

The Effect of Electron Beam Irradiation on Natural Rubber/Polystyrene Blends with Divinylbenzene

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Radiation-induced crosslinking is an effective technique for enhancing the performance of polymeric materials; however, excessive irradiation doses may lead to energy inefficiency, material degradation, and environmental concerns. This study aims to optimize the electron beam-induced crosslinking of a natural rubber/polystyrene (NR/PS) 60/40 blend by incorporating divinylbenzene (DVB) as a sensitizer, thereby improving its mechanical properties while reducing the required electron beam irradiation dose. The NR/PS 60/40 blends were prepared via melt blending and subjected to electron beam irradiation at doses ranging from 0 to 250 kGy, with and without the addition of 4.0 phr DVB. The crosslinking behavior was evaluated through gel content and swelling index measurements, while mechanical performance was assessed using tensile testing. The results showed that the NR/PS 60/40 blend containing 4.0 phr DVB achieved an optimum gel content of 92% in the NR phase at 100 kGy, whereas the NR/PS 60/40 blend without DVB required a higher irradiation dose of 150 kGy to achieve an optimum gel content of 93% in the NR phase. The optimum swelling index in the NR phase was observed at 150 kGy for both blends; however, the NR/PS 60/40 blend containing 4.0 phr DVB exhibited a lower swelling index of 8.0 compared with 9.2 for the NR/PS 60/40 blend without DVB, confirming a higher crosslink density. Furthermore, the NR/PS 60/40 blend containing 4.0 phr DVB exhibited the optimum tensile strength of 8.6 MPa at 150 kGy, whereas the NR/PS 60/40 blend without DVB achieved 7.9 MPa at 200 kGy. These findings demonstrate that incorporating 4.0 phr DVB enables NR/PS 60/40 blends to achieve comparable crosslinking and mechanical performance at a lower electron beam irradiation dose, thereby improving processing efficiency while minimizing the potential for radiation-induced degradation.

Keywords: Crosslinking, polystyrene, NR/PS blends, natural rubber, DVB, sensitizer

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Natural rubber (NR) is a widely utilized elastomer derived from renewable sources, most notably *Hevea brasiliensis*. It is distinguished by its excellent elasticity, high tensile strength, and superior resilience, which enable it to undergo significant deformation under stress and recover its original shape upon load removal. These intrinsic properties, combined with good abrasion resistance and energy dissipation capability, make NR highly suitable for a broad spectrum of industrial applications, including automotive components, vibration isolators, medical products, and engineering elastomeric systems. In addition, its renewable origin further enhances its relevance in the context of sustainable and environmentally conscious material development.

However, NR has inherent limitations in its raw state and is unsuitable for industrial applications due to its viscoelasticity, including low thermal stability, susceptibility to creep under prolonged stress, and poor resistance to solvents [1]. In addition, raw rubber lacks the required yield strength for many functional applications. Conversely, polystyrene (PS) exhibits high stiffness, good thermal stability, and dimensional stability; however, its inherent brittleness and low fracture resistance restrict its use in applications requiring high elasticity and toughness. Therefore, blending NR with PS has been explored as an approach to combine the complementary properties of both polymers, improving the overall toughness, elasticity, and thermal resistance of the resulting blend [2, 3].

Although NR/thermoplastic blends can exhibit enhanced performance, their inherent molecular incompatibility often results in phase separation and weak interfacial adhesion, which adversely affects their mechanical properties [4]. Nevertheless, blending commercially available polymers, is generally a more efficient and cost-effective approach for achieving targeted material properties compared with the synthesis of entirely new polymers. The most widely used method is sulfur vulcanization, which is a chemical crosslinking process to intensify elasticity and aging resistance [5]. This process requires high temperatures and chemical additives, which lead to toxic byproducts and environmental concerns. One of the most typical alternatives for chemical crosslinking is radiation crosslinking, which uses high-energy radiation to create crosslinked networks between NR and thermoplastic. Radiation crosslinking has become an attractive technique for modifying polymer properties because it can be carried out without conventional chemical curing agents, resulting in a cleaner process with minimal residual byproducts [6]. In addition, electron beam irradiation enables crosslinking at relatively low processing temperatures and can promote the formation of crosslinked and grafted structures between polymer chains. Electron beam irradiation has been demonstrated to induce graft copolymerization between natural rubber and styrene, resulting in the formation of NR-g-PS structures that improve the interaction between rubber and polystyrene phases [7]. However, relatively high irradiation doses are often required to achieve sufficient crosslinking in rubber-based materials. At excessive doses, chain scission may dominate over crosslinking, resulting in deterioration of mechanical properties due to radiation-induced degradation [8]. Therefore, incorporation of radiation sensitizers such as divinylbenzene (DVB) has been proposed as an effective approach to enhance crosslinking efficiency and reduce the required irradiation dose [9].

