Ultra-High Performance Concrete: Current Status and Introduction

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NYSDOT UHPC Workshop
June 28, 2017

every day counts
An Innovation Partnership with States

U.S. Department of Transportation
Federal Highway Administration

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

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What is Ultra-High Performance Concrete?

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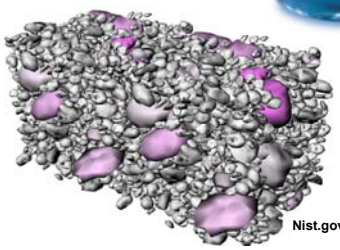
Fiber Reinforcement

Superplasticizers

Supplementary Cementitious Materials

Particle Packing Theory



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).

What is Ultra-High Performance Concrete?

Highly durable, strain-hardening concrete

What is Ultra-High Performance Concrete?

Micro-Reinforced Concrete

What is Ultra-High Performance Concrete?

Resilient Cementitious Composite

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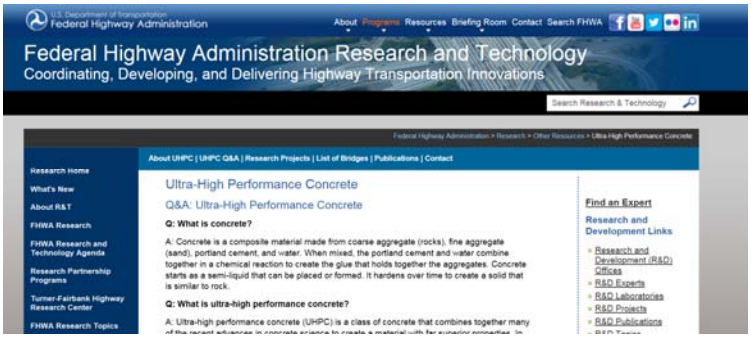
FHWA UHPC Web Resources

- 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

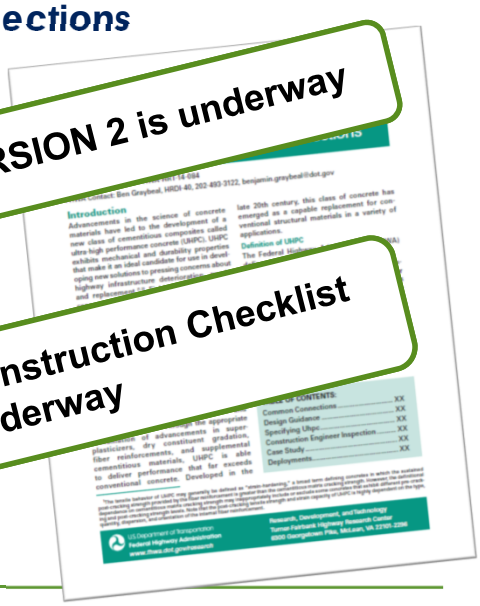
- What is UHPC?
- Example Connections
- Structural Design
- Construction
- Quality Assurance
- Deployments

Design and Construction of UHPC Field-Cast Connections

- FHWA-HRT-14-084
- Wha…
- …ctions
- …tructural Design
- Construction
- Quali…

Development of VERSION 2 is underway

Development of Construction Checklist is underway



Every Day Counts (EDC)

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

EDC-2 (2013 – 2014)
- Accelerated Bridge Construction, including PBES

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

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

Microsoft Office clip art

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.

FHWA

EDC UHPC Activities

- Technical assistance
- Workshops
- Webinars
- Peer exchanges
- Presentations

FHWA

UHPC Webinar Series

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

Sign Up in the UHPC section of the FHWA EDC Website
https://www.fhwa.dot.gov/innovation/everydaycounts/edc_4/2017_uhpc_webinar.pdf

UHPC @ American Concrete Institute

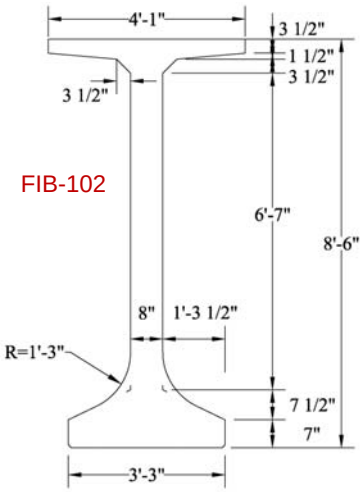
- ACI 239: UHPC
- Committee formed in 2011
- Ben Graybeal, Chair
- Initiatives:
  - Emerging Technology Report
  - Test Methods for UHPC
  - Structural Design of UHPC
  - Materials & Methods of Construction
  - Applications of UHPC
  - Research Needs

UHPC @ 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

Lisa Ricciotti

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

Conventional Detail

UHPC Detail

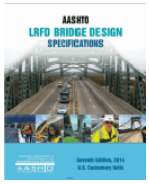
FHWA Publication HRT-14-084

Structural Design Guidance (US)

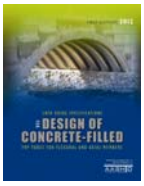
Under Development:

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



Concrete-Filled FRP Tubes

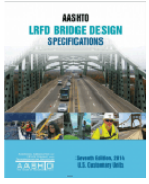
GFRP-Reinforced Concrete

Structural Design Guidance (US)

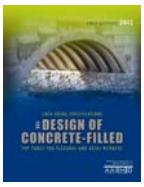
Under Development:

AASHTO LRFD Design and Construction Guide Specification for UHPC

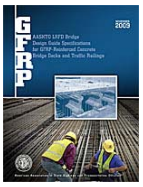
- Material Models and Guidance
- Design Guidance
- Construction Guidance



LRFD Bridge Design



Concrete-Filled FRP Tubes



GFRP-Reinforced Concrete

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Example Composition of a UHPC

Constituent	Amount (lb/yd^3)	Amount (kg/m^3)
Portland Cement	1235	733
Silica Fume	388	230
Ground Quartz	308	183
Fine Sand	1699	1008
Steel Fibers	327	194
Superplasticizer	56	33
Water	271	161

