Material Characterization of UHPC with Recycled Fibers for Future Large-Scale Structural Applications

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Abstract

Ultra-high performance concrete (UHPC) continues to emerge as a robust concrete solution with enhanced microstructure and superior mechanical behavior compared to conventional concrete. Many of the high-end UHPC commercial mixtures are proprietary, which limits the opportunities to bring material costs down without going for full non-proprietary mixtures. Nevertheless, whether proprietary or non-proprietary UHPC mixtures are considered, steel fibers remain the most expensive component, hindering large-scale applications and mass production. Thus, considering cost-effective options or alternatives for steel fibers along with the continuous development of non-proprietary or semi-proprietary UHPC mixtures can be the next big leap in the UHPC world. In this study, recycled fibers and wires derived from landfill tires are considered to provide an alternative component for manufactured steel fibers making the UHPC mixture significantly cheaper, greener, and more sustainable. Preliminary material characterization of UHPC samples is conducted herein to investigate the effect of recycled steel fibers with different volumetric ratios and compare it against reference samples with traditional high-end manufactured steel fibers. Samples from small batches with different fiber ratios are tested at early and late ages through axial compression, direct tension, and flexural loading. This project will be further extended to consider large-scale pan mixing at precast plant in California, as part of exploring seismic UHPC bridge columns with recycled wires, which is briefly introduced here as well.

Keywords: UHPC, recycled fibers, direct tension testing, compressive behavior, flexure testing

1. Introduction

The search for more reliable and better building materials led to the development of more robust cementitious materials such as ultra-high performance concrete (UHPC). The exceptional mechanical properties and superior durability of UHPC can be attributed to the careful selection of fine components with the help of steel fibers increasing the compressive and tensile strength significantly. In recent years, UHPC has been used in various bridge constructions and rehabilitations, focusing on overlay and field joint applications. In addition, the Federal Highway Administration (FHWA) and Precast/Prestressed Concrete Institute (PCI) made efforts to explore and create guidelines for using UHPC in larger structural applications such as I-girders and U-beams. Although UHPC has been emerging as a viable concrete material for large structural applications, the expensive cost driven by the materials and the proprietary (P) nature made UHPC somehow constrained attractive, and further studies regarding economical UHPC are still needed.

Research studies have been conducted to explore options on reducing the cost of UHPC. One type of emerging efforts is to investigate non-proprietary (NP) UHPC. In NP-UHPC, the advantage is that it allows fabricators to select UHPC components; however, the disadvantage is the weaker mechanical properties and the need for more experimental trials for scalability. Because of the advantages and disadvantages of P and NP-UHPC, a new way of furnishing UHPC needs to be developed to address the abovementioned concerns. Semi-proprietary UHPC (SP-UHPC), a hybrid of proprietary and NP-UHPC, could provide an excellent alternative to full P-UHPC mixes, which can be considered economical and eventually more green and sustainable. SP-UHPC aims to reduce proprietary components (typically a proprietary binder) and use local materials sourced at the user's discretion. For example, precast fabricators can use sand, cement, and admixtures in their plants. In addition, steel fibers, an expensive UHPC component, can be replaced with raw recycled fiber and wires processed from landfill tires. However, further studies are needed in studying recycled fibers for SP-UHPC, including its applications in large structures.

Research studies have been conducted on using recycled fibers in UHPC. Recycled fibers, except with rubber impurities, showed acceptable mechanical properties regarding compression and split tensile strength (Yang et al. 2019). Another very recent study showed that 0.5-1% recycled steel fibers hybrid with industrial fibers improved the quasit-static and dynamic mechanical properties of UHPC (Zhong et al. 2023). Despite the promising result of recycled fibers in UHPC, research studies investigating recycled fibers are still rather limited and focused primarily on limited or small applications. Thus, this study aims to introduce a more ambitious economical UHPC by introducing recycled fibers in SP-UHPC for large-scale structural applications. The paper is presents first the several experimental trials conducted to help understand how to optimize the recycled fibers use in UHPC for maintaining good mechanical properties. The paper also briefly introduces upcoming future work that aims at implementing recycled fibers for full precast seismic bridge columns with different types of accelerated bridge construction (ABC) connections.

