

Studies on the electrical conductivity and galvanomagnetic characteristics of short carbon fibre filled thermoplastic elastomers

D. ROY, P. B. JANA, S. K. DE, B. R. GUPTA

Rubber Technology Centre, Indian Institute of Technology, Kharagpur 721 302, India

S. CHAUDHURI, A. K. PAL

Indian Association for Cultivation of Science, Jadavpur, India

The electrical resistivity of short carbon fibre filled thermoplastic elastomers based on natural rubber-high density polyethylene (NR-HDPE) blend and styrene-isoprene-styrene (S-I-S) block copolymer has been studied by varying the concentration of fibre from the 0 to 40 phr level. A sharp drop in resistivity is observed in both cases after a critical concentration of fibre is reached, with the S-I-S system showing lower values of critical concentration. At higher concentrations, experimental values of the electrical conductivity agreed reasonably well with the calculated values from a theory based on the probability of formation of a conductive network. The effect of temperature on the resistivity of the composites has also been investigated in a temperature range of 27–120 °C and 27–90 °C for the NR-HDPE system and S-I-S system, respectively. The type of carrier in both the composites is found to be n-type, i.e. electrons, and the activation energy of hopping of the electrons for both the systems has been calculated. A Hall effect study has also been carried out to determine the carrier concentration and drift mobility of both the composites.

1. Introduction

Although studies on short carbon fibre reinforced thermoplastic elastomers have been initiated recently [1–3], the electrical properties of these composites have not received due attention. Generally, carbon black is mainly used in plastics and rubbers [4, 5] to make them conductive, but the use of carbon fibres is of recent interest. Calleja *et al.* [6] studied the electrical conductivity of high density polyethylene-carbon fibre composites in the presence of different proportions of carbon black and reported that carbon fibres provide charge transport over a large distance while carbon black improves the inter fibre contacts. Recently, Jana *et al.* [7] have studied the electrical conductivity of short carbon fibre filled neoprene vulcanizates by varying the concentration and aspect ratio of the fibre. The use of carbon fibre in making pressure sensitive nitrile rubber is also of recent interest [8]. Martinsson and White [9] have observed anisotropic electrical conductivity for injection moulded and extruded compounds of thermoplastics filled with electrically conductive carbon fibres. The critical concentration of conductive filler to transform silicon rubber from the insulating to the conductive range has been reported by Ajayi and Hepburn [10] using acetylene and furnace blacks. In the case of Brabender mixed compounds extensive fibre breakage occurs due to high shear generation during mixing

and the fibre aspect ratio decreases from an initial value of 800 to about 25 after mixing, as reported earlier [1]. However, it also has been pointed out [8] that short carbon fibre filled composites register higher conductivity values than carbon black filled composites.

In the present paper, the results of our studies on the electrical conductivity and galvanomagnetic characteristics of short carbon fibre filled thermoplastic elastomeric composites of (i) blends of natural rubber (NR) and high density polyethylene (HDPE), and (ii) the block copolymer styrene-isoprene-styrene (S-I-S) are presented. The effects of fibre concentration and temperature on electrical conductivity and galvanomagnetic properties of both the composites are analysed.

2. Theory

2.1. Conductivity of the composite

The electrical performance of conducting fibre based composites depends on the formation of a conductive network by inter-fibre contacts. At low fibre concentration no such network is formed and the conductivity of the composite is essentially that of the matrix material. At a critical fibre concentration (ϕ_c^*), a three dimensional conductive network is formed, giving a sharp increase in the conductivity, which then

increases slowly with further increase in the fibre concentration. The maximum conductivity, σ_{\max} , that can be obtained by a composite containing unidirectionally oriented fibres of conductivity, σ_{cf} , and volume fraction, ϕ_{cf} is given by [11],

$$\sigma_{\max} = \phi_{cf} \times \sigma_{cf} \quad (1)$$

Accordingly, the minimum volume resistivity (ρ_{\min}) of a composite can be expressed as,

$$\rho_{\min} = \frac{1}{\phi_{cf} \times \sigma_{cf}} \quad (2)$$

In a composite containing randomly oriented fibres, the conductivity is reduced due to the orientation of fibres out of the electrical field, thus the maximum conductivity of randomly oriented fibre composites can be expressed as [11],

$$\sigma_{\max} = \frac{2}{3\pi} \times \phi_{cf} \times \sigma_{cf} \quad (3)$$

$$\text{Therefore, } \rho_{\min} = \frac{3\pi}{2} \times \frac{1}{\phi_{cf} \times \sigma_{cf}} \quad (4)$$

We have reported in our previous papers [1–3] that the fibre orientation in composites of the NR-HDPE blend is highly unidirectional whereas S-I-S block copolymer composites gave highly random fibre orientation.