* 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

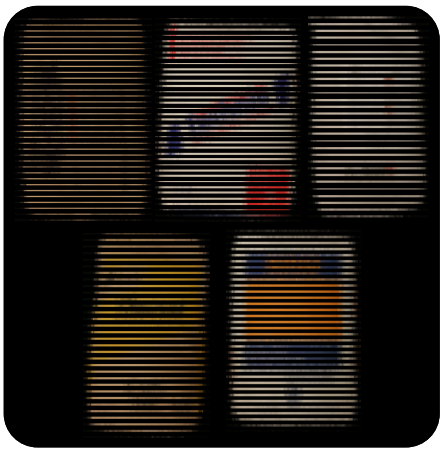
Constituent	Amount (lb/yd^3)	Amount (kg/m^3)
Portland Cement	1331	790
Silica Fume	334	198
Fly Ash (Class F)	324	192
Fine Basalt	1923	1141
Steel Fibers	199	118
Superplasticizer	47	28
Water	246	146

* 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**

Grout Type	Approximate Cost per yd^3
Portland Cement Grouts	$1000 to $2000
Repair Mortars	$1500 to $3000
Epoxy Grouts	$5000
UHPCs	$2500 to $3500

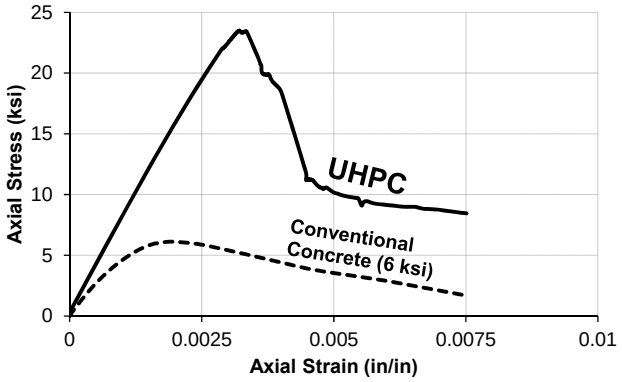
- **Non-Proprietary Versions**
  - At least $800 for UHPC raw constituents

UHPC Properties: Some Ballpark Values

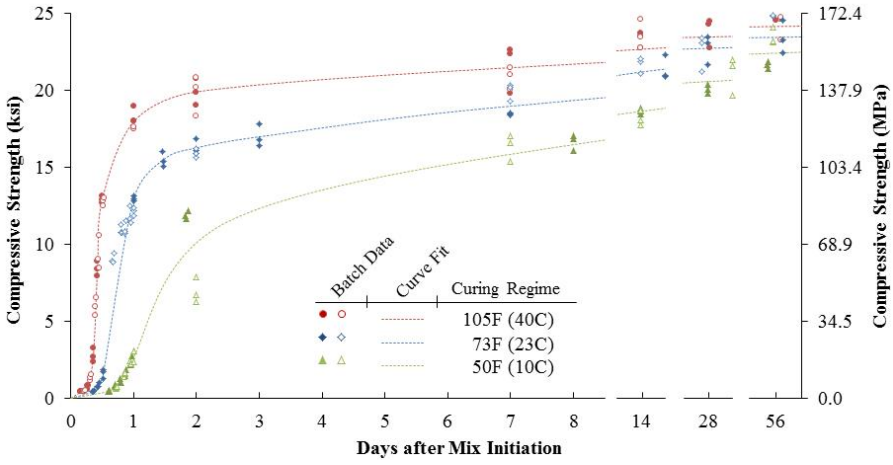
- Fresh "Slump" – Self Consolidating
- Compressive Strength – 18 to 35 ksi
- Modulus of Elasticity – 6000 to 8000 ksi
- Sustained Tensile Capacity – 0.9 to 1.5 ksi
- Interface Bond – Can surpass substrate tensile strength
- Permeability – 100x less than conventional concrete
- Freeze/Thaw Resistance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

UHPC Rheology (Video)