Using suitable sensitizers to optimize the crosslinking efficacy of induced-radiation crosslinked polymers while reducing required radiation exposure to an equivalent crosslinking effect has been one of the most promising strategies explored for this goal [6]. Unsaturated compounds with a single or multiple functions are the most often utilized sensitizers. DVB acts as an effective co-agent during gamma irradiation by promoting radiation-induced crosslinking and improving the thermal stability of the polymer [10]. These additives can be used in free radical polymerization, where they increase crosslinking density. Although several studies have investigated radiation crosslinking of natural rubber using multifunctional monomers, limited attention has been given to the use of divinylbenzene (DVB) as a sensitizer in natural rubber/polystyrene (NR/PS) blends under electron beam irradiation. DVB has been reported as an effective multifunctional co-agent in radiation processing owing to its two reactive vinyl

groups, which facilitate the formation of a three-dimensional crosslinked network and enhance crosslink density during irradiation [11]. However, the influence of DVB on the crosslinking behaviour, gel content, swelling characteristics, and mechanical properties of irradiated NR/PS blends has not been systematically established. Therefore, it is hypothesized that the incorporation of DVB could enhance structural integrity and interfacial adhesion, resulting in improved compatibility, dimensional stability, and mechanical performance of NR/PS blends after radiation-induced crosslinking. This study investigates the effect of DVB on electron beam-induced crosslinking of NR/PS blends and evaluates its potential to improve crosslinking efficiency, enabling comparable material performance at a lower irradiation dose. Such an approach may contribute to improved processing efficiency, reduced radiation exposure, and more sustainable polymer processing practices in line with Sustainable Development Goal (SDG) 12.

EXPERIMENTAL

Chemicals and Materials

Natural rubber (NR) of SMR-10 was obtained from the Kuala Pilah Rubber factory Sdn. Bhd. While polystyrene (PS) grade from Petrochemicals (M) Sdn. Bhd. Ethyl acetate and petroleum ether were used as received without purification. Ethyl acetate, petroleum ether and divinylbenzene (DVB) were obtained from Sigma-Aldrich.

Blends Preparation

The natural rubber (NR)/polystyrene (PS) blends were prepared at a weight ratio of 60/40. The NR/PS 60/40 blend consisted of 60 wt% NR and 40 wt% PS, with a total blend weight of 65.00 g. DVB was incorporated as a sensitizer at a loading of 4.0 phr (parts per hundred parts of rubber) based on the NR content [12]. NR was first introduced into the mixer, followed by the addition of PS after 3 min. DVB was subsequently added after 5 min of mixing, and the mixture was blended for a total duration of 13 min. Melt blending was conducted at 120 °C using a Brabender Plasticorder Model PL 2000, operating at a rotor speed of 50 rpm. The resulting blends were compression molded into sheets with thicknesses of 1 mm and 3 mm at 170 °C for 10 minutes [13]. Subsequently, the sheets were immediately cooled between two cold press plates at 25 °C.

Characterization Methods

Irradiation

The NR/PS 60/40 blends with and without 4.0 phr DVB were prepared as films with thicknesses of 1 mm and 3 mm, were irradiated at doses of 50, 100, 150, 200, and 250 kGy using a 3 MeV scanning electron

beam accelerator with a beam current of 1 mA and a dose rate of 10 kGy per pass. The irradiation was conducted under ambient atmospheric conditions (air) at room temperature (25 ± 2 °C) [12].

Swelling Index

The swelling test was conducted in accordance with ASTM D3616. Specimens measuring 1 cm × 1 cm were weighed and subsequently immersed in separate test tubes containing ethyl acetate and petroleum ether for 24 h. Ethyl acetate acts as a solvent for polystyrene and grafted polystyrene in natural rubber, reflecting the interactions between the natural rubber and polystyrene phases, while it does not dissolve natural rubber itself. In contrast, petroleum ether serves as a good solvent for natural rubber but does not dissolve polystyrene. After immersion, the specimens were removed, their surfaces were blotted with filter paper, and they were immediately reweighed. The samples were then air-dried for 24 h, followed by drying in a vacuum oven at 60 °C until a constant mass was obtained. For each sample, three measurements were recorded, and the mean value was reported [12]. Swelling index was calculated using Equation 1.

$$\text{Swelling Index} = \frac{\text{swollen sample weight}}{\text{dry sample weight}} \quad \text{Equation 1}$$

Gel Fraction

Gel content was determined according to the principles of ASTM D3616 with modifications to accommodate the NR/PS 60/40 blends system. The Soxhlet extraction test was performed in two sequential stages using a Soxhlet extraction apparatus. In the first stage, petroleum ether was employed as the extraction solvent, followed by ethyl acetate in the second stage. Specimens measuring 1 cm × 1 cm were weighed and placed in copper gauze bags before extraction. The bags were then subjected to Soxhlet extraction with petroleum ether for 20 h to determine the gel content of the natural rubber phase. Following extraction, the samples were air-dried for 24 h and subsequently dried in a vacuum oven at 60 °C until a constant mass was achieved, after which they were weighed. A second extraction was then conducted using ethyl acetate for 20 h to evaluate the insoluble polystyrene. After extraction, the samples were again air-dried, vacuum-dried to constant mass, and reweighed for analysis. For each sample, three measurements were recorded, and the mean value was reported. The gel content was calculated by subtracting the weight of the dried samples before extraction from the weight of the dried samples after extraction as in Equation 2 [13].

$$\text{Gel content (\%)} = \frac{\text{weight after extraction} \times 100\%}{\text{weight before extraction}} \quad \text{Equation 2}$$

Measurement of Mechanical Properties

The tensile strength and elongation at break were determined using a Universal Instron Testing Machine Model 4301 equipped with a 1 kN load cell. The crosshead speed was set at 50 mm/min according to ASTM D638. The 1 mm thick sample sheets were cut into dumbbell-shaped specimens according to ASTM D412-68 Type B using a hollow die punch. Five specimens were tested, and the average values were recorded. An impact test was carried out according to the Izod method using a Digital Universal Pendulum Fractoscope (CEAST) 6546/000 machine. The test was conducted based on ASTM D 256-88. The test specimens, with a thickness of 3 mm, were cut using a Hollow Die Punch. The specimens were cooled in a chamber using liquid nitrogen for 1 minute as an initial cooling step. The specimens were then removed from the chamber, and their surface temperature was monitored using a thermometer. The impact test was conducted when the surface temperature reached -10 °C. The test was performed on five specimens, and the average value was calculated. Hardness was evaluated using a Shore A durometer (Zwick Model 3100) in accordance with ASTM D2240-89. For each sample, five measurements were recorded, and the mean value was reported [13].