Accordingly Equation 2 has been used to calculate the volume resistivity of the NR-HDPE system and Equation 4 for the S-I-S system. The following assumptions are taken into consideration, in the application of the theory:

(i) At a 'critical' fibre concentration, inter-fibre contacts are sufficiently numerous and all fibres are electrically active.

(ii) The effect of branch points and fibre dead ends are neglected.

2.2. Hall effect

The Hall effect is a galvanomagnetic phenomenon, which is commonly used as one of the primary methods for determining the electron transport parameter of materials. Generally this effect can be used for determining the nature of charge carriers, their mobility and concentration. The principle of the Hall effect is described elsewhere [12, 13].

A measurement of Hall voltage (V_H) for a material (where electrons are charge carriers) of known dimension, current and magnetic field strength gives a value for the electron concentration, n_o as,

$$n_o = I_x \times B_z / q \times a \times V_H \quad (5)$$

where, n_o = electron concentration (m^{-3}),

I_x = current (A)

B_z = magnetic field strength (V. sec m^{-2})

q = charge of carriers (+ or -)

a = thickness, (m)

V_H = Hall voltage (V).

If the measurement of the electrical conductivity σ , is carried out during the measurement of the Hall

effect, the mobility (μ) of the carriers can be determined by the following equation.

$$\mu = -\sigma / qn_o \quad (6)$$

Depending on the type of charge carrier, n or p type, the sign of charge (q), the Hall e.m.f. (V_H) and Hall coefficient (R_H) will be either negative or positive respectively.

3. Experimental procedures

3.1. Materials

The materials used in this study were as follows; Natural rubber (NR): Crumb rubber, ISNR-5 grade, of density 920 kgm^{-3} , was obtained from the Rubber Research Institute of India, Kottayam. High density polyethylene (HDPE) : Hostalen GB 7750, density 950 kgm^{-3} , MFI 10 gm/10 min and crystalline melting range $128\text{--}132^\circ\text{C}$, was supplied by Polyolefins Industries Ltd., Bombay, India. Styrene-isoprene-styrene (S-I-S): Kraton, D-1107, with specific gravity of 0.92 and styrene to isoprene ratio of 14:86, was obtained from Shell Development Company, U.S.A. Carbon fibre: Grade RK-30, carbon fibres were obtained from R.K. Carbon Fibres Ltd., U.K. The fibres have the following characteristics: epoxy treated, density 1780 kgm^{-3} , filament length to diameters ratio, L/D of about 800 (L = 6 mm; D = 7.5 μm); electrical resistivity $1.0 \times 10^{-5} \text{ ohm-m}$, carbon content, 95% mass. Peroxide: Peroximon F-40, commercial grade was obtained from NICCO (I) Ltd. Calcutta, India. Antioxidant: Flectol B, commercial grade was also obtained from NICCO (I) Ltd., Calcutta India.

3.2. Preparation of the composite based on NR-HDPE blend

The formulation of the composites is given in Table 1. The composites were prepared in a Brabender plastic-order (model PLE-330), using a cam type rotor (50 r.p.m.) and the mixer chamber set at 150°C . The mixing sequence to obtain a uniform distribution of the fibres and hence optimum physical properties, is reported in our earlier communication, and is as follows. Initially polyethylene was melted in the mixer

TABLE I Composition of the blends

Ingredients	NR-HDPE system phr ^a	S-I-S system phr ^a
NR	70	—
HDPE	30	—
S-I-S	—	100
Carbon fibre ^b	0, 5, 10, 20, 30, 40	0, 5, 10, 20, 30, 40
Peroxide (based on rubber phase only)	0.7	—
Antioxidant	1.5	—

^a phr means parts per 100 parts of rubber or rubber in blend, gm.

