Development of Tennessee UHPC for Bridge Applications

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16. Abstract

Ultra-high performance concrete (UHPC) is known for its exceptionally high mechanical properties and enhanced durability performance. In Accelerated Bridge Construction (ABC), UHPC can be used for precast structural members as well as for bridge repairs, retrofitting and overlay construction. Densely compacted UHPC has a compressive strength of more than 17,500 psi at 28 days. However, commercially available, proprietary UHPC can be 10 to 20 times more expensive than conventional concrete, whereas non-proprietary UHPC costs around 5 to 10 times more than conventional concrete.

The goal of this research is to develop and characterize non-proprietary, cost-efficient UHPC mixes with concrete materials available and/or sourced primarily from within the state of Tennessee. The primary objective was to develop self-consolidating UHPC that would provide a compressive strength of 4,000 psi at 8 hours and 18,000 psi at 28 days focusing on repair and traditional UHPC bridge applications. Due to the inability to achieve both compressive strength requirements for a single mix, two different UHPC mixes were developed based on intended application. The first is high early strength (HES) UHPC, which would provide 4,000 psi of compressive strength at 8 hours and the second is traditional UHPC providing a compressive strength of 18,000 psi at 28 days. In this research, UHPC was produced using ASTM Type IL cement, three types of fine aggregate sourced from different regions of Tennessee, two types of supplementary cementitious materials (silica fume and metakaolin), three types of admixtures (high range water reducer, accelerator, and strength enhancing admixture), and steel fibers depending on UHPC mix type and application.

All the UHPC mixes developed in this research achieved a flow between 20 and 25.5 inch of flow as per ASTM C1611. High early strength (HES) UHPC with different types of aggregate achieved greater than 6,000 psi of compressive strength at 8 hours. All the traditional UHPC mixes achieved a compressive strength more than 18,000 psi. Other mechanical and durability testing carried out in this research included split tensile strength, modulus of elasticity, surface resistivity, drying shrinkage and mass loss. An estimated cost analysis revealed that all UHPC mixes developed in this research cost approximately $560-640 per cubic yard. Steel fibers accounted for approximately half of the total cost.

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Executive Summary

This research aimed to develop cost-effective, non-proprietary ultra-high performance concrete (UHPC) mix designs utilizing locally available materials to meet the demands of bridge and infrastructure construction. Specifically, the study focused on producing a high early-strength UHPC achieving compressive strength above 4,000 psi at 8 hours and a traditional UHPC exceeding 18,000 psi at 28 days, both with self-consolidating properties. By addressing the lack of standardized UHPC specifications within the Tennessee Department of Transportation (TDOT), this work sought to support the implementation of low-cost, durable, and high-performance concrete solutions tailored for regional use.

This research successfully demonstrated the development of cost-effective, non-proprietary ultra-high performance concrete (UHPC) mixes using locally available materials. Both high early strength UHPC—achieving over 4,000 psi compressive strength at 8 hours—and traditional UHPC—with compressive strengths exceeding 18,000 psi at 28 days—were produced with optimized mix designs and chemical admixtures. A practical mixing procedure emphasizing high-shear mixing and strict timing was established to ensure consistent performance.

The study confirmed that metakaolin is a preferred supplementary cementitious material for improved strength and workability, while steel fibers, though costly, remain essential for UHPC's mechanical benefits. Cost analysis revealed that non-proprietary UHPC can be produced at roughly one-third the cost of proprietary alternatives, enhancing feasibility for widespread use.

Additionally, existing strength-modulus relationships do not accurately predict UHPC mechanical properties, highlighting the need for further research to support structural design. Overall, this work lays a strong foundation for the adoption of affordable, high-performance UHPC in bridge and infrastructure applications and provides valuable guidance for the development of regional specifications.

Key Findings

The key findings of this project are listed below:

- High early strength (HES) UHPC (greater than 4,000 psi compressive strength at 8 hours) and traditional UHPC (greater than 18,000 psi at 28 days) have been produced using non-proprietary materials.
- The cost of non-proprietary, HES UHPC was approximately $570-580 per cubic yard. Non-proprietary traditional UHPC costs approximately $570-640 per cubic yard. Both types of UHPC use mostly locally available materials.

- Aggregate type had a minimal impact on UHPC performance, demonstrating the robustness of the mixes used.
- Existing strength-modulus relationships underestimate the modulus of elasticity for UHPC, likely due to the lack of coarse aggregate in UHPC mixes.

Key Recommendations

The key recommendations are listed below:

- A high shear concrete mixer is required to ensure adequate mixing energy is imparted.
- Metakaolin is preferred over silica fume for UHPC mixes due to the higher compressive strength achieved as well as improved workability.
- On-site field mixing of UHPC is required due to initial setting times and high likelihood of slump loss with ready mix operations.
- Mixing times must be adhered to in order to achieve appropriate slump flow.
- UHPC temperatures exceeded 95 °F, with a maximum temperature observed of 107 °F. Temperature control, particularly for the HES UHPC mixes, may impact performance and is therefore not recommended unless in-situ temperature exceeds 160 °F.

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Chapter 1 Introduction

Ultra-high performance concrete (UHPC) is a relatively new type of concrete, known for its superior mechanical and durability properties compared to conventional concrete. The compressive strength of UHPC is typically more than 18 ksi. Since UHPC is a high-performance, high-strength concrete, it can be used in infrastructure where higher mechanical strength and better durability properties are required. Additionally, UHPC allows for reduced cross-sectional areas of structural members, leading to potential cost savings. Some common applications of UHPC are bridge decks, overlays, connections, piers, beams, and columns.

Generally, conventional concrete consists of cement, coarse and fine aggregate, and water. However, UHPC is an advanced self-consolidating composite material. UHPC comprises high amounts of cement and supplementary cementitious materials (i.e., metakaolin, fly ash, and/or silica fume), fine aggregate, chemical admixtures (e.g., superplasticizer and/or accelerator), and small, discontinuous steel fibers. All UHPC materials are densely compacted by utilizing numerous particle packing methods. UHPC with optimal aggregate gradation and low water-to-cementitious materials (w/cm) ratio can significantly reduce the porosity of concrete and minimize the weaker aggregate-binder bonds at the interfacial transition zone (ITZ) compared to conventional concrete. Additionally, steel fibers in UHPC help improve mechanical properties (such as splitting tensile strength and flexural strength) and durability properties. UHPC has very low permeability due to its denser microstructure compared to conventional concrete, UHPC shows higher freeze-thaw resistance and less structural steel reinforcement corrosion as it has less contact with chloride ions. Moreover, steel fibers in the UHPC help to prevent microcrack growth.

The Federal Highway Administration (FHWA) began funding UHPC research in 2001. Since then, research has been published on various aspects of UHPC, including mix design, material properties (i.e., fresh, hardened, and durability properties), and computational modeling. However, there are no nationwide guidelines, standards, or specifications on UHPC from the FHWA or the United States Department of Transportation (USDOT).

