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Communication

Enhancing the vibration reduction ability of concrete by using steel reinforcement and steel surface treatments

Sihai Wen, D.D.L. Chung*

Composite Materials Research Laboratory, State University of New York at Buffalo, Buffalo, NY 14260-4400, USA

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Abstract

The vibration reduction ability of mortar, as expressed by the loss modulus under dynamic flexure (0.2–1.0 Hz), was increased by three (or more) orders of magnitude upon the embedment of steel rebars in the mortar, mainly due to the increase in the vibration damping capacity. By sandblasting the steel rebars, the loss modulus was increased by up to 91%, relative to the values obtained by using as-received rebars, due to the increase in the damping capacity. Surface treatment of the steel rebars by ozone had negligible effect on the loss modulus. The damping capacity was comparably enhanced by steel addition and silica fume addition.

Keywords: Reinforcement; Concrete; Mortar; Mechanical properties; Damping

1. Introduction

Vibration damping is valuable for structures because it mitigates hazards (whether due to accidental loading, wind, ocean waves, or earthquakes), increases the comfort of people who use the structures, and enhances the reliability and performance of structures. Both passive and active methods of damping are useful, although active methods are usually more expensive due to the devices involved. Passive damping most commonly involves the use of viscoelastic materials such as rubber, although these materials tend to suffer from their poor stiffness and high cost compared to the structural material (i.e., concrete). High stiffness is useful for vibration reduction. These problems with stiffness and cost can be removed if the structural material itself has a high damping capacity. The use of the structural material for passive damping also lowers the cost of damping implementation. Moreover, due to the large volume of structural material in a structure, the resulting damping ability can be substantial. Therefore, the development of concrete that inherently has a high damping capacity is of interest [1] and is the motivation behind this paper.

A method of enhancing the damping capacity of concrete involves the use of admixtures such as silica fume and latex [2]. The addition of silica fume to mortar has been shown to increase the damping capacity by two (or more) orders of magnitude [3]; the effect is less if sand is absent, because sand addition to cement paste greatly decreases the damping capacity [3].

This paper addresses another method of enhancing the damping capacity: the use of steel reinforcement. Steel reinforcement in the form of bars (called "rebars") is commonly used to improve the flexural and tensile strengths of concrete, since steel is much stronger than concrete itself (unreinforced) under flexure or tension. However, no previous attention has been given to the effect of steel reinforcement on the damping capacity. In particular, no previous attention has been given to the effect of steel surface treatment on the damping capacity, although steel surface treatment is known to affect the bond of steel to concrete [4].

The main objective of this paper is to study the effects of steel reinforcement and its surface treatment on the damping capacity of mortar. The secondary objective is to compare the effectiveness of steel and silica fume in enhancing the damping capacity of mortar. The tertiary objective is to study the effects of steel reinforcement and its surface treatment on the storage modulus (stiffness), since both high modulus and high damping capacity are desirable for vibration reduction.

As in other work [2,3], the damping capacity (loss tangent, or tan δ) and storage modulus were measured under dynamic flexure (three-point bending) at a very small deflection amplitude and at controlled frequencies in the range from 0.2 to 1.0 Hz, using a dynamic mechanical analyzer (Perkin-Elmer Corp., Norwalk, CT, USA, Model DMA 7E). Comparison of the results of this work and those of a previ-

* Corresponding author. Tel.: 716-645-2593, ext. 2243; fax: 716-645-3875.

E-mail address: ddlchung@acsu.buffalo.edu (D.D.L. Chung)

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ous work [3] allows comparison of the effectiveness of steel and of silica fume in enhancing the damping capacity of mortar. Although the samples were larger in this work, the loss tangent values obtained for the two sample sizes were essentially the same for the same sample type, as confirmed in this work by testing using two sample sizes. However, the storage modulus values obtained for the two sample sizes were not the same for the same sample type. Thus, comparison between steel and silica fume was made in this work in relation to the loss tangent, but not in relation to the storage modulus.

In studying the effect of steel surface treatment on the damping capacity and storage modulus of mortar, this work used two types of surface treatments, namely ozone treatment (to form a dark grey coating [5]) and sandblasting (to roughen the surface). Both treatments have been previously shown to increase the bond strength, which is larger for ozone treatment than sandblasting [4,5]. A higher bond strength does not imply a higher storage modulus, since the bond strength pertains to the tendency to debond, whereas the modulus pertains to the stress per unit strain in the regime of elastic deformation. A higher bond strength also does not imply a lower damping capacity, since the bond strength pertains to the tendency to debond, whereas the damping capacity pertains to the energy dissipation during vibration.