RESULTS AND DISCUSSION

Gel Content and Swelling Index

During radiation, crosslinking reactions can increase the polymer's molecular weight by forming three-dimensional network structures. As crosslinking density rises, the polymer's mechanical strength is typically enhanced [14]. Therefore, measuring gel content is a widely accepted method for evaluating the extent of crosslinking in polymer blends. The use of 4.0 phr of DVB on NR/PS 60/40 blend as a sensitizer significantly enhanced the efficiency of radiation-induced crosslinking while reducing the energy requirement for processing. Figure 1 illustrates that the gel content of the NR phase in the NR/PS 60/40 blend containing 4.0 phr of DVB increases to 92% at an irradiation dose of 100 kGy, whereas a comparable gel content is only achieved at 150 kGy for the blend without DVB. This indicates that the presence of DVB enables the attainment of an optimum degree of crosslinking at a lower radiation dose compared to blends without DVB. This suggests that DVB acts as a sensitizer, improving the interaction between polymer chains during irradiation and accelerating the crosslinking process. This reduction in the radiation dose not only improves processing efficiency but also minimizes potential radiation-induced degradation [15].

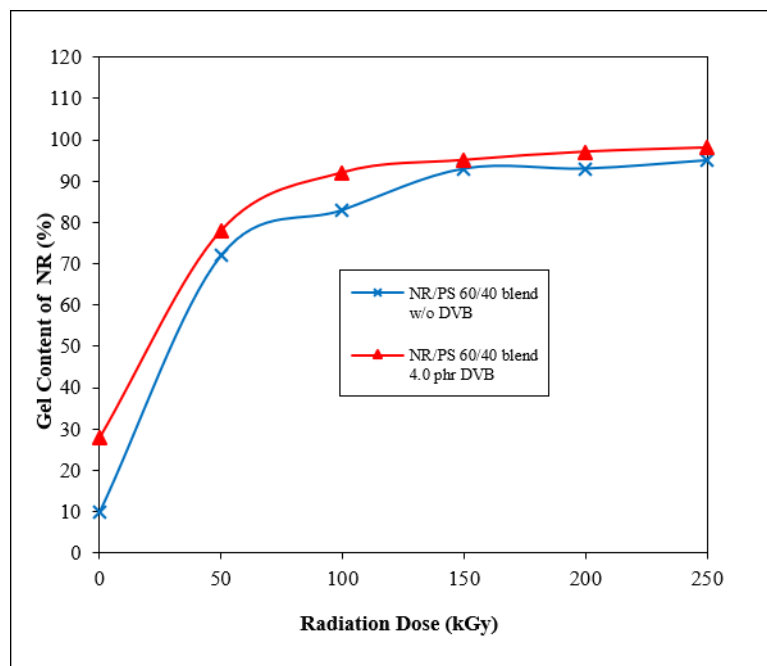


Figure 1. Influence of radiation dose on gel content of NR phase in NR/PS 60/40 blend.

Figure 2 shows the swelling index of the NR phase in the NR/PS 60/40 blend, which decreases with increasing radiation dose, indicating an increase in the degree of crosslinking. The optimum crosslinking was achieved at 150 kGy for both blends; however, the NR/PS 60/40 blend containing 4.0 phr DVB exhibited a lower swelling index of 8.0 compared with 9.2 for

the blend without DVB, confirming a higher crosslink density in the presence of DVB. In other words, the higher the degree of crosslinking, the lower the number of unlinked rubber molecules, which in turn makes it more difficult for the solvent to be absorbed and leads to a lower swelling degree in the rubber molecules [16].

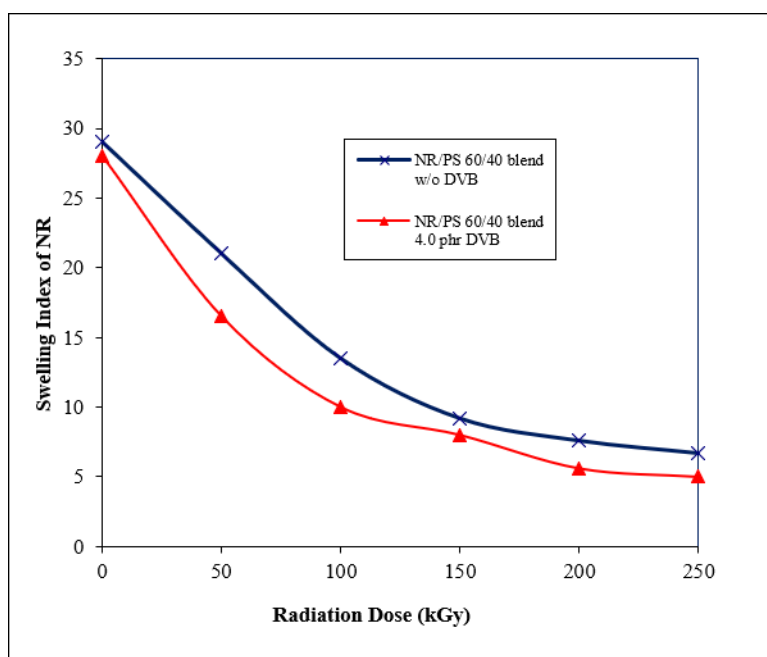


Figure 2. Influence of radiation dose on swelling index of NR phase in NR/PS 60/40 blend.

