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Pergamon
Cement and Concrete Research 34 (2004) 1889–1892
CEMENT AND CONCRETE RESEARCH

Use of fly ash as an admixture for electromagnetic interference shielding

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Received 19 November 2002; accepted 2 February 2004

Abstract

The use of fly ash as an admixture results in enhancement of the electromagnetic interference (EMI) shielding effectiveness from 4 to 8 dB at 1 GHz, whereas the use of silica fume as an admixture results in negligible effect on the shielding effectiveness. The DC electrical resistivity is decreased slightly by silica fume, but is essentially not affected by fly ash. Both fly ash and silica fume cause slight increases in the reflectivity. The effectiveness of fly ash for shielding is attributed to the Fe_2O_3 component (15.4 wt.%) in the fly ash.

Keywords: Electrical properties; Magnetic properties; Silica fume; Fly ash; Shielding

1. Introduction

Electrical utilities in the United States generate 80 million tons of fly ash as a by-product each year, primarily from coal combustion [1]. Fly ash is typically disposed in landfills, but it is preferred to convert fly ash to a construction material [1,2]. The use of fly ash as an admixture or as a cement replacement results in improved resistance to alkali–silica reaction, sulfate attack and corrosion of steel reinforcement, partly due to the refinement of the pore structure, the higher retention of alkalis, the formation of secondary calcium silicate hydrate, and the lower content of free $Ca(OH)_2$ [3–6]. Moreover, it results in increased abrasion resistance [7], decreased carbonation depth [8], reduced heat evolution during curing [9], and enhanced chemical resistance [10,11]. This article provides a new application for fly ash, namely, the use of fly ash as an admixture for enhancing the electromagnetic interference (EMI) shielding.

EMI shielding [12–15] 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 power 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. 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. As electrical connectivity helps shielding [16], the cement matrix is attractive for the development of composite materials for shielding.

Electrically conductive admixtures in the form of discontinuous fibers [17–19] have been previously used in cement for providing EMI shielding. Although the fibers are effective, they are expensive. In contrast to carbon and steel fibers, fly ash is not conductive, but it is inexpensive and contains various oxide components, such as Fe_2O_3, which may enhance shielding by absorption. Furthermore, the particulate nature of fly ash facilitates dispersion, in contrast to the fibers, which tend to cling together. To confirm that iron oxide is a component that enhances shielding, this article includes a study of the effects of Fe_2O_3 and Fe_3O_4 as admixtures on the shielding effectiveness of cement.

Silica fume [20–23] is very fine noncrystalline silica produced by electric arc furnaces as a by-product of the production of metallic silicon or ferrosilicon alloys. It is a powder with particles having diameters 100 times smaller than those of anhydrous Portland cement particles, i.e., mean particle size between 0.1 and 0.2 μm. The SiO_2

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0008-8846/$ – see front matter
doi:10.1016/j.cemconres.2004.02.003

content ranges from 85% to 98%. Both silica fume and fly ash are pozzolanic. For the sake of comparison, this article includes a study of the effect of silica fume on the shielding effectiveness of cement.

Because the electrical resistivity is a basic quantity that describes the electrical conduction behavior, this article includes measurement of the DC electrical resistivity.

2. Experimental methods

The cement used was Portland cement (Type I). The ratio of water to the total cementitious material (i.e., cement + fly ash + silica fume) was 0.35. 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 1.00% by mass of cement for all specimens. No aggregate was used, whether fine or coarse.

The fly ash (Class F) has the composition shown in Table 1. It is supplied by the Hatfield Power Station of Niagara Mohawk Energy (Syracuse, NY). The particle size ranged from 3 to 300 μm, such that 60.7 wt.% of the particles were < 38 μm in size. It was used in five proportions by weight relative to cement, namely, 0:100, 15:85, 50:50, 85:15, and 100:0. However, proportions of 85:15 and 100:0 are not suitable for practical application, due to inadequate amount of cementitious material.