Several states have developed special or project-specific specifications for UHPC. For example, DOTs in New York (2018, 2023), Oregon (2023), Florida (2023), and California (2022) have released detailed UHPC specifications. Similarly, Texas DOT (2018) and Iowa DOT (2022a, 2022b) have implemented project-specific provisions. These documents typically address material properties and construction guidelines.

Many state DOTs, including the Tennessee Department of Transportation (TDOT), have yet to formalize the use of UHPC in bridge construction. This is largely because of the high cost associated with UHPC production and construction. Pre-packaged, proprietary UHPC is very expensive compared to non-proprietary UHPC and conventional concrete. Previously, the FHWA and numerous state DOTs worked with research universities and institutions for cost-efficient, locally produced, non-proprietary UHPC. One of the major focuses of their UHPC was the reduction of total cost and implementation of locally available materials. Many state DOTs have successfully performed research and development on UHPC with local materials without compromising UHPC's desired properties.

1.1 Research Objectives

This research aimed to develop representative non-proprietary UHPC mix designs with locally available materials. The research plan was divided into two primary objectives:

- development of a high early strength UHPC with self-consolidating properties that exceed a compressive strength of 4,000 psi at 8 hours, and
- development of a traditional UHPC with self-consolidating properties and a 28 day compressive strength exceeding 18,000 psi.

Once mix designs were found to achieve these objectives, the mixes were subjected to more thorough investigation of their fresh, hardened and durability properties, along with a relative cost analysis. Currently, there are no standard specifications on UHPC from TDOT for its bridge infrastructure. Therefore, the goal is to develop low-cost, non-proprietary UHPC with locally available materials and products as well as to draft a special provision and/or specification on UHPC for road and bridge design and construction.

Chapter 2 Literature Review

UHPC is known for its exceptionally high mechanical strength and improved durability properties compared to conventional concrete. Although the cost of UHPC is still a significant concern for the construction industry, the application of UHPC in bridge construction is growing rapidly due to its high compressive strength, flexural strength, toughness, and durability properties related to shrinkage, chloride ion penetrability, and freeze-thaw resistance.

UHPC is a combination of cement, supplementary cementitious materials (SCMs), high-range water reducer (HRWR) and/or accelerator, fine aggregate, steel fibers, and water. Typically, coarse aggregates are not incorporated in the UHPC mixes. According to the FHWA's definition, UHPC is a special cement-based, densely compacted material composed of an optimized gradation with less than a 0.25 water-cement ratio with discontinuous internal steel fibers (Graybeal, 2011, 2014). Moreover, according to FHWA, the compressive strength of UHPC should be higher than 18 ksi, and post-cracking tensile strength should be higher than 0.72 ksi with significantly improved durability properties (Graybeal, 2011, 2014). Overall, there is no strict definition for UHPC.

UHPC shows typical characteristics of three different types of concrete mixes (Akhnoukh and Buckhalter, 2021): first, self-compacting concrete or self-consolidating concrete (SCC), which has higher flowability; second, a superior version of high-performance concrete (HPC) with much higher strength; and finally, fiber-reinforced concrete (FRC), which has enhanced post-cracking and ductility properties.

In the United States, research on UHPC started in the late 1980s by the United States Army Engineer Research and Development Center (ERDC) for civil and military applications (Green et al., 2015). In Europe, UHPC was first introduced and developed as reactive powder concrete in France in the 1990s (Akhnoukh and Buckhalter, 2021). Following the success in Europe, UHPC testing in North America was implemented in 1994 (Perry and Habel, 2017). The first ever infrastructure made with UHPC was the Sherbrooke Pedestrian Bridge in Quebec, Canada in 1997. In this 197 foot long bridge, the bridge deck and the chords (top and bottom) utilized UHPC, which had a compressive strength of 29 ksi (Blais and Couture, 1999).

The potential of UHPC in bridges in the United States is significant. Proprietary UHPC has been available in the United States since approximately 2000. However, proprietary UHPC is performance-based and expensive. Additionally, proprietary UHPC may not be available in all the states, and transportation costs can be significant. Thus, the FHWA and state Department of Transportation (DOT) agencies are working together to research, develop, and produce non-proprietary UHPC.

2.1 FHWA Research on UHPC

The FHWA initiated research on UHPC in 2001 (Graybeal, 2008). Previously, the FHWA supported research on UHPC by numerous agencies, research institutes, and universities. A detailed list of research publications and technical notes are available on the FHWA website (https://www.fhwa.dot.gov/publications/lists/022.cfm). Research mainly focused on fresh, mechanical, and durability properties of UHPC, the application of UHPC in Accelerated Bridge Construction (ABC), non-proprietary mix design of UHPC, and UHPC material characterization for bridge applications, such as prestressed girders, precast deck panels, connection joints, and overlay. Typical UHPC material properties are shown in Table 2-1. Information in the following table was generated at Turner-Fairbank Highway Research Center (Haber et al., 2022).

Table 2-1 Properties, typical ranges, and test methods of field-cast UHPC (Haber et al., 2022).

Property	*Expected Typical Range*	*Test Method and Details*
Density (Unit Weight)	145–160 lb/ft^3	ASTM C642
Compressive Strength at 7 days	14–20 ksi	ASTM C39 **
Compressive Strength at 28 days	18–22 ksi	
Modulus of Elasticity	5,600–8,000 ksi	ASTM C469 **
Poisson's Ratio	0.1–0.2	
Direct Tension Cracking Strength	0.75–1.2 ksi*	FHWA-developed direct tension test (Graybeal and Baby, 2013)
Direct Tension Post-cracking Strength	0.75–1.2 ksi*	
Direct Tension Strain Capacity	0.0025–0.006 inch/inch	
Direct Tension Bond Strength	0.35–0.6 ksi	ASTM C1583
Drying Shrinkage	300-1,200 microstrain	ASTM C157 **
Autogenous Shrinkage	200-900 microstrain	ASTM C1698
Chloride Ion Permeability	50–500 coulombs	ASTM C1202 **
Freeze-thaw Resistance	Relative dynamic modulus of elasticity > 95 percent	ASTM C666 ** After 600 cycles
Initial Set Time	4–10 hours	ASTM C403
Final Set Time	7–24 hours	
Alkali-silica Reaction	Innocuous	ASTM C1260 or ASTM C1567

*Note: The expected range of values for direct-tension, sustained, post-cracking tensile strength is the same as the expected range of values for direct-tension cracking strength.

**Note: Procedures are modified to conform to ASTM C1856.

Since 2015, FHWA has worked with state DOTs to promote UHPC under the "Center for Accelerating Innovation" Every Day Counts program (Federal Highway Administration, 2017). This program emphasized the advantages of applying UHPC in bridge construction, considering its typical mechanical properties, performance, and impact on the design/redesign of bridge connections and construction schedule. At the end of this program, five states had adopted UHPC connections as a standard practice for bridge projects involving prefabricated elements (Figure 2-1). Moreover, 19 states and Washington D.C. were using UHPC as a bridge component connector and were planning to institutionalize it. However, full scale utilization of UHPC in bridge elements had not been implemented by the State of Tennessee at that time.

