Chapter 2
Examination of the Dynamic Performance of Textile Reinforced Concrete with Post-consumer Waste Denim Fibers

Rachel Hollingsworth and Yohanna MejiaCruz

Abstract The disposal of clothing and textiles represents a rapidly growing environmental burden, with post-consumer denim comprising a large share of the waste stream that is rarely recycled into high-value products. At the same time, cementitious composites, one of the most widely used construction materials, are limited by their brittle nature and low energy dissipation capacity under dynamic loads. This study explores a potential link between these two challenges by evaluating post-consumer denim fibers as reinforcement in textile-reinforced concrete (TRC). For this purpose, denim fibers were incorporated at 0.5% and 1.0% by weight of cement and compared with control specimens through compression, three-point bending, and free vibration tests at various load stages. The results indicate that the addition of denim fibers enhances damping capacity and stiffness retention after cracking, and also increases the modulus of rupture, with the most consistent improvements observed at a 1.0% addition. A slight reduction in compressive strength was also observed compared with the control mix, which could reflect trade-offs in fiber–matrix interaction. However, given the limited number of specimens and the variability in the results, further testing is needed to establish the robustness of these trends. The findings suggest that denim fibers have the potential to improve the dynamic performance of cementitious composites while simultaneously offering a scalable reuse pathway for post-consumer textile waste.

Keywords Dynamic performance · Textile reinforced concrete · Free vibration · Damping ratio · Denim fibers

Introduction

Clothing and textile disposal poses a growing environmental challenge [1]. More than 90 million tons of textiles are discarded annually worldwide, including 16 million tons in the US, which significantly contributes to landfill volumes, greenhouse gas emissions, and water pollution [2, 3]. Producing denim is a resource-intensive process, as a single pair of jeans requires a considerable amount of water and generates substantial carbon emissions. Despite the scale of this problem, studies report that less than 1% of post-consumer textiles are recycled into new textiles, where most are down-cycled into low-value products, such as insulation or industrial materials. Given the limited recycling options currently available, identifying alternative sectors that can utilize textile waste on a large scale is essential. The construction industry, with its constant and high-volume demand for cementitious materials, presents a promising pathway for reusing post-consumer textiles, such as denim, combining environmental benefits with potential improvements in structural performance. Cementitious composites, such as concrete and mortar, are indispensable to modern infrastructure because of their strength, durability, and relatively low cost [4]. These advantages explain their widespread use and make them one of the most consumed construction materials worldwide. Recent advances, including the incorporation of alternative aggregates, have further expanded their applications [5]. Nevertheless, despite these benefits, the brittle nature and low inherent damping of concrete and mortar contribute to vibration-induced serviceability concerns, since limited energy dissipation capacity leads to higher vibration amplitudes under dynamic loads [6]. Common sources of such excitations include wind, machinery, human and vehicle traffic, and seismic loading. Addressing these shortcomings requires reinforcement strategies that not only retain the advantages of cementitious

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composites, but also enhance their performance under dynamic effects. In this capacity, textile fibers have shown potential in improving stiffness, crack resistance, and energy dissipation [7, 8, 9, 10], thereby offering an alternative pathway to more resilient and sustainable cementitious materials.

Textile Reinforced Concrete (TRC) is a relatively new approach that has demonstrated potential in improving properties such as toughness and crack control in cementitious composites, although research in this area remains relatively limited [11, 12]. Most existing studies have emphasized strength, toughness, and crack control under static or quasi-static loading, while damping and vibration response are comparatively unexplored. In the few cases where dynamic behavior has been examined, the focus has been mainly on high-performance fiber textiles made from carbon, glass, or aramid materials [13, 14, 8, 15, 16, 17]. In contrast, post-consumer textiles such as denim remain largely unexplored in cementitious composites. This could be partly due to concerns about the long-term durability of cellulose-based fibers in the alkaline cement matrix, where degradation processes can weaken untreated natural fibers [18]. However, denim offers potential advantages in terms of availability, low cost, and sustainability that warrant investigation, particularly with respect to its influence on dynamic performance.

