Flexural Resistance of Ultra-High Performance-Concrete Subjected to Freeze-Thaw Cycles

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Abstract

Ultra-High Performance-Concrete (UHPC) is an advanced cementitious composite material with high durability and strength properties exceeding those of conventional concrete. This paper presents the flexural resistance of UHPC and the effect of fiber percentages by volume on flexural strength of UHPC subjected to freeze-thaw cycles. Freeze-thaw testing was performed on uncracked and pre-cracked 3-in. by 3-in. by 12-in. (75-mm by 75-mm by 300-mm) prisms of non-proprietary UHPC developed at the University of Oklahoma with 2% steel fibers by volume. Freeze-thaw testing was also performed on a series of 4-in. by 4-in. by 15-in. (100-mm by 100-mm by 380-mm) prisms with no fibers, 1%, 2%, 4%, and 6% fibers by volume. Performance of all specimens was evaluated by measuring resonant frequency after every 36 or fewer cycles and residual flexural strength after the completion of 350 freeze-thaw cycles. All specimens showed no degradation of resonant frequency over time. The 3-in. by 3-in. pre-cracked specimens showed an increase in resonant frequency over the course of freeze-thaw testing while the uncracked specimens did not show a significant change in resonant frequency. The uncracked specimens exposed to freeze-thaw cycles achieved higher flexural capacity compared to the pre-cracked and no degradation compared to the control specimens. The 4-in. by 4-in. specimens with 2% and 4% fiber content exposed to freeze-thaw showed similar flexural behavior to the uncracked specimens. However, the flexural resistance of the pre-cracked, no-fibers, 1%, and 6% specimens had reduced compared to their respective control specimens.

Keywords: UHPC; Non- Proprietary; Freeze-thaw; Fibers; Flexural strength; Resonant frequency; Degradation

1. Introduction

Ultra-High Performance-Concrete (UHPC) is an advanced cementitious composite material with high durability and strength properties exceeding those of conventional concrete. UHPC was developed in the late 20th century and is a product of advancements in superplasticizers, fiber reinforcement, supplementary cementitious materials, and optimized gradation of dry materials (Graybeal 2014). The Federal Highway Administration (FHWA) defines UHPC as a material with compressive strength above 18 ksi (124 MPa), pre-and post-cracking tensile strengths above 0.72 ksi (5 MPa), and enhanced durability resulting from its discontinuous pore structure (FHWA 2022). UHPC has been used in a wide range of structural applications, including bridge deck connection joints, precast concrete elements, and high-rise buildings. Its superior combination of strength and durability makes it attractive for structural element optimization (Graybeal 2011).

A limited number of proprietary UHPC materials are available for structural applications, and their initial cost is significantly higher than conventional concrete due to the high-performance cementitious materials content and fiber reinforcement (Chang and Hossain 2021; Floyd et al. 2021). Several scholars have been conducting research in developing a cost-efficient, non-proprietary mix design for UHPC by utilizing readily available local materials and adjusting fiber content as it has a significant effect on the UHPC cost (e.g. Shafei and Karim 2022; Meng et al. 2016; Hasan et al. 2022; Floyd et al. 2021). Mix design modifications depend on the properties of the local materials used and fiber content, resulting in different UHPC characteristics and performance. A non-proprietary UHPC mix design developed at the University of Oklahoma was evaluated in this research study in terms of the concrete mechanical properties and characteristics after being subjected to extreme environmental conditions such as freeze-thaw (Looney et al. 2019).

Several research studies investigated the effect of F-T exposure on UHPC. Graybeal (2006) investigated the UHPC F-T resistance with different curing conditions by evaluating the flexural and compressive strength after being subjected to 700 F-T cycles. UHPC showed an increase in Relative Dynamic Modulus (RDM) for all curing regimes except steam curing (Graybeal 2006). UHPC also exhibited zero to a minimal reduction in flexural strength depending on the curing condition performed on specimens, indicating that the resistance of UHPC under F-T is exceptional due to its high density and low porosity. Similar findings were obtained by Lee et al. (2013) and Ma et al. (2017), where UHPC showed an increase in RDM after being subjected to 300-600 F-T cycles. An increase was also observed even after being subjected to 1000 and 1500 cycles (Lee et al. 2013; Ma et al. 2017). Research studies evaluating the durability of high strength concrete subjected to F-T cycles also demonstrated an increase in mass and RDM throughout F-T cycles (e.g. Jacobsen and Sellevold 1996). The increase could be explained by absorption of water and/or continuation of hydration during the F-T process. This suggests that UHPC specimens can self-heal micro-cracks when immersed in water after or during deterioration because of the presence of a high amount of un-hydrated cement particles in the UHPC matrix (e.g. Jacobsen and Sellevold 1996; Li et al. 2020).