Silica fume (Elkem Materials, Pittsburgh, PA, microsilica EMS 965) was used for the sake of comparison in three proportions by weight relative to cement, namely, 0:100, 50:50, and 100:0. The silica fume had particle size ranging from 0.03 to 0.5 μm, with an average size of 0.2 μm. Its composition is shown in Table 2. Comparison of Tables 1 and 2 shows that silica fume contains much more SiO_2 and much less Fe_2O_3 than fly ash.

Two types of iron oxide powder (less than 40 μm in particle size, i.e., comparable to the particle size of the fly ash) were used, namely, Fe_3O_4 (black) and Fe_2O_3 (red). Fe_3O_4 is magnetite, which is strongly ferrimagnetic. Either type of oxide was used in the proportion by weight of 50:50 relative to cement.

A rotary mixer with a flat beater was used for mixing. Cement (if applicable), water, and either fly ash or silica fume (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.

Table 1
Composition of fly ash with Si/Al atom ratio = 1.92

	Wt.%
SiO_2	50.7
Al_2O_3	22.4
Fe_2O_3	15.4
SO_3	0.9
K_2O	0.3
CaO	3.8
Loss on ignition	3.0

Table 2
Composition of silica fume

	Wt.%
SiO_2	93 (minimum)
Al_2O_3	0.7 (maximum)
CaO	0.7 (maximum)
MgO	0.7 (maximum)
Fe_2O_3	0.5 (maximum)
Na_2O	0.4 (maximum)
K_2O	0.9 (maximum)
Loss on ignition	6 (maximum)

The attenuations upon reflection and transmission were measured using the coaxial cable method (the transmission line method). 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 [24]. An HP APB-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 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. Silver paint was applied at both inner and outer edges of each specimen and at the vicinity of the edges to make electrical contact with the inner and outer conductors of the tester [24]. The sample thickness was measured for each specimen, but it was around 4.3 mm.

The DC volume electrical 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 (150 × 12 × 11 mm). The four planes were symmetrical around the midpoint along the length of the specimen, such that the outer contacts (for passing current) were 70 mm apart and the inner contacts (for measuring the voltage in relation to resistivity determination) were 50 mm apart.

Three specimens of each type were tested for the shielding effectiveness. Four specimens of each type were tested for the electrical resistivity.

3. Results and discussion

Table 3 shows that the EMI shielding effectiveness (i.e., attenuation upon transmission) is increased monotonically by increasing the fly ash proportion, while the attenuation upon reflection is decreased slightly and monotonically, whether the frequency is 1.0 or 1.5 GHz. This means that the fly ash enhances the shielding through enhancing the reflectivity. On the other hand, silica fume improves the shielding effectiveness only marginally at either frequency,

Table 3
EMI shielding effectiveness (same as attenuation upon transmission), attenuation upon reflection and DC volume electrical resistivity of cement pastes containing various proportions of fly ash or silica fume

Admixture	Proportion by weight		Specimen thickness (mm)	Attenuation upon transmission (dB)		Attenuation upon reflection (dB)		Resistivity (10^5 Ω cm)
	Admixture	Cement		1.0 GHz	1.5 GHz	1.0 GHz	1.5 GHz	
Fly ash	0	100	4.36 ± 0.37	4.00 ± 0.05	2.42 ± 0.07	4.95 ± 0.11	7.96 ± 0.30	8.2 ± 0.6
	15	85	4.30 ± 0.36	5.02 ± 0.06	4.21 ± 0.03	4.54 ± 0.10	7.45 ± 0.22	8.2 ± 0.6
	50	50	4.35 ± 0.26	6.10 ± 0.06	5.06 ± 0.06	4.36 ± 0.09	7.06 ± 0.36	8.1 ± 0.6
	85	15	4.33 ± 0.39	7.23 ± 0.08	6.21 ± 0.05	4.23 ± 0.08	6.98 ± 0.31	8.0 ± 0.6
	100	0	4.35 ± 0.30	8.01 ± 0.03	7.14 ± 0.06	4.16 ± 0.12	6.90 ± 0.33	7.6 ± 0.6
Silica fume	0	100	4.36 ± 0.37	4.00 ± 0.05	2.42 ± 0.07	4.95 ± 0.11	7.96 ± 0.30	8.2 ± 0.6
	50	50	4.24 ± 0.16	4.06 ± 0.07	3.56 ± 0.06	3.93 ± 0.12	7.36 ± 0.17	6.2 ± 0.3
	100	0	4.22 ± 0.25	4.13 ± 0.37	3.67 ± 0.09	3.90 ± 0.11	7.20 ± 0.26	5.9 ± 0.5
Fe_2O_3	50	50	4.27 ± 0.03	12.50 ± 0.18	11.41 ± 0.20	4.01 ± 0.07	4.15 ± 0.08	6.0 ± 0.5
Fe_3O_4	50	50	4.21 ± 0.10	7.50 ± 0.11	7.21 ± 0.20	4.13 ± 0.10	4.20 ± 0.15	6.1 ± 0.4

