Non-Proprietary UHPC Workshop

Consideration for Local Materials

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Outline

- Background
- Mix Design and General Overview
- Basic Steps for Non-Proprietary UHPC Mix Development
- Small-Batch Results
- Large-Batch Results
- Conclusions and Recommendations

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Background

Ultra-High Performance Concrete (UHPC)

- Cementitious composite material with high compressive strength, stiffness, and tensile strength and sustained post-cracking tensile strength and strain hardening response
- Steel fibers are typically included in the mixture to provide the required post-cracking response
- Pre-bagged commercial (or proprietary) UHPC products and non-proprietary UHPC mixtures are both available

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Background

Ultra-High Performance Concrete (UHPC)

Property	Typical Range
7-day Compressive Strength	14.5 to 19.5 ksi
14-day Compressive Strength	18 to 22 ksi
Direct Tensile Cracking Strength	0.8 to 1.2 ksi
Direct Tension Bond Test	0.35 to 0.6 ksi
Modulus of Elasticity	4,250 to 8,000 ksi
Long-term Drying Shrinkage	300 to 1,200 με
Long-term Autogenous Shrinkage	200 to 900 με
Initial setting time	4 to 10 hours
Final setting time	7 to 24 hours
Static flow	7.5 to 10 inches

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B. Graybeal, “Design and construction of field-cast UHPC Connections,” Federal Highway Administration (FHWA), FHWA-HRT-19-011, 2019

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Background

Non-Proprietary UHPC

- UHPC typically consists of:
  - Binders / SCMs
    - Cement
    - Silica fume
    - Other SCMs (e.g., fly ash, slag)
  - Fine Aggregate
    - Silica Sand / Crushed Limestone
    - Ground Quartz
  - Chemical Admixtures
    - Superplasticizer / High-Range Water Reducer (HRWR)
    - Viscosity Modifying Admixture (VMA)
  - Fibers (typically steel with 13mm length and 0.2mm diameter)

Supplementary Cementitious Materials (SCM)

Cement

Slag

Silica Fume

Silica Sand

Superplasticizer

Steel Fibers

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Background

Non-Proprietary UHPC – Sample of Previous Studies

Researcher	Year	Location	Selected-UHPC Mix Parameters						Performance	
			c: SF: SCM	*Other SCMs Used*	*w/c*	*w/b*	*Agg.:b*	*Fiber vol. fraction (%)*	*Flow (in.)*	*f'_c (ksi)*
Tadros et al.[1]	2020	A	1.0: 0.25: 0.00	-	0.25	0.200	0.88	0 and 2	8-11	25.0
		B	1.0: 0.25: 0.11	LP	0.25	0.184	1.10	0 and 2	8.9, 9.2	23.4
		C	1.0: 0.25: 0.00	-	0.24	0.195	0.77	0 and 2	9.1	23.1
		D	1.0: 0.20: 0.18	LP	0.29	0.202	0.77	0 and 2	9.1	21.4
		E	1.0: 0.25: 0.00	-	0.23	0.188	1.10	0 and 2	8.9	23.6
Lawler et al.	2019	FL	1.0: 0.15: 0.15	FA (Class F)	0.23	0.170	1:0 to 2:0	1.5 and 2	8-10	18-19
Karim et al.[2]	2019	Iowa	1.0: 0.07: 0.00	-	0.20, 0.25	0.18, 0.2, 0.23	1.12, 1.3	2	8-9	10-17
Matos et al.	2019	Portugal	1.0: 0.54: 0.27	-	0.40	-	1.0	3	11.2-12.2	21-22
Looney et al.	2019	OK	1.0: 0.17: 0.50	S	0.18 to 0.22	0.18 to 0.23	0.75, 1.0	1 and 2	9-11	16-18.2
Berry et al.	2017	Montana	SF/FA = 0.75	FA	0.24	-	1.4[3]	0 and 2	8-11	20-21
El-Tawil et al.	2016	Michigan	1.0: 0.25: 1.0	S	0.22	0.18	1.0	1.5	-	20.9-28.3
Graybeal	2013	WA, OR, ND, SD, NY, PA	1.0: 0.25: 0.25	FA	0.22 to 0.24	0.15 to 0.16	1.0	1 and 2	10.4-12.4	22.5-29
Tafraoui et al.	2009	France	1.0: 0.25: 0.25	Metakaolin	0.27	0.22	0.9, 1.18	0 and 2	-	15-27.5

c = cement; SF = silica fume; b = binders = all cementitious materials; FA = fly ash; LP = limestone powder; S = slag or GGBS
[1]liquid portion of chemical admixtures was included in w:c and w:b calculations; [2]compressive strength was measured at 7 days; [3]this is sand to cement ratio

