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Polyolefin fiber-reinforced concrete composites Part I. Damping and frequency characteristics☆

L. Yan[a], C.H. Jenkins[b,*], R.L. Pendleton[b]

[a]Pro-Eco, Oakville, Ontario, Canada L6H 5V9
[b]Department of Mechanical Engineering, South Dakota School of Mines and Technology, Rapid City, SD 57701, USA

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Abstract

The investigation of the dynamic properties of polyolefin fiber-reinforced concrete composites (FRC) was conducted with a free–free beam vibration method. The damping ratio increase and response frequency decreased with an increase in the Maximum Response Amplitude. Crimped fiber and fine smooth surface fiber- (fine fiber) reinforced concrete exhibited better damping than other FRC and plain concrete. This damping was sensitive to the Small Amplitude Response Frequency. The damping ratio, 1% minimum, in crimped FRC was double that in plain concrete at frequencies around 600 Hz and specimen age of 8 weeks. The damping ratios, 0.4% minimum, in crimped fiber and fine-FRC were higher than those in other FRCs and plain concrete only when the Maximum Response Amplitude reached a certain value (0.001 cm) at a frequency range of 1050–1250 Hz and specimen age of 24 weeks. An increase in damping with an increase in the Maximum Response Amplitude was accompanied by a large decrease in response frequency in crimped fiber and fine FRC. The damping ratio decreased and the response frequency increased with vibration cycle; again, strong tendencies existed in crimped fiber and fine FRC.
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1. Introduction

An early investigation by Bock [1] has shown that the damping ratio, ζ, for concrete free from cracks is 0.0032–0.0064, and for concrete with cracks 0.0127–0.0207. Cole [2] reported that the damping capacity of hardened cement paste, mortar, and concrete have values of log decrement, δ ($\cong 2\pi\zeta$), for cement paste ranging from 0.051 for "wet" specimens and 0.025 for the "dry" ones. The values decreased with age and no significant difference was found in damping capacity among paste, mortar, and concrete. It was also reported that as the frequency decreased below 3 Hz, the damping increased in both wet and dry specimens. The Cement and Concrete Association's Report for 1963 [3] suggests that moisture content, rather than composition, is the primary factor influencing damping capacity in concrete. It was also found that there was a tendency for damping to increase as frequency decreased; a specimen giving a log decrement of 0.045 at 5 Hz, for example, gave a value of 0.15 at 0.5 Hz.

In recent years, synthetic fiber-reinforced concrete (FRC) composites have drawn research on their properties [4–6], e.g., strength, toughness, and anti-cracking in their engineering applications. However, knowledge of the dynamic properties of such composites—like damping and frequency characteristics—also has industrial significance.

Research on other composites has shown that—at a given volume fraction of fibers—the highest stiffness is obtained from continuous fibers, while the damping produced by such composites is necessarily low; there is, however, an increase in damping in some short fiber-reinforced composites [7–10]. When a composite with short fiber reinforcement is subject to a small tensile strain cycle, the stress concentration in the vicinity of fiber ends may produce a significant viscoelastic energy loss. Alternatively, the high shear stress on fiber–matrix interface may cause

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* Corresponding author. Tel.: +1-605-394-2406; fax: +1-605-394-2405.
E-mail address: cjenkins@taz.sdsmt.edu (C.H. Jenkins).

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the interfacial bond to fail so that energy is dissipated by friction as the matrix slides over the fiber. It should be noted here that, in most cases reported in literature, the fibers are much stiffer than the matrix, and have lower damping characteristics than matrix, so that the energy loss from the fibers is usually negligible.

In synthetic FRC composites, the concrete matrix is not a good viscoelastic material, and is much stiffer than the reinforcing synthetic fiber. Although synthetic fibers are usually viscoelastic materials, which have damping ratios higher than concrete, they are usually added at low volume fractions in concrete composites. In this case, the mechanism to produce good damping may not come from hysterestic energy loss in matrix due to the strain cycling in the vicinities of fiber ends, nor from synthetic fibers. Recent studies [11–13] on interfaces in synthetic FRC composites have revealed that the interfacial bonding is mechanical, implying that the bonding strength is, in fact, not very strong. Debonding may occur under certain strain and stress conditions surrounding the fibers, which may cause energy loss under alternating loading. Concrete is a brittle material with potential micro-cracks everywhere [11,14]. These cracks may open and close during dynamic flexure, and therefore, the matrix rubs on the fiber surface, resulting in energy loss during vibration.

The objective of this study was to investigate whether or not there exists a difference in the dynamic properties between plain concrete, as a control (CNTL), and polyolefin FRC composite, and if so, what are the characteristics. In what follows we describe an experimental study conducted to discern these characteristics.

2. Experimental

The natural frequency is a characteristic of a structure that depends upon the mechanical properties, geometry, and boundary conditions of the structure. For a free–free beam subject to a flexural free vibration, the natural frequencies may be predicted [15] from the physical properties of the beam.

A free–free beam vibration excited by an impact was employed to investigate dynamic properties of FRCs. The damping ratio (ζ)—derived from typical logarithmic decrement tests—and vibration response frequency for the first mode were used to represent dynamic properties of the specimens. The values of acceleration amplitude measured by using an accelerometer can be used to calculate logarithmic decrement, assuming frequency in successive oscillations does not vary significantly (usually less than 1%).

The amplitude of an acceleration in oscillatory motion is expressed as $a_{max} = X_d\omega^2$, where X_d is the displacement amplitude and ω is the circular frequency in radian per second. Oscillating peak values of amplitude, X_{mv} in millivolts (mV), from the oscilloscope, are related to the displacement amplitude in centimeter (cm) by Eq. (1):

$$X_d = \frac{a_{max}}{\omega^2} = \frac{98.1X_{mV}}{4\pi^2 f^2} \quad (1)$$

where $f = \omega/2\pi$ is the frequency in Hz, and an accelerometer sensitivity parameter of 10 mV/g has been used.

