Dielectric Properties of Nylon 6/NBR Composites

Chapter 6

Dielectric Properties of Nylon 6/NBR Composites

Abstract

The dielectric properties such as dielectric constant, volume resistivity and dielectric loss factor of nylon 6 fibre reinforced NBR composites have been studied as a function of frequency at different fibre loadings. The effects of curing systems and bonding agents on the dielectric properties have also been studied. The dielectric constant decreases with increase in frequency; attributed to the decreased orientation polarization at higher frequencies. The dielectric constant values have been found to be lower for fibre filled systems than the gum. The DCP cured composite samples exhibit higher dielectric constant than the corresponding sulphur cured systems. The addition of bonding agents reduces the dielectric constant of the composites. The volume resistivity of the composites increases with the addition of fibres and with the incorporation of the bonding agents. The added fibres and the different bonding agents decrease the dielectric dissipation factor of the matrix.
6.1 INTRODUCTION

Polymers are, in general, good electrical insulators with volume resistivities up to $10^{20}$ ohm m. They are commonly used in the electronics industry as housings or assemblies. Electrical conductivity is an important factor in many rubber and plastic compounds which are used for antistatic applications, wire and cable sheathing, and shielding against electromagnetic interference\(^1-3\). For some applications polymers are made conductive by adding conductive materials like metals, carbon black, fibres and so forth. Incorporation of a conducting polymer into a host polymer substrate to develop a blend, composite or an interpenetrating network has been widely used as an approach to combine electrical conductivity with the desirable physical properties of a polymer\(^4-7\). The process of conduction through a polymeric system depends upon its composition, chemical structure, physical texture, morphology and the conditions of measurement\(^8\).

Dielectric properties such as the dielectric constant and the dielectric loss reveal significant information about the chemical and physical states of polymers. These properties are significantly affected by the presence of another polymer or a dopant in the polymer\(^9-13\). Miyauchi and Togashi\(^14\) explained the electrical properties and the conduction mechanism of polymer-filler particles using polymer grafted carbon black. Burton et al.\(^15\) made the electrical and electromechanical measurements of carbon black filled NR. Modification of dielectric and mechanical properties of rubber - ferrite composites containing manganese zinc ferrite has been studied by Mohammed et al.\(^16\). Todorova et al.\(^17\) investigated the electrical properties of elastomer composites filled with titanium diboride. The electrical and mechanical
properties of conductive rubber composites derived from different blends of EPDM and NBR containing acetylene black were analysed by Sau et al\(^8\). The electrical resistivity of SBR-carbon black composites has been examined by Mohanraj et al\(^9\). Bishai et al.\(^{20}\) investigated the electrical conductivity of SBR-polyester short fibre reinforced with different types of carbon black. George et al.\(^{21}\) followed the electrical properties of pineapple fibre reinforced polyethylene composites.

In many cases the analysis of dielectric properties provides a measure of the amorphous fraction of the material which is sensitive to orientation effects, mobility and to the number and interaction of participating dipoles. Dutta et al.\(^{22}\) reported the studies on the mechanical and electrical anisotropy of pineapple fibres. They found a sharp increase in dielectric constant and a fall of loss factor along the fibre direction compared to the transverse direction. Prasanth Kumar and Thomas\(^{23}\) studied the dielectric properties of short sisal fibre reinforced SBR composites. They pointed out that the chemically treated fibrous composite systems exhibited lower dielectric constant values compared to the untreated ones. The modeling of the dielectric properties of wood-polymer composites, by considering them as multi-component layered systems, was done by Hoffman et al\(^{24}\).

NBR has only moderate insulating properties and higher values of permittivity (17–14 Fm\(^{-1}\)). The considerably high dielectric loss values (1.33–2.00) cause NBR to lose its insulating properties. The present chapter deals with the investigation of the dielectric properties of nylon 6 fibre reinforced NBR composites.
6.2 RESULTS AND DISCUSSION

6.2.1 Dielectric Constant

Dielectric polarization is the polarized condition of a dielectric resulting from an applied AC or DC field and it can be expressed as the total induced dipole moment per unit volume of the dielectric. The total polarizability of the dielectric is the sum of the contributions due to the several types of displacement of charges produced in the material by an applied field. Generally, the dielectric constant of a composite material arises due to the polarization of the molecules. The dielectric constant increases with increase in polarizability. The dielectric constant ($E'$) of a composite has contributions from interfacial, orientation, atomic and electronic polarizations. The interfacial polarization occurs in a composite due to the differences in the conductivities or the polarizations of the matrix and fillers. The orientation polarization is produced, when polymers containing polar groups are placed in an electric field.