2. Experimental Test Program

2.1. UHPC Design Matrix

In this study, components from both proprietary and non-proprietary UHPC materials were combined to produce semi-proprietary UHPC. Cor-Tuf UHPC provided a proprietary pre-blended dry mixture (CT 25) that is responsible for material robustness and scalability. The non-proprietary components, such as the fine sand and cement, were obtained in a local hardware store in Reno, Nevada. High-Range Water-Reducing Admixtures (HRWRA) were used to achieve good flowability accounting for the low water-binding ratio. Lastly, since part of the objective is to assess the performance of recycled fibers in UHPC, the UHPC with recycled fibers was compared to the UHPC with manufactured fibers. Figures 1a and 1b show the physical difference between the manufactured and recycled fibers. The manufactured fibers were obtained from Tokusen with dimensions of 0.200 mm ×13.0 mm (0.0079 in × 0.511 in) and a tensile strength greater than 3000 MPa (435 ksi). Comparatively, the recycled fibers derived from landfill tires have a similar average diameter of 0.2 mm (0.008 in.); however, the length varies from 3-20 mm (0.12-0.79 in), and the tensile strength is relatively lower, resulting in about 1950 MPa (283 ksi) on average. A total of eight batches were produced using a high-shear mixer, and the design matrix is summarized in Table 1. The batch ID follows the abbreviation of the volumetric ratio of the fibers and the types of fibers (e.g., 1M and 1R as 1% manufactured and 1% recycled fibers, respectively). The fiber ratios varied from 1% to 4% of the total volume of UHPC components. However, since the density of the recycled fibers is not well specified as manufactured fibers, the recycled fibers were provided in same weight as counter manufactured fibers cases.

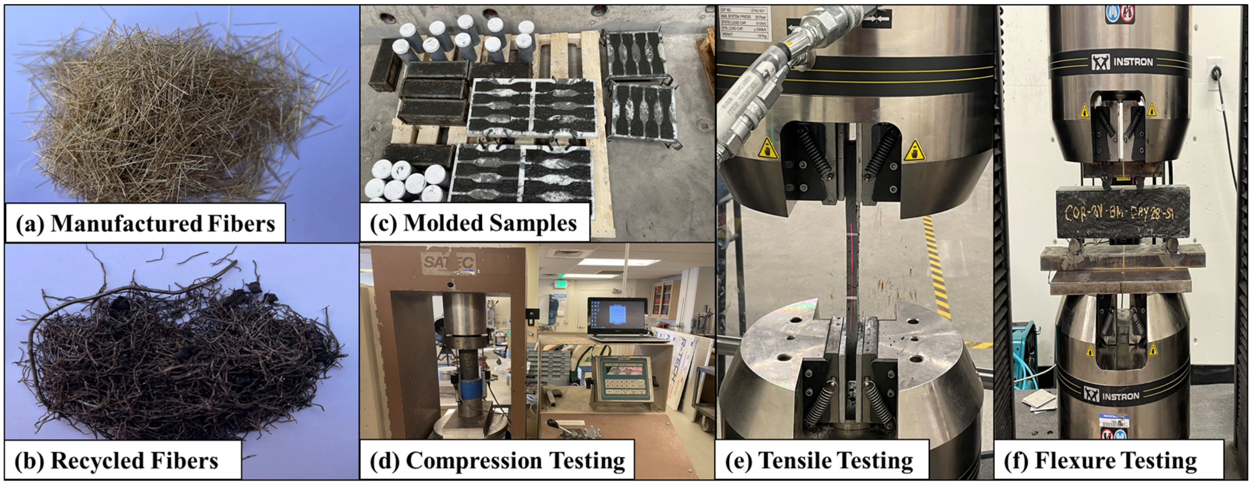

Figure 1. Test program: (a-b) difference between manufactured and recycled fibers; (c-f) experimental tests setups

Table 1. UHPC design matrix for manufactured and recycled fibers with varying fiber dosages