Fladr, Bily, and Vodicka (2016) examined resistance of UHPC exposed to 200 F-T cycles. The results showed that UHPC experienced minimal damage and minor reductions in Dynamic Elastic Modulus and flexural resistance. The authors attributed the good performance of UHPC to the high cementitious material content and the presence of fibers, which helped mitigate the effects of F-T deterioration (Fladr, Bily and Vodicka 2016). The presence of fibers in the UHPC matrix reduces the propagation of micro-cracks leading to improved performance of UHPC under F-T. Gu et al. (2018) investigated the effect of fiber content and found a 1.5% mass loss for UHPC with no fibers and only 0.5% for UHPC with 3% fiber content by volume after 800 F-T cycles. Hasnat and Ghafoori (2021) also concluded similar findings as Gu et al. (2018) and evaluated different fiber contents and types under 70 F-T cycles. Hooked fibers increased the mass loss resistance of UHPC by 9% and 30% for 2% and 3% fiber contents, while straight fibers increased the resistance by 19% and 38%, respectively, compared to the no-fiber specimens (Hasnat and Ghafoori 2021). The improvement may be attributed due to better bonding between the concrete matrix and straight fibers and better fiber distribution.

2. Material Properties and Mix Design

The J3 UHPC mix design developed by previous research conducted at the University of Oklahoma serves as the baseline mix for this study. The concrete properties and characteristics are outlined in Looney et al. (2019). The composition of J3 UHPC with a 2% steel fiber content by volume is shown in Table 1 (Looney et al. 2019). For this research, the components of the mix design were modified accordingly to ensure that the weight ratio and mix volume remain constant with varying fiber percentages. Eight 3-in. by 3-in. by 12-in. (75-mm by 75-mm by 300-mm) prisms were cast with the same mix batch, and nine 4-in. by 4-in. by 15-in. (100-mm by 100-mm by 380-mm) prisms were cast with different mix batches; However, the constituent material sources and same mixing procedure were used to ensure consistency throughout the research.

Table 1. Weight ratios of J3 UHPC Composition

Constituent	Type I Cement	Silica Fume	Slag Cement	Masonry Sand (1:1 agg/cm)	w/cm	Steel Fibers	High Ranger Water Reducer Admixture
Mix Proportion	0.6	0.1	0.3	1.0	0.2	2% by Volume	18-24 oz/cwt

Note: 1 oz = 29.59 ml, 1 lb = 0.45 kg, and cwt = 100 lb of cementitious material

The mixing procedure used followed that of Looney et al. (2019). The flow of J3 UHPC was measured using ASTM C1856 (2017), and all the F-T specimens were cast after the mix was ready. All specimens were allowed to cure in the molds for 72 hours before they were de-molded and placed in a room-temperature lime-saturated water bath for curing until moved to the F-T chamber. Two 3-in. by 3-in. by 12-in. specimens were left in the water bath until the testing day.

3. Test Setup and Procedures

3.1 UHPC Compressive Strength

Compressive strength (f'_c) testing was performed for all the mix batches at 3, 7, 28, and 56 days after casting following ASTM C39 (2021) and ASTM C1856 (2017). A set of three 3-in. by 6-in. (75-mm by 150-mm) cylinders were tested for each compressive strength age.

3.2 UHPC Freeze-Thaw Testing

F-T testing was performed on two uncracked and two pre-cracked 3-in. by 3-in. by 12-in prisms with 2% steel fibers by volume in accordance with ASTM C666 (2015). The specimens were cured for more than 56 days, and their weights were measured immediately before starting F-T testing. Two specimens were loaded until the first crack appeared using the methods of C1609 (2019) with some modifications. F-T testing was also carried out on a series of 4-in. by 4-in. by 15-in. prisms with no-fibers, 1%, 2%, 4%, and 6% fibers by volume. Two specimens were cast for each fiber percentage, except only one specimen was cast for no fibers. These prisms were cured under the same curing condition as the smaller prisms, but for only 14 days.