Some research on denim fibers has primarily focused on applications outside structural concrete. For example, denim has been investigated as an eco-friendly binder in acoustic panels [19] and as a modifier in bitumen, where it improved rutting resistance and reduced penetration, ductility, and temperature susceptibility [20]. While these findings highlight the potential of denim as an enhanced concrete addition, they leave open important questions about how alternative, low-cost fibers influence stiffness, energy dissipation, and mechanical behavior in cementitious composites. Addressing this gap, the present work investigates how post-consumer denim can be utilized to enhance the mechanical and dynamic properties of cementitious materials. In this study, shredded denim fibers from post-consumer jeans were incorporated into concrete mixes at 0.5% and 1.0% by weight of cement, alongside a control mix without fibers. The methodology involved a comprehensive evaluation of the impact of fiber additions on both cylinders and short-beam specimens. Simply supported beams were subjected to free vibration testing at different stages of load application to evaluate stiffness retention and dynamic response. This manuscript presents the detailed results and comparisons across mixes, highlighting the role of denim in modifying both static and dynamic properties of cementitious composites.

Experimental Methods

This section outlines the experimental program developed to evaluate the incorporation of post-consumer denim fibers into cementitious composites. The methodology details the materials used, the preparation of cylindrical and beam specimens, and the testing protocols adopted to assess both mechanical and dynamic behavior. By combining different specimen geometries, the program captures fundamental material properties while also addressing dynamic performance under more applied loading conditions. The testing framework was selected to investigate not only strength and stiffness retention but also the dynamic response of fiber-reinforced composites, thereby providing insights into the potential of denim fibers as a sustainable reinforcement material.

Materials

Denim Fibers

Post-consumer denim textile fibers were used to reinforce the TRC specimens. The denim was collected, washed, and dried before being manually shredded into fibers measuring approximately 50 × 0.5 mm, as illustrated in Figure 1. The fiber length corresponds to roughly one-third of the beam depth (152 mm), a ratio recommended to control preferential orientation effects during the casting process and to promote effective crack bridging [21]. The fiber width, on the other hand, was determined by the natural yarn structure of the denim, resulting in an aspect ratio of approximately 100:1, which falls within the range commonly reported for natural and recycled fibers used in cementitious composites [22, 23, 24]. To minimize bias from the fabric source or condition, fibers were shredded from multiple post-consumer garments and combined before being incorporated into the concrete mixtures.

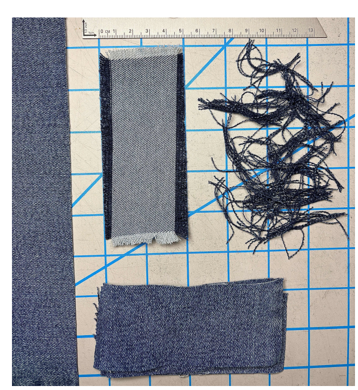

Fig. 1 Post-consumer Denim Fibers

Specimen Preparation

For this study, beam specimens measuring 152 × 152 × 610 mm (6 × 6 × 24 in.) and cylindrical specimens measuring 102 mm (4 in.) in diameter and 203 mm (8 in.) in height were cast and tested to evaluate their mechanical and dynamic properties. Three fiber contents were investigated: 0% (control), 0.5%, and 1.0% by weight of cement. These percentages were selected based on previous studies of natural and recycled fibers in cementitious composites that indicate low-volume additions showed toughness and energy dissipation enhancement while avoiding significant reductions in workability or strength [25]. The number of specimens prepared for each mix and test type is summarized in Table 1. Three replicates were produced for each fiber content to provide a minimum of data for statistical comparison.

Table 1 Test Specimen Matrix.

Specimen	0%	0.5%	1.0%
Cylinders	3	3	3
Beams	3	3	3

Concrete Mix and Casting

Quikrete Portland Cement Type I was used for all mixes conforming to ASTM C150 specifications for Type I Portland cement and contains no additives. Coarse aggregates with a maximum size of 19 mm (¾ in.) and river sand with a fineness modulus of 2.70 were used for the mix. The water-to-cement ratio was fixed at 0.68 for all batches.