Batch ID	CT25 powder, kg/m^3 (lb/ft^3)	Sand, kg/m^3 (lb/ft^3)	Cement, kg/m^3 (lb/ft^3)	HRWR, kg/m^3 (lb/ft^3)	Water, kg/m^3 (lb/ft^3)	Fibers, kg/m^3 (lb/ft^3)
1M	640.7 (40.0)	839.4 (52.4)	752.9 (47.0)	77.5 (5.0)	160.2 (10.0)	78.5 (4.9)
1R	640.7 (40.0)	839.4 (52.4)	752.9 (47.0)	77.5 (5.0)	160.2 (10.0)	78.5 (4.9)
2M	640.7 (40.0)	800.9 (50.0)	752.9 (47.0)	77.5 (5.0)	160.2 (10.0)	157.2 (9.8)
2R	640.7 (40.0)	800.9 (50.0)	752.9 (47.0)	77.5 (5.0)	160.2 (10.0)	157.2 (9.8)
3M	640.7 (40.0)	784.9 (49.0)	752.9 (47.0)	77.5 (5.0)	160.2 (10.0)	235.8 (14.7)
3R	640.7 (40.0)	784.9 (49.0)	752.9 (47.0)	77.5 (5.0)	160.2 (10.0)	235.8 (14.7)
4M	640.7 (40.0)	759.2 (47.4)	752.9 (47.0)	77.5 (5.0)	160.2 (10.0)	313.9 (19.6)
4R	640.7 (40.0)	759.2 (47.4)	752.9 (47.0)	77.5 (5.0)	160.2 (10.0)	313.9 (19.6)

2.2. Test Preparation and Procedures

For each material batch, several samples for compressive, tensile, and flexure testing were obtained as shown in Figure 1c. All samples were cured at a room temperature of about 60 ºF (15 ºC) with low humidity to represent the actual environment for casting in Nevada. Both compressive and flexure tests followed the ASTM C1856 standard for testing specimens for UHPC (Standard Practice for Fabricating as well). In compressive tests, samples were molded using 76.2 mm ×152.4 mm (3.0 in × 6.0 in), and at least three cylinders samples were taken for early and late ages. Each cylinder sample was ground such that both ends were leveled. Samples were tested using a 500 kip- SATEC load machine, and Figure 1d shows the overall test setup. The rate of loading was approximated around 1.0 MPa/s [145 psi/s], and both strain and load data were recorded using a data acquisition system.

The tensile and flexure properties were tested using a 50-kips Instron machine located at the Earthquake Engineering Laboratory at the University of Nevada, Reno. Figure 1e shows the tensile test setup using the Instron Machine. In performing the tensile test, two different sizes of dog-bone shaped coupons with dimensions 25.4 mm ×12.7 mm (1.0 in × 0.5 in) and 25.4 mm ×25.4 mm (1.0 in × 1.0 in) were used. The loading protocol followed a displacement-controlled loading with a loading rate of 0.127 mm/min and increased to 2 mm/min after the peak loading drops to 90%

(based on recommendations by Abokifa and Moustafa 2021). The strains were recorded using a laser extensometer. Similarly, each UHPC batch was tested under flexure using the Instron machine. Figure 1f shows the overall test setup. The dimensions of the beam were 304.8 mm × 76.2 mm × 76.2 mm (12.0 in × 3.0 in × 3.0 in) following the ASTM C1856 for steel fibers lengths less than 15 mm (0.6 in). The loading protocol follows the ASTM C1609 for UHPC beams tested with four-point loading with a loading rate of 0.2 mm/min (0.008 in/min) (Standard Test Method). Similar to direct tension, the deflections were measured using a laser extensometer.

3. Results and Discussion

The samples obtained were tested at both early and late ages. However, for brevity, the results presented in this paper are only concerned with late ages, specifically for days 28 and 56.

