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Some properties of nickel-coated carbon fibre–polypropylene composite at microwave frequencies

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Some properties of nickel-coated carbon fibre–polypropylene composite are considered at microwave frequencies in the range 8 to 12 GHz. The paper presents the measured values of the insertion and return losses and the equivalent input impedance in the above frequency band. Measurements were performed on composite material for different nickel-coated fibre concentrations of 0, 5, 10, 16 and 28 wt %. The filler effects shows a transition region and identifies the dependency of the electrical properties on these concentrations. Furthermore, shielding effectiveness is calculated for the given concentrations and it is found that its value could reach more than 30 dB over the whole frequency band for a specimen of 2.6 mm thickness and with 28 wt % concentration.

1. Introduction

During the last decade, conductive polymer composites have attracted great scientific interest arising from the need to produce materials of high performance such as high strength and stiffness, high fatigue resistance, resistance to chemical attacks, and good electrical conduction and thermal resistance. These materials have a wide range of applications in military, industrial, commercial and consumer applications. The polymeric composites are extensively used as passive and active elements in some electrical circuit components, in different technological applications [1–3]. However, the mechanical and electrical performance of a polymer composite can be enhanced by using certain metallic fillers such as carbon black, nickel-coated carbon fibres, aluminized glass fibres, steel fibres and aluminium powder and flakes [4–10]. A significant enhancement is obtained when the fibres are coated with metals and treated with a binder to facilitate the composite processing. It is found that the electrical transition from complete insulator to good conductor is controlled by physical parameters such as the critical volume, concentration, particle type, aspect ratio, size and shape of the filler. Recent microwave reports [11, 12] on conductive polymers such as talc-filled polypropylene and Magnex–DC composite have shown that microwaves interact with the matrix via different mechanisms. It was found that the shielding effectiveness (SE) of the conductive composite depends on the fibre electrical conductivity, distribution, concentration and matrix structure.

The present work deals with some properties of the nickel-coated carbon fibre–polypropylene composite at microwave frequencies. The composite characterization is obtained by measuring the insertion loss (IL), return loss (RL) and the equivalent input impedance, Z, in the X-band (8 to 12 GHz). The results obtained are used to determine the electric and magnetic characteristics of the composite in addition to the SE.

2. Experimental details

The material used in this work was isotatic polypropylene ($\bar{M}_n = 4.4 \times 10^5$, $\bar{M}_w = 10^5$) and nickel-coated fibres of average diameter 10 μm. Carbon fibre strands were provided by Marbo SPA, Milan, and chopped into single filaments of average length 1 mm and mixed with a polypropylene matrix using Brabender-like apparatus (Rheocord EC from Haake Inc.) operating at 200° C followed by hot compression moulding at 200° C. Sheets of different carbon fibre concentrations (0, 5, 10, 16 and 28 wt %) were prepared with the same thickness of 2.6 mm. Morphological investigations were carried out using a Philips 501 scanning electron microscope (SEM) on fractured surfaces. Specimens for SEM observation were metallized by means of Polaron sputtering apparatus with Au–Pd alloy. The micrographs obtained are shown in Fig. 1. These micrographs show broad fibre distributions for composites of coated carbon fibre content below 10 wt %. Increasing the fibre concentration beyond 10 wt % and up to 28 wt % forms networks and structural connections in the matrix, yielding a conductive mesh. The SEM micrographs also show some voids in the matrix itself and around the fibres.