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Basic Steps for Non-Proprietary UHPC Mix Development

1. Survey locally available materials
   - Fine aggregate, Cement, Source of other SCMs (e.g., slag, fly ash, silica fume)
2. Select previous research with similar types of available materials (can start by looking for study closest to you) to use as a starting point
3. Measure particle size distributions for available materials (our local cement/aggregate producer did this for us)
4. Determine appropriate proportions of materials to fall closest to the ideal curve
5. Determine compression strength of several different options using small-batch mixtures; will also get a sense of needed HRWR in small batches
6. Test additional material properties (e.g., MOR, direct tension, durability-related properties) and scalability with large-batch mixture for best performing mixture

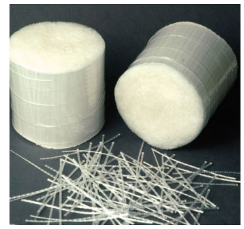
Available Materials Investigated

- **Aggregate**: Masonry Sand – TITAN (Miami)
- **Cement**: Type I/II, III, Masonry – TITAN (Miami)
- **Slag**: ARGOS USA (Tampa)
- **Superplasticizer**: Glenium 7920 – BASF
- **VMA:** MasterMatrix VMA 358 – BASF
- **Silica fume** – BASF
- **Steel Fibers**: Hiper Fiber Type A, Bekaert OL 13/.20, Dramix 4D 65/35BG, Helix 5-13
- **Synthetic Fibers**: GCP STRUX® 90/40

South Florida materials

Available Steel Fibers Investigated



	DRAMIX 4D 65/35BG	Helix 5-13	BEKAERT OL 13/.20 Hiper Fiber Type A	GCP STRUX® 90/40
Length:	35mm (1.4”)	13mm (0.5”)	13mm (0.5”)	40mm (1.55”)
Diameter:	0.55mm (0.02”)	0.5mm (0.02”)	0.2mm (0.008”)	0.43mm (0.017”)
Aspect Ratio:	65	26	65	92
Tensile Strength:	1,850 MPa (268.0 ksi)	1,700 MPa (246.5 ksi)	2,758 MPa (400.0 ksi)	620 MPa (90.0 ksi)

(high tensile strength so fibers slip before rupturing, gives ductility)

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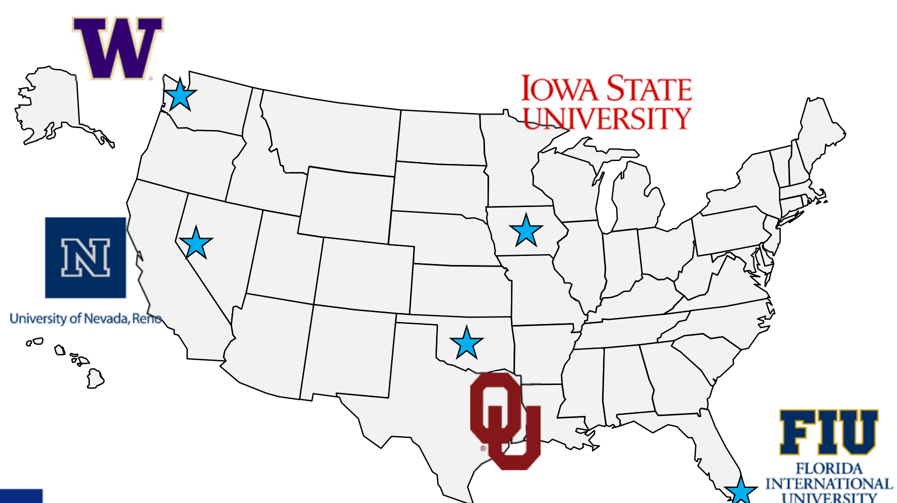
ABC-UTC – Non-Proprietary UHPC Project



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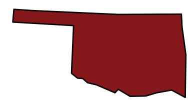
Base Mix Design

Component	Quantity
Type I Cement, lb/yd^3	1179.6
Slag, lb/yd^3	589.8
Silica Fume, lb/yd^3	196.6
w/cm	0.23
Fine Masonry Sand, lb/yd^3	1966
Steel Fibers, lb/yd^3	255.2
Steel Fibers, %	2.0
Glenium 7920, oz./cwt	15.77

