Outline

- What is UHPC?
- UHPC Efforts Underway in US and Beyond
  - FHWA: EDC3 & EDC4, Webinar Series, etc.
  - ACI, ASTM, PCI
  - US Symposium, International Conferences
  - Design Guidance Development, Pooled Fund
- Introduction to UHPC
  - Basic Properties
  - UHPC Connections
  - Deployments
Outline

• What is UHPC?
• UHPC Efforts Underway in US and Beyond
  • FHWA: EDC3 & EDC4, Webinar Series, etc.
  • ACI, ASTM, PCI
  • US Symposium, International Conferences
  • Design Guidance Development, Pooled Fund
• Introduction to UHPC
  • Basic Properties
  • UHPC Connections
  • Deployments

What is Ultra-High Performance Concrete?
What is Ultra-High Performance Concrete?

- ACI 239 – Ultra-High Performance Concrete
  - Concrete, ultra-high performance - concrete that has a minimum specified compressive strength of 150 MPa (22,000 psi) with specified durability, tensile ductility and toughness requirements; fibers are generally included to achieve specified requirements.
What is Ultra-High Performance Concrete?

- FHWA
  - UHPC is a cementitious composite material composed of an optimized gradation of granular constituents, a water-to-cementitious materials ratio less than 0.25, and a high percentage of discontinuous internal fiber reinforcement. The mechanical properties of UHPC include compressive strength greater than 21.7 ksi (150 MPa) and sustained post-cracking tensile strength greater than 0.72 ksi (5 MPa).

Highly durable, strain-hardening concrete
What is Ultra-High Performance Concrete?

Micro-Reinforced Concrete

What is Ultra-High Performance Concrete?

Resilient Cementitious Composite
Outline

- What is UHPC?
- UHPC Efforts Underway in US and Beyond
  - FHWA: EDC3 & EDC4, Webinar Series, etc.
  - ACI, ASTM, PCI
  - US Symposium, International Conferences
  - Design Guidance Development, Pooled Fund
- Introduction to UHPC
  - Basic Properties
  - UHPC Connections
  - Deployments

FHWA UHPC Web Resources

- Web Search: FHWA UHPC
- https://www.fhwa.dot.gov/research/resources/uhpc/
UHPC State-of-the-Art Report

- FHWA HRT-13-060
  - Published in June 2013
  - 300+ references
  - 600+ item bibliography

  Mix Designs, Material Properties, Design Guidelines, Deployment, etc.

Design and Construction of UHPC Field-Cast Connections

- FHWA-HRT-14-084
- What is UHPC?
- Example Connections
- Structural Design
- Construction
- Quality Assurance
- Deployments
Design and Construction of UHPC Field-Cast Connections

- FHWA-HRT-14-084
- What is UHPC?
- Example Connections
- Structural Design
- Construction
- Quality Assurance
- Deployments

Development of VERSION 2 is underway

Every Day Counts (EDC)

EDC-1 (2011 – 2012)
- Prefabricated Bridge Elements & Systems (PBES)

- Accelerated Bridge Construction, including PBES

EDC-3 (2015 – 2016)
- UHPC Connections for PBES

EDC-4 (2017 – 2018)
- UHPC Connections for PBES
**EDC UHPC Purpose**

Promote and facilitate the use of UHPC by transportation agencies to improve the strength, simplicity, and durability of prefabricated bridge element (PBE) connections.

**EDC UHPC Goal**

Raise awareness and support institutionalization.

**EDC UHPC Activities**

- Technical assistance
- Workshops
- Webinars
- Peer exchanges
- Presentations
**UHPC Webinar Series**

<table>
<thead>
<tr>
<th>Webinar Title</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Introduction to UHPC</td>
<td>March 7</td>
</tr>
<tr>
<td>Why UHPC for PBE Connections</td>
<td>April 4</td>
</tr>
<tr>
<td>Structural Design, Detailing, and Specifying UHPC</td>
<td>May 9</td>
</tr>
<tr>
<td>Construction, Inspection, and Quality Assurance</td>
<td>June 6</td>
</tr>
<tr>
<td>UHPC Implementation Stories (GA and DE)</td>
<td>July 11</td>
</tr>
<tr>
<td>UHPC on Pulaski Skyway – Owner’s Perspective</td>
<td>August 15</td>
</tr>
</tbody>
</table>