The longitudinal resonant frequency of all the prisms was measured using a James Instruments E-Meter, specimens were weighed, and their dimensions were measured immediately before beginning the F-T test. Subsequent measurements of frequency, weight, and dimensions were taken every 36 or fewer cycles as specified in ASTM C666 (2015) until a total number of 350 cycles had been achieved. Before every measurement, the F-T chamber was turned off, and the specimens were kept overnight in the machine immersed in water to adjust to room temperature.

3.3 Flexural Strength/ Modulus of Rupture Testing

Residual flexural strength tests were performed in general accordance with ASTM C1609 after the completion of 350 F-T cycles. The 3-in. by 3-in. by 12-in. and 4-in. by 4-in. by 15-in. specimens were tested 28 days and two years after completing the F-T testing, respectively. An LVDT was placed on each side of the specimen at midspan to measure the vertical deflection. An additional LVDT was attached horizontally at the bottom to measure the crack opening. Measurements of the LVDTs were taken by attaching aluminum L-bracket tabs to both sides of the specimens with a quick-setting adhesive. The full testing setup is shown in Figure 1.

Figure 1. Full test setup for (a) 3-in. by 3-in. by 12-in. and (b) 4-in. by 4-in. by 15-in. prisms

4. Results and Discussion

4.1 Compressive Strength of Specimens

Compressive strength results are taken from a previous study conducted at the University of Oklahoma (Dyachkova 2020). The f'_c results at 56 days for the 4-in. by 4-in. mix batches ranged between 17,000-18,320 psi (117–126 MPa), and for 3-in. by 3-in., average f'_c was approximately 19,000 psi (131 MPa) from companion mix batches.

4.2 Freeze-Thaw Results

4.2.1 3-in. by 3-in. by 12-in. Specimens

In this section, pre-cracked and uncracked specimens are indicated as CR1 and CR2 and UC1 and UC2, respectively. Figure 2-a shows the resonant frequency over the course of F-T testing for the pre-cracked and uncracked specimens. The uncracked specimens show almost constant frequency throughout the F-T testing, indicating no deterioration or internal damage of J3 UHPC when subjected to F-T cycles. However, the pre-cracked specimens started with a lower resonant frequency due to the presence of cracks that obstructed the vibration passing. For CR1 and CR2, there was a steady increase in the resonant frequency up to 110 cycles as shown in Figure 2-a. Then there was a fluctuation of increase and decrease over the next 100-200 cycles until they reached a steady resonant frequency. The increase in frequency during the test implies that the cracks present at the beginning of the test healed as water penetrated into them and reacted with un-hydrated cement. However, it should be noted that the resonant frequencies of the pre-cracked specimens did not reach the levels observed for the uncracked specimens. That indicates that while some healing occurred, the degree of recovery was not sufficient to restore the pre-cracked specimens to their original state. Figure 2-b displays the progression of RDM for pre-cracked specimens, whereas it shows no change for the uncracked specimens.

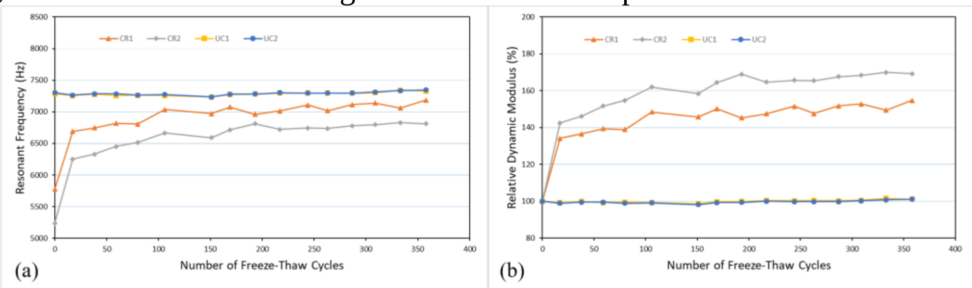

Figure 2. (a) Resonant frequency and (b) Relative dynamic modulus over the freeze-thaw test

4.2.2 4-in. by 4-in. by 15-in. Specimens

Figure 3-a shows the progression of the average resonant frequency for the sets of specimens with each fiber content. There was an increase in resonant frequency after the completion of 350 cycles for each fiber content. This indicates a gain in strength of J3 UHPC during its exposure to a F-T environment and shows that the specimens did not deteriorate over the exposure of F-T cycles. It also implies that the J3 UHPC continued its curing process throughout testing as the specimens were placed in water in the F-T machine 14 days after casting. All specimens displayed an approximately 2% increase in resonant frequency over the course of testing reflecting an increase in the RDM for each fiber content as illustrated in Figure 3-b. While the specimens with different fiber contents exhibited differing resonant frequencies, fiber content did not have a significant effect on observed trends in the freeze-thaw data.

