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Mechanical Energy Dissipation Using Cement-Based Materials with Admixtures

by Po-Hsiu Chen and D. D. L. Chung

Silica fume and a novel graphite network (8 vol.%) cementitious admixture are effective for enhancing the mechanical energy dissipation of cement-based materials, as shown under small-strain dynamic flexure at 0.2 Hz. The fraction of energy dissipated reaches 0.26, 0.58, and 0.22 for cement paste, mortar, and concrete, respectively, as provided by silane-treated silica fume and the cementitious admixture, which cause steel-reinforced concrete to increase the dissipation, loss modulus, loss tangent, and storage modulus by 16,000%, 450,000%, 16,000%, and 170%, respectively. The highest loss tangent and loss modulus obtained are 0.14 and 3.5 GPa (20.3 and 507.5 ksi), respectively. Silane-treated silica fume alone causes steel-reinforced concrete to increase the dissipation by 9900%; untreated silica fume alone gives an 8000% increase. Without steel or admixtures, the dissipation decreases from cement paste to mortar and concrete. With steel and/or the admixtures, the dissipation increases from paste to mortar and decreases from mortar to concrete. The dissipation decreases with increasing frequency, such that the presence of silica fume reduces the frequency effect.

Keywords: cement; compressive strength; damping; energy dissipation; flexural strength; graphite; mortar; silica fume.

INTRODUCTION

Mechanical energy dissipation involves the elimination of mechanical energy by conversion of the energy to another form of energy, which is commonly heat. It is relevant to vibration damping. This is passive damping. In contrast, active damping is expensive because it uses sensors and actuators in a synchronized fashion to suppress vibrations. Vibrations are undesirable for bridges, railroads, pipes, and buildings and are often associated with noise, which is also undesirable.

For passive damping effectiveness, materials that provide the conversion of mechanical energy to heat are necessary. These materials, known as damping materials, are to be distinguished from mechanical isolation materials, which are for isolating two objects so that the vibrations of one object are deterred from propagating to the other object. An example is the isolation of a building foundation from the ground below it, as it is attractive for earthquake protection. A mechanical isolation material acts like a cushion that spreads the mechanical energy to a limited extent. Thus, mechanical isolation materials are relatively soft; an example is rubber. However, due to the softness, the mechanical energy absorption is low, thus making the material ineffective for damping. This paper concerns damping materials.

The performance of a damping material is described by: 1) the loss modulus, which is the imaginary part of the complex modulus and relates to the viscous modulus; and 2) the loss tangent (also known as tanδ, where δ is the phase angle between the stress and strain waves), which describes the degree of viscous character. The behavior is purely elastic (no energy dissipation) when $\delta = 0$ degrees. The behavior is purely viscous when $\delta = 90$ degrees. The degree of viscous character increases with increasing δ. The storage modulus (the real part of the complex modulus) measures the stored energy, representing the elastic portion; the loss modulus (the imaginary part of the complex modulus and equal to the product of the storage modulus and the loss tangent) measures the energy dissipated as heat, representing the viscous portion. In the small-strain elastic regime such that the dynamic stress/strain is sinusoidal, the loss tangent is equal to twice the damping ratio.

Concrete is inherently inadequate for damping; however, due to its large volume in a concrete structure, an increase of concrete damping can make a big difference to the structure. Concrete is also attractive for its high durability compared to materials such as rubber.

Large-amplitude vibrations that involve plastic deformation are encountered in earthquakes, but small-amplitude vibrations without plastic deformation are encountered during normal structural operation. This paper is concerned with the latter.

Silica fume is 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 a particle size 100 times smaller than that of anhydrous portland cement particles—that is, a mean particle size between 0.1 and 0.2 μm (4×10^{-6} and 8×10^{-6} in.). The SiO_2 content ranges from 85 to 98%. Silica fume is pozzolanic[1] due to the cementitious character resulting from its surface reactivity, which relates to its amorphous structure.

Silica fume used as an admixture in concrete has significant effects[1-4] on the strength, modulus, ductility, vibration damping capacity, sound absorption, abrasion resistance, air void content, shrinkage, bonding strength with reinforcing steel, permeability, chemical attack resistance, alkali-silica reactivity reduction, corrosion resistance of embedded steel reinforcement, freezing-and-thawing resistance, creep rate, coefficient of thermal expansion (CTE), specific heat, thermal conductivity, defect dynamics, dielectric constant, and degree of fiber dispersion in mixtures containing short microfibers. However, silica fume addition degrades the workability.

Damping enhancement of cement paste under flexure was achieved by using silica fume as an admixture; the loss modulus at 0.2 Hz is increased by 1500% for untreated silica fume and by 2100% for silane-treated silica fume.[5-7] Hence, the silane treatment increases the loss modulus by 40% for cement paste. In the case of mortar, the silane treatment

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Po-Hsiu Chen *is a PhD Candidate in mechanical engineering at the University at Buffalo (UB-SUNY), Buffalo, NY.*

D. D. L. Chung *is a Professor of mechanical and aerospace engineering and Director of the Composite Materials Research Laboratory at UB-SUNY. She received her PhD in materials science from the Massachusetts Institute of Technology, Cambridge, MA, in 1977.*

increases the loss modulus by 210% at 0.2 Hz and by 150% at 2.0 Hz.[6] By adding silane-treated silica fume to mortar, the loss modulus is increased by 340% at 0.1 Hz and by 810% at 2.0 Hz.[7] The silanes used in References 5 through 7, which are prior works of the second author, are not the same as those used in References 8 and 9, although References 5 through 9 all involve dynamic flexural testing.

Silica fume enhances the energy dissipation due to an interfacial friction mechanism associated with the interface between silica particles and cement. In contrast, latex[10] enhances the dissipation due to a bulk viscoelastic mechanism associated with each latex particle. Compared to silica fume, latex is expensive.

A graphite network (8 vol.%) formed in cement from exfoliated graphite was shown to be effective for increasing the loss tangent to the level of rubber.[11] The network formation is enabled by the mechanical interlocking between pieces of exfoliated graphite, each of which is obtained by the exfoliation of an intercalated graphite flake and is known as a worm (due to its morphology). The high value of the loss tangent is due to the interfacial friction at the interfaces between the multiple graphite layers that make up a wall of the cellular structure of exfoliated graphite. This damping mechanism is hereby referred to as a nanoscale multi-layer mechanism. In contrast, silica fume—whether silane-treated or not—enhances the loss tangent by a much lower degree, although it significantly increases the storage modulus.[5-7] Because the graphite network mainly serves to enhance the loss tangent, while silica fume mainly serves to enhance the storage modulus, their synergistic use is promising and its investigation is thus the primary objective of this work.

Prior work[11] involving the graphite network cementitious admixture addresses the cement-matrix composite containing the graphite network, such that the admixture is a single monolith (a bulk material). However, it is more versatile and convenient to use this material as an admixture. This admixture is capable of cementitious bonding because it is mostly cement and is incorporated in the mixture when the degree of hydration of the cement in the admixture is low. The cementitious nature is attractive for achieving a good bond between the admixture and the cement matrix outside the admixture. The second objective is to investigate the effectiveness of this admixture as an admixture rather than a monolith.

The fraction of input mechanical energy dissipated per unit volume is a quantity that is practically meaningful. Prior work using silica fume in cement,[5-9] polymers in cement,[10,12] steel in cement,[13] and a graphite network in cement[11] reports the loss modulus, storage modulus, and loss tangent without evaluating this fraction. (The loss modulus values in Reference 12 are incorrectly calculated; the correct values are obtained by multiplying the reported values by 0.01.) Prior work on the use of carbon nanotube in cement[14] reports the damping ratio without evaluating the fraction of energy dissipated. Thus, the third objective is to provide an evaluation of the fraction of energy dissipated.