The effect of fibre loading on the dielectric constant ($E'$) values of nylon 6 fibre reinforced NBR composites as a function of logarithm of frequency is shown in Figure 6.1. It is evident from the figure that the dielectric constant decreases with increase in fibre loading at a given frequency. The highest $E'$ values are exhibited by the gum sample (0 phr). This is due to orientation polarization owing to the presence of permanent dipoles in the NBR matrix (-C=N group). As nylon 6 fibre is added some of the dipoles are cancelled by the dipoles present in nylon (-C=O) and thus the dielectric polarization decreases. Therefore the dielectric constant value decreases with increase in fibre loading. It is also found that for a given fibre...
loading, the $E'$ shows higher values at lower frequencies. This can be accounted by the fact that the orientation polarization decreases with increase in frequency. The complete orientation of the molecules is possible only at lower frequencies and the orientation polarization requires more time to reach the equilibrium static field value compared to electronic and atomic polarizations. Therefore as frequency increases the $E'$ reduces due to the lag in orientation polarization.

![Graph showing the effect of fibre loading on dielectric constant as a function of frequency.]

**Figure 6.1** Effect of fibre loading on dielectric constant as a function of frequency

Figure 6.2 shows the effect of different curing systems on the dielectric constants of nylon 6 fibre reinforced NBR composites as a function of frequency. Comparison has been made with samples containing 24 phr loading of fibre cured by sulphur and DCP (Samples F and M). It can be seen that the values of dielectric constant are higher for DCP cured sample than for sulphur cured sample at all frequencies. This can be attributed to the presence of polar $-\text{OH}$ groups in the former. These
-OH groups are produced during the vulcanisation process initiated by dicumyl peroxide, where the peroxide free radical (R-O') abstract a hydrogen from the polymer chain to form R-OH.

Figure 6.2  Effect of curing systems on dielectric constant as a function of Frequency

Figure 6.3 shows the effect of different bonding agents on the dielectric constants of the composites as a function of frequency. It can be seen that the dielectric constant values are lower for bonding agent added composites at all frequencies. The dielectric constant value of phthalic anhydride bonded system is slightly lower than that of hexa-resorcinol bonded composite. The good interfacial adhesion in presence of bonding agent removes the voids between the fibres and matrix thereby eliminating the pockets for moisture absorption. Thus, the modified interface reduces the dielectric constant values. In the case of phthalic anhydride bonded systems, in addition to this, the interfacial adhesion between nylon fibres and NBR
through the formation of hydrogen bonding involving the bonding agent, also
reduces the polarization and hence the dielectric constant value is lower than that of
hexa-resorcinol bonded systems. The mechanism of interfacial adhesion in phthalic

![Graph showing the effect of bonding agent on the dielectric constant as a function of frequency.](image)

**Figure 6.3** Effect of bonding agent on the dielectric constant as a function of frequency

anhydride bonded composites has been explained earlier in Chapter 4 (Scheme 4.2). 
Figure 6.4 shows the effect of hexa-resorcinol bonding agent on the dielectric constant of sulphur and DCP cured composites as a function of frequency. It can be seen that in the presence of bonding agent sulphur cured sample has higher dielectric constant values than DCP cured sample. This can be attributed to the difference in total polarizability in the two systems. In the former, permanent dipoles due to –OH groups in resorcinol are present, whereas in the latter these –OH groups may be involved in hydrogen bonding with the R-OH produced by the abstraction of hydrogen from polymer chain by peroxide free radical.
Figure 6.4  Effect of hexa-resorcinol bonding agent on the dielectric constant of sulphur and DCP cured composites

6.2.2 Volume resistivity

The study of the volume resistivity of an insulating material is important because the most desirable property of an insulator is its ability to resist the leakage of electric current. Figure 6.5 shows the plot of volume resistivity as a function of frequency at different loadings of fibres. The volume resistivity has been found to be decreased with frequency and increased with fibre concentrations. The increase in volume resistivity with fibre loading can be attributed to the decreased dielectric polarization upon the incorporation of nylon 6 fibre into the polar NBR matrix. Figure 6.6 shows the dependence of electrical conductivity ($\sigma$), which is the reciprocal of resistivity, on fibre loading at varying frequencies (10 and 13 MHz). It has been found that, as fibre concentration increases the conductivity decreases.
Figure 6.5  Effect of fibre loading on the volume resistivity as a function of frequency

Figure 6.6  Variation of conductivity with fibre loading at different frequencies
However, the conductivity has been found to be increased with frequency. The variation of volume resistivity as a function of frequency in sulphur and DCP cured composites is shown in Figure 6.7. It can be seen that the volume resistivity of DCP cured sample is lower than that cured by sulphur. This is due to the higher polarizability in the former.

![Graph showing effect of curing system on volume resistivity](image)

**Figure 6.7** Effect of curing system on the volume resistivity as a function of frequency

The variation of volume resistivity, for bonding agent added composites, is given as a function of frequency in Figure 6.8. The dielectric constant depends on the resistivity by the equation:

\[
\log R\ (298\ K) = 23 - 2 \ E'\ (298\ K) \quad \ldots\ldots\ldots\ldots(6.1)
\]

The equation shows that the electrical resistance of composites decreases exponentially with increasing dielectric constants. The incorporation of bonding
agent enhances the interfacial adhesion between the fibres and the matrix, which in turn reduces the voids at the interface thereby enhancing the volume resistivity. It can also be seen from Figure 6.8 that the volume resistivities of composites containing both hexa-resorcinol and phthalic anhydride bonding agents are higher than that of the unbonded one at the same fibre loading.

