Practical Implementation of Ultra-High Performance Concrete (UHPC)

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Vincent J. Kania, SE
Why UHPC?
Outline

- Why UHPC?
- Materials
  - Mixtures, Production, Specification
- Structural Behavior
  - Flexure, Shear, Shear Testing
What is Ultra-High-Performance Concrete?

- Characterized by:
  - Ultra-high **compressive strength**
  - High pre- and post-cracking **tensile strength**
  - Enhanced **durability** due to high density and discontinuous pore structure
Where does performance come from?

1. Fibers
2. Low w/cm
3. SCMs (especially silica fume)
4. Optimized particle packing
   ▪ Contributes to strength
   ▪ Contributes to durability
   ▪ Contributes to workability
UHPC Varieties

Well-suited to Precast

- Local Material-based Mixtures
  - Lower cost
  - Tailor to project needs
  - Local expertise required
  - Verification testing needed
Materials: PCI-UHPC
PCI-UHPC Research Project

Implementation of Ultra-High-Performance Concrete in Long-Span Precast Pretensioned Elements for Concrete Buildings and Bridges

- Develop UHPC production guidelines and guide materials specification
  - Mix development/characterization for the six participating precasters

- Develop design guidelines for transportation and buildings
  - Based on existing knowledge, refined based on additional full-scale testing
  - Provide fully worked-out design examples
Local Materials

- Use local materials where possible to limit cost

- Some new materials may be needed:
  - Fine sand
  - Superplasticizer
  - Supplemental material
Existing Precast Concrete Production Facilities
What is PCI-UHPC?

- **Flow spread:** 8 to 11 inches at point of placement
- **Temperature:** 50 to 80 deg. F
- **Compressive strength at service:** 17.4 ksi (ASTM C1856)
- **Flexural strength at service:** (ASTM C1856)
  - *Min. first-peak* = 1,500 psi
  - *Min. peak* = 2,000 psi and at least 125% of first-peak
  - *Min. residual stress at deflection of L/150* = 75% of first-peak
Identify candidate materials; Recommendations:

- **Cement**: low $C_3A$ content (< 8%), moderate fineness (< 400 m$^2$/g)
- **Silica fume**: high SiO$_2$ content (> 95%, if possible)
- **Supplemental materials (if used)**: intermediate particle size distribution between cement and silica fume, or cement and sand
- **Sand**: finer than No. 20 sieve (0.03 in/0.8 mm max)
- **Superplasticizer**: efficient for mixes with high powder contents
- **Fibers**: Steel, high tensile strength (>300 ksi), high aspect ratio (>60)
Mixture Development

1. Select mix proportions based on particle packing.
2. Trial batch in lab to achieve 9-inch flow.
3. Trial batch in plant and verify performance.
## As-Batched Mix Designs

<table>
<thead>
<tr>
<th>Precaster</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E-1</th>
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<tbody>
<tr>
<td>Cement, lb/yd³</td>
<td>1,500</td>
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<td>300</td>
<td>160</td>
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<tr>
<td>Limestone Powder, lb/yd³</td>
<td>--</td>
<td>140</td>
<td>--</td>
<td>250</td>
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<tr>
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<td>Estimated materials cost, $/yd³</td>
<td>$818</td>
<td>$701</td>
<td>$712</td>
<td>$729</td>
<td>$655</td>
<td>$801</td>
</tr>
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UHPC Production
In-Plant Trials

Focus on:
- Materials Acquisition & Handling
- Batch Sequencing
- Batching Controls
- Transport and Placement Methods
- Finishing and Curing
- QC Testing
Production Process

- Unique process for each plant
- General guidance:
  - Blend dry components first
  - Add mixing water + liquid admixtures
  - After time, mix “turns” to fluid
  - Add fibers
Production Control

Moisture:
- Sand
- Water
- Superplasticizer

Temperature:
- ICE
- Packaged ICE
Fiber Addition
Transport and Placement
Transport