In the following description, displacement amplitude, which was obtained on calculation from acceleration and frequency, is used as the main variable. Damping ratio ζ is calculated using experimental data in Eq. (2):

$$\zeta = \frac{1}{2\pi n}\ln\left(\frac{A_i}{A_{i+n}}\right) \quad (2)$$

where A_i is the amplitude of ith peak, and A_{i+n} is the amplitude of the peak n cycles after the ith peak.

2.1. Specimens

Short polyolefin fibers with different geometric features (crimped or wavy fibers and smooth-surface fibers with different areas of elliptic cross-section) were used as reinforcing elements in common concrete, water–cement ratio of 0.55:1. Five different fibers in the two general categories were used to construct seven different composition specimens. All fibers came from 3M Corp. The fiber types and volume fractions used are listed in Table 1. It is noted that CNTL01 represents plain concrete, which is a control. In the table, the fiber types are named according to their geometric features: "25 × 2, smooth," for example, denotes 25 mils (0.635 mm) in nominal diameter (short diameter of an elliptic cross-section), 2 in. (50 mm) in length, and with a smooth surface, or simply as "25 × 2 s" for smooth surface fiber; and "25 × 2 c" for crimped fiber accordingly.

Plain concrete (30 cm × 10 cm × 15 cm) and FRC specimens were cast in wooden concrete forms, consolidated with a table vibrator, and then cured in lime water for 4 weeks beginning 1 day after casting. They were then cut into suitable thickness by a rock saw. Specimens with dimensions of 30 cm × 10 cm × 2.54 cm and 30 cm × 10 cm × 1.27 cm were used in this study. The specimens cut from the same cast block were labeled with their cast

Table 1
Fiber type and volume fraction in FRC

Cast no.	Fiber type	Volume fraction
CNTL01	Plain concrete	0.0
FRC02	25 × 2 smooth[a]	2.2
FRC04	15 × 1 smooth	2.2
FRC06	15 × 1 crimped	2.2
FRC07	15 × 1 crimped	4.0
FRC08	6 × 1 smooth	0.62
FRC10	25 × 2 crimped	1.1

[a] Diameter (mil) × length (in.), surface feature (1 mil = 0.001 in., 1 in. = 25.4 mm).

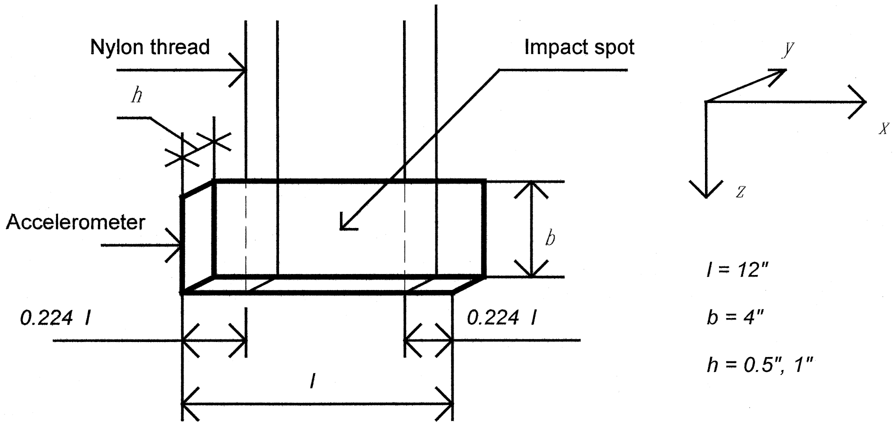

Fig. 1. Schematic of experimental setting and typical specimen dimensions for free vibration testing.

number, which was followed by a digit number to identify individual specimens.

Vibration tests were mainly conducted on two groups with ages of 8 and 24 weeks, respectively. These specimens were, therefore, considered as dry specimens [2], i.e., moisture content had been reduced to a minimum and would have little effect on the results.

2.2. Experiment details

The specimens were hung from a rigid support using two nylon filaments, as shown in Fig. 1. An accelerometer was mounted in the center on one surface of the specimen. Impacting it on the center of the opposite surface with an instrumented hammer excited transverse vibrations in the specimen. A frequency filter was used to allow signals only for the first mode to pass. A Tektronix 2630 modal analyzer was used to record specimen response and hammer excitation, and to produce FFT spectra of vibration signals. Acceleration values (in mV) during free vibration decay response (hereafter referred to as time history) were measured. Additional experimental details can be found in Ref. [11].

2.3. Terminology

The Maximum Response Amplitude did not necessarily occur in the first cycle of response time history in this study. It usually existed among the first three cycles. In order to characterize the degree of an external excitation received by a specimen, and to observe the effect of specimen deflections during vibration, we define an oscillation amplitude, which is absolutely maximum in a given time history as the Maximum Response Amplitude—denoted as A_{mV} (A_{md} as the corresponding calculated Maximum Displacement Amplitude). This can be used as the first cycle amplitude value for logarithmic decrement calculation, and as a starting point to measure frequencies. As far as cyclic sequence is concerned, we define the cycle beginning with the peak of Maximum Response Amplitude as the First Cycle.

The average values from the first 10 and 20 oscillation cycles, beginning from the First Cycle, were used to characterize the dynamic nature of specimens. A_1, A_{11}, and A_{21} from experiments were used to calculate damping ratios. These values are denoted as the ζ_{10} and ζ_{20}. The response frequency averages for the first 10 and 20 cycles are denoted as f_{10} and f_{20}, respectively. Using experimental values from individual cycles also checked these dynamic properties. Some FRC exhibited a very large difference in damping between the First Cycle and the 10th cycle; the damping value from the First Cycle was much greater than the average value from the following 10 cycles. ζ_1 was employed to denote the value for the First Cycle, and ζ_{10} and ζ_{20} denote the values which came from the cycles beginning with the peak following the Maximum Response Amplitude peak.

Comparison among specimens with "identical" natural frequency for the first mode will next be shown necessary in this study because of complex nonlinear properties (frequency and amplitude dependency) of the FRC, which exhibited variations of response frequency and damping with the Maximum Response Amplitude. It is, therefore, convenient to define a response frequency under very small Maximum Response Amplitude (around 100 mV or 10 g) as the Small Amplitude Response Frequency instead of the natural frequency.

