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Production of Cast-in-Place UHPC for Bridge Applications

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16. Abstract

This project presents a comprehensive overview of the essential aspects associated with the cast-in-place application of UHPC, including formwork requirements, surface preparation, mixing procedures, placing methods, curing techniques, grinding specifications, and mockup construction. Each section provides in-depth insights into specific guidelines and practices outlined by various regulatory bodies. The research team has developed training materials designed for a full-day workshop tailored to benefit both contractors and NDOT engineers. This workshop comprises key topics such as proportioning, batching, testing, and the placement of both non-proprietary and proprietary UHPC mixes, as well as hands-on experience in batching, testing, and placing UHPC. The study investigating fresh and hardened UHPC tests to identify fiber segregation reveals that excessive water or the use of high-range water-reducing admixtures (HRWR) can lead to fiber segregation, which is observable in both fresh and hardened states. Techniques such as Visual Stability Index (VSI) and Hardened Visual Stability Index (HVSI) are somewhat subjective, while tests like the mini-V-funnel and falling ball tests provide more objective measures. Flow time shows promise as an indicator of fiber stability, but further research and data are required to establish Quality Assurance/Quality Control (QA/QC) ranges. The study also underscores the potential of surface resistivity testing and calls for more extensive research to refine these tests for practical application in construction. The experimental work explores the influence of shrinkage-reducing admixtures (SRA) and shrinkage-compensating admixtures (SCA) on UHPC. Optimal SRA dosage effectively mitigates both total and autogenous shrinkage of UHPC, with total shrinkage decreasing from 817με to 539με and autogenous shrinkage dropping from 691με to 437με. The effectiveness of SCA varies, and its impact on shrinkage is significant under specific hot batch curing conditions, although such methods may not be feasible for all concrete applications. The report also included a draft of the special provision for cast-in-place (CIP) UHPC.

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Chapter 1 Introduction

1.1 Background

Ultra-High Performance Concrete (UHPC) represents a groundbreaking advancement in concrete technology, boasting mechanical and durability characteristics significantly surpassing traditional concrete. Its application in bridge construction promises notable enhancements in structural integrity and longevity. UHPC's outstanding qualities have garnered considerable attention within the bridge community, including recognition at the federal and state levels. In addition to its widespread use in bridge deck connections across various states, the Federal Highway Administration's Every Day Counts (EDC-6) program, titled "UHPC for Bridge Preservation and Repair", underscores its potential in bridge applications due to its exceptional mechanical strength and durability.

The Nebraska Department of Transportation (NDOT) has successfully implemented UHPC in bridge deck connections/joints, notably in the Primrose East Bridge (2013) and Belden-Laurel Bridge (2018), as illustrated in Figure 1.1. However, the UHPC unit cost in these projects was steep, reaching up to $13,000 per cubic yard. This high cost was primarily due to the expensive materials, shipping, equipment, and associated costs for transportation and accommodation of technicians using proprietary mixes. To counter this, the research team, through the NDOT project SPR-P1(18) M072 titled "Feasibility Study of Development of Ultra-High Performance Concrete for Highway Bridge Applications in Nebraska", has developed a more affordable non-proprietary UHPC mix using local materials, reducing the cost to approximately $740 per cubic yard. While the development of non-proprietary UHPC mixes is a promising step towards broader adoption, the lack of expertise in batching and handling these materials remains a challenge. Recent efforts by FHWA, various state agencies, and the Precast/Prestressed Concrete Institute (PCI) have led to the creation of UHPC use guidelines, particularly for the design and production of precast components in building and bridge applications. Additionally, ongoing projects and document developments by the American Association of State Highway and Transportation Officials (AASHTO), FHWA, American Concrete Institute (ACI) Technical Committee 239 (UHPC), and other state bodies are in progress. However, a notable gap exists in comprehensive guidelines for cast-in-place (CIP) UHPC production and handling, especially concerning non-proprietary mixes.

Figure 1.1 Proprietary UHPC batching during Belden-Laurel Bridge construction in 2018

UHPC's unique composition, featuring a high concentration of fine powders and an extremely low water-to-cement ratio, necessitates a batching and proportioning process that differs markedly from that of conventional concrete. Although UHPC is known for its high flowability, achieving the desired workability while ensuring stability poses a significant challenge. Excessive flowability can cause fiber segregation, whereas UHPC's inherent viscosity might result in inadequate flow and consolidation. A notable characteristic of UHPC is the rapid loss of workability, attributed to the high content of high-range water-reducing (HRWR) admixtures. It complicates its transportation and placement due to its inability to retain self-consolidation properties for extended periods. Preliminary studies indicate the need for specific guidelines to manage UHPC's workability and stability effectively under static and dynamic conditions.

Furthermore, our research team has recently completed a project developing a cost-effective, non-proprietary UHPC using local materials, as detailed in Table 1.1. However, this alternative to commercial UHPC faces two primary challenges hindering its application in cast-in-place scenarios: the lack of specialized training and experience in UHPC batching and handling, and the absence of guidelines to monitor and maintain workability during construction.

Table 1.1 UNL-NDOT non-proprietary UHPC mix

Mix ID	Cement	Silica Fume	Slag	Water	Ice	Sand	Fiber	HRWR	w/b
I/II: SF8:S30:B1900	1207	161	585	215	94	1603	266	66.1	0.182

Material Type	Description	Source
Sand	No.10 sand	Lyman-Richey, Omaha, NE
Cement	Type I/II	Ash Grove Cement Company, Louisville, NE
Slag	Slag	Central Plains Cement Company, Omaha, NE (terminal)
Silica fume	Force 10,000 densified microsilica	GCP Grace Construction Products
Fiber	13/.20 micro steel fiber	HiPer Fiber, LLC.
HRWR	Premia 150	Chryso

Contrary to the precast industry, where a well-controlled environment and established procedures adeptly accommodate innovative materials like UHPC, its production in cast-in-place settings presents significant challenges. Local concrete producers and contractors frequently lack the necessary training and experience for effective production and handling of UHPC. As illustrated in Figure 1.2, the current project focuses primarily on cast-in-place UHPC applications. This includes its use in bridge construction elements such as connections, joints, and repairs, specifically in batching and joint nosing areas.

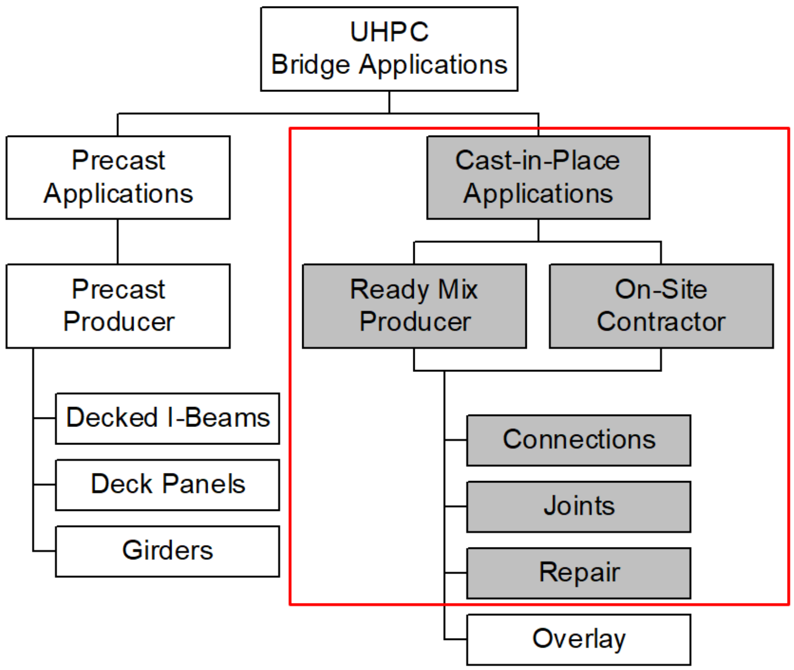


Figure 1.2 Scope of the proposed study

The research team conducted a comprehensive workshop and hands-on activities to provide essential technical training for producers, contractors, and NDOT engineers. This training covered the entire process of mixing, transporting, placing, curing, and testing cast-in-place UHPC, which is vital for achieving optimal flowability, fiber stability, and workability to prevent issues such as cold joints. To guide these processes, the research team developed specific guidelines with criteria to control and maintain UHPC workability under ready-mixed and on-site conditions. A critical aspect of this project was investigating UHPC's shrinkage behavior, focusing on mitigating cracking risks, which included both total and autogenous shrinkage, particularly in shrinkage-reducing and shrinkage-compensating admixtures. Additionally, the research team prepared specialized provisions of CIP UHPC for NDOT to promote broader utilization.

While UHPC promises substantial enhancements in the structural capacity and durability of bridge components, its widespread adoption in Nebraska has been hindered by a notable gap in training and expertise in batching and handling the material. Addressing this, there's an urgent need to develop comprehensive guidelines and training materials for producers and contractors. The proposed work is timely and holds significant potential for immediate implementation by NDOT. The outputs of this project, encompassing detailed guidelines, training materials, and special provisions, will be made accessible to producers and contractors through NDOT, paving the way for future UHPC projects. This study is poised to yield significant benefits, foremost among them being the ability to address the challenges associated with UHPC production and on-site construction. A lack of experience and established best practice guidelines raises concerns among producers and contractors. By providing the necessary knowledge and technical support for UHPC production and construction, this project aims to alleviate these concerns. The anticipated success of this initiative is expected to greatly encourage producers and contractors to embrace this innovative material, particularly in cast-in-place bridge applications, marking a significant advancement in construction methodologies.

1.2 Objectives

The primary goal of this study is to equip NDOT and contractors with essential technical support and comprehensive documentation, enhancing their capability to produce CIP UHPC effectively. To achieve this, the project sets forth several key objectives:

- To provide in-depth technical training for producers, contractors, and NDOT engineers, covering all aspects necessary for batching, mixing, transporting, placing, and testing cast-in-place UHPC;
- To develop thorough guidelines that not only facilitate UHPC production but also focus on controlling and maintaining UHPC workability under on-site conditions; and
- To create specialized provisions that guide the production and ensure the quality control of cast-in-place UHPC.

These concerted efforts are directed toward streamlining UHPC production processes and elevating the quality standards in construction projects.

1.3 Report Organization

This project report is organized into six comprehensive chapters. It begins with an introduction, followed by Chapter 2, which delves into a detailed background on the issue of excess aggregate dust in concrete and provides a summary of the state-of-the-practice for cast-in-place Ultra-High Performance Concrete (UHPC). Chapter 3 showcases the training materials utilized in the hands-on UHPC workshop. The subsequent chapters, Chapters 4 and 5, offer an in-depth analysis and results from the study focusing on the stability of UHPC and its shrinkage characteristics, particularly when using shrinkage-reducing and compensating admixtures. Chapter 6 presents a draft of the special provision for cast-in-place (CIP) UHPC.

Chapter 2 State-of-The-Practice of Cast-in-Place UHPC

2.1 Introduction

Although UHPC remains a relatively novel concept, its successful application in field projects, particularly in bridge deck connections and repairs, has been documented across several states. To deepen our understanding, the research team undertook a comprehensive review of past experiences, current practices, and specifications pertaining to UHPC, emphasizing aspects such as batching, placing, curing, and quality control. Note that due to the focus of this project, the summary is focused on cast-in-place UHPC, and information specified as applicable to precast UHPC elements is not presented here. Insights into the state-of-the-practice of cast-in-place UHPC, derived from this extensive review, are detailed in the subsequent sections.

2.2 Formwork

Table 2.1 summarizes the formwork requirements for UHPC as specified by various agencies, providing a comprehensive overview of the differing guidelines in place.

Table 2.1 Formwork requirements specified by different agencies

	Agency	Requirements
Formwork Material and Preparation	MIDOT	Formworks for UHPC must be watertight, coated to prevent water absorption, and strong enough to resist hydraulic pressure.
	FHWA (Graybeal, 2014); CDOT (2018)	Formwork should have a non-absorbent finish.
	CALTRANS (2017)	Formwork surfaces must be free of dust, debris, and excess water before UHPC placement.
	DDOT (2014)	Formwork should be made with medium-density overlay plywood formwork, which should be pre-wetted before UHPC placement.
	NYSDOT (2023); PennDOT (2021)	Formwork should made with plywood forms coated with a form release agent from the Department's Approved List of Materials.
	IADOT (2022)	Forms should be constructed from transparent plexiglass and follow approved installation drawings.
Formwork Design and Construction	ACI (2018); FHWA (Graybeal and Leonard, 2018)	Forms must be sealed properly to support the full hydrostatic pressure head of UHPC. Enclosed formworks should have an exit for trapped air.
	FHWA (Graybeal and Leonard, 2018)	Deck-level connections require top forms with adequate hold downs, and should be set at least 1/4" (6 mm) above the deck's top for overfilling.
	PCI (2022)	Forms should be grout-tight to prevent leakage of the UHPC after placement and should be constructed to minimize the restraint of early-age volumetric changes of the fresh and setting UHPC. The clear spacing between the faces of the formwork and any internal reinforcing or adjacent formwork should be no less than 1.5 times the fiber length or maximum aggregate size, whichever is greater, to permit adequate flow and consolidation of the UHPC.
Formwork Removal	FDOT (2018)	Formworks can be removed after 24 hours of UHPC placement or based on the manufacturer's recommendations.
	DDOT (2014)	Hand removal of the formwork is required.
Formwork Inspection	FHWA (Graybeal and Leonard, 2018); PennDOT (2021)	Formwork should be periodically inspected for leaks during casting, including the underside of the deck.

2.3 Surface Preparation

The bond between existing structures or precast concrete elements and UHPC plays a pivotal role in guaranteeing a robust connection while preventing water infiltration and the subsequent degradation of both concrete and rebar (Graybeal, 2014). Table 2.2 summarizes the surface preparation requirements for UHPC as outlined by various agencies, detailing the essential guidelines for effective application.

Table 2.2 Surface preparation requirements specified by different agencies

	Agency	Requirements
Surface Preparation of Precast Components	FHWA	Surface of the existing structure or precast components should be pre-wet to a surface-saturated condition, free of debris, and prepared with micro and macro textures like exposed aggregates before UHPC placement.
	DDOT (2014)	Existing structure or precast concrete in contact with UHPC should have an exposed aggregate finish.
	NYSDOT (2023)	Average amplitude of the exposed aggregate surface should be 1/8". Roughened surface of existing concrete should be continuously wetted, with surface water removed right before UHPC placement.
	FDOT (2018)	Average amplitude of the exposed aggregate surface should be between 1/8" to 3/16".
	CDOT (2018)	Average amplitude of the exposed aggregate surface should be within 1/4"±1/8", achievable through the application of a form retarder.
Aesthetic Considerations	NYSDOT (2023)	color of UHPC should match the surrounding concrete in areas visible to traffic

2.4 Mixing Procedure

UHPC's distinctive composition, marked by the absence of coarse aggregate and a notably low water-to-binder ratio (w/b), necessitates using high-shear pan mixers for patching purposes. These mixers improve efficiency with specially designed paddles that scrape materials from the mixer walls, ensuring a more uniform mix (Graybeal, 2014). However, using lower-energy mixers can inadvertently raise the temperature of UHPC, leading to a stiffer mixture (ACI, 2018). Additionally, the diversity in paddle shapes, mixer sizes, and mixing speeds contributes to varying levels of energy input, affecting the final product.

The process of loading, mixing, and the duration of mix time are crucial to achieving consistency and uniformity in UHPC. Research by El-Tawil et al. (2018) highlights how the mixing speed impacts UHPC's performance, with higher speeds enhancing workability and reducing the turnover time—the period needed for the materials to transition from powder to liquid form. Consequently, different mixing procedures might be required in field applications, depending on the rotational speed and size of the mixer's paddles.

The systematic sequence of loading and mixing materials for UHPC is critical due to its significant fine particle content and the substantial energy required for adequate mixing. The standard process generally involves three principal steps: initially blending all powder and aggregate materials for a period ranging from 30 seconds to 10 minutes, then adding water and High-Range Water-Reducing (HRWR) admixtures, and ultimately integrating fibers into the mix. This approach is bolstered by numerous studies, which recommend a total mixing duration of 5 to 12 minutes before adding fibers, as substantiated by research from Yu et al. (2014, 2015), Bonneau et al. (1997), Ambily et al. (2014), Meng et al. (2016, 2017), Wu et al. (2016), Yang et al. (2009), and Shi et al. (2015). Specific methodologies vary: some researchers, like Wille et al. (2011), Alkaysi (2015), Naaman et al. (2012), Graybeal (2013), and Berry et al. (2017), suggest first mixing dry silica fume and aggregate for 5 minutes, followed sequentially by cement and Supplementary Cementitious Materials (SCMs), water and HRWR, and finally fibers. Alternative approaches include the proposal by De Larrard and Sedran (1994) to mix powders with liquid to create a homogenous slurry before adding sand. El-Tawil et al. (2018) proposed another technique that involves dividing sand into two parts: mixing the first part with powder materials, then adding liquid, followed by the second part of sand, and eventually the fibers.

Table 2.3 offers a detailed summary of the mixing requirements for UHPC as specified by various agencies, outlining essential guidelines for its practical application and ensuring optimal results.

Table 2.3 Mixing requirements specified by different agencies

	Agency	Requirements/Recommendations
Considerations for Mixing Efficiency and Temperature Management	ACI (2018)	Mixing usually continues until UHPC transitions from powder to fluid mixture, depending on mixer energy.
	ACI (2018); FDOT (2018); CDOT (2018)	To address the issue of a stiffer mixture due to extended mixing the UHPC's temperature can be increased, replacing half or all of the water with ice or cooling constituent materials before mixing is recommended.
	FDOT (2018)	UHPC's temperature should be lower than 85°F during batching.
	CDOT (2018)	UHPC's mixing temperature should be between 55-90°F during batching.
	PCI (2022)	Mixer may only be able to handle one-half to two-thirds of its nominal capacity). Trial batching may be the best process for determining the optimal batch size for a mixer. Adding fibers through gratings with openings equal to one-half to two times the length of the fiber or using purpose-built fiber-dispensing equipment that breaks up clumps and gradually adds the fibers can be beneficial. Workers should use appropriate personal protective equipment when distributing fibers manually.

2.5 Placing Methods

Effective placement methods for UHPC are pivotal to guarantee structural integrity, peak performance, and durability in construction projects. UHPC's distinct properties, including high flowability, self-consolidating nature, and significant viscosity, necessitate tailored placement techniques. Typically, UHPC mixes are deposited in formwork or molds in a single lift, eschewing the need for consolidation (Meng and Khayat 2016). Due to its high viscosity, the flow distance during placement is often restricted. Graybeal and Leonard (2018) specify that temperature and flow during and after mixing should be within project specifications. Table 2.4 provides an exhaustive summary of these UHPC placement requirements and practices as specified by different agencies, encapsulating critical guidelines to ensure its practical application and optimal outcomes.

Table 2.4 Placing requirements specified by different agencies

	Agency	Requirements
Specific Procedures and Techniques for UHPC Placement	FHWA (Graybeal, 2014)	Flow distance should be limited to 24 inches during placement. Material is suggested to be poured from one end of the joint until the full depth is cast, with no vibration necessary.
	PennDOT (2021)	Use of vibrating screeds is allowed under certain conditions.
	CDOT (2018)	Material should not be traveling more than 15 feet during placement.
	FHWA, Graybeal and Leonard, 2018; PennDOT, 2021	For deck-level connections, top forms should be installed and tapped with a hammer to check fullness, and chimneys should be added at high points.
	(ACI, 2018; IADOT, 2022).	The placement of UHPC should be continuous to avoid cold joints, with well-distributed fibers.
	PCI (2022)	Continuously placing the UHPC from a single location and using the UHPC's flow properties to distribute the material outward into the form, or by depositing the UHPC behind the leading edge of the flow so that it integrates with the flowing material.
Measurement and Validation of Flowability During Placement	NYSDOT (2023) and CDOT (2018)	Flow should be measured using a mini-slump cone after each batch of UHPC, with a range of 7 to 10 inches.
	IADOT (2022)	Flow should be determined per ASTM C 1856 for each batch, with a diameter between 8 and 10 inches.
Other Considerations and Practices	(FHWA, Graybeal, 2014)	Forms containing UHPC should be immediately closed after placement to minimize surface dehydration. UHPC in chimneys should be periodically checked for adequate filling.

2.6 Curing Methods

Moisture and temperature play a crucial role in properly curing UHPC, much like in conventional concrete. In laboratory settings, curing typically involves immersing UHPC specimens in lime-saturated water maintained at 73°F (23°C) until testing, as El-Tawilet et al. (2018) noted. Conversely, various researchers employ different curing processes over a period of up to 28 days (Meng and Khayat 2016; Bonneau et al. 1997; Ozyildirim 2011; Wan et al. 2016). For precast UHPC elements, heat treatment is known to boost strength, with common temperatures ranging from 176-194°F (80-90°C), and PCI recommends specific protocols for controlled heating and cooling rates to avert surface crazing (Choi et al. 2016; PCI 1999). Reports by Meng and Khayat (2016) and others detail heat curing at 194°F (90°C) for 24 hours following an initial room temperature cure with wet burlap and plastic sheets. Standard curing methods such as covering with plastic sheets and surface wetting post-form removal are typically adopted in cast-in-place applications, as heat curing is often impractical in field conditions (Wille et al. 2011). Table 2.5 presents a comprehensive summary of the curing requirements and practices for cast-in-place UHPC as specified by various agencies, providing essential guidelines for effective application and achieving optimal results.

Table 2.5 Curing requirements specified by different agencies

	Agency	Requirements
General Curing Requirements and Practices	MIDOT	Covering the top surface with insulating blankets.
	IADOT (2022)	A minimum curing temperature of 60°F.
	FHWA (Graybeal and Leonard, 2018)	Immediate covering after casting to prevent water loss and suggests leak testing for deck-level connections.
	PCI (2022)	After finishing, all exposed surfaces should be immediately covered with plastic or wet burlap to prevent dehydration. Treatment with a curing compound may also be permitted, but the curing compound should be applied to the surface shortly after finishing is completed.
Considerations for Concrete Strength and Construction Operations	CDOT (2018)	A minimum of 10 ksi compressive strength before starting to disturb UHPC, with any approved curing method applied immediately after casting.
	IADOT (2022)	Different construction operations such as abutment backfilling or opening bridges to equipment and traffic based on reaching specific strength thresholds (6 ksi for abutment UHPC closure pours, 14 ksi for all joint applications).

2.7 Surface Grinding

The exceptional strength of UHPC often poses challenges in achieving effective grinding and can result in considerable wear of the grinding plate. However, a specific maximum compressive strength for grinding UHPC has not been established. Table 2.6 provides a comprehensive summary of the requirements for UHPC grinding post-construction as outlined by various agencies.

Table 2.6 Grinding requirements specified by different agencies

	Agency	Requirements
Strength Requirements for UHPC Grinding	FHWA (Graybeal and Leonard, 2018)	Grinding equipment should not be loaded until UHPC reaches a minimum compressive strength of 14 ksi to prevent damage to the bond with precast elements and fiber tearing.
	IADOT (2022) and CDOT (2018)	A minimum compressive strength of 10 ksi should be reached before surface grinding.
	PennDOT (2021)	A minimum compressive strength of 14.5 ksi should be reached before surface grinding.
Grinding Process	FHWA (Graybeal and Leonard, 2018)	If fiber pullout is observed during grinding, the operation should be suspended and not resumed until engineer approval.

2.8 Mockup

The construction of mockup sections is highly recommended to accommodate the unique workability behavior of Ultra-High Performance Concrete (UHPC), acting as a valuable resource for self-learning and ensuring adequate preparation for field casting (Graybeal and Leonard 2018). Typically, the insights acquired from these mockup sections inform necessary adjustments in various schematics, including quality assurance/quality control (QA/QC), installation/assembly, and formwork, before actual field casting. Table 2.7 outlines a detailed summary of the UHPC mockup requirements prior to construction, as specified by various agencies.

Table 2.7 Mockup requirements specified by different agencies

	Agency	Requirements
Requirements for Mockup Construction and Inspection	IADOT (2022); FDOT (2018)	Mockup should be cut transversely at locations determined by the engineer for visual inspection of the joint interface and material bond.
	FDOT (2018)	Mockup should be cast at least 30 days prior to UHPC placement and should replicate form pressure, roughened interface between precast concrete panel and UHPC, placement operations, and UHPC dimensions.
	CDOT (2018)	Mockup should be placed at least 7 days before UHPC installation.

2.9 Leak Testing for Deck-Level Connections

Graybeal and Leonard (2018) emphasize the necessity of conducting leak testing for deck-level connections, stipulating that any detected leaks must be promptly sealed should the connection not pass the leak test.

2.10 Summary

This chapter provides a comprehensive overview of the critical aspects involved in the application of UHPC, including formwork requirements, surface preparation, mixing procedures, placing methods, curing methods, grinding requirements, and mockup construction. Each section delves into specific guidelines and practices as specified by various agencies, emphasizing the importance of adhering to these standards to ensure the optimal performance, durability, and structural integrity of UHPC in construction projects.

Chapter 3 CIP UHPC Training Materials

3.1 Introduction

Drawing from a comprehensive review of the state-of-the-practice of CIP UHPC across various agencies and the research team's previous experiences, the investigators developed training materials tailored for contractors and NDOT engineers. These resources will include PowerPoint presentations and videos. A full-day workshop, complete with hands-on activities, has been organized. This workshop features a morning session of lectures on proportioning, batching, testing, and placing both non-proprietary and proprietary UHPC mixes, including a Q&A segment. The afternoon session offers practical experience in batching, testing, and placing UHPC and a small mockup section to simulate connection and repair section construction.

3.2 Hands-on Workshop Agenda

The hands-on Ultra-High-Performance Concrete (UHPC) workshop was hosted on March 16, 2022, in Room 158 of Peter Kiewit Institute in Omaha, with the agenda below:

Morning Session (8:30-11:30)

8:30 – 8:40 Opening Remarks – NDOT Representative

8:40 – 9:15 What is UHPC – Dr. Jiong Hu

9:15 – 9:45 Production of UHPC – Dr. George Morcous

9:45 – 10:00 Break

10:00 – 10:30 QA/QC of UHPC – Dr. Jiong Hu

10:30 – 11:00 Case Studies – Dr. George Morcous

11:00 – 11:30 Discussions and Q&A – Attendees

11:30 – 12:30 Lunch

Afternoon Session (12:30-3:30)

12:30 – 1:30 UHPC batching and casting demonstration #1

1:30 – 2:00 UHPC testing demonstration #1

2:00 – 3:00 UHPC batching and casting demonstration #2

3:00 – 3:30 UHPC testing demonstration #2

3.3 Training Materials

Comprehensive training materials and detailed handouts covering various topics are available in the Appendix for reference and further use.

Chapter 4 Evaluation of Fiber Stability in Fresh and Hardened UHPC

4.1 Introduction

Ultra-high-performance concrete (UHPC) is a new concrete class with mechanical and durability properties that far exceed those of conventional concrete. The use of UHPC will result in significant improvements in the structural capacity and durability of structural components. Due to its superior characteristics, UHPC has drawn substantial interest in the bridge community at both the federal and state levels (Graybeal 2014). Besides the bridge deck connections applications in multiple states, the Federal Highway Administration (FHWA) Every Day Counts (EDC-6) program "UHPC for Bridge Preservation and Repair" emphasizes the use of UHPC for other bridge applications due to its excellent mechanical and durability properties. Due to the large amount of fine powders and the very low water-to-cement ratio in UHPC, the workability of UHPC is very different from conventional concrete (Sbia et al. 2017). While it is generally expected that UHPC is self-consolidating, achieving the desired workability while maintaining stability is often challenging. As shown in Figure 4.1, severe fiber segregation could lead to aesthetics, structural, or durability concerns.

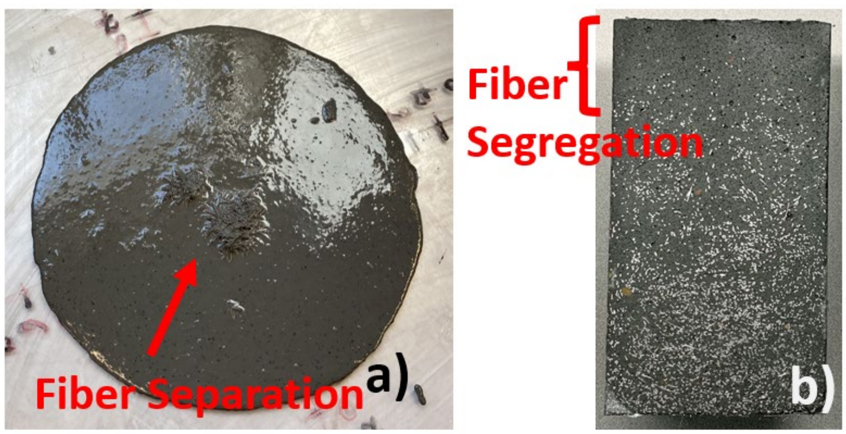


Figure 4.1 Fiber stability in UHPC. a) Fiber separation observed during flow test; b) Fiber segregation observed in concrete cylinders

While the workability of UHPC is often reported in different studies, the commonly used flow (spread) test, as per ASTM C1856, is more of a quality control tool, yet insufficient to identify issues during construction. Similar to when self-consolidation concrete (SCC) was first developed, a set of tests to evaluate the different aspects of UHPC workability is urgently needed (Russell 2008). There is also a need to establish onsite tests that can be easily performed and used in the field to identify potential issues before UHPC placement. One example of issues related to UHPC workability is the lack of viscosity for fiber stability, which is usually measured in a hardened state (Ruan and Poursaee 2019; Wang et al. 2017). A recent PCI study attempted to develop a modified static segregation test for fiber stability test (similar to ASTM C1610 for SCC). However, the method requires at least 30 minutes to complete, which is too long for QA/QC (PCI TR-9-22). A previous study from the authors shows that new tests, such as the visual stability index (VSI) and flow time, can be used to determine potential fiber segregation issues. However, the test methods are relatively subjective and might not be sensitive enough to identify issues in different placement conditions (Mendonca and Hu 2021).

This chapter presents a set of tests recently developed by the research team to identify and evaluate fiber stability in both fresh and hardened UHPC mixtures. In addition, the study assesses different UHPC fiber stability test methods to ensure proper UHPC workability before casting. With the development of onsite QA/QC methods and assurance of appropriate workability before UHPC casting, the success of this project will significantly encourage producers and contractors to adopt this innovative material in different applications.

4.2 Test Methods and Mixture Design

4.2.1 Materials and Mixture Design

In this study, Type I/II Portland cement, fine silica sand with a maximum aggregate size of No. 8 (2.36 mm), slag, silica fume, and micro straight steel fibers, 0.5 in. (13.0 mm) in length and 0.2 mm in diameter, were used. A polycarboxylate-based high-range water reducer (HRWR) and workability retaining admixture (WRT) were also used to achieve the desired workability.

Since the main focus of this study was to assess fiber stability in UHPC, three slightly different mixture designs, as shown in Table 1.1, were used, with Mix 1 as the stable mixture, and Mix 2 and 3 as the semi-stable and very unstable mixtures, respectively. While the solid contents were kept constant within the three mixtures, water, and HRWR contents were increased in Mix 2 and 3 to achieve moderate and severe fiber segregation, respectively (Li et al., 2017). The three mixtures kept Fiber content constant at 2% (by volume).

Table 4.1 Design of mixtures with different fiber stability

Mixture ID	**Unit**	**Cement**	**Slag**	**Silica fume**	**Sand**	**Fiber**	**Water**	**HRWR**	**WRT**
Mix 1	pcy	1206	586	161	1570	264	307	57.6	20.7
Mix 2	pcy	1206	586	161	1567	264	315	63.0	20.7
Mix 3	pcy	1206	586	161	1567	264	328	63.0	20.7

4.2.2 Mixing Procedure

An IMER MIX 120 pan mixer was used to prepare all mixtures. UHPC was mixed in three major steps to achieve the desired consistency: mixing dry ingredients, adding water and admixtures, and introducing steel fibers. The first step was started by loading air-dried sand and silica fume into the mixer and mixing it for five minutes, followed by adding cement and slag and mixing it for another five minutes. Before introducing water into the mixture (which starts the second step), 80% of the total HRWR and total WRT admixture were premixed with 80% of the total water, and then mixed for seven minutes in the mixer. The remaining water and HRWR admixture were premixed again and loaded into the mixer when a paste-like consistency of the mixture was observed. Once a vicious and uniform mixture was achieved, the fibers were loaded for one minute and mixed for another three minutes in the mixer before they were discharged.

4.2.3 Test Methods

Due to the similar self-consolidating nature of UHPC and self-consolidation concrete (SCC), some test methods for the workability of SCC can be modified and adapted for UHPC. As ASTM 1856 is insufficient to reflect the different aspects of the workability of UHPC, the researchers have developed various tests to evaluate UHPC workability, particularly fiber stability (see Table 2.1). Besides static and dynamic flow (ASTM C1856 and C1437), it can be used to access characteristics related to the flowability and stability of UHPC. Additional tests, such as the Visual Stability Index (VSI), mini-V-funnel, penetration, and falling ball tests, could be used to assess the fiber stability of UHPC.

Table 4.2 Comparison of SCC and UHPC test methods included in the current study

State	SCC Test Method (Standards/References)	UHPC Test Method (Standards/References)
Fresh	Slump flow (ASTM C1611)	Flow Spread (ASTM C1856/C1437)
	Visual Stability Index (VSI) (AASHTO T347)	Visual Stability Index (Mendonca and Hu, 2021)
	V-Funnel (Elinwa et al. 2008)	Mini V-Funnel
	T50 (AASHTO T347)	Flow Time
	Falling Ball (Douglas et al. 2015)	Falling Ball
Hardened	Hardened Visual Stability Index (HVSI) (AASHTO R81)	HVSI (Mendonca and Hu, 2021)
	Electric Resistivity (AASHTO T358)	Electric Resistivity

To justify the efficiency of the workability measurement on fiber stability, the research evaluates the fiber stability of UHPC in hardened states. In addition to the Hardened Visual Stability Index (HVSI) (Mendonca and Hu, 2021), a surface electric resistivity meter could be an effective tool for in-situ evaluation of fiber distribution in a quantitative manner after demold as its readings are highly dependent on fiber content. As steel fiber is highly conductive, locations in the component with a high or low amount of fibers (due to fiber segregation) show significantly different electric resistivity. The abovementioned tests were performed to justify the developed fresh UHPC test for fiber stability to predict fiber segregation in the lab- and site-casted UHPC.

4.2.3.1 Flow and Flow Time Test

The flow table test for UHPC was conducted according to ASTM C1856. The diameter of the flow at two minutes and the time when it reached 10 in. (254 mm) were measured and reported as Flow and T10in, respectively. The flow and flow time test set up is illustrated in Figure 4.2.

Figure 4.2 Flow and flow time test setup (left) and example of tests (right)

The stability of fibers was evaluated using the Visual Fiber Index (VSI) as per Mendonca and Hu (2021) based on the degree of fiber separation observed (see Figure 4.3 as an example). VSI values of 0, 1, 2, 3, and 4 indicated highly stable, stable, unstable, highly unstable, and extremely unstable mixtures, respectively.

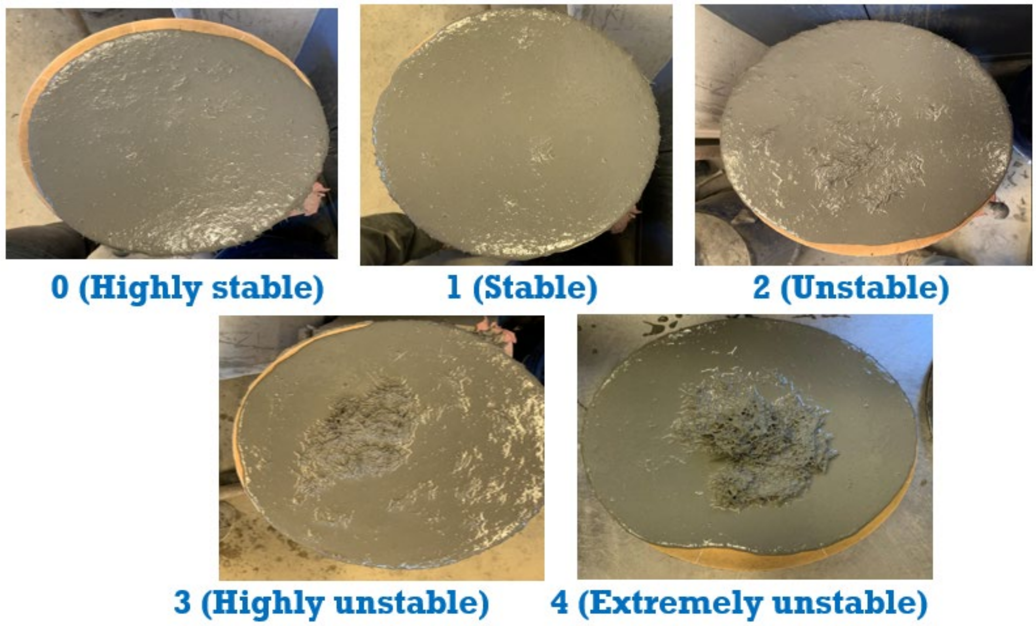


Figure 4.3 Examples of UHPC mixtures with different VSI

4.2.3.2 Mini V-funnel test

A V-shaped funnel (mini-V-funnel) with approximately 0.09 ft^3 (2.5 liters) internal volume and 0.75 in. (19 mm) square opening, as shown in Figure 4.4, was used to assess the flowability and fiber stability in UHPC mixtures. Upon the completion of mixing, the UHPC mixture was loaded into the mini-V-funnel continuously without any temping or compaction, while the opening at the bottom of the v-funnel was blocked by hand. After the mini-V funnel was filled, the material was allowed to flow out freely under gravity. The time it took the material to wholly discharge (when the light was observed from the top of the opening) was recorded as T_{V0}. Visual fiber stability was reported based on whether fibers were stuck inside the neck of the funnel and reported as VFS_{V0}. The mini-V-funnel test was also conducted in the same manner after allowing for settling for two minutes and the time for discharge and visual fiber stability were as T_{V2} and VFS_{V2}, respectively. It is evident that after two minutes of settling, the flow time could increase significantly with a higher inclination to fiber segregation if the mixture is unstable. VFS was identified as “no” or “yes” in the case of a mini-V-funnel test, the latter indicating the fiber was stuck.

Figure 4.4 Mini V-funnel test set up (from left to right: test setup dimension; blocking of mini-V-funnel opening for mixture to settle; and UHPC mixture flowing out from the opening)

4.2.3.3 Falling ball test

As shown in Figure 4.5, the falling ball test used a brass ball with a diameter of 1 in. (24.4 mm) and a mass of 0.195 lb (88.4 grams). Upon the completion of mixing, the UHPC sample was loaded into a 4" × 8" (101.6 mm × 203 mm) cylinder without any tamping or compaction. The brass ball was placed at the top surface of the concrete and then allowed to sink gradually into the UHPC under gravity. The time until no further downward movement and immersion distance were recorded as TFB and LFB, respectively. An LFB less than 8 in. (203 mm) means the brass ball cannot drop to the bottom of the cylinder, which implies fiber segregation. Upon the discharge of fresh UHPC sample after the test, visual observation of fiber accumulation at the bottom of the cylinder was reported as VFSFB, with "yes" indicating fiber segregation.

Figure 4.5 Falling-ball test set up (left: before ball settling; right: after ball settling)

4.2.3.4 Penetration test

The penetration test equipment consists of a plastic rod, a penetration head (with a combined mass of 1.8 oz or 30.8 grams), and a support frame. The penetration head is 3 in. (76.2 mm) in diameter and 2 in. (50.8 mm) in height, with the bottom portion hollow and the top part with small holes allowing air to pass through during its downward movement inside the concrete. With a support frame, the penetration head with the plastic rod was aligned in the center of a container with a minimum of 8 in. (203 mm) in diameter. A fresh UHPC sample was loaded inside the container without any consolidation during the test. The penetration head was then lowered onto the surface of the UHPC and released to allow it to penetrate freely into the fresh UHPC. The penetration depth was recorded after 30 seconds as P.

Figure 4.6 Penetration test setup and examples of results (left to right: test setup; mixture with medium penetration: and mixture with high penetration)

4.2.3.5 Hardened Visual Stability Index Test

Hardened Visual Stability Index (HVSI), as developed by Mendonca and Hu (2021), was used to quantitatively assess fiber stability in hardened UHPC based on the thickness of fiber-free or low-fiber content layer observed at the top of casted 3" × 6" (76.2 mm × 152.4 mm) UHPC cylinder cross-sections. Similar to VSI, HVSI values of 0, 1, 2, 3, and 4 indicated highly stable, stable, unstable, highly unstable, and extremely unstable mixture, respectively.

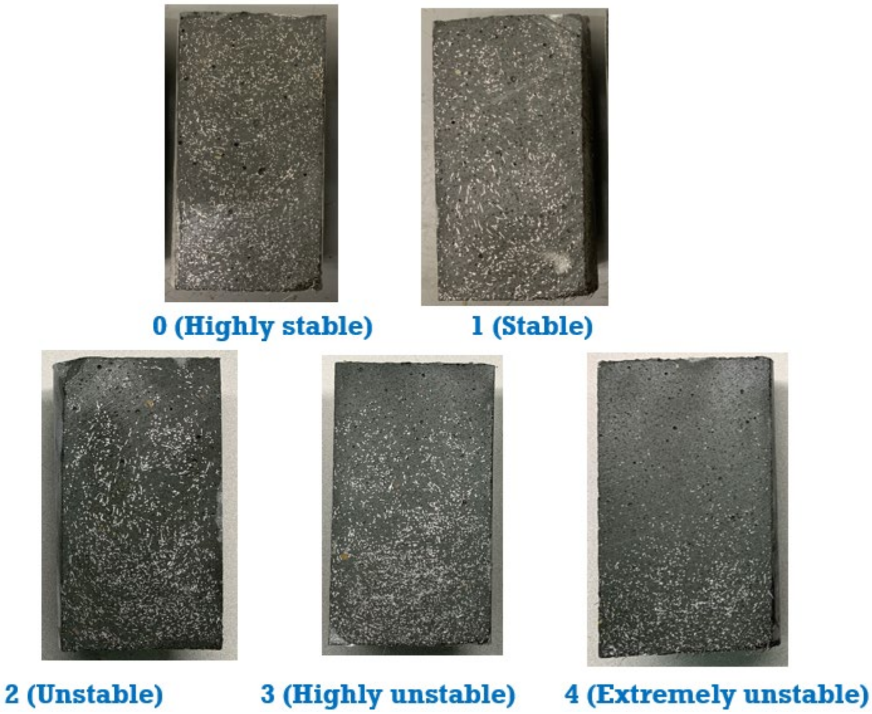


Figure 4.7 Examples of UHPC with different HVSI

4.2.3.6 Wall Stability test

A wall stability test was developed to quantitatively assess fiber stability in hardened UHPC and simulate real-world conditions. Upon completion of mixing, a UHPC sample was loaded into a form 24 in. (609 mm) in height, 12 in. (304.8 mm) in width, and 1.5 in. in depth without any forms of consolidation, as shown in Figure 4.8. After 24 hours, the specimen (the wall) was de-molded and sawed 1 in. (25.4 mm) from the side to observe fiber segregation. Additionally, a surface resistivity test as per AASHTO R81 was conducted every 3 in. (76.2 mm) vertically, starting 3 in. (76.2 mm) from the bottom of the casted wall to determine ununiform fiber distribution along the wall based on inconsistent resistivity values.

Figure 4.8 Segregation test specimen preparation and process (left: specimen casting; right: measure potential fiber segregation with resistivity meter)

4.2.3.7 Compressive strength test

The developed UHPC mixes should also meet performance requirements in the hardened state. A compressive strength test was conducted for each UHPC mixture following ASTM C1856. After a curing period of 7 days and 28 days in a water tank with lime, the 3 × 6 in. concrete cylinders were grinded on both ends and kept in an oven for 24 hours in a standardized condition (110±5°C). Three specimens were tested in each case, and an average value was reported.

4.3 Results

Results from the fresh and hardened UHPC fiber stability test evaluation are summarized below in Table 2.2. As shown in the table, while results from different tests generally agreed with each other, the sensitivities of different tests in identifying fiber segregation are different.

Table 4.3 Results from fresh and hardened UHPC fiber stability tests

Tests	**Flow**			**Mini-V-Funnel**				**Falling-ball**			**Penetration**	**HVSI**
Mixture ID	Flow	T_{10in}	VSI	T_{V0}	VF S_{V0}	T_{V2}	VF S_{V2}	T_{FB}	L_{FB}	VF S_{FB}	P	HVSI
Mix 1	10.0" (254mm)	37"	0	145"	No	187"	No	35"	8.0" 203mm)	No	0.875" (22.2mm)	0
Mix 2	11.0" (279mm)	15"	1	84"	No	135"	No	15"	7.5" (191mm)	Yes	1.50" (38.1mm)	2
Mix 3	11.5" (292mm)	10"	2	51"	No	60"*	Yes	7"	7.5" 191mm)	Yes	1.75" (44.5mm)	3

* Flow stopped due to fiber clogging

As expected, for the stable mix (Mix 1), a VSI value of 0 was obtained, which means no evidence of fiber separation or agglomeration can be observed. On the other hand, Mix 3 and 2 both showed fiber segregation. Mix 3 showed severe bleeding and fiber separation with the highest flow value of 11.5 inches (292 mm) and VSI value of 2. In addition, results confirmed that, as suggested by Mendonca and Hu (2021), UHPC mixtures with T_{10in} less than 20 seconds (flow reach 10 inches (254 mm) under 20 seconds) could have a high potential for fiber segregation.

Results from the mini-V-funnel test showed that neither Mix 1 nor Mix 2 exhibited fiber blockage. However, the apparent difference in flow time between those two mixes implies Mix 2 has a higher flowability and much lower viscosity, which could lead to fiber segregation—in the case of Mix 3, a 2-minute settling time caused flow stoppage at 60 seconds due to fibers stuck in the neck, which clearly demonstrates fiber instability.

With the falling ball test, it is evident from the full-depth immersion that Mix 1 presented a stable behavior without any fiber accumulation at the bottom of the container. On the other hand, an L_{FB} at 7.5 in. (191 mm) was reported in Mix 2 and Mix 3, which indicated a 0.5-in. (13 mm) fiber piling at the bottom of the container. Although the difference between Mix 2 and Mix 3 cannot be distinguished by L_{FB}, the T_{FB} of Mix 2 is twice that of Mix 3, which indicates a lower viscosity and a high chance of fiber segregation of Mix 3. The results showed that the falling ball test is not only an easily performed test but also could be a good indicator of fiber instability in UHPC mixtures based on fiber accumulation at the bottom of the cylinder and the sink time of the brass ball.

Results from the penetration test showed that even though the depth of penetration increased with increasing fiber instability in the mixtures, the obtained values cannot provide comprehensive information regarding the fiber segregation resistance in UHPC. While the stable mix (Mix 1) had a penetration depth of 0.875 inches, the difference in penetration depth results between Mix 2 (1.50" or 38 mm) and Mix 3 (1.75" or 44 mm) is not significant despite the considerable difference in terms of fiber stability by other test methods, which can also demonstrate the inadequacy of this test. The weight of the penetration head with the plastic rod might be too heavy for the UHPC without coarse aggregates and was not sensitive enough to access fiber stability in UHPC.

As expected, HVSI results showed that Mix 1 provided uniform fiber distribution without any sign of a fiber-free zone. In contrast, Mix 2 and Mix 3, with HVSI values of 2 and 3, established a low fiber content layer with 1.0 inches (25 mm) and 2.5 inches (64 mm) of thickness, respectively.

As shown in Figure 4.9a, while the vertical cross-sections of the wall prepared with Mix 1 showed a uniform fiber distribution, clear fiber segregations were observed in the walls cast with Mixes 2 and 3. As expected, the measured surface resistivity shown in below in the specimen prepared with Mix 1 was fairly consistent throughout the different heights. On the other hand, apparent changes in the measured resistivity along the specimens were observed in both Mix 2 and Mix 3, with a lower surface resistivity (compared to the stable mix) and a significant increase when reaching the low-fiber zone. As the high fiber content zones or fiber agglomeration areas led to higher conductivity or lower surface resistivity, fiber segregation led to lower resistivity at the bottom, while the top portions of the specimens exhibited higher surface resistivity. Compared to different fresh stability tests, the consistent results demonstrated that the surface resistivity test could effectively identify fiber instability in different UHPC mixtures in cast-in-place or precast concrete elements.