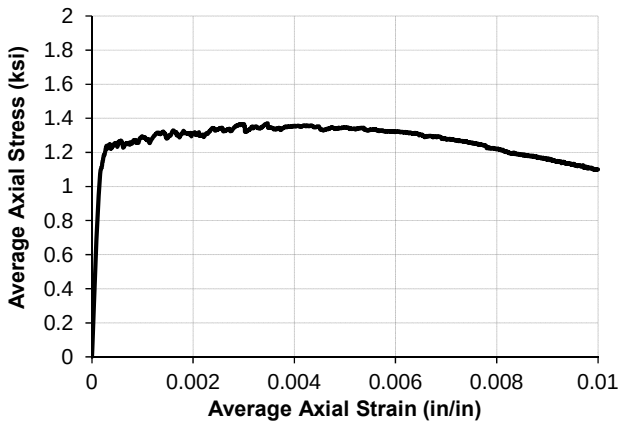
Compression Behavior



Compression Strength Gain



Tensile Behavior



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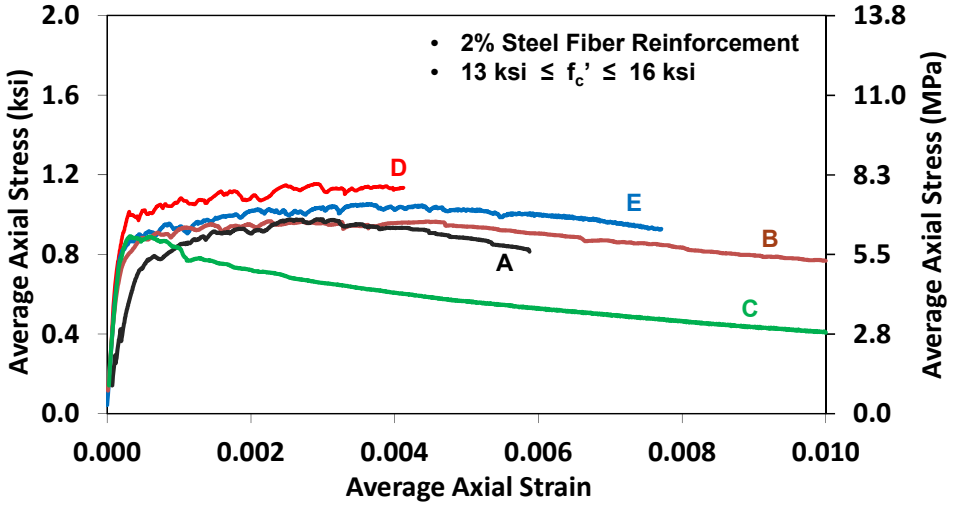
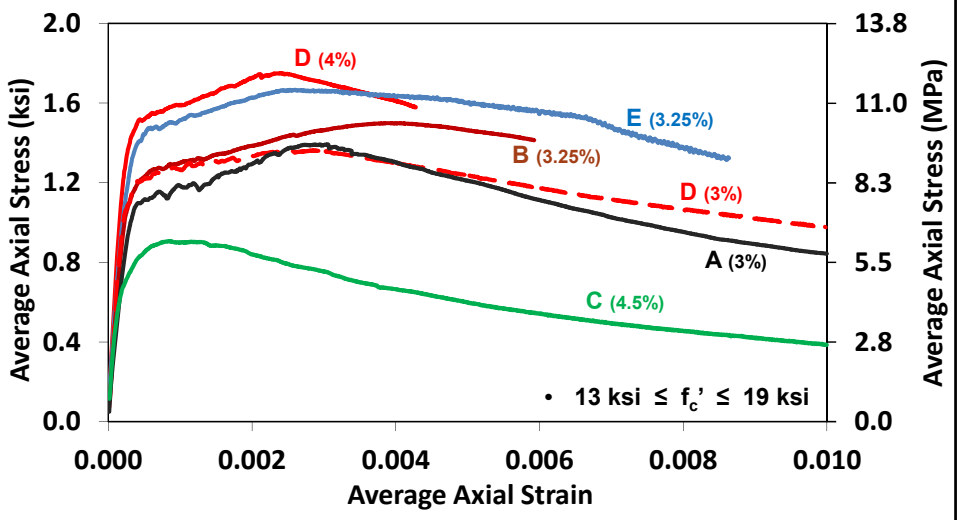
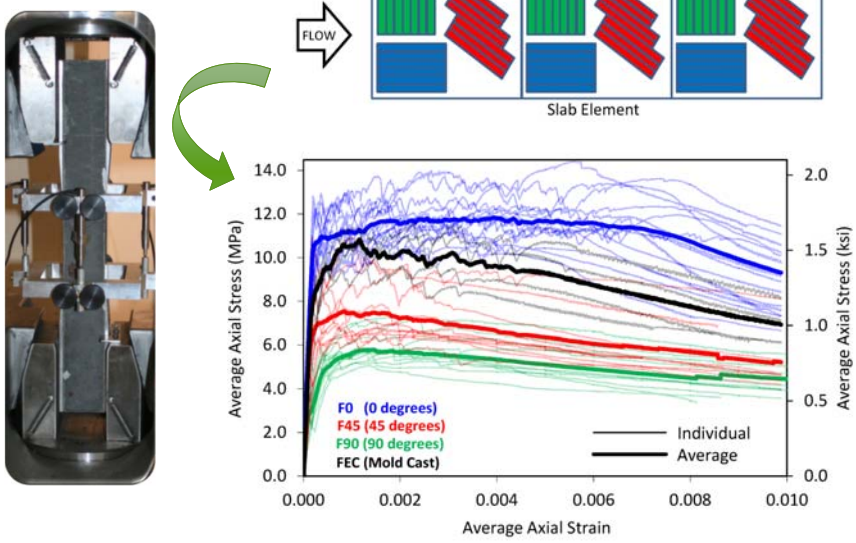


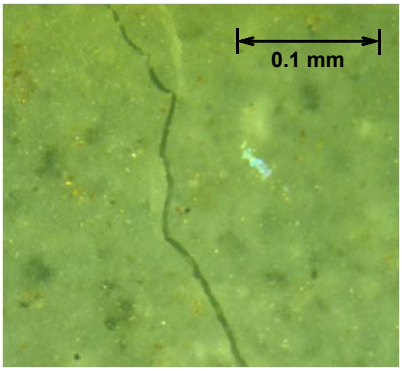
Tensile Behavior



Tensile Behavior

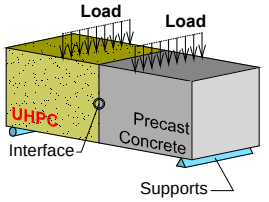


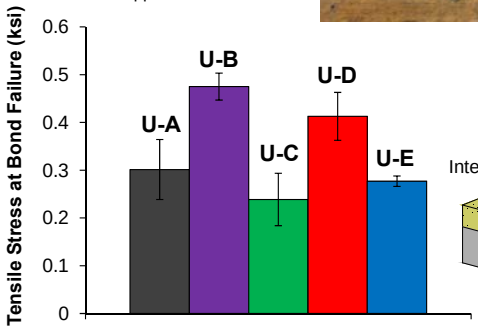
Tensile Behavior: Cracking

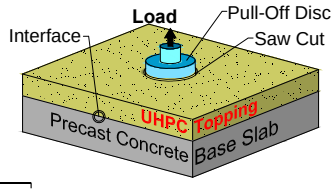


4 micrometer wide crack
at 1000x magnification

Interface Bond







Age of UHPC During Test: 14-Days

Interface Bond

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

TECHNOTE

Bond of Field-Cast Grout Materials to Precast Concrete Elements

FHWA Publication No: FHWA-HRT-16-081

FHWA Contact: Ben Graybeal, HRDI-40, 202-493-3122, benjamin.graybeal@dot.gov

Introduction

The performance of field-cast connection materials for prefabricated concrete elements using field-cast, cementitious-based grout materials is becoming a focus area for accelerated bridge construction (ABC) projects. These grout materials are required to provide sufficient strength and long-term performance equal to or better than the adjacent concrete elements that they are connecting to assure adequate stress transfer and long-term performance throughout the life of the bridge. Many aspects need to be taken into consideration when specifying the material to make these connections. This TechNote focuses on the aspects related to the bonding interface between the previously cast concrete element and the field-cast connection grouts, including test methods, factors affecting bond, and best practices for detailing and construction.