^b For NR-HDPE composites the compounds containing 0.5, 10, 20, 30 and 40 phr fibre have been designated as NH₀, NH₅, NH₁₀, NH₂₀, NH₃₀ and NH₄₀ respectively, and for S-I-S systems these are designated as S₀, S₅, S₁₀, S₂₀, S₃₀ and S₄₀ respectively.

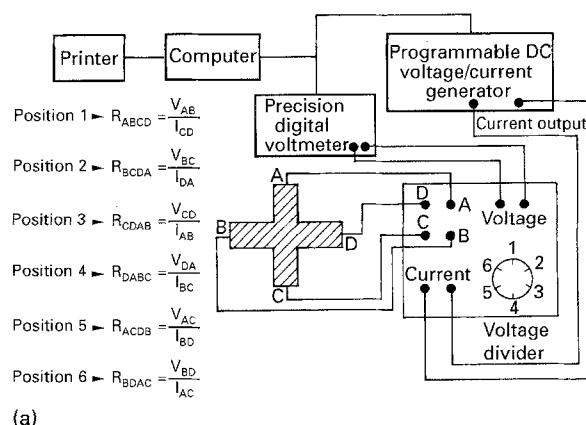
for two mins and then chopped carbon fibres were added to it and mixed for one min. This was followed by the addition of natural rubber (previously master-batched with peroxide and antioxidant) and mixed for another 3 mins. The mix was then taken out and passed through a two-roll mill with a nip setting of 2 mm. The sheeted materials was remixed in the plasticorder for 2 mins and finally passed through the two-roll mill to ensure a uniform dispersion of the fibres and homogeneity of the blend. The sheeted out stock was compression molded between aluminium foils in an automatic Toyoseiki labo-press at 170°C for 3 mins. At the end of the molding time, the sample still under compression, was cooled automatically by cooling the platens of the press to room temperature. Aluminium foils were used between the mold surfaces to reduced shrink marks on the sheet. The material was then used for electrical measurements.

3.3. Preparation of the composite based on S-I-S

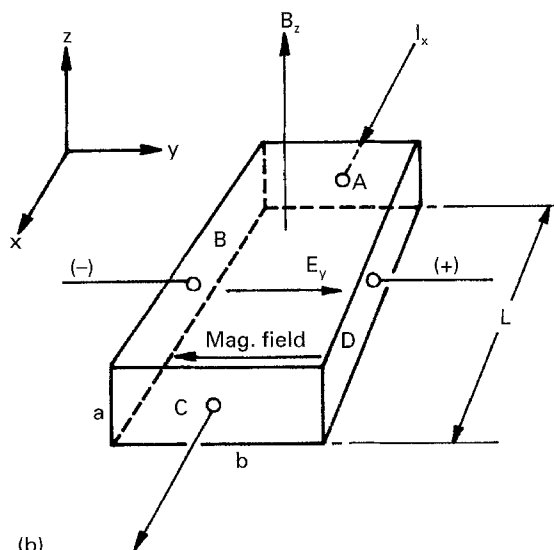
The composition of the mixes are given in Table 1. The composites were prepared in a Brabender plasticorder (model PLE 330), using a cam type rotor with a speed of 50 r.p.m. and the mixer chamber set at 150°C. Initially the S-I-S was melted in the mixer for 2 mins. Next chopped carbon fibre (6 mm in length) was added to it and mixed for another 3 mins. The mix was then taken out and sheeted through a laboratory mill with a nip setting of 2 mm. The sheeted material was then remixed in the plasticorder at 150°C for 2 mins to ensure uniform dispersion of the fibres and homogeneity of the blend. The preparation of molded sheets was done in the same way as described earlier.

3.4. Measurement of the volume resistivity and Hall effect

The volume resistivity of the composites with high resistivity was measured by using a high resistance meter (Hewlett Packard, 4329A). In the case of low resistivity composites, the measurements were carried out by the four probe technique [13], shown schematically in Figure 1a. A low applied field was used to ensure ohmic behaviour in the temperature range of 27–120°C used for the NR-HDPE system and 27–90°C for the S-I-S system respectively [14]. In the case of the S-I-S system a lower range of temperature is maintained to avoid melting and sticking of the sample to the sample holder at the higher temperature. The current and voltage were measured by a programmable dc voltage/current generator (Advantest, TR 6142) and a precision digital voltmeter (Schlumberger, U.K., model No. 7062) respectively. A fixed magnetic field of 0.51 T was applied for measuring the Hall effect (Fig. 1b). The value of the carrier concentration (n_0), the nature of the majority carriers and their drift mobility (μ) have been calculated by using Equations 5 and 6.



