

Effect of Fiber, Cement, and Aggregate Type on Mechanical Properties of UHPC

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Abstract

Ultra-High Performance Concrete (UHPC) is a new class of concrete that differentiates itself from other concrete materials due to its exceptional mechanical properties and durability. It has been used in structural rehabilitation and accelerated bridge construction, structural precast applications, and several other applications in the past decades. The mechanical properties of UHPC include compressive strength greater than 124 MPa (18 ksi) and sustained post cracking tensile strength greater than 5 MPa (0.72 ksi) when combined with steel, synthetic or organic fibers. Proprietary, pre-bagged mixtures are currently available in the market, but can cost about 20 times more than traditional concrete. This high price and the unique mixing procedure required for UHPC has limited its widespread use in the US and has motivated many researchers to develop more economical versions using locally available materials. The objective of this study was to investigate the effect of different proportions of typical UHPC mixture components on the mechanical properties of the mixtures. Particle packing theory was used to determine a few optimal mixture proportions and then modifications were made to investigate the effect. A compressive strength of around 124 MPa (18 ksi) was achieved without using any quartz particles in the mixture design.

Keywords: Non-Proprietary UHPC; Steel Fibers; Particle Packing Analysis.

1. Introduction

After water, concrete (made of aggregates, cement, and water) is the most widely used material on Earth. Conventional concrete has been one of the primary construction materials since the invention of Portland cement in 1824. During this time, there have been numerous research efforts to improve the strength, cost efficiency, and durability of concrete, and still, there are many ongoing studies to address different issues accompanied by concrete technology. One relatively recent solution for improving upon conventional concrete is ultra-high performance concrete (UHPC).

The definition of UHPC has been evolving over the past few years. Based on Federal Highway Administration (FHWA) guidelines [1], UHPC is concrete with more than 150 MPa (21.7 ksi) compressive strength at 28 days, a maximum water-to-cementitious materials ratio (w/cm) of 0.25, and containing internal fiber reinforcement to achieve post-cracking tensile strength above 5 MPa (0.72 ksi). Other researchers [2] are proposing lower required strengths (124

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MPa [18 ksi]), but have other requirements on the peak tensile strength and residual strength at different tensile deformations. Regardless of the specific definition, it has much higher compressive strength, higher tensile strength and ductility, and improved durability.

Because of these improved mechanical properties, UHPC has become a widely used material for accelerated bridge construction (ABC) and rehabilitation of existing infrastructure to enhance resiliency [3-5]. Exceptional mechanical properties of UHPC have made it an ideal option for precast concrete as well. Many precast sites have utilized UHPC to produce prefabricated bridge elements like deck panels, bridge girders or even other structural elements like tunnel segments and wind tower elements [6, 7]. Its enhanced durability has also made it a qualified candidate for extending structures' design life [8] and even in critical infrastructures for blast mitigation purposes [9]. The application of UHPC is not limited to structural applications, it has been used for many architectural elements like stairways, facades, bus shelters, and sun shades due its high durability and resistance [10, 11].

Despite all the advantages of the UHPC, its final price still remains a big concern for designers and owners. Adding steel fibers accompanied by other proprietary materials like silica fume, slag, superplasticizer, and so on, which are usually costly to produce, has made UHPC 20 to 30 times more expensive than conventional concrete and has limited the widespread use of UHPC in the U.S. infrastructure. For this reason, many different investigations have been conducted to develop non-proprietary UHPC mixtures, typically achieving close to the same mechanical properties of commercially available UHPC but with significantly lower cost. Several researchers developed the non-proprietary UHPC with locally available materials in different locations and could reach the minimum requirements for UHPC mixtures [12-14]. Several studies also studied their developed non-proprietary UHPC mixture in different applications like connecting precast deck panels in retrofit jobs [15].

Although there have been several previous efforts to develop non-proprietary UHPC mixtures, there is still more research needed for on UHPC with different types and quantities of constituent materials. The main objective of this research was first to develop a non-proprietary UHPC mixture with locally available material and then evaluate the effect of different cement types and contents, w/cm, superplasticizer and viscosity modifying admixtures contents, fiber type, and fine aggregate type and content on the compressive strength and flowability of the non-proprietary UHPC mixtures. Different cement types and contents were studied to find the optimized UHPC cement paste. Different aggregate types and contents were explored the effect of particle packing on the compressive strength. The effect of different fiber types was investigated on one of the best performing UHPC mixtures. This study was conducted using only minimal laboratory equipment to help future researchers see how similar work can be done with only limited equipment (a bread mixer and compression test machine). Recommendations are made from this research for a non-proprietary UHPC mixture using materials from Florida with a compressive strength of 124 MPa (18 ksi) and spread flow of 254 mm (10 in.); the mixture consisted of Type I/II portland cement, slag, silica fume, and limestone fine aggregate with w/cm of 0.2 and aggregate-to-cementitious material of 1.0.

2. Background and Significant of Study

Many investigators have developed non-proprietary UHPC mixtures with local material to minimize the price while maintaining similar mechanical properties to address the cost issue [16-18]; the mix proportions for the major investigations are summarized in Table 1.

Table 1. Previous research projects for developing non-proprietary UHPC mixes [2, 12, 14, 16, 18-20] (1 mm = 0.0394 in.; 1 MPa = 0.145 ksi)

Researcher	Year	Location	Selected-UHPC Mix Parameters			Performance		
			Used SCM per cement weight	w/cm	Agg.:cm	Fiber vol. fraction (%)	Flow (mm)	f'_c (MPa)
Tadros et al.*	2020	US	SF: 0.2 to 0.25 LP: 0 and 0.18	0.18 to 0.2	0.77, 0.88, 1.1	0.0 and 2.0	226-279	148-172
Lawler et al.	2019	FL	SF: 0.15 FA: 0.15	0.170	1:0 to 2:0	1.5 and 2.0	203-254	124-131
Karim et al.	2019	Iowa	SF: 0.07 and 0.25	0.18, 0.2, 0.23	1.12, 1.3	2.0	203-254	124-131
Looney et al.	2019	OK	SF: 0.17 S: 0.5	0.18 to 0.23	0.75 and 1	1.0 and 2.0	229-279	110-125
El-Tawil et al.	2016	Michigan	SF: 0.25 S: 1.0	0.18	1.0	1.5	-	144-195
Graybeal	2013	WA, OR, ND, SD, NY, PA	SF: 0.25 FA: 0.25	0.15 to 0.16	1.0	1.0 and 2.0	264-315	155-200
Tafraoui et al.	2009	France	SF: 0.25 Metakaolin: 0.25	0.22	0.9, 1.18	0.0 and 2.0	-	103-190

cm = all cementitious materials; FA=fly ash; LP=limestone powder; S=slag or GGBS;

*: In this study, the liquid portion of chemical admixtures was involved in w/c and w/b calculations;

**: this study agg/c was reported.

The composition of most UHPC includes granular constituents including fine aggregates between 0.15 and 0.61 mm (0.006 and 0.024 in.), cement with an average diameter of 0.0152 mm (0.0006 in.), crushed quartz with an average diameter of 0.010 mm (0.0004 in.), and silica fume to fill the voids between other particles and result in the highest possible matrix density [21]. Graybeal [19] conducted a comprehensive study to develop non-proprietary UHPC using available material in Washington, Oregon, North and South Dakota, New York, and Pennsylvania. Twelve cement types, five different silica fumes, thirteen supplemental materials, eight high-range water reducers, ten aggregate variations, and five various fiber reinforcements were studied. The researchers were able to obtain more than 158.6 MPa (23 ksi) strength at the age of 28 days by keeping the water- cement ratio between 0.2 and 0.25, aggregate-to-cementitious (agg./c) material ratios between 1 and 2, and using high early strength white cement.

El-Tawil et al. [16, 22] followed a similar procedure in Michigan. Type I white Portland cement, Type V Portland cement, Type I Portland cement / slag cement blend, silica fume, and silica powder were studied exclusively to see how the materials affect the final mechanical results. More than 137.9 MPa (20 ksi) strength was achieved for all mixes at 28 days. Results showed that the silica powder could be eliminated from the matrix due to its high costs, and cost analysis revealed 60% percent decrease in price compared to commercial UHPC [16, 22]. Berry et al. [17] conducted research to develop non-proprietary UHPC using the material available in Montana and reached the compressive strengths of approximately 138 MPa (20 ksi) with flows of 203 to 280 mm (8 to 11 in.). Later, the researchers studied the feasibility of using the developed material for highway bridge applications, specifically for filling the joints between precast members [23].

Other researchers have also been able to achieve compressive strengths of more than 145 MPa (21 ksi) at 28 days by maintaining the water to cement ratio between 0.2 to 0.3 and using 1 to 2% steel fibers by volume. Several mix designs were developed using Type I/II Portland cement, Class F fly ash, fine masonry sand, silica fume, and high-range water reducer. Optimized mix designs were evaluated based on the workability and compressive strength [17, 23]. Few studies went beyond mix development and attempted large scale batches for field application and evaluate the overall experience of working with non-proprietary UHPC out of the laboratory environment [24]. Non-proprietary UHPC has also been used in field-cast joints between precast concrete deck panels with a cost of less than \$1,307 per cubic meter (\$1,000 per cubic yard) with steel fibers (proprietary mixes can cost more than \$4,575 per cubic meter [\$3,500 per cubic yard] for the material alone) [17, 23].