3. Results

Tests on specimens with different thickness but the same composition showed that damping ratio varied with the Small Amplitude Response Frequency (therefore the flexural stiffness of specimens). The tendency was that the damping ratio decreased with an increase in the Small Amplitude Response Frequency. The rate of change in damping ratio with the frequency was different for crimped

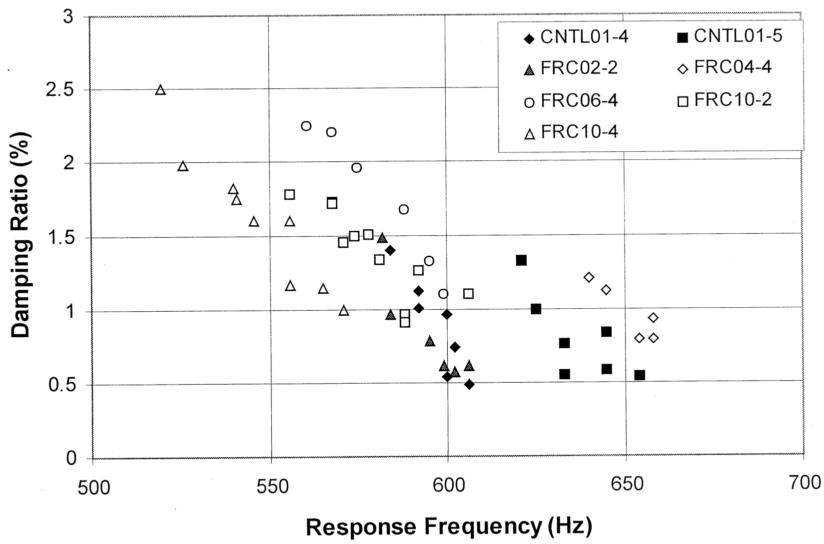

Fig. 2. The correspondence of an increase in damping ratio ζ_{10} to a decrease in response frequency f_{10} in various FRCs and plain concrete (8 weeks old).

FRC composites (CFRC) and plain concrete, with CFRC being more sensitive to the frequency than plain concrete, which exhibited a slight decrease in damping of less than 0.001 from 600 to 1200 Hz at the specimen age of 8 weeks old. Damping ratios in plain concrete specimens at age of 24 weeks, with Small Amplitude Response Frequencies ranging from 1050 to 1200 Hz, was almost the same, although they seemed closer to the lower bound of damping ratios at age of 8 weeks with a Small Amplitude Response Frequency of 1200 Hz, which ranged from 0.0043 to 0.0049. The corresponding damping ratios in plain concrete specimens at different ages with different Small Amplitude Response Amplitudes may be found in Figs. 2 and 3. It was also found that at frequencies around 1200 Hz, the difference in damping between the CFRC and plain concrete vanished. These observations suggest that a comparison in damping between FRCs and plain concrete should be conducted on the basis of "identical" Small Amplitude Response Frequency. 'Identical' here means very close.

Plain concrete and FRC showed that both their response frequencies and damping ratios changed with Maximum Response Amplitude, as shown in Tables 2 and 3. It has been found that the damping ratio increased with an increase in Maximum Response Amplitude, while the response frequency decreased with an increase in the amplitude. It is noted that FRC10-1 (CFRC) had a continuous 26 Hz total decrease in frequency compared to CNTL01-1, which had no discernible change in frequency until reaching the displacement amplitude of 0.0015 cm.

It is in fact very difficult to make specimens having the same Small Amplitude response frequency through the control of specimen thickness due to different inherent

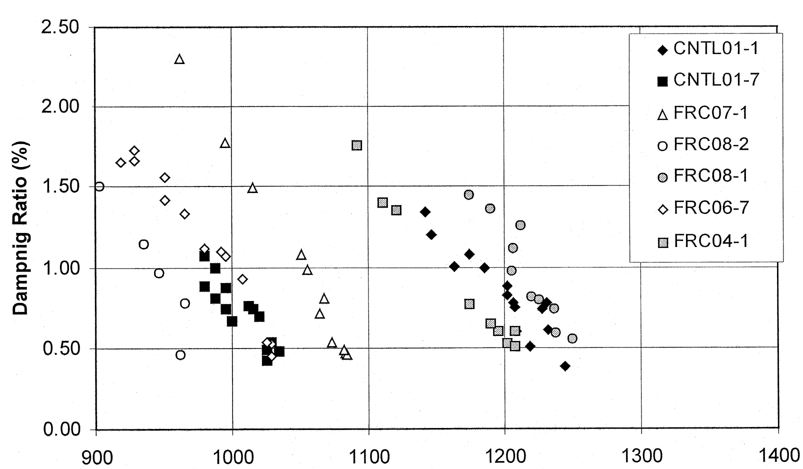

Fig. 3. The correspondence of an increase in damping ratio ζ_{10} to a decrease in response frequency f_{10} in various FRCs and plain concrete (24 weeks old).

properties and the inhomogeneity of concrete and FRC. Measurements of the thickness of the two specimens described above showed that they had only 3% difference in thickness but exhibited more than 10% difference in frequency. Nevertheless, control of thickness was the first step to get 'identical' Small Amplitude Response Frequency. It is also clear from Figs. 2 and 3 that an increase in damping ratio was always accompanied by a decrease in response frequency. Fortunately these figures allow us to choose groups of different specimens with 'identical' Small Amplitude Response Frequencies. Three groups, around 600, 1050, and 1250 Hz, were selected for comparison. The results from these groups should not sacrifice generality.

3.1. Decrease in response frequency, f_{10}, with an increase in maximum response amplitude

Fig. 4 shows variation of response frequency f_{10} with the Maximum Response Amplitude in various specimens at 8 weeks old. An obvious trend was that the greater the Maximum Response Amplitude, the smaller the response frequency of a specimen. The degree of decrement in frequency for various specimens, however, was different. The slope values indicate that the decreasing rate in CFRCs was double those in plain concrete and the smooth FRC composites (SFRC) studied, implying that CFRC had a strong tendency to lose flexural stiffness at larger amplitude. A similar observation was also found for the specimens at an age of 24 weeks [11].