Oklahoma materials



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Starting point for FIU mix design

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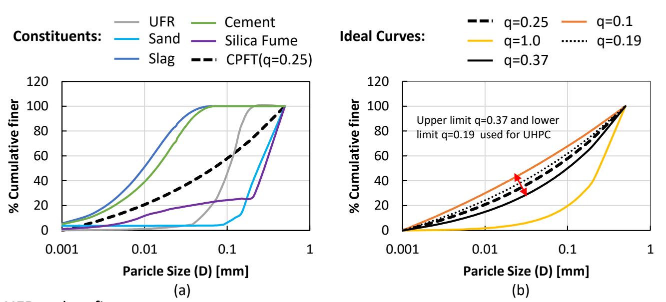
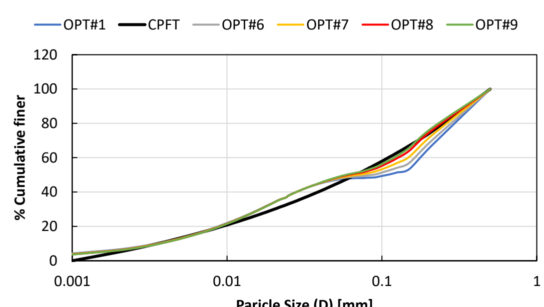
Particle Size Distribution Analysis

Mixture Optimization at FIU



(a) (b)



UFR = ultra-fine recovery material; finer than sand

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

$$D(P) = \frac{D^q - D^q_{min}}{D^q_{max} - D^q_{min}}$$

D(P) = percent passing for each diameter evaluated
D = particle diameter being evaluated
D_{min} = smallest particle diameter used in the mix design
D_{max} = largest particle size used in the mix design
q = distribution modulus

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Malvern laser particle size analyzer in Titan America Cement Lab in Miami

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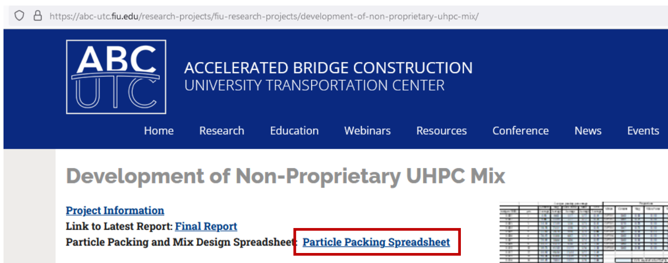
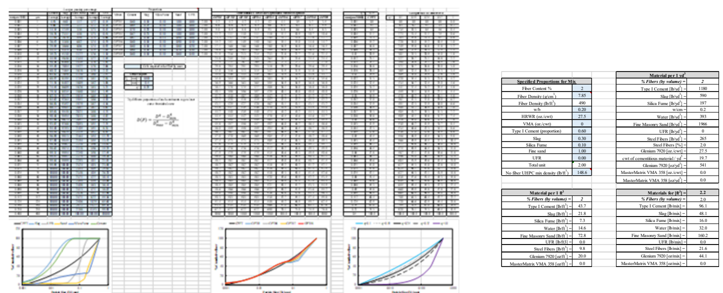
Particle Size Distribution Spreadsheet





https://abc-utc.fiu.edu/research-projects/fiu-research-projects/development-of-non-proprietary-uhpc-mix/

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Determining Amount of Material for Mixtures

Proportions for Mixtures

Constituent	Proportion	Variable
agg/cm	1.0	
Cement	0.6	P_c
Slag	0.3	P_s
Silica Fume	0.1	P_{sf}
Fine Sand	0.9	P_{sand}
UFR	0.1	P_{UFR}
Total Units	*2.0*	P_{tot}

The total units here should equal 2.0. We found 1.0:1.0 binder-to-aggregate ratio to be best.

Other Information Needed

Property	Value	Variable
Fiber Content [%]	2.0	FC
Fiber Density [lb/ft^3]	490	ρ_f
Water-to-binder ratio	0.2	w/b
HRWR [oz./cwt]	27.5	v_{HRWR}
VMA [oz./cwt]	0.0	V_{VMA}
Estimated Density [lb/ft^3]	148.6	ρ_c

Value shown here was measured on a mix with 0% fibers. 150 lb/ft^3 is a good initial estimate.

