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Electron Beam Irradiated Natural Rubber-Polyaniline Dodecylbenzenesulphonate Blends: Their Preparation, Electrical and Physical Properties

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Electron beam irradiation technique was successfully used for the first time in order to crosslink the natural rubber-polyaniline dodecylbenzenesulphonate [NR-PAni.DBSA] blends. Significant increases in crosslink densities of all blends with doses of irradiation up to 200 kGy were obtained and a reasonably high crosslink density level (in the order of 10^4 mol/cm^3) was achieved. All electron beam-irradiated NR-PAni.DBSA blends showed good tensile properties with tensile strength up to about 19.7 MPa. This kind of irradiation induced-crosslink technique at doses up to 200 kGy also did not affect electrical properties after being sufficiently stabilised for at least 24 hours. The irradiated NR-PAni.DBSA blends also exhibited good electrical properties, i.e. a single conductivity percolation threshold and high conductivities up to the order of 10^{-2} S.cm^{-1}. In other words, there is a good potential of using electron beam irradiation technique to prepare highly crosslinked, electrically conductive NR-PAni.DBSA blends.

Keywords: electron beam irradiation; natural rubber; polyaniline; tensile properties; electrical properties

Numerous previous reports[1–10] have been made on the preparation of conductive rubber blends with the protonic acid doped-polyaniline [PAni] *via* different methods. Studies[1–5,7–12] involving synthetic rubbers *e.g*. nitrile rubber, polychloroprene, EPDM [poly(ethylene-co-propylene-co-diene)], SBS [poly(butadiene-co-styrene)] copolymer *etc*., have always been given more focus than the natural rubber (NR) based ones[6,12-13].

By using a protonic acid as the doping agent, PAni becomes electrically conductive[14]. However, the presence of a strong protonic acid is believed to be able to affect the efficiency of some crosslinking agents, especially peroxides and sulphur systems. It is suggested that irradiation induced crosslinking by exposure to different types of sources, *e.g*. electron beam, gamma, X-ray *etc*., may be applied to rubber in the presence of a protonic acid doped-PAni in order to overcome this crosslink shortcoming. In the irradiation process, the crosslinking mechanism is initiated by free-radical reactions and subsequently produces inter-chain carbon-carbon bonds within the

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rubber host matrix. Some ionic species may also be created at the same time, increasing the compound's electrical conductivity[15]. This phenomenon is called "*irradiation induced conductivity*". This kind of conductivity decays with time and is about 1-2 magnitude orders lower after the extended period[16]. It is also known that crosslinking and degradation of an elastomer can occur simultaneously upon irradiation[17]. However, the ratio of their rates depend on the chemical structure of the elastomer, its physical state and also the irradiation conditions.

Faez *et al*.[11] prepared EPDM-polyaniline dodecylbenzenesulphonate [PAni.DBSA] blends by mechanical mixing and reported that the blends showed good electrical properties after they were crosslinked *via* electron beam irradiation with doses, *i.e*. 75 and 150 kGy respectively. Helaly *et al*.[12] prepared blends of natural rubber (Standard Malaysian Rubber 20 grade) with undoped polyaniline by using a two-roll mill in order to study the efficiency of undoped polyaniline as an antioxidant against thermal ageing for natural rubber. The blends were vulcanised using a zinc oxide/stearic acid system but no electrical conductivity determination was performed due to the non conductive state of undoped polyaniline. In the author's previous work[6], non vulcanised blends of epoxidised natural rubber-polyaniline dodecylbenzensulphonate [ENR-PAni.DBSA] were produced by solution mixing. Significant ring opening of the ENR was found especially for the blends with high loadings of PAni.DBSA, *i.e*. ≥30 wt %. This was attributed to the sensitivity of the epoxide group of ENR to the acidic condition of doped PAni. Ring opening of the ENR will decrease its elastomeric properties due to the formation of furanised natural rubber[18].

A regular grade of NR was used in this work as the replacement of ENR in order to overcome the 'ring opening' problem. Besides this, the electron beam irradiation was chosen as the technique of crosslinking for the natural rubber-polyaniline dodecylbenzensulphonate [NR-PAni.DBSA] blends. The main objective of this work was to study the effect of electron beam induced crosslinking on the NR-PAni.DBSA blends' electrical and physical properties. As a result, measurements and analyses were performed for the irradiated blends on their crosslink densities *via* solvent swelling test, basic tensile properties *i.e*. tensile strength, elongation at break percentage and modulus at break as well as dc electrical resistance using the two-probe technique. A scanning electron microscope (SEM) was also used in order to examine the morphological behaviour of the irradiated blends.

EXPERIMENTAL

Chemicals and Raw Materials

The conductive filler used here was commercial grade PAni.DBSA manufactured by Panipol Oy, Finland. Natural rubber, *i.e.* Standard Malaysian Rubber SMR 20 grade, manufactured by Chip Lam Seng Sdn. Bhd. was used as the only rubber host. Toluene (GPR) was chosen as the solvent for performing the swelling test as discussed below due to its good solubility with the NR-PAni.DBSA blends.

NR-PAni.DBSA Blends Preparation

NR-PAni.DBSA blends with different proportions of PAni.DBSA *i.e.* 2.5, 5.0, 7.5, 10.0, 20.0, 30.0, 40.0 and 50.0 wt %, were prepared using the Haake Rheomix 600 Internal Mixer. A fill factor of 0.80 was used for all mixing. The starting temperature for each mix was 120ºC and the rotor speed was 100 r.p.m. Stages of each mixing are summarised in *Table 1*. Samples of raw NR

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TABLE 1. STAGES OF MIXING FOR NR-PANI.DBSA BLEND MASTER BATCH USING AN INTERNAL MIXER

Stage of mixing	Timing
Addition of NR	0th minute
Addition of PAni.DBSA	1st minute
Sweeping	3rd minute
Dumping	6th minute
(Total time= 6 minutes)	

without addition of any PAni.DBSA were also prepared as experimental control.