3.2. Increase in response frequency with vibration cycles

The response frequency also varied with vibration cycles, i.e., the more vibration cycles of a specimen underwent, the higher would be the instantaneous response frequency of the specimen. The increment in the frequency, Δf (= $f_{20}-f_{10}$), under various Maximum Response Amplitudes are shown in Fig. 5. The figure shows that the instantaneous response frequency of all the specimens increased with vibration cycles. The plain concrete and SFRC had little change in the increment with an increase in the Maximum Response Amplitude, within a range of about 2–4 Hz. Regressions with linear and power functions performed, respectively, for the two plain concrete specimens show that the curves are close together, and nearly straight and horizontal in the figure, indicating the increment remained unchanged at about 2 Hz. This may imply that the dynamic properties of plain concrete are not very sensitive to vibration response amplitude.

The CFRCs, however, had an increasing increment with an increase in the Maximum Response Amplitude; the increment reached maximum of 11 Hz in the Maximum Response Amplitude range studied. The increment would have been even greater had we compared the instantaneous frequencies measured from the First Cycle and the 20th cycle. These results clearly imply that the dynamic stiffness—a product of dynamic modulus and flexural moment of inertia—of specimens was changing during vibration, getting stiffer with an attenuation of vibration amplitude.

Table 2
Change in vibration frequency and damping ratio in plain concrete (CNTLOl-1) with the Maximum Response Amplitude (8 weeks old, specimen thickness t = 27.9 mm)

A_{mV} (mV)	A_{md} (cm)	f_{10} (Hz)	ζ_{10} (%)
106	1.67e−04	1256	0.43
181	2.85e−04	1256	0.44
219	3.45e−04	1256	0.47
393	6.20e−04	1256	0.47
544	8.58e−04	1256	0.55
854	1.35e−03	1256	0.58
857	1.36e−03	1250	0.72

Table 3
Change in vibration frequency and damping ratio in crimped fiber reinforced concrete (FRC 10-1) with the Maximum Response Amplitude (8 weeks old, specimen thickness t = 27.2 mm)

A_{mV} (mV)	A_{md} (cm)	f_{10} (Hz)	ζ_{10} (%)
94	1.78e−04	1147	0.64
138	2.65e−04	1139	0.55
350	6.75e−04	1136	0.62
700	1.39e−04	1121	0.77
781	1.55e−04	1121	0.77

3.3. Increase in damping ratio with an increase in maximum response amplitude

Fig. 6 shows the damping ratio ζ_{10} increased with an increase in the Maximum Response Amplitude, which was achieved in random order, for specimens having an 'identical' Small Amplitude Response Frequency of around 600 Hz. The figure reveals that the CFRCs had a higher damping ratio than both plain concrete and the SFRCs. The damping ratio was almost doubled by the use of crimped fiber reinforcement. It was also found that FRC04 (15 × 1, s) had damping ratios somewhat greater (40%) than plain concrete, but FRC02 (25 × 2, s) had no discernible improvement in damping ratio compared with plain concrete. This may imply that the fiber diameter and aspect ratio (length to diameter) play an important role in affecting damping property of FRC. As the regressed lines in the figure are extrapolated to zero amplitude, the values of damping ratio are 1% for the CFRCs, 0.7% for FRC04, and 0.5% for FRC02 and plain concrete. The phenomenon that specimens exhibited the property that *damping ratio increases monotonically with an increase in the Maximum Response Amplitude*

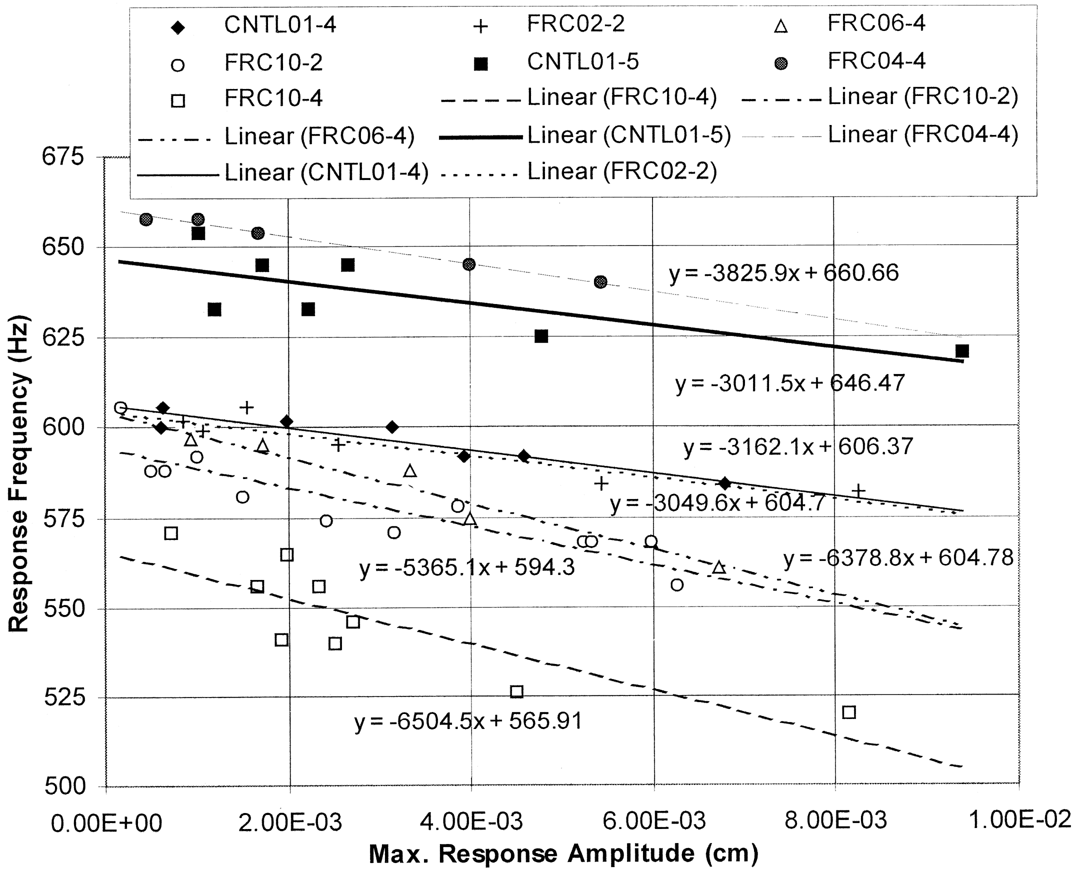

Fig. 4. Variation of response frequency with the Maximum Response Amplitude in FRCs and plain concrete (8 weeks old).