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Determining Amount of Material for Mixtures

- Cement:

$$W_c = \frac{\rho_c P_c(1-FC)}{P_{tot}} = \frac{\left(148.6\ {}^{lb}/_{ft^3}\right)(0.6)(1-0.02)}{2.0} = 43.7\ {}^{lb}/_{ft^3}$$

- Slag:

$$W_s = \frac{\rho_c P_s(1-FC)}{P_{tot}} = \frac{\left(148.6\ {}^{lb}/_{ft^3}\right)(0.3)(1-0.02)}{2.0} = 21.8\ {}^{lb}/_{ft^3}$$

- Silica Fume:

$$W_{sf} = \frac{\rho_c P_{sf}(1-FC)}{P_{tot}} = \frac{\left(148.6\ {}^{lb}/_{ft^3}\right)(0.1)(1-0.02)}{2.0} = 7.3\ {}^{lb}/_{ft^3}$$

- Water:

$$W_w = (W_c + W_s + W_{sf})\left({}^{w}/_{b}\right) = \left(43.7\ {}^{lb}/_{ft^3} + 21.8\ {}^{lb}/_{ft^3} + 7.3\ {}^{lb}/_{ft^3}\right)(0.2) = 14.6\ {}^{lb}/_{ft^3}$$

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Determining Amount of Material for Mixtures

- The amount of fine sand and UFR can be found using a similar procedure as the cementitious materials

$$W_{sand} = \frac{\rho_c P_{sand}(1-FC)}{P_{tot}}$$

$$W_{UFR} = \frac{\rho_c P_{UFR}(1-FC)}{P_{tot}}$$

- Fibers:

$$W_{fibers} = \rho_f(FC) = \left(490\ {}^{lb}/_{ft^3}\right)(0.02) = 9.8\ {}^{lb}/_{ft^3}$$

- HRWR:

$$V_{HRWR} = v_{HRWR}\frac{(W_c + W_s + W_{sf})}{100} = \left(27.5\ \frac{oz}{cwt}\right)\frac{\left(43.7\ {}^{lb}/_{ft^3} + 21.8\ {}^{lb}/_{ft^3} + 7.3\ {}^{lb}/_{ft^3}\right)}{100\ lb} = 20.0\ {}^{oz}/_{ft^3}$$

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Determining Amount of Material for Mixtures

- Take these amounts per cubic foot times your total desired volume
- More details in Final Report

  Shahrokhinasab and Garber (2021), Development of "ABC-UTC Non-Proprietary UHPC" Mix, Report No. ABC-UTC-2016-C2-FIU01-Final

Constituent	Amount per ft^3	Amount per $0.15 ft^3$
Cement [lb]	43.7	6.6
Slag [lb]	21.8	3.3
Silica Fume [lb]	7.3	1.1
Water [lb]	14.6	2.2
Fine Sand [lb]	65.5	9.8
UFR [lb]	7.3	1.1
Steel Fibers [lb]	9.8	1.5
HRWR [oz]	20.0	3.0
VMA [oz]	0.0	0.0

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Small and Large Batch Mixtures

Small-Batch (0.15 ft^3 [0.00425 m^3])

115 mixtures

Properties Measured	
Flowability	Compressive Strength

Large-Batch (2.2 ft^3 [0.0623 m^3])

10 mixtures

Properties Measured	
Flowability	Flexural Strength
Compressive Strength	Total and Drying Shrinkage
Modulus of Elasticity	Set Time
Splitting Tensile Strength	Bulk Resistivity Test

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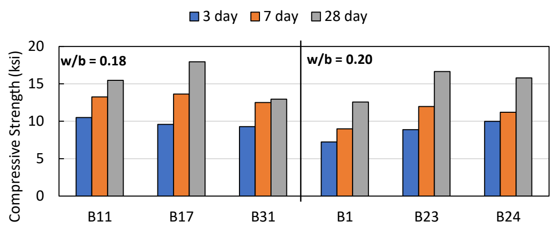
Experimental Results – Small-Batch

Aggregate Moisture Content

Natural moisture content led to large variability in results. Aggregate should be oven dried for most consistent results.