**Sign Up in the UHPC section of the FHWA EDC Website**

---

**UHPC @American Concrete Institute**

- ACI 239: UHPC
- Committee formed in 2011
- Ben Graybeal, Chair
- Initiatives:
  - Emerging Technology Report
  - Test Methods for UHPC
  - Structural Design of UHPC
  - Materials & Methods of Construction
  - Applications of UHPC
  - Research Needs
UHPC: Current Status and Introduction

UHPC @ ASTM

- ASTM Subcommittee C09.61 (Concrete: Testing for Strength)
- Focus has been on immediate needs and low-hanging fruit

- ASTM C1856 Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete
  - Passed ballot in June 2017
  - To be released for use by Fall 2017
  - Covers:
    - Making specimens (C31, C192, C42)
    - Compressive Strength (C39), Elastic Modulus (C469), Compressive Creep (C512)
    - Flexural Strength (C1609)
    - Abrasion (C944), Freeze/Thaw (C666), Chloride Ion (C1202)

UHPC @ Precast/Prestressed Concrete Institute

- Subcommittee on UHPC
- Formed in 2016
- JP Binard, Chair
- Influenced by FHWA, Dura (Voo)
- Focus on bridge applications
- Producer-driven, near-term focus
- Initiatives:
  - Comparison with existing shapes
  - Optimization for extended spans
International Interactive Symposium on UHPC

- 1st IIS-UHPC in July 2016 in Des Moines, Iowa
- 2nd IIS-UHPC on June 3-5, 2019 in Albany, NY!
- Goal:
  - Share knowledge
  - Facilitate collaboration
  - Advance the use of UHPC
- Interactive Expert Discussions
- Paper Presentations
- Student Competition
- Design Awards
- “Day 2” with Hands-On Site Visits and Peer Exchange

UHPFRC 2017 / BFUP 2017

- Designing and Building with UHPFRC:
  Standards and New Large Scale Implementations
- Montpellier, France
- October 2-4, 2017
Structural Design Guidance (International)

Specification published
- France
- Switzerland

Development Underway
- Canada

Structural Design Guidance (US)

Only existing guidance is in FHWA-HRT-14-084 which focuses on connections
**Structural Design Guidance (US)**

Under Development:
*AASHTO LRFD Design and Construction Guide Specification for UHPC*

- Led by FHWA-TFHRC (Graybeal, El-Helou)
- Coordination with TPF 1434 (Iowa, CT, GA, NY, WA)

![LRFD Bridge Design](image1)
![Concrete-Filled FRP Tubes](image2)
![GFRP-Reinforced Concrete](image3)

---

**Structural Design Guidance (US)**

Under Development:
*AASHTO LRFD Design and Construction Guide Specification for UHPC*

- Material Models and Guidance
- Design Guidance
- Construction Guidance

![LRFD Bridge Design](image1)
![Concrete-Filled FRP Tubes](image2)
![GFRP-Reinforced Concrete](image3)
Outline

- What is UHPC?
- UHPC Efforts Underway in US and Beyond
  - FHWA: EDC3 & EDC4, Webinar Series, etc.
  - ACI, ASTM, PCI
  - US Symposium, International Conferences
  - Design Guidance Development, Pooled Fund
- Introduction to UHPC
  - Basic Properties
  - UHPC Connections
  - Deployments

Example Composition of a UHPC

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Amount (lb/yd³)</th>
<th>Amount (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland Cement</td>
<td>1235</td>
<td>733</td>
</tr>
<tr>
<td>Silica Fume</td>
<td>388</td>
<td>230</td>
</tr>
<tr>
<td>Ground Quartz</td>
<td>308</td>
<td>183</td>
</tr>
<tr>
<td>Fine Sand</td>
<td>1699</td>
<td>1008</td>
</tr>
<tr>
<td>Steel Fibers</td>
<td>327</td>
<td>194</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>56</td>
<td>33</td>
</tr>
<tr>
<td>Water</td>
<td>271</td>
<td>161</td>
</tr>
</tbody>
</table>