3.1. Flow Tests

A recognizable difference between conventional concrete and UHPC is the flowability, where UHPC flows in formwork and between reinforcement bars uninhibited without using vibration. In UHPC, the flow spread is determined using the ASTM C1856, and recent PCI guidelines require the flow spread to be around 203-254 mm (8-10 in) (PCI 2022). Both static and dynamic flow tests were performed for each batch. The static flow was recorded after the UHPC settled in the flow table, typically around two minutes, and the dynamic flow was recorded after dropping the flow table 25 times in 15 seconds. The average determined diameter of UHPC flow spread for all batches is summarized in Table 2. The flowability of manufactured fibers ranges around 178-231 mm (7.0-9.1 in), while the recycled fibers shows flow spread of about 208-249 mm (8.2-9.8 in). The result indicates that flowability became an issue as the manufactured fibers increased by more than 2% of volume. However, UHPC with recycled fibers for any volume dosage demonstrated a still acceptable flowability, as suggested by PCI guidelines.

Table 2. Summary of the static and dynamic flowability tests for all tested UHPC batches

	1M	1R	2M	2R	3M	3R	4M	4R
Static Test, mm [in]	205.7 [8.1]	208.2 [8.2]	213.4 [8.4]	226.1 [8.9]	198.1 [7.8]	226.1 [8.9]	177.8 [7.0]	218.4 [8.6]
Dynamic Test, mm [in]	210.8 [8.3]	215.9 [8.5]	231.1 [9.1]	233.7 [9.2]	210.8 [8.3]	248.9 [9.8]	190.5 [7.5]	231.1 [9.1]

3.2. Compression Tests

One of the main advantages of UHPC compared to conventional concrete is its superior compression strength. Figure 2 shows the average compressive strength versus strain relationships for different dosages of manufactured and recycled fibers tested on days 28 and 56. Similarly, all samples for manufactured and recycled fibers reached the minimum required compressive strength of more than 120 MPa (17.4 ksi) as prescribed by PCI guidelines (PCI 2022 Concrete Materials Technology Committee). The average peak compressive strength for 1% recycled fibers reached around 146 MPa (21.1 ksi), with a recorded strain of 0.49%. The result recorded for 2% recycled fibers resulted in a lower compressive strength of about 129 MPa (18.7 ksi) with a measured strain of 0.43%. Compressive strength slightly increased compared to 2% recycled as the dosage of recycled fibers increased to 3% and 4%. The compressive strength recorded were around 136 and 139 MPa (19.8 and 20.1 ksi). Comparatively, the compressive strength for manufactured and recycled fibers of 1% volume performed similarly. However, as the volume of recycled fibers increased, the peak compressive strength decreased by 10-14%. The decrease in compressive strength can be attributed to impurities (e.g. tire rubbers residue) around the recycled fibers. As more recycled fibers were used, impurities were also increased in the mixture, adversely affecting the UHPC compressive strength.