Mix.	Cement Type	w/b	Mix Proportions						Fiber		Admixtures		Density (lb/ft^3)	Sand Moisture
			agg/cm	*C*	*S*	*SF*	*FA*	*UFR*	*Type*	*Content (%)*	*HRWR (oz./cwt)*	*VMA (oz./cwt)*		
B11	Titan Type I/II	0.18	1.0	0.6	0.3	0.1	1.0	0.0	-	0.0	23.81	0.00	146.10	N
B17	Titan Type I/II	0.18	1.0	0.6	0.3	0.1	1.0	0.0	-	0.0	23.81	0.00	146.40	N
B31	Titan Type I/II	0.18	1.0	0.6	0.3	0.1	1.0	0.0	-	0.0	23.81	0.00	144.90	N
B1	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	1.0	0.0	-	0.0	15.75	0.00	138.60	N
B23	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	1.0	0.0	-	0.0	23.81	0.00	146.00	N
B24	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	1.0	0.0	-	0.0	21.97	0.00	145.80	N



Aggregates were oven dried for all mixtures in Series C (small-batch) and all large batch mixtures

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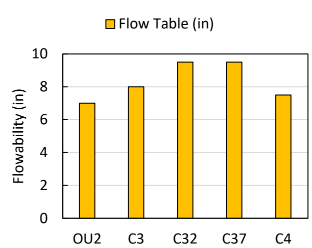
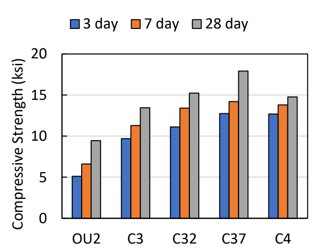
Experimental Results – Small-Batch

Cement Type

Type I/II had high strength, good workability, and was the least expensive

Mix.	Cement Type	w/b	Mix Proportions						Fiber		Admixtures		Density (lb/ft^3)	Sand Moisture
			agg/cm	*C*	*S*	*SF*	*FA*	*UFR*	*Type*	*Content (%)*	*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	135.7	N
C3	**Ash Grove Type I-II**	0.20	1.0	0.6	0.3	0.1	1.0	0	OL	2.0	22.25	0	149.0	D
C32	**Titan Type I/II**	0.20	1.0	0.6	0.3	0.1	1.0	0	OL	2.0	27.47	6.5	146.9	D
C37	**Titan Type III**	0.20	1.0	0.6	0.3	0.1	1.0	0	OL	2.0	27.47	0	149.0	D
C4	**Lehigh White Cement**	0.20	1.0	0.6	0.3	0.1	1.0	0	OL	2.0	23.35	0	146.5	D





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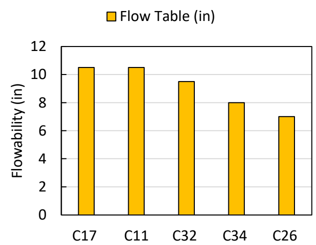
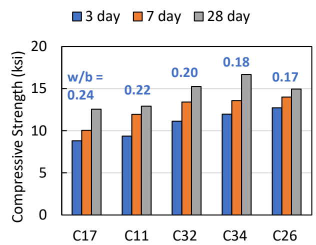
Experimental Results – Small-Batch

Water-to-Binder Ratio

w/b between 0.18 and 0.20 produced highest compressive strength w/ good flow and working time

Mix.	Cement Type	w/b	Mix Proportions						Fiber		Admixtures		Density (lb/ft³)
			agg/cm	*C*	*S*	*SF*	*FA*	*UFR*	*Type*	*Content (%)*	*HRWR (oz./cwt)*	*VMA (oz./cwt)*	
C17	Titan Type I/II	0.24	1.0	0.6	0.3	0.1	1.0	0	OL	2.0	16.39	2.47	142.8
C11	Titan Type I/II	0.22	1.0	0.6	0.3	0.1	1.0	0	OL	2.0	19.87	6.5	144.6
C32	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	1.0	0	OL	2.0	27.47	6.5	146.9
C34	Titan Type I/II	0.18	1.0	0.6	0.3	0.1	1.0	0	OL	2.0	27.47	6.5	149.8
C26	Titan Type I/II	0.17	1.0	0.6	0.3	0.1	1.0	0	OL	2.0	35.52	0	150.0





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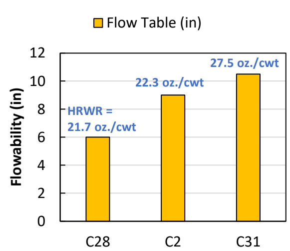
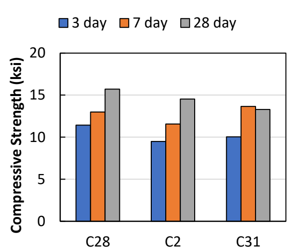
Experimental Results – Small-Batch