After dumping from the internal mixer, the raw NR and each of the NR-PAni.DBSA blends were immediately passed through a pre-warmed (~50ºC) two-roll mill in order to produce sample slabs of thickness 2.0±0.2 mm.

Electron Beam Irradiation of Samples

All prepared samples were sent to Malaysian Nuclear Agency, Bangi for electron beam irradiation using EPS 3000 Electron Beam, acceleration voltage 2 MeV, beam current 5 mA, distance from the beam window 20 cm and direct exposure on one side for each sample, at four respective fixed doses, *i.e*. 50 kGy for Set No. 1 samples, 75 kGy for Set No. 2 samples, 150 kGy for Set No. 3 samples and 200 kGy for Set No. 4 samples. Samples as control without being irradiated were also prepared and grouped as Set No. 5. All irradiated samples were also kept for at least 48 h at 23ºC in order to achieve stability before being sent for solvent swelling tests, morphological analysis, electrical and tensile property measurements.

Determination of Crosslink Densities *via* Solvent Swelling Test

Circular test pieces with a diameter of 22.0±0.2 mm and thickness 2.0±0.2 mm were swollen in toluene at 23ºC within 72 h until equilibrium swelling was achieved. Five test pieces of each sample were used to repeat each test in order to define the final result in mean value of all measurements.The swollen pieces were weighed and then placed in an oven at 70ºC for 24 h in order to remove the solvent. The weight after drying was measured again and the degree of swelling of a test piece (Q%) was calculated using *Equation 1*, where $W1$ is the weight of swollen rubber, g and $W2$ is the weight of rubber after drying, g. Weighing bottle was used to weigh the swollen sample in order to minimise error associated with volatility of the solvent. All measurements were done by using an electric balance with sensitivity, 10^{-5} g.

$$Q\% = \left(\frac{W1 - W2}{W2}\right)(100) \qquad \ldots 1$$

The solvent, toluene (C_7H_8) used here has a molar volume[19] ($V1$) of 107 cm^3/mol and cohesive energy density[19] (δ) of 8.9 $(cal/cm^3)^{0.5}$.

Measurement of Tensile Properties

Basic tensile tests *i.e* tensile strength, elongation at break percentage (EB %), modulus at 100% elongation (M100) and modulus at 300% elongation (M300) were performed according to *BS ISO* standards[20]. Six test pieces of each irradiated sample were used to repeat each test in order to define the final result as the mean value of all measurements. No measurement was carried out for the set of non irradiated samples *i.e*. Set No. 5 because they were assumed to be non crosslinked samples.

Determination of Electrical Conductivities

The dc electrical conductivities of all samples, both irradiated and non irradiated, with each test piece of dimension 2.0 cm × 2.0 cm × 0.2 cm were calculated from electrical resistance values measured using guarded 2-probe techniques[5–6,21]. For all irradiated samples, their electrical resistance measurements were done at fixed periods, *i.e*. right after released from the irradiation chamber and after being stored at 23ºC for 3, 6, 9, 12, 24, 48, 72, 96, 120, 144, 168, 336, 504 and 720 h respectively. The same test period was also applied for the non irradiated samples for comparison purposes. A Keithley 6517A electrometer with built-in voltage source up to 1 kV was used for the measurement. For each sample, six test pieces were prepared and measured in order to obtain a mean value. Electrical conductivities were calculated from the mean resistance values obtained by the 2-probe method using *Equation 2*.

$$\sigma = \left(\frac{1}{R}\right)\left(\frac{L}{A}\right) \qquad \ldots 2$$

where σ is the electrical conductivity, R is the mean value of apparent resistance (voltage/current ratio) for the test piece, L is the electrode spacing (1.5 cm) and A is the cross sectional area of test piece between the current carrying electrodes.

Morphological Study

Both irradiated and non irradiated NR-PAni.DBSA blends prepared in this work *i.e.* their sectional surfaces, were examined with SEM JOEL JSM-6701F, at accelerating voltage 2 keV with 300 times magnification, in order to determine the effect of electron beam irradiation on their morphological structures.

RESULTS AND DISCUSSION

Determination of Crosslink Densities

The diffusion theory in rubbers[22–24] is based on the assumption that swelling commences by absorption of liquid in the surface of the sample to a certain concentration equal to that of the entire sample at final equilibrium. One of the most important structural parameters characterising a crosslinked polymer is M_c, the average molecular weight between crosslinks which is directly related to the crosslink density. The magnitude of M_c significantly affects the mechanical properties of crosslinked polymers and its determination has great practical significance. Equilibrium swelling can be used to determine M_c[25–28]. Early works[19,25–28] reported the basis for the analysis of equilibrium swelling. *Equation 3* can be used for a perfect network according to the theory of Flory and Rehner[25–26]:

$$M_c = -V_1 \rho_P (\phi_P^{1/3} - \phi_P) / [\ln(1-\phi_P) + \phi_P + \chi_1 \phi_P] \qquad \ldots 3$$

where M_c is the average molecular weight of the polymer between crosslinks, V_1 is the molar volume of the solvent, ρ_p is the polymer

density, ϕ_p is the volume fraction of polymer in the swollen gel and χ_1 is the Flory–Huggins interaction parameter of polymer-solvent. The swelling ratio, q is equal to $1/\phi_p$ and can be calculated using *Equation 4* below.

$$q = \frac{1}{\phi_P} = 1 + \frac{\rho_P M_s}{\rho_s M_P} \quad \ldots 4$$

where ρ_p and ρ_s are the polymer and the solvent densities respectively and M_p and M_s are weights of dry polymer and absorbed solvent respectively.