Fig. 2 Cylinder & Beam Specimens

Mixing was performed in a Marshalltown 300DD steel drum mixer. The coarse aggregate, sand, and cement were first dry-mixed, after which water was gradually added to control uniform hydration. Once the water was incorporated (approximately after three minutes of mixing), the shredded denim fibers were added in small increments. However, because the fibers tended to clump, care was taken to separate them manually during addition. Despite this, some fiber agglomeration was unavoidable; its potential influence on the results is discussed later in this paper.

After all the fibers were added, the concrete was mixed for an additional two minutes to enhance fiber dispersion. The workability of the concrete was checked using the slump test. The fresh concrete was cast into beam and cylinder molds, as shown in Figure 2, and then placed in a curing room maintained at 95% relative humidity for 14 days. To limit evaporation and control adequate hydration, water was periodically applied to the beam specimens during curing.

Testing

Samples were tested at 14 days. Compressive strength tests on the concrete cylinders were performed using a Forney F-250-FL manual compression testing machine, as shown in Figure 3. The procedure followed ASTM C39 specifications. A constant load was applied at a frame de-rated to 30,000 lbf [130 kN] over a cross-sectional area of $81.07 cm^2$, and the maximum load at failure was recorded to obtain the compressive strength of each specimen.

Flexural strength of the beam specimens was determined using a Humboldt Model H-3030 concrete beam tester (see Figure 4). The first control beam (0% fibers) was subjected to a gradually applied load to observe crack initiation along the tensile face before free vibration testing. However, no visible cracking occurred, and the specimen failed abruptly. A second control beam was then loaded incrementally and tested in free vibration to establish an appropriate load range that could induce controlled cracking without premature failure. Based on these trials, along with the maximum failure loads recorded, the testing protocol was refined to include loading stages of 3000 lbf and 4000 lbf. All subsequent specimens were tested in free vibration at three intervals: prior to loading, after 3000 lbf, and after 4000 lbf. The maximum applied load at failure was recorded for each specimen to obtain the modulus of rupture for all elements.

Fig. 3 Compression Test Machine
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The free vibration tests were carried out to identify the first mode of vibration of the short beam specimens, including the fundamental frequency and damping ratio. A PCB accelerometer with a sensitivity of (±5%) 10.0 V/g (1.02 V/(m/s²)) was mounted at midspan on the top surface of each beam to record the response. Excitation was applied by a light tap at midspan on the underside of the beam, aligned with the accelerometer location using the rubber end of a hammer. The signals were acquired using a National Instruments M-9234 input module, with custom Python v.3.13 scripts and the `nidaqmx` library used for data collection at a sampling frequency of 2048 Hz. After reviewing the sensor specifications, it was noted that the operational frequency range of the accelerometer was below the fundamental frequency of the beam specimens. Therefore, the authors advise that the reported results should be interpreted with caution, as the measurements may underestimate the true dynamic response. The free vibration testing setup is illustrated in Figure 5.

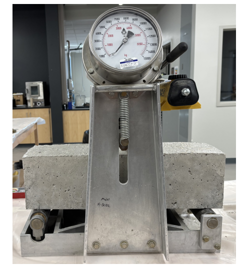

Fig. 4 Three Point Bending Test

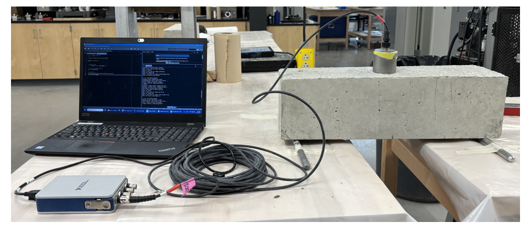

Fig. 5 Free Vibration Testing Setup

Results and Analysis

The experimental program generated results on both the dynamic response (damping and flexural stiffness) and the static mechanical properties (modulus of rupture and compressive strength) of the TRC specimens. The following sections present these findings.

