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# Mats and Fabrics for Electromagnetic Interference Shielding

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**Fabrics (with continuous electrically conductive fibers) are more effective than mats (with discontinuous conductive fibers) for electromagnetic interference shielding. Conductive fibers in the form of metal-coated polymer fibers or metal-coated carbon fibers are more effective than those in the form of bare carbon fibers. The highest shielding effectiveness of 53 dB at 1.0 GHz was attained by a metal-coated polymer fabric. The shielding is due mainly to reflection. A higher shielding effectiveness correlates with a higher reflectivity and a lower electrical resistivity. Both shielding effectiveness and reflectivity decrease with increasing frequency from 300 kHz to 1.5 GHz. The shielding effectiveness increases with thickness, as shown for bare carbon fiber mats. A nickel-coated carbon fiber mat of areal weight 9 g/m$^2$ is similar to a bare carbon fiber mat of areal weight 17 g/m$^2$ in shielding effectiveness.**

**Keywords** carbon fiber, electrical resistivity, electromagnetic, fabric, mat, nickel, shielding

## 1. Introduction

With their flexibility, conformability, and breathability, as are needed for curtains, gaskets, cable wraps, tapes, and other composite components, mats and fabrics are among the materials that are used for electromagnetic interference (EMI) shielding. These materials are made from fibers that are discontinuous and nonwoven (in the case of mats) and are continuous and woven (or knitted, in the case of fabrics). To provide shielding, the fibers used are electrically conductive. Examples are carbon fibers and metal-coated polymer fibers. Although these materials have been available commercially, a comparative study of their shielding characteristics has not been previously provided. Therefore, this paper provides such a comparative study, which includes mats and fabrics made from bare carbon fibers, metal-coated carbon fibers, and metal-coated polymer fibers.

Continuous carbon fibers are widely used as reinforcement in lightweight structural composite materials, particularly polymer-matrix composites. A less expensive form of carbon fiber is short (discontinuous) fibers, which can be made into a porous mat with the use of a small amount of an organic binder. The fibers in a mat are usually randomly oriented in two dimensions. They are made by wet-forming, as in papermaking. Applications of carbon fiber mats include electromagnetic interference (EMI) shielding (Ref 1, 2), lightning protection (Ref 2), electrical grounding, fuel cell electrodes, composite reinforcement (Ref 3, 4), and deicing (i.e., using the mat as a resistance heating element (Ref 5), which can be incorporated in or on a structural composite). As many of these applications benefit from a high electrical conductivity, metal-coated carbon fibers are often used for mats. A common metal for this purpose is nickel (Ref 2) because of its resistance to oxidation and corrosion.

EMI shielding (Ref 6-10) is in critical demand due to the interference of wireless (particularly radio frequency) devices with digital devices and the increasing sensitivity and importance of electronic devices. Shielding is particularly needed for polymer-based hoods, fenders, and firewalls of automobiles to prevent electromagnetic engine emissions from interfering with radio reception (Ref 1).

Although the incorporation of carbon fiber mats in polymers for the purpose of shielding was reported in previous work (Ref 1, 2), the effectiveness of the shielding was not compared with that of competing materials, such as metal-coated carbon fiber mats, bare carbon fiber fabrics, and metal-coated polymer fabrics. Moreover, the attenuation upon reflection was not addressed despite the significant contribution of reflection to the shielding.

## 2. Experimental Methods

The carbon fiber mats were nonwoven, made from discontinuous polyacrylonitrile (PAN)-based carbon fibers. The mats made from bare carbon fibers were from two sources, namely Technical Fiber Products, Inc. (Newburgh, NY; mats of areal weight 8-34 g/m$^2$, thickness 64-180 μm, and in-plane electrical resistivity 0.06-0.09 Ω cm, with fibers of diameter 10 μm, and tensile modulus 230 GPa) and SGL Carbon Group (St. Marys, PA; mat of areal weight 61 g/m$^2$, thickness 310 μm, and in-plane electrical resistivity 0.031 Ω cm, with fibers of diameter 7 μm, and tensile modulus 225 GPa).

The mat made from nickel-coated carbon fibers was from Technical Fiber Products, Inc., with areal weight 9 g/m$^2$, thickness 60 μm, and in-plane resistivity 0.022 Ω cm; the fiber diameter was 7 μm before coating. The nickel coating was electroplated on the fibers before the fibers were made into a mat. The nickel amounted to (50 ± 5) wt.% of the coated fibers.