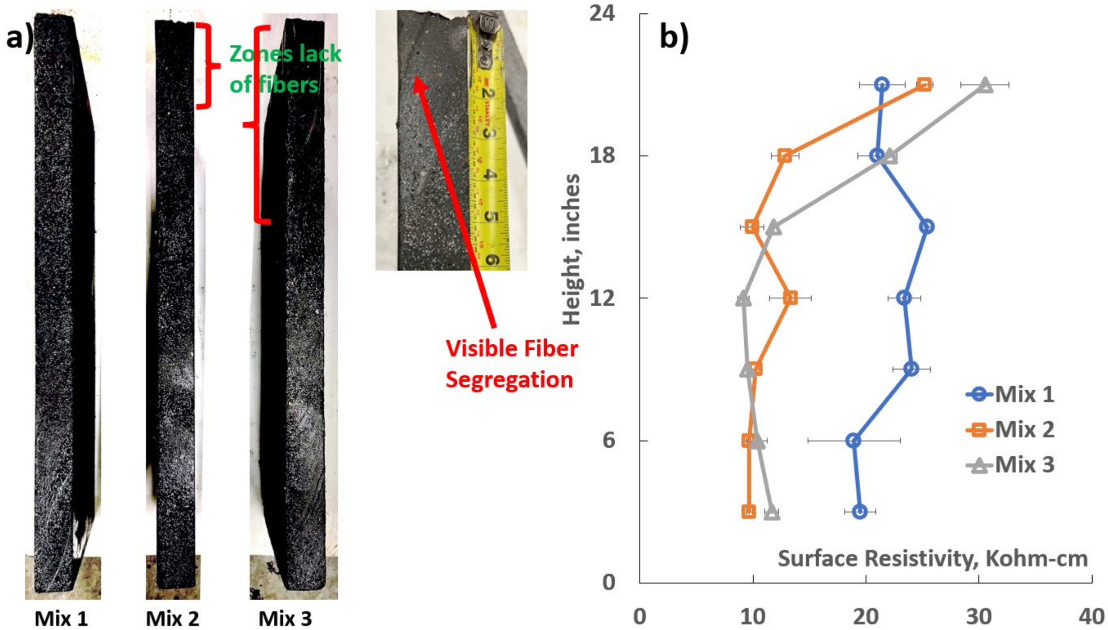


Figure 4.9 Results from wall-stability test. a) Visible fiber segregation; b) Change of measured surface resistivity along different heights

<u>4.4 Summary</u>

This chapter presented a preliminary experimental study that was carried out to evaluate if the different fresh and hardened concrete tests can effectively identify fiber segregation before or after the casting of UHPC. Key findings include the observation that excessive water or HRWR can lead to fiber segregation, noticeable in both fresh and hardened states. Although VSI and HVSI methods offer subjective means to assess fiber stability, they may lack sufficient sensitivity. Newly developed mini-V-funnel and falling ball tests provide objective measures for identifying fiber stability issues in fresh UHPC. Flow time, indicating UHPC viscosity, emerged as a potential indicator of fiber stability, but requires further data for QA/QC acceptance range establishment. In its current form, surface resistivity testing may not be sensitive enough for UHPC fiber stability assessment but shows potential for in-situ evaluation of fiber distribution in hardened UHPC. The study acknowledges the need for more extensive research to correlate these promising tests with UHPC workability across a broader range of mixtures and suggests incorporating various test methods in actual construction projects to develop a comprehensive database for practitioners.

Chapter 5 Evaluation of Shrinkage of UHPC with the Incorporation of Shrinkage-Reducing and Shrinkage-Compensating Admixtures

5.1 Introduction

Understanding the shrinkage behavior of UHPC is of paramount importance in its application, particularly due to its high binder content and low water-to-binder ratio. These unique characteristics of UHPC, while contributing to its superior strength and durability, also predispose it to higher autogenous shrinkage, potentially leading to microcracking. Such cracking not only compromises the structural integrity of UHPC but also affects its long-term performance and sustainability. Therefore, a comprehensive examination of UHPC shrinkage is crucial for optimizing its formulation and ensuring its effective use in demanding construction scenarios.

This chapter encompasses not only an extensive literature review, summarizing prior studies on UHPC shrinkage and various strategies to mitigate it but also details a comprehensive experimental analysis undertaken by the research team. This analysis focused on investigating the impact of both shrinkage-reducing and shrinkage-compensating admixtures on the total and autogenous shrinkage characteristics of UHPC. Detailed experimental programs and findings are presented below, offering insightful perspectives into the behavior of UHPC under these specific conditions.

5.2 Background and Previous Studies Related to UHPC Shrinkage

5.2.1 Background of Shrinkage of UHPC

While traditional studies on shrinkage in conventional concrete have predominantly focused on drying shrinkage, recent research indicates that for mixtures with low water-to-binder ratios like UHPC, drying shrinkage tends to be minimal. However, it is observed that UHPC exhibits significantly high autogenous shrinkage (Koh et al. 2011). This is attributed to its very low water-to-binder ratio and high cement content, coupled with the addition of silica fume. The small particle size of materials such as silica fume contributes to a finer pore structure, leading to early-age self-desiccation and pronounced autogenous shrinkage. This phenomenon is critical as it can initiate microcracking, thereby potentially diminishing the durability of UHPC.

In their 2018 study, the Federal Highway Administration (FHWA) analyzed the shrinkage properties of five distinct UHPC mixtures, encompassing both proprietary and one non-proprietary. The study highlighted that the total and autogenous shrinkage strains varied significantly due to considerable variations in mixture designs, which included differing ratios of cementitious materials and aggregates, types of cementitious materials used, and water content. The observed total shrinkage ranged from 300 με to 1283 με on the 180th day, while autogenous shrinkage fluctuated between 202 and 872 με. Complementing this, Mohebbi et al.'s 2022 study on three UHPC mixtures reported total shrinkage strains ranging from 518 με to 1283 με, with autogenous shrinkage figures between 270 με and 584 με on the 180th day. Intriguingly, the results from the FHWA study indicated that mixtures with higher water content exhibited the most significant shrinkage.

To mitigate the challenges posed by the high shrinkage characteristic of UHPC, various Departments of Transportation (DOTs) have established criteria stipulating the maximum allowable shrinkage for UHPC. The Colorado Department of Transportation (CDOT) in 2018 specified that the long-term shrinkage of UHPC must not exceed 800 με. This benchmark aligns with similar standards set by other state DOTs, including the New York Department of Transportation (NYDOT) in 2023, the Iowa Department of Transportation (IADOT) in 2022, and the Pennsylvania Department of Transportation (PennDOT) in 2018, all of which mandate that UHPC's long-term shrinkage should remain below 766 με.

5.2.2 Approaches to reduce UHPC shrinkage

Recent research efforts have been dedicated to unraveling the mechanisms governing autogenous shrinkage in UHPC. Numerous strategies for mitigating UHPC shrinkage have been identified and reported. The most prevalent methods include the utilization of shrinkage-reducing admixtures (SRAs) and shrinkage-compensating admixtures (SCAs) or expansion agents (EAs). Additionally, integrating internal curing agents such as lightweight aggregates or water-absorbing materials like superabsorbent polymers, and rice husk ash has proven effective. Other notable approaches encompass heat curing and the incorporation of microfibers to enhance UHPC's performance against shrinkage.

In their 2018 research, Xie et al. established that an increase in the content of SRAs significantly reduces both autogenous and total shrinkage in UHPC. This reduction is attributed to the lowered surface tension in the capillary pores. In their findings, a reference UHPC mixture devoid of SRA exhibited an autogenous shrinkage of approximately 480 με at 30 days, escalating to 620 με by the 180th day. Conversely, mixtures enhanced with 0.8%, 1.6%, and 2.4% SRA displayed markedly lower autogenous shrinkages of 380, 230, and 185 με at 30 days, further reducing to 400, 280, and 195 με respectively by the 180th day. Similarly, the total shrinkage of the reference mixture was recorded as 530 με at 30 days, rising to 780 με at 180 days. In contrast, UHPC mixtures containing SRA showed significantly lower total shrinkages of 440, 375, and 210 με at 30 days, which further reduced to 530, 400, and 230 με, respectively, at 180 days. Consistent findings across various studies underscore the effectiveness of shrinkage-reducing admixtures (SRAs) in lowering UHPC shrinkage from an early stage. Anshuang et al. (2017) reported that the seven-day autogenous shrinkage strains were notably reduced in mixtures with SRA—a control mixture exhibited 1080 με, while mixtures with 0.5%, 1.0%, and

2.0% SRA recorded shrinkage strains of 718, 649, and 602 με, respectively. Complementing these findings, Yoo et al. (2015) observed that the 30-day autogenous shrinkage of a reference UHPC mixture was 760 με, in contrast to 645 με and 544 με for mixtures with 1% and 2% SRA, respectively. Further supporting these results, Liu et al. (2022) documented that at three days, UHPC's autogenous shrinkage decreased by 15% with the use of SRA, indicated by a shrinkage of 305 με for a reference mixture. Between 3 to 180 days, the shrinkage strains for the reference mixture and the mixture with SRA were 325 με and 230 με at 60 days, respectively, after which the measurements started to stabilize.

Research on the application of SCA and EA in UHPC is relatively scarce, primarily due to the prevailing belief that these additives are less effective in UHPC than in conventional concrete. Shen et al. (2020) conducted a study to evaluate the impact of EAs on UHPC's autogenous shrinkage using a non-contact deformation tester. Their findings indicated that the seven-day autogenous shrinkage of a reference UHPC mixture, which reached 1700 με, was significantly reduced by 59% with the incorporation of 15% EA. This reduction was primarily attributed to the increase in CSA-CaO EA content, with the most notable shrinkage reduction occurring within the initial 48 hours, a period marked by ettringite formation. However, as ettringite formation takes about five to seven days to develop its expansive effect fully, the CSA-CaO EA only partially compensated for autogenous shrinkage during the first 24 hours, followed by a gradual reduction over the subsequent 24 hours. Complementing these findings, a study by Li et al. (2021) demonstrated the effectiveness of MgO-based EA in mitigating autogenous shrinkage in UHPC. The addition of 3%, 6%, and 9% EA resulted in reductions of 44.5%, 59.5%, and 58.9% in autogenous shrinkage at 168 hours, respectively, compared to the control mixture's shrinkage of 768 με at the same duration.

Liu et al. (2022) highlight that the synergistic effect of combining EA and SRA significantly surpasses the shrinkage reduction achieved by either additive used individually. Park et al. (2014) conducted an investigation into both the combined and separate impacts of EAs and SRAs on the free shrinkage of UHPC. Their study noted that early-age expansion in UHPC, influenced by variations in ambient temperature and the hydration heat, was evident. However, the 28-day free shrinkage of a reference UHPC specimen, which was recorded at 700 με, decreased by 8% and 21% with the application of 1% and 2% SRA, respectively. Notably, the study revealed that adding 5% and 7.5% EA resulted in a more pronounced reduction in free shrinkage compared to using SRA alone. When EA and SRA were combined, the reduction in shrinkage reached 37% relative to the reference specimen.

In their 2011 study, Soliman and Nehdi examined the influence of different drying temperatures (10°C, 20°C, and 40°C) on the autogenous and total shrinkage of UHPC. As anticipated, higher drying temperatures resulted in increased autogenous strain. Notably, using a 2% SRA was more effective in reducing autogenous shrinkage at these elevated temperatures. For example, at 40°C with a water-to-cement ratio (w/c) of 0.25, the reduction in autogenous shrinkage was 55% compared to the control mixture (580 με), while at 20°C and 10°C, the reductions were 34% (at 405 με) and 32% (at 200 με), respectively, after seven days. The study also established higher temperatures invariably led to greater total strains, independent of relative humidity (RH). Additionally, lower RH levels increased total strains under the same exposure temperature. Complementing these findings, the 2018 study by Xie et al. also explored the use of ice water in UHPC mix design as a method to lower the temperature, which consequently appeared to decrease both autogenous and total shrinkage.

5.3 Experimental Program

5.3.1 Materials and Mixture Design

In this study, Type I/II Portland cement compliant with ASTM C150 standards, alongside ground-granulated blast-furnace slag in accordance with ASTM C989 and densified silica fume were used as cementitious materials. Sand with a maximum aggregate size of two mm, and micro straight steel fibers measuring 13.0 mm in length and 0.2 mm in diameter were used as dry components. For the liquid ingredients, the research incorporated a water-reducing and retarding (WRT) admixture meeting the Type S specification as per ASTM C494, along with a modified polycarboxylate-based HRWR, conforming to the Type F specification. Additionally, two SRA (BASF MasterLife SRA 035 and GCP Eclipse Floor 200), both fulfilling the ASTM C494 Type S, and one SCA (MAPEI Expancrete) were employed to assess the autogenous and total shrinkage of UHPC. The mixing process utilized standard tap water.

In this study, six different UHPC mixtures, each with varying dosages of SRA and SCA, as delineated in Table 4.3, were prepared. The reference mixture is denoted as 'R', while 'MS', 'EC', and 'EP' represent MasterLife, Eclipse, and Expancrete. The numbers following these abbreviations indicate the percentage of each corresponding admixture relative to the binder content. It should be noted that the mass of the fine aggregate listed in Table 4.3 was in an air-dried state, with a moisture content of approximately 0.2%. Any minor variations in moisture conditions were precisely compensated based on the exact moisture content measured before batching. The fiber content incorporated into each mixture amounted to 2% of the total binder content.

Table 5.1 Designs of mixtures for shrinkage study (all in pcy)

Mixture ID	Cement	Slag	Silica fume	Sand	Fiber	Water	HRWR	WRT	SRA/SCA	w/b
R	1188	577	159	1539	255	330	56.7	20.4	0	0.200
EC6	1184	575	158	1534	254	329	56.5	20.3	6.3	0.202
EC13	1179	573	158	1529	253	327	56.3	20.2	12.6	0.204
MS13	1179	573	158	1529	253	327	56.3	20.2	12.6	0.204
EC18	1175	571	157	1524	253	326	56.1	20.2	18.6	0.206
EP84	1168	568	156	1554	264	299	61.5	20.1	84.0	0.188

5.3.2 Mixing Procedure

All UHPC mixtures were prepared using a MIX 360 mixer featuring a 38-inch drum. The process encompassed three primary stages: initially, the dry components comprising air-dried sand and silica fume were blended for 5 minutes, followed by the incorporation of cement and slag for an additional 5 minutes. Subsequently, in anticipation of adding water (marking the commencement of the second stage), a concoction of 80% HRWR, the entire portion of WRT and SRA admixtures, and 80% of the total water quantity was pre-mixed and then agitated for seven minutes. The remaining water and HRWR were similarly pre-blended and introduced into the mixer, initiating the transition from a powdery state to a paste. The point at which the UHPC turned flowable, smooth, and viscous, marked the procurement of 0.40 cubic feet of the mixture for heat of hydration and setting time assessments. After this, steel fibers were integrated into the residual mix for a minute, with a subsequent 3-minute mixing period. It's important to note that the fiber quantity was calculated explicitly for the leftover material volume. A flow test was conducted post-mixing, and samples for shrinkage and compressive strength evaluations were prepared. It should be emphasized that when utilizing smaller mixers for UHPC, varying mixing speeds may be required to attain the desired consistency.

5.3.3 Test Methods

5.3.3.1 Flow test

The flowability of each UHPC mix was assessed to ascertain appropriate workability. To measure this, a custom 20 x 20-inch square plastic plate, equipped with a standard flow cone measuring 4 inches in diameter at the bottom and 2.5 inches at the top (per ASTM C230 specifications), was employed. The flow testing procedure for UHPC adhered to the ASTM C1856 standard. The average diameter of the flow at two minutes was measured and reported.

5.3.3.2 Setting time test

The initial and final setting times were measured in accordance with ASTM C403 using a test setup, as shown in below. Note that UHPC specimens were used for this test before incorporating fiber since the fiber could interfere with the needle penetration. Times of the initial and final settings were determined from the plot of penetration resistance versus elapsed time, as the times when the penetration resistance equals 500 psi and 4000 psi, respectively.

Figure 5.1 Setting time test set up

5.3.3.3 Heat of hydration test

Besides the ASTM setting time test per ASTM C403, an isothermal calorimeter was used to measure the initial and final setting time, and heat of hydration of UHPC at constant temperature (23ºC) within the first 72 hours as per ASTM C1702. Figure 5.2 shows an isothermal calorimeter comprised of eight units, each holding separate samples during the test. The sample of freshly mixed UHPC without fibers with a mass of 100±10 grams was placed into a 125 ml plastic container and then loaded into the equipment. A computer program was used to acquire readings. Readings were taken every 60 s for 72 hours to construct the heat generation rate versus hydration time curve. The thermal initial and final setting time was determined as the first derivative of the heat evolution curve. According to Hu et al. (2014), when the first derivative curve achieves its peak value, the material is considered to reach the initial setting time. The first derivative value starts to reduce by reaching zero corresponding to the mixture's final setting time.

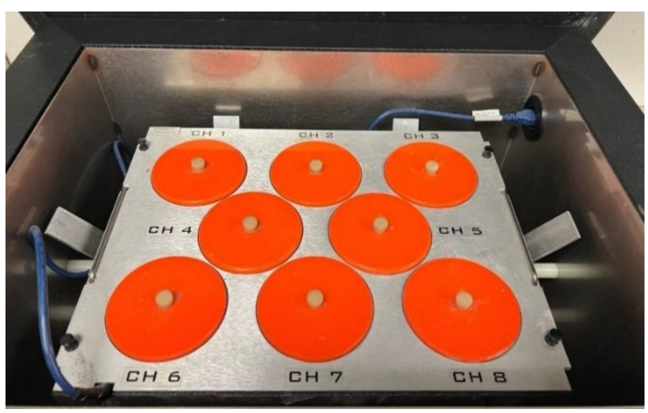


Figure 5.2 Isothermal calorimeter test units

5.3.3.4 Total and autogenous shrinkage test

Total and autogenous shrinkage of developed UHPC mixtures were measured based on ASTM C157, with standard 3” × 3” × 11.25” prism specimens. Immediately after mixing, the fresh UHPC was placed in the prism molds with an effective gage length of 10 inches in a single layer. The surface of the specimens was smoothed with several strokes of a trowel. For each UHPC mixture, four specimens were cast, two for total shrinkage (unsealed samples) and two for autogenous shrinkage (sealed samples). The samples were covered with a plastic sheet during the first 24 hours before demolding. After a 24 hour hardening period, the specimens were demolded, sealed (Figure 5.3b), and placed in a controlled environmental condition (20±3ºC temperature and 50±5% relative humidity). The length change in the original gauge length of cast samples was estimated using a length comparator at 1, 3, 7, 14, 28, 56, 90, 120, 150, and 180 days as shown in Figure 5.3a.

(a) (b) (c)

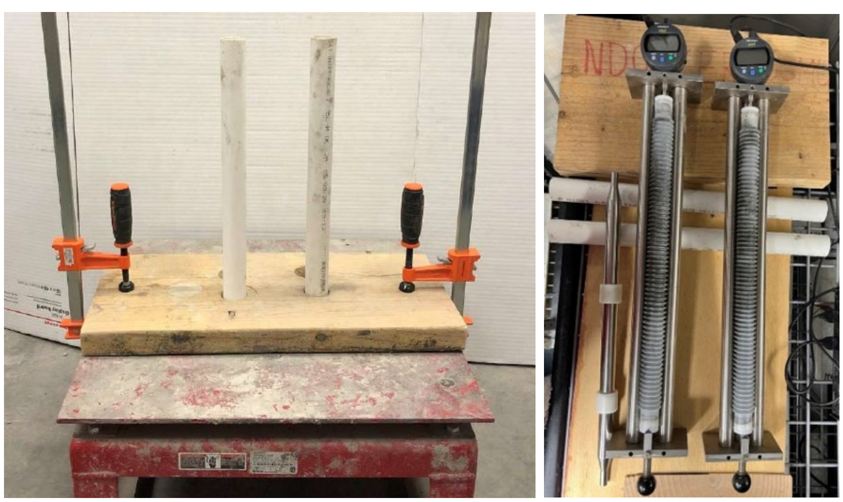
Figure 5.3 Shrinkage test set up (a) Length comparator; (b) Specimen curing after casting; and (c) Sealed and unsealed shrinkage specimens

It's widely recognized that UHPC subjected to thermal treatment demonstrates enhanced dimensional stability compared to UHPC cured at ambient temperature. To investigate the impact of post-cure thermal treatment on UHPC shrinkage, we prepared additional specimen sets for both the reference mixture and the mixture containing SCA samples and subjected them to thermal treatment. Since thermal treatment can be administered within 14 days of placement, four specimens (two Expancrete and two references) were placed in a hot bath (refer to Figure 5.4) at 180°F on the fourth day. After a 48-hour period, the samples were removed, allowed to cool to room temperature for over two hours, and then returned to the environmental chamber. The heat-cured samples were labeled EP84-Heat and R-Heat, while those without heat curing were designated EP84 and R. It is important to note that the thermal treatment was applied exclusively to specimens for total shrinkage evaluation, meaning these samples were not sealed.

Figure 5.4 Hot bath for thermal treatment of selected specimens

5.3.3.5 Short-term autogenous shrinkage test

Since ASTM C157 precludes measuring shrinkage before demolding (at 24 hours), a procedure based on ASTM C1698 was employed for short-term autogenous shrinkage assessment. This test amalgamates both volumetric and linear deformations, enabling measurements to commence immediately post-casting. As depicted in Figure 5.5a, a support structure for the tubes was crafted, and a wooden frame was securely fastened to a vibrating table. The corrugated molds were positioned within these support tubes, with their closed ends facing downward. The freshly mixed UHPC, devoid of fibers, was then poured into the molds while the vibrating table was operational. To maintain consistent tube lengths, altering the molds' dimensions through stretching or compressing was avoided. Following the casting of UHPC samples, the top plugs were sealed, and the samples were promptly placed in an environment meticulously controlled for temperature (23±1°C) and humidity (50±5%). The specimens were then situated in an autogenous shrinkage testing apparatus, as illustrated in Figure 5.5b, allowing for data acquisition every 60 seconds through LVDTs connected to a computer. This testing procedure was sustained for a duration of 21 days for each specified UHPC mixture. The calculation of autogenous shrinkage commenced from the final setting time, in line with ASTM C403 standards.



(a) (b)

Figure 5.5 Short-term autogenous shrinkage test setup (a) Stands for specimen casting; (b) Specimens during tests

5.3.3.6 Compressive strength test

The compressive strength of each UHPC mixture was evaluated per ASTM C1856 standards. Following a four-day curing period in a lime water tank, the 3” x 6” cylindrical specimens were ground at both ends and then placed in an oven for 24 hours under standardized conditions (110±5°C) before the testing commenced. The testing was conducted once the samples had cooled to room temperature, which took approximately 2.5 hours. For those samples subjected to thermal treatment, the specified UHPC specimens were immersed in a hot bath at 180°F after a day of curing in the lime water tank. Similar to the shrinkage samples, they were removed from the bath after 48 hours, allowed to cool to 90°F within 1.5 hours, and then placed in an oven for an additional 24-hour curing period, mirroring the procedure for the other compressive strength samples. It is important to note this hot bath curing method was applied exclusively to Expancrete and reference samples, paralleling the approach for shrinkage specimens. For each test condition, three specimens were evaluated, and the results were averaged to ensure reliability and accuracy in the compressive strength data.

5.3.4 Results and Discussion

5.3.4.1 Flow

Table 2.1 presents the flow results for all six mixtures, showcasing an interesting observation. Despite increasing dosages of SRA, the workability of the SRA mixtures remained largely consistent. This stability in fluidity is a notable finding, given the variations in SRA concentration. On another note, the EP84 mixture, which includes powder SCA as part of the binder content, displayed a marginally lower flow value compared to the reference mixture. This slight deviation can be attributed to the physical characteristics of the SCA component.

However, it is important to highlight all six UHPC mixtures demonstrated remarkably similar flow characteristics, underscoring their uniformity in this aspect.

Table 5.2 Flow test results

Mixture ID	Flow
R	10.5”
EC6	10.5”
EC13	10.5”
MS13	10.5”
EC18	10.5”
EP84	9.5”

5.3.4.2 Setting time

Table 5.3 and Figure 5.6 detail the outcomes of setting time tests conducted using the penetration resistance method. The results indicate a clear trend that an increase in SRA dosage corresponded with a slower rate of cement hydration, consequently leading to prolonged setting times. This observation aligns well with findings from prior research. Notably, the pattern observed in our study echoes the results reported by Weiss et al. (2008). Their research highlighted that the retardation effect of SRA is primarily due to its influence on the polarity within the mixture. The incorporation of SRA reduces polarity, diminishing the salts' capacity to dissolve and ionize in the pore solution. Additionally, the tests revealed an intriguing distinction: EC mixtures experienced a lesser delay in setting time for the same concentration of SRA than MS samples. This suggests a variance in the impact of SRA across different mixture compositions.

On the other hand, the EP84 mixture did not exhibit a noticeable delay in setting time. Its performance was roughly equivalent to the control mixture's, suggesting that EP84's composition does not significantly affect the setting time. This outcome provides an interesting contrast to the SRA and further emphasizes the nuanced effects of different types of admixtures on setting time.

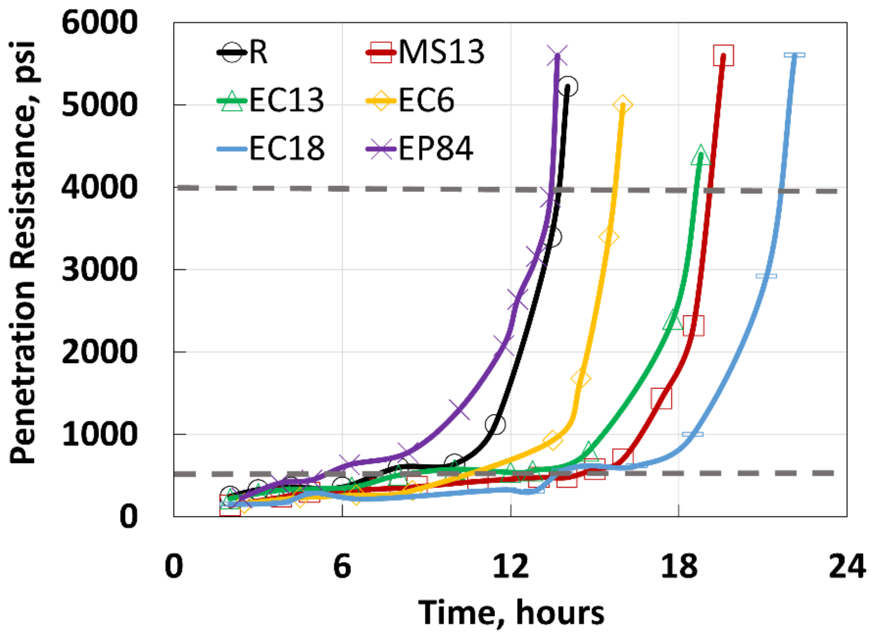


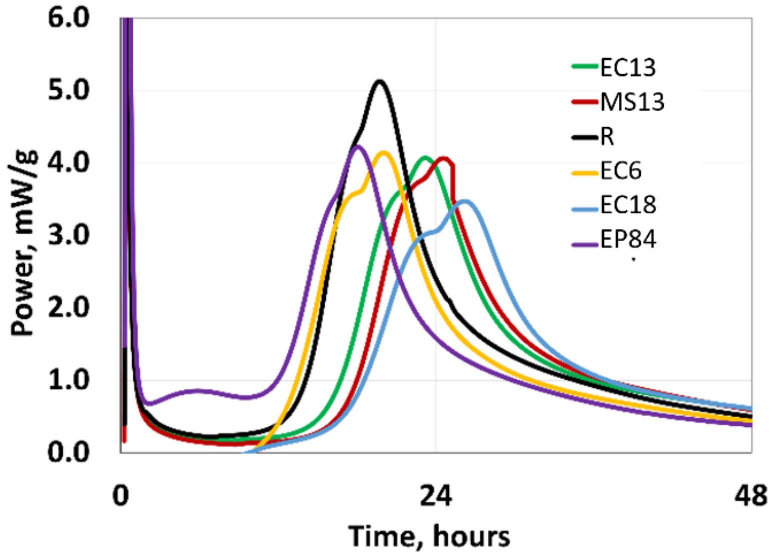
Figure 5.6 Setting time test results

Table 5.3 Calculated thermal setting time

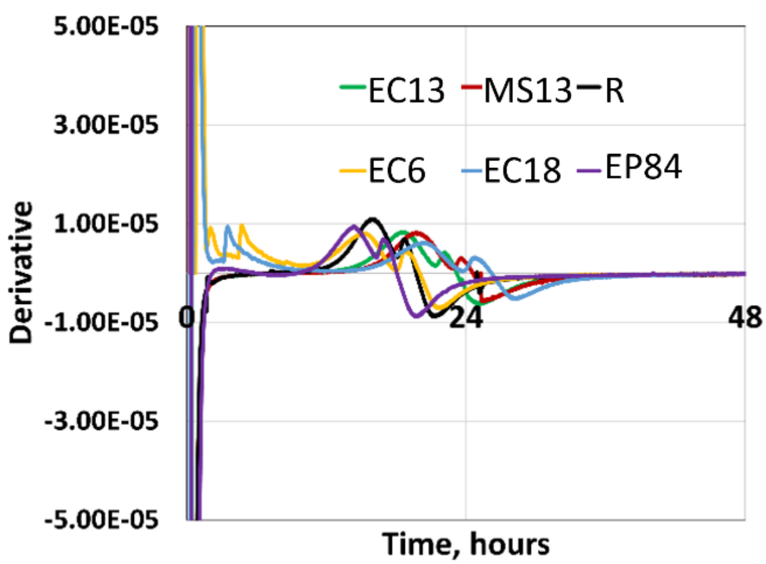
Mixture ID	Initial setting time (hours)	Final setting time (hours)
R	7.1	13.6
EC6	10.0	15.7
EC13	9.3	18.6
MS13	10.4	19.1
EC18	13.6	21.5
EP84	5.3	13.4

5.3.4.3 Heat of hydration

Figure 5.7 illustrates the results of the heat of hydration tests. The graphical representation in the figure demonstrates that incorporating SRA leads to a reduction in the peak heat release. Moreover, as the dosage of SRA increases, there is a noticeable shift of the peak towards the right, which indicates delayed hydration. In contrast, such a delay in hydration was not observed in the mixtures containing SCA. This distinction highlights the differential impact of SRA and SCA on the hydration kinetics of the mixtures. The absence of delayed hydration in SCA mixtures suggests that SCA's influence on the heat of hydration differs significantly from that of SRA, providing valuable insights into the distinct chemical interactions each admixture has within the UHPC matrix.



(a) Heat of hydration



(b) First derivative of heat generation rate

Figure 5.7 Heat of hydration test results

Table 5.4 presents the initial and final set times as determined by analyzing the derivative of heat generation during the hydration process. The results, while markedly different from those obtained via the penetration test, exhibit a parallel trend. Notably, the inclusion of SRA significantly prolongs both the initial and final setting times and diminishes the rate of heat generation at a constant temperature. This reduced rate indicates a lower degree of hydration, a key observation aligned with existing literature. Moreover, an increase in SRA dosage from 6 to 18 per cubic yards (pcy) led to a notable decrease in the peak power and a delay in its occurrence. This trend reaffirms findings from prior studies and underscores the impact of SRA concentration on the hydration process.

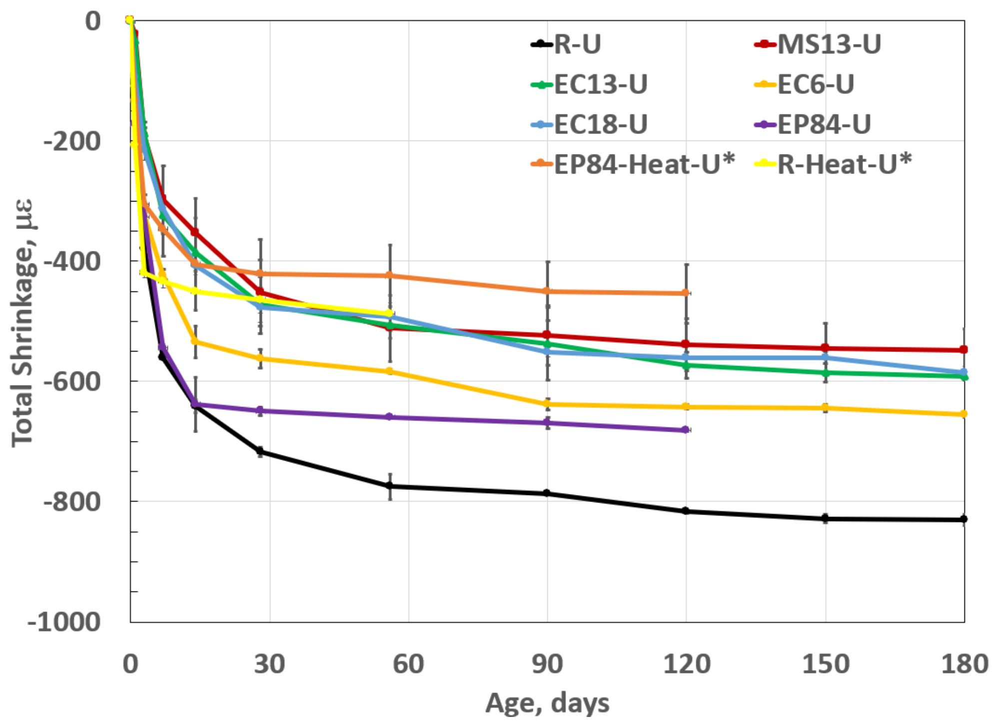
Intriguingly, the EP84 mixture displayed the shortest initial and final setting times among the tested mixtures, including the reference mixture. This occurred despite its lower peak power value. This unique behavior is attributed to the increased porosity resulting from the expansion. The higher porosity provides more space for forming hydration products, thereby accelerating the setting process. However, while Expancrete promotes faster setting times, it also interferes with cement hydration, as evidenced by the reduced peak power. This dual effect of Expancrete highlights the complex interplay between admixtures and the hydration kinetics in UHPC mixtures.

Table 5.4 Heat of hydration test results

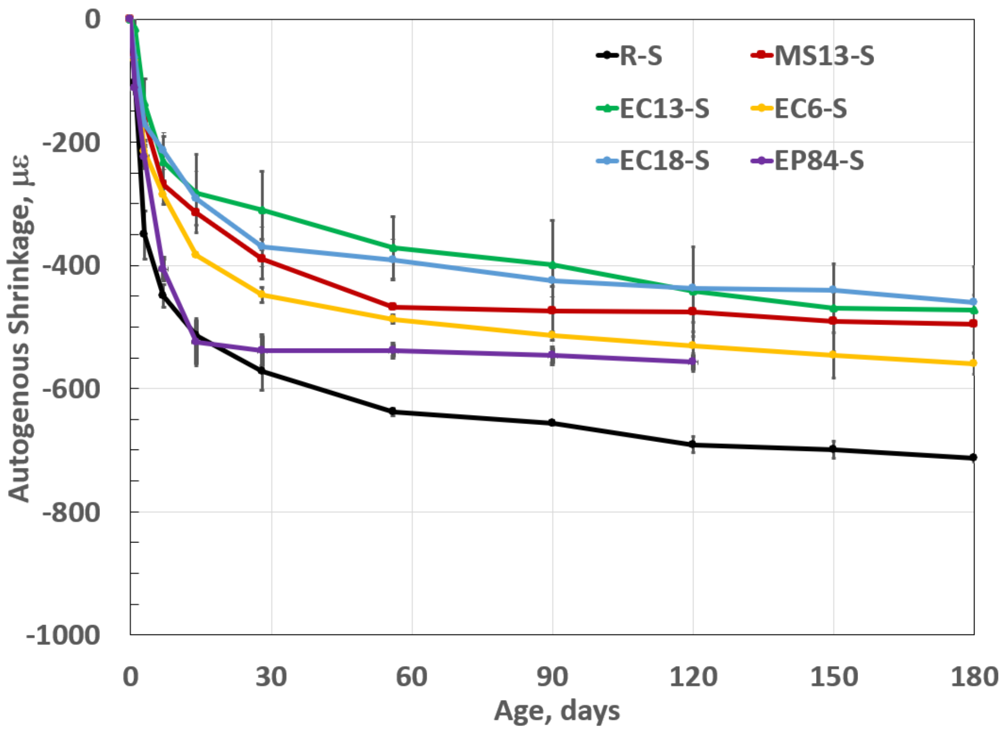
	Peak Power (mW/g)	**Initial Setting Time (hrs)**	**Final Setting Time (hrs)**
R	5.1	16.0	19.7
EC6	4.1	15.4	20.0
EC13	4.1	18.4	23.2
MS13	4.1	19.6	24.6
EC18	3.5	20.2	26.1
EP84	4.2	14.4	18.0

5.3.4.4 Total and autogenous shrinkage

Figure 5.8 presents a comprehensive analysis of how SRA, SCA, and heat treatment influence the total and autogenous shrinkage of UHPC. The results align with expectations, illustrating a significant reduction in total and autogenous shrinkage upon incorporating SRA. According to Xie et al. (2018), SRAs impact shrinkage by lowering the surface tension of pore water, which reduces hydrostatic tension forces (capillary stresses) and subsequently lessens the forces on the walls, thereby decreasing shrinkage. A closer look at the data reveals that the 28-day total shrinkage of UHPC markedly decreased from 718 με to 464 με and 453 με for the MS13 and EC13 mixtures, respectively. This trend continues over a more extended period, with 120-day measurements showing a reduction from 817 με to 573 με and 539 με for these mixtures. Similarly, the 28-day autogenous shrinkage was reduced from 571 με to 390 με and 311 με, and at 120 days from 691 με to 476 με and 437 με for MS13 and EC13, respectively. An interesting observation was made with the EC mixtures. As the SRA dosage increased from 6 pcy to 13 pcy, there was a noticeable decrease in shrinkage. However, the EC18 samples, which had a higher SRA dosage, showed similar results to the EC13, the recommended dosage by the manufacturer. This similarity indicates that increasing the SRA beyond the recommended dosage does not significantly enhance its efficiency in reducing shrinkage. Additionally, the results indicated that most mixtures began to show a plateau in shrinkage rates around 56 days post-casting. This plateau suggests the near completion of the hydration process, providing valuable insight into the timeline of UHPC's physical transformations.



(a) Total shrinkage



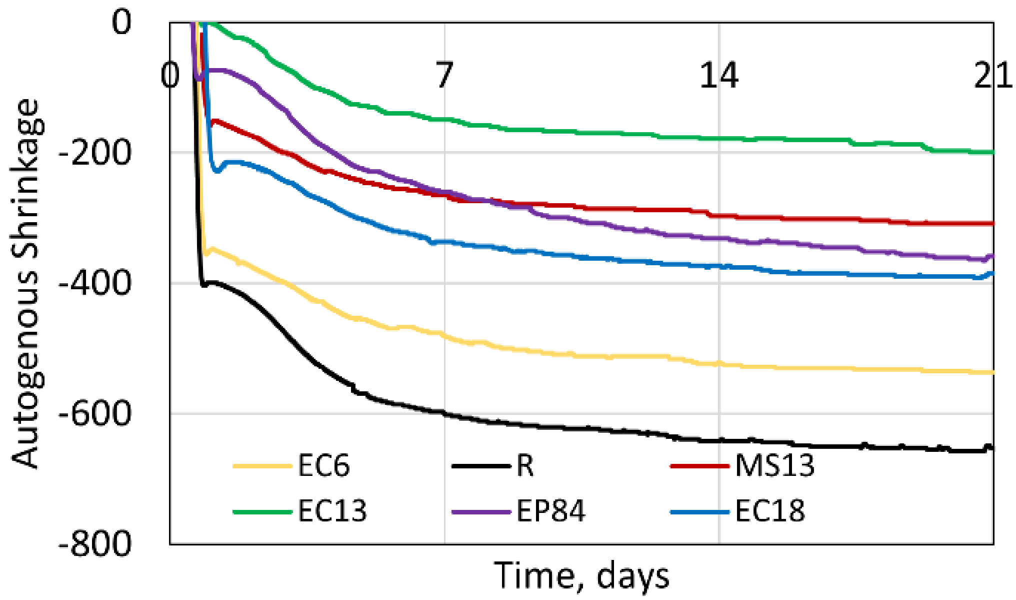
(b) Autogenous shrinkage

Figure 5.8 Total and autogenous shrinkage of UHPC

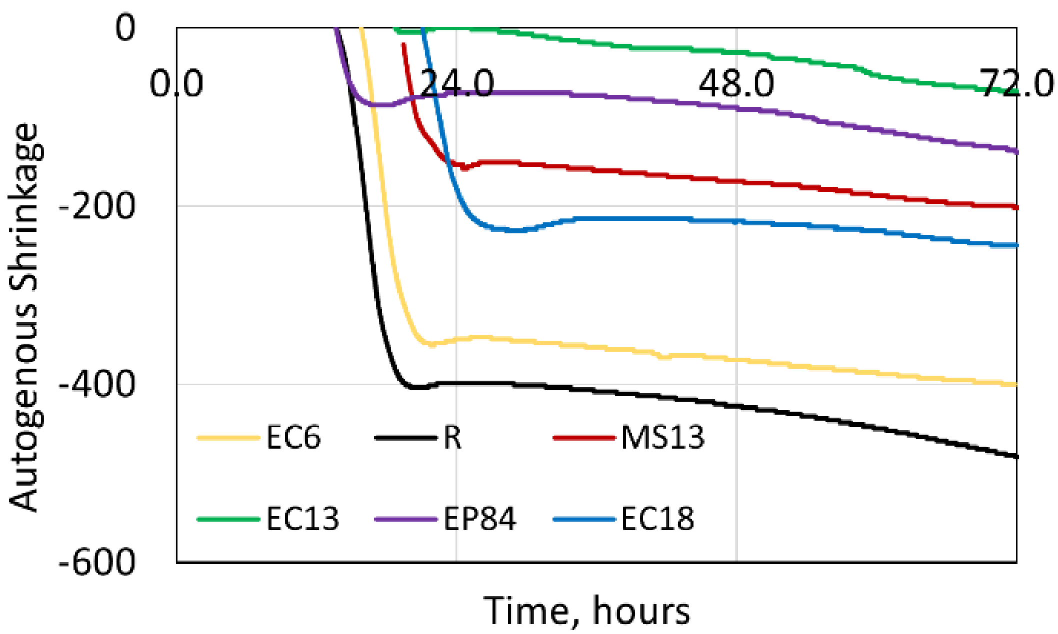
The fundamental mechanism of SCA, such as Expancrete, involves counteracting shrinkage through initial expansion during the early stages of hardening. However, Figure 5.8 reveals that Expancrete's incorporation is ineffective in reducing UHPC shrinkage under normal conditions. Contrastingly, under hot bath treatment, Expancrete showed a reduction in total shrinkage compared to the reference mixture (464 με for R-Heat and 421 με for EP84-Heat at 28 days). Without heat curing, the shrinkage differences between control and Expancrete mixtures became evident after 14 days for both total and autogenous shrinkage. Yang et al. (2019) noted that some expansive agents, particularly sulfoaluminate series, consume more water during hydration, potentially delaying expansion component formation. This delay means the excess ettringite might not stabilize during normal curing, explaining the observed shrinkage compensation in EP84 samples after 14 days. Several factors limit Expancrete's efficacy in UHPC without hot bath curing: UHPC's low water content for hydration, its dense structure with limited voids for hydration products, the high elastic modulus of the UHPC matrix hindering ettringite development, and low internal humidity due to self-desiccation and increased capillary pressure, as outlined by Li et al. (2021) and Shen et al. (2020). In contrast, thermal treatment provides a moist, warm environment, significantly reducing shrinkage. As Yang et al. (2019) and Liu et al. (2022) indicate, high temperatures form a solid skeleton, limiting shrinkage strain and improving dimensional stability. External water curing in Expancrete samples is crucial to activate expansion component formation and compensate for shrinkage strain, especially given UHPC's limited internal water for hydration.

5.3.4.5 Short-term autogenous shrinkage

Figure 5.9 shows the short-term autogenous shrinkage measurements of various UHPC mixtures, focusing on the initial 72 hours in Figure 5.9b. The graph’s time zero corresponds to the moment cement contacts water, while the strain measurements are reset to zero at the final setting time, as per ASTM C403. The test results revealed that the autogenous shrinkage of UHPC decreased with an increase in SRA content, particularly up to 13 pcy, aligning well with results from sealed prism samples. Notably, the EC13 mixture exhibited superior performance compared to the MS13 and EP84 mixtures. Interestingly, except for the R and EC6 mixtures, all others showed commendable performance within 72 hours. A significant aspect of Figure 5.9 is the reference mixture's autogenous shrinkage pattern in the first 72 hours, characterized by a substantial rise between 16 and 28 hours before a marked slowdown in the shrinkage rate. This observation echoes the findings reported by Huang and Ye (2017). For the control mixture, the 21-day autogenous shrinkage reached 660 με, with a notable 482 με recorded at 72 hours. In contrast, these values dropped to as low as 200 με (73 με at 72 hours) for the EC13 mixture. Over 21 days, the autogenous shrinkage of samples containing EC SRA at dosages of 6, 13, and 18 pcy decreased by 18%, 70%, and 58%, respectively, underscoring the significant impact of SRA dosage on shrinkage reduction.



(a) 21-day data



(b) 72-hr data

Figure 5.9 Short-term autogenous shrinkage results

5.3.4.6 Compressive strength

Table 5.5 Compressive strength test results of shrinkage mixtures showcases the results of the 4-day compressive strength tests conducted on eight different UHPC mixtures. Consistent with expectations, the addition of SRA and SCA did not significantly influence the concrete's strength. This finding is particularly noteworthy, as it highlights the neutral impact of these admixtures on the mechanical properties of UHPC. Importantly, all tested mixtures successfully met the established performance criteria in their hardened state, each achieving a minimum 4-day compressive strength of 17 ksi. This uniform achievement across different mix formulations underscores the robustness of UHPC and ability to maintain critical structural properties despite variations in admixture compositions.

Table 5.5 Compressive strength test results of shrinkage mixtures

Mixture ID	4-day Compressive strength (ksi)
R	18.22±0.06
EC6	18.43±0.14
EC13	20.13±0.97
MS13	18.15±0.30
EC18	19.22±1.10
EP84	21.28±1.97
R-Heat	21.87±0.46
EP84-Heat	19.67±1.80

5.3.5 Summary

Chapter 5 examines the impact of shrinkage-reducing admixtures (SRA) and shrinkage-compensating admixtures (SCA) on UHPC. It analyzes their effects on workability, strength, setting time, and shrinkage. While SRA and SCA do not significantly affect UHPC's workability and strength, increased SRA dosage delays hydration and extends setting times. Optimal SRA dosage effectively reduces UHPC's total and autogenous shrinkage, whereas SCA's effectiveness varies. Using the recommended dosage of SRA significantly reduces UHPC's shrinkage, with total shrinkage decreasing from 817 με to 539 με and autogenous shrinkage dropping from 691 με to 437 με. Under specific hot batch curing conditions, SCA significantly reduces shrinkage, though such methods may not be practical for all concrete applications.

Chapter 6 Draft Provision Incorporation of CIP UHPC

CAST-IN-PLACE NON-PROPRIETARY ULTRA-HIGH-PERFORMANCE CONCRETE FOR BRIDGES

000.01 - - Description of Work

1. These provisions cover the production, placement, curing, and testing of non-proprietary Ultra-High-Performance Concrete (UHPC) for structural cast-in-place concrete bridge applications, including joints, connections, repair, and preservation. Not included in these provisions are applications requiring specialized UHPC, such as deck structural repair and overlays. The concrete mixture described here shall be used as indicated in the project plans. All work shall be in accordance with the Standard Specifications, except as modified herein.

2. The requirements of this provision apply only to the non-proprietary UHPC mixture described herein and as specified in the NDOT report SPR-P1(18) M072. For a different UHPC mixture, durability requirements in addition to those specified in Table 6.3 shall be met.

000.02 - - Materials

1. **Mixture Ingredients**
   The non-proprietary UHPC mixture shall be made in accordance with the proportions provided in Table 6.1, and material specifications, including batching tolerances.

Table 6.1 Mixture Constituents and Proportions

Material	Proportion (*lb/yd*^{3})
Fine Aggregate	1,612
Portland Cement	1,214
Slag Cement	588
Silica Fume	162
Fibers	264
Water/Ice (Total content including water in sand and admixtures)	354
High-Range Water Reducer (HRWR) Admixture	TBD
Workability Retaining Admixtures (WRA)	TBD
Shrinkage Reducing Admixture (SRA)	TBD

1.1. **Fine Aggregate:** The fine aggregate meets the requirements of Section 1033 of the Standard Specifications. Aggregate specification range shall achieve 100% passing through the No. 10 sieve with a specific gravity of 2.60-2.70.

The moisture content at the time of batching shall be measured and accounted for in the total water content in each batch regardless of batch size.

Care should be applied in windy conditions as the wind can blow the finer and lighter particles away, which will result in changes to the aggregate and powder gradation.

1.2. **Portland Cement:** Type I/II Portland cement meets the requirements of Section 1004 of the Standard Specifications.
1.3. **Slag Cement:** Grade 100 slag cement meets the requirements of Section 1079 of the Standard Specifications.
1.4. **Silica Fume:** The Silica Fume meets the requirements of Section 1009 of the Standard Specifications. Silica fume incorporated into this mixture shall have a minimum silicon dioxide (SiO_2) content greater than 92%.
1.5. **Fibers:** Straight high carbon wire 0.5-inch long, 0.0078-inch diameter (13 mm long, 0.2 mm diameter [13/.20]) conforms to the requirements of ASTM A820. The steel fibers shall have a minimum tensile strength of 390 ksi. The steel fiber dosage is 2.0% by volume. Steel fibers should comply with Buy America Provisions.
1.6. **Water:** Water usage meets the requirements of Section 1005 of the Standard Specifications. It is recommended to have ice replace 25%-75% of the total water depending on ambient temperature to prevent excessive heat of the mixture. Other methods, such as chilled water, can also be used.
1.7. **High-Range Water Reducer (HRWR) Admixture:** Meeting the requirements of Section 1007 of the Standard Specifications, admixture Type A/F. The HRWR content shall be determined based on the trial batch to reach the desired workability.
1.8. **Workability Retaining Admixture (WRA):** Meeting the requirements of Section 1007 of the Standard Specifications, admixture Type A/G. The WRA content shall be determined based on the trial batch to reach the desired workability extension.
1.9. **Shrinkage Reducing Admixture (SRA):** is not required unless explicitly noted in the project plans.