Prior work involving the graphite network[11] is limited to cement paste without aggregates or steel reinforcing bar. The fourth objective is to study the effects of aggregates and steel on the energy dissipation—that is, the effects of the admixtures in the presence of aggregates and steel.

Prior work[1,5,6] has shown that silica fume, particularly after silane treatment, is effective for improving the static mechanical properties of cement-based materials. The fifth objective is to evaluate the effect of the combined use of silica fume and the graphite network on the static mechanical properties, specifically the flexural and compressive strengths.

RESEARCH SIGNIFICANCE

This work investigates the mechanical energy dissipation ability of cement-based materials under small-strain low-frequency dynamic flexure, as indicated by the loss modulus. It addresses the synergistic effects of silica fume (including its silane treatment) and a novel graphite network cementitious admixture on the dissipation ability and the static mechanical properties. It provides a comparative evaluation of cement-based materials with and without admixtures, with and without aggregates, and with and without steel reinforcing bars. Cement-based materials that exhibit up to 60% flexural energy dissipation are provided. Guidelines are provided for the design of materials for both energy dissipation and static performance.

EXPERIMENTAL METHODS

Materials

Portland cement (Type I, ASTM C150) was used. Silica fume (if used) was at 15% by mass of cement, as in prior work[1]; it had a particle size ranging from 0.03 to 0.5 μm (1×10^{-6} to 2×10^{-5} in.) with an average size of 0.2 μm (8×10^{-6} in.); it contained >93 wt.% SiO_2, <0.7 wt.% Al_2O_3, <0.7 wt.% CaO, <0.7 wt.% MgO, <0.5 wt.% Fe_2O_3, <0.4 wt.% Na_2O, <0.9 wt.% K_2O, and <6 wt.% loss on ignition.

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 ($OCH_2CHCH_2OCH_2CH_2CH_2Si(OCH_3)_3$).[5,6] The amine group in Z-6020 served as a catalyst for the curing of the epoxy and consequently allowed 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 connected to the –OH functional group on the surface of the silica fume. The silane was dissolved in ethylacetate. The concentration of silane in the ethylacetate solution was varied from 0.5% to 5.0 wt.%. Surface treatment of the silica fume was performed by immersion in the silane solution, heating to 75°C (167°F) while stirring, and then holding at 75°C (167°F) for 1.0 hours, followed by filtration and drying. After this, the silica fume was heated at 110°C (230°F) for 12 hours.

The fine aggregate was natural sand with a particle size of 0.1 to 2.36 mm (4×10^{-3} to 9×10^{-2} in.) with a typical size of approximately 0.3 mm (1×10^{-2} in.). The sand-cement ratio was 1.00. The water-cement ratio (*w/c*) was 0.35 for cement pastes without silica fume, 0.40 for cement pastes with silica fume, and 0.45 for mortars and concretes. A high-range water-reducing agent was used at 1.0% by mass of cement. The defoamer was used at 0.13% (percent of specimen volume).

The coarse aggregate had an average size of 3 and 1.5 mm (0.11 and 0.06 in.) for static and dynamic testing, respectively. The coarse aggregates were smaller than those conventionally used for concrete due to the small specimen size. The mass ratio of cement:sand:coarse aggregate was 1:1.5:2.5. Therefore, the cement-matrix composites containing sand and coarse aggregate were, strictly speaking, not concrete. Nevertheless, the term "concrete" is used.

Exfoliated graphite (worms) is obtained by rapid heating of expandable graphite flake (graphite flake intercalated with sulfuric acid and nitric acid in the presence of catalysts with a flake size of 300 μm [0.012 in.]) at 900°C (1650°F) for 2 minutes with flowing nitrogen. During exfoliation, each flake expands by hundreds of times along the direction perpendicular to the plane of the flake, resulting in a shape (like a worm) that is long along the direction of exfoliation. The worms had a length of 2 to 4 mm (0.08 to 0.16 in.). During exfoliation, the vast majority of the intercalate desorbed so that the intercalate that remains after exfoliation is low in concentration and is strongly held to the graphite.[15,16] For fabricating the graphite network cementitious admixture, the particle size of the cement is reduced by ball milling for 24 hours using ceramic cylinders as the grinding medium contained in a ceramic container. The milling reduces the typical cement particle size from 50 to 30 μm (2.0×10^{-3} to 1.2×10^{-3} in.).

For fabricating the graphite network cementitious admixture, the exfoliated graphite is mixed with the milled cement particles in the dry state for 24 hours using a ball mill without any grinding medium. The weights of the exfoliated graphite and cement in the mixture are controlled. The compression of the mixture is conducted in the dry state in a cylindrical mold with a length of 450 mm (18 in.) and an inner diameter of 31.8 mm (1.25 in.) by applying a uniaxial pressure of 5.6 MPa (810 psi [1000 lb]) via a matching piston. The entire thickness of a composite specimen is obtained in one 5.6 MPa (810 psi) compression stroke. Each resulting specimen is a disc with a diameter of 31.8 mm (1.25 in.) and a thickness ranging from 2.0 to 3.0 mm (0.08 to 0.12 in.).

After this, the disc is exposed to water for curing the cement. This involves exposure to moisture for 2 days, followed by immersion in water for 26 days. After 7 days of water immersion (when the sheet is not hard yet), the disc is removed from the water and cut by using a knife along four diameters (45 degrees apart) to make eight 45-degree pie-shaped pieces. After the cutting, the pieces are immersed in water for 1 day and are immediately used at this curing age as an admixture. Thus, the longest in-plane dimension of each piece is 16 mm (0.63 in.).

The graphite network cementitious admixture amounts to 62 vol.% of the cement-matrix composite (excluding the steel volume). Within the admixture, the graphite network amounts to 8 vol.% and the cement matrix amounts to 92 vol.%.[9]

All ingredients except the graphite network admixture (if applicable) are mixed in a rotary mixer with a flat beater. In the case of specimens for dynamic mechanical testing under flexure, the pouring of the mixture into a 150 x 25 x 4 mm (6.0 x 1.0 x 0.16 in.) steel mold to form a beam-shaped flexural specimen is conducted in two steps, such that the amount of the mixture is the same in each step and the graphite network admixture plates are placed manually between the two pours, with the admixture plane preferentially in the plane of the beam. In the case that the flexural specimen for dynamic testing contains steel reinforcing bars, two reinforcing bars with a diameter of 3 mm (0.12 in.) are placed in the 150 x 25 x 4 mm (6.0 x 1.0 x 0.16 in.) steel mold prior to pouring the cement mixture into the mold.

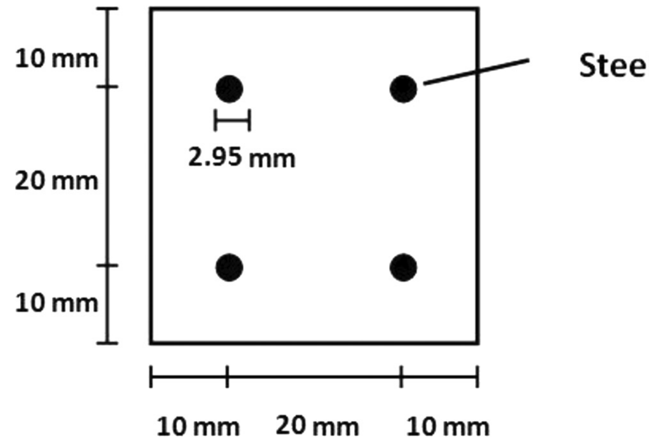

Fig. 1—Schematic illustration of 40 x 40 mm (1.6 x 1.6 in.) cross section of specimen containing steel for flexural testing up to failure. Specimen is 160 x 40 x 40 mm (6.3 x 1.6 x 1.6 in.), perpendicular to plane of drawing. Steel is shown by black areas. (Note: 1 mm = 0.0394 in.)