- Multiple batches can be combined in a ready-mix truck or auger-fed bucket (Tuckerbilt) prior to discharge

- Combined material performed consistent with the “average” of the combined batches
Curing

- Two curing processes permitted:
  - Post-Cure Thermal Treatment
  - Standard Cure
Curing

- **Standard (PCI MNL 116) Curing**
  - Does not require special equipment
  - Strength develops gradually
  - Shrinkage continues over first few months

- **Post-Cure Thermal Treatment (194°F for 48 hrs)**
  - Develops strength rapidly (often exceeds ambient cure)
  - Most shrinkage complete after treatment
  - “Locks in” creep and shrinkage
Testing Tensile Performance

Uniaxial Tension Test

Flexural Test (ASTM C1609)

Double-Punch Test

Photo: FHWA-HRT-17-053

Photo: S. Tuladhar, MS Thesis, 2017

Steel punch centering
Circumferential Extensometer

Steel punch
[1.5 in (38 mm)]
Ø=1.0 in. (25 mm)]

LVDT
Elements Produced
Demonstrated Success with PCI-UHPC

- The participating precasters successfully produced UHPC products and structural components, validating production Guidelines

- All UHPC mixtures demonstrated capacity to meet performance targets

- As production matures, we are confident that the participating precasters can consistently produce UHPC meeting design targets

- PCI-UHPC report has been published; Production guidelines and guide spec. are being published as a PCI document (imminent)
UHPC Implementation for Materials Specifiers

- **UHPC Materials Guide Specification**

- **Key considerations:**
  - **Scope:**
    - Buildings (CSI MasterFormat)
    - Transportation (DOT Format)
UHPC Structural Behavior
Applicable Structural Limit States for UHPC

- Flexure
- One-Way Shear
- Axial Compression
- Two-Way Shear
- Torsion
- Strand Development and Anchorage
- Interface Shear / Composite Action
Beam Flexure
Conventional Concrete – Nominal Flexural Strength

1. The concrete is assumed to have no capacity in tension.
2. The intended failure mode is crushing of the concrete in the compression zone.
Conventional Concrete – Flexural Behavior

Conventional reinforced concrete mechanics:
Flexural strength increases with increasing $\rho$. Tension steel strain and ultimate curvature decrease with increasing $\rho$.

3. Flexural ductility decreases with increasing longitudinal reinforcement.
UHPC Tension Capabilities

Flexural Test Results for 12”x4”x4” Rectangular Specimens

Micro-cracking

Localization and fiber pullout
UHPC Material Tension Models

1. First Crack
2. Localization & Fiber Pullout

**Elasto-Plastic**

- Stress vs. Strain
- $f_1$ vs. $\varepsilon_1$ vs. $\varepsilon_2$

**Strain Hardening**

- Stress vs. Strain
- $f_1$ & $f_2$ vs. $\varepsilon_1$ & $\varepsilon_2$

- $f_1$ & $f_2$
  - 0.75 to 1.5 ksi
- $\varepsilon_1$
  - 0.0001 to 0.0002
- $\varepsilon_2$
  - 0.002 to 0.008
UHPC – Cracked at Nominal Strength

\[ \varepsilon_{su} = \beta c \]

\[ \alpha f' c \]

\[ T = A_s f_y \]
Rebar yielding
Concrete crushing
Fiber pullout

Rebar strain hardens until long. reinf. fractures or UHPC crushes

Fiber pullout and long. reinf. fracture

Cracking of cementitious material

Concrete crushing

UHPC with $T_{\text{long. reinf.}} > T_{\text{fibers}}$

UHPC with $T_{\text{long. reinf.}} < T_{\text{fibers}}$

Conventional Reinforced Concrete
Beam Shear
Conventional Concrete with Stirrups
Conventional Concrete with Stirrups

\[ V_n = V_c + V_s \]

\[ V_s = \frac{A_v f_y d}{s} \cot \theta \]

\( \theta \) is the angle of principal compression
UHPC with Fibers
UHPC with Fibers

\[ V_f = f_t b_w d \cot \theta \]

\( f_t \) is the design tension strength of the UHPC-fiber matrix based on the mechanism of fiber pullout.