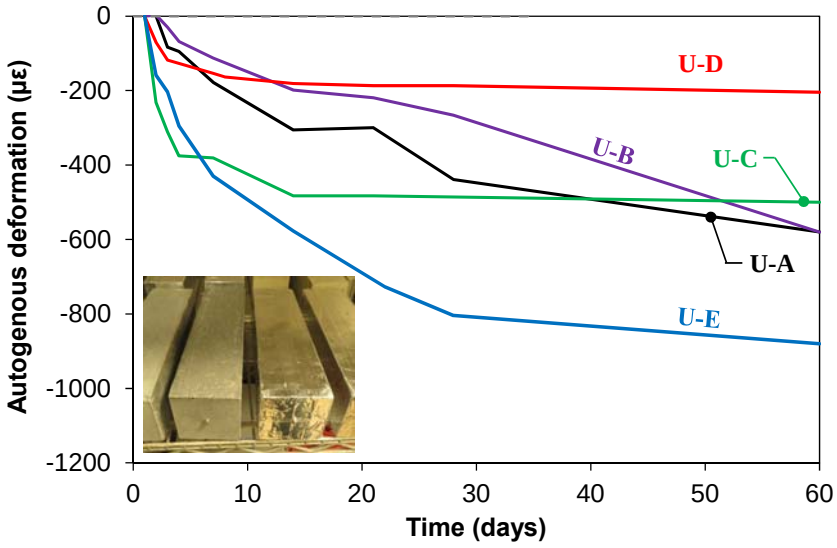
Background

In recent years, ABC has become increasingly popular for both new and replacement bridge construction throughout the United States. ABC projects typically use innovative planning strategies, novel materials, and innovative structural designs to expedite completion and reduce the onsite impacts of bridge construction.[1] Many ABC projects use prefabricated bridge elements (PBEs). These fabricated bridge elements are typically produced under controlled environmental conditions either off or near site and can offer improvements in quality and the expectation of better long-term performance. Once fabricated, PBEs are delivered and rapidly assembled. To create structural continuity, PBEs are typically connected using interfaced reinforcing bars and field-cast grout closure pours (see figure 1). The ideal closure material for PBE connections is self-consolidating; has high early-age strength; and offers exceptional durability, dimensional stability, and a bond that is stronger than the tensile capacity of the element to which it is connected. The most common connection grouts are cement-based, low-shrinkage grouts that are commonly referred to as "non-shrink" cementitious grouts. However, other grout materials have recently emerged as alternatives. Examples include epoxy-based grouts, ultra-high performance concretes (UHPCs), and

U.S. Department of Transportation
Federal Highway Administration
www.fhwa.dot.gov/research

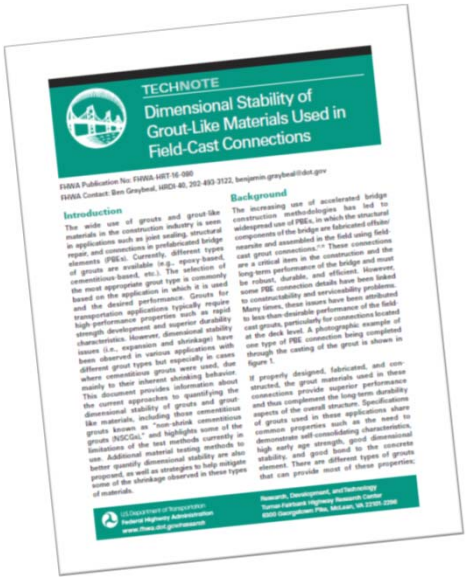
Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike, McLean, VA 22101-2296

Shrinkage Behavior



Shrinkage Behavior

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



TECHNOTE

Dimensional Stability of Grout-Like Materials Used in Field-Cast Connections

FHWA Publication No: FHWA-HRT-16-080

FHWA Contact: Ben Graybeal, HRDI-40, 202-493-3122, benjamin.graybeal@dot.gov

Introduction

The wide use of grouts and grout-like materials in the construction industry is seen in applications such as joint sealing, structural repair, and connections in prefabricated bridge elements (PBEs). Currently, different types of grouts are available (e.g., epoxy-based, cementitious-based, etc.). The selection of the most appropriate grout type is commonly based on the application in which it is used and the desired performance. Grouts for transportation applications typically require high-performance properties such as rapid strength development and superior durability characteristics. However, dimensional stability issues (i.e., expansion and shrinkage) have been observed in various applications with different grout types but especially in cases where cementitious grouts were used, due mainly to their inherent shrinking behavior. This document provides information about the current approaches to quantifying the dimensional stability of grouts and grout-like materials, including those cementitious grouts known as "non-shrink cementitious grouts (NSCGs)" and highlights some of the limitations of the test methods currently in use. Additional material testing methods to better quantify dimensional stability are also proposed, as well as strategies to help mitigate some of the shrinkage observed in these types of materials.

Background

The increasing use of accelerated bridge construction methodologies has led to widespread use of PBEs, in which the structural components of the bridge are fabricated offsite/nearsite and assembled in the field using field-cast grout connections.[1,2] These connections are a critical item in the construction and the long-term performance of the bridge and must be robust, durable, and efficient. However, some PBE connection details have been linked to constructability and serviceability problems. Many times, these issues have been attributed to less-than-desirable performance of the field-cast grouts, particularly for connections located at the deck level. A photographic example of one type of PBE connection being completed through the casting of the grout is shown in figure 1.

If properly designed, fabricated, and constructed, the grout materials used in these connections provide superior performance and thus complement the long-term durability aspects of the overall structure. Specifications of grouts used in these applications share common properties such as the need to demonstrate self-consolidating characteristics, high early age strength, good dimensional stability, and good bond to the concrete element. There are different types of grouts that can provide most of these properties;