HRWR Content

Increasing HRWR content decreased compressive strength

Mix.	Cement Type	w/b	Mix Proportions						Fiber		Admixtures		Density (lb/ft³)
			ag/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	OL	2.0	21.70	0	147.1
C2	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	1	0	OL	2.0	22.25	0	144.5
C31	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	1	0	OL	2.0	27.47	0	147.4





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Experimental Results – Small-Batch

Water-to-Binder Ratio

Water-to-cement (w/c): $w/_c = {(W_1 + W_2)}/_{C_1}$

Water-to-binder (w/b): $w/_b = {(W_1 + W_2)}/_{(C_1 + C_2)}$

Modified water-to-binder (w/b): $w^*/_b = {(W_1 + W_2 + W_3)}/_{(C_1 + C_2)}$

where:

W_1 = weight of free water
W_2 = weight of water available as moisture content in aggregates
W_3 = weight of liquid portion of chemical admixture
C_1 = weight of cement
C_2 = weight of SCMs

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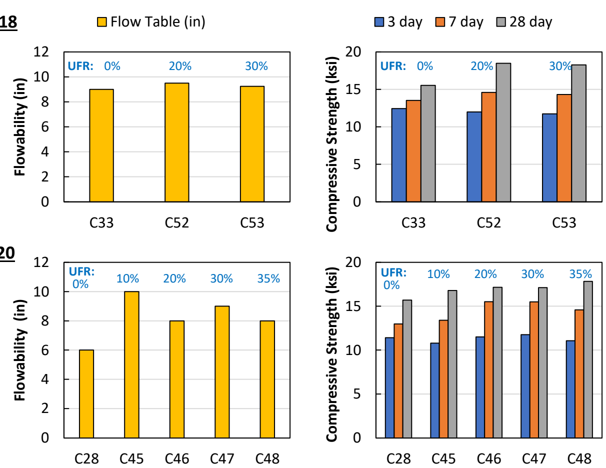
Experimental Results – Small-Batch

Fine Aggregate Type and Content

Using UFR at 20% - 30% increased strength, but required more HRWR for flowability

w/b = 0.18

w/b = 0.20



UFR = Ultra-fines recovery material

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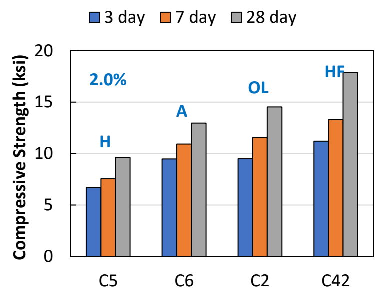
Experimental Results – Small-Batch

Observed Expansive Behavior

Uncoated fibers with high zinc contents can lead to an expansive reaction in the UHPC that greatly decreases its strength



Note: The manufacturer of the fiber communicated to the research team that the issue has been fixed, but the testing schedule did not allow for new samples to be cast and tested with the improved fibers

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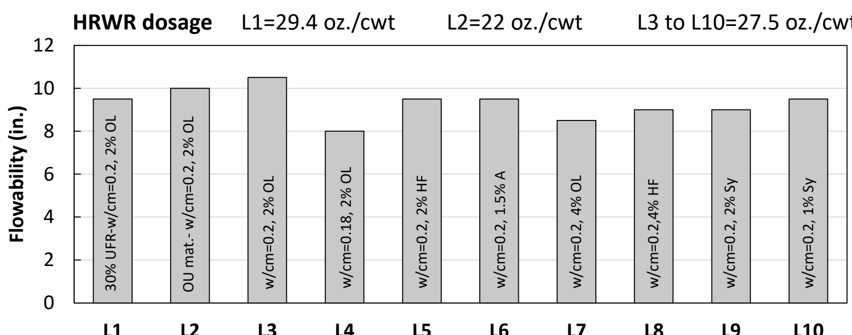
Fiber Type Legend

A = Dramix 4D 65/35BG
OL = Dramix OL 13/.20
Sy = Synthetic Fiber
HF = Hiper Fiber Type A

Experimental Results – Large-Batch

Fiber Type and Content – Flowability

(1) Fiber type did not affect flow; (2) Increased fiber content decreased flow; (3) Decreasing w/cm also decreased flow; (4) Use of ultra-fine recovery (UFR) increased HRWR demand