The mat with bare carbon fibers contained 50% 13 mm (½

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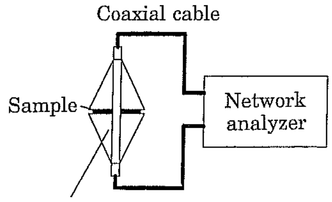


**Fig. 1** Setup for testing effectiveness of MI shielding

in.) fibers and 50% 6.4 mm (¼ in.) fibers. The mat with nickel-coated carbon fibers contained 100% 6 mm fibers.

All mats from Technical Fiber Products, Inc. contained a binder (polyvinyl alcohol, or PVA) in the amount of 10 wt.%. The mat from SGL Carbon Group contained a binder polytetrafluoroethylene (PTFE) in the amount of 5 wt.%.

The bare continuous carbon fiber woven fabric (3000 filament tows, plain weave) was a thickness 250 μm, areal weight 190 g/m$^2$, and in-plane resistivity 0.020 Ω cm (no. 530, Fiber Glast Developments Corp., Brookville, OH).

The metal-coated continuous polymer knitted fabric was a nickel/copper-coated polyester knitted mesh of thickness 220 μm and in-plane resistivity 0.003 Ω cm (Flecton, product no. 3070-500, Laird Technologies, St. Louis, MO). The polyester fabric was 20 denier (1 denier = 1 g per 9000 m of yarn). The fiber diameter was 25-38 μm both before and after the metal plating, which involved copper electroless plating followed by nickel electrolytic plating. The polyester fabric (without metal coating) areal weight was 44-78 g/m$^2$; the areal weight of the metal coating was 13.5-27.0 g/m$^2$.

The in-plane electrical resistivity values given above for the various mats were measured in this work on 100 × 10 mm specimen strips using the four-probe method and silver paint electrical contacts. The four probes were such that the outer probes (for current application) were 80 mm apart, while the inner probes (for voltage measurement) were 60 mm apart.

The attenuations upon reflection and transmission were measured using the coaxial cable method (the transmission line method; Fig. 1). The set-up consisted of an Elgal (Israel) SET 19A shielding effectiveness tester with its input and output connected to a Hewlett-Packard (HP) 8510A network analyzer (Ref 11). An HP APC-7 calibration kit was used to calibrate the system. The frequency was up to 1.5 GHz, as limited by the specimen dimensions. The specimen placed in the center plane of the tester (with the input and output of the tester on the two sides of the specimen) was in the form of an annular ring of outer diameter 97 mm and inner diameter 29 mm.

## 3. Results and Discussion

Table 1 shows the attenuation upon transmission (same as the EMI shielding effectiveness) and upon reflection at various frequencies from 300 kHz to 1.5 GHz. The attenuation upon transmission at any of the frequencies increases with increasing thickness of the bare carbon fiber mat (Fig. 2), as expected. The attenuation upon reflection is much lower than that upon transmission, indicating that reflection is a primary mechanism for the shielding. The attenuation upon reflection at any of the frequencies decreases with increasing thickness of the mat (Fig. 3), as expected as the carbon fibers are good reflectors. Figures 2 and 3 also show that the effects of the areal weight on both transmission and reflection characteristics are most significant below an areal weight of 17 g/m$^2$. Above this areal weight, the effects, though similar, are less significant.

The attenuation upon transmission observed in this work for bare carbon fiber mats is consistent with that previously reported for such mats (Ref 1). In particular, Ref 1 reported attenuation upon transmission of 25-50 dB at 0.5-1.0 GHz for carbon fiber mats of weight 11-47 g/m$^2$. The value of 25 dB for 11 g/m$^2$ (Ref 1) is quite close to the value in Table 1 for 10 g/m$^2$.

At the same mat thickness, the nickel-coated carbon fiber mat is superior to the bare carbon fiber mat for shielding, and the attenuation upon reflection is lower, as expected, because nickel is a superior reflector. This is consistent with the relatively low resistivity of the nickel-coated carbon fiber mat. The effectiveness of the 9 g/m$^2$ nickel-coated carbon fiber mat is comparable to that of the 17 g/m$^2$ bare carbon fiber mat, as indicated by similarities in attenuation upon both transmission and reflection.

The bare carbon fiber fabric was superior to the bare carbon fiber mat (61 g/m$^2$) in shielding effectiveness, but it was less reflective than the mat. This superiority is consistent with the lower electrical resistivity and is attributed to (a) the electrical connectivity provided by the continuous fibers in the fabric and (b) the greater thickness of the fabric.