while it increases the reflectivity slightly (i.e., decreasing slightly the attenuation upon reflection). Hence, fly ash is considerably more effective than silica fume in enhancing shielding.

Table 3 shows that the DC resistivity is negligibly decreased by the use of fly ash, but is slightly decreased by the use of silica fume. Although silica fume decreases the resistivity of cement more than fly ash, it is less effective than fly ash for shielding. The lower resistivity in the case of silica fume is probably due to the much smaller particle size of the silica fume and the consequent large area of the interface between silica fume and cement. The pozzolanic nature of silica fume or fly ash is believed to make this interface contribute to conductivity.

The above results on shielding and resistivity suggest that the shielding provided by the use of fly ash is not only due to reflection, but is also due to absorption, which is attributed to some of the oxide components (particularly Fe_2O_3) in the fly ash. That Fe_2O_3 indeed enhances shielding is indicated by the increase of the shielding effectiveness from 6.1 to 12.5 dB (1.0 GHz) when the fly ash is replaced by Fe_2O_3 particles in the same proportion (admixture/cement ratio of 1.0), as shown in Table 3.

Although Fe_3O_4 is more magnetic than Fe_2O_3, it is less effective for shielding than Fe_2O_3. This suggests that the shielding in Fe_2O_3 is not just due to magnetic dipoles. Electric dipoles may contribute. Both Fe_2O_3 and Fe_3O_4 are more effective than fly ash for shielding. The resistivity is slightly lowered and the reflectivity is enhanced by replacing fly ash by either type of iron oxide, suggesting the role of a nonmagnetic mechanism in the shielding enhancement.

Although iron oxide, particularly Fe_2O_3, is effective for shielding, it is not effective as a cement replacement, as shown by the relatively poor mechanical integrity of the specimens that contain iron oxide (as indicated by visual inspection). Therefore, fly ash is the recommended admixture for shielding enhancement.

An increase in frequency from 1.0 to 1.5 GHz decreases the shielding effectiveness slightly and decreases the reflectivity significantly, whether the cement replacement is fly ash, silica fume, Fe_2O_3, or Fe_3O_4. The effect of frequency on the shielding effectiveness is lessened by the presence of any of these admixtures. These trends are consistent with the contribution of both absorption and reflection to the shielding.

The effectiveness of fly ash for shielding is low compared to that of conductive admixtures, such as 0.1-μm-diameter carbon filaments [18] and 15-μm-diameter carbon fibers [19]. Nevertheless, fly ash is much lower in cost than the conductive admixtures.

4. Conclusion

The use of fly ash as an admixture results in increase of the effectiveness of the cement paste for EMI shielding, due to enhancement of the absorption and reflection of the radiation, as tested at 1.0 and 1.5 GHz. The Fe_2O_3 in the fly ash (15.4 wt.%, compared to <0.5 wt.% in silica fume) contributes to the shielding. In contrast, silica fume has little effect on the shielding effectiveness, although it decreases the resistivity slightly.

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