The crosslink density, v_e can be defined[25–28] as the total number of elastically effective chains included in a perfect network, per unit volume and is presented by *Equation 5*. N_A is Avogadro's number.

$$v_e = \frac{\rho_P N_A}{M_c} \quad \ldots 5$$

Hilderbrand's parameter δ, a measure of the cohesive energy density (CED) of a liquid is often used as a measure of intermolecular interaction. The best solvent of a given polymer is a liquid with δ as similar as possible to that of the polymer[27]. This consideration is the basis for determining the δ of a polymer[27].

The Flory–Huggins interaction parameter (χ_1) between polymer-solvent can be calculated using *Equation 6*:

$$\chi_1 = V_1 \left(\frac{\delta_1 - \delta_2}{RT} \right)^2 \quad \ldots 6$$

where δ_1 and δ_2 are the CED of solvent and polymers [δ of NR is 16.2 $(cal/cm^3)^{0.5}$; δ of PAni.DBSA is 20.8 $(cal/cm^3)^{0.5}$] respectively, V_1 the partial molar volume of the solvent, R the universal gas constant and T is the absolute temperature. By substituting the values of χ_1 for all samples into *Equation 3*, one can calculate the value of M_c for each sample and hence, using *Equation 5*, the crosslink density v_e is obtained as summarised in *Table 2*.

Significant increase in crosslink densities of all NR-PAni.DBSA blends with doses of irradiation was observed (*Table 2*). At irradiation dose 200 kGy, a reasonably high crosslink density level in the order of 10^4 mole/cm^3 was achieved and this is comparable with those levels as obtained for rubbers crosslinked *via* the conventional sulphur technique[28]. Apart from this, crosslink densities of all blends were also enhanced with the content of PAni.DBSA. Literature[7] reported that some extra crosslinking of the

TABLE 2. CALCULATED CROSSLINK DENSITIES OF NR-PANI.DBSA BLENDS

Blend (wt%NR:wt% PAni.DBSA)	Crosslinking density, $v_e \times 10^4$ (mol/cm^3)				
	Non irradiated sample	Sample irradiated at 50 kGy	Sample irradiated at 75 kGy	Sample irradiated at 150 kGy	Sample irradiated at 200 kGy
100:0	1.12	2.33	3.05	5.33	6.21
97.5:2.5	1.15	2.38	3.12	5.37	6.33
95:5	1.29	2.41	3.19	5.42	6.45
92.5:7.5	1.75	2.83	3.27	5.61	6.56
90:10	1.93	3.06	3.46	5.92	6.71
80:20	2.11	3.29	3.70	6.08	7.04
70:30	2.28	3.31	3.88	6.13	7.17
60:40	2.37	3.48	4.02	6.27	7.25
50:50	2.52	3.54	4.23	6.38	7.36

rubber matrix could be attributed to the free radicals released by PAni.DBSA itself[29] during the high temperature mixing condition and also the high irradiating doses for this case.

The Charlesby-Pinner equation[30] (*Equation 7*) was applied to all irradiated samples in order to evaluate their crosslinking and chain-scission yields (*Figure 1*).

$$S + \sqrt{S} = \frac{p_0}{q_0} + \frac{1}{\alpha P_n D} \qquad \ldots 7$$

where S is the sol fraction, P_n the number averaged degree of polymerisation, D is the radiation dose, p_0 and q_0 are fractions of ruptured and crosslinked main-chain units per unit dose proportional to the radiation chemical yields of degradation and crosslinking.

From the Charlesby-Pinner plots (*Figure 1* and *Table 3*), the NR-PAni.DBSA blend was most efficiently crosslinked at 50 wt % of added PAni.DBSA. The crosslinking extent increased almost linearly with the PAni.DBSA loading. Lower values of p_0/q_0 for higher PAni.DBSA loadings suggest an improved radical-radical interaction in the NR-PAni.DBSA blends due to decrease of free volume within the polymeric system.

Measurement of Tensile Properties

Results from the tensile properties test are shown in *Figures 2* to *5*. It was found that the electron beam irradiated NR-PAni.DBSA blends behaved very similarly with the same kind of blends crosslinked either *via* conventional sulphur[8] or peroxide[7,10] techniques. PAni.DBSA acted as a reinforcing agent for the blends, where both tensile strengths and EB % of blends enhanced with the PAni.DBSA proportion up to an optimum level, *i.e.* 20.0 wt %. The tensile strengths and EB % started to decrease for blends with ≥30.0 wt % of PAni.DBSA due to the increase of phase separation between rubber host and PAni.DBSA[10]. It is proposed that the phase-separated PAni.DBSA regions had started to determine the blends' properties, making their tensile values decrease and approach those of 'thermoplastic like' pure PAni.DBSA[1]. Samples irradiated at higher doses of 150 and 200 kGy, showed better tensile properties than those irradiated at lower doses of 50 and 75 kGy. This was attributed to their higher crosslink densities as mentioned above. Results of M100 and M300 (*Figures 4* and *5*) are also included here to show the good elastomeric features of the irradiated blends in general.

