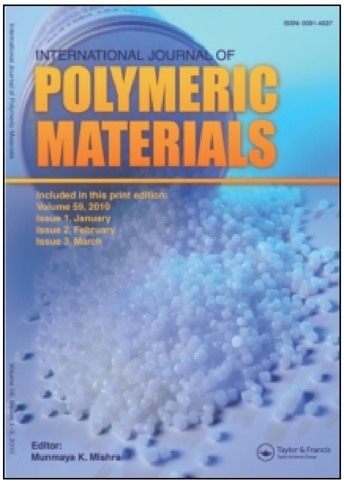

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Electrical Characterization of Metal Fiber-Polyester Composite

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The electrical properties of a metal fiber-polyester composite have been investigated as a function of temperature and frequency. The obtained results showed that the given composite behaves as n-type conductor with relatively low resistivity and low activation energy of the conduction mechanism takes place in the bulk. The complex dielectric constant was found to be a strong frequency dependent without exhibiting Maxwell-Wigner relaxation peaks. The high values of the dielectric constant agrees with the whole electrical behavior of the composite. The frequency independence of the impedance suggests that the composite has a promising electronic applications.

Keywords: Electrical properties; impedance; frequency; temperature; dielectric constant; conductor; composite

1. INTRODUCTION

Conductive polymer composites are advanced materials developed in the last twenty years with many innovative applications in the field of electronic industry. They are polymeric matrices containing either dispersed fibers or other fillers as particles or flakes. The technological interest of conductive polymer composites relies on the enhanced electrical conductivity produced by using metallic fillers [1–3].

The metal fibrous polymer composites have, in addition to their mechanical performance, applications in electromagnetic shielding for

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electronic devices and their capability in electrostatic elimination (or protection) in electronic components [4–7]. The electrical properties of metal or carbon fiber polymer composites are greatly influenced by the concentration, orientation and type of the used fillers. The influence of these factors on the physical properties involved in the conduction of electricity was illustrated by both experiment and theory. Generally it was reported that the domain process of electron transport in metal polymer composites depends on the composition of the composite itself and the condition of measurements. Most the proposed models and approaches consider conducting networks set up by fibers in the insulating polymeric matrix [8–15].

One category of the metal fiber composites is the Beki-Shield steel fibers embedded in engineering plastics as nylons, polycarbonates, and polyesters. The stainless steel fibers function by forming conductive network within the plastic matrix. The electromagnetic and electrostatic shielding efficiency can be achieved by higher conductivity, higher transfer electrical conduction, fiber finess, and high aspect ratio [6–16].

This paper reports results on the AC electrical conductivity by measuring the dielectric constants through the impedance spectroscopy which is one of the powerful techniques normally used to characterize the electrical properties of conductive polymer composites as we have reported in several publications appeared in the last decade [6, 14, 15, 17–20].

2. EXPERIMENTAL

2.1 Material

The composite used in this study is polyester plaque with 6 wt.% stainless steel fibers Beki-Shield manufactured by Bekaert Fiber Corporation in U.S.A. This composite offers a practical as well as economical solution to electromagnetic shielding problems. The fine metal fibers function as conductive fillers, and the polyester functions as a matrix. The fibers are very fine and distributed randomly as sheaves in the plastic matrix.

Our examination carried out by X-ray fluorescence technique showed that the used Bekaert plastic composite contains: Fe, Br, Ti, Na, Cr. This sample analysis helps us to have an idea about the type of inclusions existing in the given Beki-Shield composite.