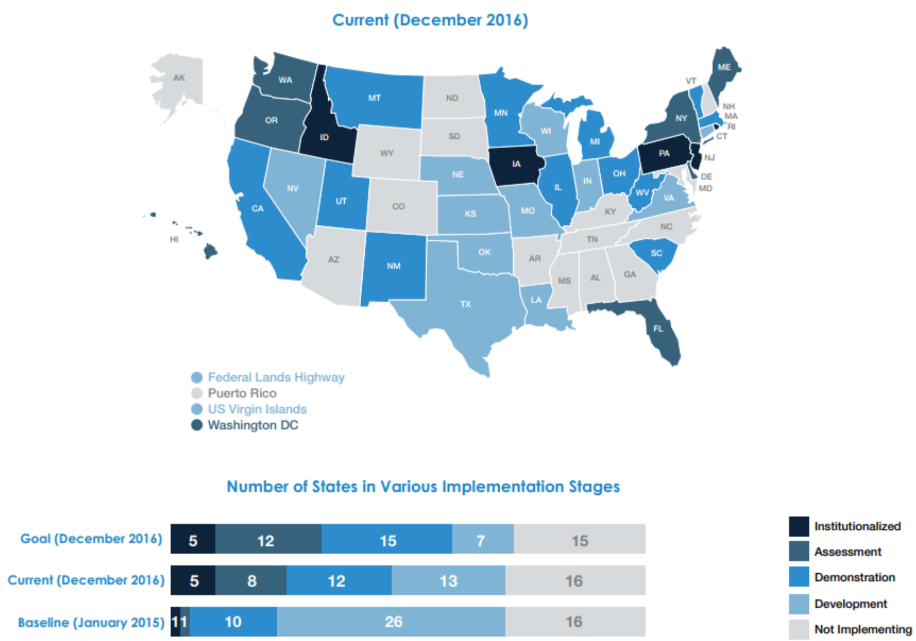

Figure 2-1 Implementation of UHPC as a connector for prefabricated bridge elements in different states (Federal Highway Administration, 2017).

In the subsequent "Every Day Counts-6 (2021-2022)" program, FHWA promoted UHPC as a preservation and repair material for bridge construction (Federal Highway Administration, 2023). Repairing with UHPC materials can be beneficial due to UHPC's long-lasting service life and low maintenance requirements. So far, three states have instituted UHPC as a preservation and repair material at the end of this program. Additionally, 13 states learned about bridge preservation and repair (Figure 2-2). Twenty-six states demonstrated and assessed UHPC on existing bridge structures (i.e., bridge overlay, link-slab and beam end repair techniques) as repair and preservation materials. The State of Tennessee was in the developmental stage under this project.

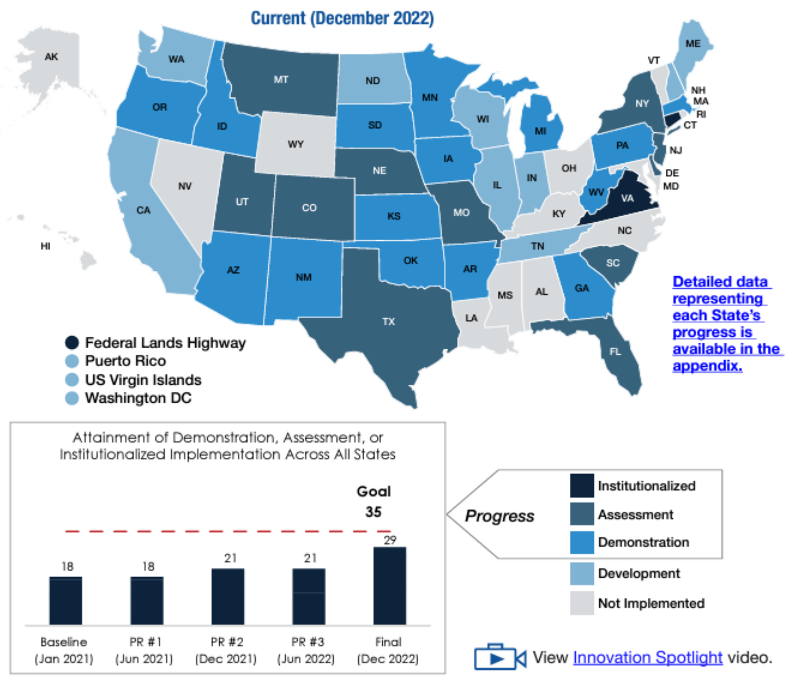

Figure 2-2 Implementation of UHPC for preservation and repair program in different states (Federal Highway Administration, 2023).

The first UHPC bridge in the United States was Mars Hill Bridge in Wapello County, Iowa in 2006 in collaboration with the Iowa Department of Transportation. This 110 foot long bridge used a proprietary UHPC mix called Ductal from Lafarge North America. Since then, the FHWA has been collaborating with state DOTs to construct bridges with UHPC materials. According to the FHWA, 341 bridges were constructed using at least one UHPC component between 2006 and 2020 (Figure 2-3). Typical applications of UHPC in these bridges are:

- connection between prefabricated elements (closure pours),
- bridge deck overlay,
- expansion joint headers,
- precast, pretensioned UHPC girders,
- precast, pretensioned UHPC piles,
- precast deck, and/or
- repair and preservation applications.

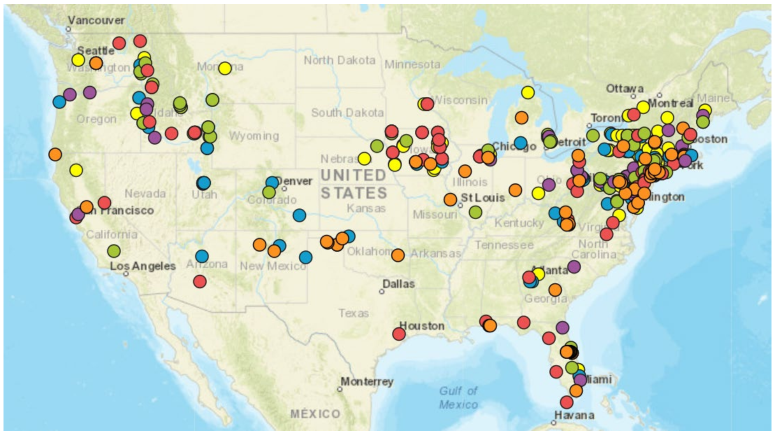

Figure 2-3 Bridges constructed with UHPC materials in the United States (Federal Highway Administration, 2023).