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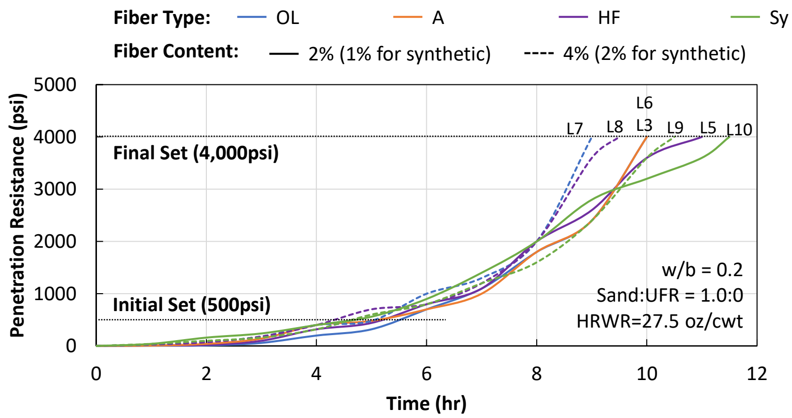
Fiber Type Legend

A = Dramix 4D 65/35BG
OL = Dramix OL 13/.20
Sy = Synthetic Fiber
HF = Hiper Fiber Type A

Experimental Results – Large-Batch

Effect of Fiber Type and Content – Set Time

(1) Increased fiber content decreased set time. (2) Fiber type did not significantly affect set time (similar fiber content had similar set times).



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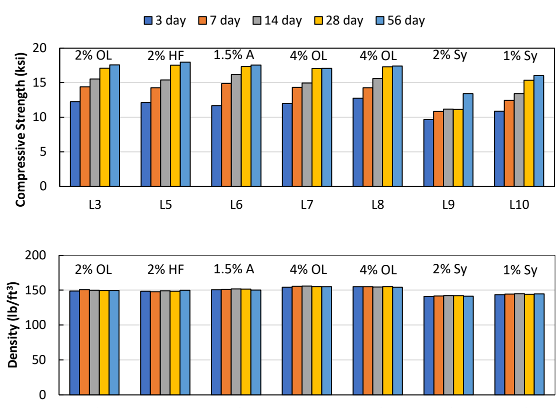
Fiber Type Legend

A = Dramix 4D 65/35BG
H = Helix 5-13 Uncoated
OL = Dramix OL 13/.20
Sy = Synthetic Fiber
HF = Hiper Fiber Type A

Experimental Results – Large-Batch

Fiber Type and Content – Compression and Density



Observations:

- Similar compressive strength and density for mixtures with steel fibers (regardless of fiber type or content)
- Synthetic fibers led to lower compressive strength and smaller density

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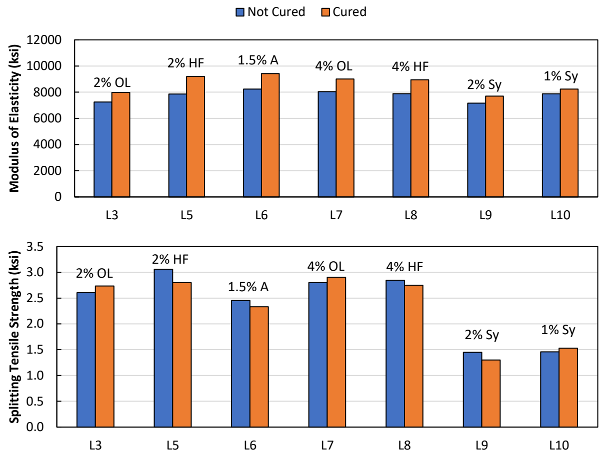
Fiber Type Legend

A = Dramix 4D 65/35BG
H = Helix 5-13 Uncoated
OL = Dramix OL 13/.20
Sy = Synthetic Fiber
HF = Hiper Fiber Type A

Experimental Results – Large-Batch

Fiber Type and Content – MOE and Splitting Tension



Observations:

- Steel fiber type and content did not have significant effect on modulus
- OL and HF fibers led to highest splitting tensile strength (no clear trend with fiber content)
- Synthetic fibers led to lower modulus and splitting tensile strength