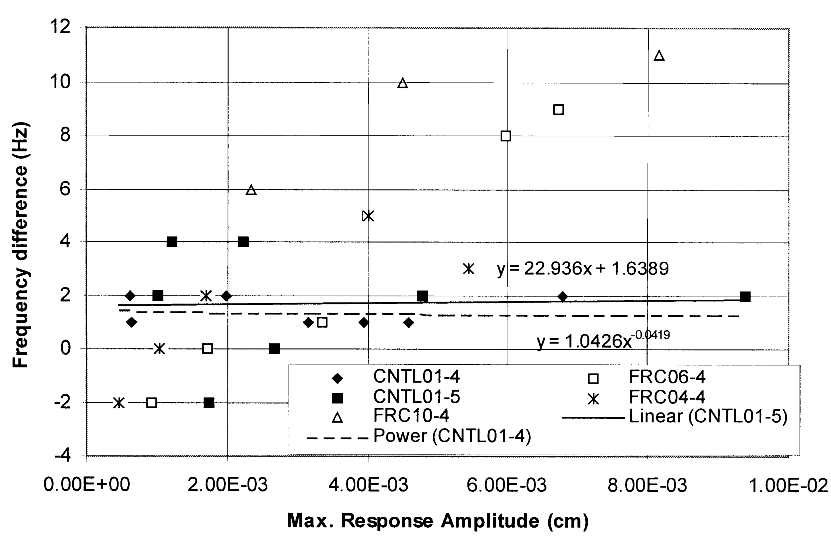

Fig. 5. Increases of response frequency ($\Delta f = f_{20} - f_{10}$) with vibration cycles at various Maximum Response Amplitudes.

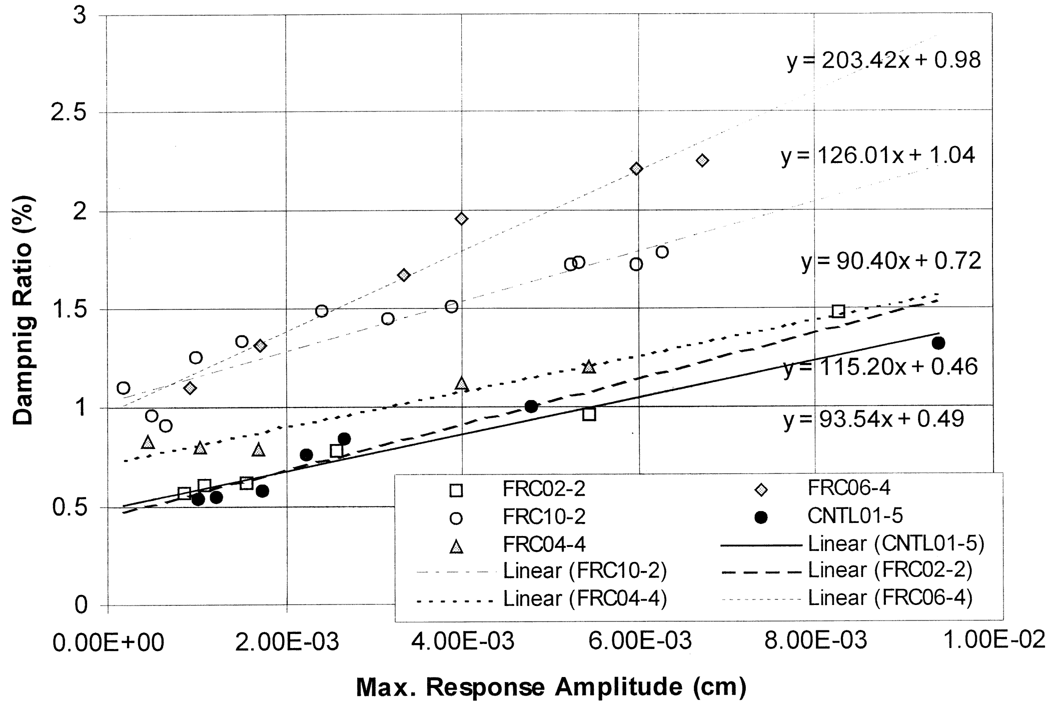

Fig. 6. Increase of damping ratio ζ_{10} of FRC and plain concrete (8 weeks old) with an increase in the Maximum Response Amplitude.

achieved may be called the Damping-Amplitude-Dependent Rule.

Specimens at the age of 24 weeks with Small Amplitude Response Frequencies around 1050 and 1250 Hz exhibited a slight difference from Fig. 6; a typical result is shown in Fig. 7. The CFRCs and the fine-fiber- (6 × 1, s in FRC08) reinforced concrete composite showed better damping in comparison with plain concrete only when the Maximum Displacement Amplitude was greater than a certain value, say 0.001 cm. The figure indicates that all the specimens had a damping ratio of about 0.31–0.45% when the regression lines are extrapolated to "zero" Maximum Response