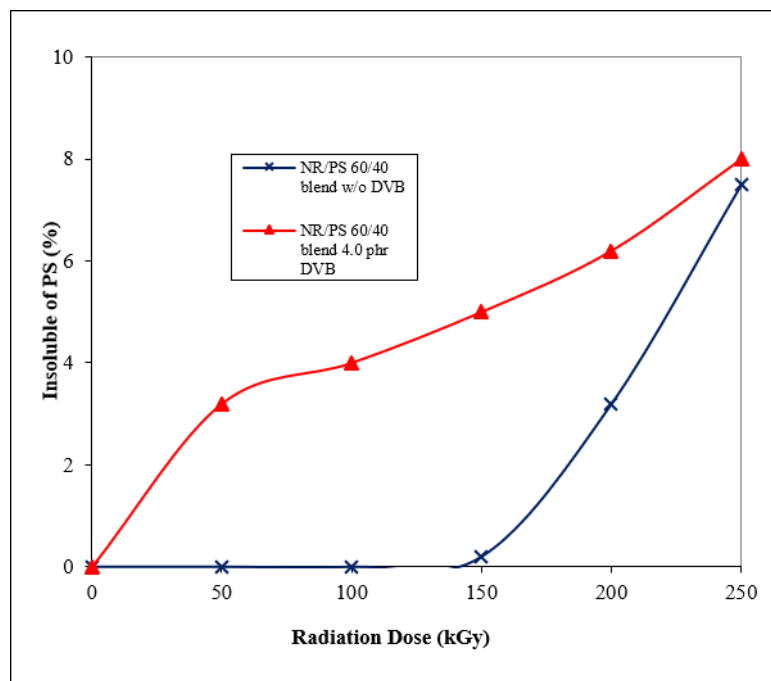


Figure 3. Influence of radiation dose on insoluble component of PS phase in NR/PS 60/40 blend.

Figures 3 and 4, respectively, show the effect of the radiation of insoluble components and the swelling index of the PS phase in the NR/PS 60/40 blend. It was found that for a blend without DVB, 200 kGy of radiation dose is needed for the PS component to be insoluble, while getting the same result at 50 kGy with the presence of 4.0 phr DVB. It is because of the effectiveness of DVB in creating insoluble components of the PS phase in the NR/PS 60/40 blend under the radiation exposure. On the other hand, the swelling index decreases as the radiation dose increases because irradiation promotes the formation of a three-dimensional crosslinked network that restricts solvent penetration into the polymer matrix. For the blend without DVB, the swelling index PS phase in the NR/PS 60/40 blend decreases only slightly from 22 to 18 at 100 kGy, indicating that crosslinking occurs but is relatively limited. In contrast, the blend containing 4.0 phr DVB exhibits a much larger decrease in swelling index, from 22 to 15 at the same radiation dose. This significant reduction is attributed to the function of DVB as a multifunctional co-agent that enhances radiation-induced crosslinking. DVB contains two reactive vinyl groups that readily react with irradiation-generated free radicals, promoting the formation of additional intermolecular crosslinks and

increasing the crosslink density of the polymer network. As the crosslink density increases, the polymer chains become more tightly connected, reducing chain mobility and limiting the diffusion of solvent molecules into the network. Consequently, the decrease in swelling index of PS is more pronounced in the NR/PS 60/40 blend containing 4.0 phr DVB compared with the blend without DVB. This behavior is consistent with the general relationship between swelling behavior and crosslink density described by the Flory–Rehner theory, where a higher crosslink density results in lower solvent uptake and reduced swelling. Similar observations have also been reported for radiation-crosslinked natural rubber and thermoplastic blends containing multifunctional co-agents, in which the addition of DVB significantly enhanced gel formation and reduced swelling due to more efficient network formation [16].

Mechanical Properties

The evaluated mechanical properties include tensile strength, elongation at break, modulus at 100% elongation (M100), impact strength and hardness. These properties were investigated over a radiation dose range of 0 to 250 kGy.

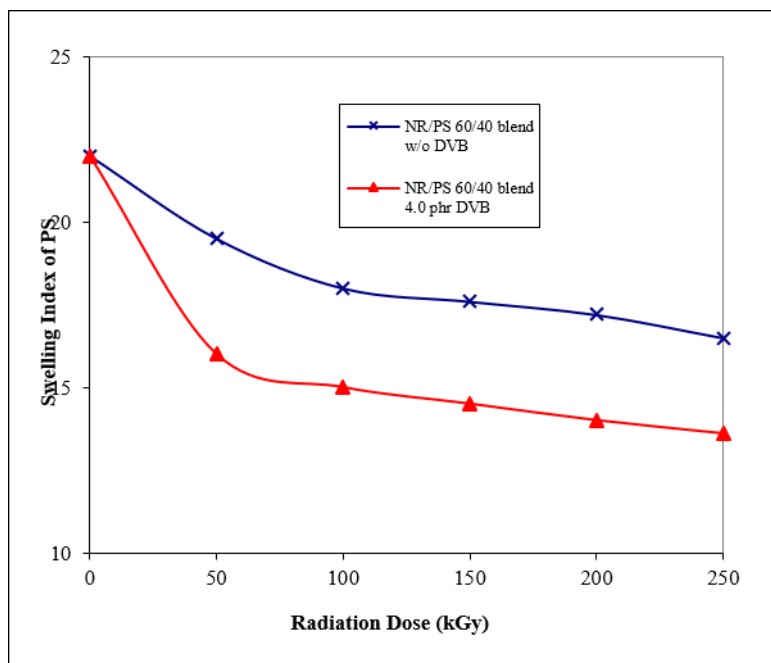


Figure 4. Influence of radiation dose on swelling index of PS phase in NR/PS 60/40 blend.

