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Electromagnetic interference shielding reaching 70 dB in steel fiber cement

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Abstract

An electromagnetic interference (EMI) shielding effectiveness of 70 dB at 1.5 GHz has been attained in cement paste that contains 0.72 vol.% stainless steel fibers of diameter 8 μm and length 6 mm. The shielding is primarily by reflection. The material exhibits electrical resistivity 16 Ω cm. The presence of sand essentially does not affect the shielding effectiveness. The fibers remain effective in the presence of steel rebars. For comparison, the shielding effectiveness of a solid piece of stainless steel is 78 dB at 1.5 GHz.

Keywords: Electrical properties; Cement paste; Fiber reinforcement; Silica fume; Shielding

1. Introduction

Electromagnetic interference (EMI) shielding [1–4] 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 underground vaults containing transformers and other electronics that are relevant to electric power and telecommunication. It is also needed for deterring electromagnetic forms of spying.

Polymer-matrix composites containing electrically conductive fillers are widely used for the shielding of electronics. In contrast to a typical polymer matrix, which is electrically insulating, the cement matrix is slightly conductive (mainly ionic conduction). Therefore, the use of a cement matrix allows some degree of electrical connectivity among the conductive filler units, even when the filler volume fraction is below the percolation threshold.

EMI shielding is one of the main applications of conventional short carbon fibers [5]. Due to the small diameter and the skin effect, carbon filaments (catalytically grown, of diameter 0.1 μm) are more effective at the same volume fraction in a composite than conventional short carbon fibers for EMI shielding, as shown for both thermoplastic [6,7] and cement [8,9] matrices (Table 1). In this paper, filaments refer to those of diameter less than 1 μm, whereas fibers refer to those of diameter 1 μm or more. The highest EMI shielding effectiveness previously reported in cement-matrix composites is 40 dB, as attained in cement paste containing 1.5 vol.% carbon filaments [10]. All these previous effectiveness measurements and those of this paper were made with the same fixture and about the same sample thickness. Therefore, comparison is meaningful.

The greater shielding effectiveness of the filaments compared to the fibers at the same volume fraction in a composite material is because of the skin effect, that is, the fact that high frequency electromagnetic radiation interacts with only the near surface region of an electrical conductor. However, carbon filaments are still not as effective as nickel fibers of diameter 2 μm at the same volume fraction, as shown for a thermoplastic matrix [11]. On the other hand, by coating a carbon filament with nickel by electroplating, a nickel filament (0.4-μm-diameter) with a carbon core (0.1-μm-diameter) is obtained [11]. The nickel filaments (0.4-μm-diameter) are more effective than nickel fibers (2-μm-diameter) for shielding due to their small diameter. At 1 GHz, a shielding effectiveness of 87 dB was attained by using only 7 vol.% nickel filaments in a thermoplastic matrix [11]. The shielding is almost all by reflection rather than absorption.

The high radio wave reflectivity of carbon filament (0.1-μm-diameter)-reinforced cement paste (at 1 GHz, 10 dB

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Table 1
EMI shielding effectiveness of various composite materials

Matrix	Filler volume fraction (%)	Fiber	Filament	Frequency (GHz)	Shielding effectiveness (dB)	Reference
Thermoplastic	19		carbon	1.0	74	[7]
Thermoplastic	20	carbon		1.0	46	[6]
Cement	0.54		carbon	1.5	26	[8]
Cement	0.84	carbon		1.5	15	[9]
Cement	1.50		carbon		40	[10]
Thermoplastic	7.0		nickel	1.0	87	[11]
Cement	0.72	steel		1.5	70	this work

higher than plain cement paste) makes carbon filament concrete attractive for use in lateral guidance in automatic highways [12]. Cement paste containing 0.5 vol.% carbon filaments exhibits reflectivity at 1 GHz that is 29 dB higher than the transmissivity. Without the filaments, the reflectivity is 3–11 dB lower than the transmissivity.

This paper is aimed at the attaining of high EMI shielding effectiveness in cement-based materials by using short steel fibers, as steel is more conductive than carbon and the shielding effectiveness of cement-based materials containing steel has not been previously reported. Since steel in the form of rebars is widely used in cement-based materials, this work includes a study of the effect of steel rebars on the shielding effectiveness of steel fiber cement-based materials.

Almost all previous work on the shielding effectiveness of cement-based materials [8–10,12] addressed cement paste, that is, the case of no aggregate. In contrast, this work provides an investigation of the effect of sand on the shielding effectiveness.