The dimensions of each test specimen were machined

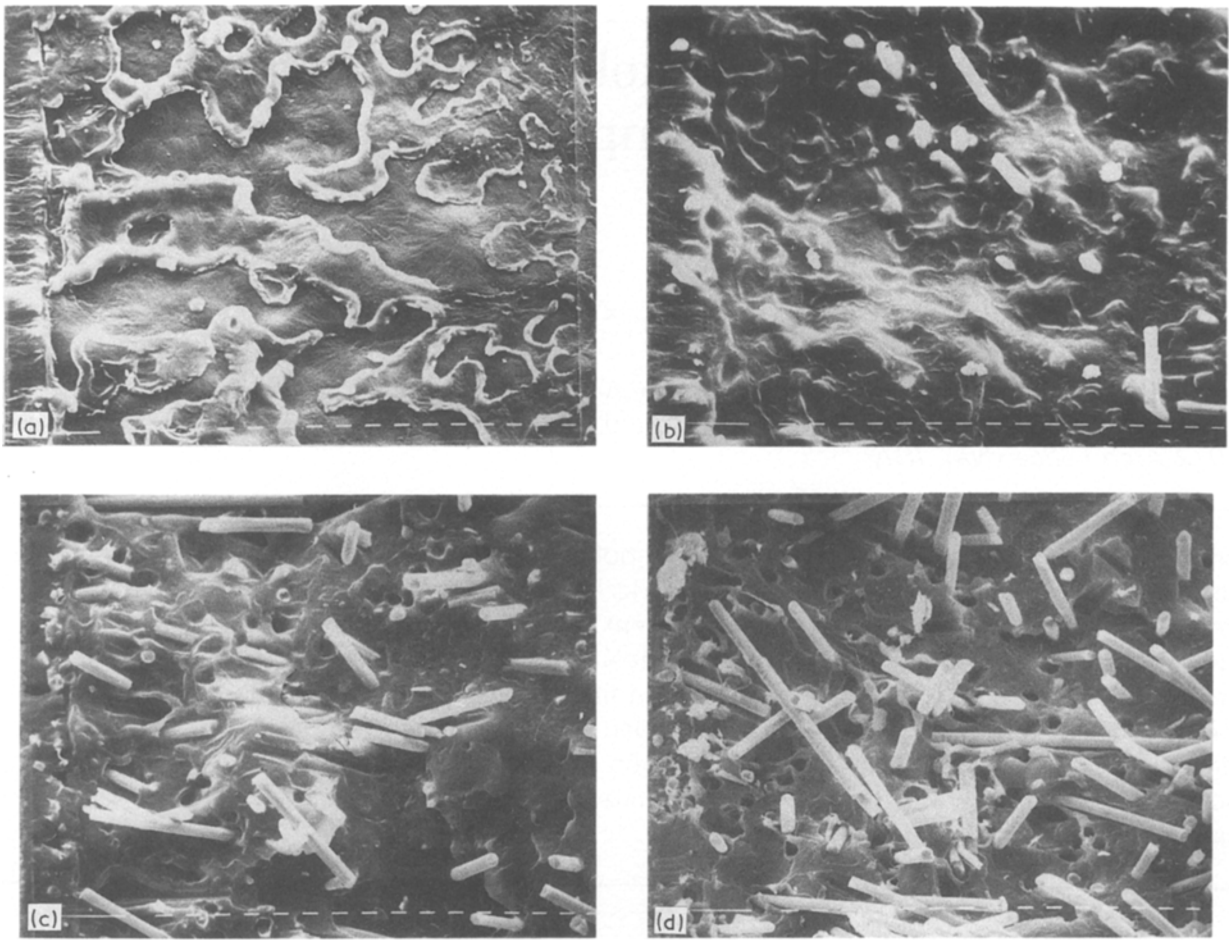

Figure 1 Scanning electron micrographs [13] of nickel-coated carbon fibre–polyproplyene composite: (a) 0, (b) 10, (c) 16, (d) 28 wt %. ($x = 10^2$).

to a suitable size for a typical rectangular waveguide operating in the X-band frequency range. Microwave measurements were carried out using a conventional HP microwave bench operating in the X-band. A specimen cut from each composite sheet was placed perpendicular to the waveguide axis to perform the IL, RL and Z measurements for the various composite concentrations. The incident, transmitted and reflected signals in the absence and presence of the specimen were measured by using the swept frequency method [11, 12, 14, 15]. The IL was obtained as the difference in dB between the incident and transmitted signal levels using the substitution method. The RL, measured by using a 20 dB directional coupler, was obtained as the difference in dB between the incident and reflected signal levels. The equivalent input impedance of the test specimen $Z = R + jX$ was measured using the slotted line method [16–18]. Uncertainties in the measurements were reduced by proper matching of the set-up. The reproducibility of the results is acceptable with deviations of the order of $\pm 5\%$.

3. Results and discussion

This work is an extension of research activity in our laboratories on the electrical characterization of conductive polymers [11, 12, 14, 15]. The present study deals with the effect of nickel-coated carbon fibres embedded in polypropylene matrix on the electromagnetic characteristics and consequently on the shielding capability of the resulting composite material.