2. **Material Submittals**

2.1. Submit the following to the Engineer for review and approval at least 15 calendar days before mixing and field casting takes place:
- Material certifications and ingredient specifications from their manufacturers
- A Quality Control plan that includes, but is not limited to, the following:
  (1) Mixture ingredient proportions to be used
  (2) Mixing protocol
  (3) Casting procedure
  (4) Sampling and testing procedure
  (5) Curing procedure
  (6) Finishing procedure after field placement
  (7) Additional information found in the Construction section below

2.2. Should the contractor submit a mix design which deviates from the mix in Table 6.1, such submittal shall include all statistical requirements to satisfy the engineering properties specified in the PCI Report titled: “Guidelines for the Use of Ultra-High-Performance Concrete (UHPC) in Precast and Prestressed Concrete PDF (TR-9-

22E)" in addition to durability requirements specified in the NDOT report SPR-P1(18) M072 titled "Feasibility Study of Development of UHPC for Highway Bridge Applications in Nebraska". Results of all tests shall be submitted to NDOT or its designated representative no later than 60 days prior to first placement of UHPC.

2.3. NDOT may waive the tests of the approved mix if these tests have been previously performed for materials supplied to NDOT by the Contractor.

2.4. No change shall be made to the approved UHPC mixture design during the progress of work without the prior written permission of the NDOT Portland Cement Concrete (PCC) Engineer.

3. **Mixture Batching**

3.1. The mixture shall meet the desired placement, finishing, and curing characteristics.

3.2. A high-shear pan mixer capable of supplying sufficient energy to the mixture is recommended for field production of cast-in-place UHPC. Due to the energy required, it is recommended to limit each batch's volume to a third of the mixer's capacity. Portable drum mixers are not permitted.

3.3. Batching of non-proprietary UHPC results in substantial increases in material temperature during batching. As noted in the Materials section, ice is recommended to be substituted for water should the ambient temperature be higher than 60^{o}F.

3.4. The following mixing procedure should be followed according to Table 6.2. If an alternate mixing procedure is proposed, the Contractor shall submit information as part of the Quality Control plan.

Table 6.2 Batching Procedure

Step Number	Description	Tentative Duration of Mixing* (*minutes*)
1	Add dry mix sand and silica fume	2
2	Add dry mix cement and slab	2
3	Add water, ice (if applicable), WRA, SRA (if applicable), and 80% of HRWR admixture	1
4	Mix until flowable	5-10
5	Add remaining/extra HRWR admixture if needed until mixture becomes fluid	2
6	Dispense steel fibers gradually during mixing duration	3
7	Additional fiber mixing, observing for improper fiber segregation or clumping	2
8	Conduct flow test and VSI test	2
9	Discharge and transport	n/a

**Subject to change due to volume of batch and mixture type.*

000.03 - - Construction

1. **Storage of Material**
   Assure the proper storage of all constituent materials, including but not limited to cement, aggregates, additives, and steel fibers, as required by the specifications provided by their suppliers/manufacturers to protect the integrity of the materials against the loss of physical, chemical, and mechanical properties.

2. **Placement Plan and Preplacement Meeting**
   2.1. The Contractor should submit a Placement Plan (with a detailed field work schedule) to the Engineer for review and approval at least 15 calendar days prior to the scheduled UHPC placement pour. No UHPC shall be placed on the project until the Engineer has reviewed and approved the required submittals.
   The following list is intended as a guide and may not address all the means and methods the Contractor may elect to use. The Contractor is expected to assemble a comprehensive list of all necessary items for executing the placement of UHPC.

   - Responsible personnel for placement
   - Equipment utilized in placement, testing, and curing of material
   - Quality Control of batch proportions – method of measurement and form of documentation of material provided
   - Quality Control of batching material
   - Batch procedure sequence
   - Proposed forming method that ensures grout-tight forms and removal plan for formwork
   - Placement procedure – including but not limited to the preparation of existing concrete surface (to ensure required roughness, cleanliness, and wetness) before UHPC placemen, in addition to spreading, finishing, and curing details

   2.2. The Contractor should arrange for an onsite meeting with the Contractor's staff, the Construction Project Manager, the Bridge Engineer, and Materials and Research Personnel. The objective of this meeting will be to outline the procedures for forming, mixing, transporting, placing, finishing, and curing of the UHPC. It should also provide an opportunity to review testing for acceptance sampling/testing procedures.

3. **Trial Batch and Test Placement**
   3.1. For contractors with no prior experience in batching and placement of NDOT non-proprietary UHPC mixture, it is required that the contractor conduct a trial batch and mockup placement to gain experience. Changes in equipment and environmental factors (ambient temperature, humidity, etc.) can impact the results of batching outcomes.
   3.2. Test specimens are required to ensure that the acceptance criteria in Table 6.3 can be met.

4. **Formwork, Casting, and Curing**

4.1. Formwork shall be watertight and coated to prevent the absorption of water and leakage of the mix after placement. Formwork shall be resistant to the hydrostatic pressure of fresh UHPC using a unit weight of 155 lb/ft^3.
4.2. Top forms are advisable to create an acceptable top surface condition and are likely necessary on sloped surfaces.
4.3. UHPC shall be placed in a single flow without lifts or the development of horizontal cold/construction joints. Provisions for temporary bulkheads should be made accordingly. Considerations should be provided in the placement plan for the effective placement of vertical cold joints in cast-in-place UHPC for applications requiring large quantities of material.
4.4. Surface preparation:
    4.4.1. Cast-in-place UHPC to previously cast conventional concrete - Expose the aggregate of the conventional concrete. Remove any loose material. Ensure the surface is clean and prewet to a saturated surface dry condition prior to UHPC placement. No standing water in the formwork should be allowed.
    4.4.2. Cast-in-place UHPC to previously cast UHPC – no blasting is necessary, however, remove any loose material. Ensure the surface is clean and prewet to the saturated surface dry condition prior to UHPC placement. No standing water in the formwork should be allowed.
4.5. Do not place UHPC at ambient temperature below 40°F, nor above 90°F.
4.6. Pumping of UHPC is not permitted.
4.7. Cover exposed surfaces with impervious material (e.g. plastic sheet) immediately after finishing and for at least 24 hours. Then, exposed surfaces should be either moist cured or covered with curing compound for at least seven days.
4.8. Unless otherwise specified, UHPC shall be given a smooth surface finish. If grinding is required, it should be done when the compressive strength of the UHPC material is between 10 ksi and 14 ksi.
4.9. No vehicular traffic, other than conventional contractor tools, is allowed on the bridge until the cast-in-place UHPC achieves a minimum of 12 ksi compressive strength and flexure strength requirements of Table 6.3 are met.

5. **Acceptance Testing**
5.1. The Engineer and Materials and Research personnel will be on site during the preparation and placement of UHPC. Coordination with the necessary personnel must be done a minimum of 48 hours prior to the anticipated UHPC placement.
5.2. Provide an appropriate location to place specimens for initial curing prior to transport to the laboratory. Curing boxes shall be equipped with supplemental heat or cooling as necessary to cure the specimens in accordance with ASTM C1856.
5.3. Acceptance testing shall be performed by the Contractor and approved by the Engineer. The required testing is summarized below in Table 6.3. The table contains test methods, minimum acceptance criteria, and expected frequencies.
Tests may be performed at more frequent intervals than described below, at the discretion of the Engineer.

    5.3.1. Flow – Testing to be completed at the mixer on individual batches and at the casting site for combined batches from concrete delivery equipment within 10 minutes before placement. Timing of this test is outlined in Table 6.2.

5.3.2. Visual Stability Index – testing to be completed at the mixer on individual batches and at the casting site for combined batches from concrete delivery equipment within 10 minutes before placement.

5.3.3. Compressive Strength – Samples shall be collected at the casting site from the equipment utilized to deliver the material within ten minutes before placement.

Three sets of three samples, (9) 3-inch x 6-inch cylinders, will be collected for each discrete placement element as outlined in the placement plan, or for every two cubic yards of material placed; whichever controls. A discrete element should include a joint between precast elements placed in a single operation without cold joints, and similarly discrete elements. Placement plans should define limits of sampling for this acceptance criteria. If the filling of the molds requires more than one trip of the delivery equipment, the number of test specimens shall be multiplied by at least one-half of the delivery trips.

Compressive testing shall occur prior to form stripping, allowing traffic, and 28 days. Three cylinders shall be tested each testing day. Additional samples collected due to multiple delivery should be tested at 28 days.

No more than 33% of test specimens are allowed to fall outside the requirements range, provided that the average for all test specimens is within acceptance criteria.

5.3.4. Flexural Strength - Samples shall be collected at the casting site from the equipment utilized to deliver the material within ten minutes before placement.

Two sets of three samples, (6) 4-inch x 4-inch x 14-inch prisms, will be collected for each discrete placement element as outlined in the placement plan, or for every two cubic yards of material placed; whichever controls. A discrete element should be considered to include a joint between precast elements placed in a single operation without cold joints, and similarly discrete elements. Placement plans should define limits of sampling for this acceptance criteria. If the filling of the molds requires more than one trip of the delivery equipment, the number of test specimens shall be multiplied by at least one-half of the delivery trips.

Flexural testing shall occur prior to allowing traffic (if earlier than 28 days) and at 28 days. Three cylinders shall be tested each testing day. Additional samples collected due to multiple deliveries should be tested at 28 days.

No more than 33% of test specimens are allowed to fall outside the requirements range, provided that the average for all test specimens is within acceptance criteria.

Table 6.3 Acceptance Criteria

Description	Test Method	Acceptance Criteria	Frequency
Flow	ASTM C1856/C1437	8 inches (minimum) 11 inches (maximum)	One per Batch
Visual Stability Index	*	0-1 within 10 minutes prior to placement	One per batch
Compressive Strength	ASTM C1859/C39	≥ 10 ksi (at form stripping) ≥ 12 ksi (at allowing traffic) ≥ 17.4 ksi (at 28 days)	(9) 3x6 inch cylinders per discrete element, or every 2 CY. Testing at form stripping, allowing traffic, and 28 days
Flexural Strength	ASTM C1856/C1609	Minimum 1.5 ksi first-crack stress; Minimum 2.0 ksi peak stress; Minimum 1.25 ratio of peak-to-first-crack stress; Minimum 0.75 ratio of residual stress at L/150 net deflection-to-first crack stress	(3 or 6) 4x4x14-inch prisms per discrete element or every 2 CY. Testing at allowing traffic (if earlier than 28 days) and 28 days
Batch Temperature**	ASTM C1064	Not for Accept/Reject Recommend utilizing sufficient ice as substitute to water and other cooling measures to keep temperature at placement below 80 F	One per Batch

**Based on the ACI publication: Flavia Mendonca and Jiong Hu (2021) "Impact of Chemical Admixtures on Time-Dependent Workability and Rheological Properties of Ultra-High-Performance Concrete", ACI Materials Journal, November.*

**Contractor to provide to Engineer for Information Only

000.04 - - Method of Measurement

1. The pay item "CAST-IN-PLACE NON-PROPRIETARY UHPC" shall be measured by plan quantity by the cubic foot (CF).

000.05 - - Basis of Payment

Pay Item	**Pay Unit**
Cast-in-Place Non-Proprietary UHPC	Cubic Feet (CF)

Payment should be considered full compensation for furnishing all submittal, materials, labor, testing, equipment calibration, results, formwork, and incidental work for completion of the work as indicated in this special provision and project plans.

References

Alkaysi, M. and El-Tawil, S. Effects of Variations in the Mix Constituents of Ultra High Performance Concrete (UHPC) on Cost and Performance. *Material and Structures*, 2015, 49: 4185-4200.

Ambily, P. S., Ravisankar, K., Umarani, C., Dattatreya, J. K., and Iyer, N. R. Development of Ultra-High-Performance Geopolymer Concrete. *Magazine of Concrete Research - Institute of Civil Engineers,* 2014, 66: 82-89.

ACI. Ultra-High-Performance Concrete: An Emerging Technology Report. *American Concrete Institute ACI 239*, 2018.

Anshuang, S., Ling, Q., Shoujie, Z., Jiayang, Z., & Zhaoyu, L. (2017). Effects of Shrinkage Reducing Agent and Expansive Admixture on the Volume Deformation of Ultrahigh Performance Concrete. *Advances in Materials Science and Engineering*, *2017*.

ASTM C150. Standard specification for portland cement. *ASTM International (American Society for Testing and Materials).* 2012

ASTM C157. Standard test method for length change of hardened hydraulic-cement mortar and concrete. *ASTM International (American Society for Testing and Materials),* 2017.

ASTM C230. Standard specification for flow table for use in tests of hydraulic cement. *ASTM International (American Society for Testing and Materials),* 2023.

ASTM C403. Standard test method for time of Setting of Concrete mixtures by penetration resistance. *ASTM International (American Society for Testing and Materials),* 2023.

ASTM C494. Standard specification for chemical admixtures for concrete. *ASTM International (American Society for Testing and Materials),* 2019.

ASTM C989. Standard specification for slag cement for use in concrete and mortars. *ASTM International (American Society for Testing and Materials),* 2022.

ASTM C1698. Standard test method for autogenous strain of cement paste and mortar. *ASTM International (American Society for Testing and Materials),* 2019.

ASTM C1702. Standard test method for measurement of heat of hydration of hydraulic cementitious materials using isothermal conduction calorimetry. *ASTM International (American Society for Testing and Materials)*, 2023.

ASTM C1856. Standard Practice for Fabricating and Testing Specimens of Ultra-High-Performance Concrete. *ASTM International (American Society for Testing and Materials)*, 2017.

Berry, M., Snidarich, R., Wood, C. Development of Non-Proprietary Ultra-High-Performance Concrete. *The State of Montana Department of Transportation,* FHWA/MT-17010/8237-001, 2017.

Bonneau, O., Lachemi, M., Dallaire, E., Dugat, J. and Aitcin, P. Mechanical Properties and Durability of Two Industrial Reactive Powder Concretes. *ACI Materials Journal*, 1997, 94: 286-290.

California Department of Transportation, Notice to Bidders and Special Provision. Contract No. 06-0K4604, Project ID 0612000105, 2015.

Choi, M. S., Lee, J. S., Ryu, K. S., Koh, K. and Kwon S. H. Estimation of Rheological Properties of UHPC Using Mini Slump Test. *Construction and Building Materials,* 2016, 106: 632-639.

Colorado Department of Transportation, Ultra High Performance Concrete. 2018.

De Larrard, F. and Sedran, T. Optimization of Ultra-High-Performance Concrete by the Use of Particle Packing. *Cement and Concrete Research*, 1994, 24: 997-1009.

District Department of Transportation, Special Provision for Ultra High-Performance Concrete. SP60, 2014.

Douglas, R., Gregori, A., Sun, Z., & Shah, S. P. (2005). Investigations of the Properties of SCC: a Method for Measuring Thixotropy and Viscosity. In *Proceedings of Knud Hojgaard Conference on Advanced Cement Based Material*, 19-30.

El-Tawil, S., Tai, Y., Meng, B., Hansen W. and Liu, Z. Commercial Production of Non-Proprietary Ultra-High-Performance Concrete. *Michigan Department of Transportation* (RC-1670)*,* 2018.

Elinwa, A. U., Ejeh, S. P., & Mamuda, A. M. (2008). Assessing of the fresh concrete properties of self-compacting concrete containing sawdust ash. *Construction and building materials*, *22*(6), 1178-1182.

Fedorsian, I. and Camoes, A. Effective Low-Energy Mixing Procedure to Develop High-Fluidity Cementitious Pastes. *Materia Rio de Janeiro,* 2016, 21(1): 11-17.

FHWA. Properties and Behavior of UHPC-Class Materials, *Federal Highway Administration, FHWA-HRT-18-036,* 2018.

FHWA. Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community, *Federal Highway Administration,* FHWA-HRT-13-060, 2013.

FDOT, Ultra High-Performance Concrete (UHPC). *Florida Department of Transportation,* 2018.

Ghafari, E., Ghahari, S. A., Costa, H., Júlio, E., Portugal, A., & Durães, L. Effect of supplementary cementitious materials on autogenous shrinkage of ultra-high performance concrete. *Construction and Building Materials*, 2016, 127, 43–48.

Graybeal, B. Design and Construction of Field-Cast UHPC Connection. *Federal Highway Administration,* Tech Note FHWA-HRT-14-084, 2014.

Graybeal, B. Development of Non-Proprietary Ultra High-Performance Concrete for Use in the Highway Bridge Sector. *Federal Highway Administration,* FHWA –HRT-13-100, 2013.

Graybeal, B. and Leonard, M. Example Construction Checklist: UHPC Connections for Prefabricated Bridge Elements. *Federal Highway Administration,* FHWA-HIF-18-030, 2018.

Haber Z. B., De la Varga, I., Graybeal, B., Nakashoji, B. and El-Helou, R. Properties and Behavior of UHPC-Class Materials. *Federal Highway Administration,* FHWA-HRT-18-036, 2018.

Hu, J., Ge, Z., & Wang, K. Influence of cement fineness and water-to-cement ratio on mortar early-age heat of hydration and set times. *Construction and Building Materials*, 2014, 50, 657–663.

Huang, H., & Ye, G. Examining the "time-zero" of autogenous shrinkage in high/ultra-high performance cement pastes. *Cement and Concrete Research*, 2017, 97, 107–114.

IADOT, Developmental Specifications for Ultra High Performance Concrete Connections. *Iowa Department of Transportation,* DS-15092, 2022.

Koh, K., Ryu, G., Kang, S., Park, J., & Kim, S. Shrinkage properties of ultra-high performance concrete (UHPC). *Advanced Science Letters*, 2011, 4(3), 948-952.

Li, P. P., Yu, Q. L., & Brouwers, H. J. H. (2017). Effect of PCE-type superplasticizer on early-age behaviour of ultra-high performance concrete (UHPC). *Construction and Building Materials*, *153*, 740-750.

Li, S., Cheng, S., Mo, L., & Deng, M. (2020). Effects of steel slag powder and expansive agent on the properties of ultra-high performance concrete (UHPC): Based on a case study.

Li, S., Mo, L., Deng, M., & Cheng, S. (2021). Mitigation on the autogenous shrinkage of ultra-high performance concrete via using MgO expansive agent. *Construction and Building Materials*, *312*.

Liu, L., Fang, Z., Huang, Z., & Wu, Y. (2022). Solving shrinkage problem of ultra-high-performance concrete by a combined use of expansive agent, super absorbent polymer, and shrinkage-reducing agent. *Composites Part B: Engineering*, *230*.

Precast/Prestressed Concrete Institute (PCI). Manual for Quality Control for Plants and Production of Structural Precast Concrete Products. *Precast/Prestressed Concrete Institute,* 4th edition, 1999, MNL-116.

Mendonca, F., & Hu, J. (2021). Impact of Chemical Admixtures on Time-Dependent Workability and Rheological Properties of Ultra-High-Performance Concrete. *ACI Materials Journal*, *118*(6).

Meng, W. and Khayat, K. H. Mechanical Properties of Ultra-High-Performance Concrete Enhanced with Graphite Nanoplatelets and Carbon Nano Fibers. *In Composites Part B*, 2016,107: 113-122.

Meng, W., Valipour, M., and Khayat, K. H. Optimization and Performance of Cost-Effective Ultra-High-Performance Concrete. *Materials and Structure,* 2017 (b). 50: n/a.

MIDOT, Special Provision for Michigan Ultra High Performance Concrete (MI-UHPC) For Field Cast Joints, *Michigan Department of Transportation*, n/a.

Mohebbi, A., Graybeal, B., & Haber, Z. (2022). Time-Dependent Properties of Ultrahigh-Performance Concrete: Compressive Creep and Shrinkage. *Journal of Materials in Civil Engineering*, *34*(6).

Naaman, A., and Wille, K. The Path to Ultra High Performance Fiber Reinforced Concrete (UHP-FRC): Five Decades of Progress. *In proceedings of Hipermat 2012, 3rd International Symposium: Ultra High Performance Concrete and Nanotechnogy in Construction, Germany,* 2012.

NYDOT, Ultra-High Performance Concrete (UHPC). ITEM 557.6601NN16, *New York State Department of Transportation,* 2023.

PADOT, Ultra High Performance Concrete. *Pennsylvania Department of Transportation*, a10303 2021.

Park, J. J., Yoo, D. Y., Kim, S. W., & Yoon, Y. S. (2014). Benefits of using expansive and shrinkage-reducing agents in UHPC for volume stability. *Magazine of Concrete Research*, *66*(14), 745–750.

PCI, Guidelines for the Use of Ultra-High-Performance Concrete (UHPC) in Precast and Prestressed Concrete", *Precast/Prestressed Concrete Institute*, PCI Concrete Materials Technology Committee TR-9-22, Chicago, IL, 2022.

Ruan, T., & Poursaee, A. (2019). Fiber-distribution assessment in steel fiber–reinforced UHPC using conventional imaging, X-ray CT scan, and concrete electrical conductivity. *Journal of Materials in Civil Engineering*, *31*(8), 04019133.

Russell, H. G. and Graybeal, B. Ultra-High Performance Concrete: A state-of-the-Art Report for the Bridge Community. *Federal Highway Administration,* FHWA-HRT-13-060, 2013.

Russell, H. G. (2008). ASTM Test Methods for Self-Consolidating Concrete. *HPC Bridge Views*, *50*.

Sbia, L. A., Peyvandi, A., Lu, J., Abideen, S., Weerasiri, R. R., Balachandra, A. M., & Soroushian, P. (2017). Production methods for reliable construction of ultra-high-performance concrete (UHPC) structures. *Materials and Structures*, *50*, 1-19.

Shen, P., Lu, L., He, Y., Wang, F., Lu, J., Zheng, H., & Hu, S. (2020). Investigation on expansion effect of the expansive agents in ultra-high performance concrete. *Cement and Concrete Composites*, *105*.

Shi, C., Wu, Z., Xiao, J., Wang, D., Huang, Z. and Fang, Z. A Review on Ultra High Performance Concrete: Part I. Raw Materials and Mixture Design. *Construction and Building Materials*, 2015, 101: 741-751.

Soliman, A. M., & Nehdi, M. L. (2011). Effect of drying conditions on autogenous shrinkage in ultra-high performance concrete at early-age. *Materials and Structures/Materiaux et Constructions*, *44*(5), 879–899.

Soliman, A. M., & Nehdi, M. L. (2014). Effects of shrinkage reducing admixture and wollastonite microfiber on early-age behavior of ultra-high performance concrete. *Cement and Concrete Composites*, *46*, 81–89.

Wang, R., Gao, X., Huang, H., & Han, G. (2017). Influence of rheological properties of cement mortar on steel fiber distribution in UHPC. *Construction and Building Materials*, *144*, 65-73.

Weiss, J., Lura, P., & Rajabipour, F. (2008). Performance of shrinkage -reducing admixtures at different humidities and at early age. *ACI Materials Journal,* 105-M55.

Wille, K., Naaman, A. E., and Parra-Montesinos, G. J. Ultra-High Performance Concrete with Compressive Strength Exceeding 150MPA (22KSi): A Simpler Way. *ACI Material Journal,* 2011 (a), n/a: 46-54.

Wille, K., Naaman, A. E., and El-Tawil, S. Optimizing Ultra-High-Performance Fiber-Reinforced Concrete, Mixtures with Twisted Fibers Exhibit Record Performance under Tensile Loading. *Concrete International*, 2011 (b), n/a: 35-41.

Wu, Z., Shi, C., Khayat, K. H., and Wan, S. Effect of Different Nanomaterials on Hardening and Performance of Ultra-High Strength Concrete (UHSC), *Cement and Concrete Composites*, 2016, 70: 24-34.

Xie, T., Fang, C., Mohamad Ali, M. S., & Visintin, P. (2018). Characterizations of autogenous and drying shrinkage of ultra-high performance concrete (UHPC): An experimental study. *Cement and Concrete Composites*, *91*, 156–173.

Yang, L., Shi, C., & Wu, Z. (2019). Mitigation techniques for autogenous shrinkage of ultra-high-performance concrete – A review. In *Composites Part B: Engineering* (Vol. 178). Elsevier Ltd.

Yang, S. L., Millard, S. G., Soutsos, M. N., Barnett, S. J. and Le, T. T. Influence of Aggregate and Curing Regime on Mechanical Properties of Ultra High Performance Concrete. *Construction and Building Materials*, 2009, 23: 2291-2298.

Yu, R., Spiesz, P., and Browers, H. J. H. Effect of Nano-Silica on the Hydration and Microstructure development of Ultra-High Performance Concrete (UHPC) with a Low Binder Amount. *Construction and Building Materials*, 2014 (a), 65: 140-150.

Yu, R., Spiesz, P., and Browers, H. J. H. Mix design and Proprieties Assessment of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC). *Cement and Concrete Research*, 2014 (b), 56: 29-39.

Yu, R., Spiesz, P., and Browers, H. J. H. Development of an Eco-Friendly Ultra-High Performance Concrete (UHPC) With Efficient Cement and Mineral Admixture Uses. *Cement and Concrete Composites,* 2015, 55: 383-394.

Yoo, D. Y., Banthia, N., & Yoon, Y. S. (2015). Effectiveness of shrinkage-reducing admixture in reducing autogenous shrinkage stress of ultra-high-performance fiber-reinforced concrete. *Cement and Concrete Composites*, *64*, 27–36.

Appendix A

Handout for Workshop on Production of Cast-in-Place UHPC for Bridge Applications

WORKSHOP ON PRODUCTION OF CAST-IN-PLACE UHPC FOR BRIDGE APPLICATIONS

Jiong Hu and George Morcous

3/16/2022

NEBRASKA
Good Life. Great Journey.
DEPARTMENT OF TRANSPORTATION

COLLEGE OF ENGINEERING

WORKSHOP OUTLINE

- **Morning Session: Lecture and Discussion**
  - Introduction of UHPC
  - Production of UHPC
  - Break
  - Testing of UHPC
  - UHPC experiences – case studies
  - Discussions and Q&A
- **Afternoon Session: Hands-on Experience**
  - UHPC batching, casting and specimen preparation
  - UHPC testing
  - Q&A

2

3 SELF-INTRODUCTION

- Name
- Employer
- Job title

4 INTRODUCTION OF UHPC

OUTLINE/LEARNING OBJECTIVES

- What is UHPC?
  - Recognize general UHPC characteristics (and the difference between UHPC and conventional concrete)
- UHPC mixture design, specifications, and properties
  - Understand the difference between UHPC and conventional concrete mixture design
- Applications of UHPC
  - Know the major applications of UHPC

5

6

WHAT IS UHPC?

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FHWA SITE OF ULTRA-HIGH PERFORMANCE CONCRETE

https://highways.dot.gov/research/structures/ultra-high-performance-concrete/ultra-high-performance-concrete

WHAT IS UHPC?

1- Federal Highway Administration (FHWA) definition:

"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). UHPC has a discontinuous pore structure that reduces liquid ingress, significantly enhancing durability compared to conventional concrete."

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WHAT IS UHPC?

Ultra-High-Performance Concrete: An Emerging Technology Report

Reported by ACI Committee 239

2- American Concrete Institute (ACI) Committee 239 defiinition:

"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."

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WHAT IS UHPC?

Designation: C1856/C1856M – 17

Standard Practice for
Fabricating and Testing Specimens of Ultra-High Performance Concrete[1]

3- ASTM C1856 (Standard Practice for Fabricating and Testing Specimens of UHPC) definition:

"… a specified compressive strength of at least 120MPa (17,000 psi), with nominal maximum size aggregate of less than 5mm (1/4 in.) and a flow between 200 and 25mm (8 and 10 in.)"

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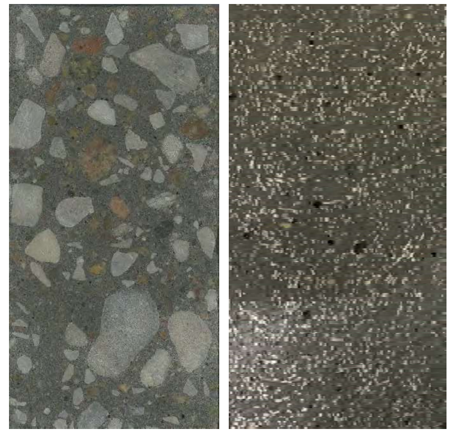
WHAT IS UHPC?

- Composition and mixture design
  - Cement-based composite material
  - High-end fiber-reinforcement concrete
  - Very dense particle packing
- Properties
  - Highly workability concrete
  - High strength
  - Inherently ductile
  - Highly durable



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PROPERTIES TYPICAL CONCRETE

	Fiber	Compressive Strength	Flexural Strength	Elastic Modulus	Chloride Penetration	Crack Resistance
Normal Concrete	-	3000-6000psi	400-600psi	2000-6000ksi	>2000 coulombs	Very low
FRC	<0.5% Polypropylene	3000-6000psi	400-600psi	2000-6000ksi	>2000 coulombs	High
	0.5 to 1.5% macro steel	3000-6000psi	-1000psi	2000-6000ksi	>2000 coulombs	High
UHPC	>2% micro steel	>17,000psi	1000-3000psi	8000-10000ksi	20-360 coulombs	Extremely high

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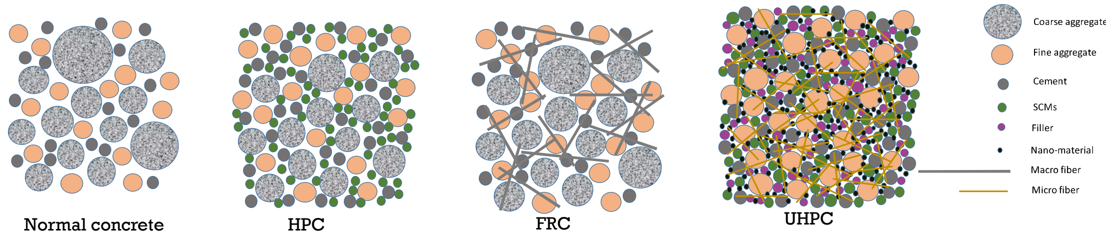
13 MIXTURE DESIGN OF UHPC

TYPICAL MIXTURE DESIGNS OF DIFFERENT CLASSES OF CONCRETE



Mix	Normal PCC	HSC	FRC-L	FRC-M	UHPC
Cement	529	820	555	582	1200
SCMs	176	80	185	194	390
Filler	0	0	0	0	355
Coarse Aggregate	1650	1800	1570	1427	0
Fine Aggregate	1204	1140	1284	1427	1720
Water	261	261	274	287	218
Fibers	0	0	8	132	263
HRWR (fl oz/yd3)	56	290	84	112	745
w/b	0.37	0.29	0.37	0.37	0.14

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TYPICAL INGREDIENTS FOR UHPC

Cement and SCMs

Chemical Admixtures

Fine sand

Steel fiber

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UHPC MIXTURE DESIGNS

Proprietary
UHPC mixtures

Non-proprietary
UHPC mixtures

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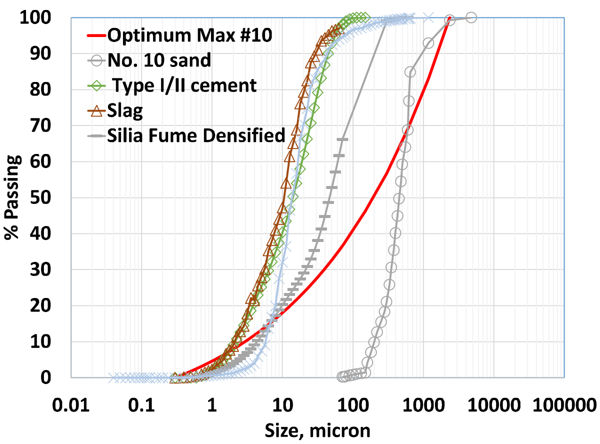
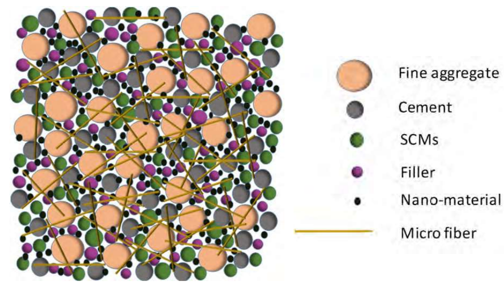
MIXTURE DESIGN OF UHPC

Mixture development - Particle packing





Modified Andreasen and Andersen model

$$P_i = \frac{D_i^q - D_{min}^q}{D_{max}^q - D_{min}^q}$$

- P_i = total percent of particle passing through sieve
- D_{max} = maximal size of particle
- D_{min} = minimum size of particle
- D_i = diameter of the current sieve
- q = exponent of the equation

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UNL-UHPC1900 MIXTURE DESIGN

- Based on the extensive study, the following (UNL-UHPC) mix with local materials is recommended. Unit cost of the UNL-UHPC is approximately \$682/yd^3

Mix ID	Cement	Slag	Silica Fume	Water & Ice	Sand	Fiber	HRWR	WRA	w/b
UNL-UHPC1900	1207	585	161	309	1603	266	57.6	20.7	0.182

	Materials	Source and location
Sand	No.10 sand	Lyman-Richey, Omaha, NE
Cement	Type I/II	Ash Grove Cement Company, Louisville, NE
Slag	Grade 100 Slag	Central Plains Cement Company, Omaha, NE (terminal)
Silica fume	Force10,000 densified microsilica	GCP Grace Construction Products
Fiber	Dramix OL 13/.20 micro steel fiber	Bekaert
HRWR	Premia 150	Chryso
WRA	Optima 100	Chryso

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APPLICATION OF UHPC

FHWA EVERY DAY COUNTS (EDC) UHPC-RELATED INITIATIVES

- EDC-3 and 4 (2015 – 2018)
  - UHPC for Prefabricated Bridge Elements (PBES)
- EDC-6 (2021 – 2022)
  - UHPC for Bridge Preservation & Repair

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APPLICATIONS OF UHPC

- Precast
  - Girders, decks…
- Cast-in-Place
  - Connections, repair, overlay…

Connections

Repair

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USEFUL LINKS/DOCUMENTS

Document	Link
FHWA Ultra-High Performance Concrete Site	https://highways.dot.gov/research/structures/ultra-high-performance-concrete/ultra-high-performance-concrete
FHWA-HRT-11-038-TechNote_UHPC	https://www.fhwa.dot.gov/publications/research/infrastructure/structures/11038/11038.pdf
FHWA-HRT-19-011-Design and Construction of Field-Cast UHPC Connections	https://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/uhpc/19011/19011.pdf
FHWA-HIF-19-030-Example Construction Checklist_UHPC Connections for Prefabricated Bridge Elements	https://www.fhwa.dot.gov/bridge/abc/docs/uhpc-construction-checklist.pdf
NYSDOT2021_557.6601NN16_Joint Fill UHPC_Performance Spec	https://www.dot.ny.gov/spec-repository-us/557.66010116.pdf
NDOT Project M069 Report (Mendonca et al. 2020), Feasibility Study of Development of Ultra-High Performance Concrete (UHPC)for Highway Bridge Applications in Nebraska)	https://dot.nebraska.gov/media/113319/m072-uhpc-project-final-report.pdf
ASTM C1856-17, Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete	
Mendonca F. and Hu J., (2021). Impact of Chemical Admixtures on Time-Dependent Workability and Rheological Properties of Ultra-High-Performance Concrete, ACI Materials Journal, 118 (6).	

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QUESTIONS?

WORKSHOP ON PRODUCTION OF CAST-IN-PLACE UHPC FOR BRIDGE APPLICATIONS

Jiong Hu and George Morcous

3/16/2022

NEBRASKA
Good Life. Great Journey.
DEPARTMENT OF TRANSPORTATION

N
COLLEGE OF ENGINEERING

WORKSHOP OUTLINE

- **Morning Session: Lecture and Discussion**
  - Introduction of UHPC
  - Production of UHPC
  - Break
  - Testing of UHPC
  - UHPC experiences – case studies
  - Discussions and Q&A
- **Afternoon Session: Hands-on Experience**
  - UHPC batching, casting and specimen preparation
  - UHPC testing
  - Q&A

PRODUCTION OF UHPC

STEPS

1. Batching
2. Mixing
3. Forming
4. Transporting and Placement
5. Finishing
6. Curing

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1-BATCHING OF UHPC

a) Clean sand with controlled moisture (ASTM C133 or C144)

b) Dry stored cementitious materials (no hard lumps)

c) Dry and covered fibers to prevent oxidation

d) Chilled water or ice to control mixture temperature (50 – 80° F)

e) Admixtures within shelf-life and not exposed to freezing

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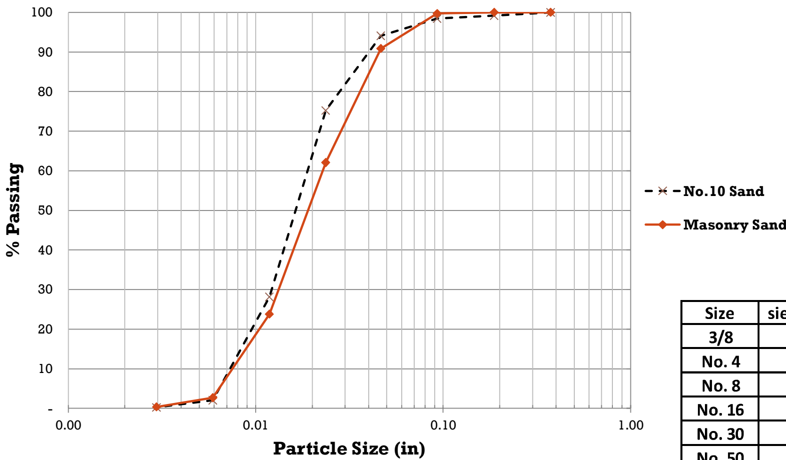
SAND



Size	sieve size (in.)	sieve size (μm)	% Passing No.10 Sand	% Passing Masonry Sand
3/8	0.374	9500	100.0	100
No. 4	0.187	4750	99.2	100
No. 8	0.093	2360	98.4	99.7
No. 16	0.046	1180	94.1	90.9
No. 30	0.024	600	75.3	62.1
No. 50	0.012	300	28.2	23.8
No. 100	0.006	150	2.1	2.7
No. 200	0.003	75	0.3	0.4

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CEMENTITIOUS MATERIALS

- Portland Cement Type I/II (ASTM C150)
- Silica Fume Densified (ASTM C1240)
- GGBFS (ASTM C989)


PRODUCT DATA SHEET
gcp applied technologies

FORCE 10,000® D

High performance concrete admixture dry densified powder

Product Description

Force 10,000® D is a dry densified microsilica (silica fume) powder designed to increase concrete compressive and flexural strengths, increase durability, reduce permeability and improve hydraulic abrasion-erosion resistance. The specific gravity of Force 10,000 D is 2.20.


ASH GROVE

DURA SLAG

ASH GROVE CEMENT COMPANY

DURA SLAG™

DURA SLAG is a slag cement or a ground granulated blast furnace slag, which has hydraulic cement properties. Using slag cement as replacement for a portion of the portland cement can enhance plastic and hardened properties of concrete. DURA SLAG meets specifications in ASTM C989 Grade 100 and AASHTO T302.

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DOMESTIC FIBER SOURCES

SUMIDEN WIRE PRODUCTS CORPORATION

HOME | ABOUT | INDUSTRIAL ALLOYS | PRODUCTS | C

Steel Fibers | About

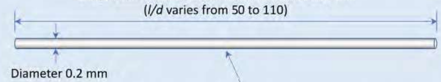
STEEL FIBERS - BUY AMERICA COMPLIANT

Beginning in January 2021, Sumiden Wire is proud to offer Buy-America-compliant high-strength steel fibers for the innovative and growing ultra-high performance concrete marketplace. These fibers are produced using steel melted and manufactured in the USA and in compliance with **ASTM A820.** Our standard product is a 0.008" (0.2 mm) diameter x 1/2" (13 mm) long brass-coated steel straight fiber (other fiber lengths are available) with typical tensile strengths over 400 ksi.

STEEL FIBER PACKAGING & SHIPMENT

Sumiden Wire's steel fibers are packaged in 44 lb. (20 kg) bags. These fibers can be shipped on pallets with 24 bags (1,056 lb.) or smaller lot sizes as needed. The steel fibers are produced in our centrally located Dickson, TN plant and can be shipped across the USA as needed. We plan to maintain an inventory to be able to handle short-notice orders, but larger orders (>5,000 lb.) should be ordered in advance.

DATA SHEET (TYPE A and TYPE X)



General Information

HiPer Fiber products are made from cold drawn high-carbon steel manufactured from steel wire rod sourced from a US Steel Mill. The Heat Number(s) used are listed on this Mill Certificate. All manufacturing steps are conducted in the United States of America in compliance with the **Buy America Act**.

Our patent-pending surface modification technology dramatically boosts fiber performance.

1. Reduce dosage without compromising UHPC performance
2. Keep standard dosage but achieve substantially improved material properties
3. Keep the fibers short to eliminate mixing problems that occur at higher dosages

Conforms to ASTM A820 Type 1

Test	Units	Tests	Test Results			
			Average	Ste Dev	Min	Max
Diameter	mm	12	0.200	0.001	0.198	0.202
Tensile Strength	N/mm2	12	2928	56.714	2824	3039
Break Load	N	12	92.2	2.281	89.5	97.4
Elongation at Break	(%)	12	2.3	0.368	1.8	2.8
Copper Content	(%)	12	66.8	1.543	64.7	68.7
Brass Weight	(g/kg)	12	4.83	0.092	4.71	4.96
Torsions	(Turns/100d)	12	67	17.367	53	99

ADMIXTURES

High-Range Water Reducer (HRWR)

CHRYSO® Fluid Premia 150

■ Description:

Characteristics:
- Physical state: liquid
- Density: Approx. 1.06
- pH: Approx. 5
- Cl ion content: Nil

CHRYSO® Fluid Premia 150 does not contain any purposely added calcium chloride or other chloride based components. It will not promote or contribute to corrosion of reinforcing steel in concrete.

Packaging:
- 55 gallon (210 L) drums
- 264 gallon (1000 L) totes
- bulk deliveries

Standard specifications:
Conforms to ASTM C 494 type A & F
AASHTO M 194 Type A & F
CRD C 87 Type A & F

Compatibility
CHRYSO® Fluid Premia 150 is compatible with all types of P cement, class C and F fly ash, slag, microsilica, calcium chlorid and approved air entraining admixtures.

CHRYSO® Fluid Premia 150 can be used in all white, color architectural concrete. For best results, each admixture m dispensed separately into the concrete mix.

Precaution:
CHRYSO® Fluid Premia 150 may freeze at temperatures below 28°F (-2°C). Although freezing does not harm **CHRYSO® Fluid Premia 150**, precautions should be taken to protect it from freezing.

If **CHRYSO® Fluid Premia 150** should happen to freeze, thaw and reconstitute with mechanical agitation.

Do not store the product at temperatures above 100°F (38°C) or under 40°F (5°C) for long periods.

Shelf life: 9 months.

CHRYSO® Fluid Optima 100

■ Description:

Characteristics:
Physical state: liquid
Color: milky, off white
Density: 1.06 ± 0.01 g/cc
pH: 7 ± 2
Cl⁻ ion content: Nil
Na²O equiv.: < 1.0%

CHRYSO®Fluid Optima 100 does not contain any purposely added calcium chloride or other chloride based components. It will not promote or contribute to corrosion of reinforcing steel in concrete.

Packaging:
- 55 gallon (210 L) drums
- 264 gallon (1000 L) totes
- bulk deliveries

Standard specifications:
Conforms to ASTM C 494 type A & G
AASHTO M 194 Type A & G
CRD C 87 Type A & G

Compatibility
CHRYSO®Fluid Optima 100 is compatible with all types of Portland cement, class C and F fly ash, slag, microsilica, calcium chloride, fibers and approved air entraining admixtures.

CHRYSO®Fluid Optima 100 can be used in all white, colored, and architectural concrete. For best results, each admixture must be dispensed separately into the concrete mix.

Precaution:
CHRYSO®Fluid Optima 100 may freeze at temperatures below 35°F (2° C). Although freezing does not harm **CHRYSO®Fluid Optima 100**, precautions should be taken to protect it from freezing.

If **CHRYSO®Fluid Optima 100** should happen to freeze, thaw and reconstitute with mechanical agitation. Do not store the product at temperatures above 100°F (38°C) or under 40°F (5°C) for long periods. This product must be stored in plastic containers, except those manufactured with PVC.

Shelf life: 9 months.

■ Safety:
CHRYSO®Fluid Optima 100 is not considered dangerous to

Workability Retaining Admixture (WRA)

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2-MIXING UHPC

- Three main phases of mixing:
  - 1- Dry mixing of constituent materials to ensure homogeneity
  - 2- With water/ice and admixtures to achieve flowability
  - 3- With fibers to ensure uniformity of distribution

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2-MIXING UHPC

- Failure to mix UHPC properly could result in:
  - Lack of workability
  - Clumping of fibers or paste
  - Fiber segregation

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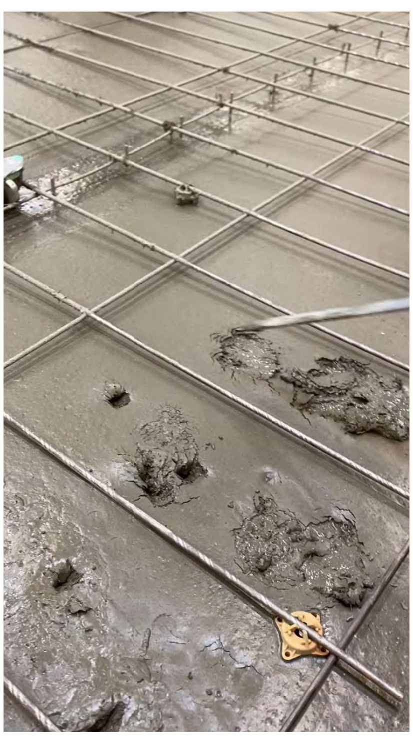

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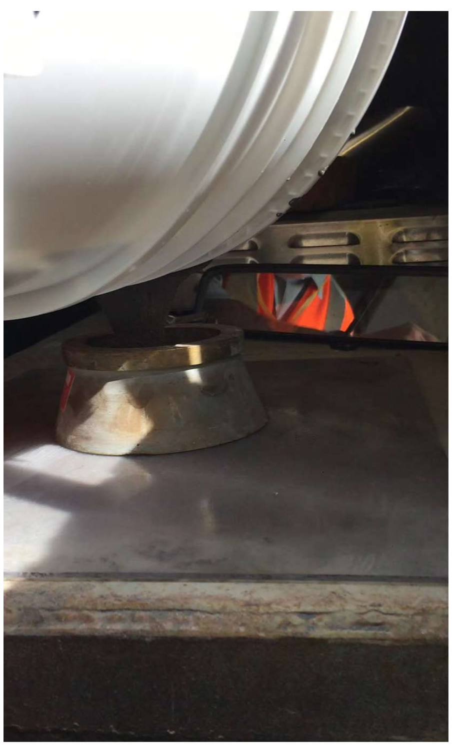

2-MIXING UHPC

- Mixer Requirements
  - Any concrete mixer can be used (drum, planetary, horizontal shaft, etc.)
  - High shear mixers are recommended due to the high mixing energy needed to transform the dry mix into fluid mix.
  - Using 50% of the mixer capacity is used to reduce the mixing duration.