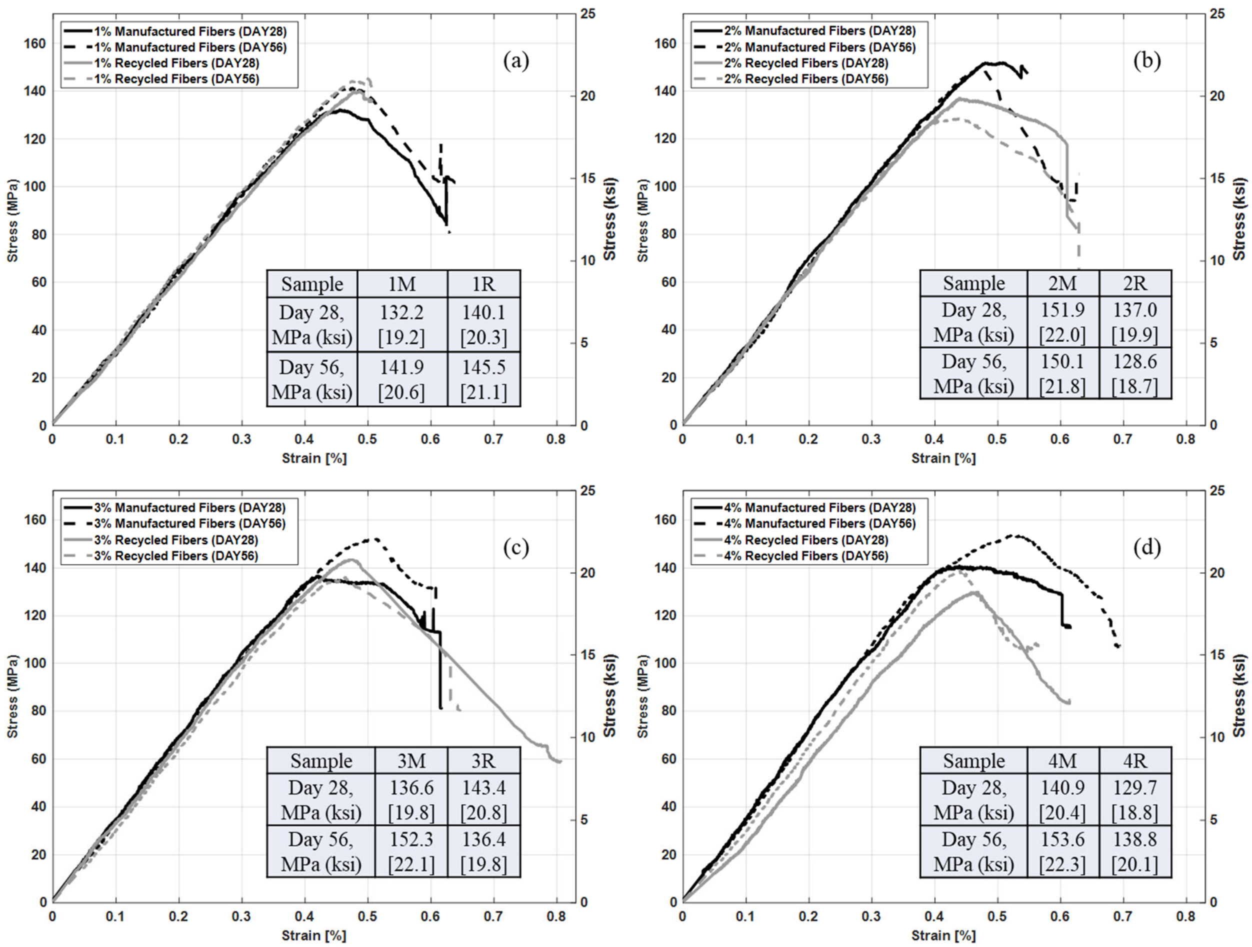

Figure 2. Compressive stress-strain relationships of tested UHPC samples at days 28 and 56.

3.3. Direct Tension Tests

The presence of fibers in UHPC provides adequate tensile strength and enhances the performance of UHPC in terms of ductility and durability. Compared to the trend in compression test, recycled fibers influenced the tensile strength of UHPC significantly as compared to UHPC with manufactured fibers. Figure 3 shows the average obtained tensile stress versus strain relationships of different manufactured and recycled fiber dosages tested on day 28. Overall, the tensile behavior of the recycled fibers achieved slightly loss ductile behavior compared to manufactured fibers. The results also concur with the recorded peak tensile strength and strain at the peak. For example, using 1% recycled fibers significantly reduced the peak tensile strength and strain at peak by 49% and 60% compared to 1% manufactured fibers. However, when the fiber dosage increased to 2%, the difference in the peak tensile strength reduced to 22%; however, the strain did not increase significantly. Increasing the fiber dosage by about 3% and 4% showed a relative increase in the peak tensile strength for both recycled and manufactured; however, adding more fiber showed reduced ductile behavior as expressed by strain capacities and values.

