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Improving the dispersion of steel fibers in cement mortar by the addition of silane

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Abstract

The dispersion of steel fibers in steel-fiber-reinforced mortar was improved by the use of silane as an admixture, as indicated by electrical resistivity measurement conducted at a low fiber volume fraction below the percolation threshold. The use of silane to coat the steel fibers rather than as an admixture was less effective.

Keywords: Fiber reinforcement; Electrical properties; Silica fume; Mortar; Dispersion

1. Introduction

Short steel fibers [1–15] are used as an admixture in concrete for improving the mechanical properties, particularly the flexural toughness, and for decreasing the drying shrinkage. The effectiveness of the fiber addition depends on the degree of fiber dispersion. However, assessment of the degree of fiber dispersion is difficult because (i) the use of microscopy to assess the degree of fiber dispersion is tedious and difficult, and (ii) mechanical properties, being sensitive to the void content and fiber–matrix bonding, as well as the degree of dispersion, do not provide a good indication of the degree of fiber dispersion. In case of steel fibers (which are about 10 orders of magnitude more conductive electrically than the cement matrix) at a volume fraction below the percolation threshold, the electrical conductivity of the composite is highly dependent on the degree of fiber dispersion. The greater is the degree of fiber dispersion, the higher is the conductivity of the composite. This is because of the relatively long length of conduction path within the matrix in case of poor fiber dispersion, as illustrated in Fig. 1. Hence, the electrical conductivity provides a relative indication of the degree of fiber dispersion when the fiber volume fraction is below the percolation threshold.

Silica fume, a fine particulate, is an admixture that can be used to improve the degree of fiber dispersion [14,16] and to improve the bond between fibers and cement matrix [17]. Polymers are admixtures that can be used to improve the bond between fiber and cement matrix [16–19]. In this paper, we report that silane (molecular, but not a polymer) is an effective admixture for improving the degree of dispersion of steel fibers. Silane has been previously shown to be an effective admixture for increasing the specific heat and the thermal conductivity [20], but it has not been previously investigated for use as an admixture to improve the dispersion of fibers in cement-based materials.

The use of silane as an admixture is to be distinguished from the use of silane to coat the surface of solid admixtures such as silica fume [21–25]. Surface treatment of an admixture using silane is intended to enhance the hydrophilicity of the admixture. For the sake of comparison, this paper also addresses the use of silane-treated steel fibers.

2. Experimental methods

The steel fibers were made of stainless steel No. 434, as obtained from International Steel Wool (Springfield, OH). The fibers were cut into pieces of length 5 mm prior to use in the amount of 0.5% by weight of cement (0.05 vol.% of

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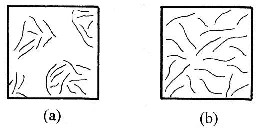

Fig. 1. Fiber dispersion below the percolation threshold. (a) Poor dispersion. (b) Good dispersion.

mortar, much below the percolation threshold). The properties of the steel fibers are shown in Table 1. The mechanical properties of mortars containing these fibers are described in Ref. [4].

The cement used was portland cement (Type I) from Lafarge (Southfield, MI). The sand used was natural sand (100% passing 2.36-mm sieve, 99.9% SiO_2). The sand/cement ratio was 1.0. The water/cement ratio was 0.35. Silica fume (Elkem Materials, Pittsburgh, PA, EMS 965) was used in the amount of 15% by weight of cement. A water-reducing agent (WR) was used in the amount of 2.0% by weight of cement. The WR was TAMOL SN (Rohm and Haas, Philadelphia, PA), which contained 93–96% sodium salt of a condensed naphthalene sulfonic acid. No coarse aggregate was used.

The silane used as an admixture was aqueous amino vinyl silane (Hydrosil 2781, Sivento, Piscataway, NJ), chosen due to its stability in aqueous systems. In contrast, the silane used for coating silica fume [19–23] is not sufficiently stable in aqueous systems. Silane was used in the amount 0.75% by weight of cement. The surfactant, used in the amount of 0.4% by weight of cement to help distribute the silane, was polyoxyethylene lauryl ether, $C_{12}H_{25}(OCH_2CH_2)_nOH$, with $n \cong 4$ from Aldrich, Milwaukee, WI. The defoamer (Colloids, Marietta, GA, 1010) was used in the amount of 0.2% by weight of cement.