For Lab Only:

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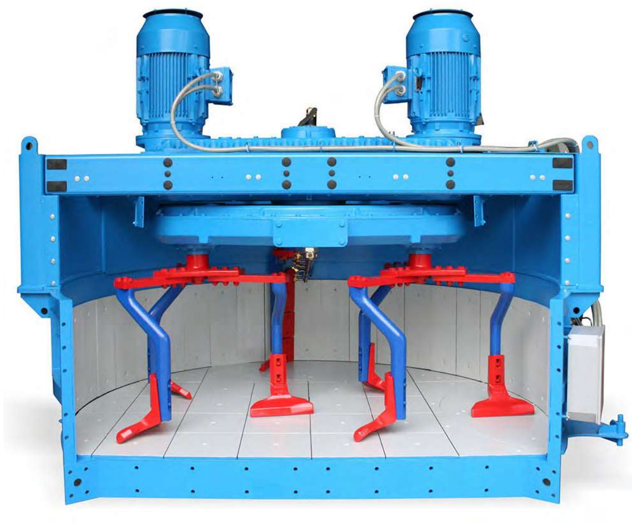
2-MIXING UHPC

For Field and Lab:

2-MIXING UHPC

For Plant Mixing:



2-MIXING UHPC

- Mixing Sequence and Duration

For Plant Mixing

Step #	Description	Duration (min)
1	Add sand automatically	1
2	Add silica fume bags manually	1
3	Mix dry	2
4	Add cement and slag automatically	1
5	Mix dry	2
6	Add water automatically	1
7	Add ice bags and admixtures manually	1
8	Mix until flowable	4
9	Dispense steel fibers manually	6
10	Mix with fibers	2
11	Discharge	2
12	Test Flow	2
	Total	**25**

For Field and Lab

Step #	Description	Duration (min)
1	Add sand and silica dume	1
2	Mix dry	2
3	Add cement and slag	1
4	Mix dry	2
5	Add water, ice and admixtures	1
6	Mix until flowable	10
7	Dispense steel fibers	2
8	Mix with fibers	2
9	Discharge	2
10	Test Flow	2
	Total	**25**

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MIXING PROCEDURE (LAB BATCHING)

Sand + silica fume Mix for 5 min (speed 1)	Cement + SCMs Mix for 5 min (speed 1)	80% water + 80% HRWR Mix for 7 min (speed 1)	20% water + 20% HRWR Mix for 7 min (speed 1)	Fibers Mix for 5 min (speed 1)

Mix for 30 sec (speed 2)

Mix ready

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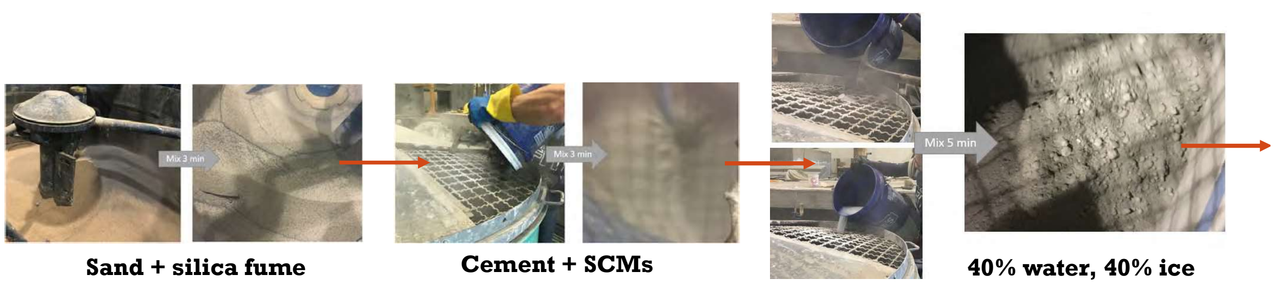
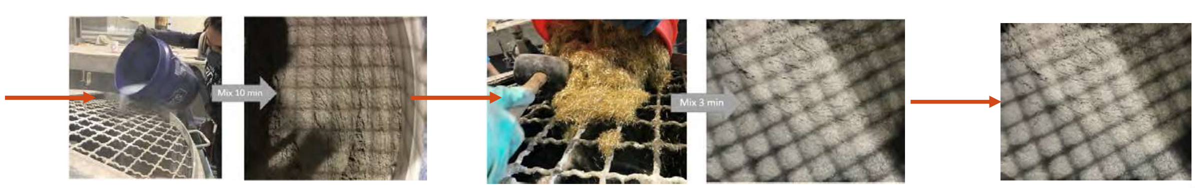
MIXING PROCEDURE (FIELD BATCHING)



Sand + silica fume

Cement + SCMs

40% water, 40% ice + 80% HRWR



20% water + 20% HRWR

Fibers

Mix ready

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Batch #	Mixer #	Step #	Description	Time (min.)																													
				2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60
1	1	1	Add & Mix Sand and Silica Fume																														
		2	Add & Mix Cement and Slag																														
		3	Add & Mix Water/Ice and Admixtures																														
		4	Add & Mix Steel Fibers																														
		5	Test Flow																														
		6	Discharge, Trasport, Pour & Return																														
2	2	1	Add & Mix Sand and Silica Fume																														
		2	Add & Mix Cement and Slag																														
		3	Add & Mix Water/Ice and Admixtures																														
		4	Add & Mix Steel Fibers																														
		5	Test Flow																														
		6	Discharge, Trasport, Pour & Return																														
3	3	1	Add & Mix Sand and Silica Fume																														
		2	Add & Mix Cement and Slag																														
		3	Add & Mix Water/Ice and Admixtures																														
		4	Add & Mix Steel Fibers																														
		5	Test Flow																														
		6	Discharge, Trasport, Pour & Return																														
4	1	1	Add & Mix Sand and Silica Fume																														
		2	Add & Mix Cement and Slag																														
		3	Add & Mix Water/Ice and Admixtures																														
		4	Add & Mix Steel Fibers																														
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		4	Add & Mix Steel Fibers																														
		5	Test Flow																														
		6	Discharge, Trasport, Pour & Return																														

3 Mixers

6 batches

4.5 ft^3 each

1 yd^3/hr

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MIXING

- FHWA - High shear mixer can be desirable. Maintaining a reduced temperature of 50°F to 60°F (10°C to 16°C) on stockpiled materials and in the mix water is recommended. Cubed ice has been demonstrated to be a viable replacement for some or all of the mix water when mixing operations occur during warm weather conditions.
- MIDOT - suggests high shear paddle mixers with 0.5 cu. yd. minimum capacity to be used. Paddle or scraper-to-pan wall clearance must be small enough to prevent the material being mixed from adhering to the sidewalls.

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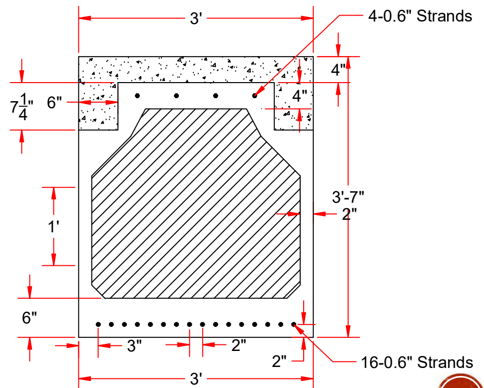
3-FORMING FOR UHPC

- Any forming material that is non-absorbing (plywood, steel, fiberglass, foam, concrete, etc.)
- Use chamfers, curves, and form release agents for ease of stripping
- Clear spacing between bars and formed surfaces is at least 1.5 x fiber length (min. ¾ in.)



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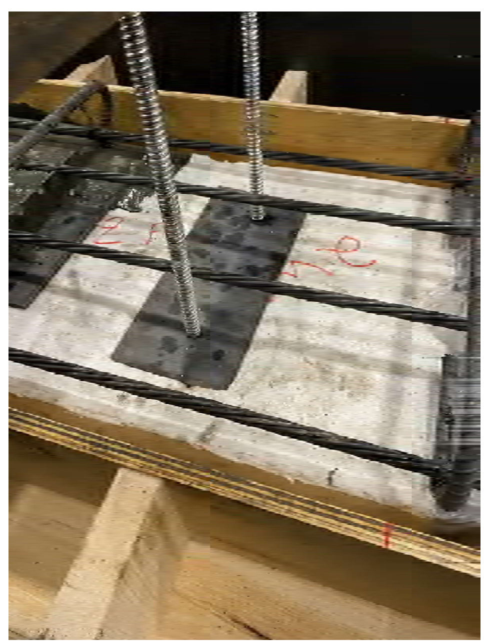
Full hydrostatic fluid pressure (use 160 pcf)



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Surface preparation of hardened concrete: Sandblasting or exposed aggregate plus pre-wetting

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3-FORMING FOR UHPC

Top form if sloped

Grout-tight forms

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FORMING

- FHWA - UHPC is typically places in a closed form, or the form is closed immediately after placement. On flat surfaces exposed to air, UHPC should be in contact with the top formwork to minimize surface dehydration. Formwork that will be in contact to UHPC should have a non-absorbing finish.
- MIDOT - The forms must be water tight and coated to prevent absorption of water. The formwork must be resistant to the hydraulic pressure of the mix.
- DCDOT - medium density overlay plywood pre wetted just ahead of the UHPC material. They need to be hand removal.

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FORMING

- FHWA - Good bonding has been demonstrated when the precast concrete element has exposed aggregate finish (it can be created applying a gelatinous retarder to the formwork where the finish is desired to delayed the hydration in that local). Pre-wetting the precast concrete interface immediately before The UHPC's placement also improves bonding.
- Caltrans - Pre-wet the precast members and forms. Before placing UHPC, voids must be free of dust, debris, and excess water.
- DCDOT - the surface preparation of the precast concrete in contact with UHPC shall have exposed aggregate finish.

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4-TRANSPORTING AND PLACEMENT

Any method that minimizes the following:

- Entrapment of air (cast from one side)
- Fiber segregation (no internal vibration)
- Forming cold joints/pour lines (min. time between lifts)
- Unfavorable alignment of fibers (direction of flow)
- Failure to fill the forms (add pressure head)
- Free Fall

No pumping

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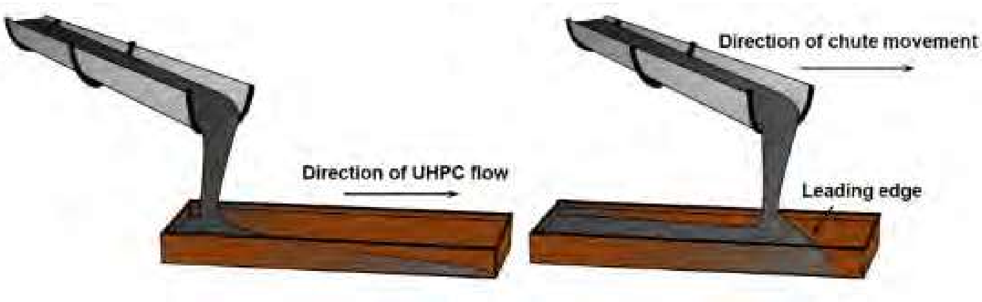
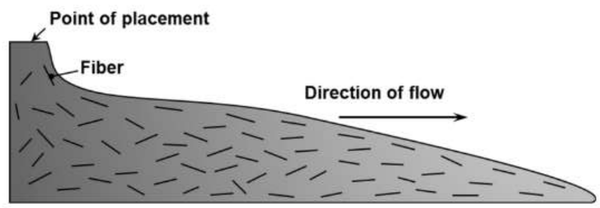

Direction of UHPC flow
Direction of chute movement
Leading edge


Point of placement
Fiber
Direction of flow

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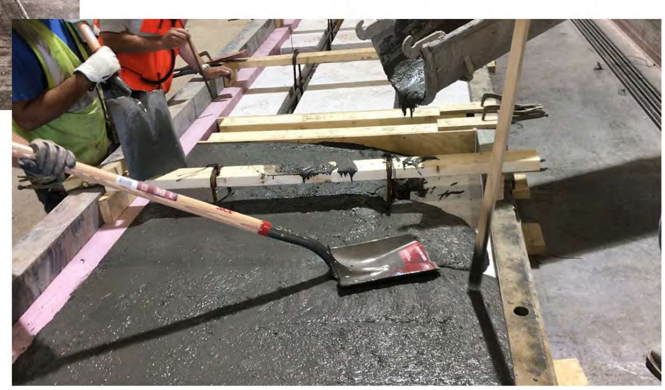

CASTING

- FHWA - UHPC should not be internally vibrated because of the detrimental impact that this type of vibration has on the fiber reinforcement.
- Caltrans - UHPC does not free-fall more than 2 feet, there are no cold joints and steel fibers has to be uniformly distributed.
- MIDOT - Pumping Mi-UHPC is not permitted. Do no place concrete at ambient air temperatures below 40ºF, nor above 90ºF. The fresh mix must not be allowed to flow farther than 24 inches during placement. Start the casting process at one end of the joint and proceed to the other end at a speed comparable to the flow speed of the fresh mix. Once the other end of the joint is reached, reverse the casting process and proceed in the other direction to cast another layer of Mi-UHPC. Continue this process until the full depth of the joint has been cast. Vibrators may not be used.

U.S. Department of Transportation Federal Highway Administration
Caltrans
MDOT Michigan Department of Transportation

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5-FINISHING

- Traditional finishing methods (screeding, raking, brooming) do not work with UHPC
- Spiked roller could be used to level the surface
- Vibratory screed is needed for stiff UHPC

5-FINISHING

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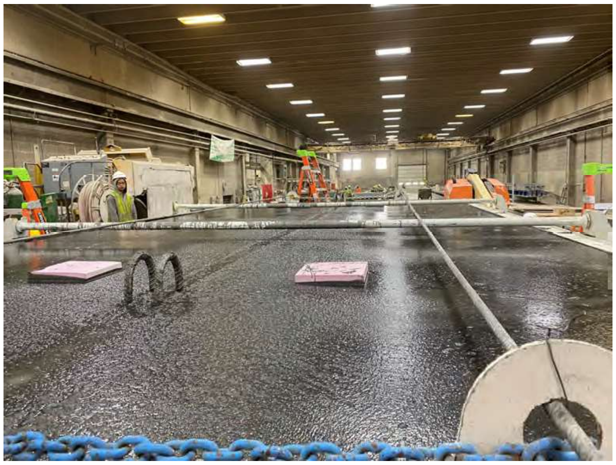
5-FINISHING

- Highly flowable UHPC could result in smooth surface without intervention



5-FINISHING

- Grinding of the UHPC surface can be performed when strength is at least 10 ksi, otherwise significant fiber pullout can happen.
- It is easier to grind joints when the strength is around 12 ksi than it is at full strength.

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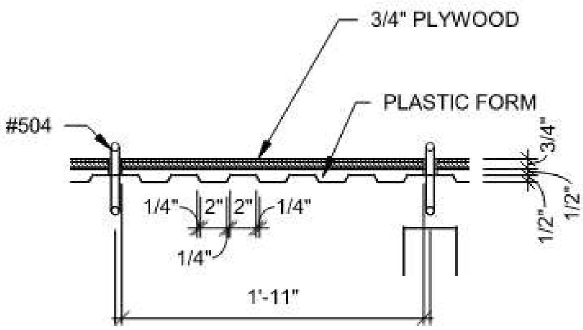
5-FINISHING

- Textured surfaces need to be formed



6-CURING

- Exposed surfaces must be covered immediately to prevent dehydration
  - Plastic sheets
  - Wood
  - Curing compound
  - Wet burlap
  - Insulated blankets

- At high temperature and low humidity, UHCP surface dries fast and cracks forming elephant shin

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6-CURING

- When cured at ambient temperature of about 73° F, concrete temperature may reach 160° F due to heat of hydration.
- Final set may take up to 24 hours due to the high dosage of admixtures
- Concrete strength usually exceeds 10 ksi in 48 hours
- For accelerated curing, higher temperature and humidity can be used.
- Post-Curing Thermal Treatment (PCTT)

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CURING

- FHWA - UHPC should remain sealed from exposure to the external environment until after initial set has occurred. UHPC can be moist cured because of the low permeability of the cementitious matrix. Supplemental heat (internally or externally) can be provided to the UHPC and the surrounding prefabricated elements to reduce initial set times and accelerate strength gain. Ideally, until UHPC reach 14 ksi (97 MPa) of compressive strength, relative movements should be minimized.
- GADOT - all specimens should be cured using the same method of curing proposed to be used in the field. A continuous curing temperature of a minimum of 60°F is recommended.
- MIDOT - The top surface of the concrete must be covered with insulating blankets. Do not apply curing compound. The concrete surfaces must be continuously cured with wet burlap.

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WORKSHOP ON PRODUCTION OF CAST-IN-PLACE UHPC FOR BRIDGE APPLICATIONS

Jiong Hu and George Morcous

3/16/2022

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  - UHPC testing
  - Q&A

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3 TESTING OF UHPC

OUTLINE/ LEARNING OBJECTIVES

- Workability
  - Recognize test procedure and criteria for UHPC workability
- Fiber stability
  - Understand test methods and criteria for fiber stability in UHPC
- Specimen casting
  - Recognize procedure for casting UHPC specimens for hardened concrete property test
- Mechanical properties
  - Recognize basic test methods and typical results of mechanical properties of UHPC

4

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WORKABILITY

FLOW TEST

Designation: C1437 – 15

Standard Test Method for Flow of Hydraulic Cement Mortar[1]

Designation: C1856/C1856M – 17

Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete[1]

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FLOW TEST

Designation: C1856/C1856M – 17

Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete[1]

6. Testing of Fresh Properties

6.1 *Flow:*

6.1.1 Determine the flow of freshly mixed UHPC in accordance with Test Method C1437, with the following exceptions.

6.1.1.1 The mold and flow table shall meet the requirements of Specification C230/C230M. The concrete pedestal and cork gasket are not required.

6.1.1.2 Fill the mold in a single layer with the fresh UHPC.

6.1.1.3 Do not tamp the UHPC in the mold and do not drop the table.

6.1.1.4 After lifting the mold, wait until a time of 2 min ± 5 s has elapsed.

6.1.1.5 Measure the diameter of the UHPC along the lines of maximum and minimum diameter, with a ruler or tape measure, recording each diameter to the nearest 1 mm [1⁄16 in.].Calculate the average of the two diameters measured. The flow value is this average.

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UHPC FLOW REQUIREMENTS

	ASTM C1856	FHWA	NYDOT	DCDOT	Caltrans	MDOT	GADOT	IADOT
Flow range (in)	8 to 10	7 to 10	7 to 10	7 to 10	7 to 10	7 to 12	7 to10	7 to 10

ACI MATERIALS JOURNAL TECHNICAL PAPER

Title No. 118-M114

Impact of Chemical Admixtures on Time-Dependent Workability and Rheological Properties of Ultra-High-Performance Concrete

by Flavia Mendonca and Jiong Hu

- Recommended flow: 7”-11” flow at two minutes (flow time should be no less than 45 seconds with standard 10” flow table)

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FIBER STABILITY

SOME IDEAS TO BORROW?

ASTM C1611

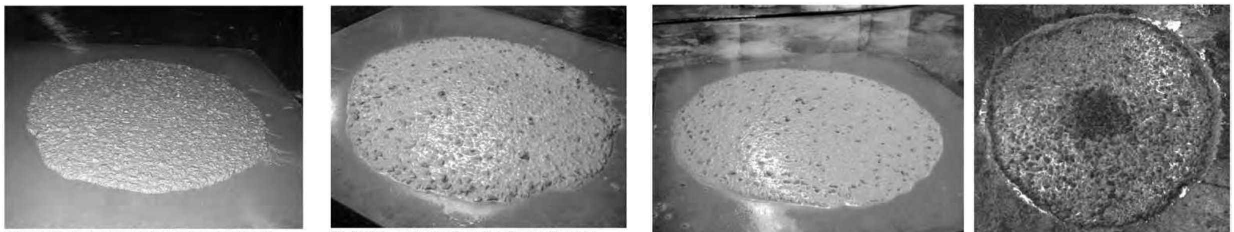


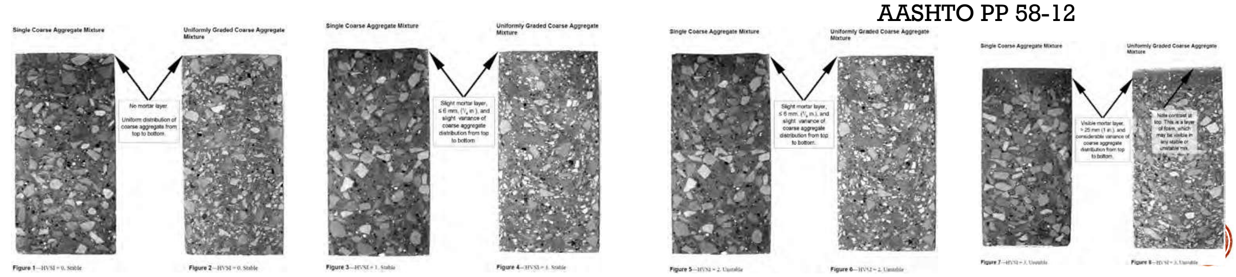
FIG. X1.1 VSI = 0 – Concrete Mass is Homogeneous and No Evidence of Bleeding.

FIG. X1.2 VSI = 1 – Concrete Shows Slight Bleeding Observed as a Sheen on the Surface.

FIG. X1.3 VSI = 2 – Evidence of a Mortar Halo and Water Sheen.

FIG. X1.4 VSI = 3 – Concentration of Coarse Aggregate at Center of Concrete Mass and Presence of a Mortar Halo.

AASHTO PP 58-12



VISUAL STABILITY INDEX (VSI) FOR UHPC

VSI value	Criteria
0 = Highly stable	No evidence of fiber agglomeration and separation
1 = Stable	Fibers slightly agglomerated (agglomerate size less than 2") but do not clearly separate from the mixture
2 = Unstable	Fibers are slightly agglomerated (agglomerate size between 2" and 3") and separated from the mixture
3 = Highly unstable	Fibers are clearly agglomerated (agglomerate size between 3" and 5" and separated from the mixture
4 = Extremely unstable	Fibers are severely agglomerated (agglomerate size larger than 5") and clear separation from the mixture

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HARDENED VISUAL STABILITY INDEX (HVSI) FOR UHPC

ACI MATERIALS JOURNAL TECHNICAL PAPER

Title No. 118-M114

Impact of Chemical Admixtures on Time-Dependent Workability and Rheological Properties of Ultra-High-Performance Concrete

by Flavia Mendonca and Jiong Hu

HVSI value	Criteria
0 = Highly Stable	No apparent fiber-free or low fiber content layer observed at the top of the cut plane. Uniform distribution of fiber from top to bottom.
1 = Stable	A thin fiber-free or low fiber content layer (thickness ≤ 0.5”) can be observed at the top of the cut plane with none or relative less amount of fibers.
2 = Unstable	A clear fiber-free or low fiber content layer (0.5” < thickness ≤ 1”) can be observed at the top of the cut plane with none or relative less amount of fibers.
3 = Highly unstable	A very significant fiber-free or low fiber content layer (3” < thickness ≤ 3”) can be observed at the top of the cut plane.
4 = Extremely unstable	The majority (thickness ≥ 3”) of the specimen was fiber-free or low fiber content.

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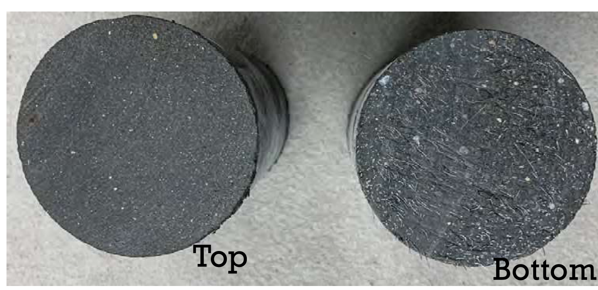
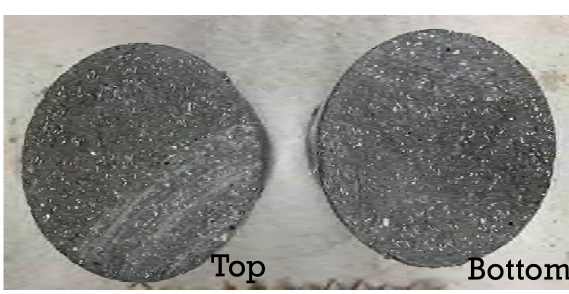
FIBER STABILITY



Appearance of grinded ends



Appearance of specimens after compressive strength test

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15 SPECIMEN PREPARATION

SPECIMENS DIMENSION

Designation: C1856/C1856M – 17

Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete[1]

TABLE 1 Summary of Specimen Sizes

Property	Test Method	Nominal Specimen Sizes	Comments
Compressive Strength	C39/C39M	75 mm by 150 mm [3 in. by 6 in.]	
Flexural Strength	C1609/ C1609M	See 8.2.2	Sizes change with fiber length

TABLE 3 Dimensions of Beams for Measuring Flexural Strength

Maximum Fiber Length (l_f)	Nominal Prism Cross Section
< 15 mm [0.60 in.]	75 mm by 75 mm [3 in. by 3 in.]
15 mm to 20 mm [0.60 in. to 0.80 in.]	100 mm by 100 mm [4 in. by 4 in.]
20 mm to 25 mm [0.80 to 1.00 in.]	150 mm by 150 mm [6 in. by 6 in]
>25 mm [1.00 in.]	200 mm by 200 mm [8 in. by 8 in.]

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SPECIMENS PREPARATION

7.2 *Molding of Specimens:*

7.2.1 Fill cylinder molds in one layer.

7.2.2 Fill prism molds from one end, in one layer.

7.2.3 Consolidate all specimens by tapping the sides of the mold 30 times with the mallet.

7.2.4 Tamping rods and internal vibrators shall not be used in fabricating and consolidating specimens from UHPC.

- Continuous pouring in one layer
- Tapping the sides
- Cover immediately after casting

Designation: C1856/C1856M – 17

Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete[1]

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CURING

- Cover specimens immediately after casting
- 24 hours in mold
- Curing room or lime-saturated water till testing

Designation: C1856/C1856M – 17

Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete[1]

7.3 *Curing:*

7.3.1 Cure field-fabricated specimens in accordance with Practice C31/C31M and cure laboratory-fabricated specimens in accordance with Practice C192/C192M, with the following exception.

7.3.1.1 Within 1 min after finishing the top surface, cover the specimen to prevent drying of the top surface.

NOTE 2—UHPC contains low quantities of mixing water and virtually no bleed water, resulting in surface drying that may impact the hardened properties, therefore it is important to cover the surface of the specimen with a plastic sheet or equivalent as quickly as possible.

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19 HARDENED CONCRETE

COMPRESSIVE STRENGTH (ASTM C1856 & ASTM C39)

End Grinder

Test Setup

- 3″ x 6″
- 145±7 psi/sec.

8.1 *Compressive Strength:*

8.1.1 Determine the compressive strength in accordance with Test Method C39/C39M, with the exceptions described in this section.

8.1.2 Only 75 mm [3 in.] diameter by 150 mm [6 in.] long cylindrical specimens shall be used for compressive strength testing.

NOTE 4—If molds in SI units are required and not available, the inch-pound mold should be permitted.

8.1.3 Prior to testing, all cylinders shall be end ground such that the ends do not depart from perpendicularity to the axis by more than 0.5° (approximately equivalent to 1 mm in 100 mm [0.05 in. in 5 in.]). The ends of the cylinders shall be ground plane to within 0.050 mm [0.002 in.].

8.1.4 Capping compounds and unbonded neoprene pads shall not be used.

8.1.5 The diameter used for calculating the cross-sectional area of a cylindrical test specimen shall be determined on each cylinder to the nearest 0.1 mm [0.04 in.].

NOTE 5—The diameter is measured to a greater accuracy than Test Method C39/C39M.

8.1.6 *Rate of Loading*—The load shall be applied at a rate of movement (platen to crosshead measurement) corresponding to a stress rate on the specimen of 1.0 ± 0.05 MPa/s [145 ± 7 psi/s].

NOTE 6—Conventional load rates as specified in Test Method C39/C39M would require approximately 15–20 min to complete a test.

NOTE 7—For a 75-mm [3 in.] diameter specimen, the loading rate is 265 ± 13 kN/min [61 500 ± 3 000 lb/min].

With Fibers

Without Fibers

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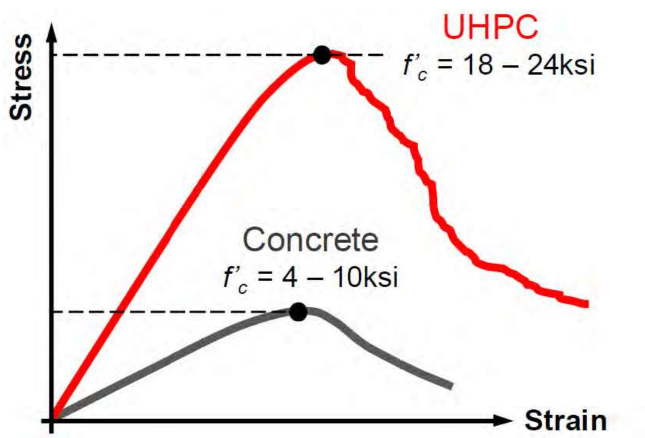
COMPRESSIVE STRENGTH TEST
TYPICAL STRESS-STRAIN CURVE



Source: FHWA

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FLEXURAL STRENGTH (ASTM C1856 & ASTM C1609)

Test Setup

- 3″ x 3″ x 14″ Prisms (1/2″ length fibers)
- 0.003 in./sec. ------ up to δ = L/900
- 0.008 in./sec. ------ up to δ = L/150 = 0.08 in.

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Designation: C1609/C1609M – 19a

Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)[1]

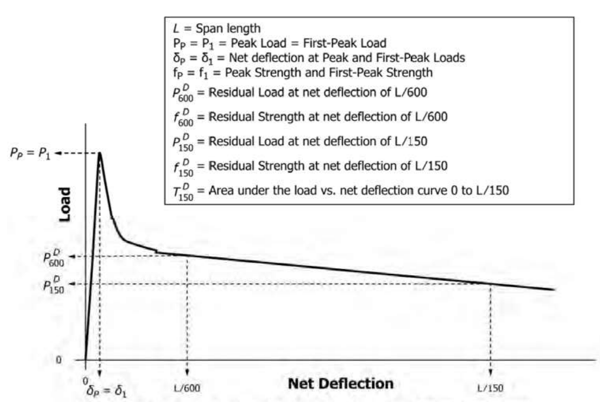
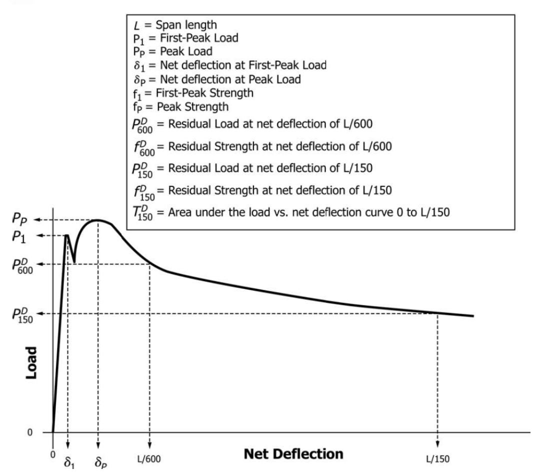


FIG. 3 Example of Parameter Calculations for First-Peak Load Equal to Peak Load (Not to Scale)



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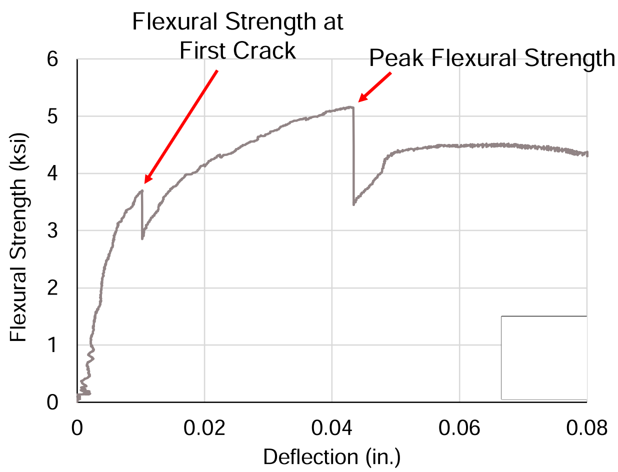
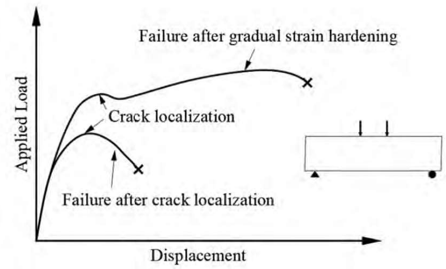
FLEXURAL STRENGTH TEST

TYPICAL STRESS-STRAIN CURVE





Failure Mode

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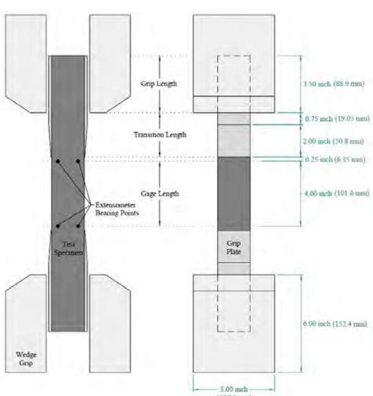
DIRECT TENSILE TEST



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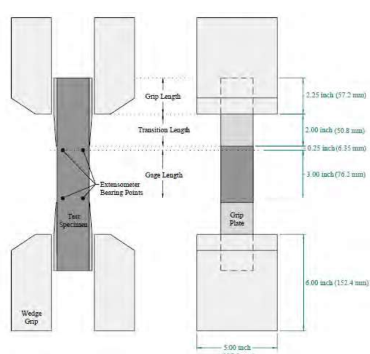

Source: FHWA.

Source: FHWA.

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New AASHTO Standard coming soon

DIRECT TENSILE TEST

- ❑ 2″ x 2″ x 24″ Prisms
- ❑ Aluminum grips from both ends.
- ❑ Load rate of 700 lb/min.

Specimen Form

Specimen Preparation

Test Setup

Failure Mode

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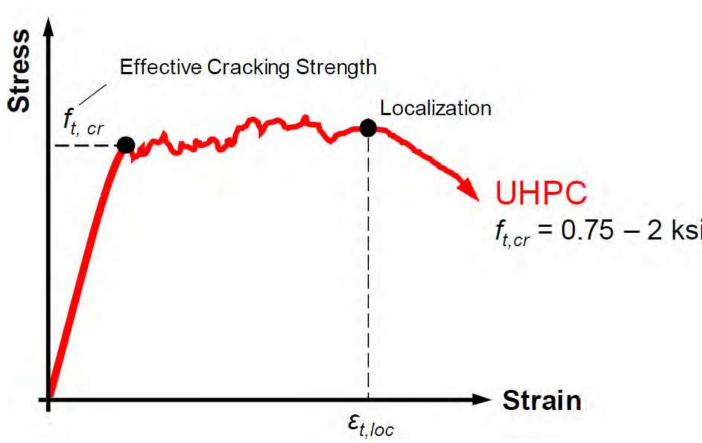
DIRECT TENSILE TEST
TYPICAL STRESS-STRAIN CURVE



Source: FHWA

Source: FHWA.

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QUESTIONS?

WORKSHOP ON PRODUCTION OF CAST-IN-PLACE UHPC FOR BRIDGE APPLICATIONS

Jiong Hu and George Morcous

3/16/2022

NEBRASKA
Good Life. Great Journey.
DEPARTMENT OF TRANSPORTATION

COLLEGE OF ENGINEERING

WORKSHOP OUTLINE

- **Morning Session: Lecture and Discussion**
  - Introduction of UHPC
  - Production of UHPC
  - Break
  - Testing of UHPC
  - UHPC experiences – case studies
  - Discussions and Q&A
- **Afternoon Session: Hands-on Experience**
  - UHPC batching, casting and specimen preparation
  - UHPC testing
  - Q&A

UHPC EXPERIENCE AND CASE STUDIES

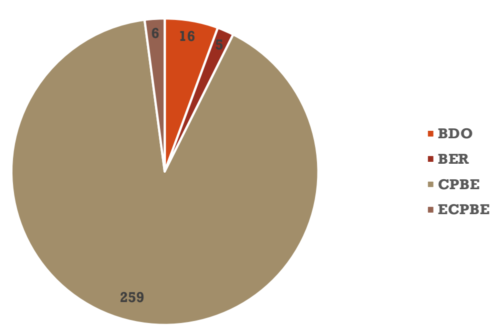
UHPC PROJECTS IN US

- Interactive Map

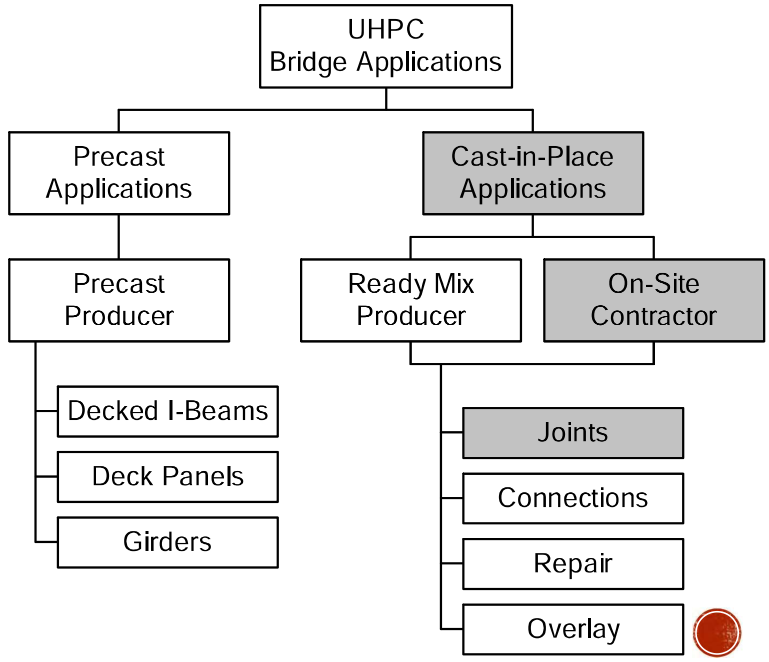
https://usdot.maps.arcgis.com/apps/webappviewer/index.html?id=41929767ce164eba934d70883d775582

UHPC PROJECTS IN US

Abbreviation	Definition
CPBE	connections between prefabricated elements
BDO	bridge deck overlay
BER	beam end repair
EJP	expansion joint header
ECPBE	repair of connections between existing prefabricated elements
PCG	precast, pretensioned UHPC girder
PCP	precast, pretensioned UHPC pile
PCD	precast deck
PR	minor preservation or repair application



UHPC IN NEBRASKA



UHPC EXPERIENCE

1. Field-Cast UHPC
   - Belden-Laurel Bridge
2. Plant-Cast UHPC
   - Slab Production
   - Box Beam Production
   - Decked I-Beam Production
3. Lab-Cast UHPC
   - Shear Strengthening Beam
   - Longitudinal Joint

FIELD-CAST UHPC

Belden-Laurel Bridge 2018

PLANT-CAST UHPC

Slab form and Ribbed Slab
(Coreslab 2019)

PLANT-CAST UHPC

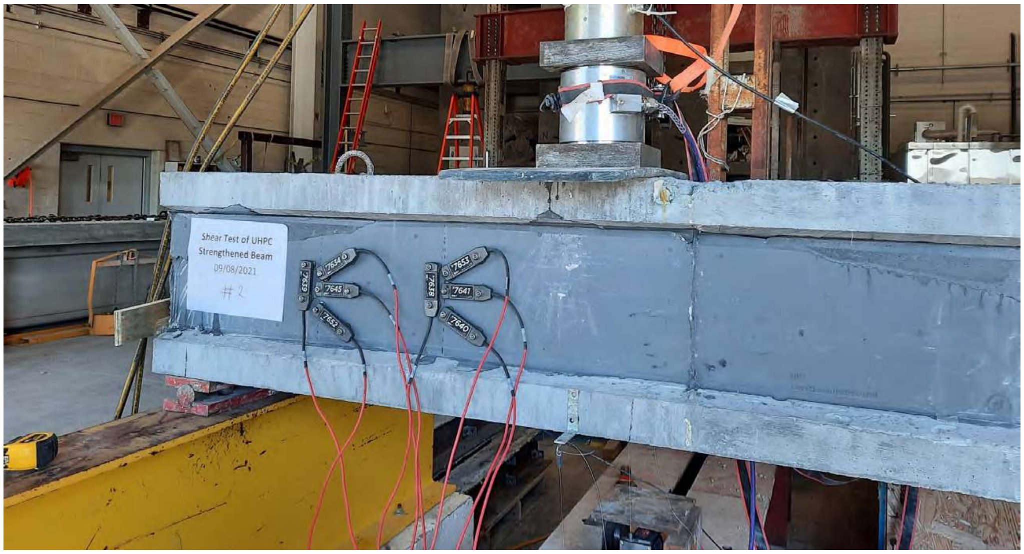
Box Beam with openings (Gage Brothers 2021)

PLANT-CAST UHPC

Decked I-Beam (Concrete Industries 2022)

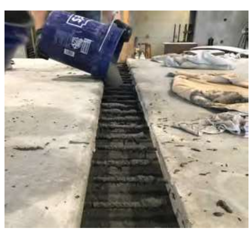
LAB-CAST UHPC

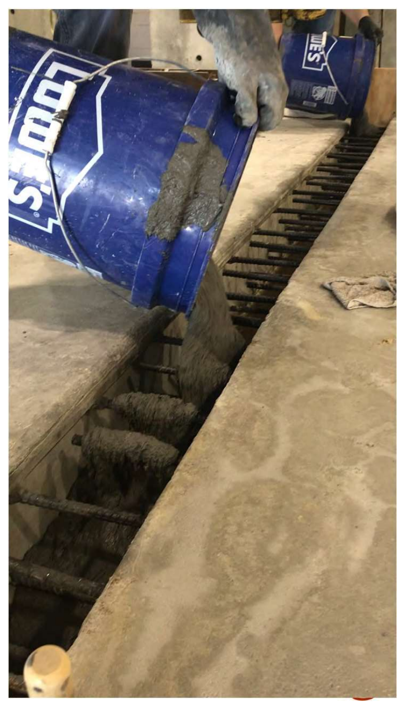
Shear Strengthened Beam 2021



LAB-CAST UHPC

Longitudinal Joint, 2020





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3 DISCUSSIONS AND Q&A

4 QUESTIONS IN THE FUTURE?

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5 DEMONSTRATION AND HANDS-ON SESSION

ACTIVITIES

- UHPC Batching (2 ft^3)
- Fresh Concrete Test (flow test)
- Specimen Casting
  - Cylinders, prisms, mock up slab casting
- Hardened Concrete Testing
  - Grinding, compressive strength, flexural strength

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PRODUCTION OF CAST-IN-PLACE UHPC FOR BRIDGE APPLICATIONS

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15. Supplementary Notes		

16. Abstract
This project presents a comprehensive overview of the essential aspects associated with the cast-in-place application of UHPC, including formwork requirements, surface preparation, mixing procedures, placing methods, curing techniques, grinding specifications, and mockup construction. Each section provides in-depth insights into specific guidelines and practices outlined by various regulatory bodies. The research team has developed training materials designed for a full-day workshop tailored to benefit both contractors and NDOT engineers. This workshop comprises key topics such as proportioning, batching, testing, and the placement of both non-proprietary and proprietary UHPC mixes, as well as hands-on experience in batching, testing, and placing UHPC. The study investigating fresh and hardened UHPC tests to identify fiber segregation reveals that excessive water or the use of high-range water-reducing admixtures (HRWR) can lead to fiber segregation, which is observable in both fresh and hardened states. Techniques such as Visual Stability Index (VSI) and Hardened Visual Stability Index (HVSI) are somewhat subjective, while tests like the mini-V-funnel and falling ball tests provide more objective measures. Flow time shows promise as an indicator of fiber stability, but further research and data are required to establish Quality Assurance/Quality Control (QA/QC) ranges. The study also underscores the potential of surface resistivity testing and calls for more extensive research to refine these tests for practical application in construction. The experimental work explores the influence of shrinkage-reducing admixtures (SRA) and shrinkage-compensating admixtures (SCA) on UHPC. Optimal SRA dosage effectively mitigates both total and autogenous shrinkage of UHPC, with total shrinkage decreasing from 718με to 453με at 28-day (830με to 549με at 180-day) and autogenous shrinkage dropping from 571με to 311με at 28-day (731με to 472με at 180-day). The effectiveness of SCA varies, and its impact on shrinkage is significant under specific hot batch curing conditions, although such methods may not be feasible for all concrete applications. The report also included a draft of the special provision for cast-in-place (CIP) UHPC.

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Chapter 1 Introduction

1.1 Background

Ultra-High Performance Concrete (UHPC) represents a groundbreaking advancement in concrete technology, boasting mechanical and durability characteristics significantly surpassing traditional concrete. Its application in bridge construction promises notable enhancements in structural integrity and longevity. UHPC's outstanding qualities have garnered considerable attention within the bridge community, including recognition at the federal and state levels. In addition to its widespread use in bridge deck connections across various states, the Federal Highway Administration's Every Day Counts (EDC-6) program, titled "UHPC for Bridge Preservation and Repair", underscores its potential in bridge applications due to its exceptional mechanical strength and durability.

The Nebraska Department of Transportation (NDOT) has successfully implemented UHPC in bridge deck connections/joints, notably in the Primrose East Bridge (2013) and Belden-Laurel Bridge (2018), as illustrated in Figure 1.1. However, the UHPC unit cost in these projects was steep, reaching up to $13,000 per cubic yard. This high cost was primarily due to the expensive materials, shipping, equipment, and associated costs for transportation and accommodation of technicians using proprietary mixes. To counter this, the research team, through the NDOT project SPR-P1(18) M072 titled "Feasibility Study of Development of Ultra-High Performance Concrete for Highway Bridge Applications in Nebraska", has developed a more affordable non-proprietary UHPC mix using local materials, reducing the material cost to approximately $740 per cubic yard, a significant decrease from the $1,956 to $3,719 per cubic yard for commercially available UHPC mixtures as reported by Alsalman et al. (2020).While the development of non-proprietary UHPC mixes is a promising step towards broader adoption, the lack of expertise in batching and handling these materials remains a challenge. Recent efforts by

FHWA, various state agencies, and the Precast/Prestressed Concrete Institute (PCI) have led to the creation of UHPC use guidelines, particularly for the design and production of precast components in building and bridge applications. Additionally, ongoing projects and document developments by the American Association of State Highway and Transportation Officials (AASHTO), FHWA, American Concrete Institute (ACI) Technical Committee 239 (UHPC), and other state bodies are in progress. However, a notable gap exists in comprehensive guidelines for cast-in-place (CIP) UHPC production and handling, especially concerning non-proprietary mixes.

Figure 1.1 Proprietary UHPC batching during Belden-Laurel Bridge construction in 2018

UHPC's unique composition, featuring a high concentration of fine powders and an extremely low water-to-cement ratio, necessitates a batching and proportioning process that differs markedly from that of conventional concrete. Although UHPC is known for its high flowability, achieving the desired workability while ensuring stability poses a significant challenge. Excessive flowability can cause fiber segregation, whereas UHPC's inherent viscosity might result in inadequate flow and consolidation. A notable characteristic of UHPC is the rapid loss of workability, attributed to the high content of high-range water-reducing (HRWR) admixtures. It complicates its transportation and placement due to its inability to retain self-consolidation properties for extended periods. Preliminary studies indicate the need for specific guidelines to manage UHPC's workability and stability effectively under static and dynamic conditions.

Furthermore, our research team has recently completed a project developing a cost-effective, non-proprietary UHPC using local materials, as detailed in Table 1.1. However, this alternative to commercial UHPC faces two primary challenges hindering its application in cast-in-place scenarios: the lack of specialized training and experience in UHPC batching and handling, and the absence of guidelines to monitor and maintain workability during construction.

Table 1.1 UNL-NDOT non-proprietary UHPC mix

Mix ID	Cement	Silica Fume	Slag	Water	Ice	Sand	Fiber	HRWR	w/b
I/II: SF8:S30:B1900	1207	161	585	215	94	1603	266	66.1	0.182

Material Type	Description	Source
Sand	No.10 sand	Lyman-Richey, Omaha, NE
Cement	Type I/II	Ash Grove Cement Company, Louisville, NE
Slag	Slag	Central Plains Cement Company, Omaha, NE (terminal)
Silica fume	Force 10,000 densified microsilica	GCP Grace Construction Products
Fiber	13/.20 micro steel fiber	HiPer Fiber, LLC.
HRWR	Premia 150	Chryso

Contrary to the precast industry, where a well-controlled environment and established procedures adeptly accommodate innovative materials like UHPC, its production in cast-in-place settings presents significant challenges. Local concrete producers and contractors frequently lack the necessary training and experience for effective production and handling of UHPC. As illustrated in Figure 1.2, the current project focuses primarily on cast-in-place UHPC applications. This includes its use in bridge construction elements such as connections, joints, and repairs, specifically in batching and joint nosing areas.

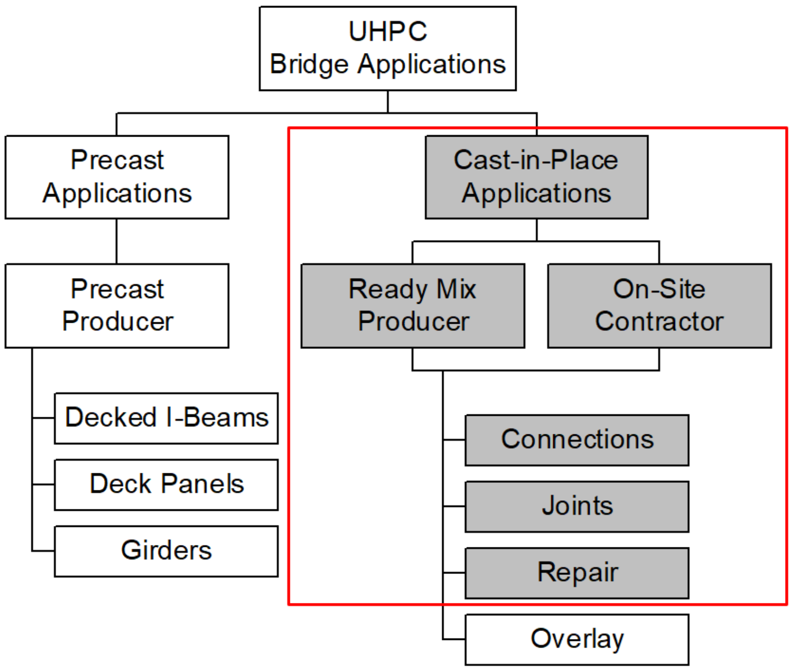


Figure 1.2 Scope of the proposed study

The research team conducted a comprehensive workshop and hands-on activities to provide essential technical training for producers, contractors, and NDOT engineers. This training covered the entire process of mixing, transporting, placing, curing, and testing cast-in-place UHPC, which is vital for achieving optimal flowability, fiber stability, and workability to prevent issues such as cold joints. To guide these processes, the research team developed specific guidelines with criteria to control and maintain UHPC workability under ready-mixed and on-site conditions. A critical aspect of this project was investigating UHPC's shrinkage behavior, focusing on mitigating cracking risks, which included both total and autogenous shrinkage, particularly in shrinkage-reducing and shrinkage-compensating admixtures. Additionally, the research team prepared specialized provisions of CIP UHPC for NDOT to promote broader utilization.