The cement covering the reinforcing bar in the plane of the beam is much smaller than the conventional thickness of one reinforcing bar diameter due to the size limitation of the testing equipment. Nevertheless, the comparative study of specimens with and without reinforcing bars provides useful information on the possible effect of reinforcing bars on the effectiveness of the admixtures.

In the case of specimens for static mechanical testing under flexure or compression, all ingredients except the graphite network cementitious admixture (if applicable) are mixed in a rotary mixer with a flat beater. Then, the graphite network cementitious admixture (if applicable) is added and mixing is conducted manually. The specimens have dimensions of 160 x 40 x 40 mm (6.3 x 1.6 x 1.6 in.) and 51 x 51 x 51 mm (2 x 2 x 2 in.) for flexural and compressive testing, respectively, as provided by using steel molds. Due to gravity, there is a degree of preferred orientation of the graphite network cementitious admixture plates in the horizontal plane during curing—that is, the plane of the flexural beam and the plane parallel to the stress in compressive testing. In the case of static flexural specimens containing steel, four parallel steel reinforcing bars with a diameter of 3 mm (0.12 in.) are positioned symmetrically in the mold along its length prior to pouring (Fig. 1). The compressive specimens do not contain steel.

For all specimens, after filling the mold, an external vibrator is used to facilitate compaction and diminish the air bubbles. The specimens are demolded after 24 hours and then cured at a relative humidity of nearly 100% for 28 days.

Testing

Dynamic testing (per ASTM D4065-94) at a controlled low frequency (0.2 to 2.0 Hz, below any resonance frequency) was conducted at room temperature (20°C [68°F]) using a dynamic mechanical analyzer in the form of a forced resonance analyzer under stress control in the small-strain regime. A sinusoidal force (stress) was applied and the displacement (strain) was measured, thus allowing the measurement of the phase angle δ. A low frequency was chosen due to the decrease in value and increase in inaccuracy of the loss tangent (tanδ) with increasing frequency. Based on prior related work, increasing the frequency to 2 Hz does not

Table 1—Dynamic flexural properties of cement-based materials at 0.2 Hz showing effects of silica fume and its silane treatment (dissipation refers to fraction of energy dissipated)

Property		No silica fume			Untreated silica fume			Silane-treated silica fume		
		Paste	Mortar	Concrete	Paste	Mortar	Concrete	Paste	Mortar	Concrete
Without steel	Storage modulus, GPa (ksi)	1.81 ± 0.12 (262 ± 17)	9.01 ± 0.31 (1310 ± 40)	10.83 ± 0.48 (1570 ± 70)	4.18 ± 0.20 (606 ± 29)	19.23 ± 0.84 (2788 ± 121)	27.82 ± 0.87 (4034 ± 126)	7.13 ± 0.54 (1030 ± 80)	28.91 ± 2.22 (4192 ± 322)	31.02 ± 1.12 (4498 ± 162)
	Loss tangent	0.030 ± 0.009	0.00041 ± 0.00009	0.00023 ± 0.00005	0.055 ± 0.011	0.026 ± 0.003	0.016 ± 0.003	0.061 ± 0.008	0.046 ± 0.008	0.021 ± 0.005
	Loss modulus, GPa (ksi)	0.054 ± 0.001 (7.8 ± 0.1)	0.00359 ± 0.00003 (0.521 ± 0.004)	0.00025 ± 0.00003 (0.036 ± 0.04)	0.230 ± 0.002 (33.4 ± 0.3)	0.499 ± 0.002 (72.3 ± 0.3)	0.440 ± 0.004 (63.8 ± 0.58)	0.435 ± 0.004 (63.1 ± 0.58)	1.331 ± 0.018 (193 ± 3)	0.653 ± 0.007 (94.7 ± 1.0)
	Dissipation	0.032 ± 0.006	0.0028 ± 0.0002	0.0013 ± 0.0003	0.104 ± 0.011	0.242 ± 0.029	0.124 ± 0.007	0.256 ± 0.042	0.461 ± 0.083	0.148 ± 0.010
With steel	Storage modulus, GPa (ksi)	1.61 ± 0.09 (233 ± 13)	8.01 ± 0.34 (1161 ± 49)	10.36 ± 0.48 (1502 ± 70)	4.59 ± 0.27 (666 ± 39)	18.81 ± 1.01 (2727 ± 146)	24.94 ± 0.71 (3616 ± 103)	6.33 ± 0.17 (917 ± 25)	23.81 ± 0.95 (3452 ± 137)	29.83 ± 0.51 (4325 ± 74)
	Loss tangent	0.028 ± 0.013	0.00065 ± 0.00011	0.00024 ± 0.00006	0.061 ± 0.018	0.041 ± 0.012	0.014 ± 0.004	0.068 ± 0.012	0.046 ± 0.013	0.019 ± 0.007
	Loss modulus, GPa (ksi)	0.045 ± 0.001 (6.5 ± 0.1)	0.00519 ± 0.00003 (0.753 ± 0.004)	0.00024 ± 0.00004 (0.035 ± 0.005)	0.275 ± 0.005 (39.8 ± 0.7)	0.771 ± 0.007 (112 ± 1)	0.351 ± 0.005 (50.9 ± 0.7)	0.430 ± 0.002 (62.3 ± 0.3)	1.088 ± 0.012 (157.8 ± 1.7)	0.568 ± 0.009 (82.3 ± 1.3)
	Dissipation	0.033 ± 0.008	0.0071 ± 0.0004	0.0014 ± 0.0004	0.123 ± 0.077	0.291 ± 0.006	0.112 ± 0.006	0.163 ± 0.072	0.321 ± 0.005	0.141 ± 0.011

affect the relative performance of the various cement-based materials.[10] This method of damping testing is as used in prior related work.[5-13] Consistency between results obtained by the Forced Resonance Method and the Free Resonance Method has been previously shown.[17]

The dynamic flexure (three-point bending) specimens are simply supported beams with dimensions of 150 x 25 x 4 mm (5.91 x 0.98 x 0.16 in.) with spans of 115 mm (4.53 in.). The loads are large enough for the deflection amplitude to range from 5 to 10 μm (2×10^{-4} to 4×10^{-4} in.) (greater than the minimum value of 5 μm [2×10^{-4} in.] that the equipment requires for accurate results). The static strain ranges from 0.03 to 0.10%; the dynamic strain—that is, the amplitude of the variation of the strain around the static strain—ranges from 0.04 to 0.07%. The static stress ranges from 0.14 to 0.31 MPa (20 to 45 psi) and the dynamic stress ranges from 0.11 to 0.21 MPa (16 to 30 psi), such that both stresses increase from cement paste to mortar and concrete. All the strains are in the regime of elastic deformation, with no damage inflicted, as confirmed by the reproducibility of the results upon repeated testing of the same specimen. Six specimens of each type were tested.

For a sinusoidal stress wave in the small-strain regime, the energy loss per unit volume E is[18]

$$E = \pi\gamma^2 G'' \quad (1)$$

where γ is the dynamic flexural strain amplitude, and G'' is the loss modulus. The quantity E is the area of the stress-strain hysteresis loop centered at the static stress-strain point. The energy input per unit volume corresponds to the area under the loading (upper) part of the loop. The fraction of energy dissipated is the energy loss per unit volume divided by the energy input per unit volume.

For static flexural testing up to failure, the midspan deflection rate is 0.5 mm/min (0.02 in./min) and the span is 120 mm (4.7 in.). The specimen is a simply supported beam. A hydraulic material testing system is used. Static compression testing up to failure according to ASTM C109-80 is performed using a hydraulic material testing system. The crosshead speed is 0.5 mm/min (0.02 in./min). Six specimens of each composition were tested.