2.2 UHPC Benefits

The major advantage of using UHPC is that it has improved mechanical and durability properties compared to conventional concrete. UHPC has a very high compressive strength, flexural strength, and modulus of elasticity. Due to these mechanical properties, UHPC can be used in bridge structures where very high compressive strength is required. With UHPC, structural members can be constructed with less concrete by minimizing section size (Hasnat and Ghafoori, 2021). Additionally, UHPC is self-consolidating concrete. These exceptional properties of UHPC may open up new possibilities for innovative and slender structural designs, leading to more aesthetically pleasing and efficient structures. UHPC's ductile behavior can be used to resist seismic loading and for blast control. Moreover, due to its ductile behavior, UHPC requires little to no maintenance and has a longer life cycle. Due to its low water-cement ratio, a large amount of unhydrated binder in the hardened UHPC acts to promote the self-healing properties of concrete, which, under extreme loading and cracking conditions, can contribute to freeze-thaw resistance (Jacobsen and Sellevold, 1999). Due to its high particle packing density, UHPC has higher density and lower porosity, which helps to increase the concrete's compressive strength and improves durability. With appropriate UHPC materials and engineered mix design, it is possible to achieve high early strength. This high early strength can be helpful in Accelerated Bridge Construction (ABC), and its suitability for prefabrication contributes to rapid and efficient construction processes. In summary, UHPC can be used in the construction sector with its superior mechanical strength and durability.

2.3 UHPC Concerns and Drawbacks

One of the drawbacks of UHPC is cost. Higher cement content, supplementary cementitious materials (e.g., silica fume and metakaolin), and steel fibers can be significantly more expensive for UHPC production compared to conventional concrete (Akhnoukh and Buckhalter, 2021; Mousavinezhad et al., 2023; Wille and Boisvert-Cotulio, 2015). Moreover, some common supplementary cementitious materials, such as fly ash produced from coal-driven energygenerating plants, may not be available in the future as the energy sector is moving toward renewable energy (Mousavinezhad et al., 2023). The transportation costs from different locations (or states) also increase UHPC costs. In addition to the cost of materials and transportation, Akhnoukh and Buckhalter (2021) pointed out that a lack of appropriate guidelines and specifications at the federal and state level for construction, sample testing, and design of UHPC components are hindering the progress. Additionally, the construction industry (including contractors and subcontractors) lacks expertise in UHPC mixing, batching, curing, and quality control procedures. Azmee and Shafiq (2018) mentioned that the structural design and construction procedures for UHPC are different from those for traditional normal-weight concrete. The lack of construction workers and designers with experience in the application of UHPC impacts its broader use. During the mixing of UHPC in the mixing machine, the temperature inside the mixing machine can be higher than with traditional concrete mixes, which may impact workability and other properties. Using locally available materials, on-site mixing, improving codes and specifications, promoting UHPC, and training industry personnel can be helpful in mitigating these problems (Azmee and Shafiq, 2018).

2.4 UHPC Costs

UHPC is more expensive than conventional concrete. Material costs for non-proprietary UHPC are typically 5 to 10 times higher than normal-weight concrete (Wille and Boisvert-Cotulio, 2015). However, readymade, prepackaged proprietary UHPC can be up to 10 to 20 times more expensive than conventional concrete (Akhnoukh and Buckhalter, 2021; Berry et al., 2017; Karim et al., 2019; Wille and Boisvert-Cotulio, 2015). Unrealized UHPC costs may also include onsite mixing and/or specialized mixing equipment.

Akhnoukh and Buckhalter (2021) mentioned in their research that proprietary commercial UHPC can cost on average $1,900-2,290 per cubic yard, whereas non-proprietary conventional concrete costs only $130 per cubic yard. Berry et al. (2017) mentioned that the commercial UHPC product costs more than $2000 per cubic yard (more than $1,500 per m^3). Researchers from the University of Connecticut, Wille and Boisvert-Cotulio (2015), proposed three non-proprietary mix designs with different combinations of concrete materials to produce UHPC for Northeast, upper-Midwest, Northwest, and for the overall United States. Their cost analysis showed that UHPC without steel fibers can be produced with a range of $353 to $498 per cubic yard, with a minimum compressive strength of 22.5 ksi. However, with the addition of fibers in the mix, the cost can be raised up to $750 per cubic yard. Rangaraju et al. (2014) estimated that the cost of UHPC without steel fibers is less than $218 per cubic yard and UHPC with steel fibers can be less than $900 per cubic yard. Stewart et al. (2022) estimated the cost is $694.67 per cubic yard.

The subsequent higher cost for UHPC production is associated with higher material costs. The cost of the materials depends on production of the materials, availability of the material, geographical location, and transportation cost. Considering all the materials incorporated into UHPC, supplementary cementitious materials (SCMs) and steel fibers cost the most.

2.5 Effect of Materials and Mix Composition on UHPC Properties

2.5.1 Effect of Cement

Typically, a higher cement content is used in a UHPC mix compared to conventional concrete. Higher cement content can positively influence early age strength development of UHPC. When higher content of cement is used in UHPC, the rate of hydration is rapid at an early age, potentially leading to durability issues, such as increases in autogenous shrinkage. Low cost SCMs may be used to address the aforementioned issues (Mousavinezhad et al., 2023). Yu et al. (2014) found that with the appropriate particle packing method (i.e., modified Andreasen and Andersen model), it is possible to get as much as 20.6 ksi with lower cement contents (e.g., 1,032 lb/yd^3) and discontinuous steel fibers (UHPC1, UHPC2 and UHPC3 in the Table 2-2). The influence of cement content on compressive strength is shown in Table 2-2. As the cement content increases in the mix, the compressive strength and flexural strength increase, and UHPC gains strength at a rate proportional to the curing age.

Table 2-2 Effect of binder content on compressive strength at 28 days (Yu et al., 2014).

References	Binders (kg/m^3)			Water/ binder ratio	Steel fibre amount (vol.%)	Compressive strength at 28 days (MPa)
	Cement	GGBS	Silica fume			
Yang [6]	950	0	238	0.2	2	190
Kang [9]	860	0	215	0.2	2	198
Hassan [15]	657	418	119	0.17	2	150
Yang [18]	657	430	119	0.15	2	120
Toledo Filho [26]	1011	0	58	0.15	2	160
Corinaldesi [57]	960	0	240	0.16	2.5	155
Habel [58]	1050	0	275	0.14	6	160
UHPC1	875	0	44	0.19	2.5	156
UHPC2	612	0	44	0.19	2.5	142
UHPC3	700	0	44	0.19	2.5	149

The rate of cement hydration increases with an increase of cement content in the UHPC mix. It has been found that the rate of hydration increases rapidly at the very beginning (first 3 days), then the hydration rate becomes slower at a later time compared to the 3 day rate of hydration (Yu et al., 2014). Half of the cement content (50%) becomes hydrated at 7 days. The hydration reaction continues after 28 days. The unhydrated cement content may contribute to the self-healing properties of UHPC.

2.5.2 Effect of Supplementary Cementitious Materials (SCMs)

The application of SCMs in UHPC concrete is widespread. The most common SCMs in the United States are fly ash, silica fume, ground granulated blast-furnace slag, and metakaolin (Du et al., 2021). The particle size of SCMs is smaller than portland cement (illustrated in Figure 2-4), which influences the particle packing of UHPC. Typically, SCMs contain large quantities of silicon dioxide (SiO_2) and/or calcium oxide (CaO), which are responsible for pozzolanic and hydraulic reactions.