TABLE 3. CONTENT OF PANI.DBSA AND p_0/q_0 OF IRRADIATED NR-PANI.DBSA BLENDS

PAni.DBSA Content (wt %)	p_0/q_0
2.5	1.21
5.0	1.17
10.0	1.14
20.0	1.10
30.0	1.06
40.0	1.02
50.0	0.99

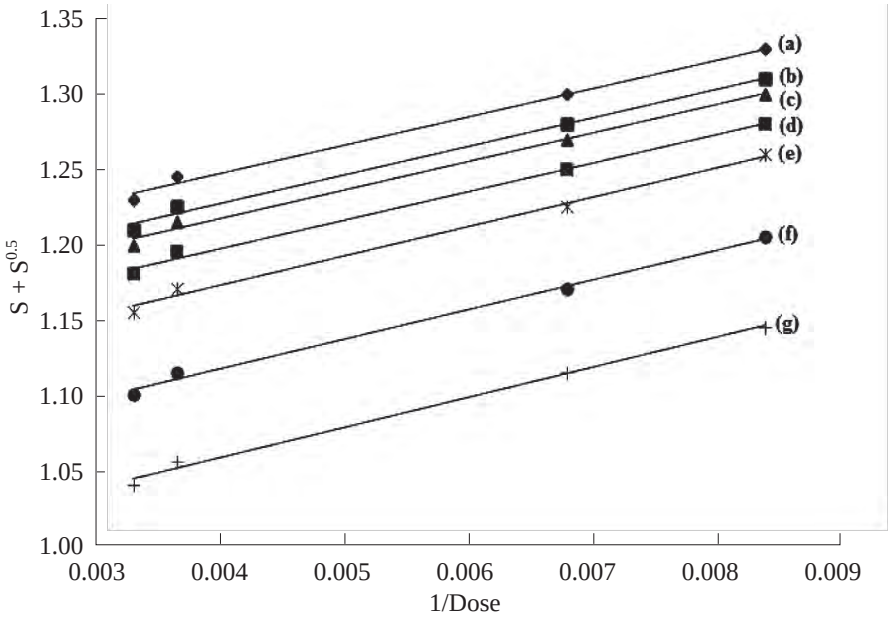


Figure 1. Charlesby-Pinner Plots of Electron Beam Irradiated NR-PAni.DBSA Blends.
(a) Blend with 2.5 wt % PAni.DBSA; (b) Blend with 5.0 wt % PAni.DBSA; (c) Blend with 10 wt % PAni. DBSA; (d) Blend with 20 wt % PAni.DBSA; (e) Blend with 30 wt % PAni.DBSA; (f) Blend with 40 wt % PAni.DBA; (g) Blend with 50 wt % PAni.DBSA.

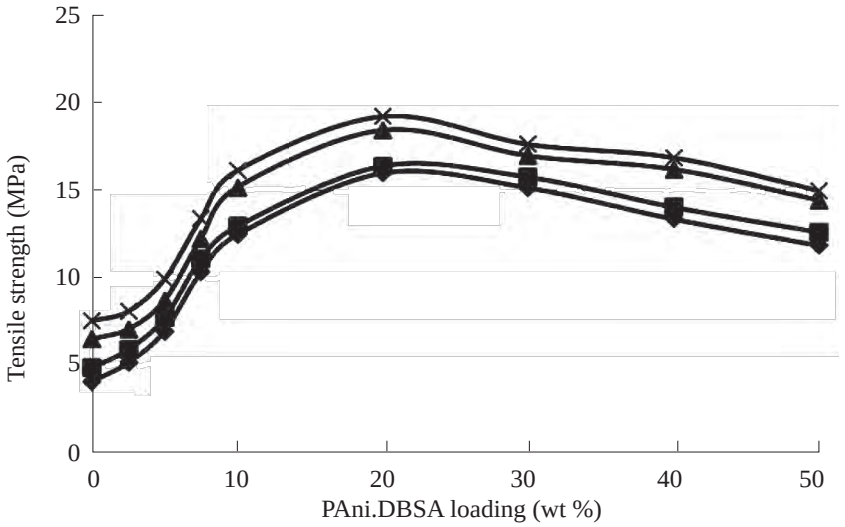


Figure 2. Tensile Strength (Error ±0.5 MPa) of Electron Beam Irradiated NR-PAni.DBSA Blends.
◆ - Irradiated at 50 kGy; ■ - Irradiated at 75 kGy; ▲ - Irradiated at 150 kGy; ×-Irradiated at 200kGy.

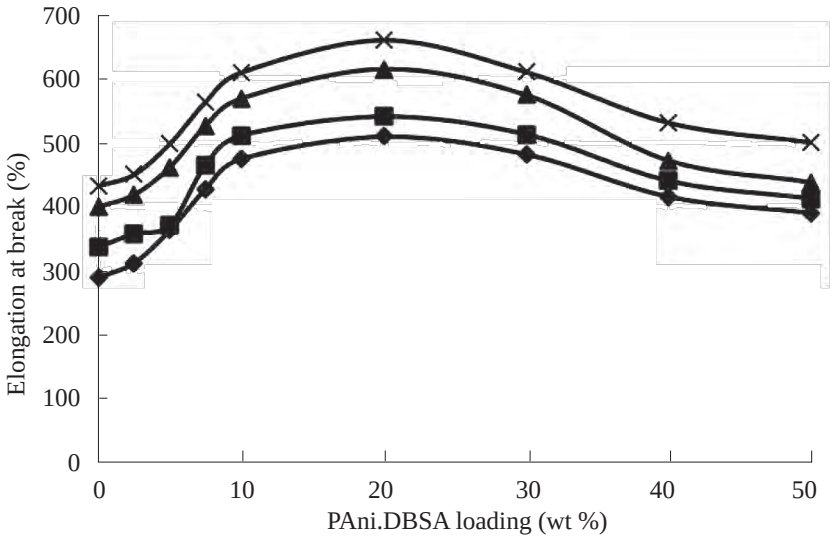


Figure 3. Elongation Percentage at Break (EB %, Error ±20%) of Electron Beam Irradiated NR-PAni.DBSA Blends.
◆ - Irradiated at 50 kGy; ■ - Irradiated at 75 kGy; ▲ - Irradiated at 150 kGy; × - Irradiated at 200kGy.