\( f_t \) is dependent on fiber type, amount, and orientation.
UHPC with Fibers

\[ V_f = f_t b_w d \cot \theta \]

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UHPC Material Tension Models

1. First Crack
2. Localization & Fiber Pullout

$\varepsilon_1$ 0.0001 to 0.0002
$\varepsilon_2$ 0.002 to 0.008

$f_1$ & $f_2$
0.75 to 1.5 ksi

Elasto-Plastic

Strain Hardening
UHPC with Fibers and Stirrups

\[ V_n = V_f + V_s \]

\[ V_s = \frac{A_v f_s d}{s} \cot \theta \]

\( f_s \) is the stress in the stirrups when fiber pullout occurs along the primary shear crack.
Beam Shear Testing
PCI-UHPC Beam Shear Testing at WJE

Cross-Sections:
PCI-UHPC Beam Shear Testing at WJE
PCI-UHPC Beam Shear Testing at WJE
PCI-UHPC Beam Shear Testing at WJE
Conventional Concrete Sample Beam Shear Testing
Baseline UHPC Beam Results (3” Web)
UHPC Beam Results (2” and 4” Web)

<table>
<thead>
<tr>
<th>Web Thickness</th>
<th>Ultimate Shear</th>
<th>Change from 3”</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 inches</td>
<td>310 kips</td>
<td>3.57 ksi</td>
</tr>
<tr>
<td>2 inches</td>
<td>236 kips</td>
<td>4.08 ksi</td>
</tr>
<tr>
<td>4 inches</td>
<td>410 kips</td>
<td>3.54 ksi</td>
</tr>
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Theoretical Shape Factor
4’-8” Deep UHPC Beam Results

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<th>Beam Height</th>
<th>Ultimate Shear</th>
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<tbody>
<tr>
<td>2’-10”</td>
<td>310 kips</td>
<td>3.57 ksi</td>
</tr>
<tr>
<td>4’-8”</td>
<td>350 kips</td>
<td>2.34 ksi</td>
</tr>
</tbody>
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Applied Load vs. Midspan Deflection - UHPC Beam 7

- Ultimate Applied Load = 693,000 lbs.
- Peak Load Deflection = 0.71 in.

- Diagonal tension crack coalescing and opening, no web compression crushing
- Web compression crushing above diagonal crack near load point
- Web compression crushing below diagonal crack near midpoint of shear span
- Diagonal crack opening and lengthening, small spalling along crack
- Diagonal crack opening and lengthening, lateral shear friction movement/slip along diagonal crack, small additional web crushing and spalling

[Graph showing load vs. deflection with labels and annotations]
4’-8” Deep UHPC Beam Results

Theoretical Shape Factor
WJE’s postmortem core removal, inspection, and image analysis showed no internal voiding but did reveal preferential fiber orientation aligned with the reported flow direction during casting.
Benefits of UHPC for Structural Members

- The tensile strength and ductility of the UHPC material translates into strength and ductility for design.
  - Adequate shear strength from fibers alone
  - Ductility in shear
- Very efficient designs are possible.
  - Reduced weight, extended spans
  - Reduced reinforcing steel
- UHPC has enhanced material durability and corrosion resistance.
Next Steps for Precast UHPC

▪ Owners, fabricators, and engineers should work together to identify efficient uses for initial UHPC implementation.

▪ Production: optimized formwork, larger members

▪ Design: shape factor, fiber orientation, stirrup stress at nominal shear strength

▪ Current Guidance: FHWA, PCI research

▪ Future Guides and Codes: AASHTO, PCI, ACI
Questions?

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