In this research, the effect of important variables on compressive strength and flowability of non-proprietary UHPC concrete was studied. Different cement types and content, w/cm, fiber types, fine aggregate type and content, superplasticizer and viscosity modifying admixtures contents were investigated to see the effect on non-proprietary UHPC mixtures. This research effort is significant for several reasons. First, Florida ranks third in the United States in the production and use of aggregate products, consuming about 153 million tons per year [25]; there would be ample available material for a Florida-based non-proprietary UHPC mixture. Additionally, most of the sand in Florida originates from limestone, which typically leads to reduced performance when used for concrete when compared to quartz fine aggregate. For this reason, only limestone fine aggregate (not quartz) was used in this study. Several studies have reported using limestone powder [13, 14, 26] and coarse and fine limestone aggregates for developing non-proprietary UHPC mixes [27-29] with varying degrees of success. The results from this research would extend to other locations where only limestone fine aggregate is available. In addition, results could be used as a guide to choose proper fiber type and content for future studies. Investigating new fiber types is important as the fiber most used for UHPC in the past (OL 13/0.20) is no longer being produce in the US.

Finally, the described research outlines a reasonable approach for developing a non-proprietary UHPC mixture with limited laboratory capabilities; only a small commercial bread mixer with about a 0.00425 cubic meter (0.15 cubic feet) capacity and a compression test machine were used in this testing program.

3. Materials and Methods

The different materials and experimental procedure used for developing the non-proprietary UHPC mixture design and determining its mechanical properties are described in this section. The research methodology is shown schematically in Figure 1 and is explained in this section.

3.1. Material Types

The UHPC mix developed in this study used a combination of fine sand (FA), ultra-fine recovery material (UFR), cement, and different supplementary cementitious materials (SCMs), including slag cement (S) and silica fume (SF). Previous studies also reported using fine quartz particles in the UHPC matrix [19, 22, 23, 30], but quartz is not locally available in Florida, with the majority of produced sand in this state coming from limestone aggregate. Silica powder was not used due to its relatively high costs.

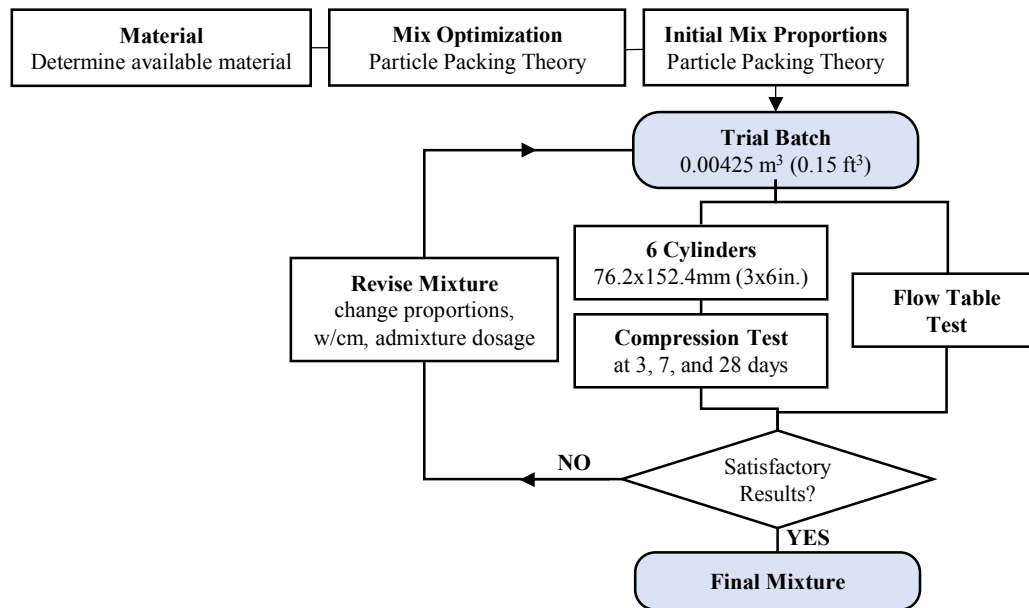


Figure 1. Research methodology for developing the non-proprietary UHPC mixture

Table 2 summarizes the material details that have been used in this study. Five different cement types and five different fiber types were used to investigate the effect of each on the mechanical properties of the UHPC. Due to the low water to cementitious ratio of UHPC, a high-range water reducer (HRWR) was used to obtain the required workability. The HRWR chosen for this study was Glenium 7920, produced by BASF. In mixes reinforced with heavier fibers, a viscosity modifying admixture (VMA) was used to prevent fiber segregation in the concrete matrix. Two different fine aggregates were chosen for this study, based on local availability: regular limestone sand and ultra-fines recovery (UFR). These solid parts are recoverable fine materials coming from waste water streams of aggregate plant system. The fine size of UFR (less than 150 μm) has made it a conveyable and stackable material ideal for several industries. As crushed quartz fine aggregate is rare in south Florida, UFR was used to improve the concrete density.

Table 2. Material detail and supplier information

Material	Details	Sign	Supplier
Fibers	DRAMIX 4D 65/35BG	A	Bekaert
	Helix 5-13	H	HELIX
	OL 13/.20	B	Dramix
	Hiper Fiber	HF	Hiper Fiber
	STRUX® 90/40	S	GCP Applied Technology
Cement	Type M- Masonry Cement		
	Type I-II		Titan America
	Type III	C	
	Type I-II		Ash Grove
	Type I		Lehigh White Cement
Ground-Granulated Blast-Furnace Slag (GGBFS)	-	S	ARGOS USA Cement
Silica Fume	Master Life® SF 10	SF	BASF
Sand	Fine Masonry	FA	Titan America
UFR	-	UFR	Titan America
HRWR	Glenium 7920	HRWR	BASF
VMA	VMA 358	VMA	BASF

The detailed specifications for the cement types used in this study are shown in Table 3.

Table 3. Manufacturer supplied properties of cements evaluated

Cement Type	Producer	28-day strength, MPa (ksi)	C ₃ S	C ₂ S	C ₃ A	C ₄ AF	Blaine Fineness (m ² /kg)	Air Content (%)	Setting Time (min)	
									Initial	Final
Masonry	Titan America	20.2 (2.9)	-	-	-	-	-	15	145	-
Type I-II	Titan America	47.0 (6.8)	63	9	6	11	398	7	109	228
Type I-II	Ash Grove	32.3 (4.7)	59	19	6	10	-	6	115	115
Type III	Titan America	54.7 (7.9)	69	6	6	11	505	6	75	155
Type I (white)	Lehigh	49.1 (7.1)	73	7	13	1	483	6.7	100	200

Four different steel fibers from various manufacturers and one synthetic fiber were used in this study to provide required tensile behavior in UHPC. Table 4 summarizes the properties of the different fibers used in this study. Figure 2 shows the different fibers used in this study. The Bekaert OL 13/.20 and Hiper Fiber Type A fibers were both brass coated, looked the same, and had similar properties. While the exact chemical composition of the fibers was not obtained, the manufacturer of the Helix 5-13 fibers did inform the researchers of a higher zinc content in the fibers used for this test program; the company has since modified the chemical composition of their fibers to decrease the zinc content. The fiber types are given a short name in Table 4 for use in the mixture design tables that follow.

Table 4. Fiber Properties

Name	Fiber	Geometry	Length, mm (in)	Diameter, mm (in)	Aspect Ratio (l/d)	Tensile strength, MPa (ksi)
A	DRAMIX 4D 65/35BG	hooked/deformed	35.6 (1.4)	0.51 (0.020)	65	1,850 (268.0)
H	Helix 5-13	twisted	12.7 (0.5)	0.51 (0.020)	65	1,700 (246.5)
B	Bekaert OL 13/.20	straight	12.7 (0.5)	0.20 (0.008)	65	2,758 (400.0)
HF	Hiper Fiber Type A	straight	12.7 (0.5)	0.20 (0.008)	65	2,800 (406.0)
S	STRUX® 90/40	straight	1.55 (40)	0.017 (0.43)	90	90.0 (620)



(a) DRAMIX 4D 65/35BG



(b) Helix 5-13



(c) Bekaert OL & Hiper Fiber



(d) STRUX® 90/40

Figure 2. Different steel fibers: (a) Bekaert 4D 65/35BG, (b) Helix 5-13, (c) BEKAERT OL 13/0.2 & Hiper Fiber and (d) STRUX® 90/40

3.2. Mixing Procedure

When compared to conventional concrete, the UHPC mixing procedure requires additional considerations regarding the mixing time and mixing energy. Due to the small particle size and very low water-cementitious materials ratio, UHPC requires more mixing energy than normal concrete to complete the wetting process. A 1.5-HP planetary mixer with 0.00566 m³ (0.2 ft³) capacity was used to make 0.00425 m³ (0.15 ft³) mixtures and was found to exert the appropriate amount of mixing energy.

The mixing process included two 10-minute phases. The first 10-minute mixing phase involved the mixing of all the dry components (other than the fibers). The sand, slag, cement, and silica fume were all premeasured and added to the mixer to blend for 10 minutes. UHPC is sensitive to moisture. For this reason, a precise quality control system should be used to monitor and measure the moisture content of aggregate and UFR. To remove the effect of natural moisture, all aggregates were oven dried before mixing. There were a few mixtures where the aggregates were not oven dried before mixing, which led to increased variability in the performance of the mixture. These cases are noted in the discussion on results.