2. Experimental methods

The steel fibers (Beka–Shield) were made of No. 304 austenitic stainless steel, as obtained from Bekaert Fiber Technologies (Marietta, GA). The fiber diameter was 8 μm. The fiber length was 6 mm. The fibers included 10 wt.% (47 vol.%) of a polyvinyl alcohol (PVA) binder, which was hydrophilic and dissolved in water during cement mixing, thus allowing fiber dispersion. ASTM Standard mild steel rebars with diameter of 0.116 in. (2.95 mm) were used. The cross-sectional area was 0.011 in.^{2} (6.83 mm^2).

The cement used was portland cement (Type I) from Lafarge (Southfield, MI). Cement pastes and mortars were made by using cement, water (water/cement ratio = 0.40 for specimens for shielding effectiveness measurement and 0.35 for specimens for resistivity measurement), silica fume (15% by mass of cement, Elkem Materials, Pittsburgh, PA, EMS 965, for helping the fiber dispersion [13]), and the steel fibers (fibers + PVA amounting to 0–5.0% by mass of cement, corresponding to fibers without PVA in the amount of 0–0.90 vol.%, in the case of cement paste; fibers + PVA amounting to 0–4.0% by mass of cement, corresponding to fibers without PVA in the amount of 0–0.46 vol.%, in the case of mortar). For example, a fiber content (including PVA) of 4% by mass of cement in cement paste corresponds to fibers (excluding PVA) in the amount of 3.6% by mass of cement, or 0.72 vol.%, and PVA in the amount of 0.4% by mass of cement, or 0.64 vol.%. A water-reducing agent (a sodium salt of a condensed naphthalenesulfonic acid, TAMOL SN, Rohm and Haas, Philadelphia, PA) was used in the amount of 1.0% by mass of cement for specimens for shielding effectiveness measurement. It was not used for specimens for resistivity measurement. The sand used in case of mortars was natural sand (100% passing 1.00-mm sieve, 99.9% SiO_2). The sand/cement ratio was 1.0.

A rotary mixer with a flat beater was used for mixing. Cement, water, silica fume, fibers (if applicable), and sand (if applicable) were mixed for 5 min. After pouring into oiled molds, an external electrical vibrator was used to facilitate compaction and decrease the amount of air bubbles. The samples were demolded after 1 day and cured in air at room temperature (relative humidity = 100%) for 28 days.

The attenuations upon reflection and transmission were measured using the coaxial cable method (the transmission line method, Fig. 1). The setup consisted of an Elgal (Israel) SET 19A shielding effectiveness tester with its input and output connected to a Hewlett-Packard (HP) 8510A network analyzer. An HP APC-7 calibration kit was used to calibrate the system. The frequency was either 1.0 or 1.5 GHz. The sample placed in the center plane of the tester (with the

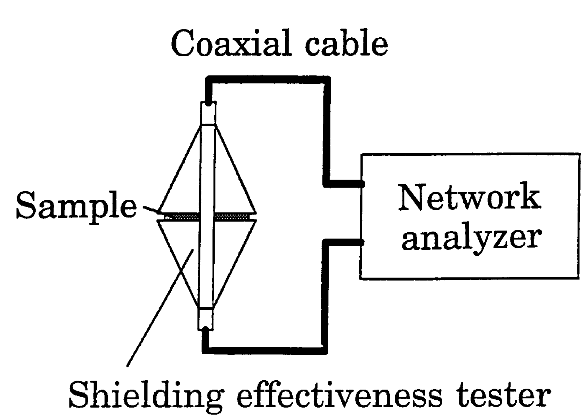

Fig. 1. EMI shielding effectiveness testing setup.