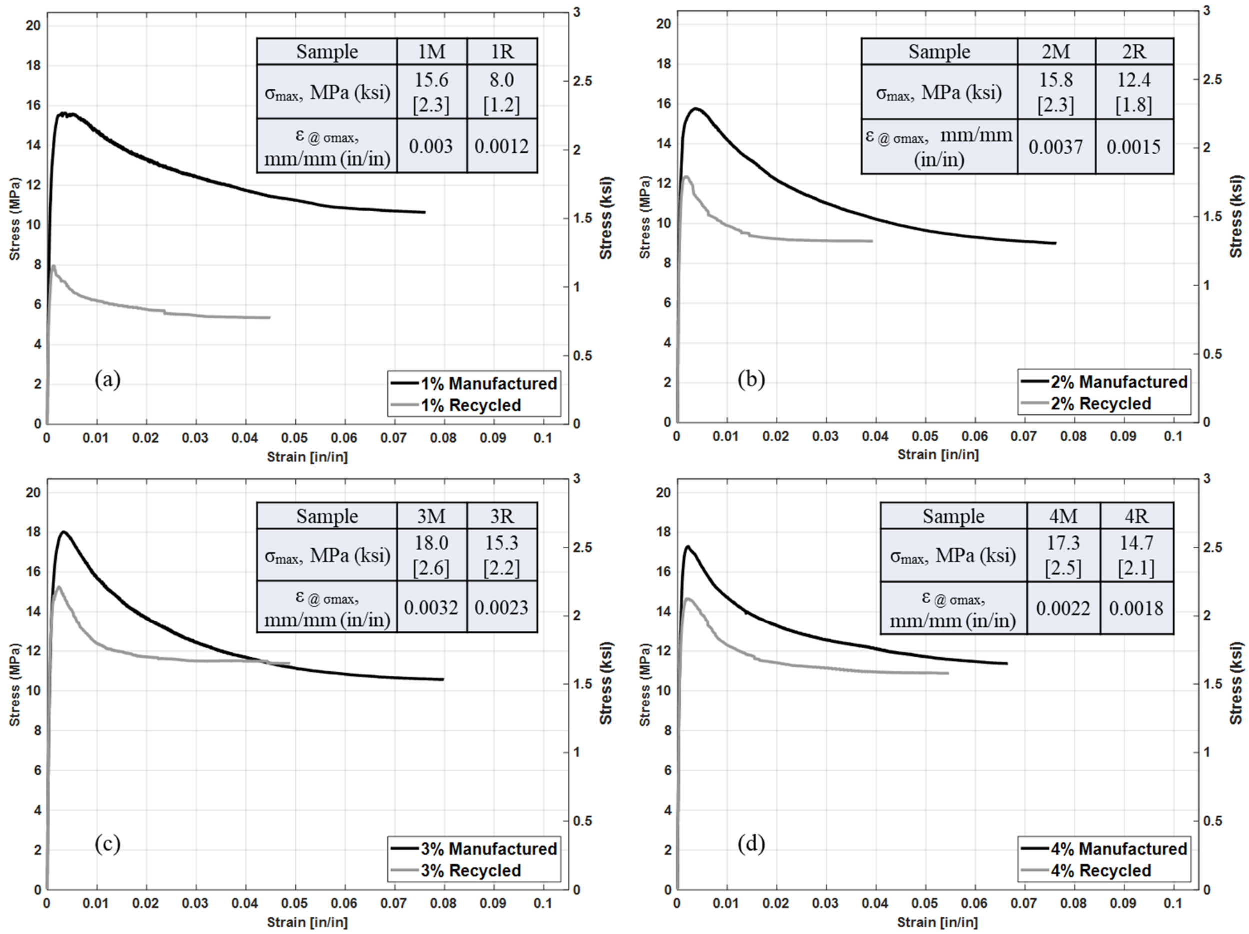

Figure 3. Direct tensile stress versus strain relationships for dog-bone specimens with different dosages of manufactured and recycled fibers tested on day 28.

3.4. Flexure Tests

Another method to determine the indirect tensile strength of UHPC is to perform a flexural test. Figure 4 shows the flexural stress versus deflection relationships for both manufactured and recycled fibers samples (prisms). The trend shows elastic behavior initially and gradually softens as it reached the peak flexural strength. An intermediate strain-hardening occurred after post peak flexural strength and was followed by the rapid decrease in strength sustained from the pull-out of individual fibers. Comparatively, UHPC with recycled fibers performed significantly lesser in terms of the peak flexural strength by 63-73%, achieving lower deflection of around 0.61-1.03 mm. Furthermore, the 1% and 2% recycled fibers did not meet the minimum criteria for peak flexural strength of greater than 13.8 MPa (2.0 ksi); however, 3% and 4% recycled fibers satisfied the requirement as both samples reached 15.2 and 16.0 MPa (2.2 and 2.3 ksi), respectively. Thus, increasing recycled fibers by more than 2% is needed to meet the minimum requirement for peak flexural strength, but makes the recycled fibers also viable solution when used with proper dosage.