Dynamic Properties: Damping and Flexural Stiffness

Damping Ratio

The damping ratios of the beam specimens were extracted from the free vibration responses using the logarithmic decrement method. Multiple acceleration–time signals were recorded for each specimen to control consistency, and the mean and standard deviation of the damping ratios were computed for each fiber content. The results are summarized in Figure 6, which compares damping behavior across three load stages: (a) unloaded (elastic range), (b) 3000 lbf (pre-cracking), and (c) 4000 lbf (cracking).

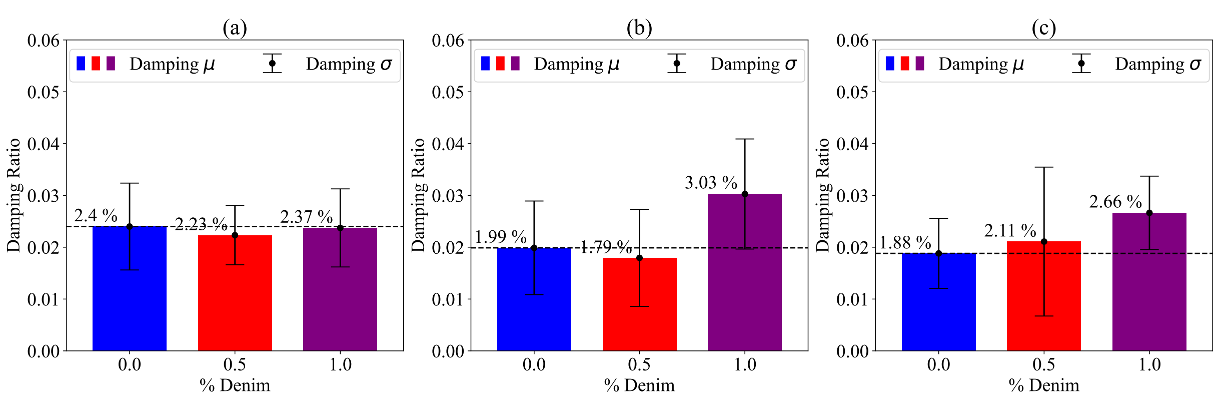

Fig. 6 Damping Extracted From Free Vibration Tests At 3 Load Stages a) Unloaded, b) 3000 lbf Load, c) 4000 lbf Load

In the unloaded condition, no significant differences were observed between the control, 0.5%, and 1.0% mixes, with average damping ratios ranging from 2.2% to 2.4%. This suggests that denim fibers did not significantly influence energy dissipation at small strain levels, likely because microcracking had not yet initiated and the fiber–matrix interaction was not activated.

At 3000 lbf, corresponding to early post-cracking behavior, the mixes diverged. The 0.5% specimens exhibited a reduction in damping ratio to approximately 1.8%, indicating that the fiber may have been insufficient to counteract the loss of energy dissipation caused by crack initiation. In contrast, the 1.0% specimens exhibited an increase in damping capacity to approximately 3.3%, indicating that a higher fiber content could have promoted effective crack bridging, resulting in enhanced energy absorption once cracks began to form.

At 4000 lbf, representing further crack development, both fiber-reinforced mixes performed better than the control, with average damping ratios of 2.1% for the 0.5% specimens and 2.7% for the 1.0% specimens. These results indicate that denim fibers mitigated the reduction in damping typically associated with crack propagation. A plausible explanation is that the fibers delay the transition from distributed microcracking to localized macrocracking, thereby sustaining energy dissipation capacity at higher load levels.

Flexural Stiffness (EI) & Stiffness Retention Ratio (REI)

The dynamic flexural stiffness of the beam specimens was extracted from the fundamental natural frequencies obtained during the free vibration tests, using Equation Equation 1. In this context, ω_n represents the angular natural frequency, L is the free span length of the beam, EI denotes the dynamic stiffness, and M stands for the mass per unit length of the beam. EI dynamic values were calculated both before cracking (within the elastic range) and after cracking at the defined load stages, namely 3000 lbf and 4000 lbf.

$$\omega_n = \left(\frac{n\pi}{L}\right)^2 \sqrt{\frac{EI}{M}} \tag{1}$$

$$REI = \frac{EI_{post}}{EI_{pre}} \tag{2}$$

To evaluate post-cracking performance, the stiffness retention ratio (REI) was defined as the ratio of post-cracking stiffness to pre-cracking stiffness of the control sample, as shown in Equation 2. The calculated REI values at 3000 lbf and 4000 lbf are presented in Figure 7.

