ABC-UTC Non-Proprietary UHPC Workshop

Introduction and Mix Development

Royce Floyd, Ph.D., S.E., P.E.
Jeffery S. Volz, Ph.D., S.E., P.E.
GRA: Amy McDaniel, Trevor Looney, Ph.D, P.E.
URA: Cole Walker, Jacob Starks

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ABC UTC
ACCELERATED BRIDGE CONSTRUCTION
UNIVERSITY TRANSPORTATION CENTER

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Workshop Agenda

1. Introduction and Mix Development – Royce Floyd (1:00 pm – 1:30 pm)
2. Mixing, Placement, and Curing – David Garber (1:30 pm – 1:45 pm)
3. Applications for ABC – Mohamed Moustafa (1:45 pm – 2:45 pm)
4. Material Properties – Royce Floyd (2:45 pm – 3:15 pm)

   Break – 3:15 – 3:30 pm
5. Considerations for Local Materials – David Garber (3:30 pm – 4:00 pm)
6. Testing Methods and Quality Control – Royce Floyd (4:00 pm – 4:30 pm)
7. Summary of UHPC Work Across the Country and Discussion – Royce Floyd (4:30 pm – 5:00 pm)

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Learning Objectives

- **Describe** locally developed non-proprietary ultra-high performance concrete (UHPC)
- **Describe** potential mix design methods and potential issues when considering local materials
- **Describe** UHPC material properties
- **List** potential applications of non-proprietary UHPC
- **Explain** major differences in testing procedures between conventional concrete and UHPC

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Goals

Why non-proprietary UHPC?

- Superior mechanical properties of high end UHPC may not be needed in some applications such as field joints in bridge decks or repairs
- Tailor properties to need, which can lead to lower material cost
- Make UHPC more accessible for small jobs
- Several DOTs see proprietary nature of UHPC leads to sole-sourcing issues
- Identified as a priority by ABC-UTC Advisory Board

Work with ODOT and ABC-UTC Partner Universities to examine non-proprietary UHPC class material for multiple applications

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Objectives

- Develop an UHPC mix using materials local to Oklahoma, then modify as ABC-UTC Non-Proprietary UHPC Mix with guidance for use in different regions
- Evaluate ABC-UTC Non-Proprietary UHPC Mix performance and repeatability using FHWA recommended tests
- Examine the effect of fiber content on material properties and structural behavior

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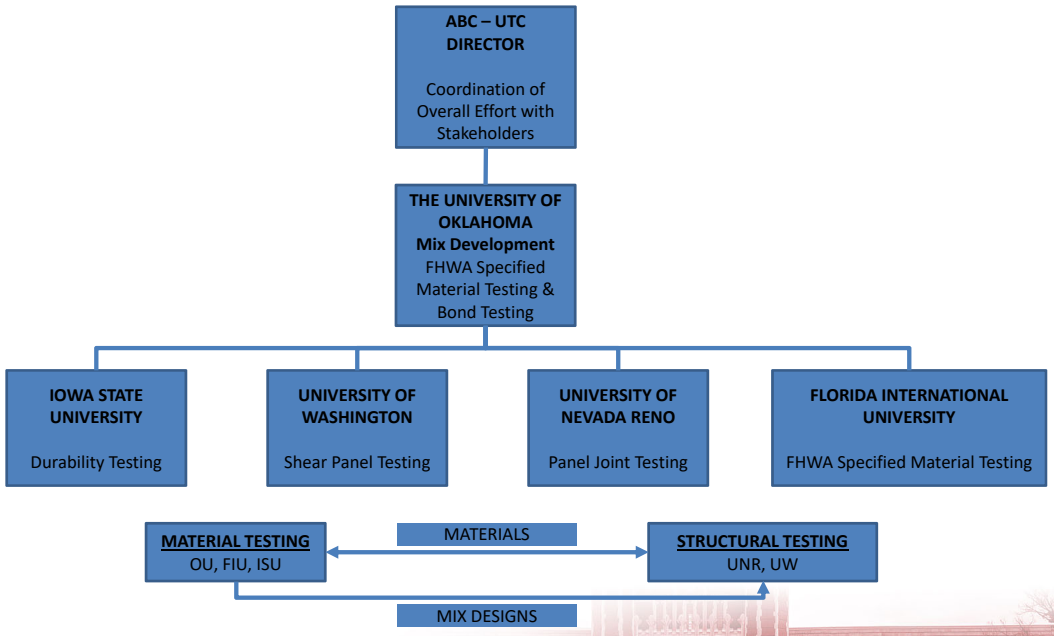