While UHPC promises substantial enhancements in the structural capacity and durability of bridge components, its widespread adoption in Nebraska has been hindered by a notable gap in training and expertise in batching and handling the material. Addressing this, there's an urgent need to develop comprehensive guidelines and training materials for producers and contractors. The proposed work is timely and holds significant potential for immediate implementation by NDOT. The outputs of this project, encompassing detailed guidelines, training materials, and special provisions, will be made accessible to producers and contractors through NDOT, paving the way for future UHPC projects. This study is poised to yield significant benefits, foremost among them being the ability to address the challenges associated with UHPC production and on-site construction. A lack of experience and established best practice guidelines raises concerns among producers and contractors. By providing the necessary knowledge and technical support for UHPC production and construction, this project aims to alleviate these concerns. The anticipated success of this initiative is expected to greatly encourage producers and contractors to embrace this innovative material, particularly in cast-in-place bridge applications, marking a significant advancement in construction methodologies.

1.2 Objectives

The primary goal of this study is to equip NDOT and contractors with essential technical support and comprehensive documentation, enhancing their capability to produce CIP UHPC effectively. To achieve this, the project sets forth several key objectives:

- To provide in-depth technical training for producers, contractors, and NDOT engineers, covering all aspects necessary for batching, mixing, transporting, placing, and testing cast-in-place UHPC;
- To develop thorough guidelines that not only facilitate UHPC production but also focus on controlling and maintaining UHPC workability under on-site conditions; and
- To create specialized provisions that guide the production and ensure the quality control of cast-in-place UHPC.

These concerted efforts are directed toward streamlining UHPC production processes and elevating the quality standards in construction projects.

1.3 Report Organization

This project report is organized into six comprehensive chapters. It begins with an introduction, followed by Chapter 2, which delves into a detailed background on the issue of excess aggregate dust in concrete and provides a summary of the state-of-the-practice for cast-in-place Ultra-High Performance Concrete (UHPC). Chapter 3 showcases the training materials utilized in the hands-on UHPC workshop. The subsequent chapters, Chapters 4 and 5, offer an in-depth analysis and results from the study focusing on the stability of UHPC and its shrinkage characteristics, particularly when using shrinkage-reducing and compensating admixtures. Chapter 6 presents a draft of the special provision for cast-in-place (CIP) UHPC.

Chapter 2 State-of-The-Practice of Cast-in-Place UHPC

2.1 Introduction

Although UHPC remains a relatively novel concept, its successful application in field projects, particularly in bridge deck connections and repairs, has been documented across several states. To deepen our understanding, the research team undertook a comprehensive review of past experiences, current practices, and specifications pertaining to UHPC, emphasizing aspects such as batching, placing, curing, and quality control. Note that due to the focus of this project, the summary is focused on cast-in-place UHPC, and information specified as applicable to precast UHPC elements is not presented here. Further details on the production of UHPC for precast applications are available in the PCI Guidelines for the Use of Ultra-High-Performance Concrete (UHPC) in Precast and Prestressed Concrete (TR-9-22) (2022). Insights into the state-of-the-practice of cast-in-place UHPC, derived from this extensive review, are detailed in the subsequent sections.

2.2 Formwork

Table 2.1 summarizes the formwork requirements for UHPC as specified by various agencies, providing a comprehensive overview of the differing guidelines in place.

Table 2.1 Formwork requirements specified by different agencies

	Agency	Requirements
Formwork Material and Preparation	MIDOT	Formworks for UHPC must be watertight, coated to prevent water absorption, and strong enough to resist hydraulic pressure.
	FHWA (Graybeal, 2014); CDOT (2018)	Formwork should have a non-absorbent finish.
	CALTRANS (2017)	Formwork surfaces must be free of dust, debris, and excess water before UHPC placement.
	DDOT (2014)	Formwork should be made with medium-density overlay plywood formwork, which should be pre-wetted before UHPC placement.
	NYSDOT (2023); PennDOT (2021)	Formwork should made with plywood forms coated with a form release agent from the Department's Approved List of Materials.
	IADOT (2022)	Forms should be constructed from transparent plexiglass and follow approved installation drawings.
Formwork Design and Construction	ACI (2018); FHWA (Graybeal and Leonard, 2018)	Forms must be sealed properly to support the full hydrostatic pressure head of UHPC. Enclosed formworks should have an exit for trapped air.
	FHWA (Graybeal and Leonard, 2018)	Deck-level connections require top forms with adequate hold downs, and should be set at least 1/4" (6 mm) above the deck's top for overfilling.
	PCI (2022)	Forms should be grout-tight to prevent leakage of the UHPC after placement and should be constructed to minimize the restraint of early-age volumetric changes of the fresh and setting UHPC. The clear spacing between the faces of the formwork and any internal reinforcing or adjacent formwork should be no less than 1.5 times the fiber length or maximum aggregate size, whichever is greater, to permit adequate flow and consolidation of the UHPC.
Formwork Removal	FDOT (2018)	Formworks can be removed after 24 hours of UHPC placement or based on the manufacturer's recommendations.
	DDOT (2014)	Hand removal of the formwork is required.
Formwork Inspection	FHWA (Graybeal and Leonard, 2018); PennDOT (2021)	Formwork should be periodically inspected for leaks during casting, including the underside of the deck.

2.3 Surface Preparation

The bond between existing structures or precast concrete elements and UHPC plays a pivotal role in guaranteeing a robust connection while preventing water infiltration and the subsequent degradation of both concrete and rebar (Graybeal, 2014). Table 2.2 summarizes the surface preparation requirements for UHPC as outlined by various agencies, detailing the essential guidelines for effective application.

Table 2.2 Surface preparation requirements specified by different agencies

	Agency	Requirements
Surface Preparation of Precast Components	FHWA	Surface of the existing structure or precast components should be pre-wet to a surface-saturated condition, free of debris, and prepared with micro and macro textures like exposed aggregates before UHPC placement.
	DDOT (2014)	Existing structure or precast concrete in contact with UHPC should have an exposed aggregate finish.
	NYSDOT (2023)	Average amplitude of the exposed aggregate surface should be 1/8”. Roughened surface of existing concrete should be continuously wetted, with surface water removed right before UHPC placement.
	FDOT (2018)	Average amplitude of the exposed aggregate surface should be between 1/8” to 3/16”.
	CDOT (2018)	Average amplitude of the exposed aggregate surface should be within 1/4"±1/8”, achievable through the application of a form retarder.
Aesthetic Considerations	NYSDOT (2023)	color of UHPC should match the surrounding concrete in areas visible to traffic

2.4 Mixing Procedure

UHPC's distinctive composition, marked by the absence of coarse aggregate and a notably low water-to-binder ratio (w/b), necessitates using high-shear pan mixers for patching purposes. These mixers improve efficiency with specially designed paddles that scrape materials from the mixer walls, ensuring a more uniform mix (Graybeal, 2014). However, using lower-energy mixers can inadvertently raise the temperature of UHPC, leading to a stiffer mixture (ACI, 2018). Additionally, the diversity in paddle shapes, mixer sizes, and mixing speeds contributes to varying levels of energy input, affecting the final product.

The process of loading, mixing, and the duration of mix time are crucial to achieving consistency and uniformity in UHPC. Research by El-Tawil et al. (2018) highlights how the mixing speed impacts UHPC's performance, with higher speeds enhancing workability and reducing the turnover time—the period needed for the materials to transition from powder to liquid form. Consequently, different mixing procedures might be required in field applications, depending on the rotational speed and size of the mixer's paddles.

The systematic sequence of loading and mixing materials for UHPC is critical due to its significant fine particle content and the substantial energy required for adequate mixing. The standard process generally involves three principal steps: initially blending all powder and aggregate materials for a period ranging from 30 seconds to 10 minutes, then adding water and High-Range Water-Reducing (HRWR) admixtures, and ultimately integrating fibers into the mix. This approach is bolstered by numerous studies, which recommend a total mixing duration of 5 to 12 minutes before adding fibers, as substantiated by research from Yu et al. (2014, 2015), Bonneau et al. (1997), Ambily et al. (2014), Meng et al. (2016, 2017), Wu et al. (2016), Yang et al. (2009), and Shi et al. (2015). Specific methodologies vary: some researchers, like Wille et al. (2011), Alkaysi (2015), Naaman et al. (2012), Graybeal (2013), and Berry et al. (2017), suggest first mixing dry silica fume and aggregate for 5 minutes, followed sequentially by cement and Supplementary Cementitious Materials (SCMs), water and HRWR, and finally fibers. Alternative approaches include the proposal by De Larrard and Sedran (1994) to mix powders with liquid to create a homogenous slurry before adding sand. El-Tawil et al. (2018) proposed another technique that involves dividing sand into two parts: mixing the first part with powder materials, then adding liquid, followed by the second part of sand, and eventually the fibers.

Table 2.3 offers a detailed summary of the mixing requirements for UHPC as specified by various agencies, outlining essential guidelines for its practical application and ensuring optimal results.

Table 2.3 Mixing requirements specified by different agencies

	Agency	Requirements/Recommendations
Considerations for Mixing Efficiency and Temperature Management	ACI (2018)	Mixing usually continues until UHPC transitions from powder to fluid mixture, depending on mixer energy.
	ACI (2018); FDOT (2018); CDOT (2018)	To address the issue of a stiffer mixture due to extended mixing the UHPC's temperature can be increased, replacing half or all of the water with ice or cooling constituent materials before mixing is recommended.
	FDOT (2018)	UHPC's temperature should be lower than 85°F during batching.
	CDOT (2018)	UHPC’s mixing temperature should be between 55-90°F during batching.
	PCI (2022)	Mixer may only be able to handle one-half to two-thirds of its nominal capacity). Trial batching may be the best process for determining the optimal batch size for a mixer. Adding fibers through gratings with openings equal to one-half to two times the length of the fiber or using purpose-built fiber-dispensing equipment that breaks up clumps and gradually adds the fibers can be beneficial. Workers should use appropriate personal protective equipment when distributing fibers manually.

2.5 Placing Methods

Effective placement methods for UHPC are pivotal to guarantee structural integrity, peak performance, and durability in construction projects. UHPC's distinct properties, including high flowability, self-consolidating nature, and significant viscosity, necessitate tailored placement techniques. Typically, UHPC mixes are deposited in formwork or molds in a single lift, eschewing the need for consolidation (Meng and Khayat 2016). Due to its high viscosity, has a limited ability to flow over long distances during placement.. Graybeal and Leonard (2018) specify that temperature and flow during and after mixing should be within project specifications. Table 2.4 provides an exhaustive summary of these UHPC placement requirements and practices as specified by different agencies, encapsulating critical guidelines to ensure its practical application and optimal outcomes.

Table 2.4 Placing requirements specified by different agencies

	Agency	Requirements
Specific Procedures and Techniques for UHPC Placement	FHWA (Graybeal, 2014)	Flow distance should be limited to 24 inches during placement. Material is suggested to be poured from one end of the joint until the full depth is cast, with no vibration necessary.
	PennDOT (2021)	Use of vibrating screeds is allowed under certain conditions.
	CDOT (2018)	Material should not be traveling more than 15 feet during placement.
	FHWA, Graybeal and Leonard, 2018; PennDOT, 2021	For deck-level connections, top forms should be installed and tapped with a hammer to check fullness, and chimneys should be added at high points.
	(ACI, 2018; IADOT, 2022).	The placement of UHPC should be continuous to avoid cold joints, with well-distributed fibers.
	PCI (2022)	Continuously placing the UHPC from a single location and using the UHPC's flow properties to distribute the material outward into the form, or by depositing the UHPC behind the leading edge of the flow so that it integrates with the flowing material.
Measurement and Validation of Flowability During Placement	NYSDOT (2023) and CDOT (2018)	Flow should be measured using a mini-slump cone after each batch of UHPC, with a range of 7 to 10 inches.
	IADOT (2022)	Flow should be determined per ASTM C 1856 for each batch, with a diameter between 8 and 10 inches.
Other Considerations and Practices	(FHWA, Graybeal, 2014)	Forms containing UHPC should be immediately closed after placement to minimize surface dehydration. UHPC in chimneys should be periodically checked for adequate filling.

2.6 Curing Methods

Moisture and temperature play a crucial role in properly curing UHPC, much like in conventional concrete. In laboratory settings, curing typically involves immersing UHPC specimens in lime-saturated water maintained at 73°F (23°C) until testing, as El-Tawilet et al. (2018) noted. Conversely, various researchers employ different curing processes over a period of up to 28 days (Meng and Khayat 2016; Bonneau et al. 1997; Ozyildirim 2011; Wan et al. 2016). For precast UHPC elements, heat treatment is known to boost strength, with common temperatures ranging from 176-194°F (80-90°C), and PCI recommends specific protocols for controlled heating and cooling rates to avert surface crazing (Choi et al. 2016; PCI 1999). Reports by Meng and Khayat (2016) and others detail heat curing at 194°F (90°C) for 24 hours following an initial room temperature cure with wet burlap and plastic sheets. Standard curing methods such as covering with plastic sheets and/or plastic sheet are typically adopted in cast-in-place applications, as heat curing is often impractical in field conditions (Wille et al. 2011). Table 2.5 presents a comprehensive summary of the curing requirements and practices for cast-in-place UHPC as specified by various agencies, providing essential guidelines for effective application and achieving optimal results.

Table 2.5 Curing requirements specified by different agencies

	Agency	Requirements
General Curing Requirements and Practices	MIDOT	Covering the top surface with insulating blankets.
	IADOT (2022)	A minimum curing temperature of 60°F.
	FHWA (Graybeal and Leonard, 2018)	Immediate covering after casting to prevent water loss and suggests leak testing for deck-level connections.
	PCI (2022)	After finishing, all exposed surfaces should be immediately covered with plastic or wet burlap to prevent dehydration. Treatment with a curing compound may also be permitted, but the curing compound should be applied to the surface shortly after finishing is completed.
Considerations for Concrete Strength and Construction Operations	CDOT (2018)	A minimum of 10 ksi compressive strength before starting to disturb UHPC, with any approved curing method applied immediately after casting.
	IADOT (2022)	Different construction operations such as abutment backfilling or opening bridges to equipment and traffic based on reaching specific strength thresholds (6 ksi for abutment UHPC closure pours, 14 ksi for all joint applications).

2.7 Surface Grinding

The exceptional strength of UHPC often poses challenges in achieving effective grinding and can result in considerable wear of the grinding plate. However, a specific maximum compressive strength for grinding UHPC has not been established. Table 2.6 provides a comprehensive summary of the requirements for UHPC grinding post-construction as outlined by various agencies.

Table 2.6 Grinding requirements specified by different agencies

	Agency	Requirements
Strength Requirements for UHPC Grinding	FHWA (Graybeal and Leonard, 2018)	Grinding equipment should not be loaded until UHPC reaches a minimum compressive strength of 14 ksi to prevent damage to the bond with precast elements and fiber tearing.
	IADOT (2022) and CDOT (2018)	A minimum compressive strength of 10 ksi should be reached before surface grinding.
	PennDOT (2021)	A minimum compressive strength of 14.5 ksi should be reached before surface grinding.
Grinding Process	FHWA (Graybeal and Leonard, 2018)	If fiber pullout is observed during grinding, the operation should be suspended and not resumed until engineer approval.

2.8 Mockup

The construction of mockup sections is highly recommended to accommodate the unique workability behavior of Ultra-High Performance Concrete (UHPC), acting as a valuable resource for self-learning and ensuring adequate preparation for field casting (Graybeal and Leonard 2018). Typically, the insights acquired from these mockup sections inform necessary adjustments in various schematics, including quality assurance/quality control (QA/QC), installation/assembly, and formwork, before actual field casting. Table 2.7 outlines a detailed summary of the UHPC mockup requirements prior to construction, as specified by various agencies.

Table 2.7 Mockup requirements specified by different agencies

	Agency	Requirements
Requirements for Mockup Construction and Inspection	IADOT (2022); FDOT (2018)	Mockup should be cut transversely at locations determined by the engineer for visual inspection of the joint interface and material bond.
	FDOT (2018)	Mockup should be cast at least 30 days prior to UHPC placement and should replicate form pressure, roughened interface between precast concrete panel and UHPC, placement operations, and UHPC dimensions.
	CDOT (2018)	Mockup should be placed at least 7 days before UHPC installation.

2.9 Leak Testing for Deck-Level Connections

Graybeal and Leonard (2018) emphasize the necessity of conducting leak testing for deck-level connections, stipulating that any detected leaks must be promptly sealed should the connection not pass the leak test.

2.10 Summary

This chapter provides a comprehensive overview of the critical aspects involved in the application of UHPC, including formwork requirements, surface preparation, mixing procedures, placing methods, curing methods, grinding requirements, and mockup construction. Each section delves into specific guidelines and practices as specified by various agencies, emphasizing the importance of adhering to these standards to ensure the optimal performance, durability, and structural integrity of UHPC in construction projects.

Chapter 3 CIP UHPC Training Materials

3.1 Introduction

Drawing from a comprehensive review of the state-of-the-practice of CIP UHPC across various agencies and the research team's previous experiences, the investigators developed training materials tailored for contractors and NDOT engineers. These resources will include PowerPoint presentations and videos. A full-day workshop, complete with hands-on activities, has been organized. This workshop features a morning session of lectures on proportioning, batching, testing, and placing both non-proprietary and proprietary UHPC mixes, including a Q&A segment. The afternoon session offers practical experience in batching, testing, and placing UHPC and a small mockup section to simulate connection and repair section construction.

3.2 Hands-on Workshop Agenda

The hands-on Ultra-High-Performance Concrete (UHPC) workshop was hosted on March 16, 2022, in Room 158 of Peter Kiewit Institute in Omaha, with the agenda below:

Morning Session (8:30-11:30)

8:30 – 8:40 Opening Remarks – NDOT Representative

8:40 – 9:15 What is UHPC – Dr. Jiong Hu

9:15 – 9:45 Production of UHPC – Dr. George Morcous

9:45 – 10:00 Break

10:00 – 10:30 QA/QC of UHPC – Dr. Jiong Hu

10:30 – 11:00 Case Studies – Dr. George Morcous

11:00 – 11:30 Discussions and Q&A – Attendees

11:30 – 12:30 Lunch

Afternoon Session (12:30-3:30)

12:30 – 1:30 UHPC batching and casting demonstration #1

1:30 – 2:00 UHPC testing demonstration #1

2:00 – 3:00 UHPC batching and casting demonstration #2

3:00 – 3:30 UHPC testing demonstration #2

3.3 Training Materials

Comprehensive training materials and detailed handouts covering various topics are available in the Appendix for reference and further use.

Chapter 4 Evaluation of Fiber Stability in Fresh and Hardened UHPC

4.1 Introduction

Ultra-high-performance concrete (UHPC) is a new concrete class with mechanical and durability properties that far exceed those of conventional concrete. The use of UHPC will result in significant improvements in the structural capacity and durability of structural components. Due to its superior characteristics, UHPC has drawn substantial interest in the bridge community at both the federal and state levels (Graybeal 2014). Besides the bridge deck connections applications in multiple states, the Federal Highway Administration (FHWA) Every Day Counts (EDC-6) program "UHPC for Bridge Preservation and Repair" emphasizes the use of UHPC for other bridge applications due to its excellent mechanical and durability properties. Due to the large amount of fine powders and the very low water-to-cement ratio in UHPC, the workability of UHPC is very different from conventional concrete (Sbia et al. 2017). While it is generally expected that UHPC is self-consolidating, achieving the desired workability while maintaining stability is often challenging. As shown in Figure 4.1, severe fiber segregation could lead to aesthetics, structural, or durability concerns.

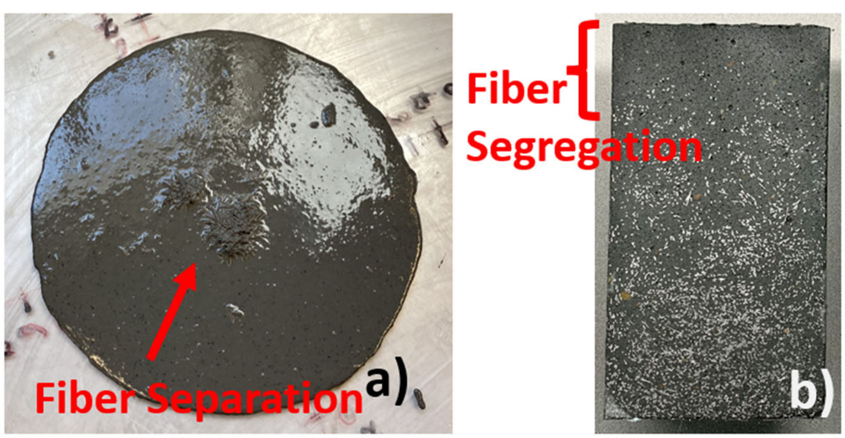


Figure 4.1 Fiber stability in UHPC. a) Fiber separation observed during flow test; b) Fiber segregation observed in concrete cylinders

While the workability of UHPC is often reported in different studies, the commonly used flow (spread) test, as per ASTM C1856, is more of a quality control tool, yet insufficient to identify issues during construction. Similar to when self-consolidation concrete (SCC) was first developed, a set of tests to evaluate the different aspects of UHPC workability is urgently needed (Russell 2008). There is also a need to establish onsite tests that can be easily performed and used in the field to identify potential issues before UHPC placement. One example of issues related to UHPC workability is the lack of viscosity for fiber stability, which is usually measured in a hardened state (Ruan and Poursaee 2019; Wang et al. 2017). A recent PCI study attempted to develop a modified static segregation test for fiber stability test (similar to ASTM C1610 for SCC). However, the method requires at least 30 minutes to complete, which is too long for QA/QC (PCI TR-9-22). A previous study from the authors shows that new tests, such as the visual stability index (VSI) and flow time, can be used to determine potential fiber segregation issues. However, the test methods are relatively subjective and might not be sensitive enough to identify issues in different placement conditions (Mendonca and Hu 2021).

This chapter presents a set of tests recently developed by the research team to identify and evaluate fiber stability in both fresh and hardened UHPC mixtures. In addition, the study assesses different UHPC fiber stability test methods to ensure proper UHPC workability before casting. With the development of onsite QA/QC methods and assurance of appropriate workability before UHPC casting, the success of this project will significantly encourage producers and contractors to adopt this innovative material in different applications.

4.2 Test Methods and Mixture Design

4.2.1 Materials and Mixture Design

In this study, Type I/II Portland cement, fine silica sand with a maximum aggregate size of No. 8 (2.36 mm), slag, silica fume, and micro straight steel fibers, 0.5 in. (13.0 mm) in length and 0.2 mm in diameter, were used. A polycarboxylate-based high-range water reducer (HRWR) and workability retaining admixture (WRT) were also used to achieve the desired workability.

Since the main focus of this study was to assess fiber stability in UHPC, three slightly different mixture designs, as shown in Table 1.1, were used, with Mix 1 as the stable mixture, and Mix 2 and 3 as the semi-stable and very unstable mixtures, respectively. While the solid contents were kept constant within the three mixtures, water, and HRWR contents were increased in Mix 2 and 3 to achieve moderate and severe fiber segregation, respectively (Li et al., 2017). The three mixtures kept Fiber content constant at 2% (by volume).

Table 4.1 Design of mixtures with different fiber stability

Mixture ID	Unit	Cement	Slag	Silica fume	Sand	Fiber	Water	HRWR	WRT
Mix 1	pcy	1206	586	161	1570	264	307	57.6	20.7
Mix 2	pcy	1206	586	161	1567	264	315	63.0	20.7
Mix 3	pcy	1206	586	161	1567	264	328	63.0	20.7

4.2.2 Mixing Procedure

An IMER MIX 120 pan mixer, comparable to the commonly used IMER MIX 750, was employed to prepare all mixtures. While the MIX 120 has a smaller capacity, its functionality is similar and better suited for the required volume in this study. UHPC was mixed in three major steps to achieve the desired consistency: mixing dry ingredients, adding water and admixtures, and introducing steel fibers. The first step was started by loading air-dried sand and silica fume into the mixer and mixing it for five minutes, followed by adding cement and slag and mixing it for another five minutes. Before introducing water into the mixture (which starts the second step), 80% of the total HRWR and total WRT admixture were premixed with 80% of the total water, and then mixed for seven minutes in the mixer. The remaining water and HRWR admixture were premixed again and loaded into the mixer when a paste-like consistency of the mixture was observed. Once a vicious and uniform mixture was achieved, the fibers were loaded for one minute and mixed for another three minutes in the mixer before they were discharged.

4.2.3 Test Methods

Due to the similar self-consolidating nature of UHPC and self-consolidation concrete (SCC), some test methods for the workability of SCC can be modified and adapted for UHPC. As ASTM 1856 is insufficient to reflect the different aspects of the workability of UHPC, the researchers have developed various tests to evaluate UHPC workability, particularly fiber stability (see Table 2.1). Besides static and dynamic flow (ASTM C1856 and C1437), it can be used to access characteristics related to the flowability and stability of UHPC. Additional tests, such as the Visual Stability Index (VSI), mini-V-funnel, penetration, and falling ball tests, could be used to assess the fiber stability of UHPC.

Table 4.2 Comparison of SCC and UHPC test methods included in the current study

State	SCC Test Method (Standards/References)	UHPC Test Method (Standards/References)
Fresh	Slump flow (ASTM C1611)	Flow Spread (ASTM C1856/C1437)
	Visual Stability Index (VSI) (AASHTO T347)	Visual Stability Index (Mendonca and Hu, 2021)
	V-Funnel (Elinwa et al. 2008)	Mini V-Funnel
	T50 (AASHTO T347)	Flow Time
	Falling Ball (Douglas et al. 2015)	Falling Ball
Hardened	Hardened Visual Stability Index (HVSI) (AASHTO R81)	HVSI (Mendonca and Hu, 2021)
	Electric Resistivity (AASHTO T358)	Electric Resistivity

To justify the efficiency of the workability measurement on fiber stability, the research evaluates the fiber stability of UHPC in hardened states. In addition to the Hardened Visual Stability Index (HVSI) (Mendonca and Hu, 2021), a surface electric resistivity meter could be an effective tool for in-situ evaluation of fiber distribution in a quantitative manner after demold as its readings are highly dependent on fiber content. As steel fiber is highly conductive, locations in the component with a high or low amount of fibers (due to fiber segregation) show significantly different electric resistivity. The abovementioned tests were performed to justify the developed fresh UHPC test for fiber stability to predict fiber segregation in the lab- and site-casted UHPC.

4.2.3.1 Flow and Flow Time Test

The flow table test for UHPC was conducted according to ASTM C1856. The diameter of the flow at two minutes and the time when it reached 10 in. (254 mm) were measured and reported as Flow and T10in, respectively. The flow and flow time test set up is illustrated in Figure 4.2.

Figure 4.2 Flow and flow time test setup (left) and example of tests (right)

The stability of fibers was evaluated using the Visual Fiber Index (VSI) as per Mendonca and Hu (2021) based on the degree of fiber separation observed (see Figure 4.3 as an example). VSI values of 0, 1, 2, 3, and 4 indicated highly stable, stable, unstable, highly unstable, and extremely unstable mixtures, respectively.

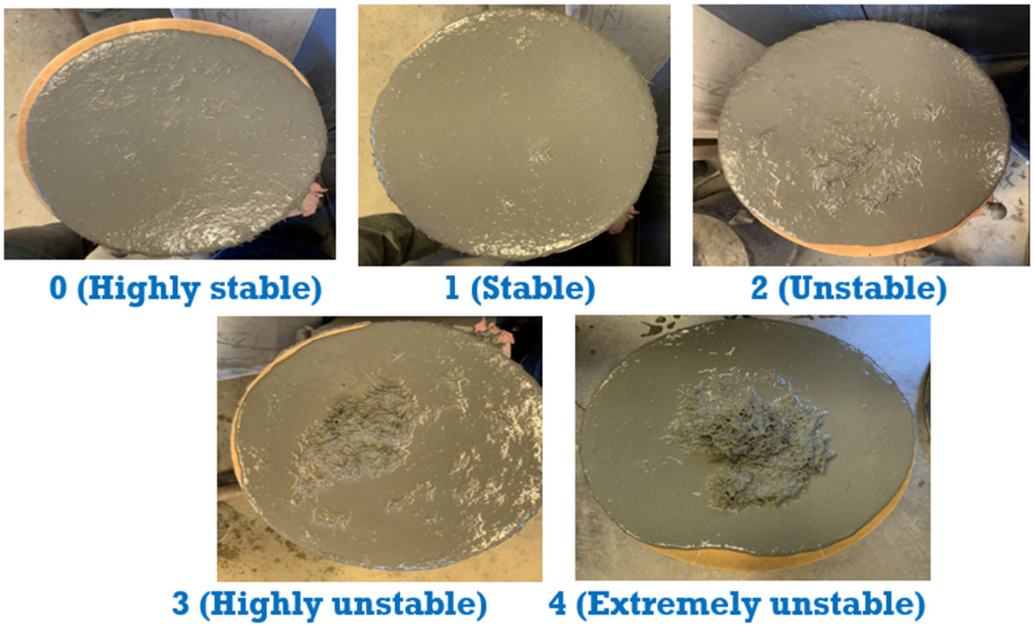


Figure 4.3 Examples of UHPC mixtures with different VSI

4.2.3.2 Mini V-funnel test

A V-shaped funnel (mini-V-funnel) with approximately 0.09 ft^3 (2.5 liters) internal volume and 0.75 in. (19 mm) square opening, as shown in Figure 4.4, was used to assess the flowability and fiber stability in UHPC mixtures. Upon the completion of mixing, the UHPC mixture was loaded into the mini-V-funnel continuously without any temping or compaction, while the opening at the bottom of the v-funnel was blocked by hand. After the mini-V funnel was filled, the material was allowed to flow out freely under gravity. The time it took the material to wholly discharge (when the light was observed from the top of the opening) was recorded as T_{V0}. Visual fiber stability was reported based on whether fibers were stuck inside the neck of the funnel and reported as VFS_{V0}. The mini-V-funnel test was also conducted in the same manner after allowing for settling for two minutes and the time for discharge and visual fiber stability were as T_{V2} and VFS_{V2}, respectively. It is evident that after two minutes of settling, the flow time could increase significantly with a higher inclination to fiber segregation if the mixture is unstable. VFS was identified as “no” or “yes” in the case of a mini-V-funnel test, the latter indicating the fiber was stuck.

Figure 4.4 Mini V-funnel test set up (from left to right: test setup dimension; blocking of mini-V-funnel opening for mixture to settle; and UHPC mixture flowing out from the opening)

4.2.3.3 Falling ball test

As shown in Figure 4.5, the falling ball test used a brass ball with a diameter of 1 in. (24.4 mm) and a mass of 0.195 lb (88.4 grams). Upon the completion of mixing, the UHPC sample was loaded into a 4" × 8" (101.6 mm × 203 mm) cylinder without any tamping or compaction. The brass ball was placed at the top surface of the concrete and then allowed to sink gradually into the UHPC under gravity. The time until no further downward movement and immersion distance were recorded as TFB and LFB, respectively. An LFB less than 8 in. (203 mm) means the brass ball cannot drop to the bottom of the cylinder, which implies fiber segregation. Upon the discharge of fresh UHPC sample after the test, visual observation of fiber accumulation at the bottom of the cylinder was reported as VFSFB, with "yes" indicating fiber segregation.

Figure 4.5 Falling-ball test set up (left: before ball settling; right: after ball settling)

4.2.3.4 Penetration test

The penetration test equipment consists of a plastic rod, a penetration head (with a combined mass of 1.8 oz or 30.8 grams), and a support frame. The penetration head is 3 in. (76.2 mm) in diameter and 2 in. (50.8 mm) in height, with the bottom portion hollow and the top part with small holes allowing air to pass through during its downward movement inside the concrete. With a support frame, the penetration head with the plastic rod was aligned in the center of a container with a minimum of 8 in. (203 mm) in diameter. A fresh UHPC sample was loaded inside the container without any consolidation during the test. The penetration head was then lowered onto the surface of the UHPC and released to allow it to penetrate freely into the fresh UHPC. The penetration depth was recorded after 30 seconds as P.

Figure 4.6 Penetration test setup and examples of results (left to right: test setup; mixture with medium penetration: and mixture with high penetration)

4.2.3.5 Hardened Visual Stability Index Test

Hardened Visual Stability Index (HVSI), as developed by Mendonca and Hu (2021), was used to quantitatively assess fiber stability in hardened UHPC based on the thickness of fiber-free or low-fiber content layer observed at the top of casted 3" × 6" (76.2 mm × 152.4 mm) UHPC cylinder cross-sections. Similar to VSI, HVSI values of 0, 1, 2, 3, and 4 indicated highly stable, stable, unstable, highly unstable, and extremely unstable mixture, respectively.

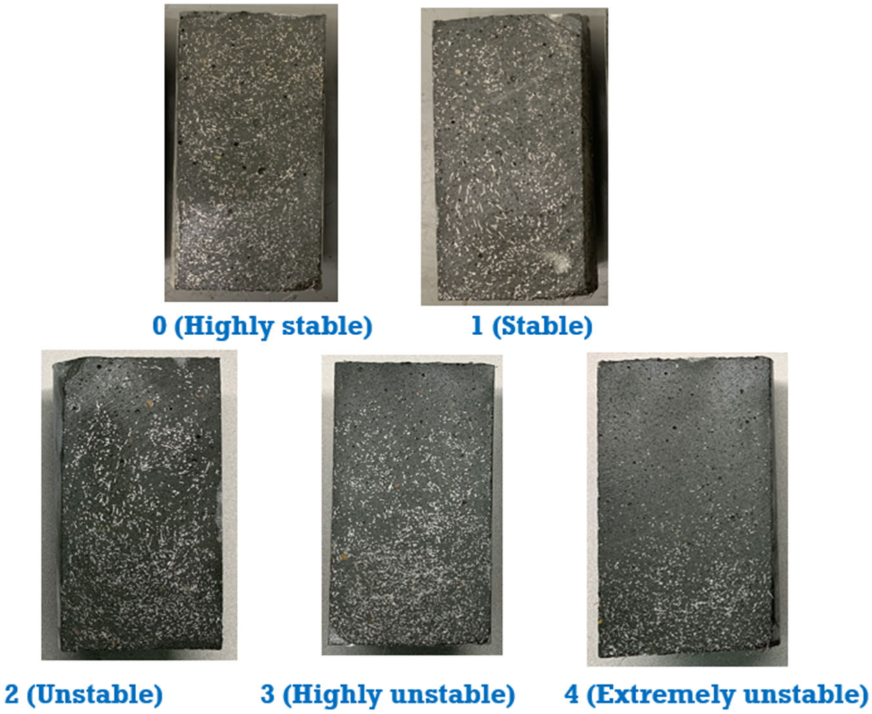


Figure 4.7 Examples of UHPC with different HVSI

4.2.3.6 Wall Stability test

A wall stability test was developed to quantitatively assess fiber stability in hardened UHPC and simulate real-world conditions. Upon completion of mixing, a UHPC sample was loaded into a form 24 in. (609 mm) in height, 12 in. (304.8 mm) in width, and 1.5 in. in depth without any forms of consolidation, as shown in Figure 4.8. After 24 hours, the specimen (the wall) was de-molded and sawed 1 in. (25.4 mm) from the side to observe fiber segregation. Additionally, a surface resistivity test as per AASHTO R81 was conducted every 3 in. (76.2 mm) vertically, starting 3 in. (76.2 mm) from the bottom of the casted wall to determine ununiform fiber distribution along the wall based on inconsistent resistivity values.

Figure 4.8 Segregation test specimen preparation and process (left: specimen casting; right: measure potential fiber segregation with resistivity meter)

4.2.3.7 Compressive strength test

The developed UHPC mixes should also meet performance requirements in the hardened state. A compressive strength test was conducted for each UHPC mixture following ASTM C1856. After a curing period of 7 days and 28 days in a water tank with lime, the 3 × 6 in. concrete cylinders were grinded on both ends and kept in an oven for 24 hours in a standardized condition (110±5°C). Three specimens were tested in each case, and an average value was reported.

4.3 Results

Results from the fresh and hardened UHPC fiber stability test evaluation are summarized below in Table 2.2. As shown in the table, while results from different tests generally agreed with each other, the sensitivities of different tests in identifying fiber segregation are different.

Table 4.3 Results from fresh and hardened UHPC fiber stability tests

Tests	**Flow**			**Mini-V-Funnel**				**Falling-ball**			**Penetration**	**HVSI**
Mixture ID	Flow	T_{10in}	VSI	T_{V0}	VFS_{V0}	T_{V2}	VFS_{V2}	T_{FB}	L_{FB}	VFS_{FB}	P	HVSI
Mix 1	10.0" (254mm)	37"	0	145"	No	187"	No	35"	8.0" 203mm)	No	0.875" (22.2mm)	0
Mix 2	11.0" (279mm)	15"	1	84"	No	135"	No	15"	7.5" (191mm)	Yes	1.50" (38.1mm)	2
Mix 3	11.5" (292mm)	10"	2	51"	No	60"*	Yes	7"	7.5" 191mm)	Yes	1.75" (44.5mm)	3

* Flow stopped due to fiber clogging

As expected, for the stable mix (Mix 1), a VSI value of 0 was obtained, which means no evidence of fiber separation or agglomeration can be observed. On the other hand, Mix 3 and 2 both showed fiber segregation. Mix 3 showed severe bleeding and fiber separation with the highest flow value of 11.5 inches (292 mm) and VSI value of 2. In addition, results confirmed that, as suggested by Mendonca and Hu (2021), UHPC mixtures with T_{10in} less than 20 seconds (flow reach 10 inches (254 mm) under 20 seconds) could have a high potential for fiber segregation.

Results from the mini-V-funnel test showed that neither Mix 1 nor Mix 2 exhibited fiber blockage. However, the apparent difference in flow time between those two mixes implies Mix 2 has a higher flowability and much lower viscosity, which could lead to fiber segregation—in the case of Mix 3, a 2-minute settling time caused flow stoppage at 60 seconds due to fibers stuck in the neck, which clearly demonstrates fiber instability.

With the falling ball test, it is evident from the full-depth immersion that Mix 1 presented a stable behavior without any fiber accumulation at the bottom of the container. On the other hand, an L_{FB} at 7.5 in. (191 mm) was reported in Mix 2 and Mix 3, which indicated a 0.5-in. (13 mm) fiber piling at the bottom of the container. Although the difference between Mix 2 and Mix 3 cannot be distinguished by L_{FB}, the T_{FB} of Mix 2 is twice that of Mix 3, which indicates a lower viscosity and a high chance of fiber segregation of Mix 3. The results showed that the falling ball test is not only an easily performed test but also could be a good indicator of fiber instability in UHPC mixtures based on fiber accumulation at the bottom of the cylinder and the sink time of the brass ball.

Results from the penetration test showed that even though the depth of penetration increased with increasing fiber instability in the mixtures, the obtained values cannot provide comprehensive information regarding the fiber segregation resistance in UHPC. While the stable mix (Mix 1) had a penetration depth of 0.875 inches, the difference in penetration depth results between Mix 2 (1.50" or 38 mm) and Mix 3 (1.75" or 44 mm) is not significant despite the considerable difference in terms of fiber stability by other test methods, which can also demonstrate the inadequacy of this test. The weight of the penetration head with the plastic rod might be too heavy for the UHPC without coarse aggregates and was not sensitive enough to access fiber stability in UHPC.

As expected, HVSI results showed that Mix 1 provided uniform fiber distribution without any sign of a fiber-free zone. In contrast, Mix 2 and Mix 3, with HVSI values of 2 and 3, established a low fiber content layer with 1.0 inches (25 mm) and 2.5 inches (64 mm) of thickness, respectively.

As shown in Figure 4.9a, while the vertical cross-sections of the wall prepared with Mix 1 showed a uniform fiber distribution, clear fiber segregations were observed in the walls cast with Mixes 2 and 3. As expected, the measured surface resistivity shown in below in the specimen prepared with Mix 1 was fairly consistent throughout the different heights. On the other hand, apparent changes in the measured resistivity along the specimens were observed in both Mix 2 and Mix 3, with a lower surface resistivity (compared to the stable mix) and a significant increase when reaching the low-fiber zone. As the high fiber content zones or fiber agglomeration areas led to higher conductivity or lower surface resistivity, fiber segregation led to lower resistivity at the bottom, while the top portions of the specimens exhibited higher surface resistivity. Compared to different fresh stability tests, the consistent results demonstrated that the surface resistivity test could effectively identify fiber instability in different UHPC mixtures in cast-in-place or precast concrete elements.

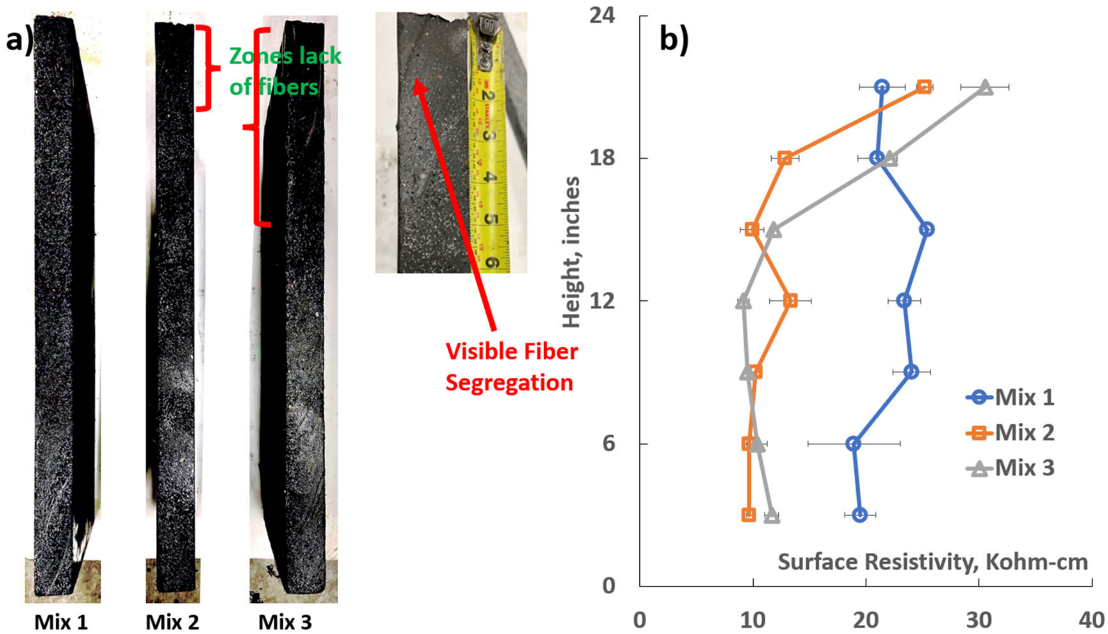


Figure 4.9 Results from wall-stability test. a) Visible fiber segregation; b) Change of measured surface resistivity along different heights

4.4 Summary

This chapter presented a preliminary experimental study that was carried out to evaluate if the different fresh and hardened concrete tests can effectively identify fiber segregation before or after the casting of UHPC. Key findings include the observation that excessive water or HRWR can lead to fiber segregation, noticeable in both fresh and hardened states. Although VSI and HVSI methods offer subjective means to assess fiber stability, they may lack sufficient sensitivity. Newly developed mini-V-funnel and falling ball tests provide objective measures for identifying fiber stability issues in fresh UHPC. Flow time, indicating UHPC viscosity, emerged as a potential indicator of fiber stability, but requires further data for QA/QC acceptance range establishment. In its current form, surface resistivity testing may not be sensitive enough for UHPC fiber stability assessment but shows potential for in-situ evaluation of fiber distribution in hardened UHPC. The study acknowledges the need for more extensive research to correlate these promising tests with UHPC workability across a broader range of mixtures and suggests incorporating various test methods in actual construction projects to develop a comprehensive database for practitioners.

Chapter 5 Evaluation of Shrinkage of UHPC with the Incorporation of Shrinkage-Reducing and Shrinkage-Compensating Admixtures

5.1 Introduction

Understanding the shrinkage behavior of UHPC is of paramount importance in its application, particularly due to its high binder content and low water-to-binder ratio. These unique characteristics of UHPC, while contributing to its superior strength and durability, also predispose it to higher autogenous shrinkage, potentially leading to microcracking. Such cracking not only compromises the structural integrity of UHPC but also affects its long-term performance and sustainability. Therefore, a comprehensive examination of UHPC shrinkage is crucial for optimizing its formulation and ensuring its effective use in demanding construction scenarios.

This chapter encompasses not only an extensive literature review, summarizing prior studies on UHPC shrinkage and various strategies to mitigate it but also details a comprehensive experimental analysis undertaken by the research team. This analysis focused on investigating the impact of both shrinkage-reducing and shrinkage-compensating admixtures on the total and autogenous shrinkage characteristics of UHPC. Detailed experimental programs and findings are presented below, offering insightful perspectives into the behavior of UHPC under these specific conditions.

5.2 Background and Previous Studies Related to UHPC Shrinkage

5.2.1 Background of Shrinkage of UHPC

While traditional studies on shrinkage in conventional concrete have predominantly focused on drying shrinkage, recent research indicates that for mixtures with low water-to-binder ratios like UHPC, drying shrinkage tends to be minimal. However, it is observed that UHPC exhibits significantly high autogenous shrinkage (Koh et al. 2011). This is attributed to its very low water-to-binder ratio and high cement content, coupled with the addition of silica fume. The small particle size of materials such as silica fume contributes to a finer pore structure, leading to early-age self-desiccation and pronounced autogenous shrinkage. This phenomenon is critical as it can initiate microcracking, thereby potentially diminishing the durability of UHPC.

In their 2018 study, the Federal Highway Administration (FHWA) analyzed the shrinkage properties of five distinct UHPC mixtures, encompassing both proprietary and one non-proprietary. The study highlighted that the total and autogenous shrinkage strains varied significantly due to considerable variations in mixture designs, which included differing ratios of cementitious materials and aggregates, types of cementitious materials used, and water content. The observed total shrinkage ranged from 200 to 1120 με at 28-day (from 300 με to 1283 με at 180-day), while autogenous shrinkage fluctuated between 190 to 800 με at 28-day (between 202 and 872 με at 180-day). Complementing this, Mohebbi et al.'s 2022 study on three UHPC mixtures reported total shrinkage strains ranging from 320 με to 420 με at 28-day (from 518 με to 1283 με at 180-day), with autogenous shrinkage figures between 300 με and 390 με at the 28-day (between 270 με and 584 με at the 180-day). Intriguingly, the results from the FHWA study indicated that pre-bagged mixtures with higher water content in the mixture design exhibited the most significant shrinkage.

To mitigate the challenges posed by the high shrinkage characteristic of UHPC, various Departments of Transportation (DOTs) have established criteria stipulating the maximum allowable shrinkage for UHPC. The Colorado Department of Transportation (CDOT) in 2018 specified that the long-term shrinkage of UHPC must not exceed 800 με at 28-day. This benchmark aligns with similar standards set by other state DOTs, including the New York Department of Transportation (NYDOT) in 2023, the Iowa Department of Transportation

(IADOT) in 2022, and the Pennsylvania Department of Transportation (PennDOT) in 2018, all of which mandate that UHPC's long-term shrinkage should remain below 766 με at 28-day.

5.2.2 Approaches to reduce UHPC shrinkage

Recent research efforts have been dedicated to unraveling the mechanisms governing autogenous shrinkage in UHPC. Numerous strategies for mitigating UHPC shrinkage have been identified and reported. The most prevalent methods include the utilization of shrinkage-reducing admixtures (SRAs) and shrinkage-compensating admixtures (SCAs) or expansion agents (EAs). Additionally, integrating internal curing agents such as lightweight aggregates or water-absorbing materials like superabsorbent polymers, and rice husk ash has proven effective. Other notable approaches encompass heat curing and the incorporation of microfibers to enhance UHPC's performance against shrinkage.

In their 2018 research, Xie et al. established that an increase in the content of SRAs significantly reduces both autogenous and total shrinkage in UHPC. This reduction is attributed to the lowered surface tension in the capillary pores. In their findings, a reference UHPC mixture devoid of SRA exhibited an autogenous shrinkage of approximately 480 με at 30 days, escalating to 620 με by the 180th day. Conversely, mixtures enhanced with 0.8%, 1.6%, and 2.4% SRA displayed markedly lower autogenous shrinkages of 380, 230, and 185 με at 30 days, further reducing to 400, 280, and 195 με respectively by the 180th day. Similarly, the total shrinkage of the reference mixture was recorded as 530 με at 30 days, rising to 780 με at 180 days. In contrast, UHPC mixtures containing SRA showed significantly lower total shrinkages of 440, 375, and 210 με at 30 days, which further reduced to 530, 400, and 230 με, respectively, at 180 days. Consistent findings across various studies underscore the effectiveness of shrinkage-reducing admixtures (SRAs) in lowering UHPC shrinkage from an early stage. Anshuang et al.