Steel reinforcement is usually used in a concrete structure anyway. However, steel surface treatment is not usually used. Therefore, the improvement of the damping capacity through steel surface treatment is a new direction that is of practical interest.

Although this paper does not address the combined use of steel reinforcement and silica fume for improving the damping capacity, the combined use is possible, as it has been shown to improve the bond between steel and concrete [6] and the corrosion resistance of steel in concrete [7]. In this paper, we found that steel reinforcement and silica fume gave similar extents of improvement (increase by two or more orders of magnitude) of the damping capacity of mortar. This suggests that the combined use of steel reinforcement and silica fume will provide an even higher damping capacity.

Although this paper addresses mortar (with fine aggregate, but no coarse aggregate) rather than concrete (with fine and coarse aggregates) due to the limitation in the sample size for dynamic mechanical testing, the large effect of steel reinforcement on the damping capacity is expected to apply to concrete as well as mortar. It is likely that the effect is even larger for concrete than for mortar, as the damping capacity of plain mortar (no reinforcement or admixture) is much lower than that of plain cement paste (due to the higher degree of homogeneity within a sand particle than within cement paste) [3] and consequently the damping capacity of plain concrete is likely lower than that of plain mortar; the fractional increase in a quantity tends to be higher when the original value of the quantity is lower.

The steel rebars used in this study were configured in a mortar beam sample under three-point dynamic bending, such that four parallel longitudinal steel rebars were symmetrically positioned near the four corners of the square cross section of the mortar sample. This configuration was chosen because the rebars at the tension side of the sample were effective in reinforcing the sample and the tension side alternated between the top and bottom sides as dynamic bending occurred around zero deflection at a deflection amplitude of 16 to 25 μm.

The loss modulus is the product of the storage modulus and the loss tangent. Since both a high storage modulus and a high loss tangent are desirable for vibration reduction, a high value of the loss modulus is desirable and the loss modulus may be used as a figure of merit. In this paper, we found that the loss modulus was increased by 39 to 91% (relative to the value for as-received steel rebars) by surface treating the steel by sandblasting. The increase in loss modulus was almost entirely due to the increase in loss tangent. The increase is significant enough for practical use of the surface treatment for vibration damping enhancement.

2. Experimental methods

Dynamic mechanical testing (ASTM D4065-94) at controlled frequencies (0.20, 0.50, and 1.00 Hz) and room temperature (20°C) was conducted under flexure using a Perkin-Elmer Corp. (Norwalk, CT, USA) Model DMA 7E dynamic mechanical analyzer. Measurements of tan δ and storage modulus were made simultaneously at various frequencies. The specimens were in the form of beams ($370 \times 12 \times 12$ mm) under three-point bending, such that the span was 350 mm. The loads used were all large enough that the amplitudes of the specimen deflection was from 16 to 25 μm (over the minimum value of 5 μm required by the equipment for accurate results). The loads were set so that each type of specimen was always tested at its appropriate stress level. Six specimens of each type were tested.

The cement used was Portland cement (Type I) from Lafarge Corp. (Southfield, MI, USA). The aggregate used was fine aggregate in the form of natural sand (100% passing through #4 U.S. sieve, 99.91% SiO_2, with the particle size analysis shown in Fig. 1 of Hou and Chung [8]); no coarse aggregate was used and the sand/cement ratio was 1.0. 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 naphthalene-sulphonic acid) was used in the amount of 1% of the cement weight. ASTM Standard mild steel rebars with diameter of 0.116 in (2.95 mm) were used. The cross-sectional area was 0.011 in^2 (6.83 mm^2). All the rebars were surface-treated prior to inclusion in concrete by one of two methods, namely (1) ozone (0.6 vol.%, in O_2) treatment at 160°C for 10 min, and (2) sandblasting at an air pressure of 90 psi (0.62 MPa). Four parallel pieces of rebars were embedded in each mortar sample along the length of the sample, such that the dis-