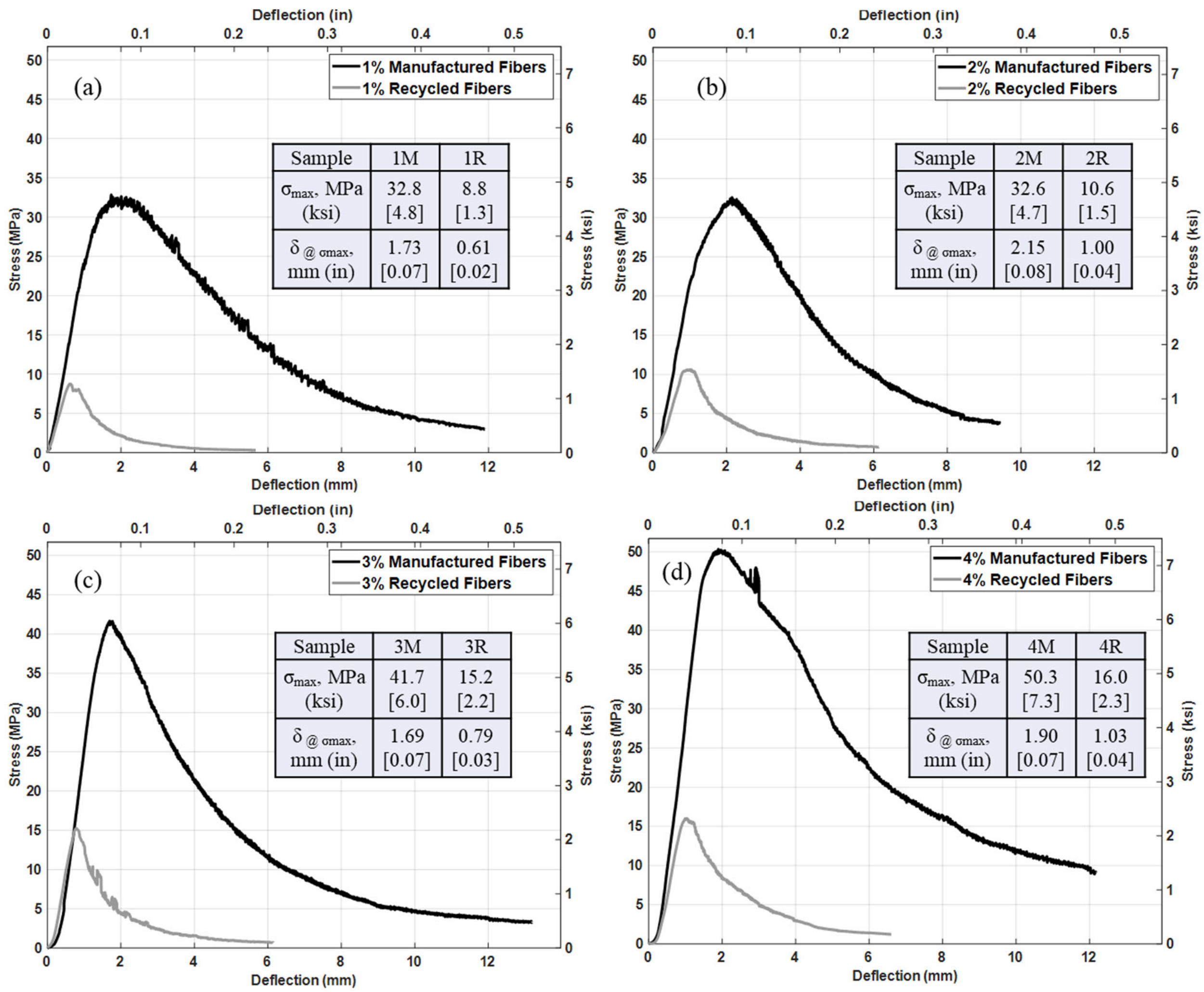

Figure 4. Flexural stress versus deflection relationships of UHPC prisms with manufactured and recycled fibers tested on day 28.