2.2 Impedance Measurements

Disk-shaped specimens were cut from a metal fiber-polyester plate of about 3 mm thickness. The dielectric measurements were performed at room temperature (25 °C) and frequency range 1 Hz to 10^6 Hz using a Solartron Impedance/Gain Phase Analyzer. The instrument is controlled by Z-60 and Z-View software package which maximizes the performance and data handling of the measuring technique. In order to get good contact with pinpoint electrodes, silver layers of identified areas were evaporated on each side of the specimen. The test set-up was kept in a shielded cavity to improve low frequency measurements. Best signal generator amplitude and bias were selected after performing series of amplitude and bias sweepings tests. The generator amplitude and dc bias in our measurements were 0.5 V and 0.0 V, respectively. Using this set-up the complex ac impedance Z^* and phase angle θ were measured in the frequency range 1 Hz to 10^6 Hz.

3. RESULTS AND DISCUSSION

This work is an extension to our research activity on the electrical characterization of conductive polymer composites [18, 19, 20]. It deals with studying the AC conductivity and dielectric properties of metal fibers-polyester composite. The dielectric constants were determined from measurements of the complex impedance ($Z^* = Z' + jZ''$) as a function of temperature in the frequency range 0.1 Hz to 10^6 Hz. Figure 1 shows the variation of the complex resistivity with frequency at different temperatures. From the plot, one can see that the real component of the impedance (Z') is frequency independent, while a relative strong increase with temperature was shown. On the other hand, the imaginary component (Z'') was found to be temperature independent and almost equal to zero below 10^5 Hz. A response takes place at frequency above 10^5 Hz which is more likely due to charge migration and activation processes.

The occurance of high real resistivity and the absence of frequency dependence lead us to suggest that composite specimen behaves as

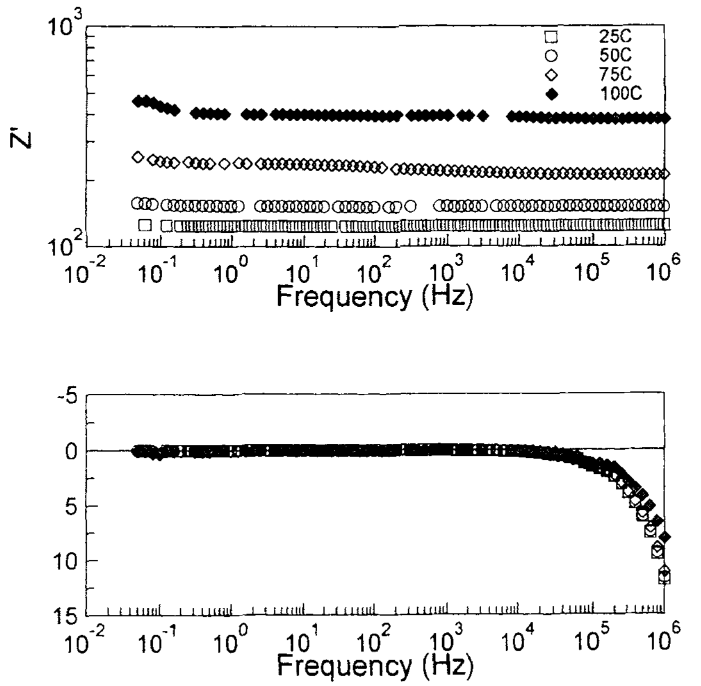


FIGURE 1 AC-resistivity $(\Omega\ \text{cm})^{-1}$ versus frequency for the fiber – Polyester composite. (Z' is the real and Z'' the imaginary component).

n-type conductor. The conduction process may be proceed in the specimen bulk through different mechanisms. The first one may be attributed to metal conduction, a type which has been reported in different conductive composite [21–23]. This behavior of conduction is normally based on charge transfer takes place through continuous conducting network formed by the fibers distribution. The second type is due to electron tunneling across the insulating films located between the fibers. If the film is thin enough then the electrons are capable to tunnel quantum mechanically between the conductive fibers leading to a lower resistance. The increase of resistivity with temperature may be associated with various mechanisms such as thermal expansion of the metal composite; and consequently the distance between the adjacent fibers is expected to vary with temperature. Thus an increase in the contact resistance is expected to work together with the temperature dependent ohmic resistance of the metallic fibers [9,22,23].