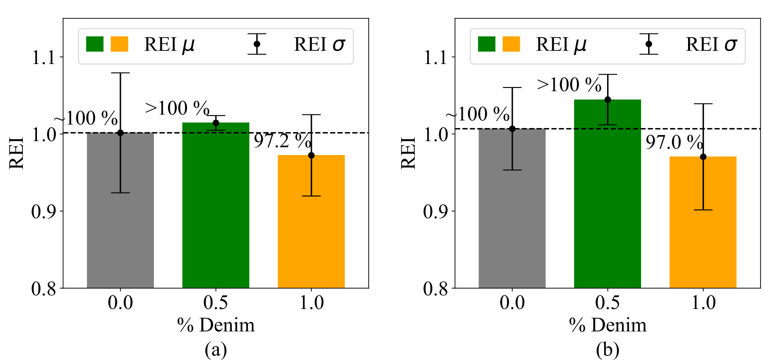

Fig. 7 REI for (a) 3000 lbf and (b) 4000 lbf

At 3000 lbf (Figure 7a), the 0.5% fiber specimens showed a modest increase in REI of approximately 1.4% relative to the control, with a standard deviation of 3.3%. Although the 0.5% specimens appeared to retain stiffness above 100%, this outcome is not physically meaningful, as stiffness should not increase once beams are subjected to higher loads and begin to crack. These values are therefore inconclusive and are attributed to the low resolution of the displacement sensors relative to the small changes being recorded, which introduced variability and inflated values in this group.

In contrast, the 1.0% fiber specimens exhibited a reduction of about 2.8%, with a higher deviation of 5.3%. The last suggests that although the average stiffness retention remained close to 97%, the large scatter between sample points shows inconsistent performance. Considering this variation, the data indicates the addition of denim at this dosage effectively maintained stiffness at this stage of loading, preventing the loss typically associated with early cracking.

Table 2 Comparison of REI and Damping at Loading Conditions

% Denim	REI μ (%)		Damping μ (%)	
	3000	4000	3000	4000
0	100.15	100.68	1.99	1.88
0.5	101.44	104.46	1.79	2.11
1	97.23	97.04	3.03	2.66

At 4000 lbf (Figure 7b), the trends persisted. The 0.5% specimens exhibited an average gain of 4.5% in REI with a relatively low deviation from the mean (3.3%), which reinforces that moderate fiber content may contribute to stable stiffness retention under progressive cracking. On the other hand, the 1.0% specimens again showed a reduction of nearly 3.0%, this time with an even larger deviation of 6.9%. On average, these specimens retained approximately 97% of their stiffness. A comparison of the REI results with the damping results at each condition is presented in Table 2.

Modulus of rupture

The modulus of rupture (MOR) values obtained from the three-point bending tests are summarized in Table 3. The control specimens (0% fiber content) exhibited an average MOR of 4.29 MPa, while the 0.5% and 1.0% fiber-reinforced specimens reached 4.59 and 4.63 MPa, respectively, which is an increase of 6.99% and 7.93%. These results demonstrate that the inclusion of denim fibers increased the ultimate flexural capacity of the TRC beams relative to the control. As shown in Table 3, the improvement was most pronounced at 1.0% fiber content, which achieved the highest MOR among all groups. This trend indicates that denim fibers enhance the crack-bridging capacity of TRC and delay the onset of brittle failure. While the increases were moderate compared to stiffness and damping improvements, the MOR results confirm that denim fibers contribute to the overall flexural strength of TRC elements.

Table 3 Modulus of Rupture.