Variations of RL and IL as function of frequency for the composite are given in Figs 2 and 3, respectively. These curves show that both RL and IL exhibit weak frequency dependency for the different filler concentrations except for the 10 wt % carbon fibre concentration. The maximum value of IL and minimum value of RL are observed for the 28 wt % specimen. The increase in IL reflects a decrease in RL and this is in agreement with the behaviour of most conductive composites [4, 5]. The variation of RL and IL with filler content is given in Fig. 4 for two frequencies, i.e. 8.5 and 10.25 GHz. It can be seen from these curves that the sum of RL and IL is proportional to the fibre content. This sum reaches an almost constant value of about 32 dB over the whole X-band for the 28 wt % fibre concentration. Furthermore it was observed that the specimen of 10 wt % carbon fibre content has a peculiar behaviour; it shows a relatively sharp maximum for RL and a broad minimum for IL at 10.3 GHz. This observation seems to agree with the study performed on the activation energy for this composite. This behaviour may be a result of the occurrence of a phase transition from insulator to conductor around this concentration [4, 19–21]. The given composite seems to be characterized by a critical concentration of carbon fibres. At this concentration a drastic change occurs in the electrical conductivity or a breakdown in its resistivity, with a corresponding change in the behaviour of its electromagnetic characteristics. This may be attributed to a formation of an

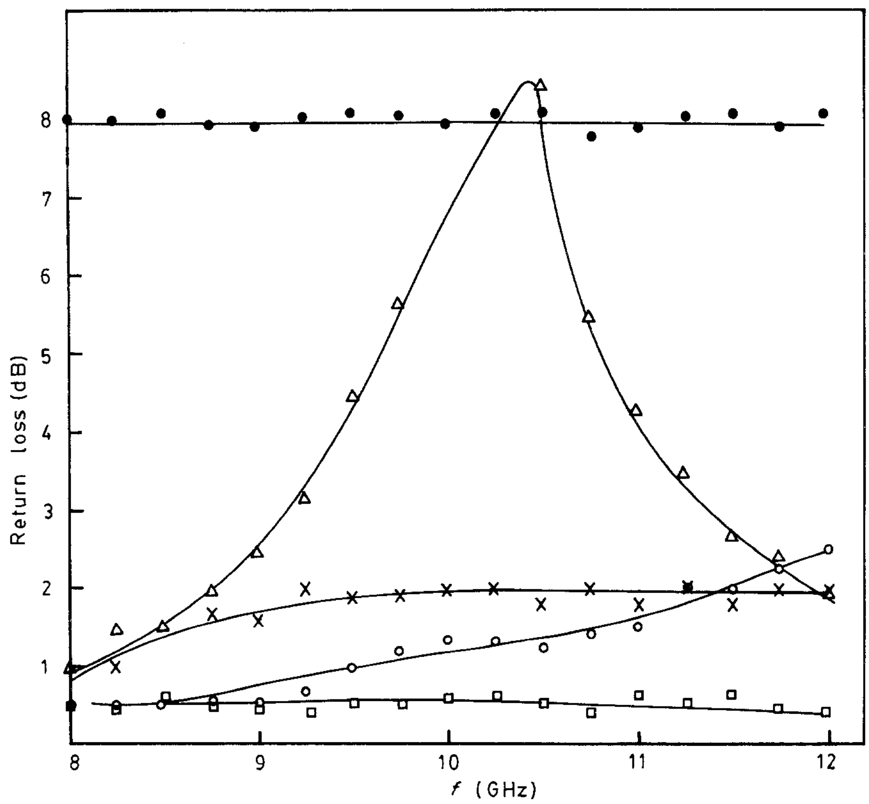

Figure 2 Variation of the RL with frequency f for different concentrations: (●) 0, (○) 5, (△) 10, (x) 16, (□) 28%.

electrical mesh or fibre interconnections within the matrix. Therefore any further increase in the filler content will only improve the resulting electromagnetic characteristics.