(2017) reported that the seven-day autogenous shrinkage strains were notably reduced in mixtures with SRA—a control mixture exhibited 1080 με, while mixtures with 0.5%, 1.0%, and 2.0% SRA recorded shrinkage strains of 718, 649, and 602 με, respectively. Complementing these findings, Yoo et al. (2015) observed that the 30-day autogenous shrinkage of a reference UHPC mixture was 760 με, in contrast to 645 με and 544 με for mixtures with 1% and 2% SRA, respectively. Further supporting these results, Liu et al. (2022) documented that at three days, UHPC's autogenous shrinkage decreased by 15% with the use of SRA, indicated by a shrinkage of 305 με for a reference mixture. Between 3 to 180 days, the shrinkage strains for the reference mixture and the mixture with SRA were 325 με and 230 με at 60 days, respectively, after which the measurements started to stabilize.

Research on the application of SCA and EA in UHPC is relatively scarce, primarily due to the prevailing belief that these additives are less effective in UHPC than in conventional concrete. Shen et al. (2020) conducted a study to evaluate the impact of EAs on UHPC's autogenous shrinkage using a non-contact deformation tester. Their findings indicated that the seven-day autogenous shrinkage of a reference UHPC mixture, which reached 1700 με, was significantly reduced by 59% with the incorporation of 15% EA. This reduction was primarily attributed to the increase in CSA-CaO EA content, with the most notable shrinkage reduction occurring within the initial 48 hours, a period marked by ettringite formation. However, as ettringite formation takes about five to seven days to develop its expansive effect fully, the CSA-CaO EA only partially compensated for autogenous shrinkage during the first 24 hours, followed by a gradual reduction over the subsequent 24 hours. Complementing these findings, a study by Li et al. (2021) demonstrated the effectiveness of MgO-based EA in mitigating autogenous shrinkage in UHPC. The addition of 3%, 6%, and 9% EA resulted in reductions of 44.5%, 59.5%, and 58.9% in autogenous shrinkage at 168 hours, respectively, compared to the control mixture's shrinkage of 768 με at the same duration.

Liu et al. (2022) highlight that the synergistic effect of combining EA and SRA significantly surpasses the shrinkage reduction achieved by either additive used individually. Park et al. (2014) conducted an investigation into both the combined and separate impacts of EAs and SRAs on the free shrinkage of UHPC. Their study noted that early-age expansion in UHPC, influenced by variations in ambient temperature and the hydration heat, was evident. However, the 28-day free shrinkage of a reference UHPC specimen, which was recorded at 700 με, decreased by 8% and 21% with the application of 1% and 2% SRA, respectively. Notably, the study revealed that adding 5% and 7.5% EA resulted in a more pronounced reduction in free shrinkage compared to using SRA alone. When EA and SRA were combined, the reduction in shrinkage reached 37% relative to the reference specimen.

In their 2011 study, Soliman and Nehdi examined the influence of different drying temperatures (10°C, 20°C, and 40°C) on the autogenous and total shrinkage of UHPC. As anticipated, higher drying temperatures resulted in increased autogenous strain. Notably, using a 2% SRA was more effective in reducing autogenous shrinkage at these elevated temperatures. For example, at 40°C with a water-to-cement ratio (w/c) of 0.25, the reduction in autogenous shrinkage was 55% compared to the control mixture (580 με), while at 20°C and 10°C, the reductions were 34% (at 405 με) and 32% (at 200 με), respectively, after seven days. The study also established higher temperatures invariably led to greater total strains, independent of relative humidity (RH). Additionally, lower RH levels increased total strains under the same exposure temperature. Complementing these findings, the 2018 study by Xie et al. also explored the use of ice water in UHPC mix design as a method to lower the temperature, which consequently appeared to decrease both autogenous and total shrinkage.

5.3 Experimental Program

5.3.1 Materials and Mixture Design

In this study, Type I/II Portland cement compliant with ASTM C150 standards, alongside ground-granulated blast-furnace slag in accordance with ASTM C989 and densified silica fume were used as cementitious materials. Sand with a maximum aggregate size of two mm, and micro straight steel fibers measuring 13.0 mm in length and 0.2 mm in diameter were used as dry components. For the liquid ingredients, the research incorporated a water-reducing and retarding (WRT) admixture meeting the Type G specification as per ASTM C494, along with a modified polycarboxylate-based HRWR, conforming to the Type F specification. Additionally, two SRA (BASF MasterLife SRA 035 and GCP Eclipse Floor 200), both fulfilling the ASTM C494 Type S, and one SCA (MAPEI Expancrete) were employed to assess the autogenous and total shrinkage of UHPC. The mixing process utilized standard tap water.

In this study, six different UHPC mixtures, each with varying dosages of SRA and SCA, as delineated in Table 4.3, were prepared. The reference mixture is denoted as 'R', while 'MS', 'EC', and 'EP' represent MasterLife, Eclipse, and Expancrete. The numbers following these abbreviations indicate the percentage of each corresponding admixture relative to the binder content. It should be noted that the mass of the fine aggregate listed in Table 4.3 was in an air-dried state, with a moisture content of approximately 0.2%. Any minor variations in moisture conditions were precisely compensated based on the exact moisture content measured before batching. The fiber content incorporated into each mixture amounted to 2% of the total binder content.

Table 5.1 Designs of mixtures for shrinkage study (all in pcy)

Mixture ID	Cement	Slag	Silica fume	Sand	Fiber	Water	HRWR	WRT	SRA/SCA	w/b
R	1188	577	159	1539	255	330	56.7	20.4	0	0.200
EC6	1184	575	158	1534	254	329	56.5	20.3	6.3	0.202
EC13	1179	573	158	1529	253	327	56.3	20.2	12.6	0.204
MS13	1179	573	158	1529	253	327	56.3	20.2	12.6	0.204
EC18	1175	571	157	1524	253	326	56.1	20.2	18.6	0.206
EP84	1168	568	156	1554	264	299	61.5	20.1	84.0	0.188

5.3.2 Mixing Procedure

All UHPC mixtures were prepared using a MIX 360 mixer featuring a 38-inch drum. The process encompassed three primary stages: initially, the dry components comprising air-dried sand and silica fume were blended for 5 minutes, followed by the incorporation of cement and slag for an additional 5 minutes. Subsequently, in anticipation of adding water (marking the commencement of the second stage), a concoction of 80% HRWR, the entire portion of WRT and SRA admixtures, and 80% of the total water quantity was pre-mixed and then agitated for seven minutes. The remaining water and HRWR were similarly pre-blended and introduced into the mixer, initiating the transition from a powdery state to a paste. The point at which the UHPC turned flowable, smooth, and viscous, marked the procurement of 0.40 cubic feet of the mixture for heat of hydration and setting time assessments. After this, steel fibers were integrated into the residual mix for a minute, with a subsequent 3-minute mixing period. It's important to note that the fiber quantity was calculated explicitly for the leftover material volume. A flow test was conducted post-mixing, and samples for shrinkage and compressive strength evaluations were prepared. It should be emphasized that when utilizing smaller mixers for UHPC, varying mixing speeds may be required to attain the desired consistency.

5.3.3 Test Methods

5.3.3.1 Flow test

The flowability of each UHPC mix was assessed to ascertain appropriate workability. To measure this, a custom 20 x 20-inch square plastic plate, equipped with a standard flow cone measuring 4 inches in diameter at the bottom and 2.5 inches at the top (per ASTM C230 specifications), was employed. The flow testing procedure for UHPC adhered to the ASTM C1856 standard. The average diameter of the flow at two minutes was measured and reported.

5.3.3.2 Setting time test

The initial and final setting times were measured in accordance with ASTM C403 using a test setup, as shown in below. Note that UHPC specimens were used for this test before incorporating fiber since the fiber could interfere with the needle penetration. Times of the initial and final settings were determined from the plot of penetration resistance versus elapsed time, as the times when the penetration resistance equals 500 psi and 4000 psi, respectively.

Figure 5.1 Setting time test set up

5.3.3.3 Heat of hydration test

Besides the ASTM setting time test per ASTM C403, an isothermal calorimeter was used to measure the initial and final setting time, and heat of hydration of UHPC at constant temperature (23ºC) within the first 72 hours as per ASTM C1702. Figure 5.2 shows an isothermal calorimeter comprised of eight units, each holding separate samples during the test. The sample of freshly mixed UHPC without fibers with a mass of 100±10 grams was placed into a 125 ml plastic container and then loaded into the equipment. A computer program was used to acquire readings. Readings were taken every 60 s for 72 hours to construct the heat generation rate versus hydration time curve. The thermal initial and final setting time was determined as the first derivative of the heat evolution curve. According to Hu et al. (2014), when the first derivative curve achieves its peak value, the material is considered to reach the initial setting time. The first derivative value starts to reduce by reaching zero corresponding to the mixture's final setting time.

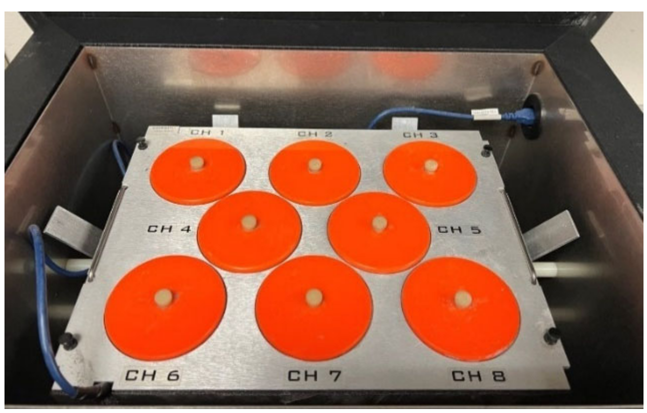


Figure 5.2 Isothermal calorimeter test units

5.3.3.4 Total and autogenous shrinkage test

Total and autogenous shrinkage of developed UHPC mixtures were measured based on ASTM C157, with standard 3” × 3” × 11.25” prism specimens. Immediately after mixing, the fresh UHPC was placed in the prism molds with an effective gage length of 10 inches in a single layer. The surface of the specimens was smoothed with several strokes of a trowel. For each UHPC mixture, four specimens were cast, two for total shrinkage (unsealed samples) and two for autogenous shrinkage (sealed samples). The samples were covered with a plastic sheet during the first 24 hours before demolding. After a 24 hour hardening period, the specimens were demolded, sealed (Figure 5.3b), and placed in a controlled environmental condition (20±3ºC temperature and 50±5% relative humidity). The length change in the original gauge length of cast samples was estimated using a length comparator at 1, 3, 7, 14, 28, 56, 90, 120, 150, and 180 days as shown in Figure 5.3a.

(a) (b) (c)

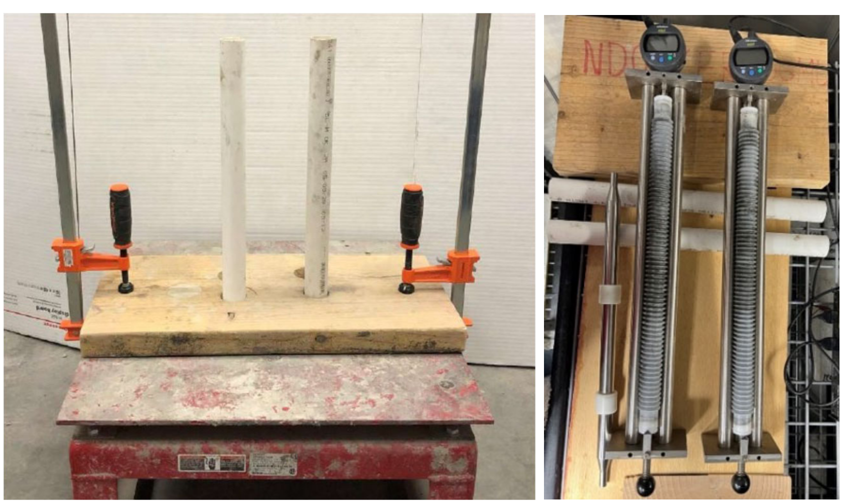
Figure 5.3 Shrinkage test set up (a) Length comparator; (b) Specimen curing after casting; and (c) Sealed and unsealed shrinkage specimens

It's widely recognized that UHPC subjected to thermal treatment demonstrates enhanced dimensional stability compared to UHPC cured at ambient temperature. To investigate the impact of post-cure thermal treatment on UHPC shrinkage, we prepared additional specimen sets for both the reference mixture and the mixture containing SCA samples and subjected them to thermal treatment. Since thermal treatment can be administered within 14 days of placement, four specimens (two Expancrete and two references) were placed in a hot bath (refer to Figure 5.4) at 180°F on the fourth day. After a 48-hour period, the samples were removed, allowed to cool to room temperature for over two hours, and then returned to the environmental chamber. The heat-cured samples were labeled EP84-Heat and R-Heat, while those without heat curing were designated EP84 and R. It is important to note that the thermal treatment was applied exclusively to specimens for total shrinkage evaluation, meaning these samples were not sealed.

Figure 5.4 Hot bath for thermal treatment of selected specimens

5.3.3.5 Short-term autogenous shrinkage test

Since ASTM C157 precludes measuring shrinkage before demolding (at 24 hours), a procedure based on ASTM C1698 was employed for short-term autogenous shrinkage assessment. This test amalgamates both volumetric and linear deformations, enabling measurements to commence immediately post-casting. As depicted in Figure 5.5a, a support structure for the tubes was crafted, and a wooden frame was securely fastened to a vibrating table. The corrugated molds were positioned within these support tubes, with their closed ends facing downward. The freshly mixed UHPC, devoid of fibers, was then poured into the molds while the vibrating table was operational. To maintain consistent tube lengths, altering the molds' dimensions through stretching or compressing was avoided. Following the casting of UHPC samples, the top plugs were sealed, and the samples were promptly placed in an environment meticulously controlled for temperature (23±1°C) and humidity (50±5%). The specimens were then situated in an autogenous shrinkage testing apparatus, as illustrated in Figure 5.5b, allowing for data acquisition every 60 seconds through LVDTs connected to a computer. This testing procedure was sustained for a duration of 21 days for each specified UHPC mixture. The calculation of autogenous shrinkage commenced from the final setting time, in line with ASTM C403 standards.



(a) (b)

Figure 5.5 Short-term autogenous shrinkage test setup (a) Stands for specimen casting; (b) Specimens during tests

5.3.3.6 Compressive strength test

The compressive strength of each UHPC mixture was evaluated per ASTM C1856 standards. Following a four-day curing period in a lime water tank, the 3” x 6” cylindrical specimens were ground at both ends and then placed in an oven for 24 hours under standardized conditions (110±5°C) before the testing commenced. The testing was conducted once the samples had cooled to room temperature, which took approximately 2.5 hours. For those samples subjected to thermal treatment, the specified UHPC specimens were immersed in a hot bath at 180°F after a day of curing in the lime water tank. Similar to the shrinkage samples, they were removed from the bath after 48 hours, allowed to cool to 90°F within 1.5 hours, and then placed in an oven for an additional 24-hour curing period, mirroring the procedure for the other compressive strength samples. It is important to note this hot bath curing method was applied exclusively to Expancrete and reference samples, paralleling the approach for shrinkage specimens. For each test condition, three specimens were evaluated, and the results were averaged to ensure reliability and accuracy in the compressive strength data.

5.3.4 Results and Discussion

5.3.4.1 Flow

Table 2.1 presents the flow results for all six mixtures, showcasing an interesting observation. Despite increasing dosages of SRA, the workability of the SRA mixtures remained largely consistent. This stability in fluidity is a notable finding, given the variations in SRA concentration. On another note, the EP84 mixture, which includes powder SCA as part of the binder content, displayed a marginally lower flow value compared to the reference mixture. This slight deviation can be attributed to the physical characteristics of the SCA component.

However, it is important to highlight all six UHPC mixtures demonstrated remarkably similar flow characteristics, underscoring their uniformity in this aspect.

Table 5.2 Flow test results

Mixture ID	Flow
R	10.5”
EC6	10.5”
EC13	10.5”
MS13	10.5”
EC18	10.5”
EP84	9.5”

5.3.4.2 Setting time

Table 5.3 and Figure 5.6 detail the outcomes of setting time tests conducted using the penetration resistance method. The results indicate a clear trend that an increase in SRA dosage corresponded with a slower rate of cement hydration, consequently leading to prolonged setting times. This observation aligns well with findings from prior research. Notably, the pattern observed in our study echoes the results reported by Weiss et al. (2008). Their research highlighted that the retardation effect of SRA is primarily due to its influence on the polarity within the mixture. The incorporation of SRA reduces polarity, diminishing the salts' capacity to dissolve and ionize in the pore solution. Additionally, the tests revealed an intriguing distinction: EC mixtures experienced a lesser delay in setting time for the same concentration of SRA than MS samples. This suggests a variance in the impact of SRA across different mixture compositions.

On the other hand, the EP84 mixture did not exhibit a noticeable delay in setting time. Its performance was roughly equivalent to the control mixture's, suggesting that EP84's composition does not significantly affect the setting time. This outcome provides an interesting contrast to the SRA and further emphasizes the nuanced effects of different types of admixtures on setting time.

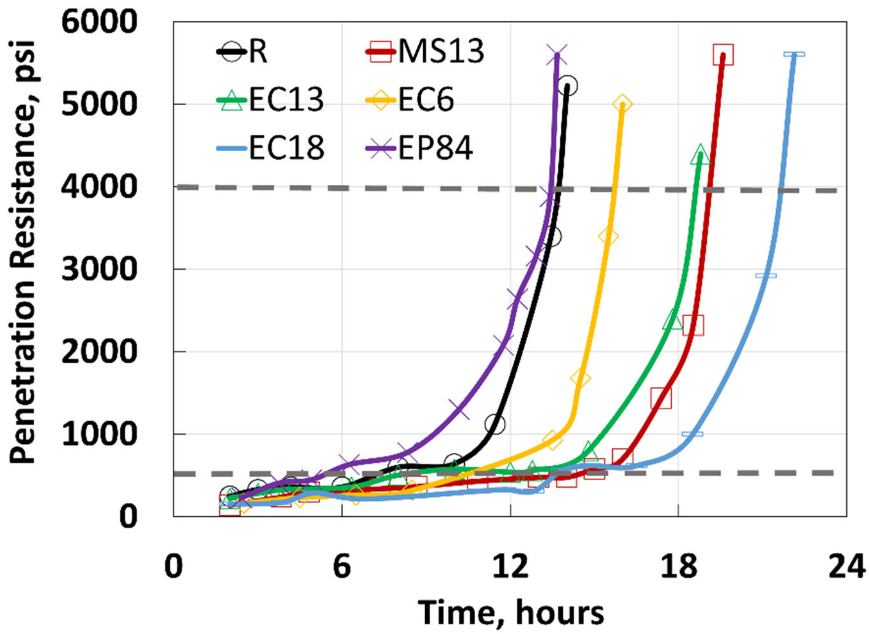


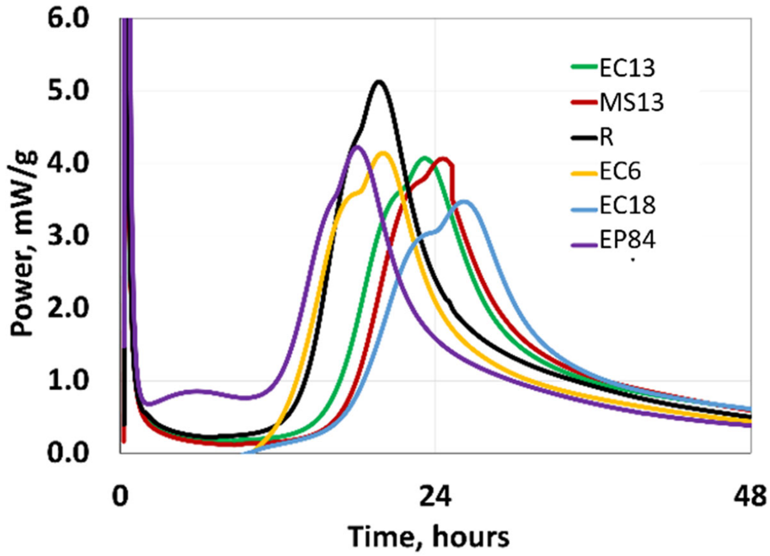
Figure 5.6 Setting time test results

Table 5.3 Calculated thermal setting time

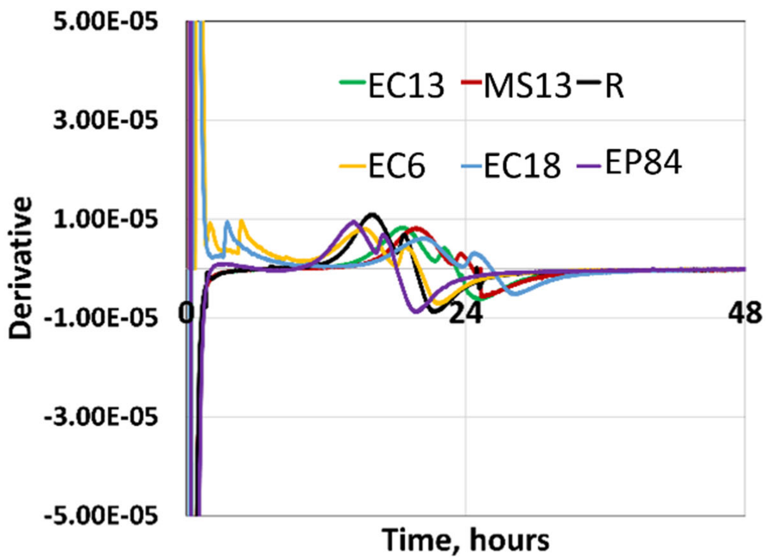
Mixture ID	Initial setting time (hours)	Final setting time (hours)
R	7.1	13.6
EC6	10.0	15.7
EC13	9.3	18.6
MS13	10.4	19.1
EC18	13.6	21.5
EP84	5.3	13.4

5.3.4.3 Heat of hydration

Figure 5.7 illustrates the results of the heat of hydration tests. The graphical representation in the figure demonstrates that incorporating SRA leads to a reduction in the peak heat release. Moreover, as the dosage of SRA increases, there is a noticeable shift of the peak towards the right, which indicates delayed hydration. In contrast, such a delay in hydration was not observed in the mixtures containing SCA. This distinction highlights the differential impact of SRA and SCA on the hydration kinetics of the mixtures. The absence of delayed hydration in SCA mixtures suggests that SCA's influence on the heat of hydration differs significantly from that of SRA, providing valuable insights into the distinct chemical interactions each admixture has within the UHPC matrix.



(a) Heat of hydration



(b) First derivative of heat generation rate

Figure 5.7 Heat of hydration test results

Table 5.4 presents the initial and final set times as determined by analyzing the derivative of heat generation during the hydration process. The results, while markedly different from those obtained via the penetration test, exhibit a parallel trend. Notably, the inclusion of SRA significantly prolongs both the initial and final setting times and diminishes the rate of heat generation at a constant temperature. This reduced rate indicates a lower degree of hydration, a key observation aligned with existing literature. Moreover, an increase in SRA dosage from 6 to 18 per cubic yards (pcy) led to a notable decrease in the peak power and a delay in its occurrence. This trend reaffirms findings from prior studies and underscores the impact of SRA concentration on the hydration process.

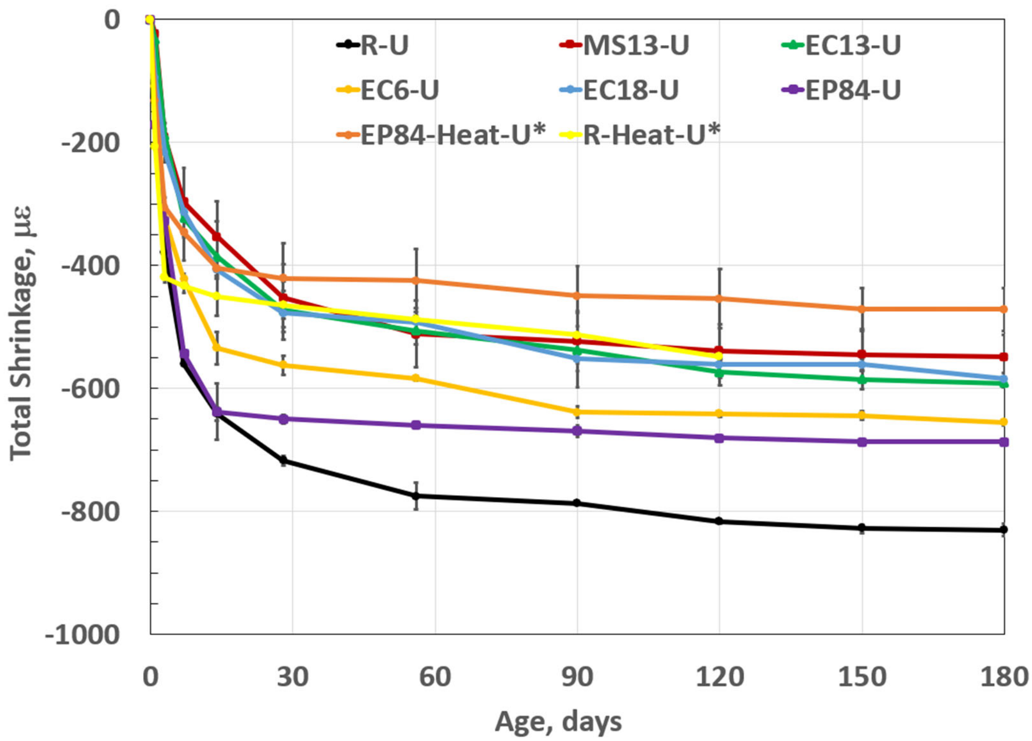
Intriguingly, the EP84 mixture displayed the shortest initial and final setting times among the tested mixtures, including the reference mixture. This occurred despite its lower peak power value. This unique behavior is attributed to the increased porosity resulting from the expansion. The higher porosity provides more space for forming hydration products, thereby accelerating the setting process. However, while Expancrete promotes faster setting times, it also interferes with cement hydration, as evidenced by the reduced peak power. This dual effect of Expancrete highlights the complex interplay between admixtures and the hydration kinetics in UHPC mixtures.

Table 5.4 Heat of hydration test results

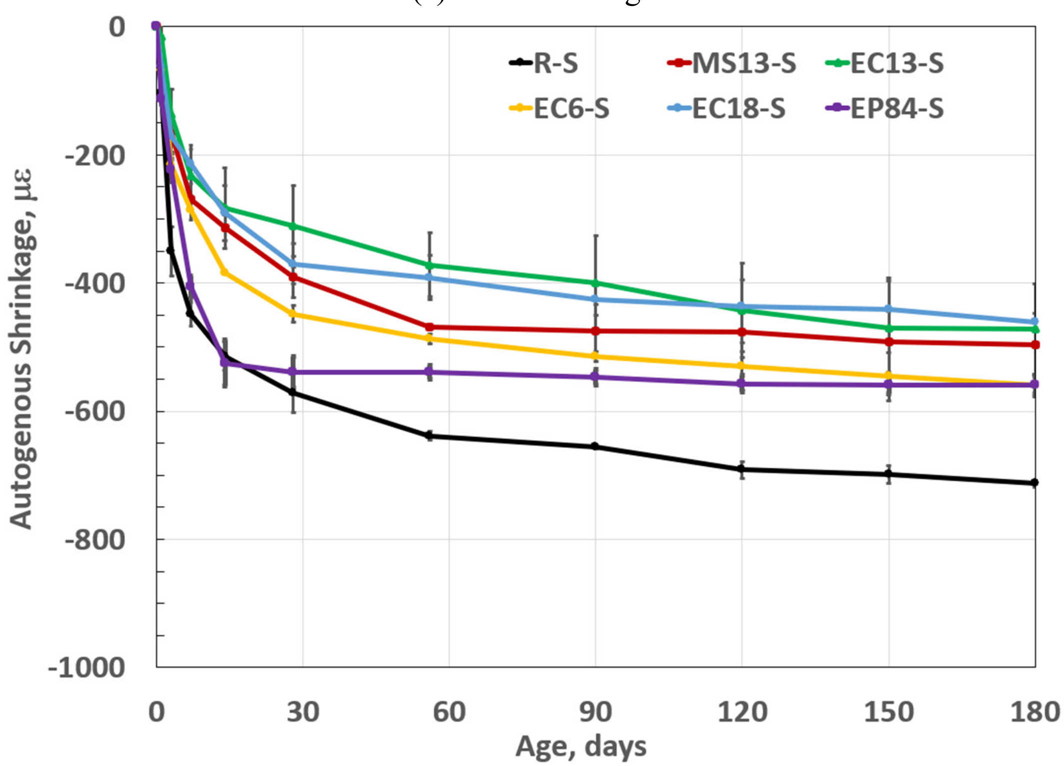
	Peak Power (mW/g)	**Initial Setting Time (hrs)**	**Final Setting Time (hrs)**
R	5.1	16.0	19.7
EC6	4.1	15.4	20.0
EC13	4.1	18.4	23.2
MS13	4.1	19.6	24.6
EC18	3.5	20.2	26.1
EP84	4.2	14.4	18.0

5.3.4.4 Total and autogenous shrinkage

Figure 5.8 presents a comprehensive analysis of how SRA, SCA, and heat treatment influence the total and autogenous shrinkage of UHPC. The results align with expectations, illustrating a significant reduction in total and autogenous shrinkage upon incorporating SRA. According to Xie et al. (2018), SRAs impact shrinkage by lowering the surface tension of pore water, which reduces hydrostatic tension forces (capillary stresses) and subsequently lessens the forces on the walls, thereby decreasing shrinkage. A closer look at the data reveals that the 28-day total shrinkage of UHPC markedly decreased from 718 με to 464 με and 453 με for the MS13 and EC13 mixtures, respectively. This trend continues over a more extended period, with 180-day measurements showing a reduction from 830 με to 591 με and 549 με for these mixtures. Similarly, the 28-day autogenous shrinkage was reduced from 571 με to 390 με and 311 με, and at 180 days from 713 με to 495 με and 472 με for MS13 and EC13, respectively. An interesting observation was made with the EC mixtures. As the SRA dosage increased from 6 pcy to 13 pcy, there was a noticeable decrease in shrinkage. However, the EC18 samples, which had a higher SRA dosage, showed similar results to the EC13, the recommended dosage by the manufacturer. This similarity indicates that increasing the SRA beyond the recommended dosage does not significantly enhance its efficiency in reducing shrinkage. Additionally, the results indicated that most mixtures began to show a plateau in shrinkage rates around 56 days post-casting. This plateau suggests the near completion of the hydration process, providing valuable insight into the timeline of UHPC's physical transformations.



(a) Total shrinkage



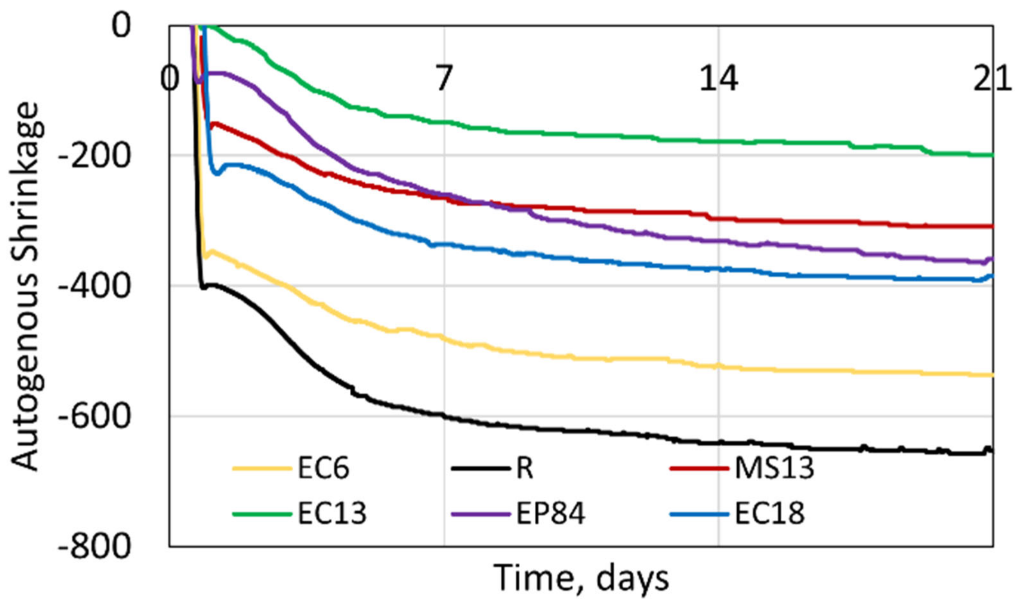
(b) Autogenous shrinkage

Figure 5.8 Total and autogenous shrinkage of UHPC

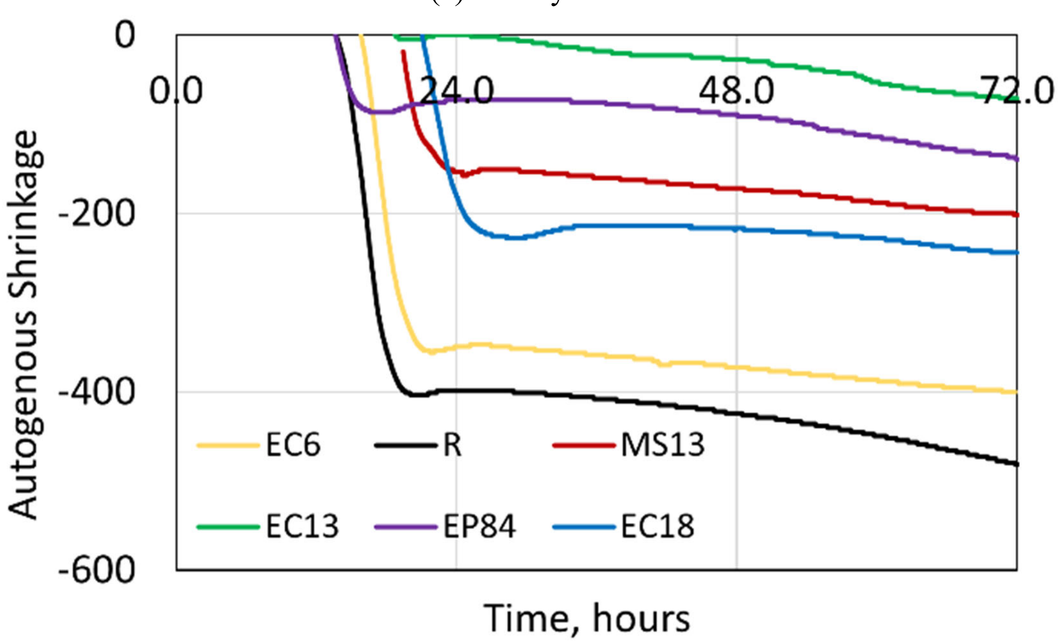
The fundamental mechanism of SCA, such as Expancrete, involves counteracting shrinkage through initial expansion during the early stages of hardening. However, Figure 5.8 reveals that Expancrete's incorporation is ineffective in reducing UHPC shrinkage under normal conditions. Contrastingly, under hot bath treatment, Expancrete showed a reduction in total shrinkage compared to the reference mixture (464 με for R-Heat and 421 με for EP84-Heat at 28 days). Without heat curing, the shrinkage differences between control and Expancrete mixtures became evident after 14 days for both total and autogenous shrinkage. Yang et al. (2019) noted that some expansive agents, particularly sulfoaluminate series, consume more water during hydration, potentially delaying expansion component formation. This delay means the excess ettringite might not stabilize during normal curing, explaining the observed shrinkage compensation in EP84 samples after 14 days. Several factors limit Expancrete's efficacy in UHPC without hot bath curing: UHPC's low water content for hydration, its dense structure with limited voids for hydration products, the high elastic modulus of the UHPC matrix hindering ettringite development, and low internal humidity due to self-desiccation and increased capillary pressure, as outlined by Li et al. (2021) and Shen et al. (2020). In contrast, thermal treatment provides a moist, warm environment, significantly reducing shrinkage. As Yang et al. (2019) and Liu et al. (2022) indicate, high temperatures form a solid skeleton, limiting shrinkage strain and improving dimensional stability. External water curing in Expancrete samples is crucial to activate expansion component formation and compensate for shrinkage strain, especially given UHPC's limited internal water for hydration.

5.3.4.5 Short-term autogenous shrinkage

Figure 5.9 shows the short-term autogenous shrinkage measurements of various UHPC mixtures, focusing on the initial 72 hours in Figure 5.9b. The graph’s time zero corresponds to the moment cement contacts water, while the strain measurements are reset to zero at the final setting time, as per ASTM C403. The test results revealed that the autogenous shrinkage of UHPC decreased with an increase in SRA content, particularly up to 13 pcy, aligning well with results from sealed prism samples. Notably, the EC13 mixture exhibited superior performance compared to the MS13 and EP84 mixtures. Interestingly, except for the R and EC6 mixtures, all others showed commendable performance within 72 hours. A significant aspect of Figure 5.9 is the reference mixture's autogenous shrinkage pattern in the first 72 hours, characterized by a substantial rise between 16 and 28 hours before a marked slowdown in the shrinkage rate. This observation echoes the findings reported by Huang and Ye (2017). For the control mixture, the 21-day autogenous shrinkage reached 660 με, with a notable 482 με recorded at 72 hours. In contrast, these values dropped to as low as 200 με (73 με at 72 hours) for the EC13 mixture. Over 21 days, the autogenous shrinkage of samples containing EC SRA at dosages of 6, 13, and 18 pcy decreased by 18%, 70%, and 58%, respectively, underscoring the significant impact of SRA dosage on shrinkage reduction.



(a) 21-day data



(b) 72-hr data

Figure 5.9 Short-term autogenous shrinkage results

5.3.4.6 Compressive strength

Table 5.5 Compressive strength test results of shrinkage mixtures showcases the results of the 4-day compressive strength tests conducted on eight different UHPC mixtures. Consistent with expectations, the addition of SRA and SCA did not significantly influence the concrete's strength. This finding is particularly noteworthy, as it highlights the neutral impact of these admixtures on the mechanical properties of UHPC. Importantly, all tested mixtures successfully met the established performance criteria in their hardened state, each achieving a minimum 4-day compressive strength of 17 ksi. This uniform achievement across different mix formulations underscores the robustness of UHPC and ability to maintain critical structural properties despite variations in admixture compositions.

Table 5.5 Compressive strength test results of shrinkage mixtures

Mixture ID	4-day Compressive strength (ksi)
R	18.22±0.06
EC6	18.43±0.14
EC13	20.13±0.97
MS13	18.15±0.30
EC18	19.22±1.10
EP84	21.28±1.97
R-Heat	21.87±0.46
EP84-Heat	19.67±1.80

5.3.5 Summary

Chapter 5 examines the impact of shrinkage-reducing admixtures (SRA) and shrinkage-compensating admixtures (SCA) on UHPC. It analyzes their effects on workability, strength, setting time, and shrinkage. While SRA and SCA do not significantly affect UHPC's workability and strength, increased SRA dosage delays hydration and extends setting times. Optimal SRA dosage effectively reduces UHPC's total and autogenous shrinkage, whereas SCA's effectiveness varies. Using the recommended dosage of SRA significantly reduces UHPC's shrinkage, with total shrinkage decreasing from 718 με to 564 με and 553 με and autogenous shrinkage dropping from 571 με to 311 με and 390 με at 28-day. Under specific hot batch curing conditions, SCA significantly reduces shrinkage, though such methods may not be practical for all concrete applications.

Chapter 6 Draft Provision Incorporation of CIP UHPC

CAST-IN-PLACE NON-PROPRIETARY ULTRA-HIGH-PERFORMANCE CONCRETE FOR BRIDGES

000.01 - - Description of Work

1. These provisions cover the production, placement, curing, and testing of non-proprietary Ultra-High-Performance Concrete (UHPC) for structural cast-in-place concrete bridge applications, including joints, connections, repair, and preservation. Not included in these provisions are applications requiring specialized UHPC, such as deck structural repair and overlays. The concrete mixture described here shall be used as indicated in the project plans. All work shall be in accordance with the Standard Specifications, except as modified herein.

2. The requirements of this provision apply only to the non-proprietary UHPC mixture described herein and as specified in the NDOT report SPR-P1(18) M072. For a different UHPC mixture, durability requirements in addition to those specified in Table 6.3 shall be met.

000.02 - - Materials

1. **Mixture Ingredients**
   The non-proprietary UHPC mixture shall be made in accordance with the proportions provided in Table 6.1, and material specifications, including batching tolerances.

Table 6.1 Mixture Constituents and Proportions

Material	Proportion (*lb/yd*^{3})
Fine Aggregate	1,612
Portland Cement	1,214
Slag Cement	588
Silica Fume	162
Fibers	264
Water/Ice (Total content including water in sand and admixtures)	354
High-Range Water Reducer (HRWR) Admixture	TBD
Workability Retaining Admixtures (WRA)	TBD
Shrinkage Reducing Admixture (SRA)	TBD

1.1. **Fine Aggregate:** The fine aggregate meets the requirements of Section 1033 of the Standard Specifications. Aggregate specification range shall achieve 100% passing through the No. 10 sieve with a specific gravity of 2.60-2.70.

The moisture content at the time of batching shall be measured and accounted for in the total water content in each batch regardless of batch size.

Care should be applied in windy conditions as the wind can blow the finer and lighter particles away, which will result in changes to the aggregate and powder gradation.

1.2. **Portland Cement:** Type I/II Portland cement meets the requirements of Section 1004 of the Standard Specifications.

1.3. **Slag Cement:** Grade 100 slag cement meets the requirements of Section 1079 of the Standard Specifications.

1.4. **Silica Fume:** The Silica Fume meets the requirements of Section 1009 of the Standard Specifications. Silica fume incorporated into this mixture shall have a minimum silicon dioxide (SiO_2) content greater than 92%.

1.5. **Fibers:** Straight high carbon wire 0.5-inch long, 0.0078-inch diameter (13 mm long, 0.2 mm diameter [13/.20]) conforms to the requirements of ASTM A820. The steel fibers shall have a minimum tensile strength of 390 ksi. The steel fiber dosage is 2.0% by volume. Steel fibers should comply with Buy America Provisions.

1.6. **Water:** Water usage meets the requirements of Section 1005 of the Standard Specifications. It is recommended to have ice replace 25%-75% of the total water depending on ambient temperature to prevent excessive heat of the mixture. Other methods, such as chilled water, can also be used.

1.7. **High-Range Water Reducer (HRWR) Admixture:** Meeting the requirements of Section 1007 of the Standard Specifications, admixture Type A/F. The HRWR content shall be determined based on the trial batch to reach the desired workability.

1.8. **Workability Retaining Admixture (WRA):** Meeting the requirements of Section 1007 of the Standard Specifications, admixture Type A/G. The WRA content shall be determined based on the trial batch to reach the desired workability extension.

1.9. **Shrinkage Reducing Admixture (SRA):** is not required unless explicitly noted in the project plans.

2. **Material Submittals**

2.1. Submit the following to the Engineer for review and approval at least 15 calendar days before mixing and field casting takes place:

- Material certifications and ingredient specifications from their manufacturers
- A Quality Control plan that includes, but is not limited to, the following:
  - (1) Mixture ingredient proportions to be used
  - (2) Mixing protocol
  - (3) Casting procedure
  - (4) Sampling and testing procedure
  - (5) Curing procedure
  - (6) Finishing procedure after field placement
  - (7) Additional information found in the Construction section below

2.2. Should the contractor submit a mix design which deviates from the mix in Table 6.1, such submittal shall include all statistical requirements to satisfy the engineering properties specified in the PCI Report titled: “Guidelines for the Use of Ultra-High-Performance Concrete (UHPC) in Precast and Prestressed Concrete PDF (TR-9-

22E)” in addition to durability requirements specified in the NDOT report SPR-P1(18) M072 titled “Feasibility Study of Development of UHPC for Highway Bridge Applications in Nebraska”. Results of all tests shall be submitted to NDOT or its designated representative no later than 60 days prior to first placement of UHPC.

2.3. NDOT may waive the tests of the approved mix if these tests have been previously performed for materials supplied to NDOT by the Contractor.

2.4. No change shall be made to the approved UHPC mixture design during the progress of work without the prior written permission of the NDOT Portland Cement Concrete (PCC) Engineer.

3. **Mixture Batching**

3.1. The mixture shall meet the desired placement, finishing, and curing characteristics.

3.2. A high-shear pan mixer capable of supplying sufficient energy to the mixture is recommended for field production of cast-in-place UHPC. Due to the energy required, it is recommended to limit each batch’s volume to a third of the mixer’s capacity. Portable drum mixers are not permitted.

3.3. Batching of non-proprietary UHPC results in substantial increases in material temperature during batching. As noted in the Materials section, ice is recommended to be substituted for water should the ambient temperature be higher than 60^{o}F.

3.4. The following mixing procedure should be followed according to Table 6.2. If an alternate mixing procedure is proposed, the Contractor shall submit information as part of the Quality Control plan.

Table 6.2 Batching Procedure

Step Number	Description	Tentative Duration of Mixing* (*minutes*)
1	Add dry mix sand and silica fume	2
2	Add dry mix cement and slab	2
3	Add water, ice (if applicable), WRA, SRA (if applicable), and 80% of HRWR admixture	1
4	Mix until flowable	5-10
5	Add remaining/extra HRWR admixture if needed until mixture becomes fluid	2
6	Dispense steel fibers gradually during mixing duration	3
7	Additional fiber mixing, observing for improper fiber segregation or clumping	2
8	Conduct flow test and VSI test	2
9	Discharge and transport	n/a

**Subject to change due to volume of batch and mixture type.*

000.03 - - Construction

1. **Storage of Material**

   Assure the proper storage of all constituent materials, including but not limited to cement, aggregates, additives, and steel fibers, as required by the specifications provided by their suppliers/manufacturers to protect the integrity of the materials against the loss of physical, chemical, and mechanical properties.

2. **Placement Plan and Preplacement Meeting**

   2.1. The Contractor should submit a Placement Plan (with a detailed field work schedule) to the Engineer for review and approval at least 15 calendar days prior to the scheduled UHPC placement pour. No UHPC shall be placed on the project until the Engineer has reviewed and approved the required submittals.

   The following list is intended as a guide and may not address all the means and methods the Contractor may elect to use. The Contractor is expected to assemble a comprehensive list of all necessary items for executing the placement of UHPC.

   - Responsible personnel for placement
   - Equipment utilized in placement, testing, and curing of material
   - Quality Control of batch proportions – method of measurement and form of documentation of material provided
   - Quality Control of batching material
   - Batch procedure sequence
   - Proposed forming method that ensures grout-tight forms and removal plan for formwork
   - Placement procedure – including but not limited to the preparation of existing concrete surface (to ensure required roughness, cleanliness, and wetness) before UHPC placemen, in addition to spreading, finishing, and curing details

   2.2. The Contractor should arrange for an onsite meeting with the Contractor's staff, the Construction Project Manager, the Bridge Engineer, and Materials and Research Personnel. The objective of this meeting will be to outline the procedures for forming, mixing, transporting, placing, finishing, and curing of the UHPC. It should also provide an opportunity to review testing for acceptance sampling/testing procedures.

3. **Trial Batch and Test Placement**

   3.1. For contractors with no prior experience in batching and placement of NDOT non-proprietary UHPC mixture, it is required that the contractor conduct a trial batch and mockup placement to gain experience. Changes in equipment and environmental factors (ambient temperature, humidity, etc.) can impact the results of batching outcomes.

   3.2. Test specimens are required to ensure that the acceptance criteria in Table 6.3 can be met.

4. **Formwork, Casting, and Curing**

4.1. Formwork shall be watertight and coated to prevent the absorption of water and leakage of the mix after placement. Formwork shall be resistant to the hydrostatic pressure of fresh UHPC using a unit weight of 155 lb/ft^3.

4.2. Top forms are advisable to create an acceptable top surface condition and are likely necessary on sloped surfaces.

4.3. UHPC must be placed continuously in a single, uninterrupted flow to avoid the creation of horizontal cold joints or construction joints.Provisions for temporary bulkheads should be made accordingly. Considerations should be provided in the placement plan for the effective placement of vertical cold joints in cast-in-place UHPC for applications requiring large quantities of material.

4.4. Surface preparation:

4.4.1. Cast-in-place UHPC to previously cast conventional concrete - Expose the aggregate of the conventional concrete. Remove any loose material. Ensure the surface is clean and prewet to a saturated surface dry condition prior to UHPC placement. No standing water in the formwork should be allowed.

4.4.2. Cast-in-place UHPC to previously cast UHPC – no blasting is necessary, however, remove any loose material. Ensure the surface is clean and prewet to the saturated surface dry condition prior to UHPC placement. No standing water in the formwork should be allowed.

4.5. Do not place UHPC if the ambient temperature is below 40°F or above 90°F, as these conditions could significantly delay hydration or cause rapid loss of workability. Exceptions to this rule may be allowed if approved by the Engineer. Pumping of UHPC is not permitted.

4.6. Cover exposed surfaces with impervious material (e.g. plastic sheet) immediately after finishing and for at least 24 hours; wet burlap is not allowed.. Then, exposed surfaces should be either moist cured with wet burlap or covered with curing compound for at least seven days.