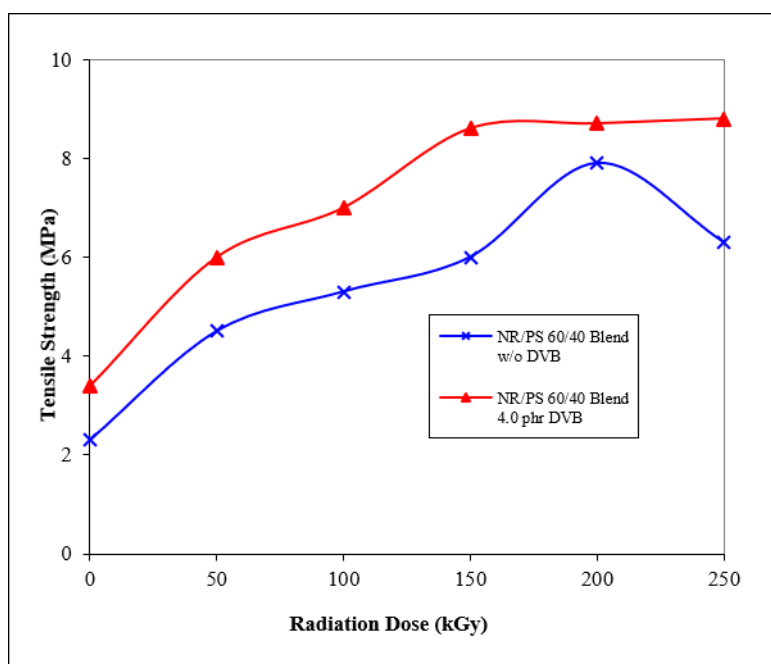


Figure 5. Influence of radiation dose on the tensile strength of NR/PS 60/40 blend.

Figure 5 shows that NR/PS 60/40 blend with the presence of 4.0 phr DVB reached its maximum tensile strength of 8.6 MPa at 150 kGy of radiation dose. Any further increases in radiation doses will only result in a slight increase in tensile strength. Meanwhile, the blend without DVB, its maximum tensile strength will stop at 7.9 MPa when exposed to 200 kGy of radiation dose and further increase of

radiation dose will cause the tensile strength to decrease. The increase in tensile strength can be attributed to the crosslinking reaction occurring within the polymer matrices. This indicates that the incorporation of 4.0 phr DVB enhances the interfacial interaction between the components, thereby improving the overall strength of the blends. A higher radiation dose enhances the degree of crosslinking; however,

excessive crosslinking can make the blend harder and more brittle, thereby reducing its tensile strength. According to Wemyss et al. [17], too much crosslinking in the rubber phase will reduce shear strength. The decline in tensile strength is caused by chain breakage on the sample surface [18].

The reduction in tensile strength at higher radiation doses is attributed to the degradation effect caused by excessive irradiation on the rubber-modified material [19]. Yunshu et al. [20] reported that exposure to electron beam radiation increases the crosslink density, which consequently enhances the tensile strength. This trend is consistent with the gel content and swelling index results obtained in the present study. As the radiation dose increases, the gel content increases while the swelling index decreases, indicating the formation of a more highly crosslinked network. The higher gel fraction reflects the increased proportion of insoluble, crosslinked polymer, whereas the lower swelling index indicates a reduced ability of the network to absorb solvent due to the restricted mobility of the polymer chains. This enhanced crosslinked structure contributes to the improvement in tensile

strength at moderate radiation doses by facilitating more efficient stress transfer and reducing chain slippage.

However, according to McKeen [21], excessive radiation doses adversely affect the mechanical properties of polymers because the rubber phase becomes damaged by irradiation. Although the gel content continues to increase and the swelling index continues to decrease, indicating further crosslinking, the tensile strength eventually declines because chain scission and oxidative degradation become increasingly significant at high radiation doses. The excessive crosslink density makes the material stiffer and more brittle, thereby reducing its ability to deform and distribute applied stress effectively. Consequently, despite the higher crosslink density, degradation becomes dominant at excessive irradiation doses, leading to a reduction in tensile strength due to radiation-induced chain scission [8]. In NR/PS blends, the polystyrene phase generally contributes to tensile strength and stiffness, whereas the natural rubber phase imparts elasticity and flexibility [22].