Durability

USACE Facility at Treat Island

UHPC Permeability

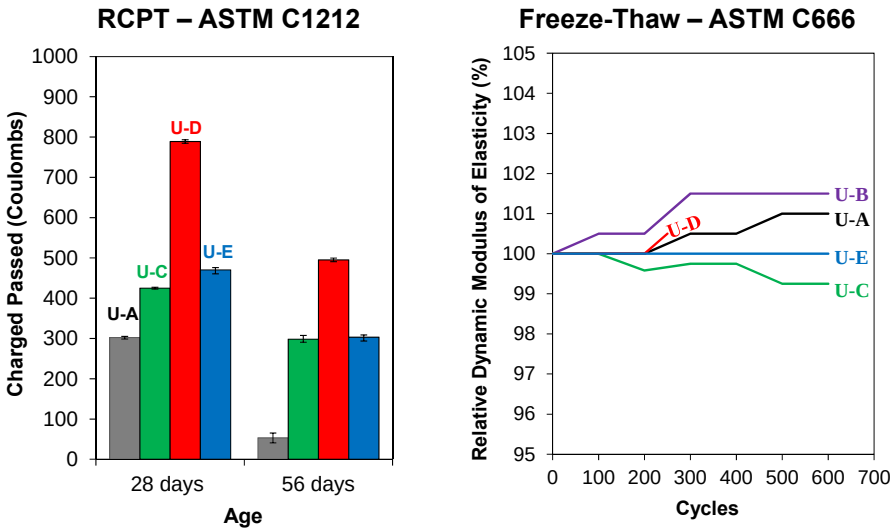
- Chloride Ion Diffusion Coefficient

  2 x 10^{-11} m^2/s for conventional concrete

  2 x 10^{-12} m^2/s for HPC

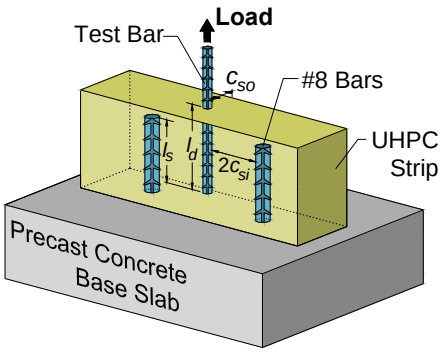
  2 x 10^{-13} m^2/s for UHPC

Durability



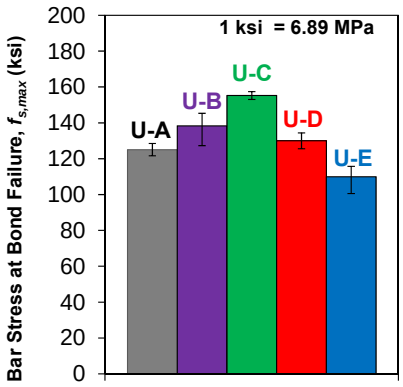
Bond to Steel Reinforcing Bars

TEST CONFIGURATION



EXAMPLE RESULT

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



Manufacturer-Recommend Fiber Vol.

Phase 1 Results:
TechBrief: FHWA-HRT-14-089
Report: FHWA-HRT-14-090

Bond to Steel Reinforcing Bars

TEST CONFIGURATION

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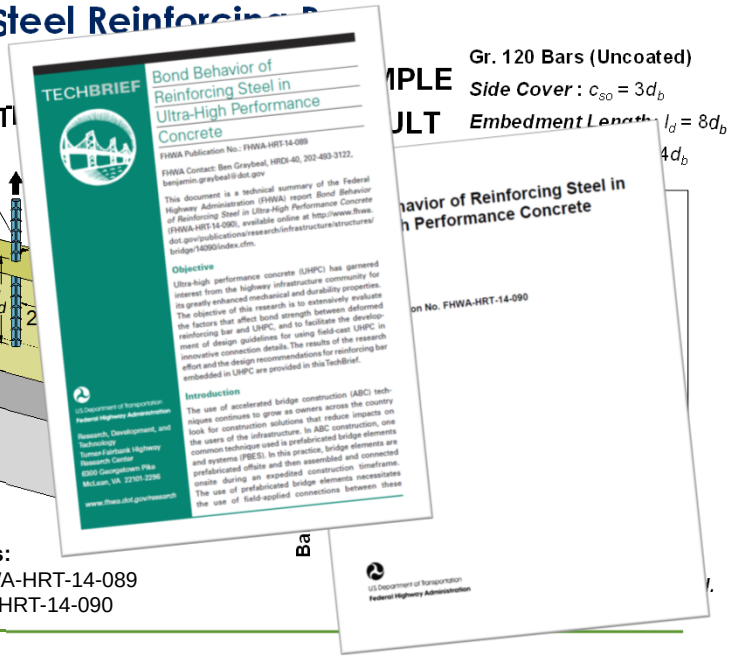
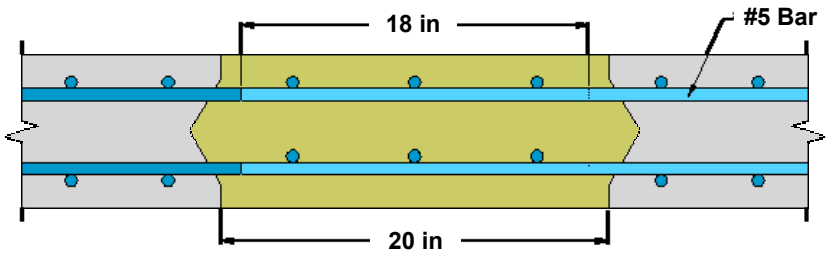


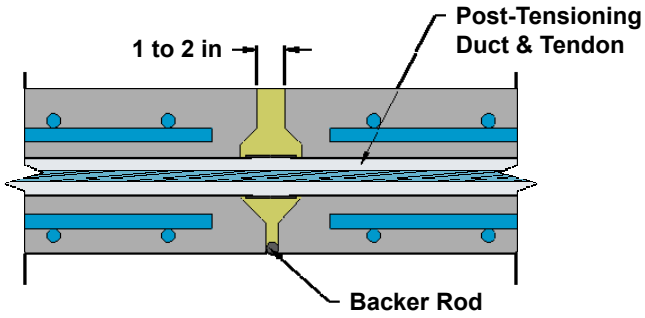
Conventional Closure Pour Connection



Closure Pour w/ Conventional Concrete

53

Post-Tensioned Connection



Post-Tensioned w/ Conventional Grout

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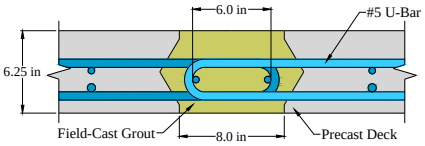
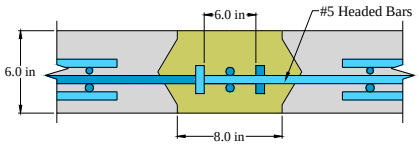
Conventional Grout Deck Panel Connections



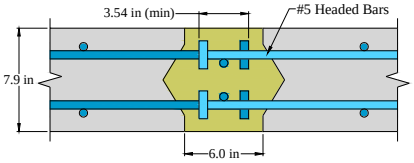
U-Bar Connection

(Zhu, Ma, and French, 2012)



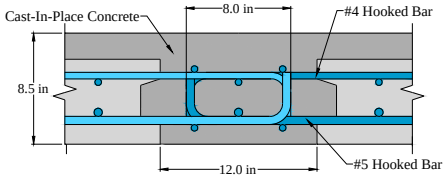
One-Layer Headed Bar Connection

(Li, Ma, Griffey, and Oesterle, 2010)



Two-Layer Headed Bar Connection

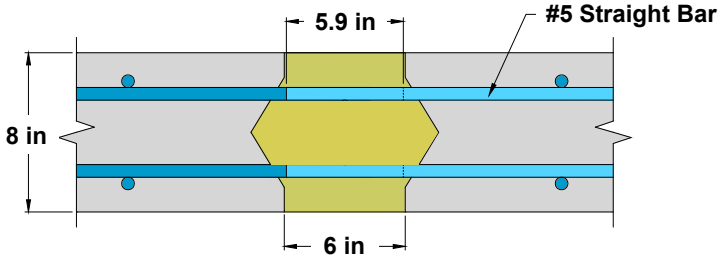
(Graybeal, 2010)