The variation of the imaginary component of the resistivity at high frequency was found less temperature dependent. This may be explained in term that the morphology of fibers-matrix forms three dimensional RC-parallel network circuits. The capacitance usually decreases with increasing frequency resulting in a decrease in the equivalent impedance, and hence a lower resistivity is observed. The ac-conductivity was plotted as a function of temperature at constant frequency in Figure 2. The plot indicates that conductivity decreases with increasing temperature as metallic behavior. The magnitude of the ac-conductivity is relatively high compared to pure polyester and lies between metallic and semiconductor behavior. This is expected from the X-ray analysis which shows a lot of impurities in the bulk such as Br, Ti, Na, Cr, in addition to the iron fibers as a filler.

To extent the analysis towards the dielectric properties of the given composite we calculate the component of the complex dielectric constant ($\varepsilon^* = \varepsilon' - j\varepsilon''$) as a function of frequency at 25 °C and 100 °C. The relation between the dielectric constants and the measured complex impedance is given by:

$$\varepsilon' = \frac{Z''}{(Z'^2 + Z''^2)\omega C_0} \tag{1}$$

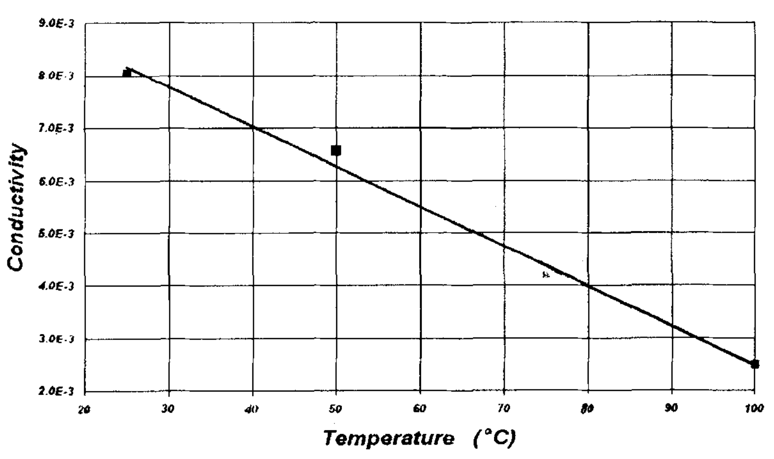
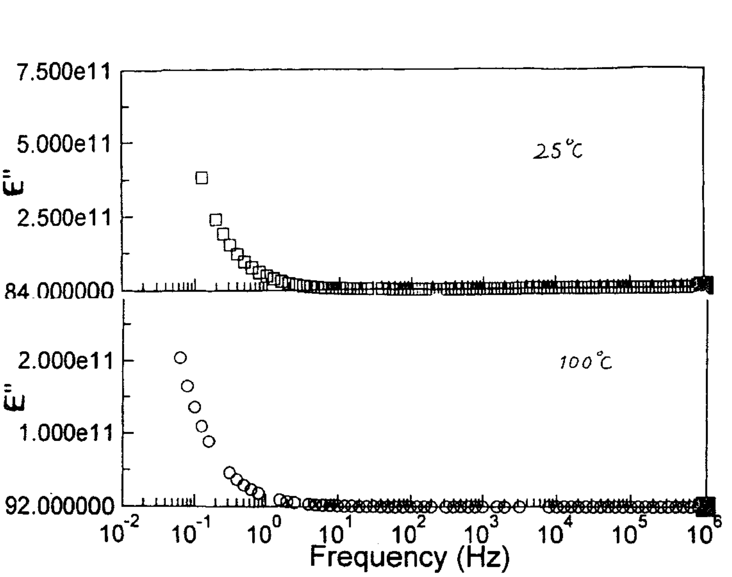