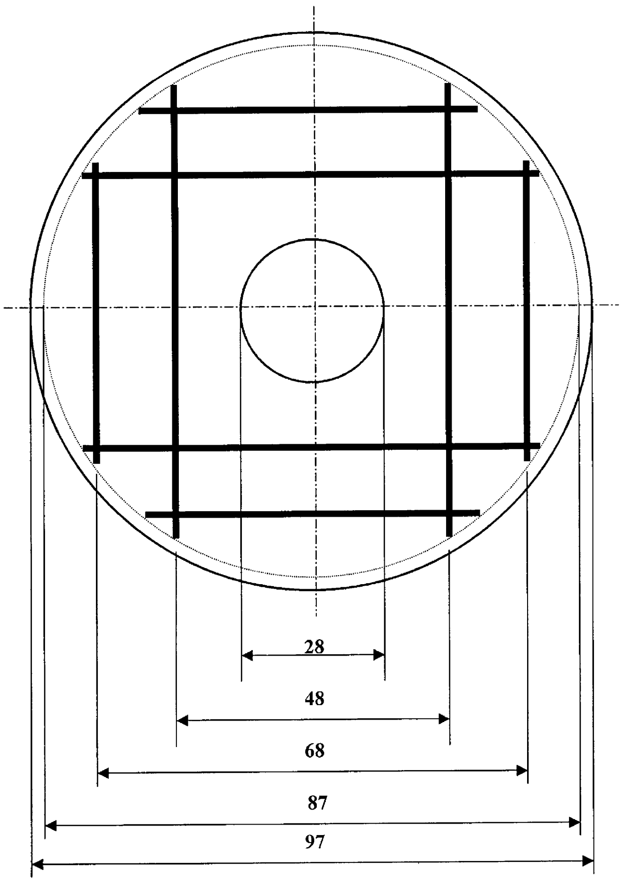

Fig. 2. Annular configuration of mortar reinforced with steel rebars (thick lines) for EMI shielding effectiveness testing. All dimensions are in millimeters.

input and output of the tester on the two sides of the sample) was in the form of an annular ring of outer diameter 97 mm and inner diameter 29 mm. The sample thickness was measured for each specimen, but it was around 4.5 mm for specimens without steel rebar and around 9.5 mm for specimens with steel rebars. Silver paint was applied at both inner and outer edges of each specimen and at the vicinity of the edges in order to make electrical contact with the inner and outer conductors of the tester [10]. The steel rebars were positioned as shown by thick lines in Fig. 2. They were in two layers that involved rebars in two perpendicular directions. Rebars in the same layer were in the same direction. The two layers touched at the junctions of the perpendicular rebars. The junctions were maintained by using wire ties.

The DC volume electrical resistivity is a common fundamental property for material characterization, although shielding is an AC behavior. Therefore, the DC resistivity was measured using the Keithley 2001 multimeter and the four-probe method. In this method, four electrical contacts were applied by silver paint around the whole perimeter at four planes perpendicular to the length of the specimen. The four planes were symmetrical around the mid-point along the length of the specimen, such that the outer contacts (for passing current) were 80 mm apart and the inner contacts (for measuring the voltage in relation to resistivity determination) were 60 mm apart. This method of resistivity measurement had been used in previous work on cement-based materials [10,13,14].

Six specimens of each composition were tested for each of the two types of tests (shielding and resistivity). Eleven cement paste compositions (from 0 to 0.90 vol.% steel fibers) were tested for the resistivity; 11 compositions (7 cement pastes, 2 mortars without rebar, and 2 mortars with rebars) were tested for the shielding effectiveness.

3. Results and discussion

Table 2 lists the electrical resistivity of cement pastes containing various volume fractions of steel fibers (excluding PVA). The percolation threshold is 0.3 vol.%. The lowest resistivity of 16 Ω cm is attained at 0.72 vol.% fibers. That the resistivity was higher for 0.90 vol.% fibers than 0.72 vol.% fibers is probably due to the drop in the degree of fiber dispersion along with the consistency at the higher fiber volume fraction.

Table 3 shows that the EMI shielding effectiveness increases monotonically with increasing steel fiber content, as expected. However, the difference in shielding effectiveness is small between pastes containing 0.72 and 0.90 vol.% fibers. Thus, the fiber content of 0.72 vol.% is optimal for shielding. The shielding effectiveness is higher at 1.5 than 1.0 GHz, as expected. The attenuation upon reflection is much smaller than that upon transmission, indicating that the shielding is primarily by reflection. The fibers increase the reflectivity (i.e., decrease the attenuation upon reflection), whether sand or rebar is present or not.

The shielding effectiveness of mortar containing 0.41 or 0.46 vol.% fibers is between the values for pastes containing 0.36 and 0.72 vol.% fibers. The low effectiveness of mortar without fiber is similar to that of paste without fiber. Thus, the shielding effectiveness is governed by the fiber volume fraction and is essentially not affected by the presence of sand.