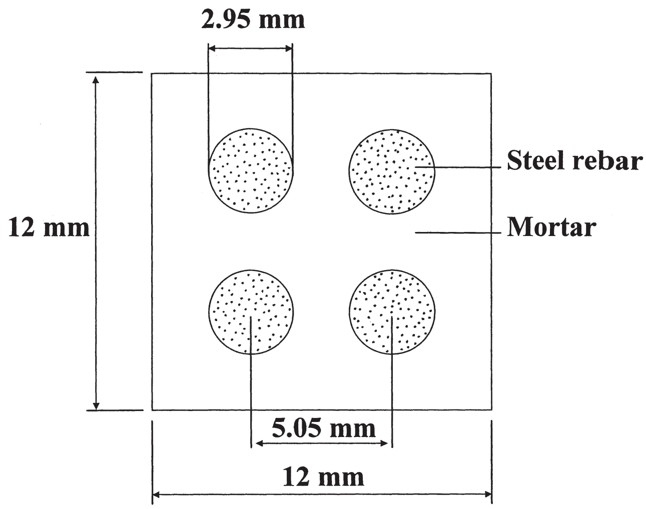

Fig. 1. A schematic illustration of the cross section of a sample, showing the positions of the four rebars in a sample.

tance between two adjacent rebar centers was 5.05 mm, as shown in Fig. 1 by the cross-sectional sketch of a sample.

All ingredients were mixed in a rotary mixer with a flat beater. After pouring the mix into oiled molds, an external electric vibrator was used to facilitate compaction and decrease the amount of air bubbles. The specimens were demolded after 1 day and then allowed to cure at room temperature in air (relative humidity = 100%) for 28 days.

3. Results

Table 1 shows the loss tangent, storage modulus, and loss modulus of plain mortar (no steel or admixture) and mortars reinforced with as-received steel and with steel that had been surface-treated by ozone exposure and sandblasting.

Steel addition increased the loss tangent by two (or more) orders of magnitude, depending on the loading frequency. Both types of steel surface treatment increased the loss tangent. Sandblasting gave the highest loss tangent: 34, 60, and 72% higher than the as-received steel values at 0.2, 0.5, and 1.0 Hz, respectively. For each type of sample, the loss tangent decreased with increasing frequency.

Steel (as-received) addition increased the storage modulus by 120, 74, and 72% at 0.2, 0.5, and 1.0 Hz, respectively. Surface treatment of steel by ozone exposure decreased the storage modulus relative to the values given by as-received steel. Surface treatment of steel by sandblasting caused the storage modulus to increase negligibly, relative to the values given by as-received steel.

Steel addition increased the loss modulus by three or more orders of magnitude, depending on the frequency. It was mainly due to the increase in loss tangent, although the increase in storage modulus also contributed. The loss modulus was negligibly affected by steel surface treatments by ozone, but was increased by sandblasting by 39, 72, and 91% at 0.2, 0.5, and 1.0 Hz, respectively, relative to the values for as-received steel.

4. Discussion

The addition of steel rebars to mortar was found in this work to increase the loss tangent by two (or more) orders of magnitude. The addition of silica fume to mortar also increased the loss tangent by two (or more) orders of magnitude [3]. The effect in the silica fume case is due to the large area of the interface (however diffuse) between silica fume and the cement matrix and the contribution of interfacial slippage (however slight) to damping [3]. Due to the large size of steel rebars compared to silica fume particles, the interface area in the steel case is negligibly small compared to that in the silica fume case. Nevertheless, the effects of steel and silica fume on the damping capacity are comparable. This means that the interface plays a minor role in affecting the damping in the steel case, but a significant role in the silica fume case. In the steel case, the high damping capacity of steel itself (i.e., material damping) must be mainly re-

Table 1
Loss tangent, storage modulus, and loss modulus of mortars with and without steel reinforcement