RESULTS

Effects of silica fume and its silane treatment

Table 1 shows the effect of silica fume addition on the dynamic flexural properties of cement pastes, mortars, and concretes in the absence and presence of steel. The silica fume addition increases the storage modulus—whether the material is cement paste, mortar, or concrete—such that the effect is stronger when the silica fume is silane-treated. This is expected because the silica particles are stiff and serve to reinforce. Moreover, the small particle size of the silica causes refinement of the pore system. The silane treatment helps because it increases the hydrophilicity, thereby improving the spatial distribution of the silica particles.[6]

The storage modulus increases from cement paste to the corresponding mortar and the corresponding concrete, whether silica fume is present or not and whether the silica fume is silane-treated or not. This is expected because the sand and stones serve to reinforce.

The loss tangent, loss modulus, and fraction of energy dissipated are all enhanced by the silica fume addition, such that the effect is stronger when the silica is silane-treated. Without silica fume, these three quantities all decrease from

Table 2—Fractional change in dynamic flexural properties (0.2 Hz) of cement-based materials due to silica fume (dissipation refers to fraction of energy dissipated)

Property		Untreated silica fume (S)			Silane-treated silica fume (S′)		
		Paste	Mortar	Concrete	Paste	Mortar	Concrete
Without steel	Storage modulus, %	130	110	160	290	220	190
	Loss tangent, %	510	6200	6900	80	11,000	9000
	Loss modulus, %	30	14,000	180,000	710	37,000	260,000
	Dissipation, %	230	8500	9100	710	16,000	11,000
With steel	Storage modulus, %	180	130	140	290	200	190
	Loss tangent, %	120	6200	5700	140	7000	7800
	Loss modulus, %	510	15,000	150,000	860	21,000	240,000
	Dissipation, %	270	4000	7800	380	4400	9900

cement paste to the corresponding mortar and corresponding concrete. However, with silica fume (whether silane-treated or not), all three quantities increase from cement paste to the corresponding mortar but decrease from mortar to the corresponding concrete.

Comparison of cement paste and the corresponding mortar shows that the addition of sand decreases the loss modulus in the absence of silica fume (due to the decrease of the loss tangent), but increases the loss modulus in the presence of silica fume (due to the increase of the storage modulus). With silica fume, mortar has a higher loss modulus than the cement paste due to the high storage modulus and the moderately high loss tangent of the mortar.

The addition of sand to cement paste decreases the loss tangent, whether silica fume (silane-treated or not) is present or not. Similarly, the addition of stones to mortar, as shown by comparing mortar and concrete, decreases the loss tangent, whether silica fume (silane-treated or not) is present or not. This effect of silica fume is attributed to the interfacial friction mechanism of energy dissipation that is accentuated by the large area of the interface between the small silica particles and the cement matrix.[1] Comparison of the loss tangent of cement paste and the corresponding mortar shows that the addition of sand to cement paste decreases by orders of magnitude the loss tangent in the absence of silica fume and substantially decreases (not by orders of magnitude) the loss tangent in the presence of silica fume. This effect of sand is due to the homogeneity within each sand particle in contrast to the heterogeneity inside cement paste. The heterogeneity helps enhance the energy loss. The sand particles do not have a sufficiently small size to provide a large enough interface area for increasing the loss tangent. Consistent with this notion is the fact that carbon fiber with a diameter of 15 μm (5.9×10^{-4} in.) as an admixture decreases the loss tangent.[6] In contrast, the small particle size (approximately 0.1 μm [4×10^{-6} in.]) makes the silica fume effective for enhancing damping. The effect of sand addition is less dramatic in the presence of silica fume because the silica fume enhances the loss tangent, thus making the negative effect of sand less significant. For similar reasons, the addition of stones to mortar decreases the loss tangent.

Silane-treated silica fume is more effective than untreated silica fume for increasing the loss tangent because of: 1) the superior spatial distribution of the silica particles in the presence of the silane, which renders the silica hydrophilic[1]; and 2) the silane coating providing a viscous mechanism of energy loss that is in addition to the interfacial friction mechanism provided by the silica particles.

The effects described previously for the effects in the absence of steel also occur in the presence of steel (Table 1). With steel, mortar with silane-treated silica fume again gives the highest loss modulus and the highest fraction of energy dissipated. However, the values are lower than the corresponding values without steel because the storage modulus is slightly decreased by the steel addition. The effect of steel on the loss tangent is negligible because the steel is in the elastic deformation regime and the diameter of the steel reinforcing bar is too small to provide adequate interface area for enhancing the loss tangent.

Although the loss tangent decreases from cement paste to the corresponding mortar and the corresponding concrete (Table 1), the fractional increase in loss tangent due to the silica fume addition increases from cement paste to the corresponding mortar or concrete (Table 2). The fractional changes in loss tangent, loss modulus, and fraction of energy dissipated are much higher for mortar than the corresponding cement paste, but the fractional change in the storage modulus is slightly lower for mortar than the corresponding cement paste. The larger fractional increases in loss tangent, loss modulus, and fraction of energy dissipated for mortar and concrete compared to cement paste are because mortar and concrete exhibit lower loss tangents than cement paste. The fractional increase in the loss modulus due to the silica fume addition increases greatly from cement paste to the corresponding mortar and the corresponding concrete because the loss modulus without silica fume decreases greatly from cement paste to mortar and concrete and the storage modulus increases from paste to mortar and concrete. For concrete, the addition of silane-treated silica fume increases the loss modulus by 260,000%. The effect of silane-treated silica fume on the loss tangent is smaller in the presence of steel (Table 2). Thus, the effect of silane-treated silica fume on the dissipation is smaller in the presence of steel (except that it is comparable in the case of cement paste with untreated silica fume).

Among all the materials in Table 1, mortars with silane-treated silica fume (with and without steel) give the two highest fractions of energy dissipated. This is consistent with the fact that they give the highest values of the loss modulus—a consequence of high values of both loss tangent and storage modulus.

Table 3 shows that the fractional increase in storage modulus due to the silane treatment decreases from paste to mortar and concrete. However, the fractional increase in loss tangent due to the silane treatment increases from paste to mortar and decreases from mortar to concrete, thus

Table 3—Fractional change in dynamic flexural properties (0.2 Hz) of cement-based materials without steel due to silane treatment of silica fume, as shown by comparing data for S and S′ in Table 1

Property		Paste	Mortar	Concrete
Without steel	Storage modulus, %	71	51	10
	Loss tangent, %	11	77	30
	Loss modulus, %	89	170	50
	Fraction of energy dissipated, %	150	400	30
With steel	Storage modulus, %	41	27	20
	Loss tangent, %	11	77	40
	Loss modulus, %	56	41	60
	Fraction of energy dissipated, %	30	10	30

Table 4—Dynamic flexural properties (0.2 Hz), showing effects of silica fume (S is untreated silica fume and S′ is silane-treated silica fume), graphite network admixture (A), and steel reinforcing bar (R) separately and in combination