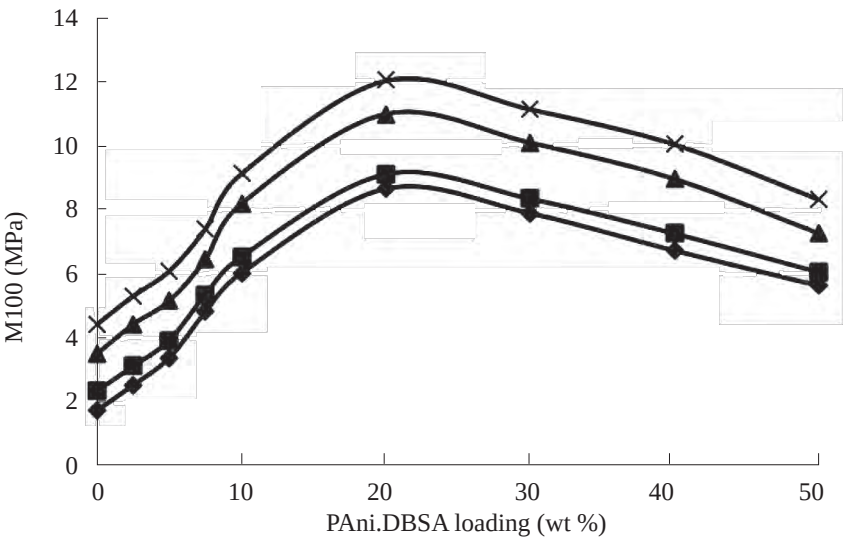


Figure 4. M100 (Error ± 0.5 MPa) of Electron Beam Irradiated NR-PAni.DBSA Blends.
◆ - Irradiated at 50 kGy; ■ - Irradiated at 75 kGy; ▲ - Irradiated at 150 kGy; × - Irradiated at 200kGy.

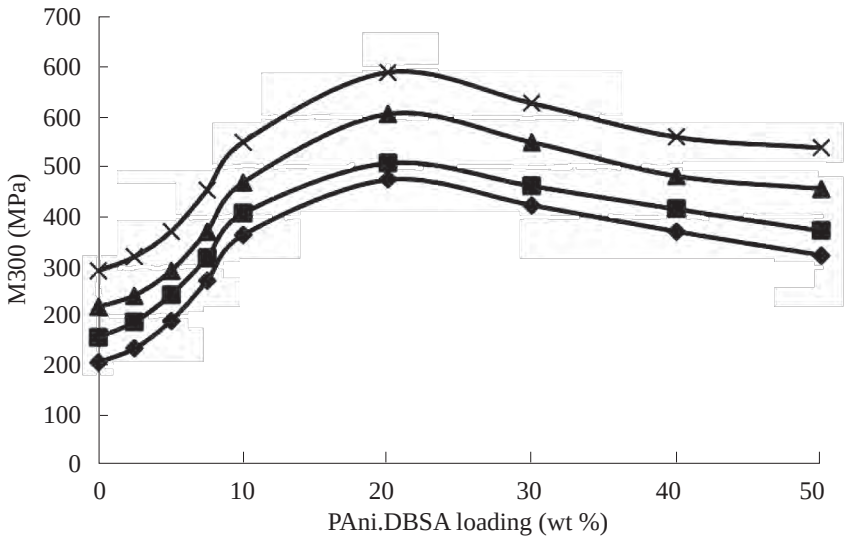


Figure 5. M300 (Error ±0.5 MPa) of Electron Beam Irradiated NR-PAni.DBSA Blends.
◆ - Irradiated at 50 kGy; ■ - Irradiated at 75 kGy; ▲ - Irradiated at 150 kGy; × - Irradiated at 200kGy.

Determination of Electrical Conductivities

The effect of storage period on the irradiated NR-PAni.DBSA blends electrical conductivities are featured in *Figure 6*. However, only examples of Set No. 2, 3 and 5 with 40 wt % of PAni.DBSA are shown here due to the very similar values of results. Non irradiated samples showed no significant changes in terms of their electrical conductivities within the fixed storage period of up to 30 days. However, for blends irradiated at doses ≤75 and ≥150 kGy respectively, there was a drop of about one order of magnitude in electrical conductivities with increasing storage period, 0 to 6 h (*Figure 6*). It is proposed that the early recorded enhancement of electrical conductivities for all irradiated samples of storage period less than 24 h is a temporary one[15] and as found from this work, it started to decrease for a storage period less than 24 h (*Figure 6*). Oral *et al*.[31] also reported the free radicals generated could be trapped and remained active for a longer period for some high molecular weight polymers.

The stabilised electrical conductivities of both non irradiated and irradiated samples were also determined (see *Figure 7* for examples that were stored 336 h before and after irradiation at 75 kGy and 150 kGy, respectively) for their percolation thresholds analysis. By fitting the data to a simple percolation model[32], it was possible to estimate the values of critical exponent (t) and correlation coefficient (R) for each case. The estimated electrical conductivity percolation thresholds for samples stored for 336 h are shown in *Table 4*.