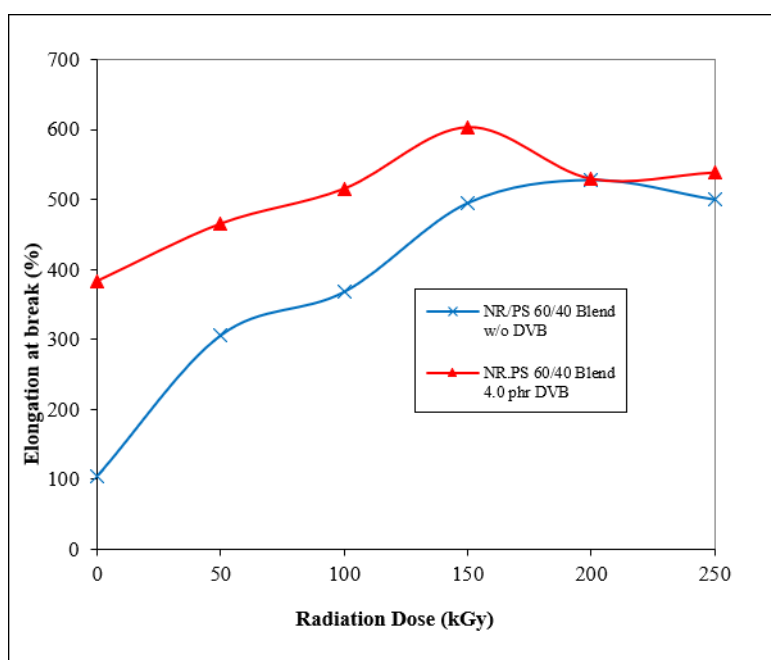


Figure 6. Influence of radiation dose on the elongation at break of NR/PS 60/40 blend.

Elongation at break reflects the mobility and flexibility of polymer chains. The effect of radiation on elongation at break is illustrated in Figure 6. For the NR/PS 60/40 blend with 4.0 phr DVB, the elongation at break initially increased with increasing radiation dose up to 150 kGy, followed by a reduction at higher irradiation doses. Although increased crosslink density generally restricts polymer chain mobility and leads to a decrease in elongation at break, the initial increase observed at lower irradiation doses may be attributed to the formation of a more interconnected network and improved interfacial interaction between the NR and PS phases. At moderate irradiation levels, the generated free radicals may promote limited crosslinking and interfacial bonding, which can reduce phase separation and enhance stress transfer between the two phases, resulting in improved deformability. However, at higher radiation doses, excessive crosslinking and chain scission reactions become dominant, reducing molecular mobility and increasing network rigidity, which ultimately decreases the elongation at break. This behaviour indicates a balance between network formation and radiation-induced degradation during irradiation [23,24]. This decrease is attributed to the material becoming stiffer and more brittle due to extensive crosslink formation. Crosslinking initially

involving long polymer chains can contribute to higher elongation at break. However, the subsequent reduction indicates an increase in crosslink density induced by radiation, which restricts chain mobility through the formation of a three-dimensional network structure.

The reduction in elongation at break for blends without DVB at radiation doses above 200 kGy can be attributed to increased crosslinking, which suppresses crystallization induced by shear. A decrease in elongation at break also suggests a higher extent of chain scission caused by radiation. Consequently, radiation doses exceeding 200 kGy lead to a reduction in shear strength, which is associated with radiation-induced chain breakage [25]. At higher radiation doses, chain scission becomes more dominant, resulting in shorter crosslinks between polymer chains and, subsequently, lower elongation at break. According to Gupta et al. [18], excessive radiation exposure promotes chain scission and reduces effective crosslinking. Crosslinking can be categorized into two types: (1) intermolecular crosslinking between two macroradicals from different polymer chains, and (2) intramolecular crosslinking between monomer units within the same macroradical chain. The intermolecular crosslinking is primarily responsible for increasing the molecular weight of the polymer.

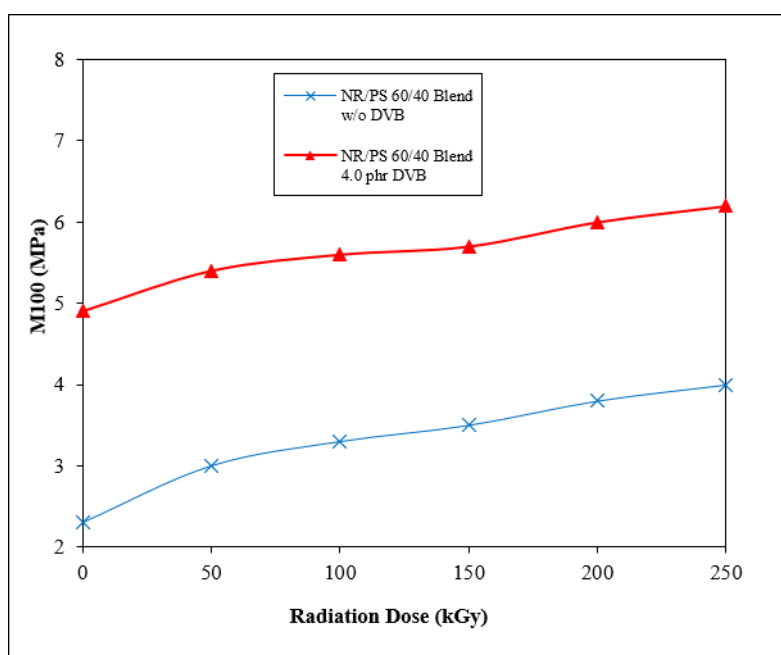


Figure 7. Influence of radiation dose on the M100 of NR/PS 60/40 blend.