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Material Properties

Property	Test Method
Flowability	ASTM C1437
Compressive Strength	ASTM C39 ASTM C109
Modulus of Elasticity and Poisson's Ratio	ASTM C469
Splitting Tensile Strength	ASTM C496
Flexural Strength	ASTM C78/C1609
Direct Tensile Strength	FHWA (Graybeal and Baby, 2013)
Total and Drying Shrinkage	Embedded VWSG ASTM C157
Compressive Creep	ASTM C512
Set Time	ASTM C403
Freeze-Thaw Resistance	ASTM C666
Rapid Chloride Ion Permeability	ASTM C1202

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UHPC History

1970s
- Early development of high strength cement pastes
- Heat and pressure curing

1980s
- Advancements in high range water reducers and silica fume
- Incorporation of steel fibers to increase ductility

1990s
- First commercial UHPC in Europe
- Available in North America around 2000

2000s
- First code-style guidelines in France and Japan
- Major studies conducted in the U.S. and Canada

2010s
- Expansion of applications
- Development of design and testing standards

2020s
- Locally developed mix designs more accessible
- Education and training

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UHPC

- FHWA Definition
  - Compressive strength greater than 18 ksi
  - Post-cracking flexural strength of 720 psi
- ACI Definition
  - Minimum compressive strength of 22,000 psi
  - Tensile ductility in the form of elastic-plastic or strain-hardening behavior under uniaxial tension
- General Definition
  - Compressive strength of 18 – 30 ksi
  - Minimum post-cracking strength of 700 – 900 psi

UHPC cylinder after compression testing

UHPC

- High flowability
- Very low to negligible permeability
- Minimal freeze-thaw susceptibility
- Durability
- Impact resistance
- Specified toughness
- Fibers to achieve specified requirements

UHPC cylinder after compression testing

Basic Principles (Richard and Cheyrezy 1995)

1. Enhanced homogeneity by eliminating coarse aggregate
2. Enhanced density by optimizing particle packing density
3. Enhanced ductility provided by fibers
   - Typically steel
   - 2% or more by volume

Basic Properties

- Typical properties of a widely studied UHPC (Graybeal 2014)

Characteristic	Average Result
Density	155 lb/ft^3 (2,480 kg/m^3)
Compressive Strength (ASTM C39, 28-Days)	24 ksi (165 MPa)
Modulus of Elasticity (ASTM C469, 28-Days)	7,000 ksi (48 GPa)
Direct Tension Cracking Strength	1.2 ksi (8.5 MPa)
Split Cylinder Cracking Strength (ASTM C496)	1.3 ksi (9.0 MPa)
Prism Flexure Cracking Strength (ASTM C1018)	1.3 ksi (9.0 MPa)
Long-Term Creep Coefficient (ASTM C 512,11.2 ksi (77MPa) Stress)	0.78
Long-Term Shrinkage (ASTM C 157, initial reading after set)	555 με
Total Shrinkage (embedded vibrating wire strain gage)	790 με
Coefficient of Thermal Expansion (AASHTO TP60-00)	8.2 x 10^{-6} in./in./°F (14.7 x 10^{-6} in./in./°C)
Chloride Ion Permeability (ASTM C1202, 28-day test)	360 coulombs
Chloride Ion Permeability (AASHTO T259, 0.5 in. (12.7 mm) depth)	<0.10 lb/yd^3 (<0.06 kg/m^3)
Scaling Resistance (ASTM C672)	No scaling
Abrasion Resistance (ASTM C944 2x Weight, ground surface)	0.026 oz. (0.73 g) lost
Freeze-Thaw Resistance (ASTM C666A, 600 cycles)	RDM = 99%
Alkali-Silica Reaction (ASTM C1260, tested for 28 days)	Innocuous