Despite its greater thickness, the bare carbon fiber fabric was inferior to the metal-coated polyester fabric in the shielding effectiveness. This inferiority is consistent with the higher resistivity and is attributed to the high effectiveness provided by the metal coating on the polymer fabric. This means that the metal coating is more effective for shielding than carbon fiber.

Despite the nonconductive nature of polyester (in contrast to the conductive nature of carbon), the Ni/Cu-coated polyester fabric is much superior to the carbon fiber fabric and any of the mats studied in this work, as indicated by higher attenuation upon transmission and lower attenuation upon reflection. The Ni/Cu-coated polyester fabric (220 μm thick) is superior to a bare carbon fiber mat (310 μm thick) that is thicker by 40% and is also superior to a bare carbon fiber fabric (250 μm thick) that is thicker by 14%. Moreover, it is superior to the nickel-coated carbon fiber mat. This superiority is consistent with the exceptionally low resistivity of the fabric (0.003 Ω cm) and is caused by the metal (Ni/Cu) coating and the electrical connectivity enabled by the continuous nature of the fibers. This means that, in the presence of a continuous metal coating, carbon fibers are not necessary for shielding. On the other hand, a disadvantage of the polyester fabric is its high areal weight (44-78 g/m$^2$), even in the absence of metal coating. With the Ni/Cu coating, the areal weight of the polyester fabric is even higher (58-105 g/m$^2$). A low weight is desirable for applications in lightweight structures, such as automobile structures.

For all the materials studied, the attenuation upon transmission decreases with increasing frequency while that upon reflection increases with increasing frequency. This means that the reflectivity, which governs the shielding effectiveness, decreases with increasing frequency. This trend is probably caused by the skin effect, i.e., the skin depth decreasing with increasing frequency.

Using the same testing equipment as in this work, Li and Chung (Ref 12) reported that short carbon fiber of length 400 μm and diameter 10 μm in the amount of 20 vol.% in a polymer matrix provides an EMI shielding effectiveness of 19 dB

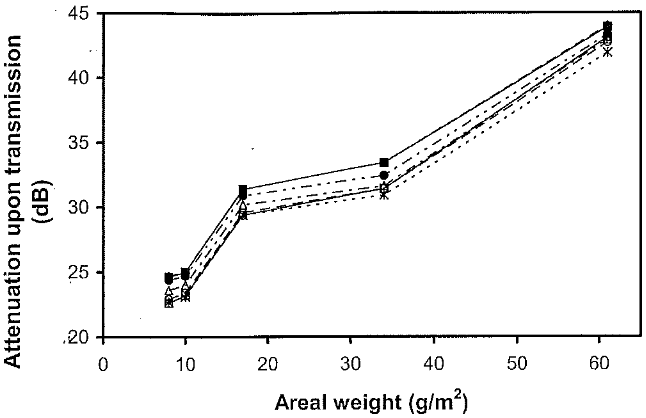


Fig. 2 Attenuation upon transmission versus areal weight for bare carbon fiber mats: (◇) 300 kHz; (■) 1 MHz; (●) 100 MHz; (△) 300 MHz; (*) 500 MHz; (O) 1.0 GHz; (□) 1.5 GHz

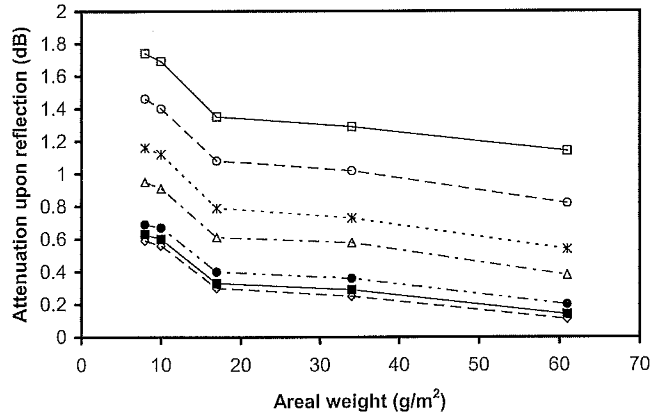


Fig. 3 . Attenuation upon reflection versus areal weight for bare carbon fiber mats: (◇) 300 kHz; (■) 1 MHz; (●) 100 MHz; (△) 300 MHz; (*) 500 MHz; (O) 1.0 GHz; (□) 1.5 GHz