Figure 7 illustrates the effect of radiation dose on the modulus at 100% elongation (M100) for the NR/PS 60/40 blend. The increase in M100 is associated with the enhanced rigidity of the polymer blend. Overall, the M100 value increased slightly with increasing radiation dose. The blend containing 4.0 phr DVB exhibits higher M100 values compared to the blend without DVB. For instance, at a radiation dose of 250 kGy, the M100 value reaches 6.2 MPa for the DVB-containing blend, whereas the blend without DVB only attains 4.0 MPa. The presence of the DVB in the NR/PS 60/40 system results in higher M100 values than in the unsensitized blend. The interaction between polymer components involves simultaneous crosslinking, chain scission, and molecular rearrangement [26]. Modulus is directly related to the number of effective crosslink junctions, which reflects the formation of a more perfect network structure. The increase in M100 with radiation dose indicates a higher degree of radiation-induced crosslinking. Although tensile strength may decrease at higher doses, the continuous increase in M100 confirms that crosslinking remains dominant. Conversely, a reduction in M100 suggests that degradation processes induced by radiation have become more significant.

M100 refers to the tensile stress at 100% elongation and is a commonly used parameter for characterizing rubber materials. It can also be used to assess the strength of the blend, particularly as NR/PS

belongs to the thermoplastic elastomer (TPE) group. The M100 results indicate the role of DVB in accelerating crosslink formation in the NR/PS blend. An increase in modulus, together with a decrease in elongation at break, reflects reduced elasticity and lower molecular mobility within the polymer chains. The M100 value increases with increasing radiation dose, which is attributed to enhanced crosslink density within the blend [27]. The formation of crosslinks also reduces the plasticizing effect of polymer chains and restricts molecular rearrangement within the polymer structure [28].

The impact properties of the NR/PS 60/40 blend are presented in Figure 8. The Izod impact strength at sub-ambient temperature increases with the incorporation of 4.0 phr DVB as a sensitizer. The presence of DVB may facilitate interfacial reactions during radiation-induced crosslinking, potentially enhancing the interaction between the NR and PS phases. Such improved interfacial adhesion may reduce phase separation and contribute to enhanced impact strength and overall mechanical performance of the irradiated blends [29]. At $-10\text{ }^{\circ}\text{C}$, the blend containing 4.0 phr DVB shows an impact strength of 180 J m^{-1} at a radiation dose of 100 kGy, whereas the blend without DVB exhibits a lower value of 158 J m^{-1} under the same irradiation conditions. The addition of 4.0 phr DVB as a sensitizer therefore reduces the radiation dose required to achieve optimum impact strength.

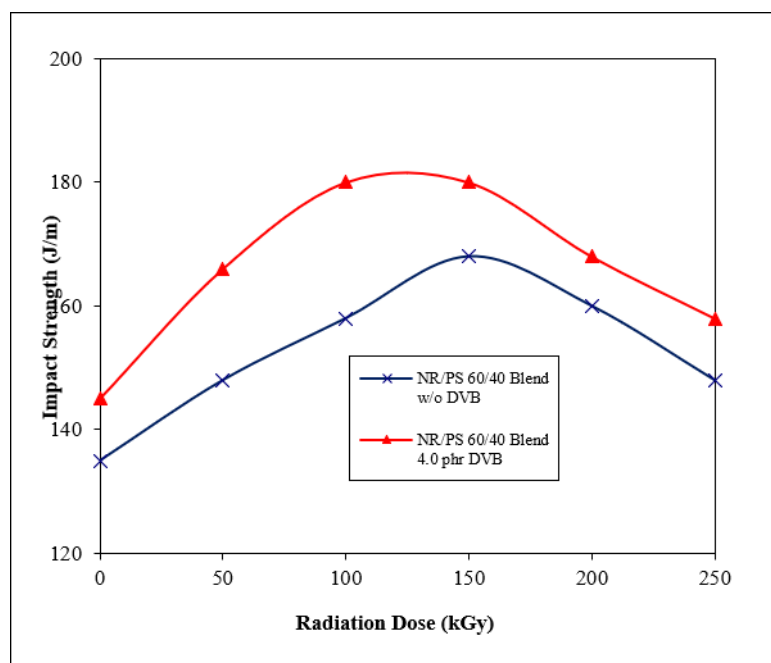


Figure 8. Influence of radiation dose on the impact strength of NR/PS 60/40 blend.

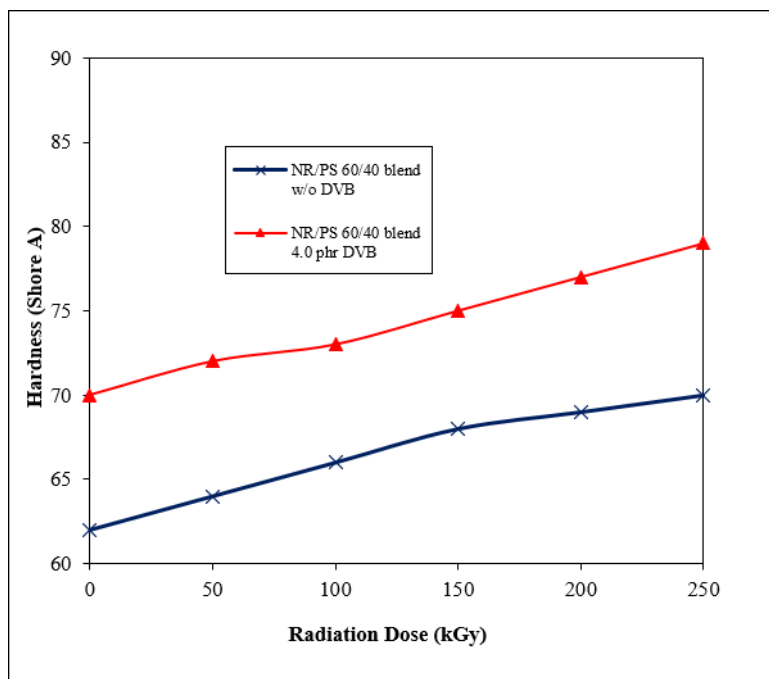


Figure 9. Influence of radiation dose on the hardness of NR/PS 60/40 blend.