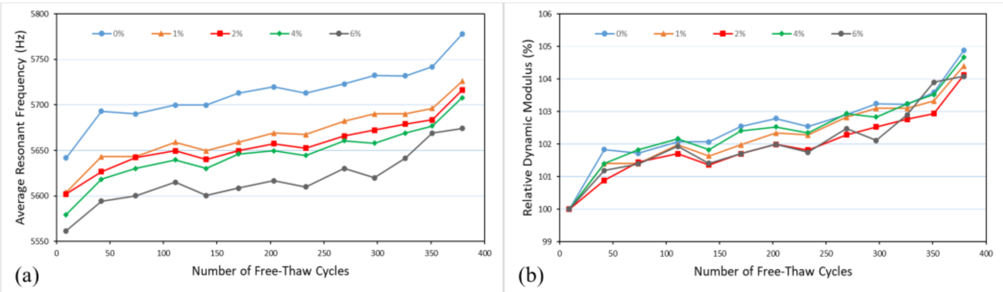

Figure 3. (a) Average resonant frequency and (b) Relative dynamic modulus over the freeze-thaw test

4.3 Flexural Strength/ Modulus of Rupture Resistance

The results of the flexural tests performed after the specimens were exposed to F-T cycles for different prism sizes were compared to control specimens that were tested at 56 day***s*** to see the change in the flexural resistance behavior before and after F-T testing. The specimens that were water cured until the day of testing are indicated as WC1 and WC2. Figure 4 presents the averaged load-displacement curves for all tested specimens. They experienced an initial linear load-displacement behavior, displacement-hardening behavior leading to a post crack peak load, and stress-sustaining behavior, as shown in Figure 4.

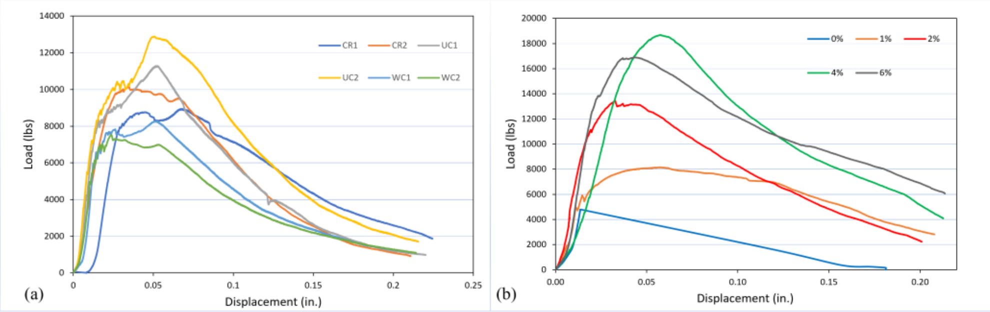

Figure 4. Average load vs displacement curves for (a) 3-in. by 3-in. and (b) 4-in. by 4-in. specimens Note: 1 lbs = 0.0044 KN and 1 in. = 25.4 mm

4.3.1 3-in. by 3-in. by 12-in. Specimens

Table 2 shows the ultimate flexural strength (f_{MOR}) for the pre-cracked, uncracked, water-cured, and control specimens tested at 56 days. Specimens maintained a ductile behavior even for the pre-cracked specimens after being subjected to 350 F-T cycles as can be seen in Figure 4-a. The specimens were still held together even after the failure load due to the steel fibers bridging the cracks in the J3 UHPC matrix.

The ultimate strength of the pre-cracked specimens was lower than the control specimen, indicating that the crack healing indicated by the RDM did not restore all the flexural resistance after the F-T exposure. However, the average strength of the pre-cracked specimens was higher than that of the water-cured specimens tested at the same age by 17% implying that the water exposure and additional hydration during the F-T cycles healed the pre-existing cracks after the first 100 F-T cycles. The average flexural strength of the uncracked specimens was 7% higher than the control specimens, indicating no degradation of the flexural resistance of J3 UHPC or deterioration in the concrete matrix occurred during F-T testing.