Property	Sample type	Frequency (Hz) 0.2	0.5	1.0
Loss tangent	A	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$
	B	$(2.73 \pm 0.19) \times 10^{-2}$	$(1.56 \pm 0.08) \times 10^{-2}$	$(7.20 \pm 0.37) \times 10^{-3}$
	C	$(3.32 \pm 0.15) \times 10^{-2}$	$(1.98 \pm 0.17) \times 10^{-2}$	$(1.07 \pm 0.09) \times 10^{-2}$
	D	$(3.65 \pm 0.27) \times 10^{-2}$	$(2.50 \pm 0.22) \times 10^{-2}$	$(1.24 \pm 0.16) \times 10^{-2}$
Storage modulus (GPa)	A	20.2 ± 3.5	27.5 ± 4.3	25.8 ± 3.7
	B	44.2 ± 4.8	47.7 ± 5.3	44.4 ± 5.0
	C	36.9 ± 4.3	41.0 ± 3.9	38.4 ± 3.0
	D	46.0 ± 4.0	51.2 ± 6.4	49.3 ± 5.8
Loss modulus (GPa)	A	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$
	B	1.21 ± 0.22	0.74 ± 0.12	0.32 ± 0.05
	C	1.23 ± 0.20	0.81 ± 0.15	0.41 ± 0.07
	D	1.68 ± 0.27	1.28 ± 0.27	0.61 ± 0.15

Note on sample type designations: A, no rebar; B, as-received steel rebar; C, ozone-treated steel rebar; D, sandblasted steel rebar.

sponsible for the high damping capacity. That surface treatments of steel rebars have relatively minor effects (within the same order of magnitude) on the damping capacity supports the notion that the interface plays a minor role in the steel case.

Both steel addition (this work) and silica fume addition [3] increased the storage modulus of mortar. The modulus increase in the steel case is attributed to the high tensile modulus of steel itself. Since the steel rebars were continuous along the length of a sample, the steel-mortar bond played a minor role, as shown by the small effects of steel surface treatments compared to the effect of steel addition. The modulus increase in the silica fume case is attributed partly to the high modulus of each silica fume particle and partly to the relatively strong bond between silica fume and cement (due to the pozzolanic action of silica fume). The importance of the interface in the silica fume case is supported by the large effect of silica fume surface treatment on the modulus [2,9].

Surface treatment of steel by ozone exposure increased the loss tangent (relative to the value for the as-received steel) but decreased the storage modulus, such that the loss modulus was not affected. In contrast, surface treatment of steel by sandblasting increased the loss tangent while essentially not affecting the storage modulus. These results mean that the coating provided by ozone exposure softened the composite (probably because of the poor stiffness within the coating), but it provided a microstructure that enhanced the damping capacity. On the other hand, the surface roughening provided by sandblasting increased the area of the interface between steel and mortar and enhanced the frictional damping, thereby increasing the loss tangent even more than ozone treatment, while not affecting the stiffness of the composite.

We recommend the use of sandblasting of steel rebars to improve the vibration reduction ability of steel-reinforced concrete. In addition to increasing the loss tangent, as found in this work, sandblasting increases the bond strength through mechanical interlocking and increases the corrosion resistance through cleaning the steel surface and making it more uniform in surface composition [4]. We further suggest the use of silica fume as an admixture, whether in combination with as-received or sandblasted steel, since the silica fume increases the loss tangent and storage modulus [3], in addition to enhancing the steel-concrete bond strength and improving the corrosion resistance of steel in concrete (due to decreased water absorptivitiy) [7].

For any type of sample, the loss tangent decreased with increasing frequency, as expected. As a result, the loss modulus also decreased with increasing frequency. Relative to the values for as-received steel, sandblasting of steel increased the loss modulus by 39, 72, and 91% at 0.2, 0.5, and 1.0 Hz, respectively. Hence, the effect of sandblasting increased with increasing frequency. Even at the lowest frequency of 0.2 Hz, the effect was substantial.

5. Conclusions

Vibration reduction requires a high vibration damping capacity as well as high stiffness. The vibration damping capacity of mortar, as expressed by the loss tangent under dynamic flexure, was found to be increased by two (or more) orders of magnitude upon the embedment of steel rebars in the mortar along the length of the mortar sample. The stiffness, as expressed by the storage modulus, increased by up to 120% upon the embedment of steel rebars. Surface treatment of the steel by sandblasting increased the loss tangent by up to 72% relative to the value for as-received steel-reinforced mortar. Sandblasting had negligible effect on the storage modulus. Surface treatment of the steel by ozone exposure increased the loss tangent by up to 49%, relative to the value for as-received steel-reinforced mortar, but decreased the storage modulus by up to 17%, relative to the value for as-received steel-reinforced mortar. The effects of steel surface treatments were small compared to those of steel addition. The effects of steel addition were comparable to those of silica fume addition to the mortar. The use of sandblasted steel rebars in concrete for vibration reduction is recommended. The combined use of steel and silica fume for vibration reduction is suggested.

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