Note: RDM = relative dynamic modulus

Constituent Materials

- Typical matrix materials include:
  - Cement
  - Silica fume
  - Fine quartz sand
  - High-range water reducing admixtures (HRWR)
- Other materials
  - Silica flour
  - Small coarse aggregate
  - Other SCMs

UHPC constituent materials before initial mixing

Constituent Materials

- Steel Fibers
  - Straight, crimped, hooked, or twisted
  - 0.5 in. to 1 in. (13 mm to 25 mm) long
  - 0.005 in. to 0.020 in. (0.13 mm to 0.5 mm) diameter
  - High strength – greater than 300 ksi (2100 MPa)
  - Typically 0.5 in. (13 mm) straight fibers at 2% by volume

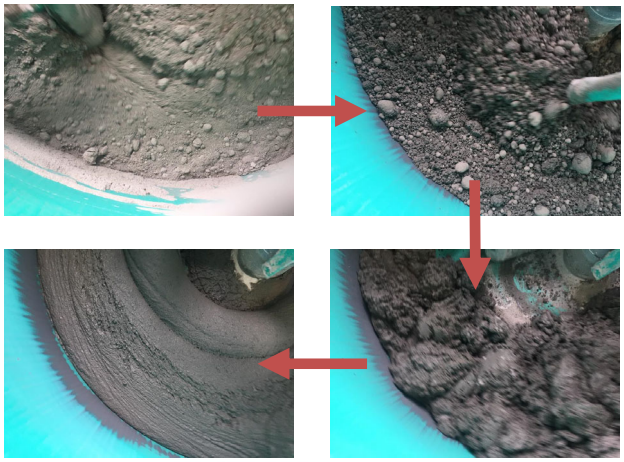
Addition of steel fibers to mixer in the field

Mixture Proportioning

- Proportioning principles:
  - Low water-binder ratio (w/b): 0.15 – 0.25
  - Reduce void space
  - Incorporate steel fibers to improve ductility but must consider competing effects of flowability and fiber suspension
- Create homogeneous matrix with properties on microscopic level
- All cementitious materials may not hydrate (Morin et al. 2001; Habel et al. 2006)
- Often use proprietary, pre-packaged mix designs

Mixing Procedure

- Blend dry components first
- Add water and admixtures
- Time required to achieve fluidity is dependent on the mixing energy
- Fibers added after achieving fluidity



Placement

- Typically high fluidity
  - Self-consolidating concrete
  - Measured with flow test
- Can be proportioned with flow properties for high slopes and overlays

Flow test

Bridge deck panel joint field placement

Laboratory joint placement

Testing

- Methods require modification for properties of UHPC – ASTM C1856
  - Flow table testing with modification (ASTM C1437)
  - Specimens made using ASTM C31/C192 with placement in a single layer and no tamping
  - Specimen size modifications; e.g. 3 in. x 6 in. cylinders for compression (ASTM C39)
  - Increased load rates (e.g. 150 psi/s for compression)
  - Cylinders must be ground plane; no capping is allowed

Applications

- Connections
- Highway bridges
  - Bulb tee and pi-shaped girders
  - Joints between bulb tees
  - Joints between full-depth deck panels
- Pedestrian bridges
- Rehabilitation and retrofit
- Piles/Foundations
- Seismic force resisting elements

Initial Motivation in Oklahoma

Bridge Joint Deterioration

Deteriorated bridge deck expansion joint (photo courtesy of Walt Peters)

http://www.toledoblade.com/local/2011/07/08/Defective-bridge-expansion-joint-causes-I-75-delays.html

