gel content decreases, i.e., beyond 6 mm beam loses its energy successively. It is reported that beam loses its energy sequentially when passing through a thick material.[12] Literature says that a 6-mm thick material which has a density of water can be uniformly cured with EB radiation.[12]

Adhesion strength of irradiated innerliner to irradiated ply showed an improvement compared with the control. Similarly adhesion strength of irradiated plies also showed an increase compared with that of the unirradiated control sample (Table VI). Tack is the one of the most important property as far as composite structures are considered; those are prepared from different components. It is found that tack between different components improve upon treatment with electron beam.

We also found that abrasion resistance index of the irradiated tread compound showed a decreasing trend with increase in radiation dose. This may be due to the increased -C-C- crosslink of the compound which make it a little less flexible thereby increasing the tendency to abrade fast (Table IV). Table V shows that the penetration of EB is upto 6 mm only for accelerator 2 MeV.

TABLE V
Gel Content of Tread Sample

Effect of 10 Mrad radiation dose on 15 mm thick tread	Gel (%)
Upto 2 mm	70
Upto 4 mm	70
Upto 6 mm	70
Upto 8 mm	55
Upto 15 mm	40

TABLE VI
Adhesion Strength of Rubber to Fabric

Sample	kg/25 mm
0 Mrad innerliner + 0 Mrad ply	15 Substrate failure
0 Mrad innerliner + 5 Mrad ply	30
5 Mrad innerliner + 5 Mrad ply	29
0 Mrad ply + 0 Mrad ply	12
5 Mrad ply + 5 Mrad ply	16 Substrate failure

Study on tire made of irradiated components

Uncured tread and proportionate inner liner of tire size 4.50 to 10 were collected from M/s CEAT Ltd and were irradiated for doses 5 and 7. These doses were decided considering a balance in all properties, according to compound study. One each set of tread and inner liner was exposed to 5 Mrad and 7 Mrad doses. After exposure to EB radiation, the tread and proportionate innerliners were sent back to M/s CEAT Ltd. for tire building and curing. Tires with irradiated components of 5 Mrad and 7 Mrad gave a reduction of 23.5 and 14%, respectively, in normal standard cure time.

Endurance studies illustrated that tire with components irradiated to 5 Mrad dose had an improved life (Table VII). The tire which was cured with 14% less cure time failed after 136.8 h on the wheel. This can be attributed to additional crosslinks formed on irradiation that increased the strength of uncured tread compounds and inner liners. But tire made of components irradiated to 7 Mrad dosage failed comparatively earlier. This may be due to above a dose of 5 Mrads C-C crosslink density becomes excessive that makes the tread compound too rigid and thus less resistant to applied load. Otherwise it also possible that the cure time, which was 76.5% of the standard cure time may be too short to get the appropriate strength through C-S crosslinks. The values of Vr content of tread given Table VII indicate that 7 Mrad

TABLE VII
Endurance Test Result of Tires with Irradiated and Unirradiated Components

Feature	Hours for failure	% Load at failure	Reason for failure	Cure time at 169°C (min)
D	130	180	Shoulder separation	21.3
A	136.8	200	Shoulder separation	18.3
B	117.5	180	Shoulder separation	16.3

D, tire with unirradiated components; A, tire with components irradiated to 5 Mrad EB radiation; B, tire with components irradiated to 7 Mrad EB radiation.

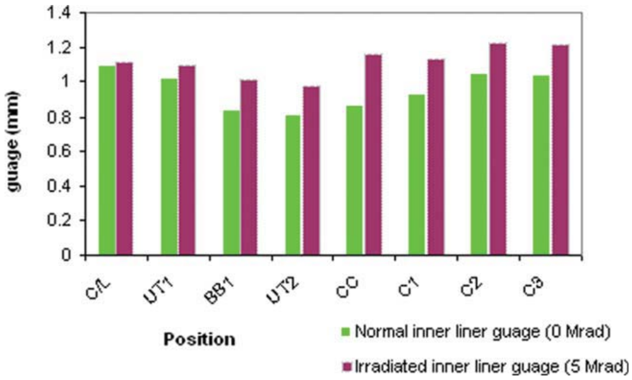

Figure 9 Irradiated and unirradiated inner liner gauge at different positions of a cut tire. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

irradiated sample did not receive complete cure during sulfur cure as the time given was too short. The inner portion of the tread showed a Vr content much less than 5 Mrad irradiated sample and unirradiated sample. Adhesion strength between rubber to fabric of failed tire is also improved in 5 Mrad exposure (Table VI).