The relative variation of RL as a function of frequency is shown in Fig. 2 for different fibre concentrations. The range of this variation was found to be less than 2 dB over the whole X-band except for the case of the specimen with 10 wt % fibre concentration. The dependence of IL on frequency is shown in Fig. 3. The largest variation is 7 dB for the specimen of 10 wt % fibre concentration. The frequency dependence on the RL and IL of each specimen may be due to some structural effects such as the geometrical distribution of the filler and the interaction of the electromagnetic waves with coated carbon fibres. The wave interaction with fibres seems to reflect and absorb the electromagnetic energy, as with other conductive fillers. This behaviour is a direct consequence of the structural properties of the composite sample used (see Fig. 1). This type of fibre concentration makes the composite specimen with high fibre content behaves as

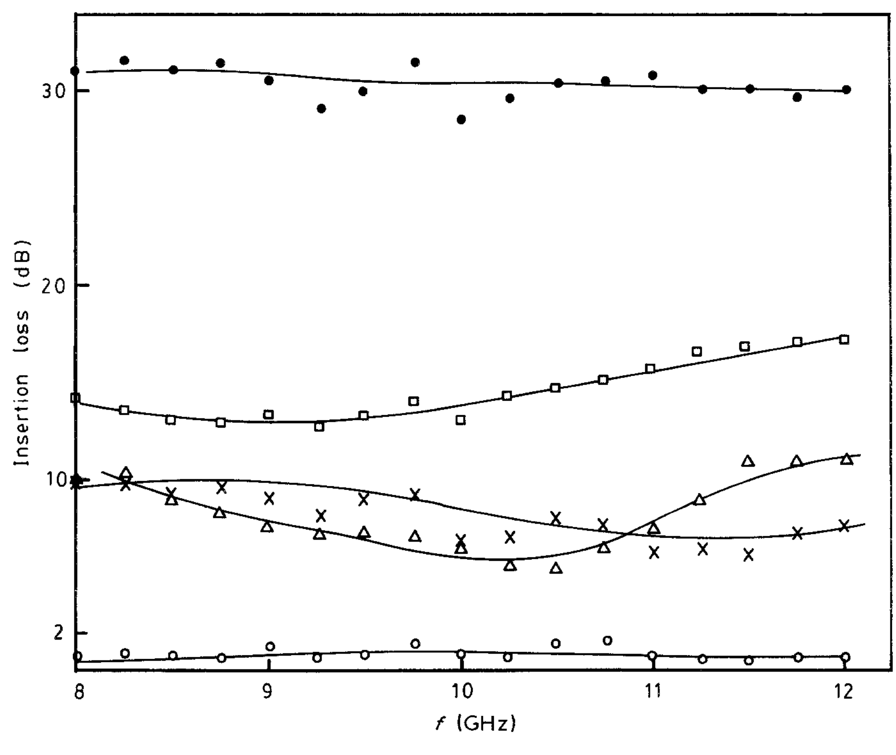

Figure 3 Variation of the IL with frequency f for different concentrations: (○) 0, (x) 5, (△) 10, (□) 16, (●) 28%.