4. Upcoming Future Work

To further assess the viability of recycled fibers from landfill tires and build on the conducted material characterization tests of recycled fibers in SP-UHPC, our next research phase aims at promoting economical UHPC mixtures for large-scale and full structural applications utilizing local and sustainable materials. Eight full UHPC columns with varying parameters, such as fibers type including both recycled wires and manufactured fibers, reinforcement detailing and ABC seismic connections, will be constructed and tested at UNR to investigate the use of full precast UHPC bridge columns in both seismic and non-seismic regions. Figure 5a schematically illustrates the UHPC columns to be connected to conventional reinforced concrete footings using socket and grouted duct seismic ABC connections. The UHPC columns will be constructed and cast at the Con-Fab precast/prestressed California. The footings will be provided by Jensen Precast Nevada and delivered along with UHPC columns to be assembled at UNR sometime in summer 2023. After the columns specimens assembly, all specimens will be tested at the Earthquake Engineering Laboratory (EEL) at UNR under both seismic dynamic and quasi-static cyclic loading. Figure 5b shows a schematic diagram for proposed shake table test setup at UNR.

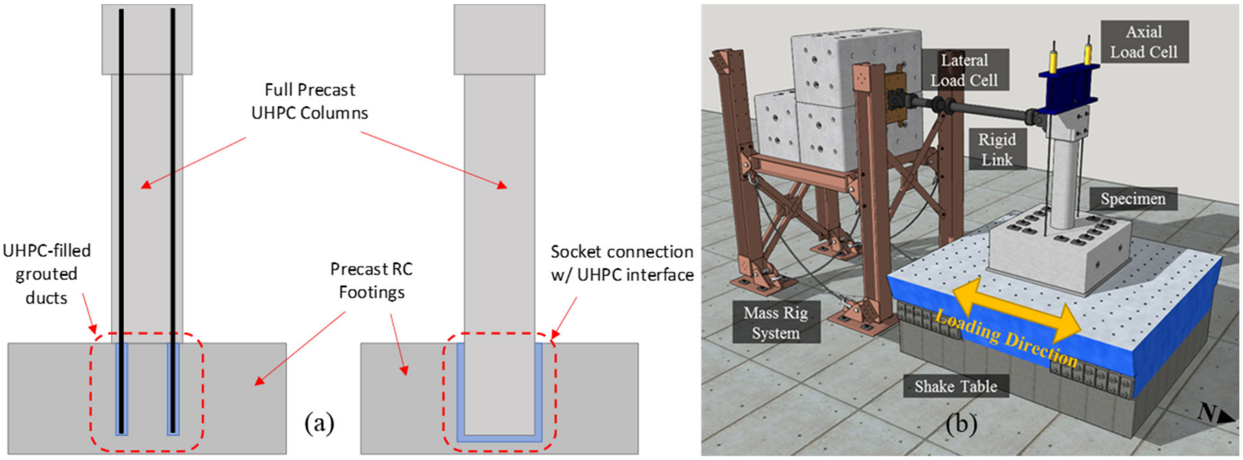

Figure 5. Schematic illustration of upcoming research of precast UHPC columns with ABC connections

5. Conclusions

This study provides a preliminary mechanical characterization of semi-proprietary UHPC with recycled fibers of different dosages and compares it to reference UHPC with manufactured virgin fibers. The following conclusions can be drawn from this phase of exploratory study:

- UHPC with recycled fibers is comparable to manufactured fibers in compression, but underperform in both direct tension and flexure. Nevertheless; 3% or 4% recycled fibers can result in acceptable UHPC that satisfies emerging requirements suggested by PCI for instance;
- Increasing the volume of recycled fibers by more than 2%, is recommended as mentioned above, but it is expected to result in a minor reduction in compressive strength by ~10-14%;
- The recommended higher fiber dosage of recycled fibers significantly improve the direct tensile strength relative to manufactured fibers, but slighter improvement for ductility.
- Overall, recycled fibers use in UHPC is very promising, if used with correct dosage, and highly recommended to consider further for structural applications in large future studies.

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