* Teichmann and Schmidt report titled “Mix Design and Durability of UHPC” from the Proceedings of the 4th Intl Ph.D. Symposium in Civil Engineering
Example Composition of a UHPC

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Amount (lb/yd³)</th>
<th>Amount (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland Cement</td>
<td>1331</td>
<td>790</td>
</tr>
<tr>
<td>Silica Fume</td>
<td>334</td>
<td>198</td>
</tr>
<tr>
<td>Fly Ash (Class F)</td>
<td>324</td>
<td>192</td>
</tr>
<tr>
<td>Fine Basalt</td>
<td>1923</td>
<td>1141</td>
</tr>
<tr>
<td>Steel Fibers</td>
<td>199</td>
<td>118</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>47</td>
<td>28</td>
</tr>
<tr>
<td>Water</td>
<td>246</td>
<td>146</td>
</tr>
</tbody>
</table>

* Wille and Boisvert-Cotulio report titled “Development of Non-Proprietary UHPC for Use in the Highway Bridge Sector” (FHWA NTIS-PB2013-100587)

Fiber Reinforcement
Availability of UHPC-Class Materials

Example Proprietary Versions

Non-Proprietary Versions

FHWA-HRT-13-100: Dr. Kay Willie at UCONN

Cost of PBE Grouts including UHPC...

- Products on the Market

<table>
<thead>
<tr>
<th>Grout Type</th>
<th>Approximate Cost per yd³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland Cement Grouts</td>
<td>$1000 to $2000</td>
</tr>
<tr>
<td>Repair Mortars</td>
<td>$1500 to $3000</td>
</tr>
<tr>
<td>Epoxy Grouts</td>
<td>$5000</td>
</tr>
<tr>
<td>UHPCs</td>
<td>$2500 to $3500</td>
</tr>
</tbody>
</table>

- Non-Proprietary Versions
  - At least $800 for UHPC raw constituents
UHPC Properties: Some Ballpark Values

- Fresh “Slump” – Self Consolidating
- Compressive Strength – 18 to 35 ksi
- Modulus of Elasticity – 6000 to 8000 ksi
- Sustained Tensile Capacity – 0.9 to 1.5 ksi
- Interface Bond – Can surpass substrate tensile strength
- Permeability – 100x less than conventional concrete
- Freeze/Thaw Resistance – RDM > 95%
- Rebar Bond – $8d_b$ embedment can deliver yield

UHPC Rheology (Video)
Compression Behavior

![Compression Behavior Graph]

Compression Strength Gain

![Compression Strength Gain Graph]
**Tensile Behavior**

- 2% Steel Fiber Reinforcement
- 13 ksi ≤ $f'_c$ ≤ 16 ksi
**Tensile Behavior**

- **Average Axial Stress (ksi) vs. Average Axial Strain**
  - Graph showing different curves representing different samples labeled A (3%), B (3.25%), C (4.5%), D (3%), and E (3.25%).
  - The x-axis represents average axial strain, while the y-axis represents average axial stress.
  - The graph highlights the tensile behavior where the stress-strain relationship is depicted.

- **Note:** The stress-strain relationship is crucial for understanding the structural integrity and performance of UHPC under tensile loads.

---

**Tensile Behavior**

- **Graph showing Tensile Behavior with Slab Element**
  - Diagram illustrating the tensile behavior with a slab element and different stress-strain curves.
  - The curves represent various orientations and casting methods (0 degrees, 45 degrees, 90 degrees, and typical casting).
  - The x-axis represents average axial strain, while the y-axis represents average axial stress.

- **Analysis:**
  - The curves indicate the uniformity and range of stress-strain behaviors under tensile loads, which is essential for structural design considerations.