All samples before and after irradiation tested in this work generally retained their identical electrical conductivity values within the same magnitude orders, (*Figure 7*). In terms of derived percolation threshold (*Table 4*), both non irradiated and irradiated samples

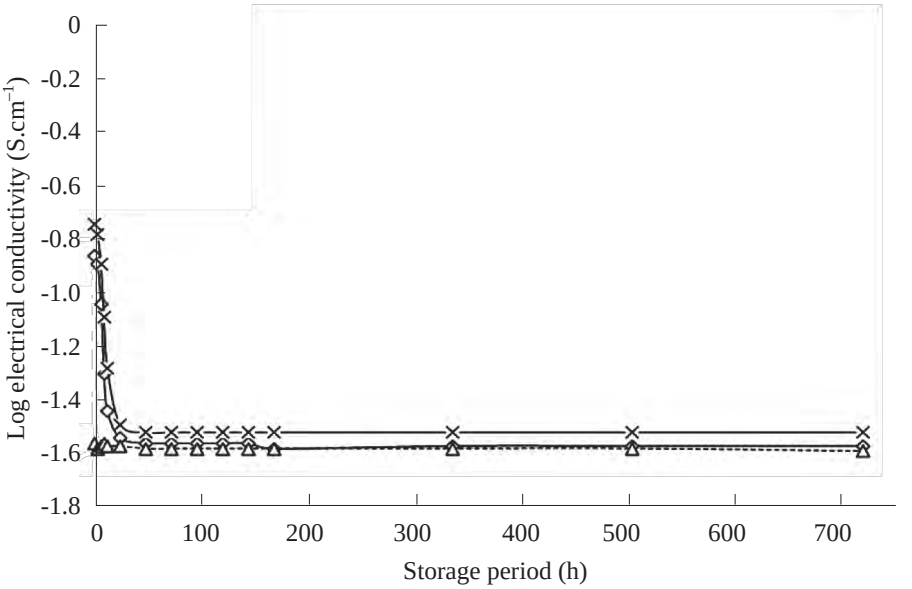


Figure 6. Electrical Conductivities vs. Storage Periods for the Electron Beam Irradiated NR-PAni.DBSA Blends (with 40 wt % of PAni.DBSA Loading).
◊ - Irradiated at 75 kGy; × - Irradiated at 150 kGy; △ - Non irradiated sample.

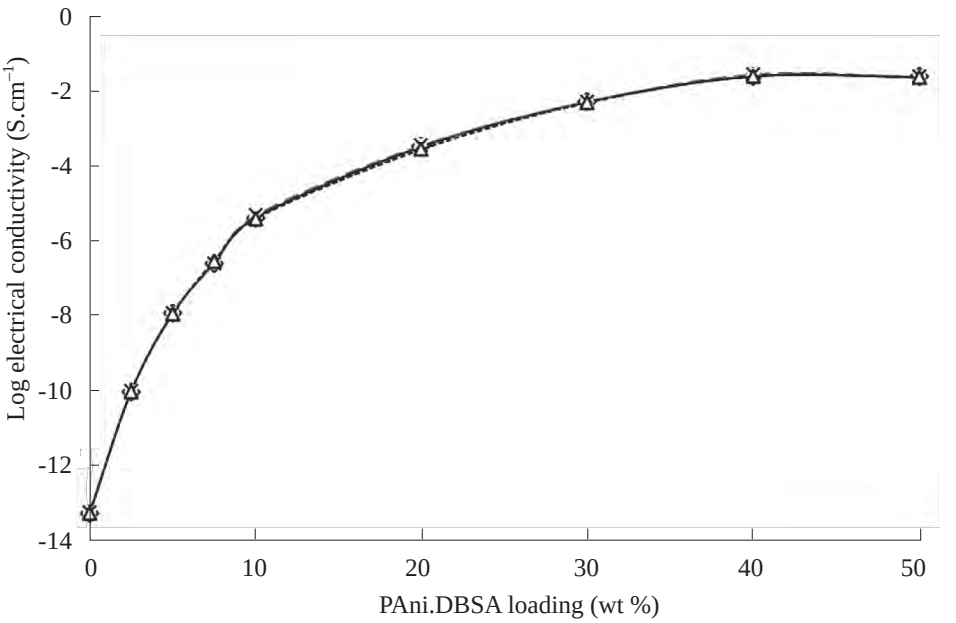


Figure 7. Electrical Conductivities for the Raw NR and NR-PAni.DBSA Blends (Before and After Irradiation with Storage Period, 336 h) as a Function of PAni.DBSA Loading (wt %).
◊ - Irradiated at 75 kGy; × - Irradiated at 150 kGy; △ - Non irradiated sample.

TABLE 4. ELECTRICAL CONDUCTIVITY PERCOLATION THRESHOLDS FOR NR-PANI.DBSA BLENDS (BEFORE AND AFTER IRRADIATION WITH STORAGE PERIOD, 336 H)

NR-PAni.DBSA blend	Estimated percolation threshold, (wt %/volume % of PAni.DBSA content)	Critical exponent, *t*	Correlation coefficient, *R*
Set No. 1: Irradiated at dose, 50 kGy	5.5/4.94	3.9	0.98
Set No. 2: Irradiated at dose, 75 kGy	5.5/4.94	3.9	0.99
Set No. 3: Irradiated at dose, 150 kGy	5.6/5.03	4.0	0.99
Set No. 4: Irradiated at dose, 200 kGy	5.6/5.03	4.0	0.99
Set No. 5: Non irradiated sample	5.6/5.03	4.0	0.99