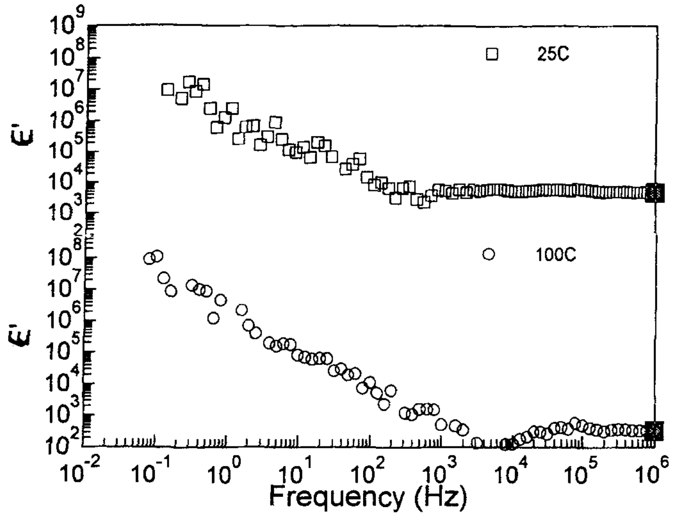
FIGURE 2 The ac-conductivity versus temperature for the fiber-polyester composite.

$$\varepsilon'' = \frac{Z'}{(Z'^2 + Z''^2)\omega C_0} \tag{2}$$

where, ω is the angular frequency of the applied ac-signal and C_0 is the electrodes capacitance. Figure (3a, b) shows the calculated values of (ε') and (ε'') as a function of frequency. The plot shows that (ε'') decreases exponentially from about a value of 3×10^{11} to about zero below 1 Hz. Therefore, the Maxwell Wigner relaxation peaks are depressed because this strong dependence of (ε'') on the applied frequency below 1 Hz. This behavior is usually obvious for such *n*-type conductor. The variation of (ε') versus frequency at 25 °C and 100 °C is shown in Figure (3b) where (ε') decreases exponentially with increasing the frequency. However, (ε') drops at 20 °C from 10^7 to about 10^3 below 1 kHz; while it drops from 10^7 to 10^2 below 5 kHz at 100 °C. It is worth to notice that such concentration of 6 wt.% to metallic fibers affects greatly the dielectric behavior of the given composite. On the other hand, the temperature variation of (ε') may be attributed to enhancement of the relaxation time of the electrical conduction.



a)



b)

FIGURE 3 The complex dielectric constant versus frequency at different temperatures for the fiber-polyester composite.

The apparent activation energy was calculated from Arrhenius type equation normally used in determination the electrical conductivity [8]. The activation energy determined from the slope of the natural logarithm of the conductivity vs $1000/T$, shown in Figure 4, is about 0.2 eV which is comparable to that value found by us for pan-based-carbon fibers which showed a semiconducting behavior [24]. However, it is acceptable in accordance with the conduction in the metal-type fillers. Hence, we may add that our observed results are consistent with those reported previously by Kwan *et al.* [25] on metallo-polymer composite of silver and silver coated glass spheres dispersed in polyester matrix.

Finally, the correlation of the present results with those of commercial carbon resistors indicates that the given composite has good stability and excellent electrical behavior. Figure 5 displays the impedance and the phase angle vs frequency for some commercial carbon resistors ranging from 1 kΩ up to 100 MΩ. The plot shows that resistors of low nomenant impedance has less frequency dependence than that of high impedance. Such frequency dependence of carbon resistors leeds to limit greatly the capability of the electronic devices. Hence, we believe that our composite will have promissing electronic applications.