90° Hooked Bar Connection

(Azizinamini, Power, Myers, and Ozyildirim, 2014)

UHPC Deck Panel Connection



Straight Bar Connection w/ UHPC

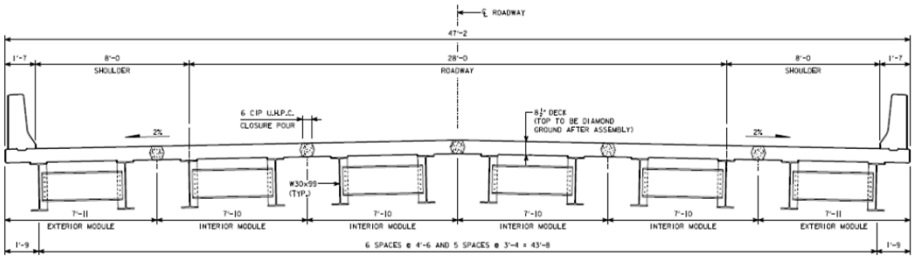
Deck-Level Connections

TechBrief: FHWA-HRT-11-022 Report: NTIS PB2011-101995

UHPC Deck-Level Connection Testing (Video)

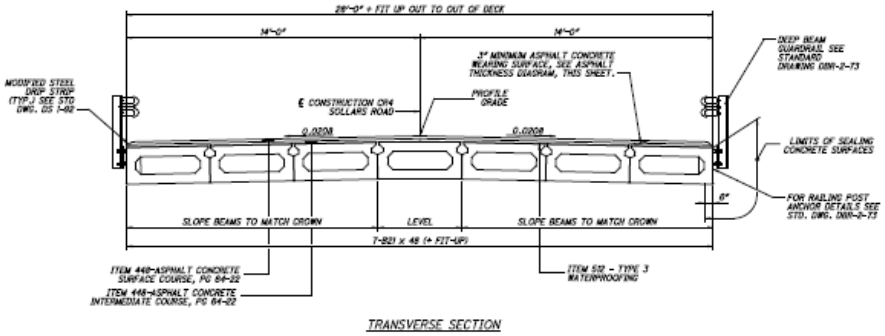
UHPC Deck-Level Connection Testing (Video)

UHPC Connections b/t Modular Decked Units



U.S. 6 over Keg Creek
Pottawattamie County, Iowa

UHPC Connections b/t Adjacent Box Beams

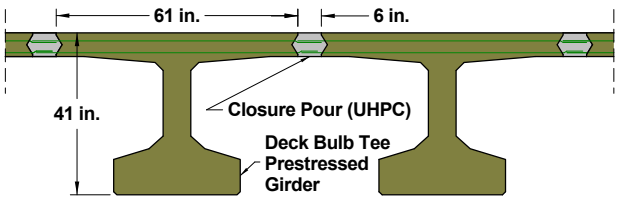


Sollars Road over Lees Creek
Fayette County, Ohio

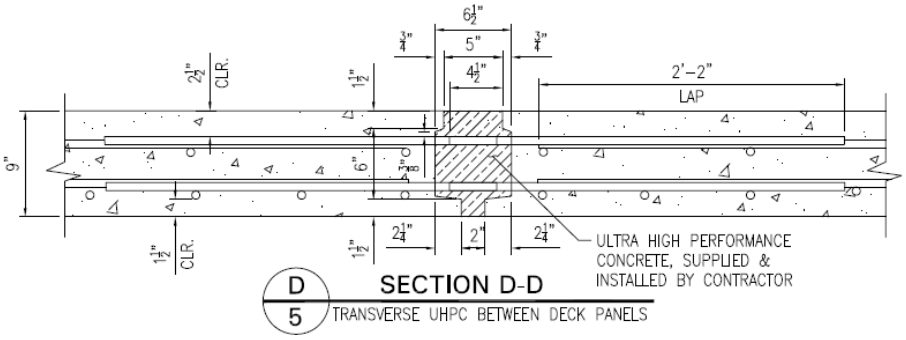
Adjacent Box Beam Connections

UHPC Connections b/t Deck-Bulb-Tee Girders

SR 31 over
Canandaigua Outlet
Lyons, New York



Rebar Lap Splice Connection



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 ½ inches
  - Bottom cover is 1 ½ inches
  - Steel fiber length is 13 mm (½ inch)

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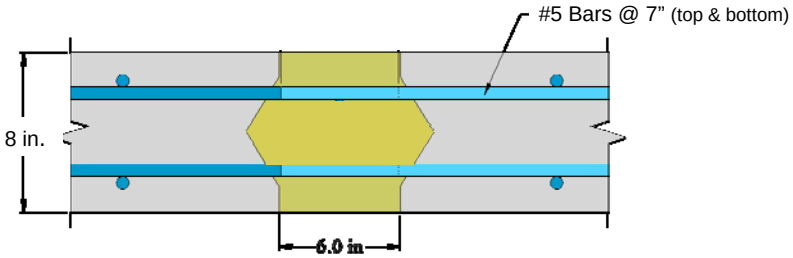
Design Example – Precast Deck



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.

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Design Example – Rebar Lap Splice

#5 Bars (60 ksi) Top & Bottom:

- Clear cover *top*
  - ***2-1/2**" ≥ 1-7/8" ($3d_b$)*
- Clear cover *bottom*
  - *1-1/4" ($2d_b$) ≤ **1-1/2"** ≤ 1-7/8" ($3d_b$)*

- 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 = $1.5l_{fiber} = 0.75"$
  - Maximum = $l_s = 4.75"$
- UHPC with $f'_c \geq 14$ ksi

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UHPC Connections for Shear Interfaces

Steel Girder Connection

Concrete Girder Connection

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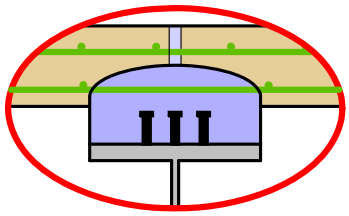
UHPC Composite Connection Testing