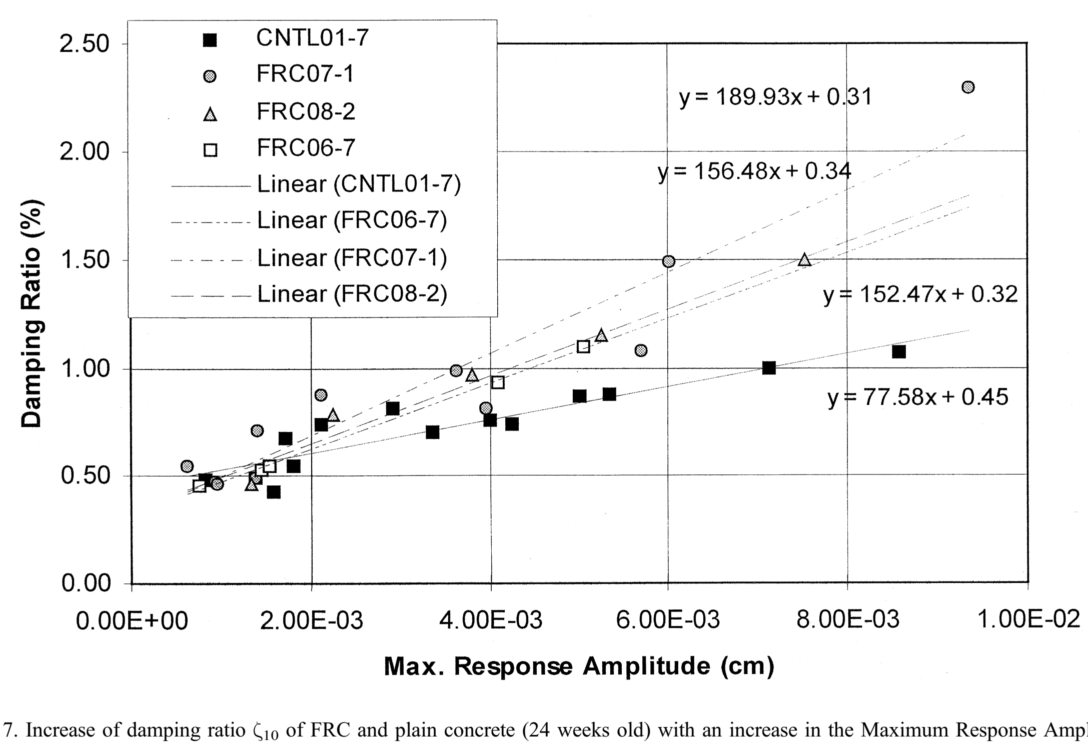

Fig. 7. Increase of damping ratio ζ_{10} of FRC and plain concrete (24 weeks old) with an increase in the Maximum Response Amplitude.

Amplitude, i.e., no significant difference exists among concrete and FRCs. At ages of 8 and 24 weeks, the damping ratio for plain concrete specimens are rather consistent, say, 0.43–0.49%. These data may be considered consistent with the 0.32–0.64% of Bock [1] and 0.40% of Cole [2]. It should be noted, however, that the damping ratios of CFRCs at 24 weeks old decreased considerably when compared with those at the age of 8 weeks with a Small Amplitude Response Frequency of 600 Hz, while that of plain concrete remained almost the same.

3.4. Decrease in damping ratio with vibration cycling

The measurements of damping ratios for the first 10-cycle average (ζ_{10}) and the first 20-cycle average (ζ_{20}) showed that these two damping ratios were different, ζ_{10} being greater than ζ_{20}. This indicates that the damping ratio decreased with a vibration cycles (therefore, vibration amplitude). This decrement ($\zeta_{10}-\zeta_{20}$) was also increasing with an increase in the Maximum Response Amplitude, i.e., the larger the amplitude, the greater the decrement, as shown in Fig. 8. The rate of decrease, however, was different for different FRCs and plain concrete. The decrease in damping ratio with cycling for the CFRCs was greater than those for plain concrete and SFRC (FRC04, 15 × 1, s). This phenomenon was coincident with the observation that the instantaneous response frequency increased with cycling, as depicted in Section 3.2, further confirming that both damping ratio and instantaneous response frequency are vibration amplitude-dependent.

3.5. Sudden drop of damping ratio in the first response cycle

A sudden drop of vibration peak in the First Cycle took place in vibration time histories of CFRCs (FRC06, FRC07, and FRC10) and fine-fiber-reinforced concrete composite (FRC08). A comparison in damping ratio between this drop, ζ_1, and the following decay, ζ_{10}, at various Maximum Response Amplitudes is shown as in Fig. 9. It is seen from the figure that this sudden drop produced a damping ratio ζ_1 much greater (generally double) than ζ_{10}, implying that the damping mechanism for the drop may be different from those for the subsequent decay.

3.6. Recoverability of results for the same specimen

All specimens in this study were subjected to large accelerations in a range 10–400 g. The vibrations were, therefore, very "severe" according to Zeller's scale [16], a scale of vibration intensity. It was observed that specimens could be used only for a limited number of impacts due to the high vibration intensity and concentrated impact spot. The repeatability or recoverability of the experimental results for a specimen depended both on number of impacts and the energy input of each impact. It was not intended to investigate how the input energy affected the dynamic properties. It was observed, however, that a heavy impact