4.7. Unless otherwise specified, UHPC shall be given a smooth surface finish. If grinding is required, it should be done when the compressive strength of the UHPC material is between 10 ksi and 14 ksi.

4.8. No vehicular traffic, other than conventional contractor tools, is allowed on the bridge until the cast-in-place UHPC achieves a minimum of 12 ksi compressive strength and flexure strength requirements of Table 6.3 are met.

5. **Acceptance Testing**

5.1. The Engineer and Materials and Research personnel will be on site during the preparation and placement of UHPC. Coordination with the necessary personnel must be done a minimum of 48 hours prior to the anticipated UHPC placement.

5.2. Provide an appropriate location to place specimens for initial curing prior to transport to the laboratory. Curing boxes shall be equipped with supplemental heat or cooling as necessary to cure the specimens in accordance with ASTM C1856.

5.3. Acceptance testing shall be performed by the Contractor and approved by the Engineer. The required testing is summarized below in Table 6.3. The table contains test methods, minimum acceptance criteria, and expected frequencies.

Tests may be performed at more frequent intervals than described below, at the discretion of the Engineer.

5.3.1. Flow – Testing to be completed at the mixer on individual batches and at the casting site for combined batches from concrete delivery equipment within 10 minutes before placement. Timing of this test is outlined in Table 6.2.

5.3.2. Visual Stability Index – testing to be completed at the mixer on individual batches and at the casting site for combined batches from concrete delivery equipment within 10 minutes before placement.

5.3.3. Compressive Strength – Samples shall be collected at the casting site from the equipment utilized to deliver the material within ten minutes before placement.

Three sets of three samples, (9) 3-inch x 6-inch cylinders, will be collected for each discrete placement element as outlined in the placement plan, or for every two cubic yards of material placed; whichever controls. A discrete element should include a joint between precast elements placed in a single operation without cold joints, and similarly discrete elements. Placement plans should define limits of sampling for this acceptance criteria. If the filling of the molds requires more than one trip of the delivery equipment, the number of test specimens shall be multiplied by at least one-half of the delivery trips.

Compressive testing shall occur prior to form stripping, allowing traffic, and 28 days. Three cylinders shall be tested each testing day. Additional samples collected due to multiple delivery should be tested at 28 days.

No more than 33% of test specimens are allowed to fall outside the requirements range, provided that the average for all test specimens is within acceptance criteria.

5.3.4. Flexural Strength - Samples shall be collected at the casting site from the equipment utilized to deliver the material within ten minutes before placement.

Two sets of three samples, (6) 4-inch x 4-inch x 14-inch prisms, will be collected for each discrete placement element as outlined in the placement plan, or for every two cubic yards of material placed; whichever controls. A discrete element should be considered to include a joint between precast elements placed in a single operation without cold joints, and similarly discrete elements. Placement plans should define limits of sampling for this acceptance criteria. If the filling of the molds requires more than one trip of the delivery equipment, the number of test specimens shall be multiplied by at least one-half of the delivery trips.

Flexural testing shall occur prior to allowing traffic (if earlier than 28 days) and at 28 days. Three cylinders shall be tested each testing day. Additional samples collected due to multiple deliveries should be tested at 28 days.

No more than 33% of test specimens are allowed to fall outside the requirements range, provided that the average for all test specimens is within acceptance criteria.

Table 6.3 Acceptance Criteria

Description	Test Method	Acceptance Criteria	Frequency
Flow	ASTM C1856/C1437	8 inches (minimum) 11 inches (maximum)	One per Batch
Visual Stability Index	*	0-1 within 10 minutes prior to placement	One per batch
Compressive Strength	ASTM C1859/C39	≥ 10 ksi (at form stripping) ≥ 12 ksi (at allowing traffic) ≥ 17.4 ksi (at 28 days)	(9) 3x6 inch cylinders per discrete element, or every 2 CY. Testing at form stripping, allowing traffic, and 28 days
Flexural Strength	ASTM C1856/C1609	Minimum 1.5 ksi first-crack stress; Minimum 2.0 ksi peak stress; Minimum 1.25 ratio of peak-to-first-crack stress; Minimum 0.75 ratio of residual stress at L/150 net deflection-to-first crack stress	(3 or 6) 4x4x14-inch prisms per discrete element or every 2 CY. Testing at allowing traffic (if earlier than 28 days) and 28 days
Batch Temperature**	ASTM C1064	Not for Accept/Reject Recommend utilizing sufficient ice as substitute to water and other cooling measures to keep temperature at placement below 80 F	One per Batch

**Based on the ACI publication: Flavia Mendonca and Jiong Hu (2021) "Impact of Chemical Admixtures on Time-Dependent Workability and Rheological Properties of Ultra-High-Performance Concrete", ACI Materials Journal, November.*

**Contractor to provide to Engineer for Information Only

000.04 - - Method of Measurement

1. The pay item “CAST-IN-PLACE NON-PROPRIETARY UHPC” shall be measured by plan quantity by the cubic foot (CF).

000.05 - - Basis of Payment

Pay Item	**Pay Unit**
Cast-in-Place Non-Proprietary UHPC	Cubic Feet (CF)

Payment should be considered full compensation for furnishing all submittal, materials, labor, testing, equipment calibration, results, formwork, and incidental work for completion of the work as indicated in this special provision and project plans.

CAST-IN-PLACE PROPRIETARY PRE-BAGGED ULTRA-HIGH-PERFORMANCE CONCRETE FOR BRIDGES

000.01 - - Description of Work

3. These provisions cover the production, placement, curing, and testing of proprietary pre-bagged Ultra-High-Performance Concrete (UHPC) for structural cast-in-place concrete bridge applications, including joints, connections, repair, and preservation. Not included in these provisions are applications requiring specialized UHPC, such as deck structural repair and overlays. The concrete mixture described here shall be used as indicated in the project plans. All work shall be in accordance with the Standard Specifications, except as modified herein.

4. The requirements of this provision apply only to the proprietary pre-bagged UHPC mixtures by qualified manufacturers. For different UHPC mixtures, durability requirements in addition to those specified in Table 6.3 shall be met.

000.02 - - Materials

4. **UHPC**

Provide a proprietary UHPC product with independent test data showing the proposed UHPC product meets the material property requirements as listed in Table 6.1, unless otherwise noted in the contract documents or as directed by NDOT engineer. Material properties listed below will be verified by the manufacturer and submitted for approval.

Table 6.4 UHPC Requirements

Description	**Test Method**	**Acceptance Criteria**
Compressive Strength	ASTM C1859/C39 (at 28 days)	≥ 17.4 ksi
Long-Term Shrinkage	AASHTO T160 (1 year)	≤ 800 micro-strain
Freeze-Thaw Resistance	AASHTO T 161 / ASTM C666A (600 cycles)	Relative Dynamic Modulus of Elasticity > 95%
Rapid Chloride Ion Penetrability	AASHTO T 277 / ASTM C1202 (after 56 days)	≤ 250 coulombs (4”x8” cylinders, without fiber)

5. **Storage**

The material should be Ultra-High Performance Concrete, with all components supplied by one manufacturer.

The container shall include the following information: The name of the manufacturer, the brand name of the product, the date of manufacture.

6. **Material Submittals**

6.1. Submit the following to the Engineer for review and approval at least 15 calendar days before mixing and field casting takes place:

- Material certifications from their manufacturers
- A Quality Control plan that includes, but is not limited to, the following:
  - (1) Mixing protocol
  - (2) Casting procedure
  - (3) Sampling and testing procedure
  - (4) Curing procedure
  - (5) Finishing procedure after field placement
  - (6) Additional information found in the Construction section below

6.2. NDOT may waive the tests of the approved mix if these tests have been previously performed for materials supplied to NDOT by the Contractor.

7. **Mixture Batching**

7.1. The mixture shall meet the desired placement, finishing, and curing characteristics.

7.2. Mixer, per recommendation from the manufacturer, should be used for UHPC batching. A high-shear pan mixer capable of supplying sufficient energy to the mixture is generally recommended for field production of cast-in-place UHPC. Due to the energy required, it is recommended to limit each batch's volume to a third of the mixer's capacity. Portable drum mixers are not permitted.

7.3. Mix and place UHPC in accordance with the manufacturer's recommendations. Use mixing equipment that is recommended by the UHPC manufacturer. Noted that batching of UHPC generally results in substantial increases in material temperature during batching, and ice is recommended to be substituted for water should the ambient temperature be higher than 60ºF.

7.4. The mixing procedure as provided by the manufacturer should be followed according to Table 6.2. If an alternate mixing procedure is proposed, the Contractor shall submit information as part of the Quality Control plan.

Table 6.5 Batching Procedure

Step Number	Description	Tentative Duration of Mixing* (*minutes*)
1	Batching per manufacturer instruction	NA
2	Conduct flow test and VSI test	2
3	Discharge and transport	n/a

**Subject to change due to volume of batch and mixture type.*

000.03 - - Construction

6. **Storage of Material**
Assure the proper storage of all constituent materials, including but not limited to premix, additives, and steel fibers, as required by the specifications provided by their suppliers/manufacturers to protect the integrity of the materials against the loss of physical, chemical, and mechanical properties.

7. **Placement Plan and Preplacement Meeting**
7.1. The Contractor should submit a Placement Plan (with a detailed field work schedule) to the Engineer for review and approval at least 15 calendar days prior to the scheduled UHPC placement pour. No UHPC shall be placed on the project until the Engineer has reviewed and approved the required submittals.
The following list is intended as a guide and may not address all the means and methods the Contractor may elect to use. The Contractor is expected to assemble a comprehensive list of all necessary items for executing the placement of UHPC.

- Responsible personnel for placement
- Equipment utilized in placement, testing, and curing of material
- Quality Control of batch proportions – method of measurement and form of documentation of material provided
- Quality Control of batching material
- Batch procedure sequence
- Proposed forming method that ensures grout-tight forms and removal plan for formwork
- Placement procedure – including but not limited to the preparation of existing concrete surface (to ensure required roughness, cleanliness, and wetness) before UHPC placemen, in addition to spreading, finishing, and curing details

7.2. The Contractor should arrange for an onsite meeting with the Contractor's staff, the Construction Project Manager, the Bridge Engineer, and Materials and Research Personnel. The objective of this meeting will be to outline the procedures for forming, mixing, transporting, placing, finishing, and curing of the UHPC. It should also provide an opportunity to review testing for acceptance sampling/testing procedures.

8. **Trial Batch and Test Placement**
8.1. For contractors with no prior experience in batching and placement of NDOT non-proprietary UHPC mixture, it is required that the contractor conduct a trial batch and mockup placement to gain experience. Changes in equipment and environmental factors (ambient temperature, humidity, etc.) can impact the results of batching outcomes.
8.2. Test specimens are required to ensure that the acceptance criteria in Table 6.3 can be met.

9. **Formwork, Casting, and Curing**

9.1. Formwork shall be watertight and coated to prevent the absorption of water and leakage of the mix after placement. Formwork shall be resistant to the hydrostatic pressure of fresh UHPC using a unit weight of 155 lb/ft^3.

9.2. Top forms are advisable to create an acceptable top surface condition and are likely necessary on sloped surfaces.

9.3. UHPC must be placed continuously in a single, uninterrupted flow to avoid the creation of horizontal cold joints or construction joints. Provisions for temporary bulkheads should be made accordingly. Considerations should be provided in the placement plan for the effective placement of vertical cold joints in cast-in-place UHPC for applications requiring large quantities of material.

9.4. Surface preparation:

9.4.1. Cast-in-place UHPC to previously cast conventional concrete - Expose the aggregate of the conventional concrete. Remove any loose material. Ensure the surface is clean and prewet to a saturated surface dry condition prior to UHPC placement. No standing water in the formwork should be allowed.

9.4.2. Cast-in-place UHPC to previously cast UHPC – no blasting is necessary, however, remove any loose material. Ensure the surface is clean and prewet to the saturated surface dry condition prior to UHPC placement. No standing water in the formwork should be allowed.

9.5. 4.5. Do not place UHPC if the ambient temperature is below 40°F or above 90°F, as these conditions could significantly delay hydration or cause rapid loss of workability. Exceptions to this rule may be allowed if approved by the Engineer.

9.6. Pumping of UHPC is not permitted.

9.7. Cover exposed surfaces with impervious material (e.g. plastic sheet) immediately after finishing and for at least 24 hours; wet burlap is not allowed. Then, exposed surfaces should be either moist cured with wet burlap or covered with curing compound for at least seven days.

9.8. Unless otherwise specified, UHPC shall be given a smooth surface finish. If grinding is required, it should be done when the compressive strength of the UHPC material is between 10 ksi and 14 ksi.

9.9. No vehicular traffic, other than conventional contractor tools, is allowed on the bridge until the cast-in-place UHPC achieves a minimum of 12 ksi compressive strength and flexure strength requirements of Table 6.3 are met.

10. **Acceptance Testing**

10.1. The Engineer and Materials and Research personnel will be on site during the preparation and placement of UHPC. Coordination with the necessary personnel must be done a minimum of 48 hours prior to the anticipated UHPC placement.

10.2. Provide an appropriate location to place specimens for initial curing prior to transport to the laboratory. Curing boxes shall be equipped with supplemental heat or cooling as necessary to cure the specimens in accordance with ASTM C1856.

10.3. Acceptance testing shall be performed by the Contractor and approved by the Engineer. The required testing is summarized below in Table 6.3. The table contains test methods, minimum acceptance criteria, and expected frequencies.
Tests may be performed at more frequent intervals than described below, at the discretion of the Engineer.

10.3.1. Flow – Testing to be completed at the mixer on individual batches and at the casting site for combined batches from concrete delivery equipment within 10 minutes before placement. Timing of this test is outlined in Table 6.2.

10.3.2. Visual Stability Index – testing to be completed at the mixer on individual batches and at the casting site for combined batches from concrete delivery equipment within 10 minutes before placement.

10.3.3. Compressive Strength – Samples shall be collected at the casting site from the equipment utilized to deliver the material within ten minutes before placement.

Three sets of three samples, (9) 3-inch x 6-inch cylinders, will be collected for each discrete placement element as outlined in the placement plan, or for every two cubic yards of material placed; whichever controls. A discrete element should include a joint between precast elements placed in a single operation without cold joints, and similarly discrete elements. Placement plans should define limits of sampling for this acceptance criteria. If the filling of the molds requires more than one trip of the delivery equipment, the number of test specimens shall be multiplied by at least one-half of the delivery trips.

Compressive testing shall occur prior to form stripping, allowing traffic, and 28 days. Three cylinders shall be tested each testing day. Additional samples collected due to multiple delivery should be tested at 28 days.

No more than 33% of test specimens are allowed to fall outside the requirements range, provided that the average for all test specimens is within acceptance criteria.

10.3.4. Flexural Strength - Samples shall be collected at the casting site from the equipment utilized to deliver the material within ten minutes before placement.

Two sets of three samples, (6) 4-inch x 4-inch x 14-inch prisms, will be collected for each discrete placement element as outlined in the placement plan, or for every two cubic yards of material placed; whichever controls. A discrete element should be considered to include a joint between precast elements placed in a single operation without cold joints, and similarly discrete elements. Placement plans should define limits of sampling for this acceptance criteria. If the filling of the molds requires more than one trip of the delivery equipment, the number of test specimens shall be multiplied by at least one-half of the delivery trips.

Flexural testing shall occur prior to allowing traffic (if earlier than 28 days) and at 28 days. Three cylinders shall be tested each testing day. Additional samples collected due to multiple deliveries should be tested at 28 days.

No more than 33% of test specimens are allowed to fall outside the requirements range, provided that the average for all test specimens is within acceptance criteria.

Table 6.6 Acceptance Criteria

Description	Test Method	Acceptance Criteria	Frequency
Flow	ASTM C1856/C1437	8 inches (minimum) 11 inches (maximum)	One per Batch
Visual Stability Index	*	0-1 within 10 minutes prior to placement	One per batch
Compressive Strength	ASTM C1859/C39	≥ 10 ksi (at form stripping) ≥ 12 ksi (at allowing traffic) ≥ 17.4 ksi (at 28 days)	(9) 3x6 inch cylinders per discrete element, or every 2 CY. Testing at form stripping, allowing traffic, and 28 days
Flexural Strength	ASTM C1856/C1609	Minimum 1.5 ksi first-crack stress; Minimum 2.0 ksi peak stress; Minimum 1.25 ratio of peak-to-first-crack stress; Minimum 0.75 ratio of residual stress at L/150 net deflection-to-first crack stress	(3 or 6) 4x4x14-inch prisms per discrete element or every 2 CY. Testing at allowing traffic (if earlier than 28 days) and 28 days
Batch Temperature**	ASTM C1064	Not for Accept/Reject Recommend utilizing sufficient ice as substitute to water and other cooling measures to keep temperature at placement below 80 F	One per Batch
**Based on the ACI publication: Flavia Mendonca and Jiong Hu (2021) "Impact of Chemical Admixtures on Time-Dependent Workability and Rheological Properties of Ultra-High-Performance Concrete", ACI Materials Journal, November.* **Contractor to provide to Engineer for Information Only			

000.04 - - Method of Measurement

2. The pay item "CAST-IN-PLACE PROPRIETARY PRE-BAGGED UHPC" shall be measured by plan quantity by the cubic foot (CF).

000.05 - - Basis of Payment

Pay Item	**Pay Unit**
Cast-in-Place Proprietary Pre-Bagged UHPC	Cubic Feet (CF)

Payment should be considered full compensation for furnishing all submittal, materials, labor, testing, equipment calibration, results, formwork, and incidental work for completion of the work as indicated in this special provision and project plans.

References

Alkaysi, M. and El-Tawil, S. Effects of Variations in the Mix Constituents of Ultra High Performance Concrete (UHPC) on Cost and Performance. *Material and Structures*, 2015, 49: 4185-4200.

Alsalman, A., Dang, C. N., Martí-Vargas, J. R., & Hale, W. M. (2020). Mixture-proportioning of economical UHPC mixtures. *Journal of Building Engineering*, 27, 100970.

Ambily, P. S., Ravisankar, K., Umarani, C., Dattatreya, J. K., and Iyer, N. R. Development of Ultra-High-Performance Geopolymer Concrete. *Magazine of Concrete Research - Institute of Civil Engineers,* 2014, 66: 82-89.

ACI. Ultra-High-Performance Concrete: An Emerging Technology Report. *American Concrete Institute ACI 239*, 2018.

Anshuang, S., Ling, Q., Shoujie, Z., Jiayang, Z., & Zhaoyu, L. (2017). Effects of Shrinkage Reducing Agent and Expansive Admixture on the Volume Deformation of Ultrahigh Performance Concrete. *Advances in Materials Science and Engineering*, *2017*.

ASTM C150. Standard specification for portland cement. *ASTM International (American Society for Testing and Materials).* 2012

ASTM C157. Standard test method for length change of hardened hydraulic-cement mortar and concrete. *ASTM International (American Society for Testing and Materials),* 2017.

ASTM C230. Standard specification for flow table for use in tests of hydraulic cement. *ASTM International (American Society for Testing and Materials),* 2023.

ASTM C403. Standard test method for time of Setting of Concrete mixtures by penetration resistance. *ASTM International (American Society for Testing and Materials),* 2023.

ASTM C494. Standard specification for chemical admixtures for concrete. *ASTM International (American Society for Testing and Materials),* 2019.

ASTM C989. Standard specification for slag cement for use in concrete and mortars. *ASTM International (American Society for Testing and Materials),* 2022.

ASTM C1698. Standard test method for autogenous strain of cement paste and mortar. *ASTM International (American Society for Testing and Materials),* 2019.

ASTM C1702. Standard test method for measurement of heat of hydration of hydraulic cementitious materials using isothermal conduction calorimetry. *ASTM International (American Society for Testing and Materials)*, 2023.

ASTM C1856. Standard Practice for Fabricating and Testing Specimens of Ultra-High-Performance Concrete. *ASTM International (American Society for Testing and Materials)*, 2017.

Berry, M., Snidarich, R., Wood, C. Development of Non-Proprietary Ultra-High-Performance Concrete. *The State of Montana Department of Transportation,* FHWA/MT-17010/8237-001, 2017.

Bonneau, O., Lachemi, M., Dallaire, E., Dugat, J. and Aitcin, P. Mechanical Properties and Durability of Two Industrial Reactive Powder Concretes. *ACI Materials Journal*, 1997, 94: 286-290.

California Department of Transportation, Notice to Bidders and Special Provision. Contract No. 06-0K4604, Project ID 0612000105, 2015.

Choi, M. S., Lee, J. S., Ryu, K. S., Koh, K. and Kwon S. H. Estimation of Rheological Properties of UHPC Using Mini Slump Test. *Construction and Building Materials,* 2016, 106: 632-639.

Colorado Department of Transportation, Ultra High Performance Concrete. 2018.

De Larrard, F. and Sedran, T. Optimization of Ultra-High-Performance Concrete by the Use of Particle Packing. *Cement and Concrete Research*, 1994, 24: 997-1009.

District Department of Transportation, Special Provision for Ultra High-Performance Concrete. SP60, 2014.

Douglas, R., Gregori, A., Sun, Z., & Shah, S. P. (2005). Investigations of the Properties of SCC: a Method for Measuring Thixotropy and Viscosity. In *Proceedings of Knud Hojgaard Conference on Advanced Cement Based Material*, 19-30.

El-Tawil, S., Tai, Y., Meng, B., Hansen W. and Liu, Z. Commercial Production of Non-Proprietary Ultra-High-Performance Concrete. *Michigan Department of Transportation* (RC-1670)*,* 2018.

Elinwa, A. U., Ejeh, S. P., & Mamuda, A. M. (2008). Assessing of the fresh concrete properties of self-compacting concrete containing sawdust ash. *Construction and building materials*, *22*(6), 1178-1182.

Fedorsian, I. and Camoes, A. Effective Low-Energy Mixing Procedure to Develop High-Fluidity Cementitious Pastes. *Materia Rio de Janeiro,* 2016, 21(1): 11-17.

FHWA. Properties and Behavior of UHPC-Class Materials, *Federal Highway Administration, FHWA-HRT-18-036,* 2018.

FHWA. Ultra-High Performance Concrete: A State-of-the-Art Report for the Bridge Community, *Federal Highway Administration,* FHWA-HRT-13-060, 2013.

FDOT, Ultra High-Performance Concrete (UHPC). *Florida Department of Transportation,* 2018.

Ghafari, E., Ghahari, S. A., Costa, H., Júlio, E., Portugal, A., & Durães, L. Effect of supplementary cementitious materials on autogenous shrinkage of ultra-high performance concrete. *Construction and Building Materials*, 2016, 127, 43–48.

Graybeal, B. Design and Construction of Field-Cast UHPC Connection. *Federal Highway Administration,* Tech Note FHWA-HRT-14-084, 2014.

Graybeal, B. Development of Non-Proprietary Ultra High-Performance Concrete for Use in the Highway Bridge Sector. *Federal Highway Administration,* FHWA –HRT-13-100, 2013.

Graybeal, B. and Leonard, M. Example Construction Checklist: UHPC Connections for Prefabricated Bridge Elements. *Federal Highway Administration,* FHWA-HIF-18-030, 2018.

Haber Z. B., De la Varga, I., Graybeal, B., Nakashoji, B. and El-Helou, R. Properties and Behavior of UHPC-Class Materials. *Federal Highway Administration,* FHWA-HRT-18-036, 2018.

Hu, J., Ge, Z., & Wang, K. Influence of cement fineness and water-to-cement ratio on mortar early-age heat of hydration and set times. *Construction and Building Materials*, 2014, 50, 657–663.

Huang, H., & Ye, G. Examining the "time-zero" of autogenous shrinkage in high/ultra-high performance cement pastes. *Cement and Concrete Research*, 2017, 97, 107–114.

IADOT, Developmental Specifications for Ultra High Performance Concrete Connections. *Iowa Department of Transportation,* DS-15092, 2022.

Koh, K., Ryu, G., Kang, S., Park, J., & Kim, S. Shrinkage properties of ultra-high performance concrete (UHPC). *Advanced Science Letters*, 2011, 4(3), 948-952.

Li, P. P., Yu, Q. L., & Brouwers, H. J. H. (2017). Effect of PCE-type superplasticizer on early-age behaviour of ultra-high performance concrete (UHPC). *Construction and Building Materials*, *153*, 740-750.

Li, S., Cheng, S., Mo, L., & Deng, M. (2020). Effects of steel slag powder and expansive agent on the properties of ultra-high performance concrete (UHPC): Based on a case study.

Li, S., Mo, L., Deng, M., & Cheng, S. (2021). Mitigation on the autogenous shrinkage of ultra-high performance concrete via using MgO expansive agent. *Construction and Building Materials*, *312*.

Liu, L., Fang, Z., Huang, Z., & Wu, Y. (2022). Solving shrinkage problem of ultra-high-performance concrete by a combined use of expansive agent, super absorbent polymer, and shrinkage-reducing agent. *Composites Part B: Engineering*, *230*.

Precast/Prestressed Concrete Institute (PCI). Manual for Quality Control for Plants and Production of Structural Precast Concrete Products. *Precast/Prestressed Concrete Institute,* 4th edition, 1999, MNL-116.

Mendonca, F., & Hu, J. (2021). Impact of Chemical Admixtures on Time-Dependent Workability and Rheological Properties of Ultra-High-Performance Concrete. *ACI Materials Journal*, *118*(6).

Meng, W. and Khayat, K. H. Mechanical Properties of Ultra-High-Performance Concrete Enhanced with Graphite Nanoplatelets and Carbon Nano Fibers. *In Composites Part B*, 2016,107: 113-122.

Meng, W., Valipour, M., and Khayat, K. H. Optimization and Performance of Cost-Effective Ultra-High-Performance Concrete. *Materials and Structure,* 2017 (b). 50: n/a.

MIDOT, Special Provision for Michigan Ultra High Performance Concrete (MI-UHPC) For Field Cast Joints, *Michigan Department of Transportation*, n/a.

Mohebbi, A., Graybeal, B., & Haber, Z. (2022). Time-Dependent Properties of Ultrahigh-Performance Concrete: Compressive Creep and Shrinkage. *Journal of Materials in Civil Engineering*, *34*(6).

Naaman, A., and Wille, K. The Path to Ultra High Performance Fiber Reinforced Concrete (UHP-FRC): Five Decades of Progress. *In proceedings of Hipermat 2012, 3rd International Symposium: Ultra High Performance Concrete and Nanotechnogy in Construction, Germany,* 2012.

NYDOT, Ultra-High Performance Concrete (UHPC). ITEM 557.6601NN16, *New York State Department of Transportation,* 2023.

PADOT, Ultra High Performance Concrete. *Pennsylvania Department of Transportation*, a10303 2021.

Park, J. J., Yoo, D. Y., Kim, S. W., & Yoon, Y. S. (2014). Benefits of using expansive and shrinkage-reducing agents in UHPC for volume stability. *Magazine of Concrete Research*, *66*(14), 745–750.

PCI, Guidelines for the Use of Ultra-High-Performance Concrete (UHPC) in Precast and Prestressed Concrete", *Precast/Prestressed Concrete Institute*, PCI Concrete Materials Technology Committee TR-9-22, Chicago, IL, 2022.

Ruan, T., & Poursaee, A. (2019). Fiber-distribution assessment in steel fiber–reinforced UHPC using conventional imaging, X-ray CT scan, and concrete electrical conductivity. *Journal of Materials in Civil Engineering*, *31*(8), 04019133.

Russell, H. G. and Graybeal, B. Ultra-High Performance Concrete: A state-of-the-Art Report for the Bridge Community. *Federal Highway Administration,* FHWA-HRT-13-060, 2013.

Russell, H. G. (2008). ASTM Test Methods for Self-Consolidating Concrete. *HPC Bridge Views*, *50*.

Sbia, L. A., Peyvandi, A., Lu, J., Abideen, S., Weerasiri, R. R., Balachandra, A. M., & Soroushian, P. (2017). Production methods for reliable construction of ultra-high-performance concrete (UHPC) structures. *Materials and Structures*, *50*, 1-19.

Shen, P., Lu, L., He, Y., Wang, F., Lu, J., Zheng, H., & Hu, S. (2020). Investigation on expansion effect of the expansive agents in ultra-high performance concrete. *Cement and Concrete Composites*, *105*.

Shi, C., Wu, Z., Xiao, J., Wang, D., Huang, Z. and Fang, Z. A Review on Ultra High Performance Concrete: Part I. Raw Materials and Mixture Design. *Construction and Building Materials*, 2015, 101: 741-751.

Soliman, A. M., & Nehdi, M. L. (2011). Effect of drying conditions on autogenous shrinkage in ultra-high performance concrete at early-age. *Materials and Structures/Materiaux et Constructions*, *44*(5), 879–899.

Soliman, A. M., & Nehdi, M. L. (2014). Effects of shrinkage reducing admixture and wollastonite microfiber on early-age behavior of ultra-high performance concrete. *Cement and Concrete Composites*, *46*, 81–89.

Wang, R., Gao, X., Huang, H., & Han, G. (2017). Influence of rheological properties of cement mortar on steel fiber distribution in UHPC. *Construction and Building Materials*, *144*, 65-73.

Weiss, J., Lura, P., & Rajabipour, F. (2008). Performance of shrinkage -reducing admixtures at different humidities and at early age. *ACI Materials Journal,* 105-M55.

Wille, K., Naaman, A. E., and Parra-Montesinos, G. J. Ultra-High Performance Concrete with Compressive Strength Exceeding 150MPA (22KSi): A Simpler Way. *ACI Material Journal,* 2011 (a), n/a: 46-54.

Wille, K., Naaman, A. E., and El-Tawil, S. Optimizing Ultra-High-Performance Fiber-Reinforced Concrete, Mixtures with Twisted Fibers Exhibit Record Performance under Tensile Loading. *Concrete International*, 2011 (b), n/a: 35-41.

Wu, Z., Shi, C., Khayat, K. H., and Wan, S. Effect of Different Nanomaterials on Hardening and Performance of Ultra-High Strength Concrete (UHSC), *Cement and Concrete Composites*, 2016, 70: 24-34.

Xie, T., Fang, C., Mohamad Ali, M. S., & Visintin, P. (2018). Characterizations of autogenous and drying shrinkage of ultra-high performance concrete (UHPC): An experimental study. *Cement and Concrete Composites*, *91*, 156–173.

Yang, L., Shi, C., & Wu, Z. (2019). Mitigation techniques for autogenous shrinkage of ultra-high-performance concrete – A review. In *Composites Part B: Engineering* (Vol. 178). Elsevier Ltd.

Yang, S. L., Millard, S. G., Soutsos, M. N., Barnett, S. J. and Le, T. T. Influence of Aggregate and Curing Regime on Mechanical Properties of Ultra High Performance Concrete. *Construction and Building Materials*, 2009, 23: 2291-2298.

Yu, R., Spiesz, P., and Browers, H. J. H. Effect of Nano-Silica on the Hydration and Microstructure development of Ultra-High Performance Concrete (UHPC) with a Low Binder Amount. *Construction and Building Materials*, 2014 (a), 65: 140-150.

Yu, R., Spiesz, P., and Browers, H. J. H. Mix design and Proprieties Assessment of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC). *Cement and Concrete Research*, 2014 (b), 56: 29-39.

Yu, R., Spiesz, P., and Browers, H. J. H. Development of an Eco-Friendly Ultra-High Performance Concrete (UHPC) With Efficient Cement and Mineral Admixture Uses. *Cement and Concrete Composites,* 2015, 55: 383-394.

Yoo, D. Y., Banthia, N., & Yoon, Y. S. (2015). Effectiveness of shrinkage-reducing admixture in reducing autogenous shrinkage stress of ultra-high-performance fiber-reinforced concrete. *Cement and Concrete Composites*, *64*, 27–36.

Appendix A

Handout for Workshop on Production of Cast-in-Place UHPC for Bridge Applications

WORKSHOP ON PRODUCTION OF CAST-IN-PLACE UHPC FOR BRIDGE APPLICATIONS

Jiong Hu and George Morcous

3/16/2022

NEBRASKA
Good Life. Great Journey.
DEPARTMENT OF TRANSPORTATION

COLLEGE OF ENGINEERING

WORKSHOP OUTLINE

- **Morning Session: Lecture and Discussion**
  - Introduction of UHPC
  - Production of UHPC
  - Break
  - Testing of UHPC
  - UHPC experiences – case studies
  - Discussions and Q&A
- **Afternoon Session: Hands-on Experience**
  - UHPC batching, casting and specimen preparation
  - UHPC testing
  - Q&A

2

3

SELF-INTRODUCTION

- Name
- Employer
- Job title

4

INTRODUCTION OF UHPC

OUTLINE/LEARNING OBJECTIVES

- What is UHPC?
  - Recognize general UHPC characteristics (and the difference between UHPC and conventional concrete)
- UHPC mixture design, specifications, and properties
  - Understand the difference between UHPC and conventional concrete mixture design
- Applications of UHPC
  - Know the major applications of UHPC

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6

WHAT IS UHPC?

7

FHWA SITE OF ULTRA-HIGH PERFORMANCE CONCRETE

https://highways.dot.gov/research/structures/ultra-high-performance-concrete/ultra-high-performance-concrete

WHAT IS UHPC?

1- Federal Highway Administration (FHWA) definition:

"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). UHPC has a discontinuous pore structure that reduces liquid ingress, significantly enhancing durability compared to conventional concrete."

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WHAT IS UHPC?

Ultra-High-Performance Concrete: An Emerging Technology Report

Reported by ACI Committee 239

2- American Concrete Institute (ACI) Committee 239 defiinition:

"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."

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WHAT IS UHPC?

Designation: C1856/C1856M – 17

Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete[1]

3- ASTM C1856 (Standard Practice for Fabricating and Testing Specimens of UHPC) definition:

"… a specified compressive strength of at least 120MPa (17,000 psi), with nominal maximum size aggregate of less than 5mm (1/4 in.) and a flow between 200 and 25mm (8 and 10 in.)"

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WHAT IS UHPC?

- Composition and mixture design
  - Cement-based composite material
  - High-end fiber-reinforcement concrete
  - Very dense particle packing
- Properties
  - Highly workability concrete
  - High strength
  - Inherently ductile
  - Highly durable

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PROPERTIES TYPICAL CONCRETE

	Fiber	Compressive Strength	Flexural Strength	Elastic Modulus	Chloride Penetration	Crack Resistance
Normal Concrete	-	3000-6000psi	400-600psi	2000-6000ksi	>2000 coulombs	Very low
FRC	<0.5% Polypropylene	3000-6000psi	400-600psi	2000-6000ksi	>2000 coulombs	High
	0.5 to 1.5% macro steel	3000-6000psi	-1000psi	2000-6000ksi	>2000 coulombs	High
UHPC	>2% micro steel	>17,000psi	1000-3000psi	8000-10000ksi	20-360 coulombs	Extremely high

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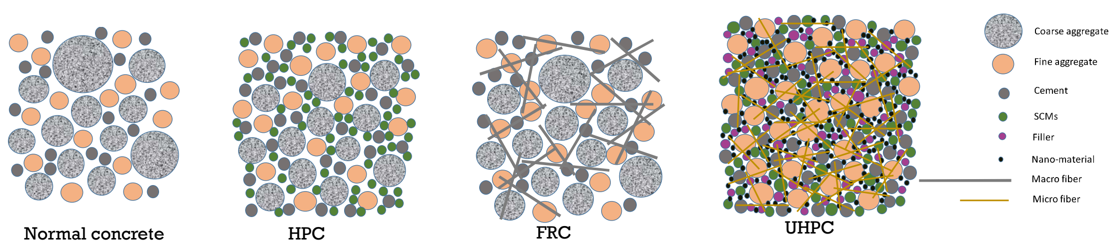
13 MIXTURE DESIGN OF UHPC

TYPICAL MIXTURE DESIGNS OF DIFFERENT CLASSES OF CONCRETE



Mix	Normal PCC	HSC	FRC-L	FRC-M	UHPC
Cement	529	820	555	582	1200
SCMs	176	80	185	194	390
Filler	0	0	0	0	355
Coarse Aggregate	1650	1800	1570	1427	0
Fine Aggregate	1204	1140	1284	1427	1720
Water	261	261	274	287	218
Fibers	0	0	8	132	263
HRWR (fl oz/yd3)	56	290	84	112	745
w/b	0.37	0.29	0.37	0.37	0.14

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TYPICAL INGREDIENTS FOR UHPC


Cement and SCMs


Chemical Admixtures


Fine sand


Steel fiber

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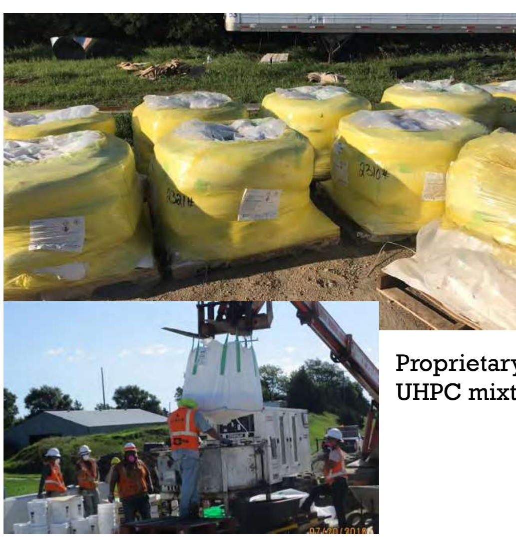
UHPC MIXTURE DESIGNS


Proprietary UHPC mixtures


Non-proprietary UHPC mixtures

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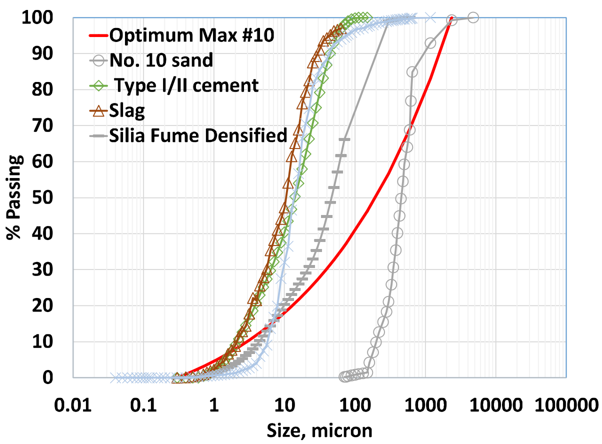
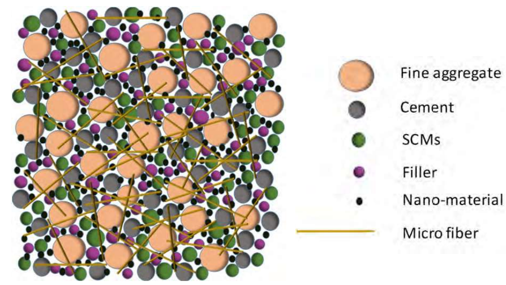
MIXTURE DESIGN OF UHPC

Mixture development - Particle packing





Modified Andreasen and Andersen model

$$P_i = \frac{D_i^q - D_{min}^q}{D_{max}^q - D_{min}^q}$$

- P_i = total percent of particle passing through sieve
- D_{max} = maximal size of particle
- D_{min} = minimum size of particle
- D_i = diameter of the current sieve
- q = exponent of the equation

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UNL-UHPC1900 MIXTURE DESIGN

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Nebraska Department of Transportation
Project SPR-1(18) M072
January 2020

Executive Summary,
Research Readiness Level Assessment and Technology Transfer

Feasibility Study of Development of Ultra High-Performance Concrete (UHPC) for Highway Bridge Applications in Nebraska

- Based on the extensive study, the following (UNL-UHPC) mix with local materials is recommended. Unit cost of the UNL-UHPC is approximately $682/yd^3

Mix ID	Cement	Slag	Silica Fume	Water & Ice	Sand	Fiber	HRWR	WRA	w/b
UNL-UHPC1900	1207	585	161	309	1603	266	57.6	20.7	0.182

	Materials	Source and location
Sand	No.10 sand	Lyman-Richey, Omaha, NE
Cement	Type I/II	Ash Grove Cement Company, Louisville, NE
Slag	Grade 100 Slag	Central Plains Cement Company, Omaha, NE (terminal)
Silica fume	Force10,000 densified microsilica	GCP Grace Construction Products
Fiber	Dramix OL 13/.20 micro steel fiber	Bekaert
HRWR	Premia 150	Chryso
WRA	Optima 100	Chryso

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APPLICATION OF UHPC

FHWA EVERY DAY COUNTS (EDC) UHPC-RELATED INITIATIVES

- EDC-3 and 4 (2015 – 2018)
  - UHPC for Prefabricated Bridge Elements (PBES)
- EDC-6 (2021 – 2022)
  - UHPC for Bridge Preservation & Repair

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APPLICATIONS OF UHPC

- Precast
  - Girders, decks…
- Cast-in-Place
  - Connections, repair, overlay…

Connections

Repair

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USEFUL LINKS/DOCUMENTS

Document	Link
FHWA Ultra-High Performance Concrete Site	https://highways.dot.gov/research/structures/ultra-high-performance-concrete/ultra-high-performance-concrete
FHWA-HRT-11-038-TechNote_UHPC	https://www.fhwa.dot.gov/publications/research/infrastructure/structures/11038/11038.pdf
FHWA-HRT-19-011-Design and Construction of Field-Cast UHPC Connections	https://www.fhwa.dot.gov/publications/research/infrastructure/structures/bridge/uhpc/19011/19011.pdf
FHWA-HIF-19-030-Example Construction Checklist_UHPC Connections for Prefabricated Bridge Elements	https://www.fhwa.dot.gov/bridge/abc/docs/uhpc-construction-checklist.pdf
NYSDOT2021_557.6601NN16_Joint Fill UHPC_Performance Spec	https://www.dot.ny.gov/spec-repository-us/557.66010116.pdf
NDOT Project M069 Report (Mendonca et al. 2020), Feasibility Study of Development of Ultra-High Performance Concrete (UHPC)for Highway Bridge Applications in Nebraska)	https://dot.nebraska.gov/media/113319/m072-uhpc-project-final-report.pdf
ASTM C1856-17, Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete	
Mendonca F. and Hu J., (2021). Impact of Chemical Admixtures on Time-Dependent Workability and Rheological Properties of Ultra-High-Performance Concrete, ACI Materials Journal, 118 (6).	

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QUESTIONS?

WORKSHOP ON PRODUCTION OF CAST-IN-PLACE UHPC FOR BRIDGE APPLICATIONS

Jiong Hu and George Morcous

3/16/2022

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- **Afternoon Session: Hands-on Experience**
  - UHPC batching, casting and specimen preparation
  - UHPC testing
  - Q&A

PRODUCTION OF UHPC

STEPS

1. Batching
2. Mixing
3. Forming
4. Transporting and Placement
5. Finishing
6. Curing

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1-BATCHING OF UHPC

a) Clean sand with controlled moisture (ASTM C133 or C144)

b) Dry stored cementitious materials (no hard lumps)

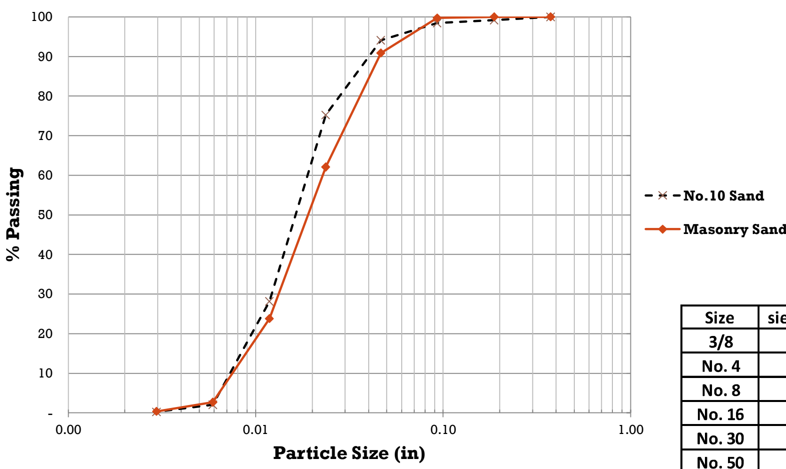
c) Dry and covered fibers to prevent oxidation

d) Chilled water or ice to control mixture temperature (50 – 80° F)

e) Admixtures within shelf-life and not exposed to freezing

5

SAND



Size	sieve size (in.)	sieve size (µm)	% Passing No.10 Sand	% Passing Masonry Sand
3/8	0.374	9500	100.0	100
No. 4	0.187	4750	99.2	100
No. 8	0.093	2360	98.4	99.7
No. 16	0.046	1180	94.1	90.9
No. 30	0.024	600	75.3	62.1
No. 50	0.012	300	28.2	23.8
No. 100	0.006	150	2.1	2.7
No. 200	0.003	75	0.3	0.4

6

CEMENTITIOUS MATERIALS

- Portland Cement Type I/II (ASTM C150)
- Silica Fume Densified (ASTM C1240)
- GGBFS (ASTM C989)

7

DOMESTIC FIBER SOURCES

SUMIDEN WIRE PRODUCTS CORPORATION

HOME | ABOUT | INDUSTRIAL ALLOYS | PRODUCTS

Steel Fibers About

STEEL FIBERS - BUY AMERICA COMPLIANT

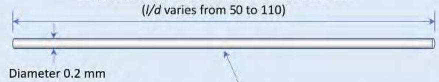
Beginning in January 2021, Sumiden Wire is proud to offer Buy-America-compliant high-strength steel fibers for the innovative and growing ultra-high performance concrete marketplace. These fibers are produced using steel melted and manufactured in the USA and in compliance with ASTM A820. Our standard product is a 0.008" (0.2 mm) diameter x 1/2" (13 mm) long brass-coated steel straight fiber (other fiber lengths are available) with typical tensile strengths over 400 ksi.

STEEL FIBER PACKAGING & SHIPMENT

Sumiden Wire's steel fibers are packaged in 44 lb. (20 kg) bags. These fibers can be shipped on pallets with 24 bags (1,056 lb.) or smaller lot sizes as needed. The steel fibers are produced in our centrally located Dickson, TN plant and can be shipped across the USA as needed. We plan to maintain an inventory to be able to handle short-notice orders, but larger orders (>5,000 lb.) should be ordered in advance.

DATA SHEET (TYPE A and TYPE X)

Length can be customized from 10 mm to 22 mm
(*l/d* varies from 50 to 110)



Diameter 0.2 mm

Surface (brass coated) is modified to optimize interaction with UHPC matrix (patent pending)

General Information

HiPer Fiber products are made from cold drawn high-carbon steel manufactured from steel wire rod sourced from a US Steel Mill. The Heat Number(s) used are listed on this Mill Certificate. All manufacturing steps are conducted in the United States of America in compliance with the **Buy America Act**.

Our patent-pending surface modification technology dramatically boosts fiber performance.

1. Reduce dosage without compromising UHPC performance
2. Keep standard dosage but achieve substantially improved material properties
3. Keep the fibers short to eliminate mixing problems that occur at higher dosages

Conforms to ASTM A820 Type 1

Test	Units	Tests	Test Results			
			Average	Ste Dev	Min	Max
Diameter	mm	12	0.200	0.001	0.198	0.202
Tensile Strength	N/mm2	12	2928	56.714	2824	3039
Break Load	N	12	92.2	2.281	89.5	97.4
Elongation at Break	(%)	12	2.3	0.368	1.8	2.8
Copper Content	(%)	12	66.8	1.543	64.7	68.7
Brass Weight	(g/kg)	12	4.83	0.092	4.71	4.96
Torsions	(Turns/100d)	12	67	17.367	53	99

ADMIXTURES

High-Range Water Reducer (HRWR)

CHRYSO® Fluid Premia 150

Description:

Characteristics:
- Physical state: liquid
- Density: Approx. 1.06
- pH: Approx. 5
- Cl ion content: Nil

CHRYSO® Fluid Premia 150 does not contain any purposely added calcium chloride or other chloride based components. It will not promote or contribute to corrosion of reinforcing steel in concrete.

Packaging:
- 55 gallon (210 L) drums
- 264 gallon (1000 L) totes
- bulk deliveries

Standard specifications:
Conforms to ASTM C 494 type A & F
AASHTO M 194 Type A & F
CRD C 87 Type A & F

Compatibility
CHRYSO® Fluid Premia 150 is compatible with all types of F cement, class C and F fly ash, slag, microsilica, calcium chlorid and approved air entraining admixtures.

CHRYSO® Fluid Premia 150 can be used in all white, color architectural concrete. For best results, each admixture m dispensed separately into the concrete mix.

Precaution:
CHRYSO® Fluid Premia 150 may freeze at temperatures below 28°F (-2°C). Although freezing does not harm **CHRYSO® Fluid Premia 150** , precautions should be taken to protect it from freezing.

If **CHRYSO® Fluid Premia 150** should happen to freeze, thaw and reconstitute with mechanical agitation.

Do not store the product at temperatures above 100°F (38°C) or under 40°F (5°C) for long periods.

Shelf life: 9 months.

CHRYSO® Fluid Optima 100

Description:

Characteristics:
Physical state: liquid
Color: milky, off white
Density: 1.06 ± 0.01 g/cc
pH: 7 ± 2
Cl^- ion content: Nil
Na^2O equiv.: < 1.0%

CHRYSO®Fluid Optima 100 does not contain any purposely added calcium chloride or other chloride based components. It will not promote or contribute to corrosion of reinforcing steel in concrete.