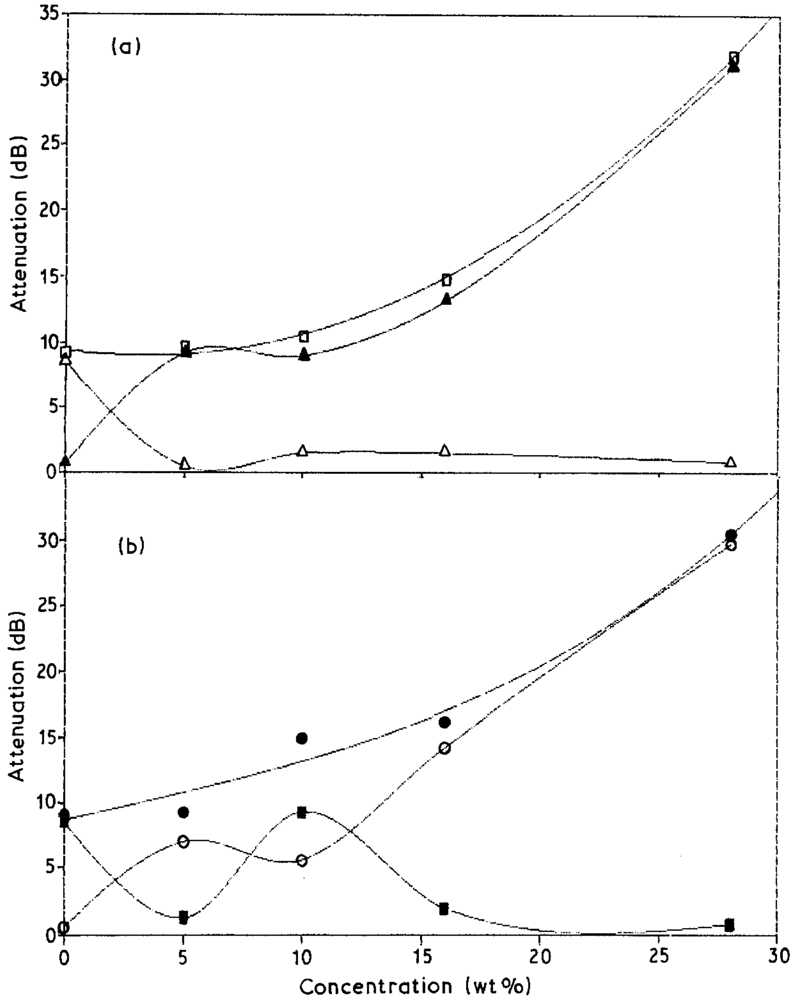

Figure 4 Variation of (△, ■) RL; (▲, ○) IL; and (□, ●) SE with filler content at (a) 8.5 and (b) 10.25 GHz.

a conductive mesh to improve the electromagnetic shielding effectiveness, which depends on the coated fibre content.

Results for the normalized equivalent input impedance, i.e.

$$z = Z/Z_w = |z|\angle\phi \quad (1)$$

where $Z = R + jX\Omega$ is the equivalent input impedance and Z_w is the wave impedance for the TE_{10} mode propagating in the guide, are shown in Fig. 5 for the magnitude of the normalized equivalent input impedance $|z|$, and in Fig. 6 for the phase ϕ for different fibre concentrations. These curves indicate once again that specimens of lower carbon fibre content (0 and 5 wt %) and higher content (16 and 28 wt %) exhibit weak frequency dependence, and the relatively low

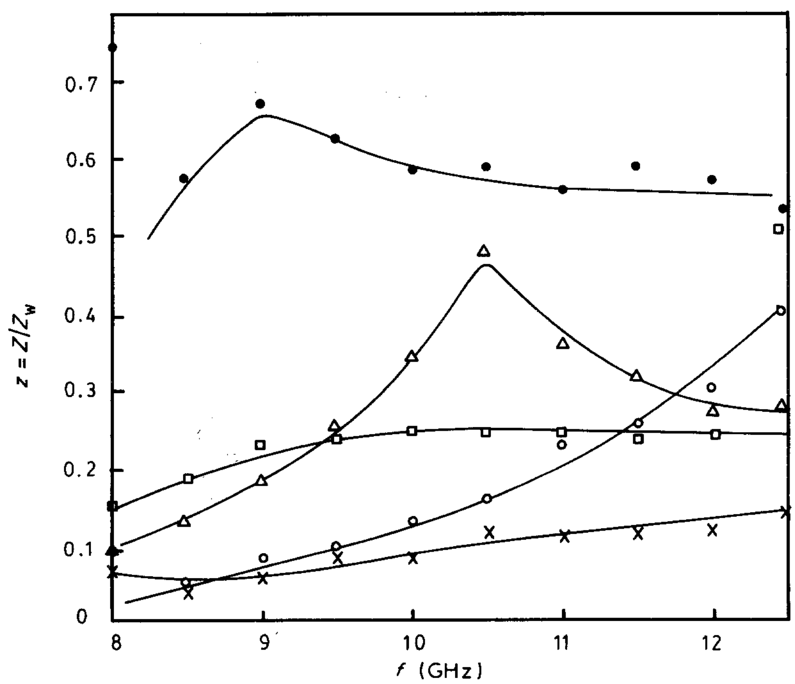

Figure 5 Magnitude of the normalized equivalent input impedance $|z|$ against frequency f for different concentrations: (●) 0, (○) 5, (△) 10, (□) 16, (x) 28%.