(a)



(b)

Figure 1 Schematic diagrams of the experimental setup for the measurement of (a) volume resistivity and (b) Hall effect.

4. Results and discussion

4.1. Minimum volume resistivity (ρ_{min}) of the composites

The volume resistivity of both the composites at room temperature against the volume fraction of fibre is plotted in Fig. 2 and the experimental results are compared with Equations 2 and 4 for the NR-HDPE and S-I-S systems respectively. The theoretical values of minimum volume resistivity have been calculated by using a conductivity value for carbon fibre (σ_{cf}) of 1.0×10^5 (Ohm m)⁻¹ [15] and are tabulated in Table II.

The volume resistivity versus volume percent of fibre for both systems show three zones. These are (i) at low fibre loading where the resistivity of the composite is very high, being more or less equal to that of pure thermoplastic elastomers. This indicates that very few continuous fibre contacts are formed (insulating zone). (ii) Intermediate fibre loading where the resistivity falls sharply beyond a particular value of fibre loading (first critical fibre loading, $V_{f,c1}$). This indicates the formation of an increasing number of continuous fibre contacts with increasing fibre loading (semi-conducting zone). Finally (iii) high fibre loading where the resistivity tends to become more or less constant and falls only marginally with increasing fibre loading. This indicates that beyond a particular

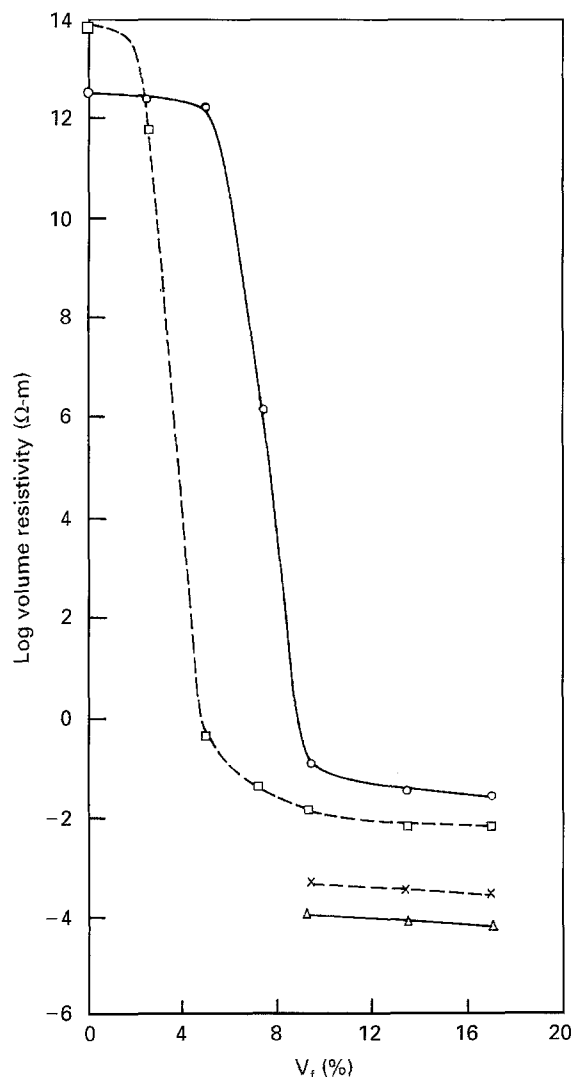


Figure 2 Effects of CF concentration on volume resistivity; (—○—) NR-HDPE, experimental; (—□—) SIS experimental; (—×—) SIS theoretical and (—△—) NP-HDPE theoretical.

TABLE II Theoretical values of ρ_{\min} and σ_{\max}

Sample Number	Resistivity $\rho_{\min} \times 10^4$ (ohm-m)	Conductivity $\sigma_{\max} \times 10^{-1}$ (ohm-m) ⁻¹
NH ₅	4.00	0.25
NH ₁₀	2.04	0.49
NH ₂₀	1.07	0.93
NH ₃₀	0.75	1.34
NH ₄₀	0.58	1.71
S ₅	18.80	0.05
S ₁₀	9.61	0.10
S ₂₀	5.06	0.19
S ₃₀	3.51	0.28
S ₄₀	2.75	0.36

critical fibre loading, (second critical fibre loading, $V_{f,c2}$), the continuous fibre contact become so numerous that it forms a conducting network (conducting region).