---

**Conclusion:**

The graphs and diagrams provide a comprehensive view of the tensile behavior of UHPC, highlighting its performance under various conditions. This understanding is vital for optimizing structural applications and ensuring safety and efficiency in construction projects.
Tensile Behavior: Cracking

4 micrometer wide crack at 1000x magnification

Interface Bond

Age of UHPC During Test: 14-Days
Interface Bond

- FHWA-HRT-16-081
- Best Practices
- Test Methods
- Suggestions for increasing bond strength

Shrinkage Behavior

- Autogenous deformation ($\mu$ε) vs. Time (days)
- U-D
- U-B
- U-C
- U-A
- U-E
Shrinkage Behavior

- FHWA-HRT-16-080
- Best Practices
- Test Methods
- Performance expectations

Durability

USACE Facility at Treat Island
UHPC Permeability

- Chloride Ion Diffusion Coefficient

\[ 2 \times 10^{-11} \text{ m}^2/\text{s} \text{ for conventional concrete} \]

\[ 2 \times 10^{-12} \text{ m}^2/\text{s} \text{ for HPC} \]

\[ 2 \times 10^{-13} \text{ m}^2/\text{s} \text{ for UHPC} \]
**Bond to Steel Reinforcing Bars**

**TEST CONFIGURATION**

- Load
- Test Bar
- #8 Bars
- UHPC Strip
- Precast Concrete Base Slab

**EXAMPLE RESULT**

- Gr. 120 Bars (Uncoated)
- Side Cover: $c_{so} = 3d_b$
- Embedment Length: $l_e = 8d_b$
- Splice Length: $l_s = 6.4d_b$

- EXAMPLE RESULT

- $1 \text{ ksi} = 6.89 \text{ MPa}$

- Manufacturer-Recommend Fiber Vol.

**Phase 1 Results:**
- TechBrief: FHWA-HRT-14-089
- Report: FHWA-HRT-14-090
Conventional Closure Pour Connection

Closure Pour w/ Conventional Concrete

Post-Tensioned Connection

Post-Tensioned w/ Conventional Grout
**Conventional Grout Deck Panel Connections**

- **U-Bar Connection**
  
  - Field-Cast Grout
  - Precast Deck
  - #5 U-Bar

- **One-Layer Headed Bar Connection**
  
  - Cast-In-Place Concrete
  - #4 Hooked Bar
  - #5 Headed Bars

- **Two-Layer Headed Bar Connection**
  
  - 3.54 in (min)
  - 6.0 in
  - #5 Headed Bars

- **90° Hooked Bar Connection**
  
  - Azizinamini, Power, Myers, and Ozyildirim, 2014

---

**UHPC Deck Panel Connection**

- **Straight Bar Connection w/ UHPC**
  
  - 8 in
  - 6 in
  - 5.9 in
  - #5 Straight Bar
Deck-Level Connections

#5 Rebar Lap Splice


UHPC Deck-Level Connection Testing (Video)
UHPC Deck-Level Connection Testing (Video)

UHPC Connections b/t Modular Decked Units

U.S. 6 over Keg Creek
Pottawattamie County, Iowa
UHPC Connections b/t Adjacent Box Beams

Sollars Road over Lees Creek
Fayette County, Ohio

Adjacent Box Beam Connections
**UHPC Connections b/t Deck-Bulb-Tee Girders**

SR 31 over Canandaigua Outlet
Lyons, New York

**Rebar Lap Splice Connection**

D **SECTION D-D**

TRANVERSE UHPC BETWEEN DECK PANELS

ULTRA HIGH PERFORMANCE CONCRETE, SUPPLIED & INSTALLED BY CONTRACTOR
Design Example - Precast Deck

- Design Example
  - Rebar Size and Spacing
    - Deck panels would be the same procedure as CIP deck
  - Connection splice design
    - Using FHWA-HRT-14-084
- Given information
  - Girder spacing is 9 feet
  - Deck thickness is 8 inches
  - Concrete strength is 6000 psi
  - Top cover is 2 1/2 inches
  - Bottom cover is 1 1/2 inches
  - Steel fiber length is 13 mm (1/2 inch)

**Interlaced Straight Bar Connection**

*Note: Clear cover for deck panel is 2-1/2 inches at the top and 1-1/2 inches at the bottom.*
Design Example - Rebar Lap Splice

#5 Bars (60 ksi) Top & Bottom:

- Clear cover top
  - $2\frac{1}{2}'' \geq 1\frac{7}{8}'' (3d_b)$
- Clear cover bottom
  - $1\frac{1}{4}'' (2d_c) \leq 1\frac{1}{2}'' \leq 1\frac{7}{8}'' (3d_c)$

