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Communication

Effect of carbon fibers on the vibration-reduction ability of cement

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Abstract

The addition of short carbon fibers (0.5% by weight of cement) to cement paste containing silica fume (15% by weight of cement) and methylcellulose (0.4% by weight of cement) causes the loss tangent under flexure at a loading frequency of ⩽1 Hz to decrease by up to 25% and the storage modulus (⩽2 Hz) to increase by up to 67%, such that both effects increase in the order: as-received fibers, ozone-treated fibers, dichromate-treated fibers, and silane-treated fibers. The addition of methylcellulose to cement paste containing silica fume causes the loss tangent to increase by up to 50% and the storage modulus to decrease by up to 14%. Silane treatment of silica fume has little effect on the loss tangent, but increases the storage modulus by up to 38%.

Keywords: Fiber reinforcement; Cement paste; Mechanical properties; Silica fume; Silane

Admixtures such as silica fume, latex, and methylcellulose are known to improve the vibration-reduction ability of cement paste through increases in both loss tangent (damping capacity) and storage modulus (stiffness), as measured under dynamic flexure [1]. The addition of sand is known to degrade the vibration-reduction ability of cement paste through decreases in both loss tangent and storage modulus [2]. The positive effect of silica fume on the loss tangent is due to the small particle size of silica fume and the resulting large area of the interface between silica fume and cement. The positive effect of latex and methylcellulose on the loss tangent is due to the viscoelastic damping by these polymers. The negative effect of sand on the loss tangent is due to the large particle size of sand (compared to that of silica fume) and the greater degree of compositional homogeneity within a sand particle than that within cement paste; in other words, the volume occupied by sand is less effective for damping than the volume occupied by cement paste.

Short fibers are used as an admixture to decrease the drying shrinkage and increase the flexural toughness. In the case of carbon fibers, the flexural strength is also enhanced [3–8]. They are usually used along with silica fume, which serves to help the fiber dispersion in the mix [9]. The effect of fiber addition on the vibration-reduction ability has not been previously reported. This paper is focused on this effect for the case of carbon fibers. Included in the study is the effect of fiber surface treatment, which enhances the bond between fiber and cement matrix, thereby increasing the tensile strength, modulus, and ductility of the composite [10,11].

1. Methods

The carbon fibers were isotropic pitch-based, unsized, and of length ∼5 mm, as obtained from Ashland Petroleum Co. (Ashland, Kentucky, USA). The fiber properties are shown in Table 1. As-received and three types of surface-treated fibers were used. The fiber content was 0.5% by weight of cement. The surface treatments involved (a) ozone (O_3), (b) an aqueous solution of potassium dichromate ($K_2Cr_2O_7$, 30 wt%) and sulfuric acid (H_2SO_4, 40 wt%, which enhances the oxidation ability), and (c) silane. The ozone treatment for surface oxidation involved exposure of the fibers to O_3 gas (0.6 vol%, in O_2) at 160°C for 5 min. Prior to O_3 exposure, the fibers had been dried at 160°C in air for 30 min. The potassium dichromate treatment for surface oxidation involved immersion in the dichromate solution and heating to 60°C while stirring for 2 h, followed by filtration and washing with water and then drying at 110°C for 6 h. For the silane treatment, the silane-coupling agent was 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 Corp. (Midland, MI, USA). 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

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Table 1
Properties of carbon fibers

Filament diameter	15 ± 3 μm
Tensile strength	690 MPa
Tensile modulus	48 GPa
Elongation at break	1.4%
Electrical resistivity	$3.0 \times 10^{-3}\ \Omega \cdot$ cm
Specific gravity	1.6 g cm^{-3}
Carbon content	98 wt %

surface of silica fume or carbon fiber. The silane was dissolved in ethylacetate. Surface treatment was performed by immersion in the silane solution, heating to 75°C while stirring, and holding at 75°C for 1 h, followed by filtration, washing with ethylacetate, and drying. After this, heating was conducted in a furnace at 110°C for 12 h.

No aggregate (fine or coarse) was used. The water/cement ratio was 0.35. A water-reducing agent (TAMOL SN, Rohm and Haas Co., Philadelphia, PA, USA; sodium salt of a condensed naphthalenesulphonic acid) was used in the amount of 2% by weight of cement.