For the second 10-minute mixing phase, half of the HRWR was added to the required water and was poured into the mixer over the course of 2 minutes. After that, the rest of the HRWR was added to the mixture and left to mix until the powder material became a flowable paste, which typically took 6 to 11 minutes of additional mixing time. Once the

concrete paste was produced, the fibers were added to the mixture and allowed to mix for an additional 2 minutes. The transition from a powder to a fluid takes additional time depending on the water-cementitious materials ratio and the HRWR dosage. The average total mixing time varied between 20 to 25 minutes. Figure 3 shows the steps required for the mixing procedure.

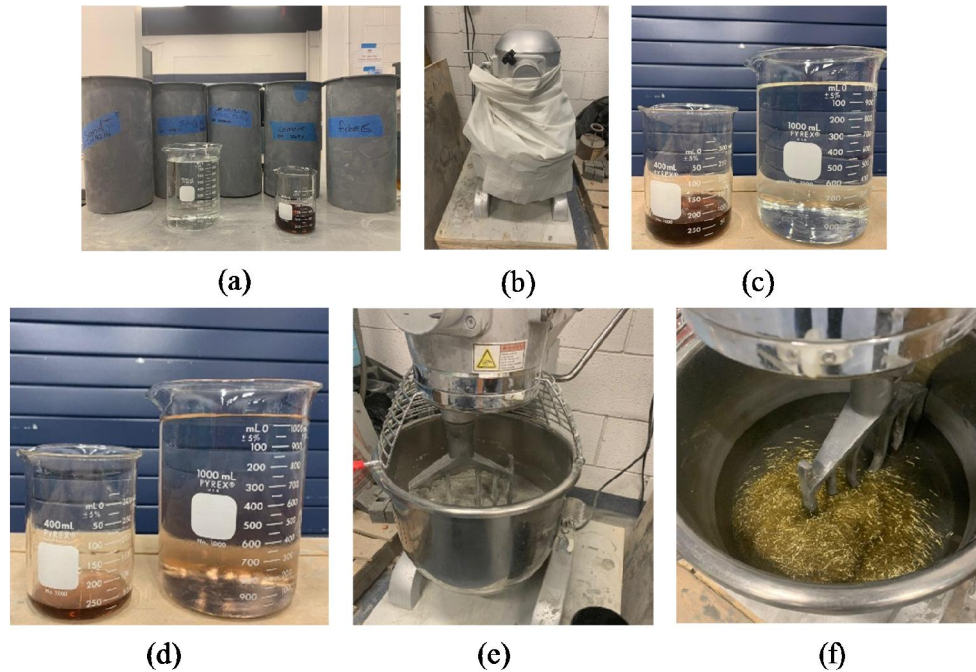


Figure 3. General Mixing procedure (a) weighted material, (b) dry mixing, (c) weighted water and HRWR, (d) blending half of HYWR with required water, (e) second 10 minutes of mixing with water and HRWR, and (f) adding fibers

3.3. Mix Optimization

The mix optimization process included two phases: physical optimization and chemical reaction optimization. Physical optimization, also known as the particle packing analysis, is a process to minimize voids in the concrete matrix and maximize the density. In other words, particle packing optimization in a concrete mixture is accomplished by selecting the right size and amount of each constituent to reduce the volume of voids in the paste. The chemical reaction optimization also refers to choosing SCMs to expedite and improve cement hydration, which usually is considered simultaneously with the particle packing process.

In the particle packing analysis, several constituents with different particle size distribution curves are combined in proportions that result in an ideal curve for the dry constituents. There were several efforts to find the ideal curve to get the highest packing density. Andreasen and Andersen [31] defined an equation for the ideal particle size distribution curve to obtain the densest mixture with specific materials. Later, this equation was modified by Funk and Dinger [32] to account for the smallest particle size. The model is shown below as Equation 1.

$$D(P) = \frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q} \quad (1)$$

where:

$D(P)$: is the percent passing for each diameter evaluated,

D : the particle diameter being evaluated,

D_{min} : the smallest particle diameter used in the mix design,

D_{max} : the largest particle size used in the mix design,

q : distribution modulus.

The largest particle size of all the materials used in this study was 500 μm (2.0×10^{-5} in.), which was in the fine sand aggregates. The smallest particle diameter is around 1 μm (3.9×10^{-8} in.) from the silica fume. For UHPC mixtures developed based on the modified Andreasen and Andersen curve, q is typically selected between 0.19 for finer mixtures and 0.37 for coarser mixtures [2]. The idealized curve with a distribution modulus of 0.25 is shown with the distributions

for the materials used and the optimized mixture designs in Figure 4. This distribution modulus is based on previous work by other researchers [18, 33, 34].

To start the analysis, the particle size distribution curves for each material were required. Dry constituents in UHPC are very fine. The particle size distribution curves for these materials cannot typically be determined using a physical sieving process. Commercial laser diffraction devices can be used to determine the particle size distributions for very fine particles ($0.1\mu\text{m}$ to $1000\mu\text{m}$) and enable the operator to produce distribution curves for any material. A particle size distribution analysis was completed for the materials used in this research using a Malvern laser particle size analyzer; this was completed by Titan America in Miami. The particle size distributions for the primary dry materials used in this study are shown in Figure 4 (a).

Several different mix designs were created and analyzed using a developed spreadsheet tool. The proportions were used for each aggregate-to-cementitious material ratio of 0.8, 0.9, 1.0, 1.1, and 1.2, and their cumulative percent passing curve was compared to the optimum packing curve created using the modified equation by Funk and Dinger [32]. The trial-and-error process revealed the optimum aggregate-to-cementitious material ratio was 1.0.

Keeping the aggregate-to-cementitious material equal to 1.0, several mix designs were evaluated by how close they were to the ideal curve produced by Equation 1. The mixture designs with the minimum difference from the ideal curve were chosen as the base mixture designs for the experimental program. Figure 4 shows the distribution curves of different constituents and optimized mixture designs compared to the idealized curve (labelled "CPFT").

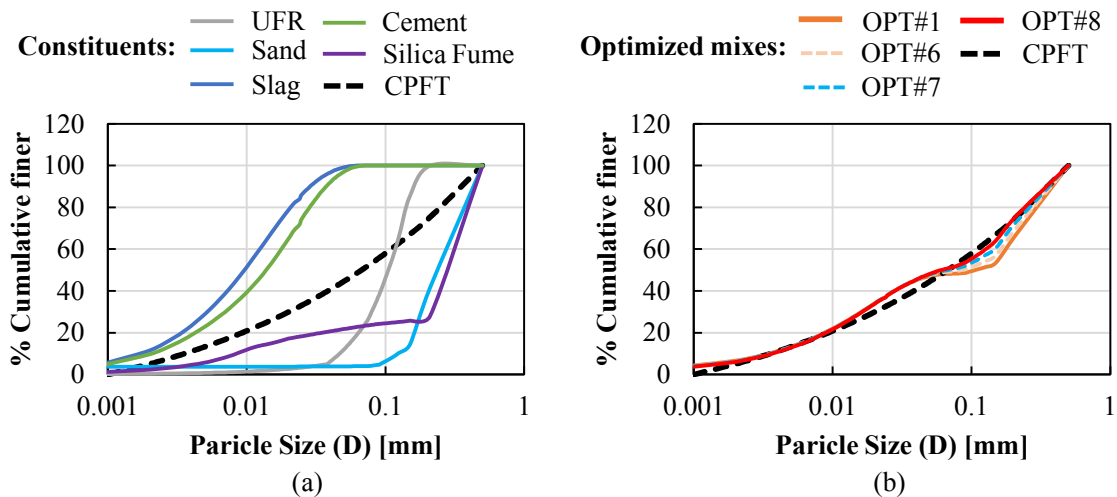


Figure 4. Particle packing analysis, (a) Distribution curve of different constituents and (b) qualified mix proportions close to the optimum curve

Table 5 summarizes the optimized mixture proportions based on this particle packing analysis. An ideal cement to slag to silica fume ratio (0.6:0.3:0.1) was determined based on this analysis, OPT#1 in Table 5. Modifying the sand to UFR ratio was found to improve the particle packing in the range where there was the largest difference between the mixture curves and idealized curves; four mixtures with UFR were designed as comparisons OPT#6 through OPT#9 in Table 5.

Table 5. Proportions of the initial qualified mixes

Mixes	Agg./C	Cement %	Slag %	Silica Fume %	Sand %	UFR %
		Cementitious Materials			Aggregate	
OPT#1	1.0	0.6	0.3	0.1	1.00	0.00
OPT#6	1.0	0.6	0.3	0.1	0.90	0.10
OPT#7	1.0	0.6	0.3	0.1	0.80	0.20
OPT#8	1.0	0.6	0.3	0.1	0.70	0.30
OPT#9	1.0	0.6	0.3	0.1	0.65	0.35

These proportions were considered as the starting point for the experimental work. Different combinations of constituents were also used to see how chemical reactions develop in the mixtures. To achieve the highest possible mechanical properties and proper flowability, a trial-and-error process was conducted. Different variables including water-to-cementitious material ratio, HRWR dosage, and initial proportions were evaluated during the trial-and-error process.