Du et al. (2022) used off-specification fly ash (OSFA) and slag in UHPC mixes at different percentage replacements of cement and found autogenous shrinkage reduced at 28 days compared to mixes without SCMs. Fly ash improved the workability of fresh UHPC as the size of fly ash is smaller (finer) compared to cement particles in addition to having a ball-bearing effect due to its spherical shape.

Karim et al. (2019) used cement and silica fume as binders for their UHPC. Using silica fume in a large quantity can adversely affect the compressive strength and splitting tensile strength due to poor workability and compaction. The autogenous shrinkage and drying shrinkage increase with higher silica fume contents. However, silica fume helps to reduce the depth of chloride penetration by filling the voids in the concrete.

Mousavinezhad et al., (2023) found that different SCMs, i.e., fly ash, silica fume, metakaolin, slag, and natural pozzolan (ground pumice) increase the rate of hydration, reduce heat during the hydration reaction, and improve durability properties. However, pumice, metakaolin, and slag are more angular, and pumice and metakaolin have higher surface areas than fly ash, leading to higher water absorption by these SCMs. As the percentage of natural pozzolan and metakaolin increase in the mixes, the shrinkage can be reduced.

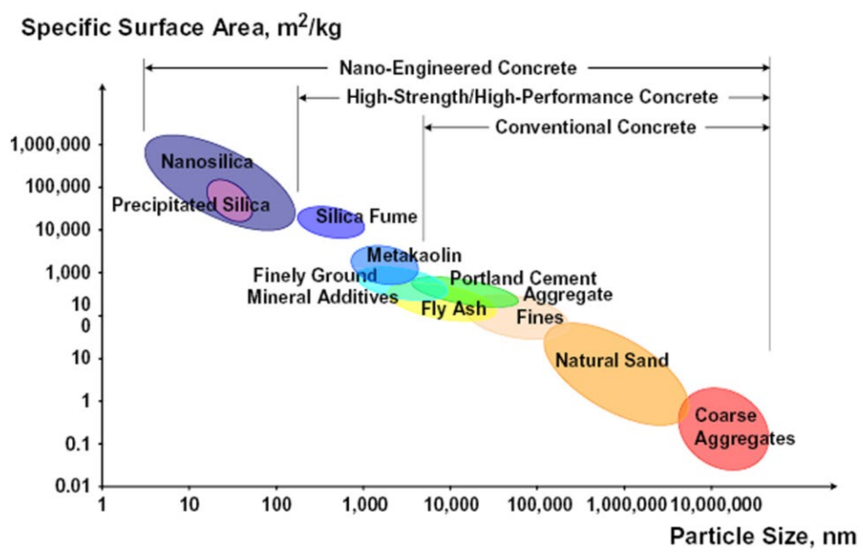

Figure 2-4 Specific surface area and size related to UHPC materials (Sobolev and Gutiérrez, 2005).

2.5.3 Effect of Water-to-Cementitious Materials Ratio

The water-to-cementitious materials (w/cm) ratio plays a crucial role in UHPC's strength, durability, and workability. Typically, in UHPC mix design, the w/cm ratio is kept low compared to conventional concrete. However, low w/cm ratio can make UHPC less workable. From the literature, it was found that w/cm ratios typically range from 0.12 to 0.21.

The hydration rate rises with an increase in the w/cm ratio and increases further with higher cement contents (Yu et al., 2014). High w/cm ratios lead to capillary pores in the concrete, increasing the permeability of concrete and decreasing the strength. For this reason, in UHPC, typically a low w/cm ratio is used. Increasing the w/cm ratio from 0.20 to 0.25 has been found to decrease compressive strength by up to 20% (Karim et al., 2019).

2.5.4 Effect of Chemical Admixtures

To achieve the high compressive strength of UHPC, a very low water-binder ratio is typically used, which negatively affects workability. Superplasticizers or high-range water reducers (HRWRs) are commonly used in UHPC to address this issue. Common superplasticizers used in UHPC are polycarboxylate and phosphonate-based, which are available throughout the United States (Graybeal, 2014). Accelerators have also been used to achieve the high early strengths necessary in some ABC applications. Shrinkage reducing admixture (SRAs) and viscosity modifying admixture (VMAs) may also be used to reduce shrinkage and segregation, respectively (Du et al., 2021; Shahrokhinasab et al., 2021).

The type, mixing method, and amount of superplasticizer highly influence the properties of UHPC. Generally, the addition of HRWR improves the flowability of UHPC (Berry et al., 2017; Du et al., 2022; Tue et al., 2008). Moreover, a superplasticizer reduces viscosity (Du et al., 2022; Tue et al., 2008). Additionally, HRWR helps to mitigate/reduce entrapped air in the UHPC mix. However, Du et al. (2022) mentioned that high content of HRWR may hinder the homogeneity/uniformity of concrete constituents, causing the segregation of UHPC materials.

How the HRWRs are added in the mixture influences fresh concrete's air content and workability. In the mixture, the HRWR can be added in three ways: (1) direct addition (with mixing water), (2) stepwise addition (added into the mixture in two steps), and (3) delayed addition (mixing HRWR at a certain time after addition of water) (Tue et al., 2008). It has been found that both stepwise and delayed addition improves fluidity and reduces the viscosity and air content of the mix compared to direct addition. When the HRWR is added stepwise, the cement particles can continue hydrating without being hampered by the HRWR. Overall, the delayed addition method performs slightly better than the stepwise addition method.

2.5.5 Effect of Fiber Type and Volume Fraction

Different types of fibers (e.g., steel fibers, glass fibers, synthetic fibers, and mineral fibers) have been used in UHPC previously. Most commonly, steel fibers are used (Du et al., 2021). The volume fraction, aspect ratio, surface condition, and shape of fibers influence a wide range of UHPC properties. Typically, when the fiber aspect ratio (ratio between fiber length and diameter) increases, flexural strength and toughness improve due to the larger fiber-matrix bond area (Du et al., 2021). This fiber-matrix bond can be improved by roughening the surface of the steel fibers by different treatment methods and using appropriate shapes and types of steel fibers.

The most commonly used steel fiber in the United States has a diameter of 0.008 inch (0.2 mm) and length of 0.5 inch (13 mm) with a minimum tensile strength of 290 ksi (Graybeal, 2014). Steel fiber volume fractions have ranged from 0.5% to 6% (Yu et al. 2014) with a 2% fiber volume fraction being the most common.

It has been shown that 3% steel fibers by volume can improve flexural strength and splitting tensile strength significantly compared to UHPC without steel fibers (Hasnat and Ghafoori, 2021). The splitting tensile strength is significantly higher (37-38% increase) for 3% fibers compared to 2% fibers (17-18% increase) in the mixes. The maximum flexural strength improved, on average, 43% with the inclusion of 3% straight steel fibers and 36% with the inclusion of 3% hooked steel fibers compared to UHPC without steel fibers. With the addition of 2% straight and hooked fibers in the concrete mix, the flexural strength increases by 29% and 23% on average compared with UHPC without steel fibers.