The cement used was portland cement (Type I) from Lafarge Corp. (Southfield, MI, USA). The silica fume (Elkem Materials, Inc., Pittsburgh, PA, USA, EMS 965) was used in the amount of 15% by weight of cement. The methylcellulose, used in the amount of 0.4% by weight of cement, was from Dow Chemical Co. (Midland, MI, USA, Methocel A15-LV). The defoamer (Colloids Inc., Marietta, GA, USA, 1010), used whenever methylcellulose was used, was in the amount of 0.13 vol%.

A rotary mixer with a flat beater was used for mixing. Methylcellulose (if applicable) was dissolved in water and then the defoamer was added and stirred by hand for about 2 min. Then this mixture (if applicable), cement, water, water reducing agent, silica fume, and fibers (if applicable) were mixed in the mixer for 10 min. 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.

Table 2
Loss tangent (tan δ, ±0.002) of cement pastes

	With as-received silica fume			With silane-treated silica fume		
Formulation[a]	0.2 Hz	1.0 Hz	2.0 Hz	0.2 Hz	1.0 Hz	2.0 Hz
A	0.082	0.030	$<10^{-4}$	0.087	0.032	$<10^{-4}$
A^+	0.102	0.045	$<10^{-4}$	0.093	0.040	$<10^{-4}$
A^+F	0.089	0.033	$<10^{-4}$	0.084	0.034	$<10^{-4}$
A^+O	0.085	0.043	$<10^{-4}$	0.084	0.032	$<10^{-4}$
A^+K	0.079	0.039	$<10^{-4}$	0.086	0.035	$<10^{-4}$
A^+S	0.076	0.036	$<10^{-4}$	0.083	0.033	$<10^{-4}$

[a] A = cement + water + water reducing agent + silica fume; A^+ = A + methylcellulose + defoamer; A^+F = A^+ + as-received fibers; A^+O = A^+ + O_3-treated fibers; A^+K = A^+ + dichromate-treated fibers; A^+S = A^+ + silane-treated fibers.

Table 3
Storage modulus (GPa, ±0.03) of cement pastes

	With as-received silica fume			With silane-treated silica fume		
Formulation[a]	0.2 Hz	1.0 Hz	2.0 Hz	0.2 Hz	1.0 Hz	2.0 Hz
A	12.71	12.14	11.93	16.75	16.21	15.95
A^+	11.52	10.61	10.27	15.11	14.73	14.24
A^+F	13.26	13.75	13.83	17.44	17.92	18.23
A^+O	14.14	14.46	14.72	18.92	19.36	19.57
A^+K	15.42	16.15	16.53	19.33	19.85	20.23
A^+S	17.24	17.67	15.95	21.34	21.65	21.97

[a] See Table 2 for abbreviations.

Dynamic mechanical testing (ASTM D4065-94) at controlled frequencies (0.2, 1.0, and 2.0 Hz) and room temperatures (20°C) were conducted under flexure using a Perkin-Elmer Corp. (Norwalk, CT, USA) Model DMA 7E dynamic mechanical analyzer. Measurement of tan δ and storage modulus were made simultaneously at various frequencies. The heating rate was 2°C/min, which was selected to prevent any artificial damping peaks that may be caused by higher heating rates. The specimens were in the form of beams (120 × 8 × 3 mm) under three-point bending, such that the span was 115 mm. The loads were all large enough so that the amplitude of the specimen deflection was from 6.5 to 9 μm (over the minimum value of 5 μm required by the equipment for accurate results). The loads were set so that each different type of specimen was always tested at its appropriate stress level. Three specimens of each composition were tested.

Twelve compositions, as listed in Table 2, were studied.

2. Results

Tables 2, 3, and 4 give the dynamic flexural properties of twelve types of cement pastes. Six of the types have as-received silica fume; the other six have silane-treated silica fume.