The silane used to treat steel fibers was a silane coupling agent, namely a 1:1 (by weight) mixture of Z-6020 ($H_2NCH_2CH_2NHCH_2CH_2CH_2Si(OCH)_3)_3$) and Z-6040 ($OCH_2CHCH_2OCH_2CH_2CH_2Si(OCH)_3)_3$) from Dow Corning (Midland, MI). Both silanes can react with active groups (like –OH) on the surface of fibers and silica fume and form chemical bonds. The amine group in Z-6020 can help the epoxy end of the Z-6040 molecule react with the surface of fiber or silica fume. The other end of the silane molecule reacts with cement during cement curing. In addition, the amine group in Z-6020 serves as the catalyst for the curing of epoxy and consequently allows the Z-6020 molecule to attach to the epoxy end of the Z-6040 molecule. The trimethylsiloxy ends of the Z-6020 and Z-6040 molecules then connect to the –OH functional group on the surface of silica fume or carbon fibers. The silane was dissolved in ethyl acetate. Surface treatment was performed by immersing in the silane solution, heating to 75°C while stirring, and holding at 75°C for 1 h, followed by filtration, washing with ethyl acetate, and drying. After this, heating was conducted in a furnace at 110°C for 12 h.

A rotary mixer with a flat beater was used for mixing. The cement, silica fume, sand, steel fibers and water reducing agent were mixed at a low speed. A defoamer–water mixture (if applicable) and a silane–surfactant–water mixture (if applicable) were successively added to the cement mix mentioned above and mixed for 10 min at a high speed. After pouring into molds, an external vibrator was used to facilitate compaction and decrease the amount of air bubbles. The samples were demolded after 24 h and then cured in air at room temperature and a relative humidity of 100% for 28 days.

DC volume electrical resistivity was measured on rectangular samples of size 70 × 10 × 10 mm, 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 midpoint along the length of the specimen, such that the outer contacts (for passing current) were 60 mm apart and the inner contacts (for measuring the voltage in relation to resistivity determination) were 50 mm apart. Eight samples of each composition were tested.

3. Results and discussion

The electrical resistivities of mortars are shown in Table 2. The addition of silane had negligible effect on the resistivity of mortar, as shown by comparing the first two entries in Table 2. The addition of steel fibers decreased the resistivity, such that the fractional decrease was largest when silane was used as an admixture along with the fibers, as shown by comparing the last three entries in Table 2. This effect of the silane admixture is attributed to the improved dispersion of the steel fibers. The use of silane as a coating

Table 1
Properties of steel fibers

Nominal diameter	60 μm
Tensile strength	970 MPa
Tensile modulus	200 GPa
Elongation at break	3.2%
Volume electrical resistivity	6×10^{-5} Ω cm
Specific gravity	7.7 g cm^{-3}

Table 2
Electrical resistivity of mortars

Admixtures	Resistivity (10^6 Ω cm)	Fractional decrease in resistivity due to fibers
None	4.25 (±4.1%)	–
Silane	4.17 (±5.1%)	–
Steel fibers	2.03 (±5.3%)	48–57%
Steel fibers + silane	1.65 (±3.9%)	57–64%
Silane-treated steel fibers	1.87 (±4.8%)	52–60%

on steel fibers (last entry in Table 2) gave less effect than the use of silane as an admixture. The effect of silane is believed to be due to the hydrophilic nature of silane.

Although mechanical testing results are not shown in this paper, we have performed compressive testing (using cubic specimens) and tensile testing (using dog-bone-shaped specimens) on the steel fiber mortars in the last three entries of Table 2 and found that the compressive strength, modulus and ductility, and the tensile strength, modulus and ductility are all close for the three types of mortars. The compressive and tensile ductilities are slightly lower for the steel-fiber-reinforced mortar with silane as an admixture than for the silane-treated steel-fiber-reinforced mortar. This difference is consistent with the reported effect of silane as an admixture on silica fume cement paste without fibers [26].

4. Conclusion

The use of silane as an admixture in steel-fiber-reinforced mortar was found to improve the dispersion of the steel fibers, as shown by a decrease in the electrical resistivity for the case of the fibers being below the percolation threshold. The use of silane as a coating on the steel fibers rather than as an admixture was less effective.

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