Packaging:
- 55 gallon (210 L) drums
- 264 gallon (1000 L) totes
- bulk deliveries

Standard specifications:
Conforms to ASTM C 494 type A & G
AASHTO M 194 Type A & G
CRD C 87 Type A & G

Compatibility
CHRYSO®Fluid Optima 100 is compatible with all types of Portland cement, class C and F fly ash, slag, microsilica, calcium chloride, fibers and approved air entraining admixtures.

CHRYSO®Fluid Optima 100 can be used in all white, colored, and architectural concrete. For best results, each admixture must be dispensed separately into the concrete mix.

Precaution:
CHRYSO®Fluid Optima 100 may freeze at temperatures below 35°F (2° C). Although freezing does not harm **CHRYSO®Fluid Optima 100**, precautions should be taken to protect it from freezing.

If **CHRYSO®Fluid Optima 100** should happen to freeze, thaw and reconstitute with mechanical agitation. Do not store the product at temperatures above 100°F (38°C) or under 40°F (5°C) for long periods. This product must be stored in plastic containers, except those manufactured with PVC.

Shelf life: 9 months.

Safety:
CHRYSO®Fluid Optima 100 is not considered dangerous to

Workability Retaining Admixture (WRA)

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2-MIXING UHPC

- Three main phases of mixing:
  - 1- Dry mixing of constituent materials to ensure homogeneity
  - 2- With water/ice and admixtures to achieve flowability
  - 3- With fibers to ensure uniformity of distribution

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12

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2-MIXING UHPC

- Failure to mix UHPC properly could result in:
  - Lack of workability
  - Clumping of fibers or paste
  - Fiber segregation

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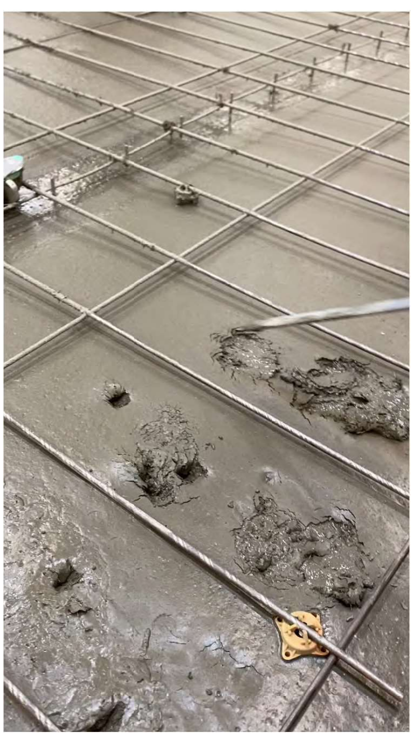

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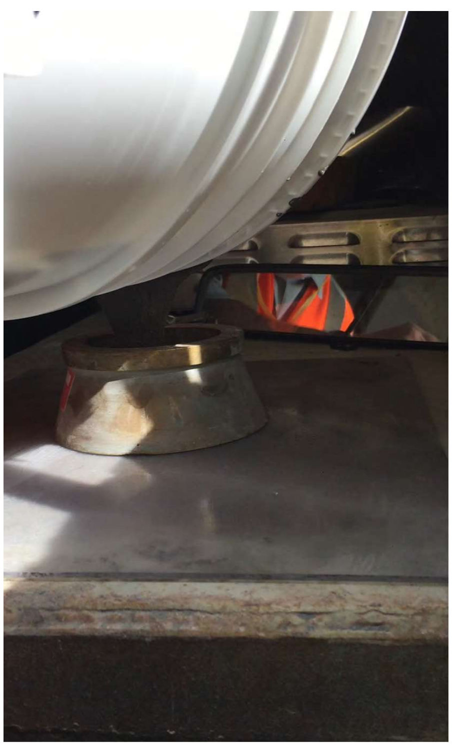

2-MIXING UHPC

- Mixer Requirements
  - Any concrete mixer can be used (drum, planetary, horizontal shaft, etc.)
  - High shear mixers are recommended due to the high mixing energy needed to transform the dry mix into fluid mix.
  - Using 50% of the mixer capacity is used to reduce the mixing duration.

For Lab Only:

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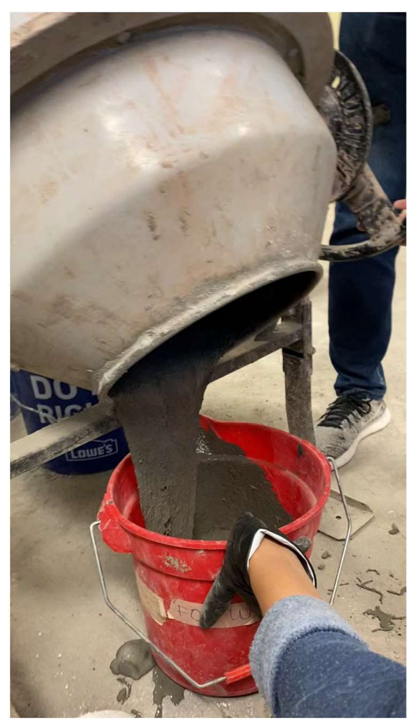
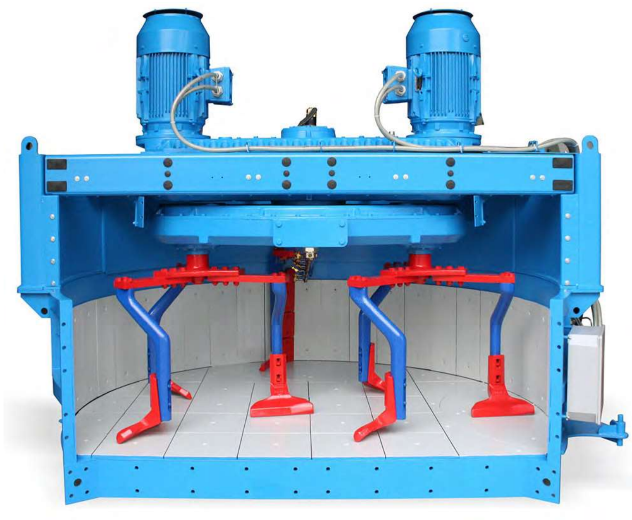
2-MIXING UHPC

For Field and Lab:



2-MIXING UHPC

For Plant Mixing:



2-MIXING UHPC

- Mixing Sequence and Duration

For Plant Mixing

Step #	Description	Duration (min)
1	Add sand automatically	1
2	Add silica fume bags manually	1
3	Mix dry	2
4	Add cement and slag automatically	1
5	Mix dry	2
6	Add water automatically	1
7	Add ice bags and admixtures manually	1
8	Mix until flowable	4
9	Dispense steel fibers manually	6
10	Mix with fibers	2
11	Discharge	2
12	Test Flow	2
	Total	**25**

For Field and Lab

Step #	Description	Duration (min)
1	Add sand and silica dume	1
2	Mix dry	2
3	Add cement and slag	1
4	Mix dry	2
5	Add water, ice and admixtures	1
6	Mix until flowable	10
7	Dispense steel fibers	2
8	Mix with fibers	2
9	Discharge	2
10	Test Flow	2
	Total	**25**

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MIXING PROCEDURE (LAB BATCHING)

Mix for 30 sec (speed 2)

Sand + silica fume Mix for 5 min (speed 1)

Cement + SCMs Mix for 5 min (speed 1)

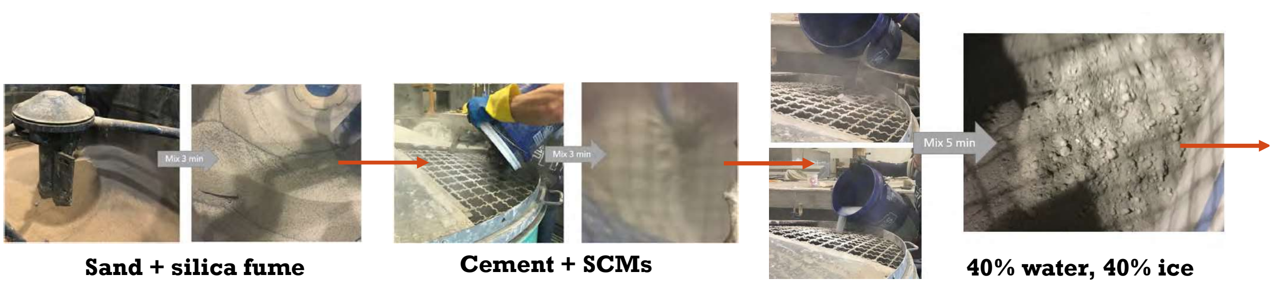
80% water + 80% HRWR Mix for 7 min (speed 1)

20% water + 20% HRWR Mix for 7 min (speed 1)

Fibers Mix for 5 min (speed 1)

Mix ready

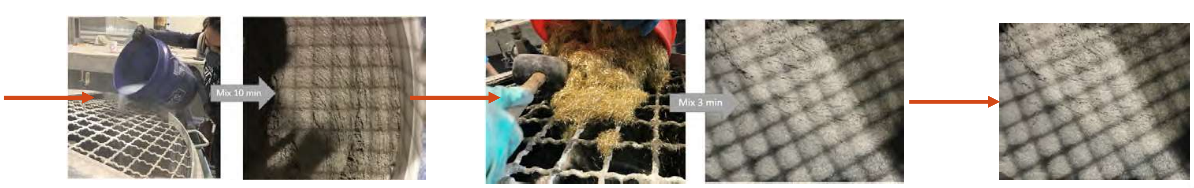
MIXING PROCEDURE (FIELD BATCHING)



Sand + silica fume

Cement + SCMs

40% water, 40% ice + 80% HRWR



20% water + 20% HRWR

Fibers

Mix ready

Batch #	Mixer #	Step #	Description	Time (min.)																													
				2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50	52	54	56	58	60
1	1	1	Add & Mix Sand and Silica Fume																														
		2	Add & Mix Cement and Slag																														
		3	Add & Mix Water/Ice and Admixtures																														
		4	Add & Mix Steel Fibers																														
		5	Test Flow																														
		6	Discharge, Trasport, Pour & Return																														
2	2	1	Add & Mix Sand and Silica Fume																														
		2	Add & Mix Cement and Slag																														
		3	Add & Mix Water/Ice and Admixtures																														
		4	Add & Mix Steel Fibers																														
		5	Test Flow																														
		6	Discharge, Trasport, Pour & Return																														
3	3	1	Add & Mix Sand and Silica Fume																														
		2	Add & Mix Cement and Slag																														
		3	Add & Mix Water/Ice and Admixtures																														
		4	Add & Mix Steel Fibers																														
		5	Test Flow																														
		6	Discharge, Trasport, Pour & Return																														
4	1	1	Add & Mix Sand and Silica Fume																														
		2	Add & Mix Cement and Slag																														
		3	Add & Mix Water/Ice and Admixtures																														
		4	Add & Mix Steel Fibers																														
		5	Test Flow																														
		6	Discharge, Trasport, Pour & Return																														
5	2	1	Add & Mix Sand and Silica Fume																														
		2	Add & Mix Cement and Slag																														
		3	Add & Mix Water/Ice and Admixtures																														
		4	Add & Mix Steel Fibers																														
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		6	Discharge, Trasport, Pour & Return																														
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		3	Add & Mix Water/Ice and Admixtures																														
		4	Add & Mix Steel Fibers																														
		5	Test Flow																														
		6	Discharge, Trasport, Pour & Return																														

3 Mixers

6 batches

4.5 ft^3 each

1 yd^3/hr

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MIXING

- FHWA - High shear mixer can be desirable. Maintaining a reduced temperature of 50°F to 60°F (10°C to 16°C) on stockpiled materials and in the mix water is recommended. Cubed ice has been demonstrated to be a viable replacement for some or all of the mix water when mixing operations occur during warm weather conditions.
- MIDOT - suggests high shear paddle mixers with 0.5 cu. yd. minimum capacity to be used. Paddle or scraper-to-pan wall clearance must be small enough to prevent the material being mixed from adhering to the sidewalls.

U.S. Department of Transportation Federal Highway Administration

MDOT Michigan Department of Transportation

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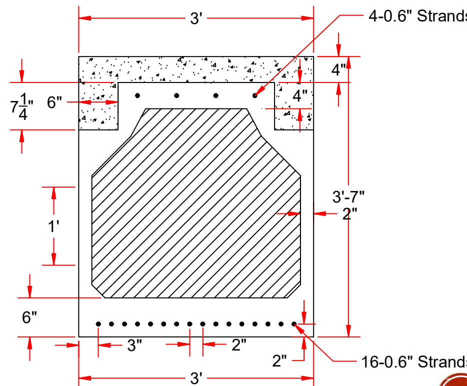
3-FORMING FOR UHPC

- Any forming material that is non-absorbing (plywood, steel, fiberglass, foam, concrete, etc.)
- Use chamfers, curves, and form release agents for ease of stripping
- Clear spacing between bars and formed surfaces is at least 1.5 x fiber length (min. ¾ in.)



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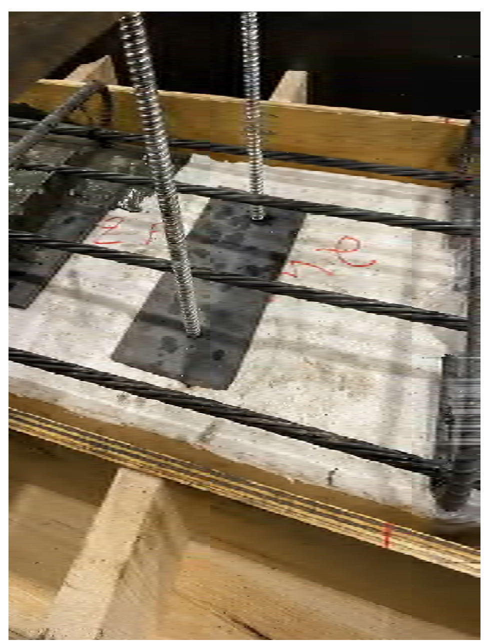
Full hydrostatic fluid pressure (use 160 pcf)



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Surface preparation of hardened concrete: Sandblasting or exposed aggregate plus pre-wetting

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3-FORMING FOR UHPC

Top form if sloped

Grout-tight forms

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FORMING

- FHWA - UHPC is typically places in a closed form, or the form is closed immediately after placement. On flat surfaces exposed to air, UHPC should be in contact with the top formwork to minimize surface dehydration. Formwork that will be in contact to UHPC should have a non-absorbing finish.
- MIDOT - The forms must be water tight and coated to prevent absorption of water. The formwork must be resistant to the hydraulic pressure of the mix.
- DCDOT - medium density overlay plywood pre wetted just ahead of the UHPC material. They need to be hand removal.

U.S. Department of Transportation Federal Highway Administration

MDOT Michigan Department of Transportation

d. District Department of Transportation

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FORMING

- FHWA - Good bonding has been demonstrated when the precast concrete element has exposed aggregate finish (it can be created applying a gelatinous retarder to the formwork where the finish is desired to delayed the hydration in that local). Pre-wetting the precast concrete interface immediately before The UHPC's placement also improves bonding.
- Caltrans - Pre-wet the precast members and forms. Before placing UHPC, voids must be free of dust, debris, and excess water.
- DCDOT - the surface preparation of the precast concrete in contact with UHPC shall have exposed aggregate finish.

U.S. Department of Transportation Federal Highway Administration

Caltrans

d. District Department of Transportation

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4-TRANSPORTING AND PLACEMENT

Any method that minimizes the following:

- Entrapment of air (cast from one side)
- Fiber segregation (no internal vibration)
- Forming cold joints/pour lines (min. time between lifts)
- Unfavorable alignment of fibers (direction of flow)
- Failure to fill the forms (add pressure head)
- Free Fall

No pumping

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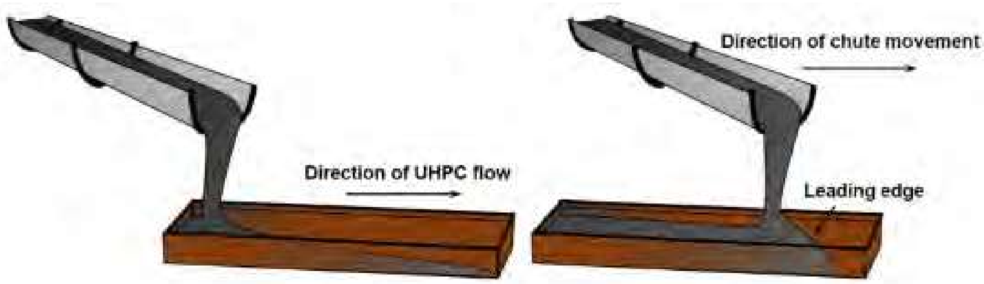
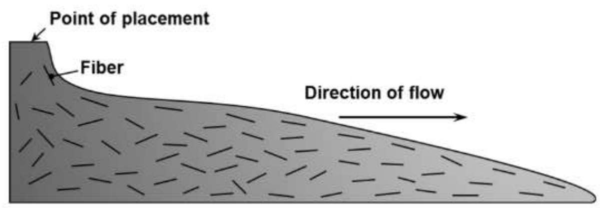

Direction of UHPC flow
Direction of chute movement
Leading edge


Point of placement
Fiber
Direction of flow

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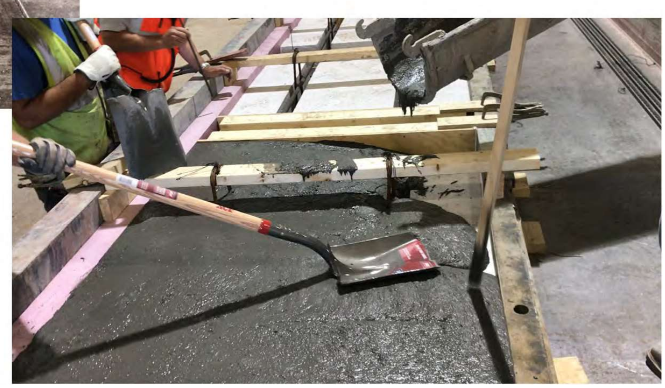

CASTING

- FHWA - UHPC should not be internally vibrated because of the detrimental impact that this type of vibration has on the fiber reinforcement.
- Caltrans - UHPC does not free-fall more than 2 feet, there are no cold joints and steel fibers has to be uniformly distributed.
- MIDOT - Pumping Mi-UHPC is not permitted. Do no place concrete at ambient air temperatures below 40ºF, nor above 90ºF. The fresh mix must not be allowed to flow farther than 24 inches during placement. Start the casting process at one end of the joint and proceed to the other end at a speed comparable to the flow speed of the fresh mix. Once the other end of the joint is reached, reverse the casting process and proceed in the other direction to cast another layer of Mi-UHPC. Continue this process until the full depth of the joint has been cast. Vibrators may not be used.

U.S. Department of Transportation Federal Highway Administration

Caltrans

MDOT Michigan Department of Transportation

5-FINISHING

- Traditional finishing methods (screeding, raking, brooming) do not work with UHPC
- Spiked roller could be used to level the surface
- Vibratory screed is needed for stiff UHPC

5-FINISHING

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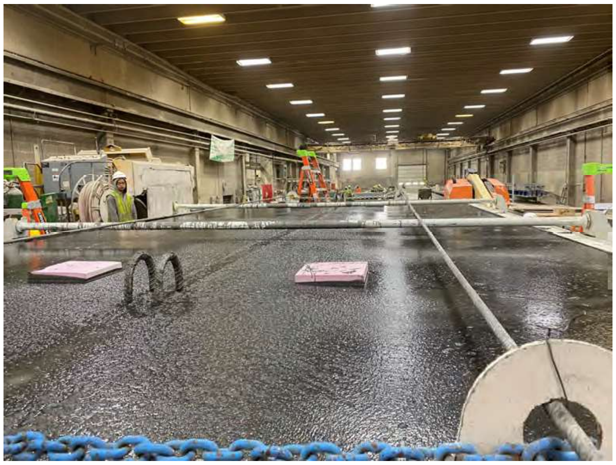
5-FINISHING

- Highly flowable UHPC could result in smooth surface without intervention



5-FINISHING

- Grinding of the UHPC surface can be performed when strength is at least 10 ksi, otherwise significant fiber pullout can happen.
- It is easier to grind joints when the strength is around 12 ksi than it is at full strength.

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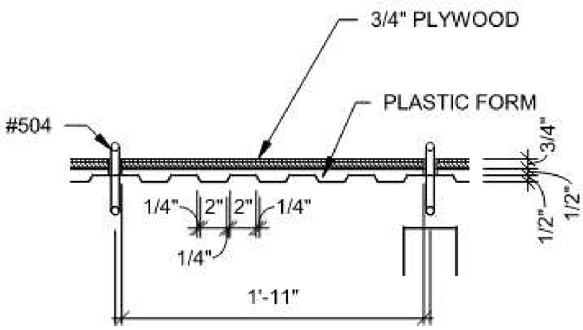
5-FINISHING

- Textured surfaces need to be formed



6-CURING

- Exposed surfaces must be covered immediately to prevent dehydration
  - Plastic sheets
  - Wood
  - Curing compound
  - Wet burlap
  - Insulated blankets

- At high temperature and low humidity, UHCP surface dries fast and cracks forming elephant shin

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6-CURING

- When cured at ambient temperature of about 73° F, concrete temperature may reach 160° F due to heat of hydration.
- Final set may take up to 24 hours due to the high dosage of admixtures
- Concrete strength usually exceeds 10 ksi in 48 hours
- For accelerated curing, higher temperature and humidity can be used.
- Post-Curing Thermal Treatment (PCTT)

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CURING

- FHWA - UHPC should remain sealed from exposure to the external environment until after initial set has occurred. UHPC can be moist cured because of the low permeability of the cementitious matrix. Supplemental heat (internally or externally) can be provided to the UHPC and the surrounding prefabricated elements to reduce initial set times and accelerate strength gain. Ideally, until UHPC reach 14 ksi (97 MPa) of compressive strength, relative movements should be minimized.
- GADOT - all specimens should be cured using the same method of curing proposed to be used in the field. A continuous curing temperature of a minimum of 60°F is recommended.
- MIDOT - The top surface of the concrete must be covered with insulating blankets. Do not apply curing compound. The concrete surfaces must be continuously cured with wet burlap.

U.S. Department of Transportation Federal Highway Administration

GDOT Georgia Department of Transportation

MDOT Michigan Department of Transportation

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WORKSHOP ON PRODUCTION OF CAST-IN-PLACE UHPC FOR BRIDGE APPLICATIONS

Jiong Hu and George Morcous

3/16/2022

NEBRASKA
Good Life. Great Journey.
DEPARTMENT OF TRANSPORTATION

COLLEGE OF ENGINEERING

WORKSHOP OUTLINE

- **Morning Session: Lecture and Discussion**
  - Introduction of UHPC
  - Production of UHPC
  - Break
  - Testing of UHPC
  - UHPC experiences – case studies
  - Discussions and Q&A
- **Afternoon Session: Hands-on Experience**
  - UHPC batching, casting and specimen preparation
  - UHPC testing
  - Q&A

2

3

TESTING OF UHPC

OUTLINE/ LEARNING OBJECTIVES

- Workability
  - Recognize test procedure and criteria for UHPC workability
- Fiber stability
  - Understand test methods and criteria for fiber stability in UHPC
- Specimen casting
  - Recognize procedure for casting UHPC specimens for hardened concrete property test
- Mechanical properties
  - Recognize basic test methods and typical results of mechanical properties of UHPC

4

5

WORKABILITY

FLOW TEST

Designation: C1437 – 15

Standard Test Method for Flow of Hydraulic Cement Mortar[1]

Designation: C1856/C1856M – 17

Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete[1]

6

FLOW TEST

Designation: C1856/C1856M – 17

Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete[1]

6. Testing of Fresh Properties

6.1 *Flow:*

6.1.1 Determine the flow of freshly mixed UHPC in accordance with Test Method C1437, with the following exceptions.

6.1.1.1 The mold and flow table shall meet the requirements of Specification C230/C230M. The concrete pedestal and cork gasket are not required.

6.1.1.2 Fill the mold in a single layer with the fresh UHPC.

6.1.1.3 Do not tamp the UHPC in the mold and do not drop the table.

6.1.1.4 After lifting the mold, wait until a time of 2 min ± 5 s has elapsed.

6.1.1.5 Measure the diameter of the UHPC along the lines of maximum and minimum diameter, with a ruler or tape measure, recording each diameter to the nearest 1 mm [1/16 in.]. Calculate the average of the two diameters measured. The flow value is this average.

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UHPC FLOW REQUIREMENTS

	ASTM C1856	FHWA	NYDOT	DCDOT	Caltrans	MDOT	GADOT	IADOT
Flow range (in)	8 to 10	7 to 10	7 to 10	7 to 10	7 to 10	7 to 12	7 to10	7 to 10

ACI MATERIALS JOURNAL TECHNICAL PAPER

Title No. 118-M114

Impact of Chemical Admixtures on Time-Dependent Workability and Rheological Properties of Ultra-High-Performance Concrete

by Flavia Mendonca and Jiong Hu

- Recommended flow: 7”-11” flow at two minutes (flow time should be no less than 45 seconds with standard 10” flow table)

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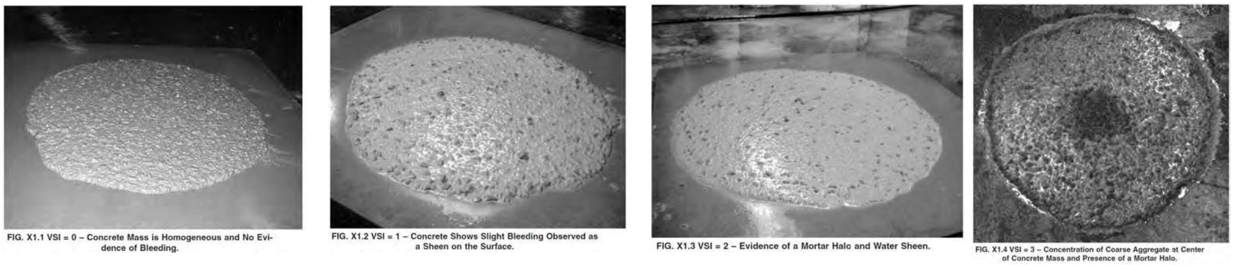
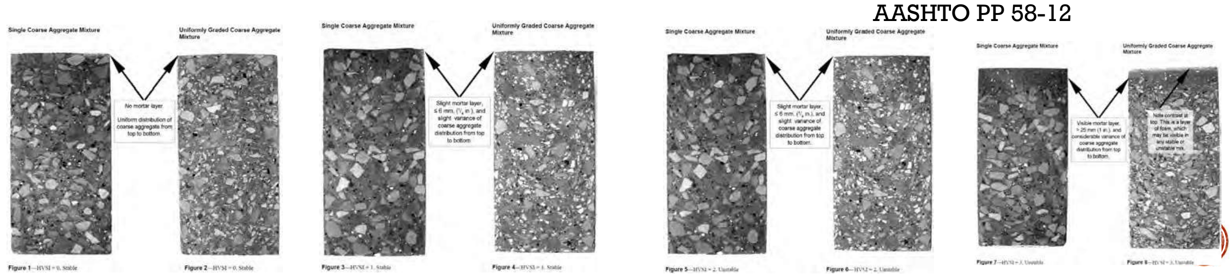
FIBER STABILITY

SOME IDEAS TO BORROW?

ASTM C1611



AASHTO PP 58-12



VISUAL STABILITY INDEX (VSI) FOR UHPC

VSI value	Criteria
0 = Highly stable	No evidence of fiber agglomeration and separation
1 = Stable	Fibers slightly agglomerated (agglomerate size less than 2”) but do not clearly separate from the mixture
2 = Unstable	Fibers are slightly agglomerated (agglomerate size between 2” and 3”) and separated from the mixture
3 = Highly unstable	Fibers are clearly agglomerated (agglomerate size between 3” and 5” and separated from the mixture
4 = Extremely unstable	Fibers are severely agglomerated (agglomerate size larger than 5”) and clear separation from the mixture

ACI MATERIALS JOURNAL TECHNICAL PAPER

Title No. 118-M114

Impact of Chemical Admixtures on Time-Dependent Workability and Rheological Properties of Ultra-High-Performance Concrete

by Flavia Mendonca and Jiong Hu

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HARDENED VISUAL STABILITY INDEX (HVSI) FOR UHPC

ACI MATERIALS JOURNAL TECHNICAL PAPER
Title No. 118-M114
Impact of Chemical Admixtures on Time-Dependent Workability and Rheological Properties of Ultra-High-Performance Concrete
by Flavia Mendonca and Jiong Hu

HVSI value	Criteria
0 = Highly Stable	No apparent fiber-free or low fiber content layer observed at the top of the cut plane. Uniform distribution of fiber from top to bottom.
1 = Stable	A thin fiber-free or low fiber content layer (thickness ≤ 0.5”) can be observed at the top of the cut plane with none or relative less amount of fibers.
2 = Unstable	A clear fiber-free or low fiber content layer (0.5” < thickness ≤ 1”) can be observed at the top of the cut plane with none or relative less amount of fibers.
3 = Highly unstable	A very significant fiber-free or low fiber content layer (3” < thickness ≤ 3”) can be observed at the top of the cut plane.
4 = Extremely unstable	The majority (thickness ≥ 3”) of the specimen was fiber-free or low fiber content.

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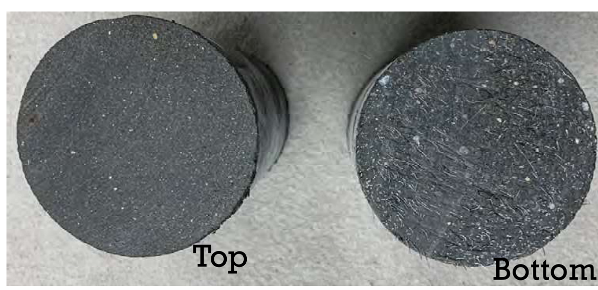
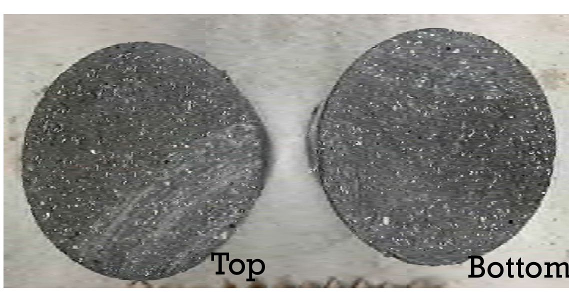
FIBER STABILITY



Appearance of grinded ends



Appearance of specimens after compressive strength test

14

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SPECIMEN PREPARATION

SPECIMENS DIMENSION

Designation: C1856/C1856M – 17

Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete[1]

TABLE 1 Summary of Specimen Sizes

Property	Test Method	Nominal Specimen Sizes	Comments
Compressive Strength	C39/C39M	75 mm by 150 mm [3 in. by 6 in.]	
Flexural Strength	C1609/ C1609M	See 8.2.2	Sizes change with fiber length

TABLE 3 Dimensions of Beams for Measuring Flexural Strength

Maximum Fiber Length (l_f)	Nominal Prism Cross Section
< 15 mm [0.60 in.]	75 mm by 75 mm [3 in. by 3 in.]
15 mm to 20 mm [0.60 in. to 0.80 in.]	100 mm by 100 mm [4 in. by 4 in.]
20 mm to 25 mm [0.80 to 1.00 in.]	150 mm by 150 mm [6 in. by 6 in]
>25 mm [1.00 in.]	200 mm by 200 mm [8 in. by 8 in.]

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SPECIMENS PREPARATION

Designation: C1856/C1856M – 17

Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete[1]

7.2 *Molding of Specimens:*

7.2.1 Fill cylinder molds in one layer.

7.2.2 Fill prism molds from one end, in one layer.

7.2.3 Consolidate all specimens by tapping the sides of the mold 30 times with the mallet.

7.2.4 Tamping rods and internal vibrators shall not be used in fabricating and consolidating specimens from UHPC.

- Continuous pouring in one layer
- Tapping the sides
- Cover immediately after casting

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CURING

Designation: C1856/C1856M – 17

Standard Practice for Fabricating and Testing Specimens of Ultra-High Performance Concrete[1]

- Cover specimens immediately after casting
- 24 hours in mold
- Curing room or lime-saturated water till testing

7.3 *Curing:*

7.3.1 Cure field-fabricated specimens in accordance with Practice C31/C31M and cure laboratory-fabricated specimens in accordance with Practice C192/C192M, with the following exception.

7.3.1.1 Within 1 min after finishing the top surface, cover the specimen to prevent drying of the top surface.

NOTE 2—UHPC contains low quantities of mixing water and virtually no bleed water, resulting in surface drying that may impact the hardened properties, therefore it is important to cover the surface of the specimen with a plastic sheet or equivalent as quickly as possible.

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19 HARDENED CONCRETE

COMPRESSIVE STRENGTH (ASTM C1856 & ASTM C39)


End Grinder


Test Setup

- 3″ x 6″
- 145±7 psi/sec.

8.1 *Compressive Strength:*

8.1.1 Determine the compressive strength in accordance with Test Method C39/C39M, with the exceptions described in this section.

8.1.2 Only 75 mm [3 in.] diameter by 150 mm [6 in.] long cylindrical specimens shall be used for compressive strength testing.

NOTE 4—If molds in SI units are required and not available, the inch-pound mold should be permitted.

8.1.3 Prior to testing, all cylinders shall be end ground such that the ends do not depart from perpendicularity to the axis by more than 0.5° (approximately equivalent to 1 mm in 100 mm [0.05 in. in 5 in.]). The ends of the cylinders shall be ground plane to within 0.050 mm [0.002 in.].

8.1.4 Capping compounds and unbonded neoprene pads shall not be used.

8.1.5 The diameter used for calculating the cross-sectional area of a cylindrical test specimen shall be determined on each cylinder to the nearest 0.1 mm [0.04 in.].

NOTE 5—The diameter is measured to a greater accuracy than Test Method C39/C39M.

8.1.6 *Rate of Loading*—The load shall be applied at a rate of movement (platen to crosshead measurement) corresponding to a stress rate on the specimen of 1.0 ± 0.05 MPa/s [145 ± 7 psi/s].

NOTE 6—Conventional load rates as specified in Test Method C39/C39M would require approximately 15–20 min to complete a test.

NOTE 7—For a 75-mm [3 in.] diameter specimen, the loading rate is 265 ± 13 kN/min [61 500 ± 3 000 lb/min].

With Fibers

Without Fibers

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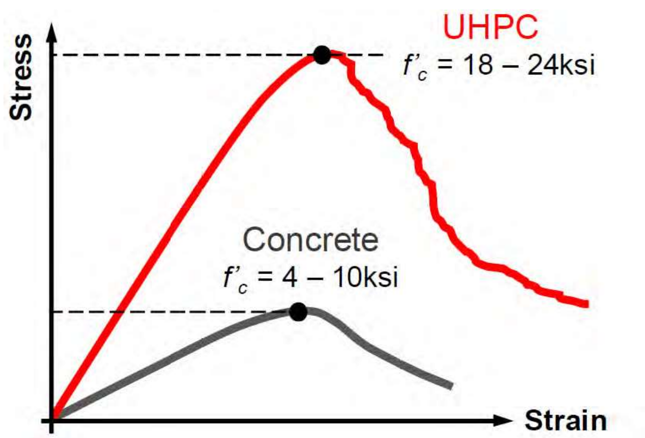
COMPRESSIVE STRENGTH TEST
TYPICAL STRESS-STRAIN CURVE



Source: FHWA

22

FLEXURAL STRENGTH (ASTM C1856 & ASTM C1609)

Test Setup

- ❑ 3″ x 3″ x 14″ Prisms (1/2″ length fibers)
- ❑ 0.003 in./sec. ------ up to δ = L/900
- ❑ 0.008 in./sec. ------ up to δ = L/150 = 0.08 in.

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ASTM INTERNATIONAL **Designation: C1609/C1609M – 19a**

Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)[1]

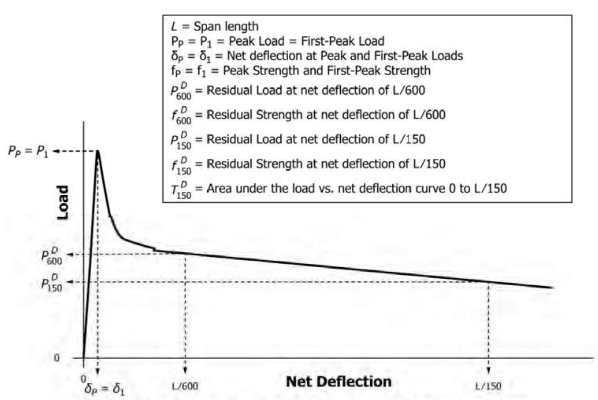
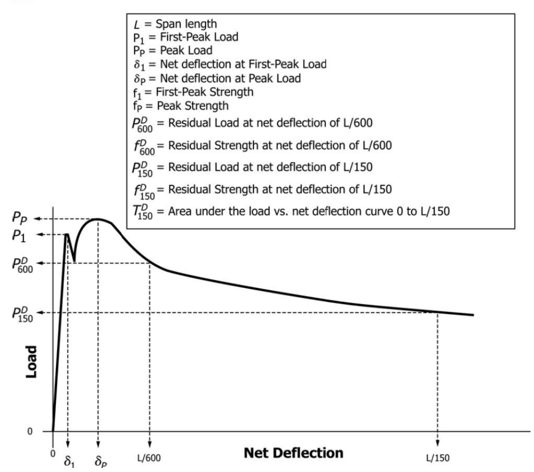


FIG. 3 Example of Parameter Calculations for First-Peak Load Equal to Peak Load (Not to Scale)



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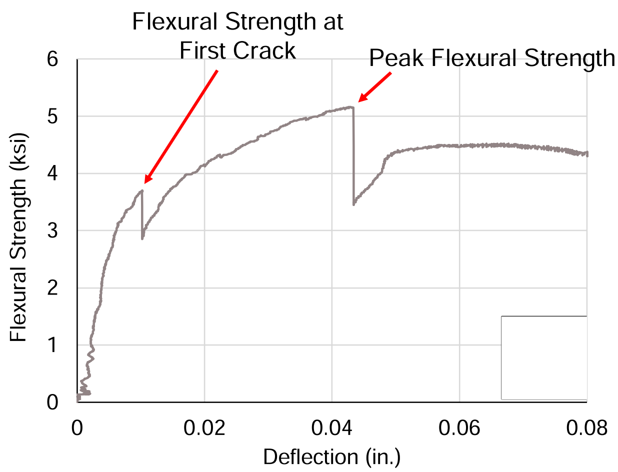
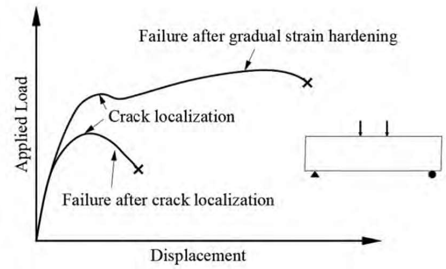
FLEXURAL STRENGTH TEST

TYPICAL STRESS-STRAIN CURVE





Failure Mode

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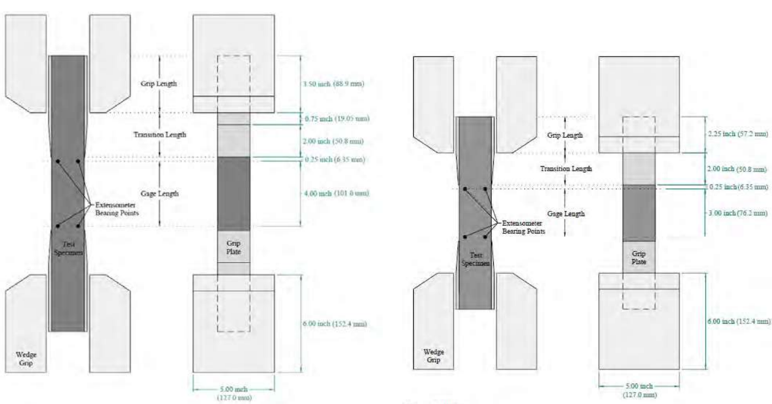
DIRECT TENSILE TEST


Tension Testing of Ultra-High Performance Concrete

PUBLICATION NO. FHWA-HRT-17-053

FEBRUARY 2019



Source: FHWA.

Source: FHWA.

Source: FHWA.

New AASHTO Standard coming soon

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DIRECT TENSILE TEST

- ❑ 2″ x 2″ x 24″ Prisms
- ❑ Aluminum grips from both ends.
- ❑ Load rate of 700 lb/min.

Specimen Form

Specimen Preparation

Test Setup

Failure Mode

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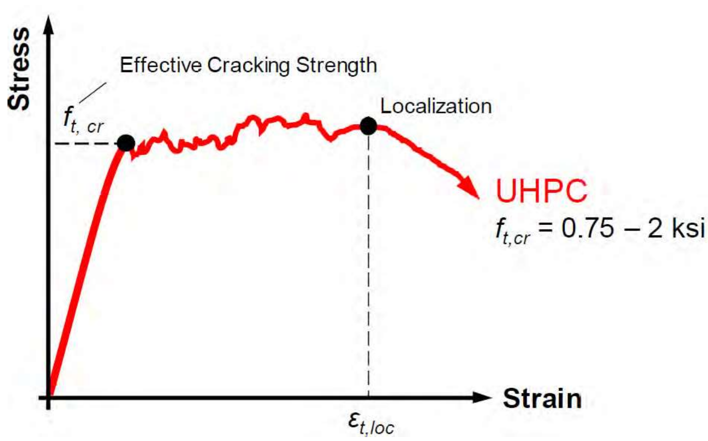
DIRECT TENSILE TEST
TYPICAL STRESS-STRAIN CURVE



Source: FHWA

Source: FHWA.

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QUESTIONS?

WORKSHOP ON PRODUCTION OF CAST-IN-PLACE UHPC FOR BRIDGE APPLICATIONS

Jiong Hu and George Morcous

3/16/2022

NEBRASKA

Good Life. Great Journey.

DEPARTMENT OF TRANSPORTATION

COLLEGE OF ENGINEERING

WORKSHOP OUTLINE

- **Morning Session: Lecture and Discussion**
  - Introduction of UHPC
  - Production of UHPC
  - Break
  - Testing of UHPC
  - UHPC experiences – case studies
  - Discussions and Q&A
- **Afternoon Session: Hands-on Experience**
  - UHPC batching, casting and specimen preparation
  - UHPC testing
  - Q&A

UHPC EXPERIENCE AND CASE STUDIES

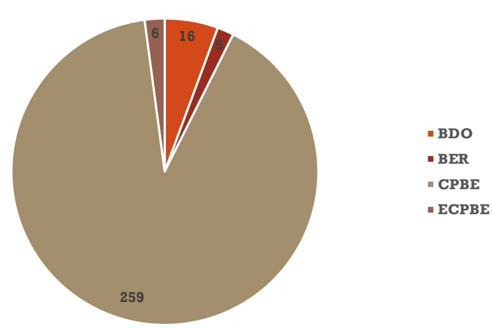
UHPC PROJECTS IN US

- Interactive Map

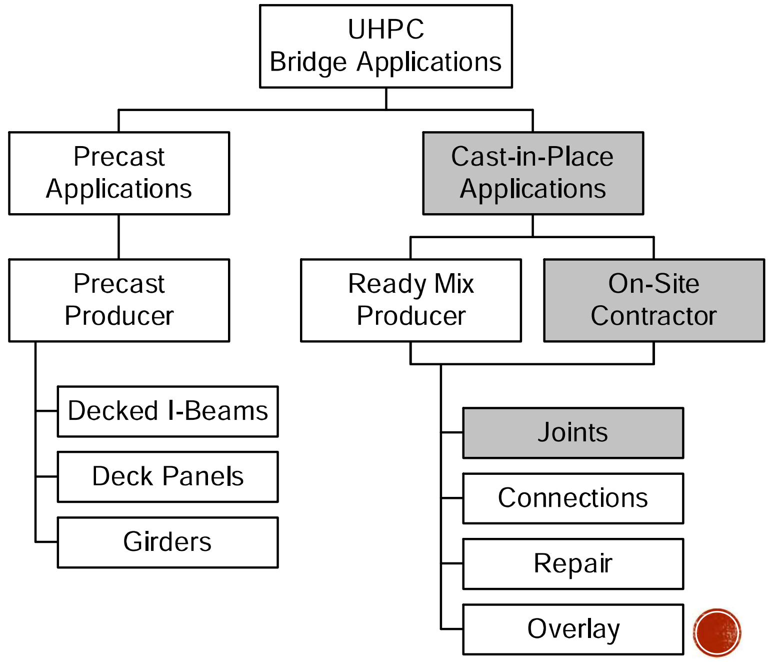
https://usdot.maps.arcgis.com/apps/webappviewer/index.html?id=41929767ce164eba934d70883d775582

UHPC PROJECTS IN US

Abbreviation	Definition
CPBE	connections between prefabricated elements
BDO	bridge deck overlay
BER	beam end repair
EJP	expansion joint header
ECPBE	repair of connections between existing prefabricated elements
PCG	precast, pretensioned UHPC girder
PCP	precast, pretensioned UHPC pile
PCD	precast deck
PR	minor preservation or repair application



UHPC IN NEBRASKA



UHPC EXPERIENCE

1. Field-Cast UHPC
   - Belden-Laurel Bridge
2. Plant-Cast UHPC
   - Slab Production
   - Box Beam Production
   - Decked I-Beam Production
3. Lab-Cast UHPC
   - Shear Strengthening Beam
   - Longitudinal Joint

FIELD-CAST UHPC

Belden-Laurel Bridge 2018

PLANT-CAST UHPC

Slab form and Ribbed Slab
(Coreslab 2019)

PLANT-CAST UHPC

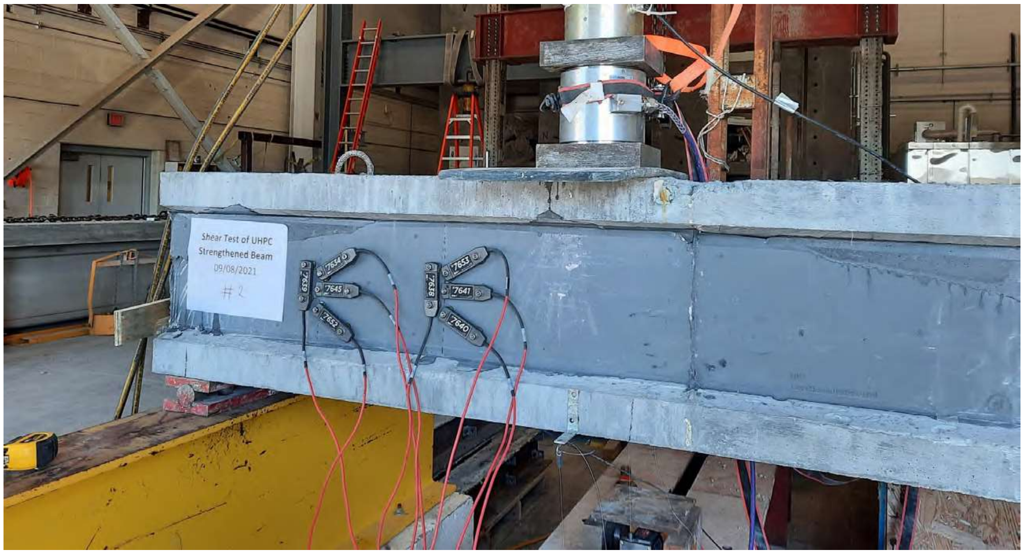
Box Beam with openings (Gage Brothers 2021)

PLANT-CAST UHPC

Decked I-Beam (Concrete Industries 2022)

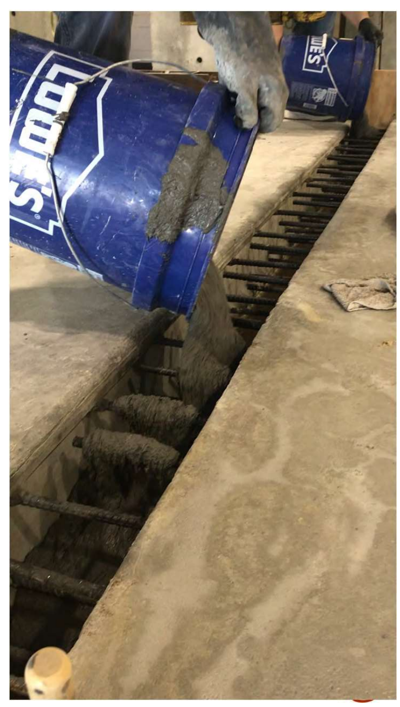
LAB-CAST UHPC

Shear Strengthened Beam 2021



LAB-CAST UHPC

Longitudinal Joint, 2020



WORKSHOP ON PRODUCTION OF CAST-IN-PLACE UHPC FOR BRIDGE APPLICATIONS

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2

3 DISCUSSIONS AND Q&A

4 QUESTIONS IN THE FUTURE?

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DEMONSTRATION AND HANDS-ON SESSION

ACTIVITIES

- UHPC Batching (2 ft^3)
- Fresh Concrete Test (flow test)
- Specimen Casting
  - Cylinders, prisms, mock up slab casting
- Hardened Concrete Testing
  - Grinding, compressive strength, flexural strength

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