The S-I-S system shows much lower critical fibre loadings ($V_{f,c1} = 0.022$ and $V_{f,c2} = 0.05$) as compared to the NR-HDPE system ($V_{f,c1} = 0.05$ and $V_{f,c2} = 0.09$). Assuming that the first critical fibre loading corresponds to the onset of formation of a continuous

conducting path and that the second critical fibre loading represents the onset of formation of a conducting network, it can be concluded that in the S-I-S system, which gives random fibre orientation [2] the phenomena of formation of conducting paths and then a conducting network starts at much lower fibre loading than in the NR-HDPE system, which gives unidirectional fibre orientation [1].

The values of resistivity calculated from Equations 2 and 4 for unidirectional and random orientation give comparable results, only in the conducting zone. These equations cannot be applied for fibre concentration below $V_{f,c2}$. At fibre loading above $V_{f,c2}$, the S-I-S system is closer to Equation 4 than is the NR-HDPE system to Equation 2. These deviations from the equations are due to the fact that all the fibres do not contribute to the electrical conduction due to the contact resistance and fibre dead ends. From the comparison of experimental results with the theoretically calculated values, it can be said that a system containing randomly oriented fibres gives much less contact resistance (i.e S-I-S system) than the unidirectionally oriented fibre composites (i.e. NR-HDPE system).

4.2. Effect of temperature on the volume resistivity

The dependence of volume resistivity on temperature in both conductive carbon black and carbon fibre filled composites has been studied by various authors [14,16–18]. According to these studies, the volume resistivity depends on several factors such as the thermal expansion co-efficient, thermal conductivity and temperature dependence of the electrical performance of matrix and fibre, fibre aspect ratio and it's concentration.

Fig. 3(a, b) show the volume resistivity of carbon fibre filled NR-HDPE and S-I-S composites respectively, as a function of temperature (27–120 °C for NR-HDPE and 27–90 °C for S-I-S) at different fibre loadings for both the heating and the cooling cycles. It is observed from the figures that at all the temperatures the S-I-S composites show lower resistivity compared to the NR-HDPE composites as discussed earlier. It is further seen that the volume resistivity of both the composites increases with the increase in temperature and the rate of increase is maximum at low fibre loading. The nature of $\rho = f(T)$ can be explained by a hopping or tunnelling conductivity mechanism. The mechanism states that with increasing temperature, the inter-fibre average distance increases due to uneven thermal expansion of the matrix and carbon fibre. A similar increase in inter-fibre distance with temperature were reported in the case of carbon fibre filled neoprene vulcanizates [18]. The increased distance between the fibres deters the easy tunnelling or hopping of carriers (electrons or holes). In such a condition, the probability of tunnelling becomes less, due to the scattering of carriers into the thermoplastic rubber (TPR) layers between the fibres. Therefore, at lower concentration, the resistivity significantly increases with temperature. But as the fibre loading increases, the above effect is minimized due to the