UHPC Repair Applications

Expansion Joint Headers

Original bridge deck expansion joint on SH-3E over N. Canadian River, OK

UHPC expansion joint headers on SH-3E over N. Canadian River, OK

Comparison of elastomeric nosing and UHPC expansion joint headers

Potential UHPC Repair Applications

End Region Deterioration

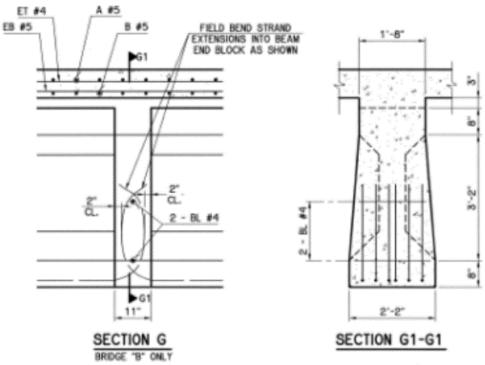
In-service prestressed concrete girder with end region spalling

Laboratory testing of UHPC encapsulation repair for shear and corrosion damage (Ahmadi 2021)

Potential UHPC Repair Applications

Cracking of Live Load Continuity Connections

Typical cracking in Oklahoma continuity connections (photo courtesy of Walt Peters)



Typical Oklahoma continuity connection detail (plans courtesy of Walt Peters)

Potential UHPC Repair Applications

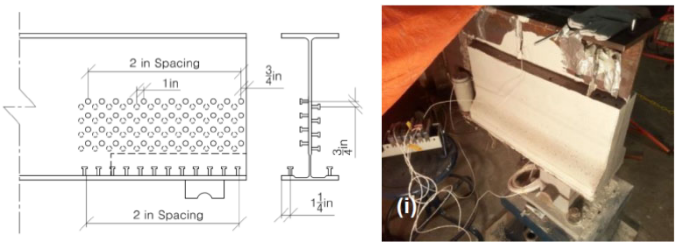
Cracking of Live Load Continuity Connections

Two-span loading configuration used for testing continuity joints showing loads applied at mid-span of each beam

Laboratory testing of UHPC encapsulation repair for cracked continuity connections (Mesigh 2021)

Potential UHPC Repair Applications

Steel Girder Ends



Test of steel girder end repaired with UHPC (Zmetra 2015)

Concrete Girder Ends

Test of concrete girder end repaired with UHPC (Shafei et al. 2020)

Non-Proprietary UHPC Mix Development

Basic

- Portland Cement
- Fine Sand
- Silica Fume
- HRWR
- Fibers
- Water

Non-Proprietary UHPC Mix Development

Basic
- Portland Cement
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Variations
- Type I
- Type III

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Non-Proprietary UHPC Mix Development

Basic
- Portland Cement
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- Fibers
- Water

Variations
- Type I
- Type III
- Fly Ash
- Slag Cement

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Non-Proprietary UHPC Mix Development

Basic
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- Fine Sand
- Silica Fume
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- Water

Variations
- Type I
- Type III
- Fly Ash
- Slag Cement

- Glass Powder
- Ground Quartz
- Silica Flour

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Non-Proprietary UHPC Mix Development

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Non-Proprietary UHPC Mix Development

Water/Cementitious Material Ratio

- 0.21 – 0.28 theoretical minimum

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Non-Proprietary UHPC Mix Development

Water/Cementitious Material Ratio

- 0.21 – 0.28 theoretical minimum
- 0.18 – 0.25 typical for UHPC

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Non-Proprietary UHPC Mix Development

Water/Cementitious Material Ratio

- 0.21 – 0.28 theoretical minimum
- 0.18 – 0.25 typical for UHPC
- Lack of uniform water dispersion – referred to as desiccation
- Requires very high dosages of high range water reducers

Non-Proprietary UHPC Mix Development

Fibers

- Straight, crimped, hooked, or twisted steel

Non-Proprietary UHPC Mix Development

Fibers

- Straight, crimped, hooked, or twisted steel
- ½ in. – 1 in. length, 0.005 in. – 0.020 in. diameter

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Non-Proprietary UHPC Mix Development

Fibers

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- ½ in. – 1 in. length, 0.005 in. – 0.020 in. diameter
- 2% by volume dosage most common due to workability issues and cost