OPT#1, which resulted from the particle packing analysis, was used as the starting point for the trial batching process. Later, after purchasing UFR, OPT#6 to OPT#9 were also tested. Considering OPT#1 as a base mix design, different cement types, water contents, mixing times, superplasticizer dosages, fiber contents and fiber types, and VMA contents were all evaluated based on the compressive strength and flowability tests, which were conducted according to ASTM 1856 [35]. After determining proper type and content of constituents, OPT#6 to OPT#9 were cast to investigate the effect of fine aggregate (UFR) content.

The selected proportions are within the ranges used by previous researchers. The water-to-cementitious material ratio was varied between 0.15 to 0.23, which is also consistent with previous research. These limits and the actual material properties that are typically included for developing non-proprietary UHPC mixture vary based on the application of UHPC and required mechanical properties. More details on the optimization process can be found in Shahrokhinasab and Garber [36]. A total of 115 0.00425-m³ (0.15-ft³) batches and 690 76.2 mm by 152.4 mm (3-in. by 6-in.) cylinders were cast during this experimental program.

3.4. Curing and Storage

All samples were stored at room temperature 23-25°C (73-77 °F). All samples were kept in molds with sealed top surface and demolded 24 hours before testing at each age.

4. Results And Discussion

In addition to developing the non-proprietary UHPC mix and determining the appropriate proportions, the effect of each variable evaluated was determined through several trial batches. The results are summarized in the following sections. The mixtures that best represented a comparison were selected and included in each section below.

4.1. Effect of Cement Type

Five different cement types were used to evaluate their effect on the final properties of the non-proprietary UHPC. OPT#1 was used as a base mix design with 2% steel fibers by volume, and HRWR and VMA dosage were determined to get flow between 178 and 254 mm (7 and 10 in.). Details of each mix design are summarized in Table 6. One of the mixtures (OU2) did not use oven-dried sand and used DRAMIX 4D 65/35BG fibers; the other four mixtures used oven-dried sand with OL 13/.20 fibers.

Table 6. Mixture proportions and characteristics for investigation of cement type

Mix.	Cement Type	w/cm	Mix Proportions						Fiber Type	Content (%)	Admixtures		Density (kg/m ³)	Sand Moisture
			agg/cm	C	S	SF	FA	UFR			HRWR (oz./cwt)	VMA (oz./cwt)		
OU2	Masonry Cement	0.20	1.0	0.6	0.3	0.1	1.0	0	A	2.0	15.77	0	2174	N
C3	Ash Grove Type I-II	0.20	1.0	0.6	0.3	0.1	1.0	0	B	2.0	22.25	0	2387	D
C32	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	1.0	0	B	2.0	27.47	6.5	2353	D
C37	Titan Type III	0.20	1.0	0.6	0.3	0.1	1.0	0	B	2.0	27.47	0	2387	D
C4	Lehigh White Cement	0.20	1.0	0.6	0.3	0.1	1.0	0	B	2.0	23.35	0	2347	D

Flowability and compressive strengths are shown in Figure 5. Use of the masonry cement led to the lowest compressive strength, with 28-day strengths less than 70 MPa (10.2 ksi) and density less than 2242.6 kg/m³ (140 lb/ft³). The poor performance of the masonry cement could be due to the additional air content in the resulting concrete mixture (evident from the lower density) and possibly due to increased lime content. The Type I/II cement and Lehigh White cement had similar strengths, around 100 MPa (14.5 ksi). The Type III cement resulted in the highest 28-day strengths, reaching an average compressive strength of 120 MPa (17.5 ksi) at 28 days. Type III cement showed a noticeably shortened working time compared to other cement types, although the initial flowability of UHPC made by Type III cement was almost same as other cement types. Considering the decreased working time for Type III cement and its initially higher price compared to Type I/II, it was not used for large-scale batches. The working time issue of Type III cement should be addressed through trial batches before it is used in UHPC.

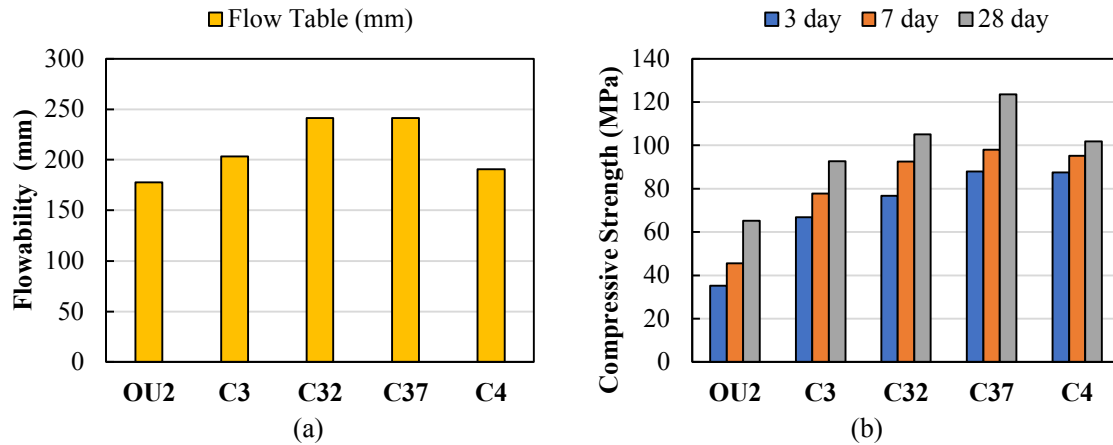


Figure 5. Mix designs with different cement type: (a) flowability of mixes with different cement type and (b) effect of cement type on compressive strength (1 mm = 0.0394 in.; 1 MPa = 0.145 ksi)

Type I/II cement was used for most mixtures in this experimental program and recommended for the final mixture as it led to reasonable strength and more consistent mixtures with reasonable working time.

4.2. Effect of Water-to-Cementitious Materials Ratio

The hydration process of cementitious material is a critical factor that affects the final mechanical properties of concrete. This fact is especially true for UHPC due to the very fine aggregate (maximum aggregate size does not exceed 500 μm) and relatively high specific surface area. Lower water-to-cementitious materials ratios (w/cm) usually result in higher compressive strength, but there are thresholds for both high and low w/cm depending on the material used in the concrete mixture. The minimum w/cm threshold is determined based on the minimum amount of water required to complete the hydration process in the cementitious materials. In other words, reducing the w/cm past a certain point does not enhance the strength due to incomplete hydration process. In addition, decreasing the w/cm decreases the workability and flowability of fresh concrete, which will then cause more HRWR to be required.

There is no exact w/cm to guarantee the full hydration process, as it depends on cement fineness, chemical composition of the clinker used and grain size. Previous studies [37–39] reported numbers between 0.35 to 0.45 for full cement hydration for conventional concrete but the value differs for each mixture design and depends on the constituents used in the concrete matrix. To find the optimum w/cm for the non-proprietary UHPC in this research, mixtures with w/cm between 0.17 to 0.24 were tested, which coincides with typical w/cm for UHPC mixtures [17, 18, 24, 40]. Five mixtures used to compare the effect of the w/cm are shown in Table 6.

The HRWR content was increased for smaller w/cm to maintain the workability of the mixture; even with the increased HRWR content, the flow still decreased with w/cm, as shown in Figure 6 (a).

Table 7. Mixture proportions and characteristics for investigation of water-cementitious materials ratio (dried sand used in all mixtures)

Mix.	Cement Type	w/cm	Mix Proportions						Fiber Type	Fiber Content (%)	Admixtures		Density (kg/m^3)
			agg/cm	C	S	SF	FA	UFR			HRWR (oz./cwt)	VMA (oz./cwt)	
C17	Titan Type I/II	0.24	1.0	0.6	0.3	0.1	1.0	0	B	2.0	16.39	2.47	2287
C11	Titan Type I/II	0.22	1.0	0.6	0.3	0.1	1.0	0	B	2.0	19.87	6.5	2316
C32	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	1.0	0	B	2.0	27.47	6.5	2353
C34	Titan Type I/II	0.18	1.0	0.6	0.3	0.1	1.0	0	B	2.0	27.47	6.5	2400
C26	Titan Type I/II	0.17	1.0	0.6	0.3	0.1	1.0	0	B	2.0	35.52	0	2403

Results showed that the optimum w/cm ratio for this mixture was around 0.18 to 0.20, as shown in Figure 6 (b). The compressive strength increased as the w/cm decreased from 0.24 to 0.18. The compressive strength decreased when the w/cm ratio was further decreased from 0.18 to 0.17. A w/cm ratio of 0.20 is recommended for this mixture as it led to a mixture with high strength and good workability. The w/cm shown here do not include the water from chemical admixtures.