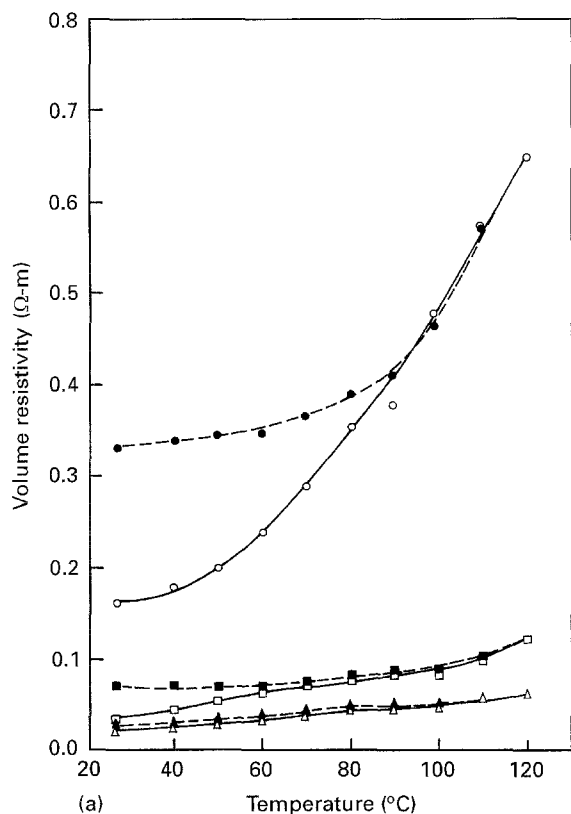


Figure 3a Variation of volume resistivity with temperature (—) heating and (---) cooling for the composites of NR-HDPE system. (○) (●) NH-20, (□) (■) NH-30 and (△) (▲) NH-40.

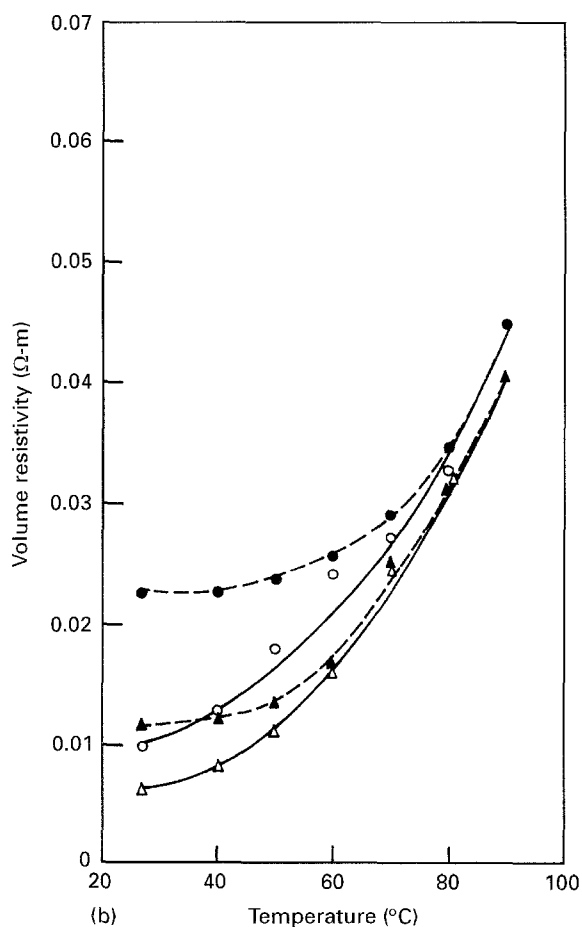


Figure 3b Variation of volume resistivity with temperature; (—) heating and (---) cooling for composites of the S-I-S system. (○) (●) S₂₀, (△) (▲) S₄₀.

greater number of inter-fibre contacts, thus ensuring a larger probability of tunnelling through the greater number of close-knit inter-fibre positions. This is reflected in the gradual decrease in the steepness of the $\rho = f(T)$ curve with increasing fibre concentration.

The heating cooling curve in the $\rho = f(T)$ relationship has also been obtained for different loadings of fibre. It is observed from the figure that at 20 phr loading in both the cases the heating and cooling curves do not follow the same path, which may be due to the lag between the sample temperature and Dewar temperature [19]. With increasing carbon fibre loading, the distance between heating and cooling curves disappears, probably due to the better heat transfer through the extensive inter fibre contacts [7], as observed in the 40 phr loading in both cases. Another interesting observation is that there is a permanent increase in 'p' values after cooling (at 27 °C) from the initial value recorded at the start of the experiment (heating cycle) at 27 °C. It is observed from Fig. 3(a, b) that 20 phr filled composite shows an increase in 'p' values from 0.165 ohm-m to 0.33 ohm-m and 0.001 to 0.002 ohm-m, respectively, for NR-HDPE and S-I-S composites. The reason for this permanent change in electrical resistivity can be explained in the following way. During the heating cycle the matrix expands, and the amount of expansion is much higher in the case of NR-HDPE composites compared to S-I-S composites, due to the two phase structure of the former as shown in our dynamic mechanical studies [1]. Due to this two phase structure the expected contraction does not take place in the cooling cycle and this creates some permanent gaps between the fibres, which deters the easy tunnelling of carriers. Therefore, a permanent change in 'p' values is observed after a heating/cooling cycle.