However, the effect of steel fibers on compressive strength and elastic modulus was minimal. The compressive strength of the UHPC with 3% hooked fibers increased by only 6% on average. The elastic modulus of the UHPC with both straight and hooked steel fibers increased by only 3-8%. Moreover, it was found that compared to the hooked steel fibers, straight steel fibers can improve the elastic modulus by up to 11%. This is to be expected as fibers only become effective or "activate" upon cracking (i.e., subjected to tensile loading).

2.5.6 Effect of Fine Aggregate on UHPC

The size, shape, surface area, price, quantity, and mixing proportion of fine aggregate play an important role in the development of UHPC. Masonry sand, volcanic rock, micro-sand, manufactured sand, river sand, and normal sand have been used by numerous researchers (Aljawad et al., 2022; Alsalman et al., 2017; Du et al., 2022; Karim et al., 2019; Mousavinezhad et al., 2023; Rangaraju et al., 2014; Wille and Boisvert-Cotulio, 2015; Yu et al., 2014).

Quartz sand (150 μm to 600 μm) is a common aggregate for UHPC but may not be locally available, leading to increased cost. On the other hand, river sand is typically locally available at relatively low cost (Du et al., 2021). Previously, South Carolina (Rangaraju et al., 2014), Missouri (Meng et al., 2017), and Kansas (Aljawad et al., 2022) used river sand as fine aggregate. One of the alternatives to river sand is masonry sand, which is finer than river sand. Montana DOT (Berry et al., 2017) and Iowa DOT (Karim et al., 2019) used masonry sand in their UHPC mixes. In addition, manufactured sand may also be used but has more angularity and roughness than natural sand. The increased angularity and roughness of manufactured sand can be detrimental to the workability of UHPC.

Other than conventional fine aggregate used in UHPC, lightweight sand and volcanic rock are unique due to the porous nature of sand. These materials can hold water and release water when concrete hydrates further (i.e., internal curing). This internal curing process is effective for UHPC as all the binders do not hydrate fully during the hydration process when higher contents of cementitious materials are incorporated in the concrete. It has been reported that the degree of hydration of cement is less than 35% at 28 days (Du et al., 2021). Internal curing can be beneficial by reducing shrinkage and increasing strength (Meng and Khayat, 2017).

For the practical application of UHPC, the concrete needs to be self-consolidating concrete. That is why the size of fine aggregate plays an important part. According to the FHWA, the maximum aggregate size should be 0.125 inch (3.2 mm) and less than ¼ times the length of fibers used. Another FHWA report mentioned that the maximum particle size of fine aggregate used in UHPC should be less than 0.047 inch (1.2 mm) (Graybeal, 2013).

The ratio of cement and aggregate plays an important role in UHPC mixes. An aggregate ratio of 1.0-2.0 by weight has been recommended (Graybeal, 2013; Wille and Boisvert-Cotulio, 2015). Hasnat and Ghafoori (2021) designed their UHPC with three different aggregate-to-cementitious materials ratios (V_A/V_{cm}) (i.e., 0.8, 1.0, and 1.2). Results showed that as the V_A/V_{cm} increased from 0.8 to 1.2, compressive strength decreased. Similar trends were observed for splitting tensile strength. However, when the V_A/V_{cm} ratio was increased from 0.8 to 1.2, drying shrinkage decreased, which was attributed to a higher restraining effect of the filler materials as the V_A/V_{cm} of the UHPCs increased (Hasnat and Ghafoori, 2021).

2.5.7 Particle Packing Theory

Very high compressive strength can be attained by minimizing pores inside the UHPC. This is achieved by compacting the UHPC particles densely. The concept of packing the particles densely for concrete was initially conceptualized by Fuller and Thompson (1907). They showed that the particle packing of aggregates affects the overall properties of the concrete. With this concept, Andreasen and Andersen (1930) proposed a particle packing model by ensuring optimal particle distribution for minimizing porosity in the concrete considering all the materials in the concrete. Their proposed model is as follows in Equation 2-1.

$$P(D) = \left(\frac{D}{D_{max}}\right)^q \quad (2\text{-}1)$$

where:

$P(D)$ is the fraction of particles smaller than size D,

D_{max} is the maximum particle size in the mix, and

q is the distribution modules value.

The Andreasen and Andersen model does not incorporate minimum particle size in their equation. Practically, the size (diameter) of the smallest particle of the concrete materials would be known while selecting materials for the mix design (Brouwers and Radix 2005). To solve this problem, Funk and Dinger (1994) proposed another model by modifying the Andreasen and Andersen model. In this modified Andreasen and Andersen model, Funk and Dinger (1994) introduced the minimum particle size, D_{min}. Yu et al. (2014) reported this modified Andreasen and Andersen model in Equation 2-2 as follows:

$$P(D) = \frac{D^q - D_{min}{}^q}{D_{max}{}^q - D_{min}{}^q} \qquad (2\text{-}2)$$

where:

$P(D)$ is the fraction of particles smaller than size D,

D_{max} is the maximum particle size in the mix,

D_{min} is the minimum particle size in the mix, and

q is the distribution modules value.

The minimum and maximum q value can be between 0 and 1. Andreasen and Andersen (1930) specified a q of approximately 0.37 for optimal packing density. However, Mehdipour and Khayat (2018) mentioned that the q value of UHPC mix design should be between 0.21 and 0.25. Yu et al. (2015) adopted the q value of 0.23.

Chapter 3 Methodology

3.1 Materials

This section contains a description of the materials (i.e., fine aggregate, cementitious materials, admixtures, and fibers) used to prepare UHPC mixes in this research.

3.1.1 Aggregates

In this study, UHPC was designed to include only fine aggregates. Since the primary objective of this study was to develop UHPC using locally available materials, three types of fine aggregates were used – two natural sands and a crushed limestone manufactured sand. The primary goal of using multiple aggregates was to assess the robustness of mix designs.

The specific gravity (SSD), absorption capacity, and bulk density/unit weight of the fine aggregates were determined in accordance with ASTM C128 (2022) and ASTM C29 (2023), respectively. The results are presented in Table 3-1. Sieve analysis was conducted according to ASTM C136 (2019); the results are shown in Appendix A, while the fineness modulus is summarized in Table 3-1. To reduce costs, the fine aggregates were used with the as-received gradation (i.e., no specialized gradation was used).

Table 3-1 Fine aggregate properties.

Aggregate	*Specific Gravity (SSD)*	*Absorption Capacity (%)*	*Fineness Modulus*	*Bulk Unit weight (pcf)*
Natural sand 1 (NS1)	2.57 ± 0.03	1.1 ± 0.1	2.54 ± 0.02	103.4 ± 0.4
Natural sand 2 (NS2)	2.59 ± 0.01	0.7 ± 0.1	2.59 ± 0.07	99.2 ± 0.1
Crushed limestone manufactured sand (MS)	2.80 ± 0.02	1.1 ± 0.1	2.87 ± 0.05	109.4 ± 0.5

3.1.2 Cement

For this project, two types of cement, ASTM C595 (2023) Type IL and ASTM C150 (2022) Type III, were used, based on their applicability. In Tennessee, ASTM Type I/II cement has almost completely been replaced by ASTM Type IL cement. The full manufacturer's mill reports are included in Appendix I.