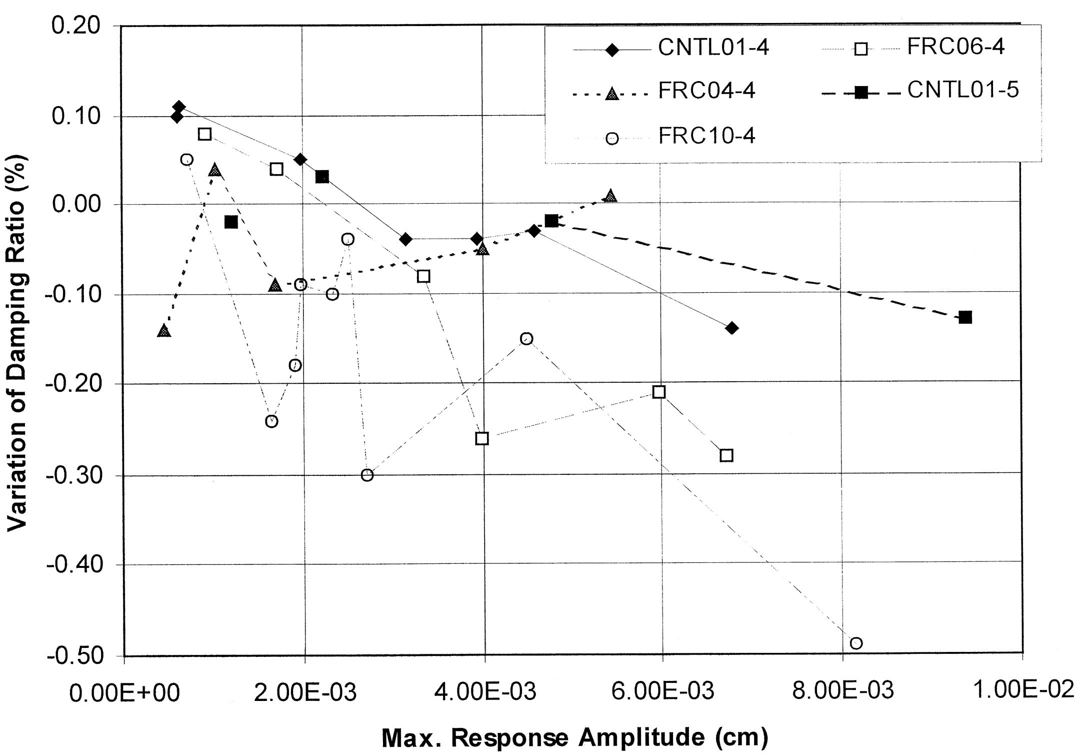

Fig. 8. Decrease in damping ratio ($\Delta\zeta = \zeta_{10}-\zeta_{20}$) with vibration cycles in plain concrete and FRCs (8 weeks old) at different Maximum Response Amplitudes.

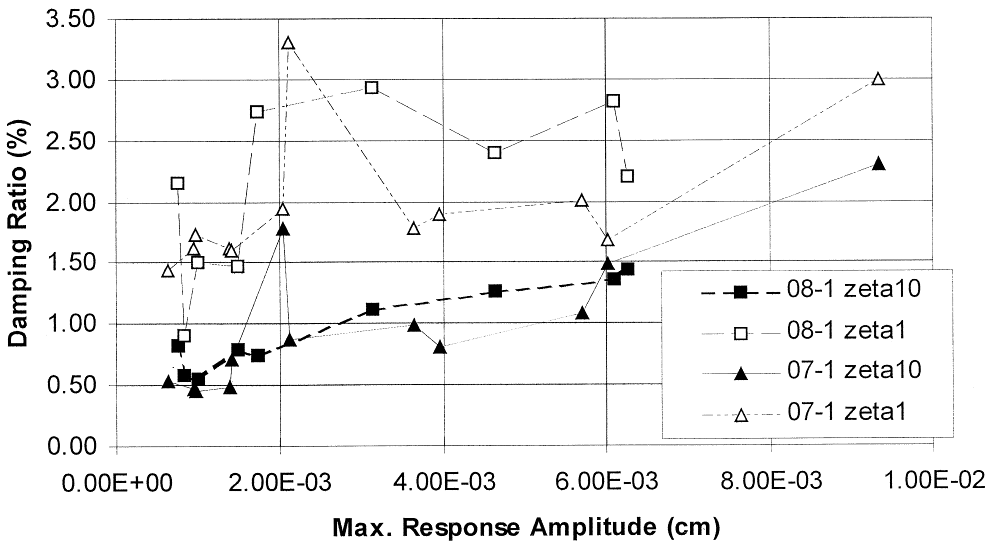

Fig. 9. A comparison of damping ratio between ζ_1 and ζ_{10} in crimped fiber reinforced concrete FRC07-1 and fine fiber-reinforced concrete FRC08-1 (24 weeks old).

causing a large amplitude (for example, 0.008 cm) caused the damping ratios measured in the subsequent impacts to be higher, and the maximum response frequency to be lower, than those obtained at the same amplitude before the heavy impact.

4. Discussion

Experiment has shown that plain concrete has a damping ratio about 0.005 at an age of 8 weeks with a Small Amplitude Response Frequency of 600 Hz, and about 0.004 at an age of 24 weeks with a Small Amplitude Response Frequency of 1250 Hz. This coincides with Bock's data for crack-free concrete [1]. The mechanism controlling damping in concrete is still not clearly known and is not the objective of this study.

Crimped fiber and fine-fiber- (6×1, s) reinforced concrete composites exhibited higher damping than plain concrete and other SFRCs. This obvious increase in damping does not follow the rule of mixtures. By using a damping ratio of 0.035 [17] for polypropylene (a member of polyolefin family) fiber and the damping ratio measured for concrete in the present study, the rule of mixtures (2% volume fiber fraction) shows a damping ratio in FRC is only 12% greater than that of plain concrete. The experiment showed, however, that the damping ratios in CFRCs and fine-fiber- (6×1, s) reinforced concrete composite were not only greater than 12%, but increased with the Maximum Response Amplitude. Furthermore, no discernible damping improvement has been found in coarse fiber- (25×1, s and 25×2, s) reinforced concrete composites.

The Young's modulus of polypropylene fiber ranges from 1.5 [17] to 8 GPa [18], depending on manufacturing conditions. The Young's modulus of concrete is about 20–28 Gpa [17]. Therefore, at the same strain, the stress in the matrix is greater than in fiber. The failure strain for concrete in tension [18] is only about $50–500 \times 10^{-6}$. When the concrete matrix is strained to failure, the fiber may remain in the region far below its yielding, resulting in a negligible hysteretic damping in an individual fiber in addition to the fact of low volume fraction.

Research on other short fiber-reinforced composites [7–9] suggests the damping mechanisms may be the energy dissipation through micro-plastic strain due to the stress concentration in the matrix in the vicinity of fiber ends, or interfacial friction taking place at an amplitude beyond a critical value due to the low interfacial cohesion.

In terms of stress concentration, the reinforcing fiber ends are not sharp enough to cause significant stress concentrations in the matrix [9], and the fiber is not stiff enough to cause an accountable residual stress in the surrounding matrix during curing. Moreover, concrete itself has a damping ratio of no more than 0.5%, as found in this study. Consequently, viscoelastic or hysteretic damping in the matrix due to stress concentration does not account for the increased damping in damping-improved FRCs.