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Non-Proprietary UHPC Mix Development

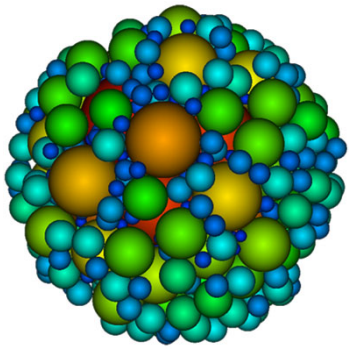
Fibers

- Straight, crimped, hooked, or twisted steel
- ½ in. – 1 in. length, 0.005 in. – 0.020 in. diameter
- 2% by volume dosage most common due to workability issues and cost
- Flowability vs. fiber suspension

Non-Proprietary UHPC Mix Development

Particle-Combination Optimization Strategies

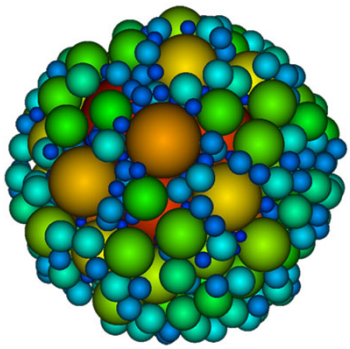
- Minimize the void space/increase density



Non-Proprietary UHPC Mix Development

Particle-Combination Optimization Strategies

- Minimize the void space/increase density
- Optimization techniques include:
  - Discrete element models
  - Particle packing models
  - Optimization curves



Typical Non-Proprietary UHPC Formulation

Sample UHPC Formulation

Constituent	Proportions
Portland Cement	2/3
Silica Fume	1/6
Fly Ash	1/6
w/cm	0.23
agg/cm	1.0
HRWR (oz/cwt)	21.0

The Role of Chemistry

Sample UHPC Formulation

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Portland Cement	2/3
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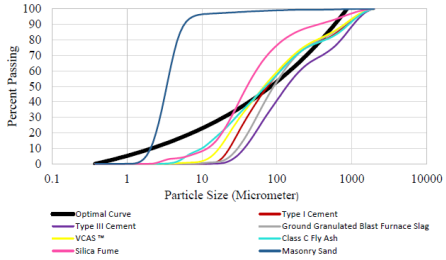
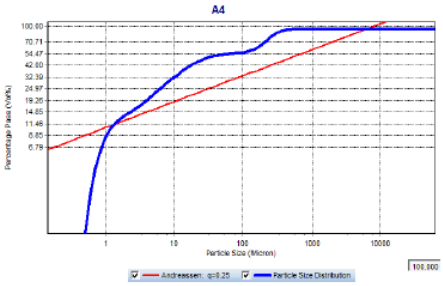
Non-Proprietary UHPC Mix Development

Nine (9) Separate Series Investigated in ODOT Sponsored Project

- Series A: Established design baseline using previous UHPC research
- Series B: Established optimal water/cement/HRWR proportions
- Series C: Introduced supplementary cementitious materials
- Series D: Optimized particle packing



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



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Non-Proprietary UHPC Mix Development

Nine (9) Separate Series Investigated in ODOT Sponsored Project

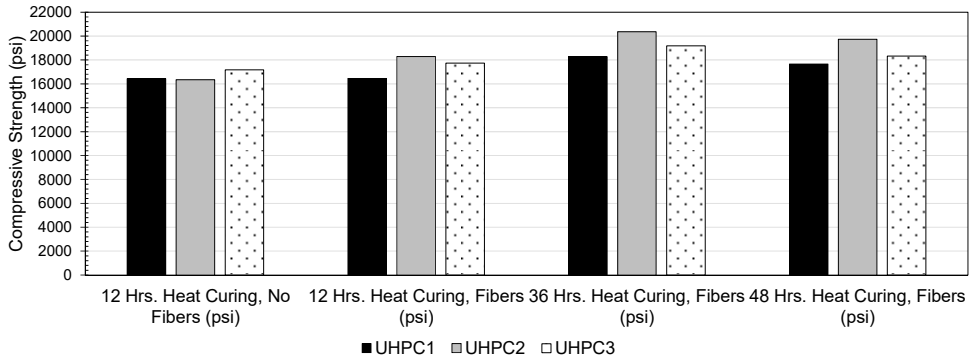
- Series A: Established design baseline using previous UHPC research
- Series B: Established optimal water/cement/HRWR proportions
- Series C: Introduced supplementary cementitious materials
- Series D: Optimized particle packing
- Series E: Established effects and benefits of Type I vs. Type III
- Series F: Evaluated the aggregate/cementitious material ratio
- Series G: Evaluated the role of slag cement in UHPC
- Series H: Investigated additional current UHPC research
- Series J: Combined the most promising variables and added fibers and heat curing