3.1.3 Supplementary Cementitious Materials (SCMs)

While different SCMs were used during the small batch trial process (for which results are not included), only silica fume and metakaolin were ultimately used in various UHPC mixes. Both SCMs are known for their rapid pozzolanic reactivity, leading to higher early strength. Both were obtained from local suppliers and used in mixes as replacements for ASTM C595 Type IL cement, with a maximum replacement of 10% by mass. The silica fume met the requirements of ASTM C1240 (2020). The metakaolin met the requirements of ASTM C618 Class N calcined pozzolans (2023).

3.1.4 Chemical Admixtures

A high range water reducer (HRWR), with a typical dosage rate of 2 to 12 oz/cwt, was used at the maximum dosage rate for all high early strength (HES) UHPC mixes. The polycarboxylate-based HRWR admixture met ASTM C494 Type F (2024) requirements. For the regular UHPC mixes, the dosage rate was increased to approximately twice the recommended amount for most mixes. Accelerator, meeting ASTM C494 Type C (2024), was used only with HES UHPC mixes at a maximum dosage of 45 oz/cwt. Also, for the HES UHPC mixes, a specialty strength-enhancing admixture (with additional water reducing effects consistent with ASTM C494 Type A (2024)) was used to increase early age strength. All chemical admixtures were obtained from the same supplier.

3.1.5 Fibers

The steel fibers used in this research have a length of approximately ½ inch and an aspect ratio of 65. The fibers are straight, brass coated (for corrosion resistance), and striated (for enhanced bond strength to the cementitious matrix). They have a specific gravity of 7.8. These steel fibers were developed primarily for use in UHPC (El-Tawil, S., 2022).

3.2 Experimental Method

This section thoroughly discusses the methodological approach used to select mix designs that meet the required performance parameters.

3.2.1 Trial Mix Designs

In the initial phase of the study, trial mixes were conducted to identify approximate mix designs that produced the desired fresh and hardened concrete properties. Trials were prepared in a 4 quart planetary mixer according to ASTM C305 (2020) as seen in Figure 3-1. Mixes were evaluated for flow (ASTM C230 (2023) and ASTM C1437 (2020)) and compressive strength using 2 x 2 x 2 inch cubes (ASTM C109 (2024), as seen in Figure 3-2). A flow of at least 9 inches was targeted, in addition to compressive strengths of 4,000 and 18,000 psi at 8 hours and 28 days, respectively. A mortar flow of 9 inches was previously found to correlate well with appropriate slump flow for SCC (Stewart et al., 2022).

Figure 3-1 Planetary mixer used for small batch mixing.

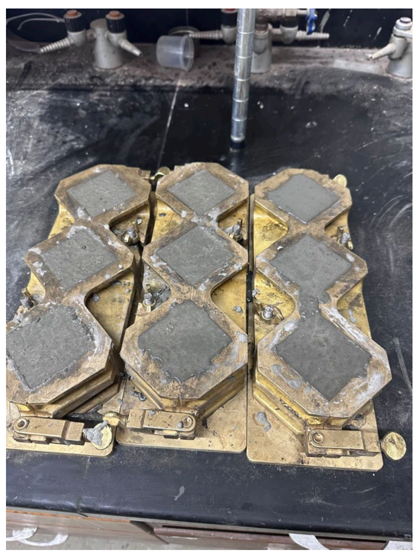

Figure 3-2 Preparation of 2 x 2 x 2 in mortar cubes for small batch compressive strength testing.

Small batch mixes were utilized to limit material usage and ultimately allowed for trialing over 100 different mixes. From these trial small batch mixes, it was identified that high early strength (greater than 4,000 psi at 8 hours) and high late age strength (greater than 18,000 psi at 28 days) were not consistently achievable with the same mix. Some preliminary mixes and resulting flows and compressive strengths are shown in Table 3-2.

Table 3-2 Trial mixes and resultant qualifying criteria.

Mix	*B-11*	*B-50*	*B-57*
Cement	1,900 pcy, Type IL	1,900 pcy, Type IL	1,900 pcy, Type IL
Fine Aggregate	1,900 pcy, NS1	1,900 pcy, MS	1,900 pcy, NS1
Steel Fibers	1%	1%	1%
w/cm	0.18	0.18	0.18
HRWR (oz/cwt)	12	12	12
Accelerator (oz/cwt)	20	45	45
Strength-Enhancing (oz/cwt)	0	3	3
ASTM C1437 Flow (in)	9.5	10	10.25
Compressive Strength at 8 hours (psi)	3,756 ± 420	5,340 ± 115	4,130 ± 70
Compressive Strength at 28 days (psi)	11,566 ± 80	16,680 ± 970	14,260 ± 875

Therefore, moving forward, and in consultation with TDOT, two approaches were devised to accomplish the original goals. The first case was to develop a high early strength UHPC mix with self-consolidating properties that was able to achieve at least a 4,000 psi compressive strength at 8 hours. The second case was a more traditional UHPC mix with self-consolidating properties that would achieve at least an 18,000 psi compressive strength at 28 days. Table 3-3 illustrates some of the small batch trial mixes that were closer to achieving (or did achieve) an 18,000 psi compressive strength at 28 days.

Table 3-3 Trial mixes and resultant qualifying criteria for traditional UHPC.

Mix	*B-105*	*B-107*
Cement	1,900 pcy, Type III	1,900 pcy, Type III
Fine Aggregate	1,900 pcy, NS1	1,900 pcy, MS
Steel Fibers	1%	1%
w/cm	0.18	0.18
HRWR (oz/cwt)	25	27.5
Accelerator (oz/cwt)	0	0
Strength-Enhancing (oz/cwt)	0	0
ASTM C1437 Flow (in)	10.5	8.75
Compressive Strength at 28 days (psi)	17,940 ± 410	18,555 ± 265

SCMs were next considered for replacement of the portland cement in order to assess any improvements in long-term strength for the traditional UHPC mixes. Some example mixes are shown in Table 3-4.

Table 3-4 Trial mixes and resultant qualifying criteria for traditional UHPC including SCMs. Note: MK = metakaolin and CA = Class C fly ash.

Mix	*B-103*	*B-16*	*B-108*
Cementitious Materials	1,900 pcy, Type IL 10% MK	1,900 pcy, Type IL 20% CA	1,900 pcy, Type IL 10% MK / 10% CA
Fine Aggregate	1,900 pcy, NS1	1,900 pcy, NS1	1,900 pcy, MS
Steel Fibers	1%	1%	1%
w/cm	0.18	0.18	0.18
HRWR (oz/cwt)	20.7	12	24
Accelerator (oz/cwt)	0	45	0
Strength-Enhancing (oz/cwt)	0	0	0
ASTM C1437 Flow (in)	11.0	11.5	10.5
Compressive Strength at 28 days (psi)	18,490 ± 550	15,540 ± 255	20,368 ± 320

From the trial mixing, two baseline mix designs were established as shown in Table 3-5. The mix designs are nearly identical, with the exception of chemical admixtures used and dosage rates. For all mixes, as-received fine aggregates were used instead of graded aggregates. While the use of graded aggregates would likely have increased the compressive strengths achieved, one of the primary objectives of this research was to create a low-cost UHPC. As such, if the target minimum strengths were achieved with as-received aggregates, then the mix design was deemed successful without further optimization. To reduce the cost further, only 1% steel fibers were used, as steel fibers are the most expensive component of UHPC.