Additional ingredient(s)		Storage modulus, GPa (ksi)	Loss tangent	Loss modulus, GPa (ksi)	Fraction of energy dissipated
Cement paste	None	1.81 ± 0.12 (262 ± 17)	0.030 ± 0.009	0.054 ± 0.001 (7.83 ± 0.15)	0.032 ± 0.006
	S	4.18 ± 0.20 (606 ± 29)	0.055 ± 0.011	0.230 ± 0.002 (33.4 ± 0.3)	0.104 ± 0.011
	S′	7.13 ± 0.54 (1034 ± 78)	0.061 ± 0.008	0.435 ± 0.004 (63.1 ± 0.58)	0.256 ± 0.042
	A	1.92 ± 0.15 (278 ± 22)	0.128 ± 0.014	0.245 ± 0.002 (35.5 ± 0.3)	0.121 ± 0.017
	S′ + A	3.88 ± 0.35 (562 ± 51)	0.125 ± 0.027	0.485 ± 0.009 (70.3 ± 1.3)	0.184 ± 0.021
	S′ + A	4.92 ± 0.13 (713 ± 19)	0.128 ± 0.019	0.629 ± 0.002 (91.2 ± 0.3)	0.248 ± 0.019
	R	1.61 ± 0.09 (233 ± 13)	0.028 ± 0.013	0.045 ± 0.001 (6.53 ± 0.15)	0.033 ± 0.008
	S + R	4.59 ± 0.27 (666 ± 39)	0.061 ± 0.018	0.275 ± 0.005 (39.8 ± 0.7)	0.123 ± 0.077
	S′ + R	6.33 ± 0.17 (917 ± 25)	0.068 ± 0.012	0.430 ± 0.002 (62.3 ± 0.3)	0.163 ± 0.072
	A + R	1.91 ± 0.12 (276 ± 17)	0.096 ± 0.010	0.183 ± 0.001 (26.5 ± 0.1)	0.072 ± 0.006
	S + A + R	4.41 ± 0.32 (639 ± 46)	0.117 ± 0.029	0.516 ± 0.009 (74.1 ± 1.3)	0.222 ± 0.005
	S′ + A + R	5.81 ± 0.26 (842 ± 38)	0.119 ± 0.033	0.697 ± 0.008 (101 ±1)	0.258 ± 0.008
Mortar	None	9.01 ± 0.31 (1306 ± 45)	0.00041 ± 0.00009	0.00359 ± 0.00003 (0.521 ± 0.004)	0.0028 ± 0.0002
	S	19.23 ± 0.84 (2788 ± 121)	0.026 ± 0.003	0.499 ± 0.002 (72.3 ± 0.3)	0.242 ± 0.029
	S′	28.91 ± 2.22 (4192 ± 322)	0.046 ± 0.008	1.331 ± 0.018 (193 ± 3)	0.461 ± 0.083
	S + A	21.01 ± 0.83 (3046 ± 120)	0.134 ± 0.015	2.821 ± 0.012 (409 ± 2)	0.541 ± 0.062
	S′ + A	26.71 ± 0.83 (3872 ± 120)	0.139 ± 0.021	3.543 ± 0.017 (513 ± 2)	0.577 ± 0.042
	R	8.01 ± 0.34 (1161 ± 49)	0.00065 ± 0.00011	0.00519 ± 0.00003 (0.753 ± 0.004)	0.0071 ± 0.0004
	S + R	18.81 ± 1.01 (2727 ± 146)	0.041 ± 0.012	0.771 ± 0.007 (111.8 ± 1.0)	0.291 ± 0.006
	S′ + R	23.81 ± 0.95 (3452 ± 137)	0.046 ± 0.013	1.088 ± 0.012 (157.8 ± 1.7)	0.321 ± 0.005
	S + A + R	22.14 ± 1.42 (3210 ± 205)	0.092 ± 0.018	2.223 ± 0.026 (322 ± 4)	0.488 ± 0.033
	S′ + A + R	25.44 ± 1.13 (3688 ± 163)	0.102 ± 0.015	2.587 ± 0.016 (375 ± 2)	0.512 ± 0.028
Concrete	None	10.83 ± 0.48 (1570 ± 70)	0.00023 ± 0.00005	0.00025 ± 0.00003 (0.036 ± 0.04)	0.0013 ± 0.0003
	S	27.82 ± 0.87 (4034 ± 126)	0.016 ± 0.003	0.440 ± 0.004 (63.8 ± 0.58)	0.124 ± 0.007
	S′	31.02 ± 1.12 (4498 ± 162)	0.021 ± 0.005	0.648 ±0.007 (94.7 ± 1.0)	0.148 ± 0.010
	S + A	27.34 ± 0.67 (3964 ± 97)	0.028 ± 0.006	0.763 ± 0.004 (110 ± 1)	0.193 ± 0.011
	S′ + A	30.56 ± 1.43 (4431 ± 207)	0.042 ± 0.013	1.279 ± 0.011 (185 ± 2)	0.231 ± 0.024
	R	10.36 ± 0.48 (1502 ± 70)	0.00024 ± 0.00006	0.00024 ± 0.00004 (0.035 ± 0.005)	0.0014 ± 0.0004
	S + R	24.94 ± 0.71 (3616 ± 103)	0.014 ± 0.004	0.351 ± 0.005 (50.9 ± 0.7)	0.112 ± 0.006
	S′ + R	29.83 ± 0.51 (4325 ± 74)	0.019 ± 0.007	0.568 ± 0.009 (82.3 ± 1.3)	0.141 ± 0.011
	S + A + R	26.11 ± 1.11 (3785 ± 160)	0.031 ± 0.009	0.813 ± 0.012 (11.8 ± 1.7)	0.194 ± 0.022
	S′ + A + R	27.81 ± 2.01 (4032 ± 291)	0.039 ± 0.008	1.079 ± 0.035 (156 ± 5)	0.219 ± 0.041

causing the loss modulus and the dissipation to follow the same behavior of increase followed by decrease. The positive effects of the silane treatment on the loss modulus and the fraction of energy dissipated are less for concrete than paste due to the relatively small positive effect of silane treatment on the storage modulus of concrete. The positive effects of silane treatment on the loss modulus and the fraction of energy dissipated are greatest for mortar.

Table 3 also shows the effects of the silane treatment in the presence of steel. The effects are all positive, but they tend to be less than those in the absence of steel, particularly in relation to the fraction of energy dissipated.

Effects of silica fume, graphite network cementitious admixture, and steel in various combinations

Table 4 shows the effects of silica fume, graphite network cementitious admixture, and steel in various combinations on the dynamic flexural properties of cement paste, mortar, and concrete. Silica fume (whether silane-treated or not) is much more effective than the graphite network cementitious admixture (A in Table 4) for increasing the storage modulus but is much less effective than the cementitious admixture for increasing the loss tangent.

The combined use of silica fume and the graphite network cementitious admixture (SA in Table 4) provides a synergistic effect so that both storage modulus and loss tangent are high. When the silica fume is silane-treated, the effect is even stronger, mainly due to the increase in storage modulus due to the silane treatment. As a consequence of the synergistic effect, the loss modulus is higher than what can be provided by any of the admixtures used as the sole admixture. This synergistic effect is due to the silica fume enhancing the storage modulus, while the graphite network cementitious admixture enhances the loss tangent.

The cement paste with the graphite network admixture as the sole admixture exhibits a storage modulus of 1.9 GPa (276,000 psi), which is close to that of the cement paste without admixture (1.8 GPa [260,000 psi]; Table 4) and is much lower than the value of 9.3 GPa (1,400,000 psi) for the graphite network cementitious admixture itself (not as an admixture).[13] This means that the cementitious admixture is not effective for stiffening, but the admixture itself is much stiffer than plain cement paste.

The cement paste with the graphite network admixture as the sole admixture exhibits a loss tangent of 0.13 (Table 4), which is higher than the value for plain cement paste (0.03; Table 4) and that for cement paste containing silica fume as the sole admixture (0.055 or 0.061; Table 4) but is lower than the value of 0.81 for the graphite network admixture itself.[11] This means that the graphite network admixture is effective for enhancing the loss tangent, although the enhanced loss tangent remains low compared to the value of the admixture itself.

The cement paste with the graphite network cementitious admixture as the sole admixture exhibits a loss modulus of 0.25 GPa (36,000 psi) (Table 4), which is comparable to or lower than the value for cement paste containing silica fume as the sole admixture (0.23 or 0.44 GPa [33,000 or 64,000 psi]; Table 4) and is much lower than the value of 7.5 GPa (1,100,000 psi) for the graphite network cementitious admixture itself[11] but is much higher than the value for plain cement paste (0.05 GPa [7000 psi]; Table 4).