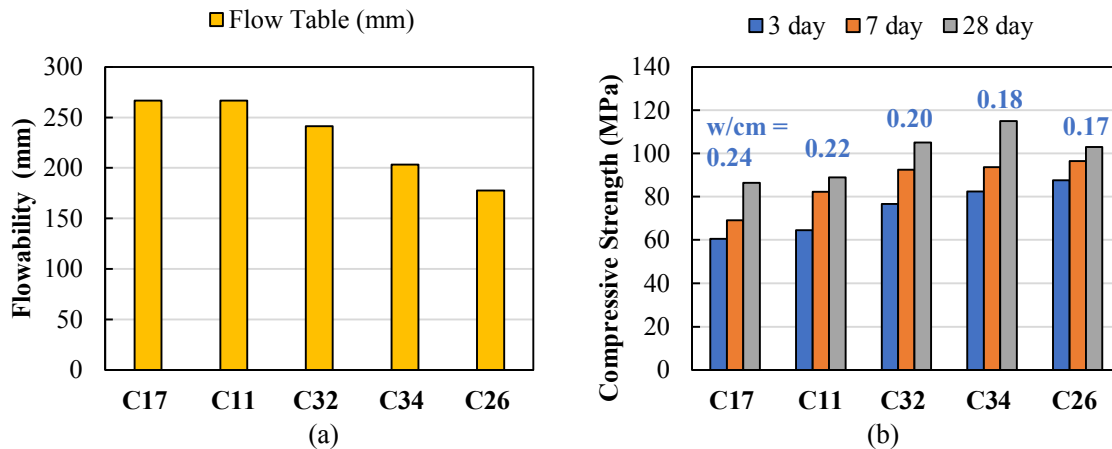


Figure 6. Effect of water-to-cement ratio on (a) flowability and (b) compressive strength (1 mm = 0.0394 in; 1 MPa = 0.145 ksi)

4.3. Effect of HRWR and VMA Content

Effect of HRWR Content

In general, a base amount of HRWR was designed for all the mixtures and was used initially to provide required workability and flowability of mixtures with low w/cm. The actual amount of HRWR was then modified during the mixing procedure based on the workability of each mixture, with a target flow between 200 and 250 mm (8 and 10 in.). Three mixtures that had similar mixture proportions with different HRWR contents are summarized in Table 8. The HRWR dosages were selected to get approximate flows of 150, 200, and 250 mm (6, 8, and 10 in.).

Table 8. Mixture proportions and characteristics for investigation of HRWR effect (dried sand used in all mixtures)

Mix.	Cement Type	w/cm	Mix Proportions						Fiber		Admixtures		Density (kg/m ³)
			agg/cm	C	S	SF	FA	UFR	Type	Content (%)	HRWR (oz./cwt)	VMA (oz./cwt)	
C28	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	1	0	B	2.0	21.70	0	2356
C2	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	1	0	B	2.0	22.25	0	2315
C31	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	1	0	B	2.0	27.47	0	2380

As would be expected, increasing the HRWR content increased the flow of the mixture, shown in Figure 7 (a). Increasing the HRWR content decreased the 28-day compressive strength for these three mixtures, shown in Figure 7 (b). This was likely because increasing HRWR also increased the amount of total liquid in the mixture and thus also increased w/cm. The water in chemical admixtures is usually neglected when determining the water content in a mixture and w/cm, due to their small proportions. The added water from the chemical admixtures was not considered when determining the total water content or w/cm in this research. The most accurate way of calculating w/cm is to consider the free water and water content of other constituents including aggregates and chemical admixtures. The results in this research would support that this additional water should be considered when determining the total water content in non-proprietary UHPC mixtures.

The small flow for mixture C28 required compacting of the material in the mold to ensure that no voids were present in the cylinder; this compaction of the material may have led to higher compressive strength. Having a flow less than 203 mm (8 in.) is not practical. Additionally, there was noticeable fiber segregation for mixtures with too high of flows. Fiber segregation and different fiber contents in different cylinders may be why the 7-day strength was higher than the 28-day strength for C31. Based on the testing with differing amounts of HRWR, HRWR contents are recommended in the 22 to 27 oz./cwt range based on obtaining a flow between 203 and 254 mm (8 and 10 in.).

Another important concern about HRWR or any other chemical admixture, is their water content or liquid part that can affect the w/cm of mixture. In this study the liquid part of chemical admixtures was neglected in w/cm calculations due to their low proportion, but to get accurate results, especially for overdosed HRWR mixes with very low amount of w/cm, the water content of chemical admixtures should be involved in total water calculations.

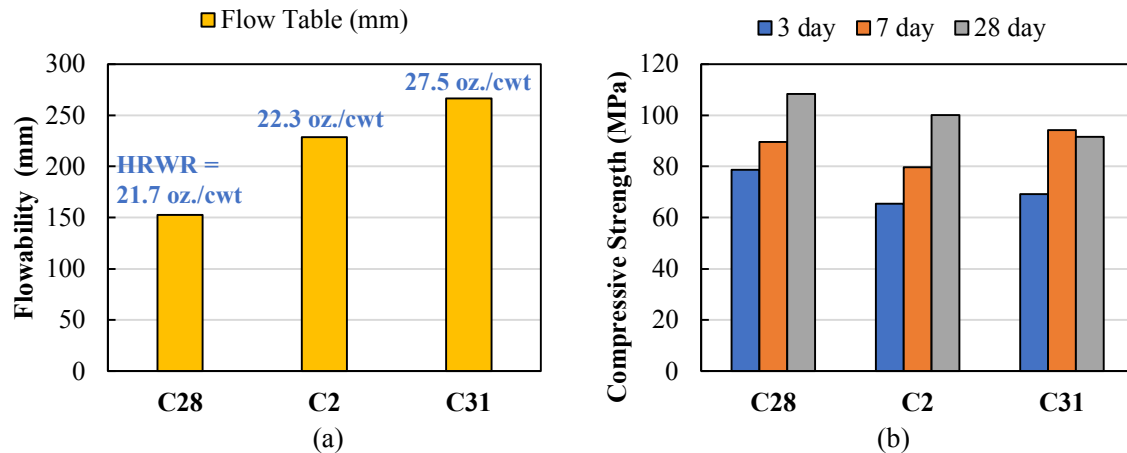


Figure 7. Effect of HRWR content on (a) flowability and (b) compressive strength (1 mm = 0.0394 in.; 1 MPa = 0.145 ksi)

Effect of VMA Content

Viscosity modifying admixture (VMA) is a water-soluble polymer that has been used in concrete technology to modify the viscosity of mixing water and increase the ability of cementitious paste to retain its constituents in suspension [41]. VMAs have been widely used for self-compacting concrete SCC with slump flows ranging from 26 to 31 inches [41]. VMA is also used for pumped concrete, under water concrete, lightweight concrete, sprayed concrete or shotcretes, and even for porous concrete [42]. In this experiment, VMAs were used to help prevent steel fiber segregation in the UHPC mixes. Some fiber types are typically heavier and longer and are more prone to settle and segregate in the concrete mixture. In these cases, VMA will modify the viscosity of the whole mixture and make fibers distribute more uniformly.

The effect of VMA was investigated on a fiber type that did not require VMA to stabilize the fiber in the mixture (Dramix OL 13/0.2); this allowed for a 0 oz./cwt to be compared to mixtures with VMAs. The effect of VMA were evaluated through three mixture designs and their proportions are shown in Table 9. The water content of the VMA was not considered in the w/cm calculation due to its small proportion compared to the total water.

Table 9. Mixture proportions and characteristics for investigation of VMA effect (dried sand used in all mixtures)

Mix.	Cement Type	w/cm	Mix Proportions						Fiber		Admixtures		Density (kg/m ³)
			agg/cm	C	S	SF	FA	UFR	Type	Content (%)	HRWR (oz./cwt)	VMA (oz./cwt)	
C28	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	1.0	0	B	2.0	21.70	0	2356
C16	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	1.0	0	B	2.0	26.55	3.02	2382
C29	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	1.0	0	B	2.0	21.70	6.50	2347

The flow and compressive strength for similar mixtures with different amounts of VMA are shown in Figure 8. VMA increased the flow (comparing C28 and C29 with similar HRWR contents), see Figure 8 (a). The VMA content did not influence the compressive strength of these three mixtures, shown in Figure 8 (b). VMAs are not suggested to be used with the standard fiber types used for UHPC (i.e., with 12.7-mm length and 0.20-mm diameter [0.5-in. length and 0.008-in. diameter]), but they can be used to stabilize other types of fibers that may tend to float or settle during the mixing procedure without affecting the strength of the mixture. No VMAs are recommended in the standard proposed mixture since the standard UHPC fiber type is recommended.

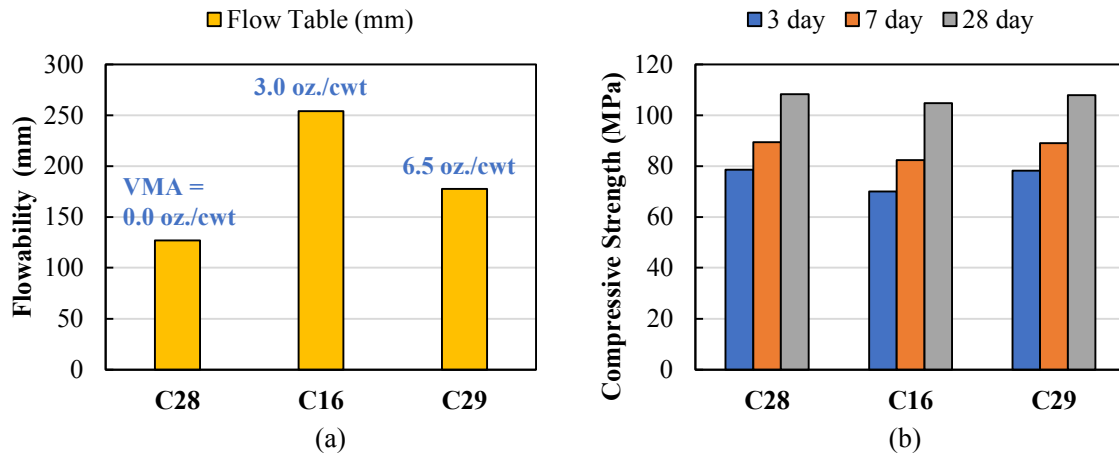


Figure 8. Effect of VMA content on (a) flowability and (b) compressive strength (1 mm = 0.0394 in.; 1 MPa = 0.145 ksi)

Four additional mixtures were also performed to investigate the influence of VMA on working time and the corresponding 28-day compressive strength. The details for these four mixture designs are provided in Table 10.