Table 2
Electrical resistivity of cement pastes containing silica fume and various amounts of steel fibers

Fibers (vol.%)	Resistivity (Ω cm)
0	$(6.1 \pm 0.1) \times 10^5$
0.03	$(1.3 \pm 0.1) \times 10^5$
0.06	$(7.8 \pm 0.1) \times 10^4$
0.09	$(4.5 \pm 0.4) \times 10^3$
0.18	$(1.4 \pm 0.1) \times 10^3$
0.27	$(9.4 \pm 0.8) \times 10^2$
0.36	57 ± 4
0.45	38 ± 3
0.54	23 ± 2
0.72	16 ± 1
0.90	40 ± 3

Table 3
Attenuation (dB) of radio wave (1.0 and 1.5 GHz) upon transmission and upon reflection

Rebar	Sand/ cement ratio	Fibers (vol.%)	Specimen thickness (mm)	Transmission		Reflection	
				1.0 GHz	1.5 GHz	1.0 GHz	1.5 GHz
No	0	0	4.36 ± 0.40	4.06 ± 0.13	2.35 ± 0.09	5.51 ± 0.21	8.75 ± 0.30
No	0	0.09	4.45 ± 0.17	19.4 ± 2.6	19.2 ± 2.8	2.94 ± 0.31	2.95 ± 0.43
No	0	0.18	4.54 ± 0.32	27.7 ± 3.0	29.7 ± 3.6	2.78 ± 0.25	2.77 ± 0.29
No	0	0.27	4.47 ± 0.25	37.8 ± 4.6	43.3 ± 3.4	2.07 ± 0.17	2.30 ± 0.18
No	0	0.36	4.39 ± 0.23	52.3 ± 2.8	57.6 ± 3.0	1.61 ± 0.12	1.89 ± 0.16
No	0	0.72	4.47 ± 0.16	59.1 ± 3.3	69.8 ± 5.4	1.28 ± 0.08	1.66 ± 0.12
No	0	0.90	4.48 ± 0.20	58.0 ± 4.6	71.3 ± 5.8	1.20 ± 0.09	1.80 ± 0.14
No	1.0	0	4.39 ± 0.43	4.38 ± 0.52	1.75 ± 0.02	5.55 ± 0.17	10.43 ± 0.11
No	1.0	0.46	4.44 ± 0.38	56.8 ± 0.38	62.2 ± 0.40	1.15 ± 0.09	1.40 ± 0.10
Yes	1.0	0	9.04 ± 0.38	14.9 ± 3.1	8.66 ± 1.74	4.07 ± 0.23	5.73 ± 1.06
Yes	1.0	0.41	9.90 ± 0.48	60.8 ± 3.0	67.6 ± 5.5	1.23 ± 0.13	1.41 ± 0.07

The attenuation upon transmission is the same as the EMI shielding effectiveness. Silica fume (15% by mass of cement) was used in all cases.

Comparison of the last two rows of Table 3 shows that the steel fibers remain highly effective for enhancing shielding when steel rebars are present. The contribution to shielding by the steel rebars is small compared to that by the steel fibers.

The high shielding effectiveness of steel fiber cement paste is attributed to the small diameter and high reflectivity of the steel fibers. The ferromagnetic property of steel also helped enhance the shielding effectiveness. The magnetic property was shown by the attraction of the steel fibers to a magnetic stirrer used in stirring a water-based dispersion of the steel fibers in a separate work.

The shielding effectiveness of a solid piece of 304 stainless steel (4.12-mm-thick) is 77 and 78 dB at 1.0 and 1.5 GHz, respectively, as measured in this work. Thus, steel fiber cement is inferior to (but not greatly inferior to) solid stainless steel of a similar thickness for shielding.

4. Conclusion

An EMI shielding effectiveness of 70 dB at 1.5 GHz has been attained in cement paste that contains 0.72 vol.% 304 stainless steel fibers of diameter 8 μm and length 6 mm. This material exhibits electrical resistivity 16 Ω cm and also contains silica fume and PVA for helping the fiber dispersion. The shielding is primarily by reflection, as shown by the attenuation of only 1.7 dB upon reflection at 1.5 GHz. Even at a steel fiber content of just 0.36 vol.%, the shielding effectiveness is 58 dB at 1.5 GHz and the resistivity is 57 Ω cm. At 1.0 GHz, the shielding effectiveness is lower, reaching 60 dB at 0.72 vol.% fibers. These values of the shielding effectiveness are higher than all values that have been previously reported for cement-based materials, but are lower than the value of 78 dB for a solid piece of 304 stainless steel. The shielding effectiveness is governed by the fiber volume fraction and is essentially not affected by the presence of sand or the presence of steel rebars.

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