The loss tangent (Table 2) is increased slightly by the addition of methylcellulose. Further addition of carbon fibers decreases the loss tangent, such that the loss tangent de-

Table 4
Loss modulus (GPa, ±0.03) of cement pastes

	With as-received silica fume			With silane-treated silica fume		
Formulation[a]	0.2 Hz	1.0 Hz	2.0 Hz	0.2 Hz	1.0 Hz	2.0 Hz
A	1.04	0.39	$<10^{-3}$	1.46	0.52	$<10^{-3}$
A^+	1.18	0.48	$<10^{-3}$	1.41	0.59	$<10^{-3}$
A^+F	1.18	0.45	$<10^{-3}$	1.47	0.61	$<10^{-3}$
A^+O	1.20	0.62	$<10^{-3}$	1.59	0.62	$<10^{-3}$
A^+K	1.22	0.63	$<10^{-3}$	1.66	0.70	$<10^{-3}$
A^+S	1.31	0.63	$<10^{-3}$	1.77	0.71	$<10^{-3}$

[a] See Table 2 for abbreviations.

creases in the order: as-received fibers, ozone-treated fibers, dichromate-treated fibers, and silane-treated fibers. These trends apply whether the silica fume is as-received or silane-treated, and whether the loading frequency is 0.2 or 1.0 Hz.

The storage modulus (Table 3) is decreased by the addition of methylcellulose. Further addition of carbon fibers increases the storage modulus, such that the modulus increases in the order: as-received fibers, ozone-treated fibers, dichromate-treated fibers, and silane-treated fibers. These trends apply whether the silica fume is as-received or silane-treated, and whether the frequency is 0.2, 1.0, or 2.0 Hz.

The loss modulus (Table 4, product of loss tangent and storage modulus) is increased by the addition of methylcellulose, except for the case of the paste with silane-treated silica fume at 0.2 Hz. Further addition of carbon fibers increases the loss modulus very slightly, if at all.

3. Discussion

Carbon fibers are effective for increasing the storage modulus, particularly if they are surface treated. However, they decrease the loss tangent, particularly if they are surface treated. The increase in storage modulus is due to the reinforcing ability of the fibers. The decrease in loss tangent is probably similar in origin to the decrease in loss tangent upon the addition of sand [2] [i.e., the fiber diameter (15 μm) is not small enough for the fiber-matrix interface area to be large enough to enhance damping significantly]. The fiber-matrix interface is stronger, as indicated by an increase in storage modulus; the loss tangent is lower. This is due to the decrease in the ability of the fiber-matrix interface to contribute to damping when the interface is stronger. The tensile strength depends on the fiber surface treatment [11] in exactly the same way as the storage modulus (i.e., the higher the strength, the higher the modulus).

For vibration reduction, a high loss tangent and a high storage modulus are desirable. The loss modulus is a figure of merit that combines both virtues. Due to the opposite trends of loss tangent and storage modulus upon fiber addition or methylcellulose addition, the loss modulus is insignificantly changed by fiber or methylcellulose addition. Thus, carbon fiber addition is not effective for enhancing the ability of cement paste containing silica fume to reduce vibrations.

The addition of methylcellulose to cement paste containing silica fume (but no fiber) causes the loss tangent to increase by up to 50% and the storage modulus to decrease by up to 14%, as expected from the viscoelastic nature of methylcellulose and the high stiffness of cement paste with silica fume. In contrast, the addition of methylcellulose to plain cement paste (without silica fume) causes both loss tangent and storage modulus to increase [1].

Comparison of cement pastes with as-received and silane-treated silica fume shows that silane treatment of silica fume has little effect on the loss tangent, but increases the storage modulus by up to 38%. The increase in storage modulus is believed to be due to the strengthening of the interface between silica fume and cement. Consistent with the increase in storage modulus is the increase in tensile strength [11].

4. Conclusion

The addition of carbon fibers (0.5% by weight of cement) to cement paste containing silica fume (15% by weight of cement) and methylcellulose (0.4% by weight of cement) causes the loss tangent under flexure to decrease by up to 25% and the storage modulus to increase by up to 67%, such that both effects depend on the fiber surface treatment and increase in the order: as-received fibers, ozone-treated fibers, dichromate-treated fibers, and silane-treated fibers. The addition of methylcellulose to cement paste containing silica fume (but no fiber) causes the loss tangent to increase by up to 50% and the storage modulus to decrease by up to 14%. Silane treatment of silica fume has little effect on the loss tangent, but increases the storage modulus by up to 38%.

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