The temperature dependence of volume resistivity of the composites can be interpreted on the basis of the following equation [20].

$$\rho = \rho_0 T_{\text{exp}}(E_{\text{hop}}/KT) \quad (7)$$

where ρ is the volume resistivity, ρ_0 represents a pre-exponential factor, E_{hop} is the activation energy for hopping, K is the Boltzman constant and T is the absolute temperature. According to the tunnelling or hopping conductivity mechanism, E_{hop} is related to the height of the barrier and the values of E_{hop} at different fibre loadings of both systems are tabulated in Table III. With change in fibre loading from 15 to 40 phr the change of E_{hop} values with fibre concentration are at the expected level [14]. The activation

TABLE III Calculated values of E_{hop} of the conducting composites of NR-HDPE blend and S-I-S

phr	$E_{\text{hop}} \times 10^{20}$	
	NR-HDPE system	S-I-S system
15	—	6.60
20	1.89	2.63
30	1.44	2.10
40	1.22	1.85

energies of conduction in carbon black filled rubber is found to be higher than the carbon fibre filled composites. The values of E_{hop} varied from 0.42×10^{-19} to 1.65×10^{-19} J in the case of carbon black filled composites whereas for carbon fibre filled composites it varied from 1.10×10^{-20} to 0.96×10^{-20} J [11]. In both cases it is observed that there is a steady decrease of E_{hop} values as the fibre loading increases, with the S-I-S system showing comparatively less activation energy than the NR-HDPE system probably due to the higher conductivity of the former system.

4.3. Application of the Hall effect in the conductive rubber composites

Electrical conduction occurs through the movements of electrons or ions, depending upon different types of carriers, which may be electrons or holes (a hole is an electron vacancy carrying an equivalent positive charge) in the case of an electronic conductor and cations or anions in the case of an ionic conductor. In conducting polymer composites, the mechanism of current conduction is electronic where carriers may be electrons ($-e$) or holes ($+e$) depending upon the nature of the conductive filler. In each case, the conductivity follows the equation:

$$\sigma = q \times n \times \mu \quad (8)$$

where, q = charge of carrier, (eV), n = carrier concentration, (m^{-3}) and μ = drift mobility of the carrier, ($\text{m}^2 \text{v}^{-1} \text{s}^{-1}$).

Hall measurements of both the composites were carried out to understand the nature and concentration (n) of the charge carriers and their drift mobility (μ) during the measurement of volume resistivity. The values of conductivity, mobility and carrier concentration of both the NR-HDPE and S-I-S system have been tabulated in Table IV. It has been observed that most of the carriers are electrons. It is also seen from Table IV that the carrier concentration of the composites increases significantly with fibre loading but there is a drop in the values of the mobility with increasing fibre loading and as expected the conductivity increases with fibre loading. It is also observed from Table IV that due to higher conductivity of S-I-S composites than the NR-HDPE composites the values of carrier concentration and mobility varies accordingly. As the fibre loading increases, the probability of hopping of electrons increases due to the increased number density of neighbouring carbon fibres, resulting in an increase in carrier concentration. The mobility of the carriers is directly related with the square of the jump distance [21, 22] and as the fibre loading increases, the increase in probability of hopping reduces the jump distance and therefore the mobility decreases.

The effect of temperature on conductivity, carrier concentration and mobility of the composites has also been studied at a temperature range of 27–120 °C for NR-HDPE system and 27–90 °C for S-I-S system and the results are tabulated in Tables V and VI respectively. It is observed from these tables that with increasing

TABLE IV The conductivity, carrier concentration and mobility of the composites at room temperature

Sample Number	Conductivity (σ) (ohm-m^{-1})	Carrier concentration (n) (m^{-3})	Drift mobility (μ) ($\text{m}^2 \text{v}^{-1} \text{s}^{-1}$)
NH ₂₀	6.1	5.5×10^{22}	6.9×10^{-4}
NH ₃₀	28.0	5.5×10^{23}	3.1×10^{-4}
NH ₄₀	40.7	10.5×10^{24}	2.5×10^{-4}
S ₁₅	27.8	1.2×10^{23}	14.5×10^{-4}
S ₂₀	100.0	7.2×10^{23}	8.7×10^{-4}
S ₃₀	142.8	2.5×10^{24}	3.6×10^{-4}
S ₄₀	156.2	3.5×10^{24}	2.8×10^{-4}