Non-Proprietary UHPC Mix Development

Three (3) Most Promising Mixes for Fiber Addition and Heat Curing

Series J Mixes	UHPC 1 (J8)	UHPC 2 (J3)	UHPC 3 (J13)
Type I Cement, lb/yd^3	1179.6	1179.6	786.4
Type III Cement, lb/yd^3	0	0	196.6
Fly Ash, lb/yd^3	294.9	0	0
Slag Cement, lb/yd^3	0	589.8	786.4
Silica Fume, lb/yd^3	196.6	196.6	196.6
VCAS™, lb/yd^3	294.9	0	0
w/cm	0.2	0.2	0.2
Fine Masonry Sand, lb/yd^3	1966	1966	1966
Steel Fibers, lb/yd^3	255.2	255.2	255.2
Steel Fibers, %	2.0	2.0	2.0
Glenium 7920, oz./cwt	15.77	15.77	14.88

Compression Results



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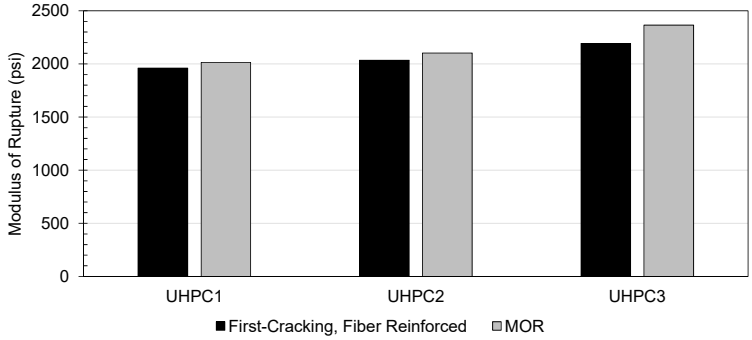
MOR Results



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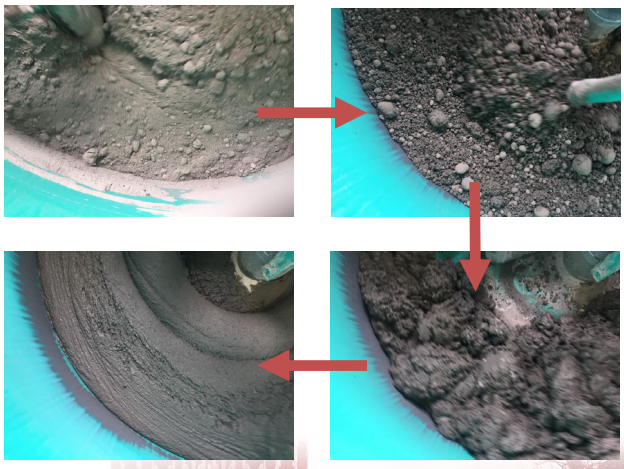
Mix Development

Final ABC-UTC Mix Design

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



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Conclusions

- Non-proprietary UHPC can achieve superior properties desired for many applications and similar properties to commercial UHPC
- ABC-UTC non-proprietary UHPC mix was developed and tested as part of a collaborative effort within the ABC-UTC
  - Type I portland cement, slag, and silica fume
  - Tested at OU, FIU, UNR, UW, and ISU
- Estimated cost of ABC-UTC non-proprietary UHPC is \$400-\$800/yd^3

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