Table 10. Mixture proportions and characteristics for investigation of working time (dried sand used in all mixtures)

Mix.	Cement Type	w/cm	Mix Proportions							Fiber	Admixtures		Density (kg/m ³)
			agg/cm	C	S	SF	FA	UFR	Type	Content (%)	HRWR (oz./cwt)	VMA (oz./cwt)	
C35	Titan Type I/II	0.20	1	0.6	0.3	0.1	1	0	B	2	27.47	0.00	2411
C36	Titan Type I/II	0.20	1	0.6	0.3	0.1	1	0	B	2	27.47	6.50	2406
C40	Titan Type I/II	0.17	1	0.6	0.3	0.1	1	0	B	2	29.39	0.00	2507
C41	Titan Type I/II	0.17	1	0.6	0.3	0.1	1	0	B	2	29.39	9.16	2428

The mixing procedure for these four mixtures was the same as the other mixtures. The only difference was that not all the cylinders were cast immediately after the mixing procedure was completed. The flow was measured every 10 minutes for 20 to 60 minutes, until the flow of the mixture dropped below 127 mm (5 in.). Two cylinders were cast at three different times after casting. The flow versus time for these four mixtures are shown in Figure 1. The mixture with a w/cm of 0.20 had a higher flow over time with VMA compared to the same mixture without VMA, shown in Figure 1 (a). The VMA content had no effect on the flow for the mixtures with a w/cm of 0.17, shown in Figure 1 (b). All mixtures were slightly agitated by hand mixing at the end of the testing; in all cases the hand mixing increased the flow. This can be done in the field (by hand or in a separate mixer) to extend the working time of the mixtures.

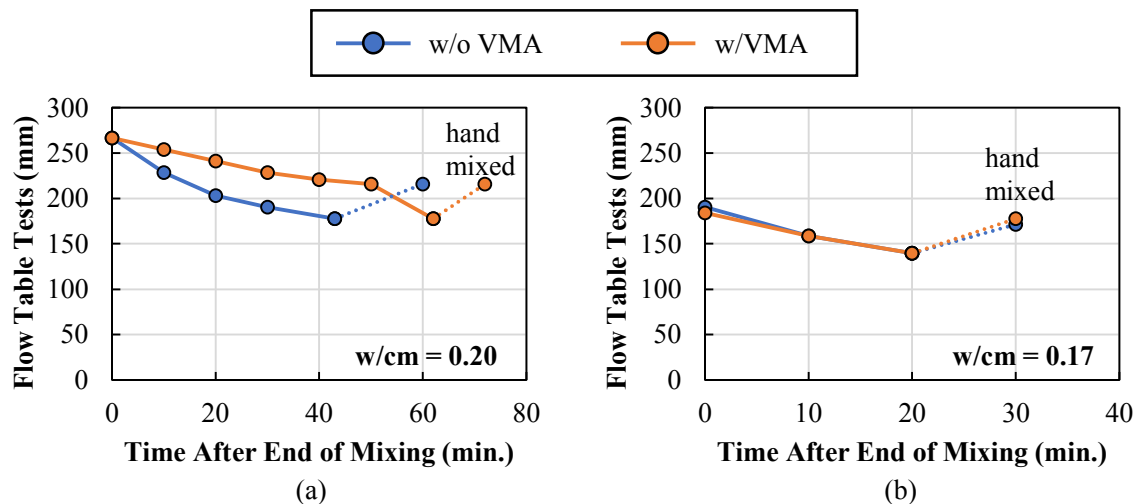


Figure 1. Flow versus time for mixtures with and without VMA and (a) w/cm of 0.2 and (b) w/cm of 0.17 (1 mm = 0.0394 in.)

The compressive strength was measured at the same age for the cylinders taken from different times after the end of mixing from the mixtures with w/cm of 0.20 (7 days) and w/cm of 0.17 (28 days). There was a slight increase in compressive strength the longer they were cast after the end of mixing for the cylinders with w/cm of 0.20. There was no effect for the cylinders with w/cm of 0.17. Similar compressive strengths were observed for specimens with and without VMA for both values of w/cm.

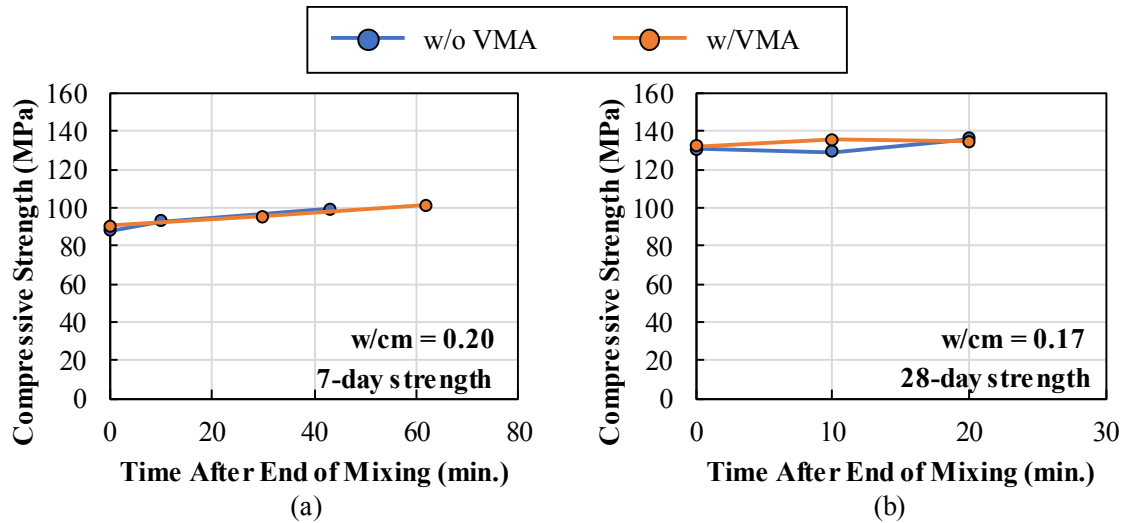


Figure 10. Compressive strength versus time after mixing for mixtures with and without VMA and (a) w/cm of 0.2 and (b) w/cm of 0.17 (1 MPa = 0.145 ksi)

4.4. Effect of Fiber Type

Previous researchers [16-18, 23, 43] have tested the effect of different fiber contents, ranging from 1% to 5% fiber content by volume. The typical fiber content for UHPC mixes is 2% by volume, which is what was selected for this research. Five different fiber types including four steel fibers and one synthetic fiber were investigated in this study:

- Dramix 4D 65/35BG (A);
- Helix 5-13 Uncoated (H);
- Dramix OL 13/20 (B);
- Hiper Fiber Type A (HF);
- STRUX® 90/40 (S).

All different fiber types were used with the OPT#1 mixture design for performance comparison, as shown in Table 11. VMAs were used with two of the heavier fiber types to help to stabilize the fibers. Helix (H) fibers and Bekaert 4D 65/35BG (A) fibers were the heaviest and most challenging fibers to keep in suspension in the concrete mixture. While the recommended dosage by the manufacturer was 10 oz./cwt, the lower doses of VMA noted in Table 11 were effective at preventing segregation. These amounts were determined by gradually adding the VMAs to the mixture until the mix was viscous enough to stabilize the fibers. The recommended dosage by manufacturer usually comes from of an average required amount for series of experimental tests, therefore, proper dosage may slightly be different from recommended value by manufacturer, according to the mixture constituents.

Table 11. Mixture proportions and characteristics for investigation of fiber type (dried sand used in all mixtures)

Mix.	Cement Type	w/cm	Mix Proportions						Fiber		Admixtures		Density (kg/m³)
			ag/cm	C	S	SF	FA	UFR	Type	Content (%)	HRWR (oz./cwt)	VMA (oz./cwt)	
C5	Titan Type I/II	0.20	1.0	0.60	0.3	0.1	1.0	0	H	2.0	24.72	6.41	2342
C6	Titan Type I/II	0.20	1.0	0.60	0.3	0.1	1.0	0	A	2.0	24.72	8.24	2345
C2	Titan Type I/II	0.20	1.0	0.60	0.3	0.1	1.0	0	B	2.0	22.25	0	2315
C42	Titan Type I/II	0.20	1.0	0.60	0.3	0.1	1.0	0	HF	2.0	27.47	0	2380
L9	Titan Type I/II	0.20	1.0	0.60	0.3	0.1	1.0	0	S	2.0	27.47	0	2268

The flowability and compressive strength for the five mixtures with different fiber types are shown in Figure 11. Similar flowability was achieved for all five fiber types using differing amounts of HRWR and VMA. The Hiper Fiber (HF in C42) and Dramix OL 13/.20 (B in C2) were found to have higher compressive strengths than the other types of fibers. Samples containing synthetic fibers showed lower compressive strengths and density than those with steel fibers. These samples had the smallest compressive strengths of all the different fiber types and contents tested. This lower compressive strength of samples with synthetic fibers, could be due to the lower strength of the synthetic fibers compared to steel fibers. Additionally, the lower strength of specimens with synthetic fibers could be explained by higher fiber clumps when synthetic fibers were used. Clumping of the fibers occurred in some cases where the fibers were added rapidly to the mixer, when long or heavy fibers were used, or when synthetic fibers were used. These clumps could trap some air and make voids in the concrete matrix which result in lower density and compressive strength.