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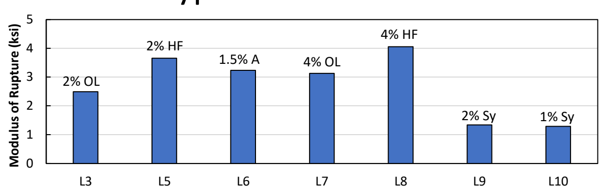
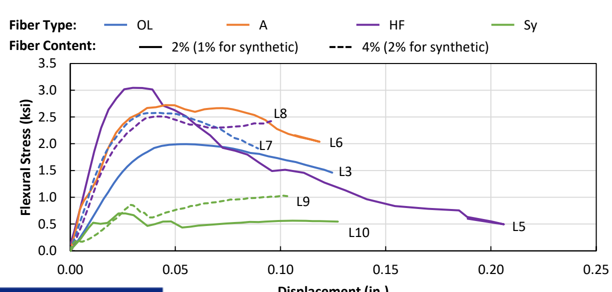
Fiber Type Legend

A = Dramix 4D 65/35BG
H = Helix 5-13 Uncoated
OL = Dramix OL 13/.20
Sy = Synthetic Fiber
HF = Hiper Fiber Type A

Experimental Results – Large-Batch

Fiber Type and Content – Flexural Strength





Observations:

- All steel fibers led to MOR strengths over 2.5 ksi
- Increasing fiber content led to higher modulus of rupture for OL and HF fibers
- Type A fibers had similar MOR to OL fibers
- HF fibers led to highest MOR strength
- Synthetic fibers had lowest MOR strength

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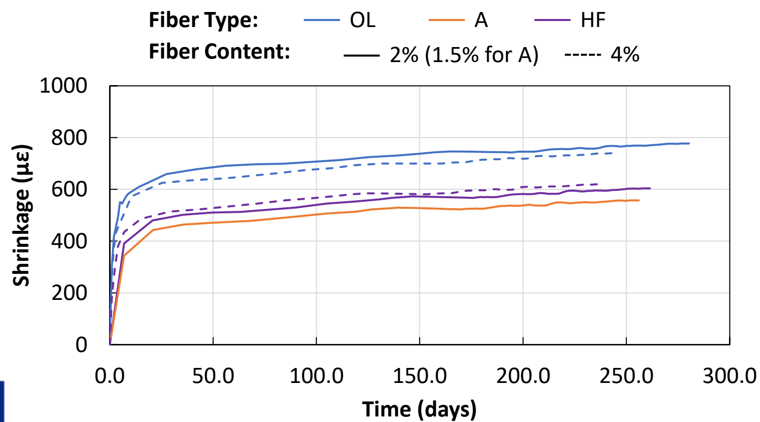
Experimental Results – Large-Batch

Fiber Type and Content – Shrinkage

HF and A fibers had less shrinkage than OL fiber specimens; similar shrinkage between 2% and 4% with same fiber type



(shrinkage measured with VWGs; specimens stored in climate-controlled lab)

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Conclusions and Recommendations

1. There is a significant amount of research on developing non-proprietary UHPC mixtures using many different types of materials
2. You can investigate development of a non-proprietary UHPC mixture using the procedure outlined at the beginning
   - Mix designs can be used in different parts of the country, but it is a good idea to adapt for local materials and at a minimum make trial batches
3. Some general findings from this work:
   - Fine aggregate moisture had large affect on repeatability of UHPC properties; we oven dried aggregate to solve this issue
   - VMA content did not influence compressive strength and could be used to stabilize heavier steel fibers in the mixtures (about 10 oz./cwt)
   - Use of fibers with 0.5-inch length, 0.008-inch diameter, and tensile strength of 400 ksi led to the best overall performance of the UHPC
   - Uncoated fibers with high zinc contents can lead to expansive reaction in the UHPC that greatly decreases its strength; this reaction can be observed in small (0.15 ft^3) trial batches

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ABC-UTC Non-Proprietary Mixture

Final Mixture Proportions and Approx. Cost

Mix.	Cement Type	w/b	Mix Proportions					Fiber		Admixtures	
			ag/cm	*C*	*S*	*SF*	*FA*	*Type*	*Content (%)*	*HRWR (oz./cwt)*	*VMA (oz./cwt)*
L3	Titan Type I/II	0.20	1.0	0.6	0.3	0.1	1.00	HF or OL	2.0	27.5	0

Approximate Cost per Component

- Type I/II Cement: $100/ton
- Silica Fume: $1,000/ton
- Slag: $100/ton
- Fine Masonry Sand: $15/ton
- UFR: currently not a commercial product
- HRWR: $0.15 per oz.
- VMA: $0.14 per oz.
- Fibers: $2.00/lb.
- Water: $0.004/gallon ($0.00048/lb)

Approximately $800 per cubic yard

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Thank You

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