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

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

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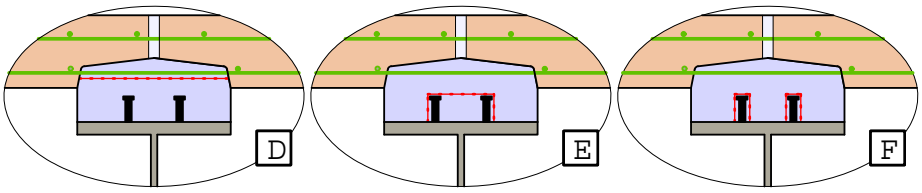
Design Guidance – Interface Shear



Examples of minimum shear planes for horizontal shear transfer

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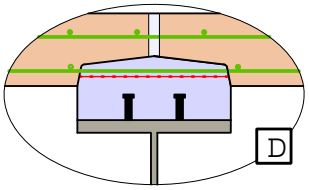
Design Guidance – Interface Shear

Example Calculation -Fatigue Stress

- Given:
  - Q = 550 in^3
  - V_r= 40 kips
  - I = 21,800 in^4
  - b = 8 inches



$$\tau = (V_r * Q)/ (I*b)$$

$$\tau = (40 * 550)/ (21,800 * 8)$$

$$\tau = 126 \text{ psi} < 150 \text{ psi} \quad \text{OK}$$

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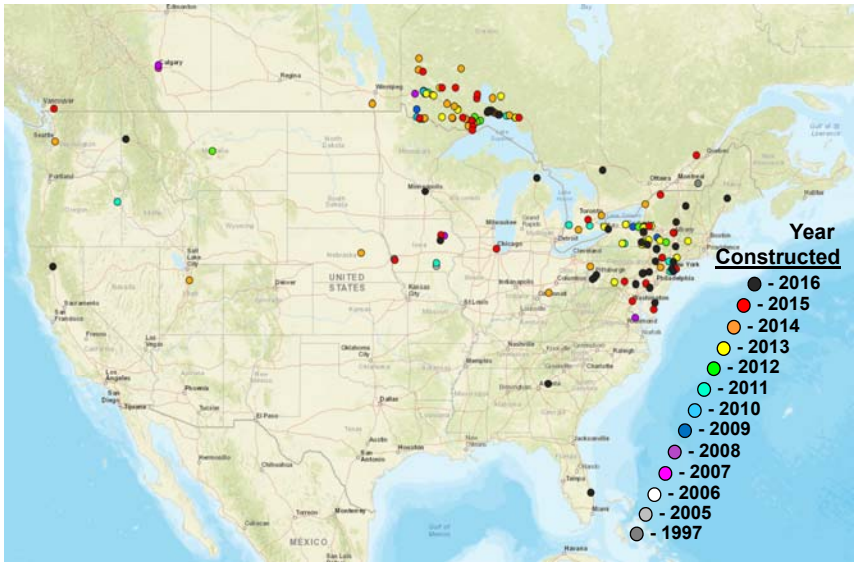
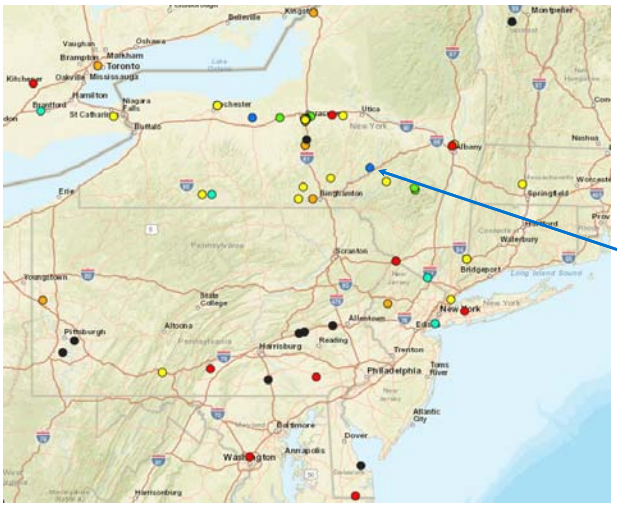
UHPC Deployments Across US and Canada



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

UHPC Deployments Across US and Canada



SR 23 Bridge

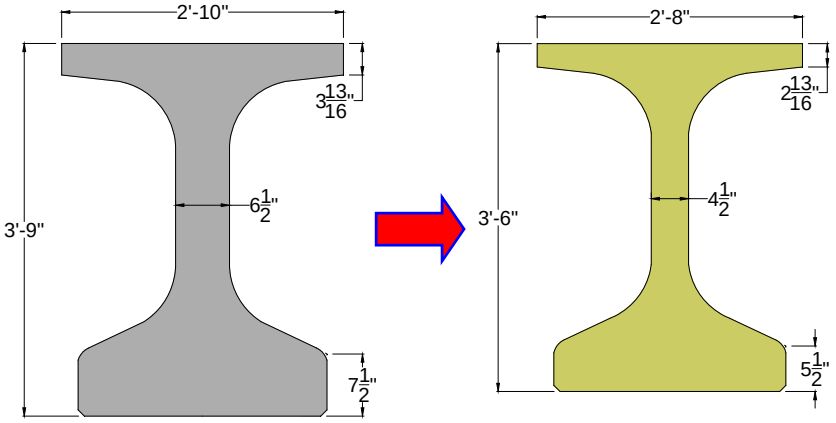
Bridge Name / Route: SR 23
Crossing Feature: Otego Creek
State or Province: NY
City or County: Oneonta
Owner: New York State Department of Transportation
UHPC Application: Deck-level connections between full-depth precast concrete deck panels
Year Constructed: 2009
GPS Latitude: 42.47
GPS Longitude: -75.11

Elevation view of single span bridge over water supported by abutments - Photo Credit: FHWA

Link: http://usdot.maps.arcgis.com/apps/webappviewer/index.html?id=41929767ce164eba934d70883d775582
Web Search: "FHWA UHPC" then click Deployments tab