Table 2. Flexural strength of 3-in. by 3-in. F-T specimens

Specimen	CR1	CR2	UC1	UC2	WC1	WC2	Control Specimen at 56 Days
f_{MOR} (psi)	2,858	3,277	3,763	4,288	2,649	2,484	3,695
Ratio of Flexural Stress to Ultimate Stress at 56 Days	0.77	0.89	1.02	1.16	0.72	0.67	-

Note: 1 psi = 6.89 KPa

4.3.2 4-in. by 4-in. by 15-in. Specimens

Table 3 summarizes the average ultimate flexural strength for the 4 in. by 4 in. specimens after F-T testing and the flexural strength of 4-in. by 4-in. control specimens cast from the same batch tested at 56 days. The no fibers specimen had a sudden and brittle failure resulting in the specimen breaking in half, while the rest showed a ductile behavior as shown in Figure 4-b and held together even after failure. For most specimens, the failure crack occurred in the middle third region, and for those that failed outside of this region but not more than 5% of the span length outside the middle third region, a correction was applied following ASTM C78 (2022). It was observed that the crack widths were larger in specimens with less fiber volume. That is attributed to the larger number of fibers maintaining the two pieces of the specimen together at failure. Figure 5 illustrates the crack pattern and crack opening width for each fiber content.

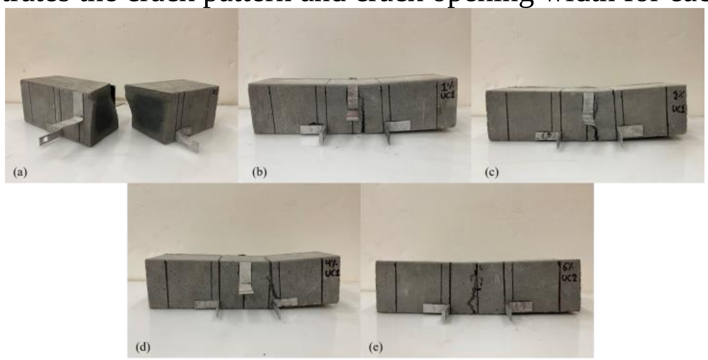

Figure 5. 4 in. by 4 in. Specimens after completion of ultimate flexural strength test for (a) 0%, (b) 1%, (c) 2%, (d) 4%, and (e) 6% steel fibers

The behavior of the F-T specimens was similar to the control specimens, as increasing fiber content resulted in a significant increase in flexural resistance. The flexural resistance of the 2% and 4% F-T specimens was comparable to that of the control specimens, while it decreased for the 1% and 6% by 17% and 16%, respectively. The most significant strength reduction occurred in the no-fiber specimen, which exhibited a 49% decrease in strength after being subjected to F-T cycles. That indicates that fibers play a crucial role in resistance to extreme environmental exposure. Although all specimens showed the same increase in RDM, the presence of fibers helped to reinforce the concrete leading to better flexural resistance up to 4% fiber content by volume. The 6% did not appear to have a significant effect on improving the flexural resistance of UHPC.

Table 3. Average flexural strength of 4-in. by 4-in. (100-mm by 100-mm) F-T specimens

Fiber Content	0%	1%	2%	4%	6%
f_{MOR} (psi)	893	2,039	3,078	4,023	3,496
Control f_{MOR} at 56 Days (psi)	1,735	2,470	3,040	4,140	4,140
Ratio of Flexural Stress to Control at 56 Days	0.51	0.83	1.013	0.97	0.84

Note: 1 psi = 6.89 KPa

5. Conclusion

From the above-mentioned results and discussion, it can be concluded that:

- Pre-cracked 3-in. by 3-in. specimens showed a significant increase in resonant frequency, indicating that the cracks present at the beginning of the test healed over time. Meanwhile, the uncracked specimens showed no change in resonant frequency.
- All 4-in. by 4-in. specimens showed an approximately 2% increase in resonant frequency after completion of the F-T test. That implies that fiber content did not have a significant effect on observed trends in the freeze-thaw data.
- Uncracked 3-in. by 3-in. and 4-in. by 4-in. specimens with 2% and 4% fiber content maintained flexural resistance after F-T testing. Meanwhile, pre-cracked 3-in. by 3-in. with 2% fiber content and 4-in. by 4-in. specimens with 0%, 1%, and 6% showed deterioration in UHPC flexural resistance after F-T exposure.

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