According to Chalykh et al. [30], the improvement in impact strength is attributed to enhanced interfacial adhesion between the component phases, resulting from radiation-induced grafting. In contrast, Ren et al. [31] suggest that the increase in impact strength is related to the formation of higher gel content. Salakhov et al. [32] reported that the impact strength of rubber–plastic blends is influenced by several factors, including the inherent properties of the matrix, characteristics of the rubber phase, rubber concentration, particle size and morphology, phase composition, crosslink density within the rubber phase, cohesive strength of the rubber phase, and interfacial adhesion between the two phases. Furthermore, Seier et al. [33] found that incorporating a reactive sensitizer into rubber/PS blends improves phase interaction and enhances compatibility between the rubber and PS phases. In the NR/PS 60/40 blend, DVB was observed to enhance impact strength by promoting crosslinking within the rubber phase and strengthening interfacial adhesion between the rubber and PS phases.

Hardness is a measure of a material's resistance to localized deformation. The hardness results exhibited a trend similar to that observed for M100%. Radiation-induced crosslinking is commonly associated with the hardness level of blends exposed to radiation. Figure 9 illustrates the effect of irradiation dose on the Shore A hardness of the NR/PS 60/40 blend. As the irradiation dose increases, the Shore A hardness of both blends increases correspondingly. However, the NR/PS 60/40 blend containing 4.0 phr DVB exhibits higher Shore A hardness than the blend without DVB

at all irradiation doses. The presence of 4.0 phr DVB enhances the hardness of the blend, indicating that DVB promotes a higher crosslink density. Generally, DVB can increase copolymerization and also crosslink grafting of polystyrene chains [34]. According to Yeon et al. [34], studies on pure polystyrene (PS) exposed to γ -radiation at 5 Mrad showed an increase in hardness compared to the unirradiated sample. This is attributed to the predominance of crosslinking over chain scission in the PS structure. A similar trend was observed in a ternary blend of poly(vinylidene fluoride)/poly(methyl methacrylate)/polystyrene, where hardness increased upon exposure to γ -radiation.

Based on the gel content, swelling index, and mechanical property results, DVB was found to be an effective sensitizer for radiation-induced crosslinking in the NR/PS 60/40 blend, enabling effective crosslinking at lower irradiation doses. DVB contains two vinyl groups, each possessing one double bond. According to Ashfaq et al. [35], the effectiveness of polyfunctional monomers used as sensitizers in radiation-induced crosslinking is influenced by several factors, including the number of double bonds present.

CONCLUSION

The study demonstrated that incorporating 4.0 phr DVB as a radiation sensitizer enhanced the electron beam-induced crosslinking efficiency and mechanical performance of NR/PS 60/40 blends. Through melt blending followed by electron beam irradiation, the presence of DVB increased the gel content and

reduced the swelling index in the NR phase, indicating more efficient crosslink formation. The blend containing 4.0 phr DVB achieved a gel content of 92% in the NR phase at an irradiation dose of 100 kGy, whereas the blend without DVB required a higher irradiation dose of 150 kGy to attain a comparable gel content of 93%. The minimum swelling index was observed at 150 kGy for both blends; however, the blend containing 4.0 phr DVB exhibited a lower swelling index of 8.0 compared with 9.2 for the blend without DVB, confirming a higher crosslink density. Mechanical evaluation further demonstrated that DVB improved the overall performance of the NR/PS 60/40 blends. The blend containing 4.0 phr DVB exhibited a higher tensile strength of 8.6 MPa at 150 kGy, whereas the blend without DVB reached only 7.9 MPa at 200 kGy. At -10°C , the blend containing 4.0 phr DVB achieved an optimum Izod impact strength of 180 J m^{-1} at 100 kGy, compared with 168 J m^{-1} for the blend without DVB at 150 kGy. In addition, the blend containing 4.0 phr DVB exhibited higher M100% values than the blend without DVB. The hardness of the blend containing 4.0 phr DVB was 73 Shore A at 100 kGy, compared with 66 Shore A for the blend without DVB under the same irradiation conditions. The optimum irradiation condition was achieved at a lower dose for the NR/PS blend containing 4.0 phr DVB compared with the blend without DVB. The incorporation of DVB enhanced radiation crosslinking efficiency, allowing the NR/PS blend to achieve comparable or improved mechanical properties at 100 kGy, while a higher dose of 150 kGy was required for the blend without DVB. The novelty of this work lies in demonstrating that DVB is an effective sensitizer for electron beam-induced crosslinking of NR/PS 60/40 blends, enabling comparable or improved crosslinking and mechanical performance at lower irradiation doses than blends without DVB. These findings demonstrate that incorporating DVB can enhance the efficiency of electron beam-induced crosslinking, allowing the NR/PS blend to achieve improved properties at a lower irradiation dose. This approach may contribute to improved processing efficiency while reducing the risk of radiation-induced degradation associated with excessive irradiation.

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