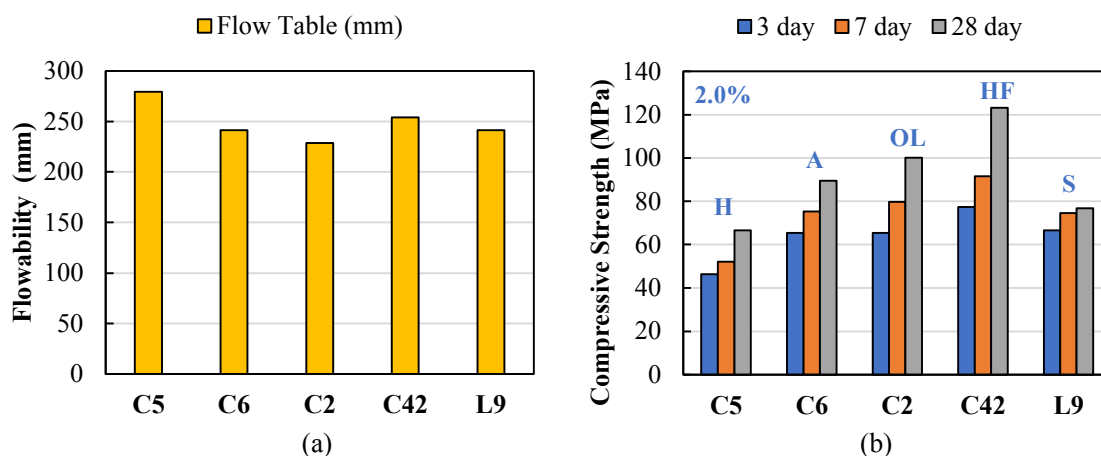


Figure 11. Effect of Fiber type on (a) flowability and (b) compressive strength (1 mm = 0.0394 in.; 1 MPa = 0.145 ksi)

The mixtures presented here all had reasonable distribution of the fibers according to visual inspection after testing. Sample photographs of the cylinders after compression failure are shown in Figure 12. There were some mixtures where the heavier fibers segregated and settled during mixing, before VMA was used.

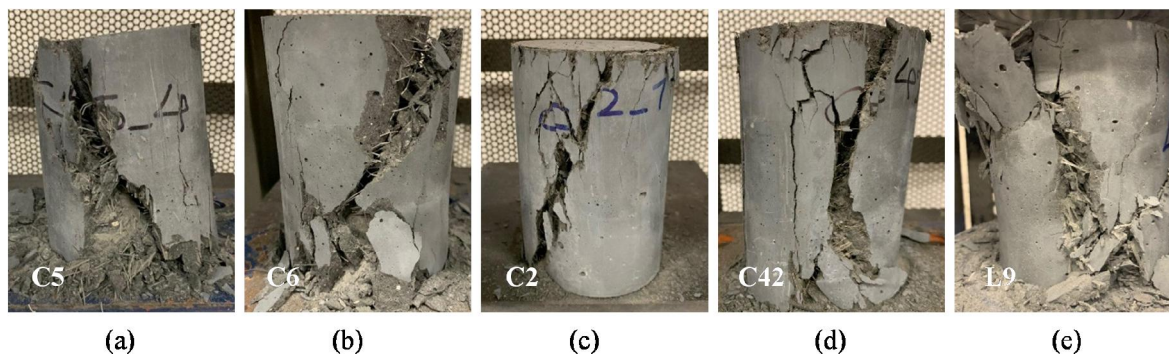


Figure 12. Sample cylinders after compression failure for different fiber types: (a) Helix 5-13, (b) Dramix 4D 65/35BG, (c) OL 13/.20, (d) Hiper Fiber Type A, and (e) Strux 90/40

As mentioned above, the Helix 5-13 fibers had a higher zinc content and no brass coating, which led to an expansive reaction occurring between the fibers and the concrete, as shown in Figure 13. The concrete expanded about 12.7 mm (0.5 in.) outside the top of the cylinder before demolding, shown in Figure 13 (a). When the cylinder molds were removed, part of the cylinders broke off the top, visible in Figure 13 (b). The concrete still held load but failed at much lower loads than other cylinders (40.9 MPa (5.9 ksi)). These findings suggest that higher zinc content in fibers can negatively affect the mechanical properties of the UHPC mixture due to some unwanted chemical reactions. The manufacturer of the fiber has fixed this issue. But this example highlights the importance of mixing trial batches before using new fiber sources in field applications.

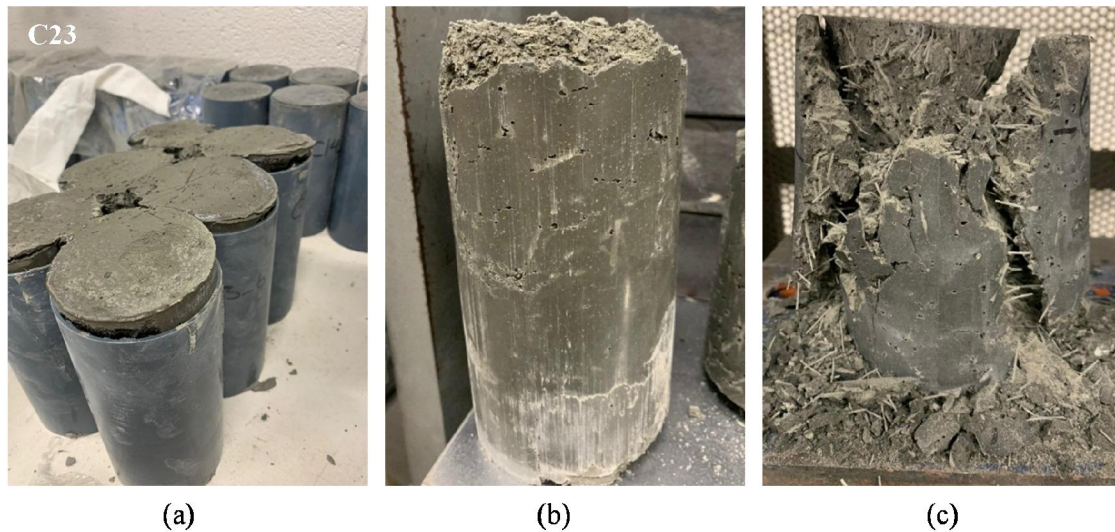


Figure 13. Example of expansion caused by concrete mixture reacting with zinc in fibers for C23 (a) before demolding, (b) after demolding before testing, and (c) after testing

Based on these test results, one of the fibers with a 13-mm (0.5-in.) length and 0.2-mm (0.00787-in.) diameter with a brass coating would lead to the highest compressive strength. The longer hooked fibers and synthetic fibers may appropriate for use in cases where the highest compressive strength is not required. Zinc-coated fibers or fibers with high zinc contents should be avoided.

4.5. Effect of Fine Aggregate Content

Ultra-fines recovery (UFR) material was used in some mixtures to improve the particle packing of the mixtures. UFR is made of limestone with lower stiffness, resistance, and strength compared to quartz particles made of rock crystal quartz. It has a very fine particle size, which minimizes the porosity of concrete by filling the gaps between courser particles and increasing the density. UFR was used to improve the distribution curve of OPT#1 and make it closer to the ideal curve driven from Equation 1. The particle packing analysis showed that replacing 10 to 35% of regular sand with UFR brought the base mix distribution curve (OPT#1) much closer to the ideal curve (shown in Figure 4). Table 12 summarizes the proportions of five mix designs obtained by replacing 0, 10, 20, 30, and 35% of sand with UFR to study the effect of UFR on the flowability and compressive strength. Adding UFR to the concrete mix increased the total special surface area, which required more HRWR to result in the same flowability. For this reason the required dosage of HRWR increased with increasing replacement ratios of UFR in the concrete mix.

Table 12. Mixture proportions and characteristics for investigation of using ultra-fine recovery (UFR) (dried sand used in all mixtures)

Mix.	Cement Type	w/cm	Mix Proportions						Fiber		Admixtures		Density (kg/m ³)
			agg/cm	C	S	SF	FA	UFR	Type	Content (%)	HRWR (oz./cwt)	VMA (oz./cwt)	
C28	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	1.00	0.00	B	2.0	21.70	0	2356
C45	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	0.90	0.10	B	2.0	27.47	0	2347
C46	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	0.80	0.20	B	2.0	27.47	0	2377
C47	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	0.70	0.30	B	2.0	29.39	0	2364
C48	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	0.65	0.35	B	2.0	29.39	0	2360

The measured flow and compressive strength for these mixtures with varying UFR amounts and w/b of 0.20 are shown in Figure 14. Compressive strength results showed that replacing 10, 20, 30 and 35% of sand with UFR enhanced the 28-strength 7.0, 9.3, 8.9 and 13.6%, accordingly. Flowability results showed that even by overdosing the HRWR, C47 with 30 % UFR and C48 with 35% UFR were less flowable than C45 with 10% UFR. Although the flow was 200 mm (8 inches), it was harder to work with the UHPC with a 35-percent UFR replacement.