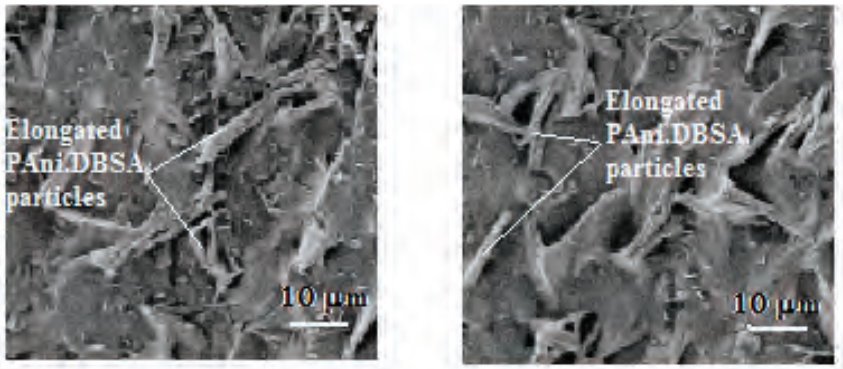
exhibited very close estimated values, *i.e.* 5.5 to 5.6 wt % or 4.94 to 5.03 volume % of PAni. DBSA loading. As a result, the electron beam irradiated crosslinking technique used in this study did not interrupt the NR-PAni.DBSA blends' electrical properties after the blends were sufficiently stabilised for at least 24 h after the irradiation.

Morphological Study

SEM was used to study all NR-PAni. DBSA blends in order to determine the effect of electron beam irradiation on their morphological structures. *Figure 8* shows the example micrographs of a blend consisting 20 wt % of PAni.DBSA before and after irradiation at a dose of 200 kGy. As observed from all the micrographs, the elongated rod-like structures of the PAni.DBSA dispersed particles were seen to form the electrically conductive networks within the NR matrix and the level of network formation was enhanced with increasing PAni.DBSA loading. The formation of elongated rods instead of the spherical particles observed for conventional carbon blacks by the conductive PAni has been reported previously[8,33–34]. Identical morphological structures were also found for all samples with the same level of PAni. DBSA loading before and after irradiation (*Figure 8*). This is evidence that the NR-PANi. DBSA blends' morphological structures were not affected by the electron beam irradiation up to a dose of 200 kGy. The finding here is in agreement with the results as discussed earlier, where identical electrical conductivity values were observed for either non irradiated or irradiated blends with the same proportion of PAni.DBSA attributed to the similar level of built-up conductive networks.

CONCLUSION

Significant increases in crosslink densities of all NR-PAni.DBSA blends with doses of electron beam irradiation as high as 200 kGy were successfully observed and a reasonably high crosslink density level up to the order of 10^4 mol/cm^3 was also reached. PAni.DBSA played its role as a reinforcing agent here up to an optimum loading level of 20.0 wt %, which is very similar to conventional sulphur or peroxide crosslinked PAni.DBSA based



(a) (b)

Figure 8. Scanning Electron Micrographs of NR-PAni.DBSA Blend with 20 wt % of PAni.DBSA Loading. (a) Non irradiated Blend; (b) Blend Irradiated with Electron Beam at Dose, 200 kGy.

blends. As found from the SEM micrographs, NR-PAni.DBSA blends' morphological structures were not affected by the electron beam irradiating process at doses up to 200 kGy. The electron beam induced crosslink technique also did not interrupt the blends' electrical properties after the blends were sufficiently stabilised for at least 24 hours. The irradiated NR-PAni.DBSA blends showed good electrical properties *i.e.* a single conductivity percolation threshold and high conductivities up to the order of 10^{-2} S.cm^{-1}, due their unaffected morphological structures and also a reasonably good dispersion level of the loaded PAni.DBSA[7].

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REFERENCES

1. VALLIM, M.R., FELISBERTI, M.I. AND DE PAOLI, M.-A. (2000) Blends of Polyaniline with Nitrilic Rubber. *J. Appl. Polym. Sci.*, **75**, 677–684.

2. DAVIES, S.J., RYAN, T.G., WILDE, C.J. AND BEYER, G. (1995) Processable Forms of Conductive Polyaniline. *Synthetic Met.*, **69**, 209–210.

3. CARONE, E., D'ILARIO, L. AND MARTINELLI, A. (2002) New Conductive Thermoplastic Elastomers. Part II. Physical and Chemical-Physical Characterization. *J. Appl. Polym. Sci.*, **86**, 1259–1264.

4. TASSI, E.L. AND DE PAOLI, M.-A. (1992) An Electroactive Elastomer: Polyaniline/ Nitrile Rubber. *Polymer*, **33**, 2427–2430.

5. YONG, K.C., FOOT, P.J.S., MORGAN, H., COOK, S. AND TINKER, A.J. (2006) Conductive Poly(butadiene-*co*-acrylonitrile)-Polyaniline Dodecylbenzenesulfonate [NBR-PAni. DBSA] Blends prepared in Solution. *Eur. Polym. J.*, **42**, 1716–1727.

6. YONG, K.C., FOOT, P.J.S., MORGAN, H., COOK, S., TINKER, A.J. AND AHMAD MD. ARIS. (2008) Electrical Conductive Epoxidised Natural Rubber-Polyaniline Dodecylbenzenesulfonate Blends prepared by Solution Mixing. *J. Rubb. Res*., **11(2)**, 59–77.

7. YONG, K.C. AND MT. SAAD, C.S. (2009) Novel Peroxide-Vulcanized NBR-PAni. DBSA Blends, Part 1: Preparation & Characterization. *J. Appl. Polym. Sci*., **112**, 3199–3208.

8. YONG, K.C. AND MT SAAD, CHE SU. (2010) High Temperature-Mechanical Mixing to prepare Electrically Conductive Sulfur-Vulcanised Poly(butadiene-co-acrylonitrile)-Polyaniline Dodecylbenzenesulfonate Blends. *J. Rubb. Res*., **13(1)**, 1–17.