Figure 2 shows an optical microscope photograph of the mechanically polished surface of the cement paste containing untreated silica fume and the graphite network cementitious admixture. Due to the cementitious nature of this admixture, the interface between this admixture and the silica fume cement paste matrix shows no pore or gap. The cement matrix is continuous from the silica fume cement paste region to the graphite network admixture region.

Table 4 also shows that steel has little effect on the storage modulus or the loss tangent. The addition of the graphite network admixture to steel-reinforced cement paste increases the loss tangent without much effect on the storage modulus. The further addition of silica fume increases the storage modulus significantly and increases the loss tangent slightly, such that the effects are stronger when the silica fume has been silane-treated. The highest fraction of energy dissipated among the cement pastes in Table 4 is 0.26, as provided by steel-reinforced cement paste containing silane-treated silica fume and the graphite network admixture.

Fig. 2—Optical microscope photograph of polished surface of cement paste containing untreated silica fume and graphite network cementitious admixture. Part of edge of piece of this admixture is shown at right lower portion of photo. Bright regions are graphite, which has probably been smeared by polishing, as suggested by slightly shiny appearance of admixture edge. Dark regions are cement.

The effects of silica fume, graphite network admixture, and steel for cement pastes, mortars, and concretes are similar (Table 4). The storage modulus is much higher for mortar than the corresponding paste due to the stiffening by the sand. The storage modulus is higher for concrete than the corresponding mortar due to the stiffening by the stones. The loss modulus and dissipation are particularly high for the mortars. The highest fraction of energy dissipated among the mortars is 0.58, as provided by steel-reinforced mortar containing silane-treated silica fume and the graphite network admixture. However, the loss tangent is lower for concrete than the corresponding mortar, thus resulting in a low loss modulus and low dissipation for the concretes. The highest fraction of energy dissipated among the concretes is 0.23, as provided by concrete containing silane-treated silica fume and the graphite network admixture; the value is essentially the same whether the concrete contains steel or not. Silane-treated silica fume and the graphite network admixture together cause steel-reinforced concrete to increase the energy dissipation, loss modulus, loss tangent, and storage modulus by 16,000%, 450,000%, 16,000%, and 170%, respectively.

Comparison of all cement-based materials studied in this work

Table 5 shows the fraction of energy dissipated for cement pastes, mortars, and concretes in comparison. Without additional ingredients (the "none" case), the fraction of energy dissipated decreases from paste to mortar and concrete. With additional ingredients (the rest of the columns in Table 5), the fraction of energy dissipated increases from paste to mortar and decreases from mortar to concrete. Thus, the highest fraction of energy dissipated occurs in mortars. This fraction increases from paste to mortar because of the high storage modulus of mortar. This fraction decreases from mortar to concrete because of the low loss tangent of concrete.

Table 5—Fraction of energy dissipated (0.2 Hz) for cement pastes, mortars, and concretes in comparison. Abbreviations for additional ingredients are as explained in Table 4

	None	S′ + A	R	S + R	S′ + R	S′ + A + R
Pastes	0.032 ± 0.006	0.248 ± 0.019	0.033 ± 0.008	0.123 ± 0.077	0.163 ± 0.072	0.258 ± 0.008
Mortars	0.0028 ± 0.0002	0.577 ± 0.042	0.0071 ± 0.0004	0.291 ± 0.006	0.321 ± 0.005	0.512 ± 0.028
Concretes	0.0013 ± 0.0003	0.231 ± 0.024	0.0014 ± 0.0004	0.112 ± 0.006	0.141 ± 0.011	0.219 ± 0.041

Table 6—Fractional increase in dissipation (0.2 Hz), which refers to fraction of energy dissipated. Abbreviations for additional ingredients are as explained in Table 4

Additional ingredients		S′ + A	R	S + R	S′ + R	S′ + A + R
Fractional increase in dissipation relative to "none" case	Pastes, %	680	0	280	400	710
	Mortars, %	21,000	150	10,000	11,000	18,000
	Concretes, %	18,000	0	8400	11,000	17,000
Fractional increase in dissipation relative to "R" case	Pastes, %	—	—	270	380	690
	Mortars, %	—	—	4000	4400	7100
	Concretes, %	—	—	8000	9900	16,000

Table 7—Static flexural and compressive strengths of cement pastes, mortars, and concretes, showing effects of silica fume (S is untreated silica fume and S′ is silane-treated silica fume), graphite network admixture (A), and steel reinforcing bar (R) separately and in combination

	Additional ingredient(s)	Compressive strength without steel, MPa (psi)	Flexural strength without steel, MPa (psi)	Flexural strength with steel, MPa (psi)
Paste	None	54.2 ± 2.1 (7860 ± 300)	3.84 ± 0.16 (556 ± 23)	7.44 ± 0.20 (1080 ± 30)
	S	63.4 ± 3.2 (9190 ± 460)	5.15 ± 0.44 (747 ± 63)	9.71 ± 0.54 (1410 ± 80)
	S′	67.1 ± 2.5 (9730 ± 360)	5.30 ± 0.25 (768 ± 36)	9.98 ± 0.39 (1450 ± 60)
	A	38.9 ± 3.1 (5640 ± 450)	3.21 ± 0.23 (465 ± 33)	7.03 ± 0.66 (1020 ± 100)
	S + A	58.1 ± 4.5 (8420 ± 650)	4.23 ± 0.31 (613 ± 45)	9.66 ± 0.71 (1400 ± 100)
	S′ + A	61.7 ± 2.6 (8950 ± 380)	4.67 ± 0.47 (677 ± 68)	9.36 ± 0.64 (1360 ± 90)
Mortar	None	56.2 ± 5.2 (8150 ± 750)	5.58 ± 0.41 (809 ± 59)	8.30 ± 0.23 (1200 ± 30)
	S	66.7 ± 3.8 (9670 ± 550)	7.13 ± 0.37 (1030 ± 50)	10.73 ± 0.43 (1556 ± 62)
	S′	69.8 ± 3.2 (10,100 ± 500)	7.68 ± 0.77 (1110 ± 110)	10.91 ± 0.41 (1582 ± 59)
	S + A	60.2 ± 4.5 (8730 ± 650)	6.21 ± 0.56 (900 ± 81)	8.06 ± 0.61 (1170 ± 90)
	S′ + A	63.5 ± 1.8 (9210 ± 260)	6.46 ± 0.62 (937 ± 90)	9.31 ± 0.66 (1350 ± 100)
Concrete	None	65.2 ± 1.9 (9450 ± 280)	8.80 ± 0.11 (1280 ± 20)	9.93 ± 0.35 (1430 ± 50)
	S	71.4 ± 2.2 (10,400 ± 300)	9.29 ± 0.24 (1350 ± 30)	11.33 ± 0.41 (1643 ± 59)
	S′	73.1 ± 3.0 (10,600 ± 400)	8.81 ± 0.33 (1280 ± 50)	11.45 ± 0.31 (1660 ± 45)
	S + A	66.9 ± 4.7 (9700 ± 680)	8.39 ± 0.29 (1220 ± 40)	9.87 ± 0.40 (1430 ± 60)
	S′ + A	69.2 ± 5.0 (10,000 ± 700)	8.68 ± 0.25 (1260 ± 40)	10.33 ± 0.39 (1498 ± 57)

Table 6 shows that the fractional increase in the fraction of energy dissipated due to the additional ingredient(s) is much higher for mortar and concrete than the corresponding cement paste, except for the case in which steel is the only additional ingredient (that is, the "R" case, in which the fractional increases are small for paste, mortar, and concrete). The fractional increase tends to be slightly higher for mortar than the corresponding concrete.

Table 6 also shows that the fractional increase in the fraction of energy dissipated for cement-based materials containing steel due to the additional ingredients other than steel (that is, relative to the "R" case) increases from paste to the corresponding mortar and the corresponding concrete. The highest fractional increase of 16,000% is obtained in concrete by using silane-treated silica fume with the graphite network admixture. The effect of steel on the loss modulus is negligible for all the formulations studied (Table 4) whether the silica fume and graphite network admixture are used or not.