Specimen	0%	0.5%	1.0%
fr (MPa)	4.29	4.59	4.63

Compressive strength

The results of the compression tests on the concrete cylinders are summarized in Figure 8. The 0.5% and 1.0% fiber-reinforced specimens exhibited average compressive strengths of 18.86 and 21.84 MPa, corresponding to decreases of 22.6% and 10.4% compared with the control specimens. It is worth noting that there was a considerable standard deviation present in the data for the 0.5% cylinder samples, this was likely due to visible voids in the base of one of the cylinder samples that had not been sufficiently compacted, resulting in a much lower compressive strength measured for that sample.

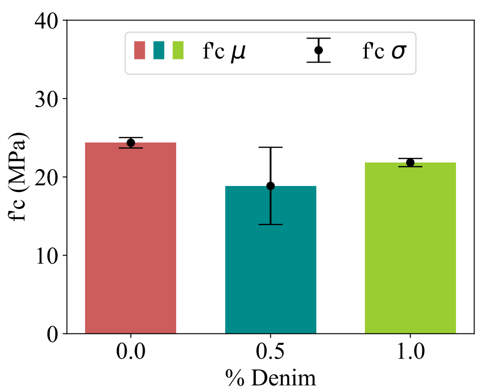

Fig. 8 f'c control 0%, 0.5% and 1.0% samples

This trend aligns with other studies that showed findings where fibers slightly reduced compressive capacity due to increased porosity or weak fiber–matrix bonding [23, 26, 27]. Larger decreases in compressive strength were generally seen at higher percentages of fiber content. However, one study did see an increase in compressive strength at a higher fiber content of 1.5% [28]. Further investigation into the effects of higher fiber contents is necessary to determine the optimum percentage of fiber to improve the mechanical properties of TRC.

It was necessary to test the specimens after 14 days of curing rather than the standard 28 days. According to previous studies, this shorter cure time likely contributed to the lower compressive strengths that were measured in the lab[28, 23]. The relationship between compressive strength and fiber content in this study is illustrated in Figure 8.

Conclusion

This study investigated the dynamic performance of textile-reinforced concrete (TRC) incorporating post-consumer denim fibers as a sustainable reinforcement material. The results demonstrated that denim fibers improved the damping capacity and post-cracking stiffness retention of TRC beams, with the 1.0% fiber content samples showing the greatest enhancement in damping and around 97% stiffness retention post-cracking. The stiffness retention ratio and modulus of rupture confirmed that fiber reinforcement contributed to greater ductility and delayed brittle failure. Although compressive strength decreased slightly with fiber addition, the tradeoff was offset by gains in flexural behavior and energy dissipation capacity.

In the interpretation of the data, it should be remembered that there was a considerable amount of variability, especially in the results from the 0.5% fiber content specimens. Results showed a stiffness retention ratio (REI) of over 100%, which does not have any physical meaning as stiffness in concrete should decrease post-cracking. It was determined that low sensor resolution in the range of the fundamental frequencies of these elements is likely the reason for this variability. Further investigation with a larger number of specimens and proper sensor frequency band is necessary to obtain more conclusive results.

Overall, the findings highlight the potential of denim fibers to improve the dynamic performance of TRC while also providing a viable recycling pathway for a significant textile waste stream. By integrating waste-derived fibers into cementitious composites, this work advances both structural performance and sustainability objectives, offering an alternative to more costly technical textiles. By addressing both performance gaps in TRC research and the challenge of textile waste management, this study demonstrates that post-consumer denim can serve as a practical and sustainable fiber reinforcement for concrete applications.

Future Work

While the present study demonstrates the potential of denim fiber reinforcement in TRC, further research is needed to expand the scope and strengthen the reliability of the findings. Future investigations should focus on extending the testing program to longer structural elements to excite multiple modes of vibration, with measurements taken from multiple sensors rather than a single accelerometer. Additional studies are also needed to evaluate a wider range of fiber contents to identify the optimal percentage for maximizing improvements in damping and stiffness. Further work should examine the influence of denim fibers on the stress–strain behavior of TRC, as well as incorporate a larger number of specimens to improve the statistical reliability of the results. In addition, Scanning Electron Microscopy (SEM) analysis would be a valuable contribution, providing a detailed assessment of fiber dispersion, orientation, and bonding mechanisms, and better correlating microstructural observations with observed mechanical and dynamic properties.

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