9. YONG, K.C. (2012) Electrically Conductive Poly(butadiene-*co*-acrylonitrile)-Polyaniline Dodecylbenzenesulfonate [NBR-Pani.DBSA] Blends with Hydroquinone as Compatibiliser. *J. Rubb. Res*., **15(3)**, 153–166.

10. YONG, K.C. (2012) Novel Peroxide-Vulcanized NBR-PAni.DBSA Blends, Part 2: Effects of Conductive Filler Particles Alignment. *J. Appl. Polym. Sci*., **124**, 729–739.

11. FAEZ, R., SCHUSTER, R.H. AND DE PAOLI, M.-A. (2002) A Conductive Elastomer based on EPDM and Polyaniline: II Effect of the Crosslinking Method. *Eur. Polym. J*., **38(12)**, 2459–2463.

12. HELALY, F.M., DARWICH, W.M. AND ABD EL-GHAFFAR, M.A. (1999) Effect of Some Polyaromatic Amines on the Properties of NR and SBR Vulcanizates. *Polym. Degrad. Stabil*., **64**, 251–257.

13. YONG, K.C. (2011) Epoxidized Natural Rubber-Polyaniline Dodecylbenzenesulonate Blends: Effect of Strain. *Rubb. Chem. Technol*., **84(4)**, 580–593.

14. POUSSIN, D., MORGAN, H. AND FOOT, P.J.S. (2003) Thermal Doping of Polyaniline by Sulfonic Acids. *Polym. Int*., **52**, 433–438.

15. BODUGOZ-SENTURK, H. AND GUVEN, O. (2011) Enhancement of Conductivity in Polyaniline-[Poly(vinylidene chloride)-co-(vinyl acetate)] Blends by Irradiation. *Radiat. Phys. Chem*., **80(2)**, 153–158.

16. SHULTZ, A.R. (1986) Encyclopedia of Polymer Science and Engineering, **Vol. 4**, New York: John Wiley, 418.

17. WOODS, R.J. AND PIKAEV, A.K. (1994) Applied Radiation Chemistry: Radiation Processing, New York: John Wiley, 343.

18. GELLING, I.R. (1991) Epoxidised Natural Rubber. *J. nat. Rubb. Res*., **6(3)**, 184–205.

19. GWAILY, S.E., BADAWY, M.M., HASSAN, H.H. AND MADANI, M. (2003) Influence of Thermal Aging on Crosslinking Density of Boron Carbide/Natural Rubber Composites. *Polym. Test.*, **22**, 3–7.

20. BRITISH STANDARDS INSTITUTION (2005). Rubber, Vulcanised or Thermoplastic-Determination of Tensile Stress-Strain Properties. *BS ISO 37*.

21. YONG, K.C. (2011) Sulfur-Vulcanised Epoxidised Natural Rubber (ENR)-Carbon Black Blends with Reproducible Electrical Conductivity Behaviour. *J. Rubb. Res*., **14(3)**, 151–166.

22. LAWANDY, S.N. AND WASSEF, N.T. (1990) Penetration of Oil into Polychloroprene Rubber. *J. Appl. Polym. Sci*., **40**, 323–331.

23. LAWANDY, S.N. AND HELALY, F.H. (1986) Diffusion of a Volatile Liquid in Polychloroprene Rubber. *J. Appl. Polym. Sci*., **32**, 5276–5286.

24. REGAS, F.P. AND VALKANES, G.N. (1984) Physical Characterization of Suspension-Crosslinked Polystyrene Particles and

Their Sulfonated Products: 1. Nonionic Networks. *Polymer*, **25**, 245–253.

25. FLORY, P.J. (1953) Principles of Polymer Chemistry, New York: Cornell University Press.

26. BRANDRUP, J. AND JMMERJAT, E.H. (1989) Polymer Handbook, New York: John Wiley, 1175.

27. TAGER, A. (1972) Physical Chemistry of Polymer, Moscow: Mir Publishers.

28. EL-SABBAGH, S.H. AND YEHIA, A.A. (2007) Detection of Crosslink Density by Different Methods for Natural Rubber Blended with SBR and NBR. *Egypt. J. Solids*, **30(2)**, 157–173.

29. TAKAHASHI, K., NAKAMURA, K., YAMAGUCHI, T., KOMURA, T., ITO, S., AIZAWA, R. AND MURATA, K. (2002) Characterization of Water-Soluble Externally HCl-Doped Conducting Polyaniline. *Synthetic Met*. **128**, 27–33.

30. CHAPIRO, A. (1962) Radiation Chemistry of Polymeric Systems, New York: John Wiley.

31. ORAL, E. AND MURATOGLU, O.K. (2007) Radiation Crosslinking in Ultra-High Molecular Weight Polyethylene for Orthopedic Applications. *Nucl. Instrum. Methods Phys. Res. B*. **265(1)**, 18–22.

32. STAUFFER, D. (1985) Introduction to Percolation Theory, London: Taylor and Francis.

33. FIZAZI, A., MOULTON, J., PAKBAZ, K., RUGHOOPUTH, S.D., PAUL SMITH AND HEEGER, A.J. (1990) Percolation on A Self-Assembled Network: Decoration of Polyethylene Gels with Conducting Polymer. *Phys. Rev. Lett.*, **64(18)**, 2180–2183.

34. POMFRET, S.J., ADAMS, P.N., COMFORT, N.P. AND MONKMAN, A.P. (2000) Electrical and Mechanical Properties of Polyaniline Fibres produced by One-Step Wet Spinning Process. *Polymer*, **41(6)**, 2265–2269.