Table 7 shows that the flexural and compressive strengths are increased by the silica fume addition, whether aggregates are present or not and, in relation to the flexural strength, whether steel is present or not. The effects are stronger when the silica fume is silane-treated, except for the flexural strength of concrete without steel. However, the addition of the graphite network admixture (A in Table 7) decreases the flexural and compressive strengths, as shown for cement pastes with and without steel under flexure and for cement pastes without steel under compression. The resulting flexural strength is much lower than the value of 15 MPa

Table 8—Ranking of energy dissipation performance (0.2 Hz) of cement-based materials of this work with consideration of cement pastes, mortars, and concretes (with and without steel). Top four performers are all mortars. Ingredient abbreviations are as explained in Table 4

Dissipation ranking	1	2	3	4		
Overall ranking	3	4	1	2	Baseline mortar	Baseline concrete
Ingredients	S′ + A	S + A	S′ + A + R	S + A + R	R	R
Storage modulus, GPa (ksi)	26.71 ± 0.83 (3872 ± 120)	21.01 ± 0.83 (3046 ± 120)	25.44 ± 1.13 (3688 ± 163)	22.14 ± 1.42 (3210 ± 205)	8.01 ± 0.34 (1161 ± 49)	10.36 ± 0.48 (1502 ± 70)
Loss tangent	0.139 ± 0.021	0.134 ± 0.015	0.102 ± 0.015	0.092 ± 0.018	0.00065 ± 0.00011	0.00024 ± 0.00006
Loss modulus, GPa (ksi)	3.543 ± 0.017 (513 ± 2)	2.821 ± 0.012 (409 ± 2)	2.587 ± 0.016 (375 ± 2)	2.223 ± 0.025 (322 ± 4)	0.00519 ± 0.00003 (0.753 ± 0.004)	0.00024 ± 0.00004 (0.035 ± 0.005)
Fraction of energy dissipated	0.5877 ± 0.042	0.541 ± 0.062	0.512 ± 0.028	0.488 ± 0.033	0.0071 ± 0.0004	0.0014 ± 0.0004
Flexural strength, MPa (psi)	6.46 ± 0.62 (937 ± 90)	6.21 ± 0.56 (900 ± 81)	9.31 ± 0.66 (1350 ± 96)	8.06 ± 0.61 (1169 ± 88)	8.30 ± 0.23 (1203 ± 33)	9.93 ± 0.35 (1430 ± 51)
Compressive strength without steel, MPa (psi)	63.5 ± 1.8 (9210 ± 260)	60.2 ± 4.5 (8730 ± 650)	63.5 ± 1.8 (9210 ± 260)	60.2 ± 4.5 (8730 ± 650)	56.2 ± 5.2 (8150 ± 750)	65.2 ± 1.9 (9450 ± 270)

Table 9—Effect of frequency of dynamic flexural properties of cement pastes

Additional ingredient(s)	Frequency, Hz	Storage modulus, GPa (ksi)	Fractional increase in storage modulus relative to 0.2 Hz	Loss tangent	Fraction decrease in loss tangent relative to 0.2 Hz	Loss modulus, GPa (ksi)	Fraction of energy dissipated	Fractional decrease in dissipation relative to 0.2 Hz
None	0.2	1.81 ± 0.12 (262 ± 17)	—	0.030 ± 0.009	—	0.054 ± 0.001 (7.8 ± 0.1)	0.032 ± 0.006	—
	1.0	1.96 ± 0.08 (284 ± 12)	8.3%	0.008 ± 0.002	73%	0.016 ± 0.001 (2.3 ± 0.1)	0.009 ± 0.001	72%
	2.0	2.11 ± 0.14 (306 ± 20)	17%	0.0018 ± 0.0006	94%	0.004 ± 0.001 (0.6 ± 0.1)	0.002 ± 0.001	94%
Untreated silica fume	0.2	4.18 ± 0.20 (606 ± 29)	—	0.055 ± 0.011	—	0.230 ± 0.002 (33.4 ± 0.3)	0.104 ± 0.011	—
	1.0	4.22 ± 0.20 (611 ± 29)	1.0%	0.022 ± 0.008	60%	0.093 ± 0.002 (13.5 ± 0.3)	0.066 ± 0.011	37%
	2.0	4.46 ± 0.13 (646 ± 19)	6.7%	0.016 ± 0.004	71%	0.071 ± 0.001 (10.3 ± 0.1)	0.044 ± 0.008	58%
Silane-treated silica fume	0.2	7.13 ± 0.54 (1030 ± 80)	—	0.061 ± 0.008	—	0.435 ± 0.004 (63.1 ± 0.58)	0.256 ± 0.042	—
	1.0	7.25 ± 0.36 (1050 ± 50)	1.7%	0.032 ± 0.005	48%	0.232 ± 0.003 (33.6 ± 0.44)	0.110 ± 0.035	57%
	2.0	7.29 ± 0.48 (1060 ± 70)	2.2%	0.019 ± 0.004	69%	0.139 ± 0.003 (20.2 ± 0.44)	0.069 ± 0.021	73%

(2200 psi) for the graphite network admixture itself[11] and the resulting compressive strength is much lower than the value of 280 MPa (41,000 psi) for the graphite network admixture itself.[11] This suggests that continuity in the graphite network, which occurs in the admixture itself,[11] is needed for the network to be able to reinforce. On the other hand, the combined use of silica fume and the graphite network admixture results in flexural and compressive strengths that are higher than those of the corresponding materials without the admixtures, with the exception of concretes, for which the strengths are comparable to those of the corresponding materials without the admixtures. Silane-treated silica fume tends to be more effective than untreated silica fume, although the difference is negligible when the data scatter is considered. For all the pastes, mortars, and concretes, whether steel is present or not (in the case of the flexural strength because steel is not used in the compressive testing), the combined use of silica fume (whether silane-treated or not) and the graphite network admixture gives flexural and compressive strengths that are comparable to or higher than those of the corresponding materials without these admixtures. For the same admixture(s), the flexural and compressive strengths increase in this order: cement paste, mortar, and concrete, but the effect on the flexural strength is relatively small when steel is present.

A comparison of all the cement pastes, mortars, and concretes—with and without steel—is discussed in the following, taking into consideration the loss tangent, loss modulus, and fraction of energy dissipated. The top four performers—all mortars—are listed in Table 8. The material that gives the highest energy dissipation performance is mortar (without steel) containing silane-treated silica fume and the graphite network admixture. Second in the dissipation ranking is the corresponding material with untreated silica fume. Third is the material with silane-treated silica fume, the graphite network admixture, and steel. Fourth is the corresponding material with untreated silica fume. However, the flexural strength is higher in the presence of steel, such that the strength is higher when the silica fume is silane-treated. Thus, the flexural strength is highest for the material that is ranked third in terms of the dissipation. Because the fractional difference in dissipation performance among the four materials in Table 9 is small compared to the fractional difference in flexural strength, the material ranked third in terms of the dissipation is the most highly ranked material when both the static and dynamic mechanical properties are considered.

Compared to the baseline mortar and concrete (without the admixtures), Table 8 shows that the top-performing material according to the overall ranking is much superior in the storage modulus, loss tangent, loss modulus, and fraction of energy dissipated to the baseline materials. Moreover, it is superior to the baseline mortar and comparable to the baseline concrete in terms of the flexural and compressive strengths.