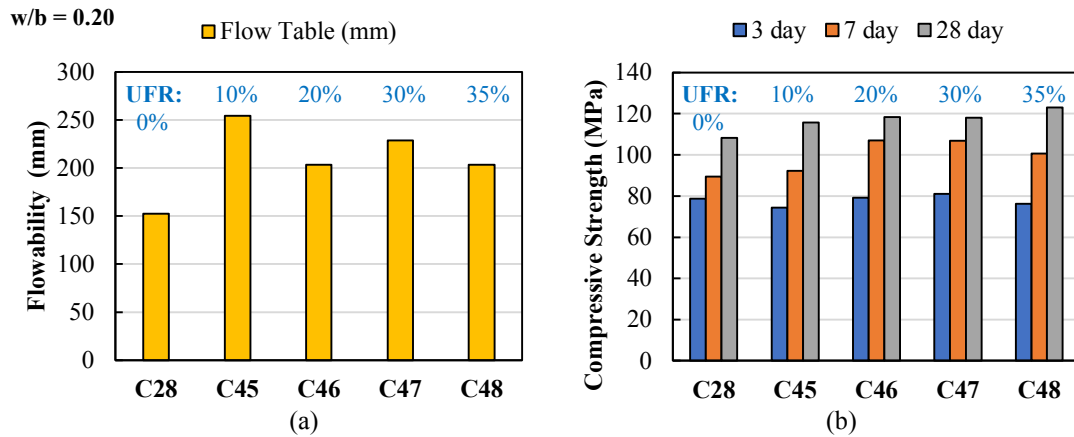


Figure 14. Effect of fine aggregate content on (a) flowability and (b) compressive strength (1 mm = 0.0394 in; 1 MPa = 0.145 ksi)

Two additional mixtures were cast with a lower w/cm and UFR contents of 20 and 30 percent. Details for these mixtures are provided in Table 13.

Table 13. Mixture proportions and characteristics for investigation using ultra-fine recovery (UFR) with w/b of 0.18 (dried sand used in all mixtures)

Mix.	Cement Type	w/b	Mix Proportions						Fiber Type	Fiber Content (%)	Admixtures		Density (lb/ft ³)
			agg/cm	C	S	SF	FA	UFR			HRWR (oz./cwt)	VMA (oz./cwt)	
C28	Titan Type I/II	0.18	1	0.6	0.3	0.1	1.00	0.00	OL	2.0	27.47	0	149.4
C45	Titan Type I/II	0.18	1	0.6	0.3	0.1	0.80	0.20	OL	2.0	38.08	0	150.7
C46	Titan Type I/II	0.18	1	0.6	0.3	0.1	0.70	0.30	OL	2.0	38.08	0	150.8

The measured flow and compressive strength for these mixtures with varying UFR amounts and w/cm of 0.18 are shown in Figure 15. Compressive strength results showed that replacing 20 and 30 percent of sand with UFR increased the 28-strength 19.1 and 17.6 percent, respectively, compared to the mixtures without any UFR.

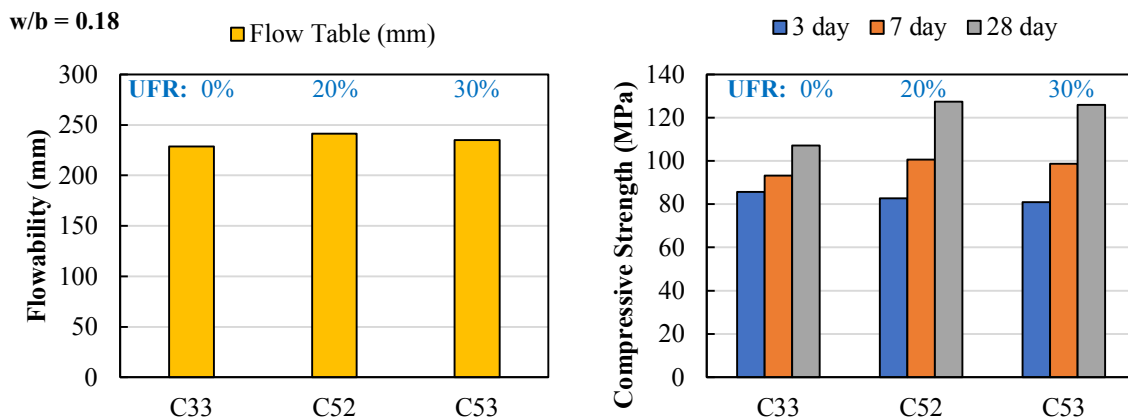


Figure 15. Effect of fine aggregate content on (a) flowability and (b) compressive strength (with w/cm = 0.18)

According to the results, the use of UFR up to 35% improved the mechanical properties of UHPC.

5. Conclusions

The primary goal of this research was to develop a non-proprietary UHPC mixture and evaluate the effect of different cement types and contents, w/cm, superplasticizer and VMA contents, fiber type, and fine aggregate type and content on the compressive strength and flowability of non-proprietary UHPC mixtures. More than 600 individual specimens were tested to determine the compressive strength of non-proprietary UHPC mixture designs using different fine aggregates and steel fibers. Two mixture designs with the most promising results and fiber types are summarized in Table 14.

Table 14. Proposed mixture designs with limestone fine aggregate based on the availability of UFR

Mixes	Agg./cm	Cement (%)	Slag (%)	Silica Fume (%)	Sand (%)	UFR (%)	Recommended values			Expected Compressive Strength MPa (ksi)
							Fiber Content (%)	w/cm	HRWR dosage (oz./cwt)	
OPT#1	1.0	0.6	0.3	0.1	1.00	0.00	2.0	0.20	26	117.2 (17.0)
OPT#9	1.0	0.6	0.3	0.1	0.65	0.35	2.0	0.20	28	124.1 (18.0)

OPT#1 is the recommended mixture if UFR is not available. Because it does not have UFR a lower dosage of HRWR is required to reach the desired flowability. Mixture OPT#9 has better particle packing since 35% of the fine aggregate is replaced by UFR. Fibers with a 13-mm (0.5-in.) length and 0.2-mm (0.00787-in.) diameter with a brass coating and 2,750 MPa (400 ksi) tensile strength, exhibited the best performance in both mixtures, but other fiber types provide reasonable results for some applications if proper adjustments are made to the admixture dosages.

The conclusions of this evaluation on non-proprietary UHPC include:

- UHPC is sensitive to the moisture content of dry constituents (aggregates); the moisture content of the fine aggregate affected the repeatability of UHPC mixtures. It is important to use oven dried fine aggregates to ensure accurate and proper results. This may be difficult for field applications. More research should be done to investigate mixtures with fine aggregates with natural moisture contents.
- Five different cement types were studied in this research. The use of masonry cement led to the lowest compression strengths, which was probably due to its higher air content. Type III cement led to the highest measured strength but had shorter working time. Type I/II and Lehigh White cement had similar compressive strength and workability and had compressive strength within 10 percent of Type III cement.
- Five different w/cm were tested between 0.17 and 0.24, which corresponds to the typical range for UHPC mixtures. Higher compressive strength was observed with lower w/cm as was expected. Mixtures with lower w/cm had issues with workability and required more superplasticizer to maintain the required flowability. Based on this, the optimum w/cm ratio for non-proprietary UHPC was found to be between 0.18 to 0.20.
- Different dosage of HRWR were used to keep the flow between 150, 200, and 250 mm (6, 8, and 10 in.). Compression strength of mixtures with higher dosage of HRWR was lower than mixtures with less HRWR dosage. This observation was potentially due to the additional water in HRWR causing an increased w/cm. This additional water in the chemical admixtures was not considered when calculating w/cm and the amount of water to add to each mixture, which is similar to what has been done in most previous studies on UHPC. Due to very high sensitivity of UHPC mixtures to water content, it is recommended to consider the liquid parts of chemical admixtures in w/cm calculations and when determining the amount of water to add to a mixture.
- The use of VMA was found to be a good option when using fiber types where fiber segregation may be a concern. VMA did not affect the compressive strength of the mixtures tested in this research, but more research is needed to study the effect of VMA on the rheology of UHPC. Additional variables like maximum aggregate size, w/cm, HRWR dosage, and VMA dosage should be further investigated.
- The use of typical fibers with 13-mm (0.5-in.) length and 0.2-mm (0.00787-in.) diameter, and tensile strength of 2,750 MPa (400 ksi) led to the highest compressive strengths. This size fiber distributed well without the addition of VMA.
- New fiber types should be tested in small trial batches to ensure adequate performance before being used in field applications. Zinc-coated fibers and uncoated fibers with high zinc contents can lead to an expansive reaction in UHPC that breaks down the concrete matrix and greatly decreases the strength of the concrete. Whether or not a fiber reacts with the concrete mixture can be determined through these small trial mixtures.
- Using UFR improved the particle packing of the UHPC mixture, which was expected to result in better mechanical properties. Replacing 10 to 30 percent of fine sand with UFR in the mixture resulted in a 7 to 19 percent increase in the compressive strength depends on the w/cm.

6. Declarations

6.1. Author Contributions

Conceptualization, E.S., T.L., R.F., and D.G.; methodology, E.S., T.L., R.F., and D.G.; writing—original draft preparation, E.S., T.L., R.F., and D.G.; writing—review and editing, E.S., T.L., R.F., and D.G. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

Data sharing is not applicable to this article.

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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