![Graph](image)

**Figure 6.8**  Effect of bonding agent on volume resistivity as a function of frequency

Figure 6.9 shows the effect of hexa-resorcinol bonding agent on the volume resistivities of sulphur and DCP cured composites as a function of frequency. It can be seen that the volume resistivity of hexa-resorcinol bonded composite cured by DCP is higher than that cured by sulphur. The difference in behaviour is attributed to the difference in the total polarizability of the two systems.
6.2.3 Dissipation factor

Dissipation factor or loss tangent is the ratio of the electrical power dissipated in a material to the total power circulating in the circuit. It is the tangent of the loss angle, directly analogous to the tan $\delta$ function relevant to the dynamic mechanical testing, describing the relationship between storage ($G'$) and loss ($G''$) moduli ($\tan \delta = G''/G'$). The visco-elastic nature of NBR matrix creates similarities in the material responses to both mechanical and electrical stimuli. Under the dynamic excitation, the independent and measured variables move out of phase (stress and strain in mechanical tests, voltage and current in electrical tests). Most of the polymers exhibit more than one region of dielectric loss. The measurement of dissipation factor ($\tan \delta$) of an insulating material is thus important since the loss tangent is a measure of the electrical energy which is converted to heat in an insulator. This heat raises the insulator temperature and accelerates its deterioration.
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The effect of dissipation factor ($\tan \delta$) as a function of the logarithm of frequency at different fibre loading is given in Figure 6.10. The dissipation factor has been found to be increased with frequency and decreased with fibre concentration. A strong relaxation is observed, with a peak at a frequency of 5 MHz, which is due to the $\alpha$-transition. The positions of peaks are identical for both filled and unfilled systems. The addition of fibres decreases the relaxation magnitude at each frequency. The two prime factors contributing to the loss factor ($E''$) are the dipole polarization and ionic conductance. Most of the polymers exhibit more than one region of dielectric loss. The numerical value of dissipation factor is determined by both polarity and carrier mobility. The polarity determines the nature of relaxation and the relaxation time determines the value of $\tan \delta$ at specific frequency for that relaxation.

![Figure 6.10](image.png)

Figure 6.10  Effect of fibre loading on dissipation factor as a function of frequency
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It can be seen from Figure 6.10 that, at any given frequency, the intensity of dielectric loss peak decreases regularly as a function of fibre loading i.e.; higher for gum (0 phr) and decreases with fibre loading. The increment in dissipation factor with frequency for the gum sample is associated with its amorphous phase relaxation. Since NBR contains polar groups it may also be due to dipolar relaxation. The decrease in tan δ value with the incorporation of nylon fibres into NBR matrix can be attributed to the increase in relaxation time. This can be due to the dipole–dipole interaction between the nylon 6 fibres and NBR, both of which containing polar groups.

Figure 6.11 shows the effect of different curing systems on the dissipation factor, as a function of the logarithm of frequency. It can be seen from the figure that the dissipation factor values of DCP cured sample is higher than that of sulphur cured sample.

![Graph showing the effect of curing system on dissipation factor](image)

**Figure 6.11** Effect of curing system on dissipation factor as a function of Frequency
The effect of bonding agents on the dissipation factor (tan δ) as a function of the logarithm of frequency is given in Figure 6.12. The dissipation factor of both hexa-resorcinol and phthalic anhydride bonded composites are lower than that of the unbonded one.

Figure 6.12 Effect of bonding agent on dissipation factor as a function of Frequency

Figure 6.13 shows the effect hexa-resorcinol bonding agent on the dissipation factor of sulphur and DCP cured composites as a function of frequency. It can be seen that the dissipation factor of hexa-resorcinol bonded composite cured by sulphur is higher than that cured by DCP. The difference in the dissipation factor values of bonded composites can be attributed to the difference in the relaxation magnitudes.
6.3 CONCLUSIONS

The dielectric properties such as dielectric constant, volume resistivity and dielectric loss factor of short nylon 6 fibre reinforced NBR composites have been studied as a function of frequency at different fibre loadings. The effect of curing systems and bonding agents on the dielectric properties has also been studied. The dielectric constant values have been found to be lower for fibre filled systems than gum. Composite sample cured by DCP exhibited higher dielectric constant value than that cured by sulphur which can be attributed to the presence of polar -OH groups in the former. The addition of the bonding agent reduced the dielectric constant of the composites. It has been found that in the presence of hexa-resorcinol bonding agent the sulphur cured sample has higher dielectric constant values than DCP cured sample which has been attributed to the difference in the total
polarizability of the two systems. The volume resistivity of the composites was found to be increased with the addition of fibres and with the incorporation of bonding agents. The conductivity of the composites decreased with increase in fibre loading. The added fibres and different bonding agents decreased the dielectric dissipation factor of the matrix. A dielectric relaxation has been observed at a frequency of 5 MHz.

References

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