- Embedment Length, $l_d \geq 8d_b + 2d_b = 6.25''$ (bot. bars)
- Splice Length, $l_s \geq 6.25'' \times 0.75 = 4.75''$ (rounded)
- Bar clear spacing:
  - Minimum = $1.51_{fiber} = 0.75''$
  - Maximum = $1.51 = 4.75''$
- UHPC with $f'_c \geq 14$ ksi

UHPC Connections for Shear Interfaces

Steel Girder Connection

Concrete Girder Connection
Design Guidance - Interface Shear

UHPC Interface Shear Connections Require:
- UHPC
- Follow LRFD Provisions of 5.8.4 and 6.10.10
- Clear shear plane height ≤ 3 in.
- Cyclic stress on minimum shear plane ≤ 150 psi
- Static stress on minimum shear plane ≤ 750 psi

Note:  
1. Intentionally roughen precast surfaces
2. UHPC flow length ≤ 10 ft

TechBrief: FHWA-HRT-12-042  Report: NTIS PB2012-107569

UHPC Composite Connection Testing

NYSDOT UHPC Workshop
Examples of minimum shear planes for horizontal shear transfer

Design Guidance - Interface Shear

Example Calculation - Fatigue Stress

- Given:
  - $Q = 550 \text{ in}^3$
  - $V_f = 40 \text{ kips}$
  - $I = 21,800 \text{ in}^4$
  - $b = 8 \text{ inches}$

$$\tau = \frac{(V_f \times Q)}{(I \times b)}$$
$$\tau = \frac{(40 \times 550)}{(21,800 \times 8)}$$
$$\tau = 126 \text{ psi} < 150 \text{ psi \ OK}$$
UHPC: Current Status and Introduction

UHPC Deployments Across US and Canada

Source: https://www.fhwa.dot.gov/research/resources/uhpc/bridges.cfm

Link: http://arcgis.map.arcgiscitymap MORH:4102767/708;0464348/701885/373022722
Web Search: "FHWA UHPC" then click Deployments tab
Mars Hill Bridge

Iowa 45” Bulb Tee
SW ≈ 0.7 kip/ft

Modified Bulb Tee
SW ≈ 0.56 kip/ft
**π-Girder**

- 33” depth spans 80’; weight = 932 lb/ft
- Family of girders up to 47” depth

Reports: NTIS PB2009-115496, NTIS PB2014-100626

Jakway Bridge
Buchanan County, Iowa
UHPC for Lightweight Bridge Decks

Dahlonega Road Bridge in Wapello County, Iowa

Franklin Avenue Bridge
Minneapolis, Minnesota
Deck Panel Connections

Franklin Ave. Bridge
Minneapolis, MN

UHPC for Adjacent Box Beam Repair

Florida DOT Rehabilitation of SR-714 at Danforth Creek in Fall 2016

Florida DOT
What is Ultra-High Performance Concrete?

Capable Solution for Today’s Challenges and Tomorrow’s Opportunities
PDH Question #1

• Which of these is not normally a constituent in a UHPC mix design? (single answer)

a) Water
b) Superplasticizer
c) Retarder
d) Portland cement
e) Fiber reinforcement
PDH Question #2

• TRUE or FALSE?

• The ASTM C143 (AASHTO T119) slump value for UHPC is normally 3 to 5 inches.

---

PDH Question #3

• Which of these is a key material property of UHPC? (multiple answer)

   a) Sustained post-cracking tensile capacity,
   b) Compressive strength greater than 21 ksi,
   c) Biodegradable,
   d) Discontinuous pore structure resulting in enhanced durability,
PDH Question #4

• **TRUE** or **FALSE**?

• Unlike conventional concrete, UHPC’s are designed to be expansive and thus shrinkage is never a problem.

PDH Question #5

• UHPC has been used in which if these bridge components? (multiple answer)

  a) Field-cast connections between prefabricated elements,
  b) Pre-tensioned bridge girders,
  c) Cable stayed bridge cables,
  d) Lightweight bridge deck panels,