TABLE V The effect of temperature on conductivity (σ) carrier concentration (n) and mobility (μ) of NR-HDPE system

Temp. (°C)	Conductivity (σ) (ohm-m^{-1})			Carrier concentration (n) (m^{-3}) $\times 10^{-22}$			Drift mobility (μ) ($\text{m}^2 \text{v}^{-1} \text{s}^{-1}$) $\times 10^4$		
	phr			phr			phr		
	20	30	40	20	30	40	20	30	40
27	6.01	27.8	40.6	5.5	55	100	6.9	3.15	2.5
40	5.50	22.4	36.6	4.4	19	30	7.9	7.4	7.6
50	5.00	17.9	31.9	3.1	14	28	10	8.0	7.1
60	4.10	15.0	30.8	1.5	11	22	17	8.5	8.7
70	3.60	14.2	26.0	1.1	9.0	18	20	9.9	9.0
80	3.00	12.9	22.3	0.75	6.0	12	25	13.4	11.0
90	2.60	12.2	20.5	0.55	3.2	6.0	30	24	20.0
100	2.10	12.1	18.7	0.40	1.8	5.0	32	42	23.0
110	1.75	10.0	17.6	0.14	1.2	3.8	77	52	29.0
120	1.50	8.10	16.2	0.06	0.75	1.3	160	67	78.0

TABLE VI The effect of temperature on conductivity (σ) carrier concentration (n) and mobility (μ) of S-I-S system

Temp. (°C)	Conductivity (σ) (ohm-m) ⁻¹				Carrier concentration (n)(m ⁻³) × 10 ⁻²²				Drift mobility (μ)(m ² v ⁻¹ s ⁻¹) × 10 ⁴			
	phr				phr				phr			
	15	20	30	40	15	20	30	40	15	20	30	40
27	27.7	100	143	156	12	72	250	350	14.5	8.7	3.6	2.8
40	18.5	79	106	123.5	5.5	45	110	140	21	10.9	6.0	5.5
50	9.3	55	72.5	91.7	1.4	25	45	68	42	14	10	8.4
60	8.5	41	42.2	60.6	1.1	14	20	29	48	18	13	13.0
70	4.3	36	33.1	39.4	0.46	11	12.5	16	58	21	16.5	15.2
80	3.2	31	23.5	32.4	0.28	7.4	7.6	11	71	26	19.2	18.0
90	1.2	22	13.3	24.6	0.086	4.5	3.8	7	88	31	22.0	21.2

temperature, both the conductivity and the carrier concentration decrease but the mobility of the carriers increases in both systems, with the S-I-S composites showing considerably higher values of conductivity, carrier concentration and mobility than the corresponding NR-HDPE system. At the same time, it is also observed from the table that with increasing fibre concentration in both systems, the conductivity and carrier concentration increase, whereas the mobility of the composites decreases. As the temperature increases, due to uneven thermal expansion of the matrix and fibre, as explained earlier, the inter-fibre distance increases and therefore the average contact area among the fibres decreases which in turn decreases the hopping frequency of the electrons resulting in a decrease in conductivity and carrier concentration.

5. Conclusions

(1) The volume resistivity of both composites drops considerably after a critical fibre concentration in the composites due to the larger number of inter-fibre contacts at higher loading. The S-I-S composites show much lower values of the critical fibre concentration than the corresponding NR-HDPE composites.

(2) The electrical resistivity of both the S-I-S and NR-HDPE composites increases with the increase in temperature and the changes of resistivity during cooling are irreversible.

At 40 phr fibre concentration a negligible change in resistivity values in the NR-HDPE system are observed during cooling cycle, indicating extensive inter-fibre contacts.

(3) Hall effect studies confirmed that the majority of carriers in both the systems are electrons. With the increase of fibre concentration in the composite the conductivity and carrier concentration increase but the mobility of the carriers decreases. The S-I-S composites show much higher values of conductivity,

carrier concentration and mobility than the corresponding NR-HDPE composites. At higher temperatures, the conductivity and carrier concentration of the composites decrease along with the increase in mobility of the carriers.

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