Concrete is a material in which micro-cracks are pervasive, especially under tensile load [14,18]. The potential cracks are formed during curing due to the shrinkage of cement mortar. The addition of fibers will not reduce total crack area and length, but may redistribute and reduce the size of individual cracks [18], because the concrete must shrink to a certain extent during curing, but is lacking in ductility. Bock [1] reported that the cracked concrete exhibits higher damping than crack-free concrete. This was also observed in our experiment where a plain concrete specimen changed its properties after receiving a number of impacts, resulting in a damping ratio as high as 3% or more [11]. Obviously, the cracks Bock regarded are not the potential and micro-cracks formed during curing, and are not our present interest. If the improvement in damping is due merely to the micro-cracks, concrete should have higher damping because cracks in FRC are arrested by fiber addition, and plain concrete may have cracks of larger size. The experiments showed that only crimped fibers and fine-fiber reinforcements produced such an improvement, and plain concrete is among specimens with the lowest damping.

The increase in response frequency with vibration cycling in specimens having improved damping implies the dynamic flexural stiffness of the beam specimens was increasing with a corresponding decrease in response amplitude. If the crack density and sizes were fixed to certain values (as soon as the specimen reached the Maximum Response Amplitude) at the very beginning of the vibration, the increase in the frequency would mean that the crack density and sizes in the cross-section area of the beam were decreasing or the crack sizes were shrinking. It is unlikely for a brittle material like concrete to behave in this way. The slightly increasing of the dynamic stiffness at a smaller oscillating amplitude may be due to the "fiber bridging effect", because when the relative movement along fiber–matrix interface decreases, fiber bridging would be effective again through friction. Therefore, we cannot conclude that the improvement in damping property in some FRCs is merely due to micro-cracks.

Recent works [11,13] on direct observation of the interfaces between polyolefin fiber and concrete matrix under a scanning electron microscope (SEM) shows that the bond between fiber and concrete is mainly mechanical, and may be strengthened by interfacial roughness and anchoring of fiber tendrils in the matrix. Thus, the bond strength would not be expected to be very strong, although its strength has not yet been found by the authors from the literature. Wang et al. [4] reported the bond strengths for other synthetic fibers, e.g., 0.16 MPa for nylon and 0.11–0.29 MPa for polyester. It is assumed that the bond strength for polyolefin fiber–concrete interface would be no more than this order, if the interface is not roughened. If there is no such asperity, the bond strength will be merely static friction, mainly depending on the normal pressure the matrix exerts on a fiber. A sudden debonding—breaking the compact interface, followed by an interfacial slip—will take place when the shear stress on the interface is greater than the bond strength or, alternatively, a relative displacement is greater than a critical value the interface can sustain.

A sudden drop in peak amplitude in the First Cycle indicates a sudden loss of vibration energy. Plain concrete and coarse FRC did not exhibit this phenomenon within the range of the Maximum Response Amplitude studied. This would imply that the sudden drop in the peak amplitude is related to fiber geometry and size, as well as strain and stress conditions in the interface. This may result in a sudden debonding taking place at the fiber ends, and at the intersections of crack and fiber, where the shear strain may be great enough to break bonds. Calculations of energy loss based on these assumptions have been shown to correlate with the experimental results, and can be found elsewhere [11,19]. As soon as this debonding has taken place, it is possible for the interface to have a relative movement between fiber and matrix along the interface. The released potential micro-cracks would be rubbing on the fiber through opening and closing under an alternating strain, the vibration energy thus being further dissipated through this interfacial friction. Therefore, the interfacial slip may be the mechanism for the following cycles after the First Cycle. In this case, the damping ratio may be strain-dependent and repeatable as the Maximum Response Amplitude is reduced. It may be anticipated that, if the Maximum Response Amplitude is small enough, damping for all fresh FRCs and plain concrete would not have much difference; in other words, a good damping in FRC must be triggered by a certain threshold energy.

As the Maximum Response Amplitude reaches a critical value, these cracks will extend their lengths and consume more energy through the extension. In this case, the dynamic properties will not be repeatable when the Maximum Response Amplitude is reduced. Although we have not measured the other mechanical properties after the nonrepeatability occurred, it seems clear that the flexural stiffness of the specimen was lowered as observed by a decrease in vibration response frequency.

5. Conclusions

The dynamic properties of polyolelin monofilement short FRC were studied with a free–free beam vibration method. Fibers in diameters of 25, 15, and 6 mils with smooth surface and crimped shape, respectively, and in length of 1 and 2 in., were used in this study. The following phenomena have been found from this study.

1. The reinforcements with fibers of 25-mil and 15-mil diameters with crimped (wavy) shape improved the damping property of the FRCs by doubling the damping ratio of concrete at a specimen age of 8 weeks and a Small Amplitude Response Frequency around 600 Hz.

2. The reinforcements with fibers of 6-mil diameter with smooth surface, and of 25- and 15-mil diameters with crimped shape improve the damping property of FRCs having an Small-Amplitude Response Frequency around 1050–1250 Hz and an age of 24 weeks, after the strain in the matrix reaches a critical value for these specimens.

3. The damping in the above mentioned FRCs exhibits a variation with the Maximum Response Amplitude, i.e., the greater the amplitude, the greater the damping ratio. Although this tendency exists in other FRCs and plain concrete, it is not as strong as those in the "damping-improved" FRCs.

4. The damping-improved FRCs exhibit a variation of response frequency inversely with the Maximum Response

Amplitude, i.e., the greater the amplitude, the lower the frequency. Although the same trend occurs in both plain concrete and coarse SFRCs, it is not as strong as those having improved damping.

5. The damping-improved FRCs exhibit an increase in instantaneous response frequency with vibration cycling. This trend also increases with an increase in the Maximum Response Amplitude in the FRCs; no such increase was found in plain concrete.

6. The damping-improved FRCs exhibit an obvious decrease in damping ratio with vibration cycles.

It is, therefore, concluded that crimped fiber and fine-fiber reinforcements can improve damping of concrete composites. In these damping-improved FRCs, an increase in damping is always accompanied by a decrease in response frequencies; and the damping and the response frequency are amplitude- (and therefore, strain) dependent. It is believed that the improvement in damping is due to the interfacial debonding and the subsequent interfacial friction. The details of these mechanisms can be found in Ref. [19].

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