Cut tire analysis was performed by taking cured tire cross-sections to find any defects in molding and to measure inner liner gauges and any distortion in carcass across the cross section. Figure 9 shows that the irradiated inner liner has better gauge retention as compared with normal, unirradiated inner liner. At all position, it could be seen that the irradiated inner liner maintained the gauge unlike the unirradiated inner liner, after curing. This points out that irradiation of inner liner helps to keep the gauge which required after curing. This enables tire industries to reduce the inner liner gauge and save material.

Figure 10 portrays the photographs of tire cross sections from cut tire analysis. These show that tire made with irradiated components has better shape and finish compared with normal tire made with unirradiated components.

CONCLUSIONS

EB radiation pretreatment of tire components improves the tack and green strength. Betterment in mechanical properties with a reduced cure time helps to produce premium quality tires in a less time. The productivity increases, as tire with 5 Mrad irradiated components is cured with 14% reduction in cure time. But the properties of tire components did not deteriorate, moreover tire life increased. All these are attributed to the C-C crosslinks formed on radiation treatment. Moreover, finish and shape of the tires got better by making use of irradiated components. The squeezing out of the innerliner through the carcass layers was almost nil for the irradiated

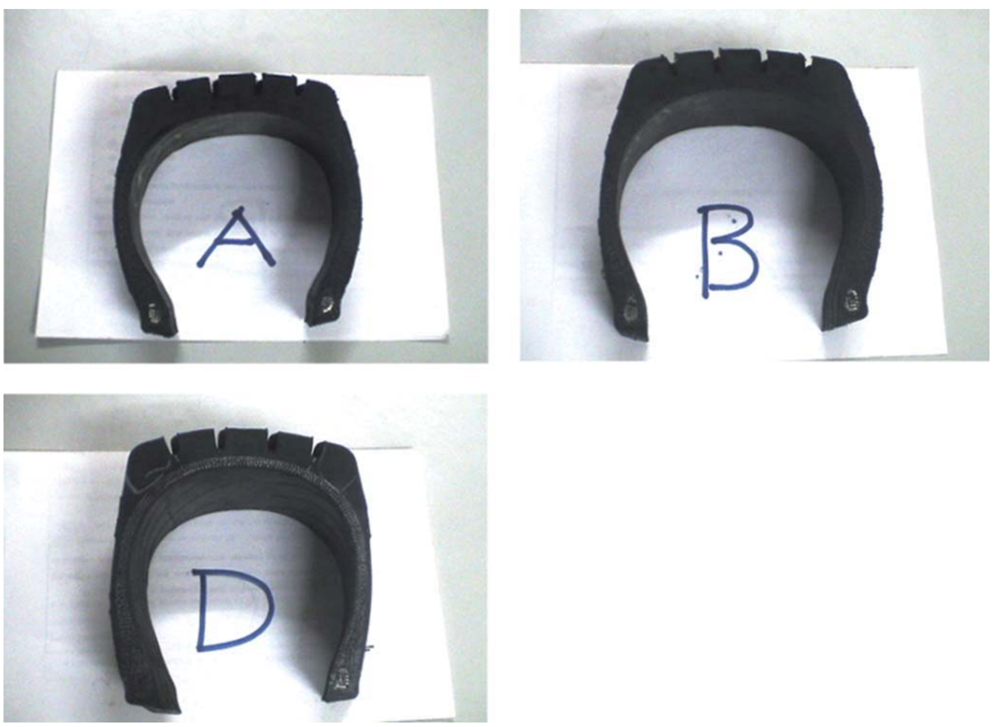

Figure 10 Sections cut from tires made with irradiated and unirradiated components. (A) Tire with components irradiated to 5 Mrad EB radiation, (B) tire with components irradiated to 7 Mrad EB radiation, (D) tire with unirradiated components.

inner liner on heat curing. This will enable tire makers to keep the exact gauge of the innerliner at the time of building the tire. Usually they used to keep thicker inner liner. This would facilitates material saving and cost reduction. Tire industries may look forward to pretreating tire components i.e., inner liner, tread, and plies, as the technique makes it possible to produce superior quality tires, save material, and increase productivity.

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