**Table 1 EMI shielding effectiveness (same as attenuation upon transmission) and attenuation upon reflection of mats and fabrics**

| | Frequency | Bare carbon fiber mats | | | | | Nickel-coated carbon fiber mat | Carbon fiber fabric | Ni/Cu-coated polyester fabric |
|---|---|---|---|---|---|---|---|---|---|
| Areal weight, g/m$^2$ | ... | 8 | 10 | 17 | 34 | 61 | 9 | 190 | 58-105 |
| Thickness, μm | ... | 60 | 80 | 110 | 180 | 310 | 60 | 250 | 220 |
| Resistivity, Ω cm | ... | 0.078 | 0.083 | 0.064 | 0.094 | 0.031 | 0.022 | 0.020 | 0.003 |
| Attenuation upon transmission, dB | 300 kHz | 24.7 | 25.0 | 31.4 | 33.4 | 44.0 | 32.3 | 49.9 | 67.8 |
| | 1 MHz | 24.6 | 25.0 | 31.4 | 33.4 | 43.9 | 32.3 | 49.9 | 66.9 |
| | 100 MHz | 24.4 | 24.7 | 30.9 | 32.4 | 43.3 | 31.1 | 50.4 | 65.7 |
| | 300 MHz | 23.6 | 24.0 | 30.2 | 31.6 | 42.9 | 30.0 | 48.5 | 62.1 |
| | 500 MHz | 22.7 | 23.1 | 29.4 | 30.9 | 41.9 | 29.1 | 45.8 | 58.2 |
| | 1.0 GHz | 22.9 | 23.4 | 29.6 | 31.4 | 42.7 | 29.0 | 43.6 | 53.4 |
| | 1.5 GHz | 22.6 | 23.2 | 29.4 | 31.4 | 43.1 | 28.5 | 45.4 | 49.9 |
| Attenuation upon reflection, dB | 300 kHz | 0.59 | 0.56 | 0.30 | 0.25 | 0.11 | 0.27 | 0.16 | 0.05 |
| | 1 MHz | 0.63 | 0.60 | 0.33 | 0.29 | 0.14 | 0.30 | 0.19 | 0.09 |
| | 100 MHz | 0.69 | 0.67 | 0.40 | 0.36 | 0.20 | 0.38 | 0.27 | 0.13 |
| | 300 MHz | 0.95 | 0.91 | 0.61 | 0.58 | 0.38 | 0.61 | 0.48 | 0.31 |
| | 500 MHz | 1.16 | 1.12 | 0.79 | 0.73 | 0.54 | 0.79 | 0.63 | 0.46 |
| | 1.0 GHz | 1.46 | 1.40 | 1.08 | 1.02 | 0.82 | 1.08 | 0.95 | 0.76 |
| | 1.5 GHz | 1.74 | 1.69 | 1.35 | 1.29 | 1.14 | 1.36 | 1.17 | 1.02 |

at 1 GHz. In contrast, the shielding effectiveness at 1 GHz exceeds 22 dB for the mats and fabrics of this work. The difference in performance is probably due to the greater electrical connectivity in the mats and fabrics, compared with that in a discontinuous fiber composite with a nonconductive matrix. However, shielding effectiveness as high as 87 dB at 1 GHz has been reported for a nickel filament (0.4 μm diameter, >100 μm length) composite with 7 vol.% filament and a nonconductive polymer matrix (Ref 13).

## 4. Conclusions

Fabrics and mats containing electrically conductive fibers are effective for shielding at 300 kHz to 1.5 GHz, with fabrics superior to mats as a result of their continuous fibers and consequent electrical connectivity.

Conductive fibers in the form of metal-coated polymer fibers or metal-coated carbon fibers are superior for shielding compared with bare carbon fibers, with the most effective ones being metal-coated polyester fibers. A fabric of these fibers gives a shielding effectiveness of 53 dB at 1.0 GHz.

Shielding is mainly caused by reflection, with higher shielding effectiveness correlating to higher reflectivity and lower electrical resistivity. The attenuation upon reflection is 1.7 dB or below, whereas that upon transmission is 23 dB or above.

The shielding effectiveness increases with thickness and the attenuation upon reflection decreases with thickness, as shown for bare carbon fiber mats. A nickel-coated carbon fiber mat of areal weight 9 g/m$^2$ is similar to a bare carbon fiber mat of areal weight 17 g/m$^2$ in shielding effectiveness and reflectivity. Both shielding effectiveness and reflectivity decrease with increasing frequency from 300 kHz to 1.5 GHz.

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