Due to the silane treatment of the silica fume, the material of Overall Rank 1 is more expensive than that of Overall Rank 2. The material of Overall Rank 1 provides dissipation of 51%, whereas that of Overall Rank 2 provides dissipation of 49%. Advantages of the material of Overall Rank 1 over that of Overall Rank 2 include a higher storage modulus, loss modulus, and flexural strength. The loss tangent and compressive strength are comparable between Overall Ranks 1 and 2. The fact that 50% of the input mechanical energy is dissipated by the cement-based material is attractive. The dissipation provided by the baseline mortar or concrete is below 1%.

The effect of the presence of steel on the loss modulus is small. For example, the material of Overall Rank 1 dissipates 51% of the energy, while the corresponding material without steel (Overall Rank 3) dissipates 58% of the energy. The fact that the presence of steel reduces the loss modulus is related to the fact that the presence of steel reduces the loss tangent from 0.14 to 0.10 and is because steel takes up some volume that would have been occupied by the high-damping cement-based material. Nevertheless, the presence of steel increases the flexural strength from 6.5 to 9.3 MPa (940 to 1350 psi), thus making the steel valuable.

The recommended design of the mixture to be poured to the graphite network admixture and/or steel is a mortar mixture, with the weight of the ingredients expressed relative to a volume of 1 yd^3 (0.76 m^3): 1430 lb (649 kg) cement, 1430 lb (649 kg) sand, 642 lb (291 kg) water, and 214 lb (97 kg) silica fume. The total weight per yd^3 is 3710 lb (1683 kg), which corresponds to a density of 2.20 g/cm^3 (137 lb/ft^3).

This paper addresses materials rather than structures and evaluates small-sized specimens. For practical applications, further work is necessary to evaluate the behavior of larger specimens.

Effect of frequency

Table 9 shows the effect of frequency on the dynamic flexural properties for cement pastes. As the frequency increases, the storage modulus increases, the loss tangent decreases, and the loss modulus decreases. These effects are consistent with the viscoelastic nature and the associated strain rate dependence. The fractional increase in storage modulus due to the frequency increase is small compared to the fractional decrease in loss tangent due to the frequency increase. Hence, the decrease in dissipation with increasing frequency is mainly due to the decrease in the loss tangent.

The fractional decreases in loss tangent and dissipation due to the frequency increase are much smaller when silica fume is present (Table 9). This means that the presence of silica fume helps to reduce the detrimental effect of increasing frequency, thereby allowing dissipation to remain substantial at relatively high frequencies. This beneficial effect of silica fume is attributed to the interfacial mechanism of damping provided by the silica fume being able to operate at relatively high frequencies. The interfacial mechanism dominates in the presence of silica fume due to the small particle size of the silica fume. Without silica fume, the interfacial mechanism is less significant so that the conventional viscoelastic mechanism dominates. The conventional viscoelastic mechanism is apparently more sensitive to the frequency than the interfacial mechanism. The effect of the silane treatment of the silica fume on the frequency dependence is small compared to the effect of the presence of silica fume.

Comparison with prior work

The highest loss tangent obtained is 0.14, which is for mortar containing silane-treated silica fume and the graphite network admixture. This is higher than the value of 0.015 previously reported at 1 Hz for cement containing $Li_5La_3Ta_2O_{12}$ particles[19] and higher than the value of 0.062 for concrete containing silica particles of an average diameter of 30 nm (1.2×10^{-6} in.).[17] It is the same as the value of 0.14 for cement containing carbon nanotubes.[14] In spite of the small size of the silica particles[17] and the carbon nanotube[14] and the consequent large area of the interface between the filler and the cement matrix, the loss tangent is not higher than the highest value obtained. This reflects the multi-layer structure in each ligament of the graphite network, which provides interfaces inside the multi-layer. However, the highest loss tangent obtained is smaller than the value of 0.25 for cement mortar containing styrene-acrylate admixture[12] and the value of 0.81 at 0.2 Hz for the graphite network admixture itself[11]; it is also small compared to the value of 0.67 for rubber at the same frequency.[20] It is expected that the loss tangent of this work is smaller than that of the graphite network admixture itself because the material of this work contains this admixture in a limited amount. Rubber and styrene-acrylate enhance the energy dissipation by the viscoelastic deformation mechanism rather than the interfacial mechanism. The two mechanisms are competitive in relation to the loss tangent enhancement, but the viscoelastic deformation mechanism tends to cause a loss in stiffness.

The highest loss modulus obtained is 3.5 GPa (5.1×10^5 psi), which is for the case of mortar containing silane-treated silica fume and the graphite network admixture. This value is higher than the value of 1.4 GPa (2.0×10^5 psi) for cement containing styrene-acrylate admixture[12] due to the negative effect of the polymer admixture on the stiffness. The value of this work is also higher than the value of 2.85 GPa (4.1×10^5 psi) for concrete containing silica particles of an average diameter of 30 nm (1.2×10^{-6} in.)[17] due to the relatively low value of the loss tangent provided by the silica particle addition. On the other hand, the value of this work is lower than the value of 7.5 GPa (1.1×10^6 psi) for the graphite network admixture itself,[11] as expected because the material of this work contains this admixture in a limited amount.

Effective damping requires high values of both the loss tangent and loss modulus. The graphite network admixture itself gives loss tangents and loss moduli that are higher than those of this work, but its elastic modulus is low.[19] Concrete containing silica particles with a diameter of 30 nm (1.2×10^{-6} in.)[17] gives loss tangents and loss moduli that are lower than the highest dissipation material of this work. Cement mortar containing styrene-acrylate admixture[12] gives a higher loss tangent but a lower loss modulus than the highest dissipation material of this work.

CONCLUSIONS

Silica fume (15% by mass of cement) and a graphite network (8 vol.%, formed from exfoliated graphite) cementitious plate admixture (with preferred orientation in the plane of the specimen beam, 62 vol.% with the steel volume excluded) are effective for enhancing the energy dissipation of cement-based materials under small-strain dynamic flexure. The dissipation decreases with increasing frequency, but silica fume reduces the frequency effect.

The fraction of energy dissipated reaches 0.26, 0.58, and 0.22 for cement paste, mortar, and concrete, respectively, as provided by silane-treated silica fume and the graphite network admixture, which cause steel-reinforced concrete to increase the dissipation, loss modulus, loss tangent, and storage modulus by 16,000%, 450,000%, 16,000%, and 170%, respectively.

The highest loss tangent and loss modulus obtained are 0.14 and 3.5 GPa (2.0×10^4 and 5.1×10^5 psi) respectively, which are for the case of mortar containing silane-treated silica fume and the graphite network admixture. These admixtures cause steel-reinforced mortar to increase the dissipation by 7100% and cause steel-reinforced cement paste to increase the dissipation by 690%. Without steel, these admixtures cause mortar to increase the dissipation by 21,000%.

Silane-treated silica fume without the graphite network admixture causes steel-reinforced concrete to increase the dissipation by 9900%; untreated silica fume gives a corresponding 8000% increase.

Without steel or admixtures, the fraction of energy dissipated decreases from cement paste to mortar and concrete. With steel and/or admixtures, this fraction increases from cement paste to mortar and decreases from mortar to concrete. As a result, the highest fraction of energy dissipated occurs in mortars. This fraction increases from cement paste to mortar because of the relatively high storage modulus of mortar. This fraction decreases from mortar to concrete because of the relatively low loss tangent of concrete.

Silica fume addition increases the flexural and compressive strengths, whereas the graphite network admixture addition decreases these strengths. However, for all the pastes, mortars, and concretes—with or without steel—the combined use of silica fume (whether silane-treated or not) and the graphite network admixture gives flexural and compressive strengths that are comparable to or higher than those of the corresponding materials without these admixtures.

Based on static and dynamic properties, the most highly ranked cement-based material obtained is steel-reinforced mortar containing silane-treated silica fume and the graphite network admixture. This material exhibits high energy dissipation compared to the mortar or concrete without these admixtures and exhibits flexural and compressive strengths that are superior or comparable to those of the mortar or concrete without the admixtures.

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