Mars Hill Bridge

Mars Hill Bridge

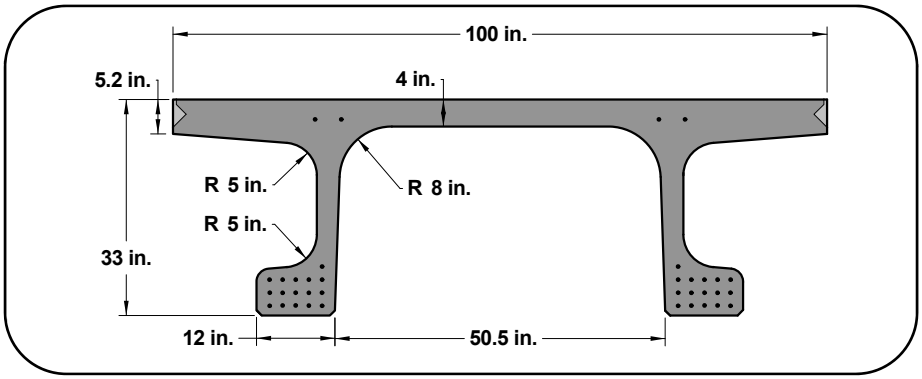


Iowa 45" Bulb Tee
SW ≈ 0.7 kip/ft

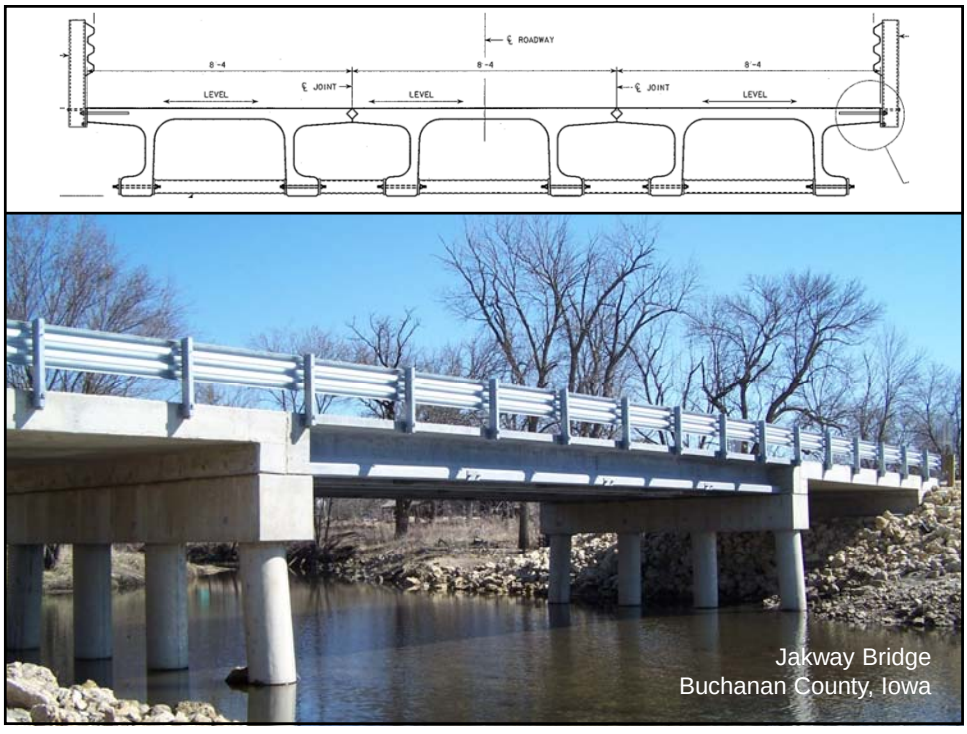
Modified Bulb Tee
SW ≈ 0.56 kip/ft

π-Girder

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



Reports: NTIS PB2009-115496, NTIS PB2014-100626

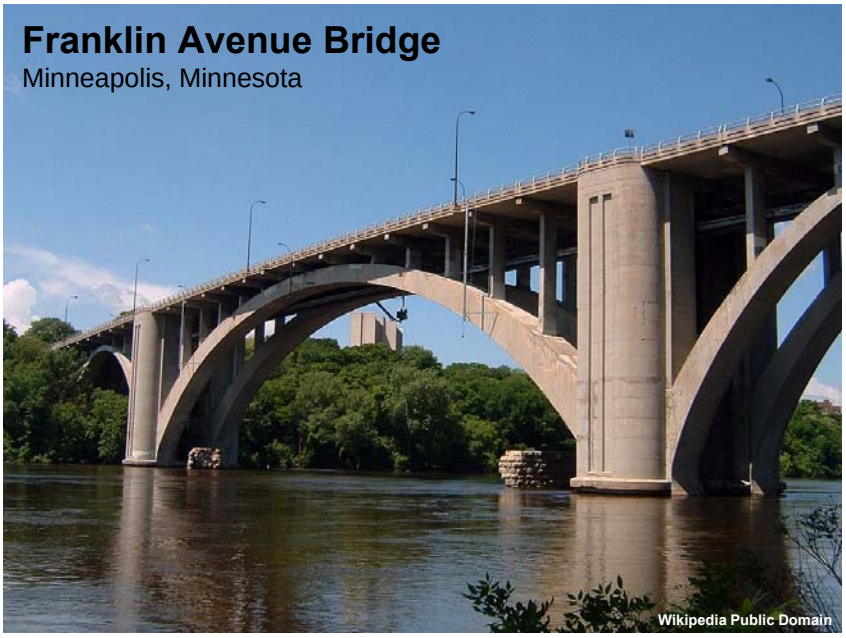


UHPC for Lightweight Bridge Decks

Dahlonega Road Bridge in Wapello County, Iowa

Franklin Avenue Bridge

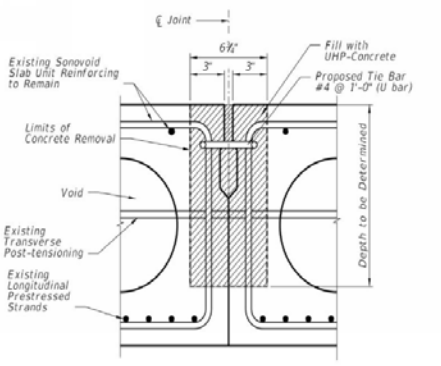
Minneapolis, Minnesota



Deck Panel Connections

Franklin Ave. Bridge
Minneapolis, MN

UHPC for Adjacent Box Beam Repair



SLAB UNIT CONNECTION DETAIL USING UHP-CONCRETE

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

Florida DOT

What is Ultra-High Performance Concrete?

What is Ultra-High Performance Concrete?

Capable Solution
for Today's Challenges
and Tomorrow's Opportunities

Ultra-High Performance Concrete: Current Status and Introduction

Ben Graybeal, Ph.D., P.E.
Team Leader – Bridge Engineering Research
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NYSDOT UHPC Workshop
June 28, 2017

every day counts
An Innovation Partnership with States

U.S. Department of Transportation
Federal Highway Administration

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,