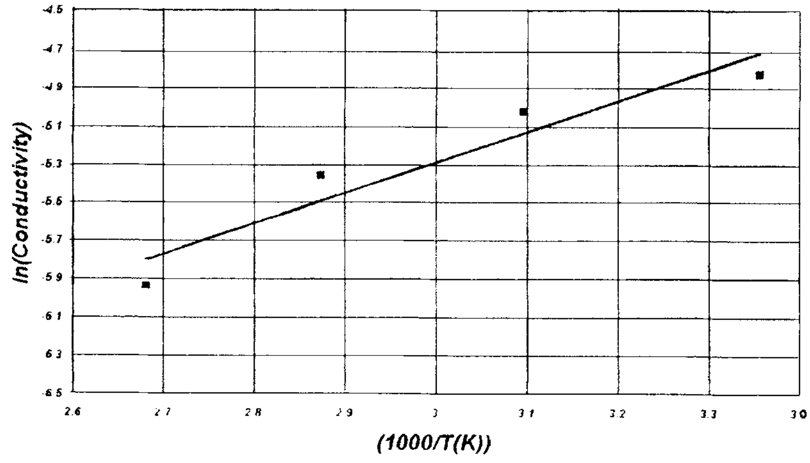


FIGURE 4 Natural Logarithm of the ac – conductivity versus $1000/T$ for the fiber polyester composite.

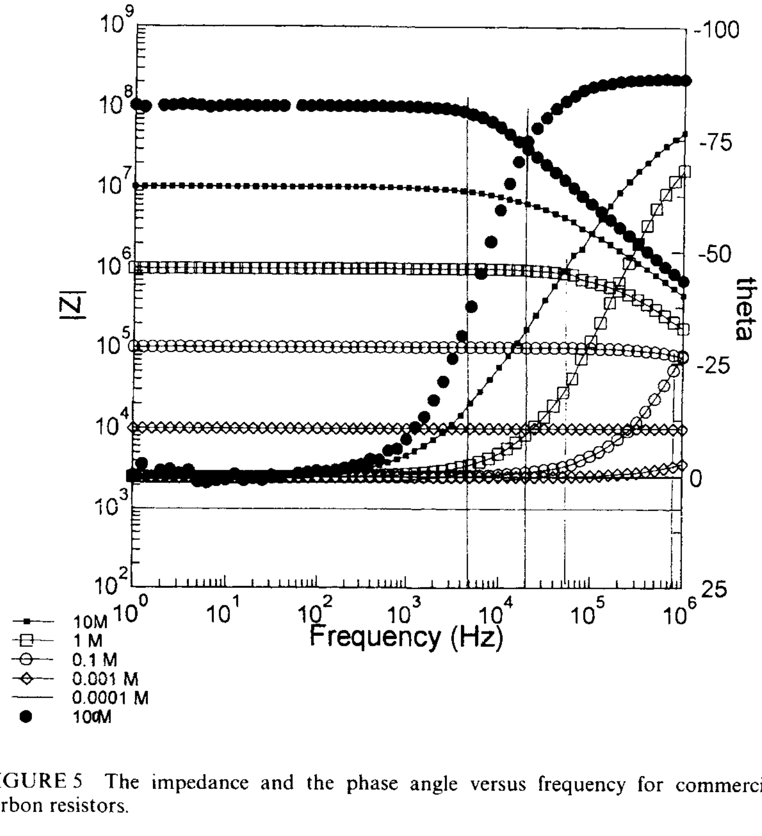


FIGURE 5 The impedance and the phase angle versus frequency for commercial carbon resistors.

4. CONCLUSIONS

The electrical properties of a metal fiber-polyester composite has been investigated as a function of temperature in the frequency range 0.1 Hz to 1 MHz. The obtained results showed that the composite behaves as *n*-type conductor although its concentration is less than the usually percolation limit. The magnitude of the resistivity was found relatively low due to the conduction mechanism operating in the bulk. The activation energy calculated from Arrhenius relation was small reflects the metallic behavior of the composite. The complex dielectric constant was found to be a strong frequency dependent; therefore, the Maxwell-Wigner relaxation peaks are depressed. The value of the dielectric constant is very high, and this agrees with the electrical behavior of the composite. The frequency independence of the impedance suggests that the composite may have promising electronic applications.

Acknowledgement

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