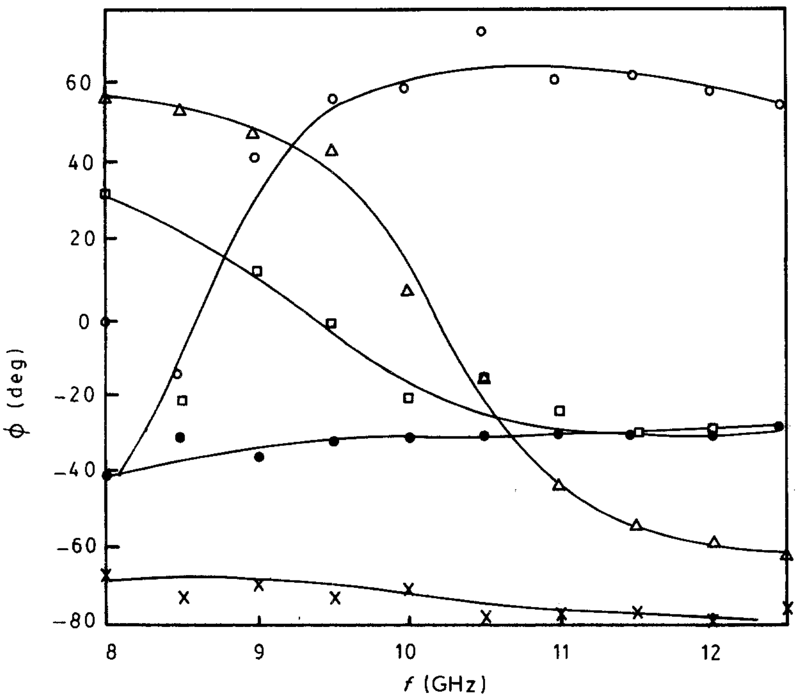

Figure 6 Phase of the equivalent input impedance, ϕ against frequency f for different concentrations: (●) 0, (○) 5, (△) 10, (□) 16, (x) 28%.

value of $|z|$ for specimens of high fibre content is attributed to the conductive-like behaviour of the specimen. However, for the case of 10 wt % fibre concentration the peculiar behaviour around 10.3 GHz is repeated here as a peak in the value of $|z|$ and a transition in ϕ from positive to negative values.

One of the important applications of this composite material is its utilization for the reduction of electromagnetic interference or SE, to and from the different devices used in communication systems and subsystems. The value of the SE can be obtained from a knowledge of the operating frequency, thickness of the specimen, electric and magnetic characteristics of the material (i.e. permittivity ε, permeability μ and conductivity σ; and in short its value is given [21, 23] by

$$\mathrm{SE} = R + A + B \quad \mathrm{dB} \qquad (2)$$

where R is the total reflection loss in dB, A is the absorption loss in dB and B is the correction term in dB due to multireflections, which is ignored when $A \leqslant 15$ dB.

The values of ε, μ and σ can be obtained from the measured values of the equivalent impedance. However, the value of SE is related to IL [23] by

$$\mathrm{SE} = \mathrm{IL} = 10 \log (P_i/P_t) \qquad (3)$$

where P_i is the incident electromagnetic power and P_t is the transmitted electromagnetic power through the specimen. But since RL is not zero for all concentrations, then the SE can be given as the combination of IL and RL, i.e.

$$\mathrm{SE} = \mathrm{RL} + \mathrm{IL}$$

$$= 10\left[\log\left(\frac{P_i}{P_r}\right) + \log\left(\frac{P_i}{P_t}\right)\right] \quad \mathrm{dB} \qquad (4)$$

where P_r is the electromagnetic power reflected from the specimen.

It should be noticed here that the value of B in Equation 2 can be ignored since the thickness of the specimen is much less than one-quarter of the waveguide wavelength, and also because of the high value of A for both 16, and 28 wt % fibre concentrations. Using Equation 4, it can be concluded that the SE is as presented in Fig. 4 and it is greater than 20 dB for a specimen of 2.6 mm thickness and with fibre concentration greater than 16 wt %. The value of the SE would be expected to reach around 40 and 75 dB for 5 and 10 mm specimen thickness, respectively. These values seem to be reasonably good considering the other characteristics of this composite material. Finally, the obtained values of SE are in very good agreement with values obtained from electrical resistivity measurements carried on these composites, which will be reported in a later communication [25].

4. Conclusions

Some properties of polypropylene–nickel-coated carbon composite have been studied at microwave frequencies in the X-band. These properties cover measurements of RL, IL and Z for specimens of 2.6 mm thickness and for different concentrations of nickel-coated carbon fibres ranging from 0 to 28 wt %. Evaluation of the SE shows that its value is approximately constant over the whole X-band. It can be concluded that with 33 wt % fibres concentration and 5 mm specimen thickness the value of SE could be greater than 70 dB over the whole X-band.

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