Table 3-5 Preliminary mix designs.

Case/Application	High Early Strength (HES) UHPC	UHPC
Cement Type	ASTM C 595 Type IL	ASTM C 595 Type IL
Fine Aggregate Type	Ungraded NS1	Ungraded NS1
w/cm	0.18	0.18
Cementitious Content	1,900 pcy	1,900 pcy
Fine Aggregate Content	1,900 pcy	1,900 pcy
Fiber Volume	1%	1%
HRWR Admixture	~12 oz/cwt	~25 oz/cwt
Accelerating Admixture	~45 oz/cwt	0
Strength-Enhancing Admixture	~3 oz/cwt	0

3.2.2 Full Scale Candidate Mixes

Once candidate mixes were identified from the small-scale trial batches, full-scale mixes were evaluated to assess the likelihood of achieving success with the larger batches.

3.2.2.1 Mixer Selection

Since UHPC mixes require a low w/cm, the energy required for adequate mixing is much greater than that of traditional concrete mixes. As such, a high energy shear mixer, as opposed to a drum mixer, is required. For this research, a variety of different shear mixers were investigated based on availability, cost, and applicability to TDOT for on-site mixing. Ultimately, an IMER 120 Plus mixer with a maximum mixing capacity of 3 ft^3 was chosen as shown in Figure 3-3. The paddle speed of the IMER 120 Plus is 38 rpm. Larger versions available, depending on application and site needs.

Figure 3-3 IMER 120 Plus high shear mixer.

3.2.2.2 Mixing Procedure

It is well known that the mixing procedure can have an impact on the fresh and hardened properties of UHPC. Therefore, a standardized mixing procedure was developed to ensure consistency with each mix. This mixing procedure was initially established for the small-batch mixes and slightly adjusted to accommodate larger batches in the high shear mixer. This procedure was optimized for both slump flow and compressive strength.

All cementitious materials were mixed together for at least 5 minutes. Fine aggregate was then added and mixed for an additional 4 to 5 minutes. The fine aggregate was added in an oven-dry moisture state such that no hydration would prematurely start. At the same time, the water and all chemical admixtures were mixed thoroughly in a separate container for several minutes. While some research indicates that there may be additional optimization by adding chemical admixtures at a later time or in more than one step, the goal of this procedure was to simplify the process as much as possible to ensure consistency in field conditions.

Once all materials were pre-mixed appropriately, the water-admixture solution was slowly added to the mixer over a period of 1½ to 2½ minutes, then mixed for at least 5 minutes. If necessary, the direction of the rotating blades may be changed (i.e., clockwise versus counter-clockwise) to ensure homogeneous mixing and eliminate any clumping. After a maximum of 5 minutes, the steel fibers were gradually added to the mixer and mixed for an additional 1½ to 2 minutes. The total mixing time after the addition of water should not exceed 8 minutes for HES UHPC and 10 minutes for traditional UHPC. The concrete should be discharged within 10 minutes after the addition of water. Placement of the UHPC should occur as quickly as possible. Fresh properties of UHPC might be altered when different types of mixer machines are in use.

3.2.2.3 Fresh Property Testing

Generally, ASTM C1856 (2024) was followed for specimen fabrication and testing, except where noted in the following sections. Slump flow testing was conducted according to ASTM C1611 (2021) and AASHTO T347 (2021), as shown in Figure 3-4. Reported values in Chapter 4 are the average of at least 2 batches for each mix.

Figure 3-4 Slump flow measurement.

While UHPC does not require air entrainment due to its high density and impermeability, the air content of the fresh concrete mix was measured by the Sequential Pressure Method (i.e., Super Air Meter (SAM)) according to AASHTO T395 (2022). Air content readings were taken at pressures of 14 ± 0.05, 30 ± 0.05, and 45 ± 0.05 psi. Air contents reported in Chapter 4 were taken at the initial pressure reading (Figure 3-5(a)), while SAM numbers represent readings across all pressure ranges (Figure 3-5(b)).

(a) **(b)**

Figure 3-5 (a) Air content and (b) SAM readings according to AASHTO T395 (2022).

Though the high shear mixer had a capacity of 3 ft^3, it was found that such a large batch volume could not be adequately mixed. As such, batch sizes were decreased to 1.5 ft^3. Therefore, from each batch, at least 15 4x8 inch cylinders were prepared for a variety of subsequent strength tests according to ASTM C192 (2024). In order to accomplish fresh property testing, at least 2 1.5 ft^3 batches were typically prepared for each mix. Cylinders were mixed among batches for strength testing to distribute variability. All cylinders for later testing were lime water cured per ASTM C511 (2021) at 73 °F, unless otherwise specified.

Two 6 inch diameter cylindrical plastic molds were prepared for setting time testing as seen in Figure 3-6 per ASTM C403 (2023) and AASHTO T197 (2023). To minimize evaporation from the top surface of the UHPC, plastic sheeting covered the samples between tests. Initial and final setting were defined as when the penetration resistance reaches 500 and 4000 psi, respectively.

Two 4x8 inch cylinders were also used for temperature measurements per ASTM C1064 (2023) and AASHTO T309 (2022). As seen in Figure 3-7, cylinders were prepared with an embedded wireless thermocouple used to monitor the temperature profile during initial curing. TDOT specifications do not allow internal concrete temperatures to exceed 160 °F; therefore, it was important to verify that all UHPC mixes did not exceed this threshold. Specimens were cured at 73 °F.

A summary of all fresh property tests and associated standards is given in Table 3-6.

Figure 3-6 Setting time measurements with concrete penetrometer.

Figure 3-7 Cylinders with embedded wireless thermocouples monitoring internal concrete temperature profiles at early ages.

Table 3-6 Summary of fresh property experimental tests with applicable ASTM and/or AASHTO standards.

Property Measured	*Test Method*
Slump Flow	ASTM C1611 (2021) / AASHTO T347 (2021)
Air Content	AASHTO T395 (2022)
SAM	AASHTO T395 (2022)
Unit Weight	ASTM C138 (2023) / AASHTO T121 (2023)
Maximum Temperature	ASTM C1064 (2023) / AASHTO T309 (2022)
Initial Setting Time	ASTM C403 (2023) / AASHTO T197 (2023)
Final Setting Time	ASTM C403 (2023) / AASHTO T197 (2023)

3.2.2.4 Hardened Property Testing

Performance of UHPC cylinders was evaluated after specific curing times to investigate compressive strength, split tensile strength, and modulus of elasticity. For the high early strength UHPC mixes, compressive and split tensile strengths were measured at 8 hours and then at 1, 3, 7 and 28 days according to ASTM C39 (2024) / AASHTO T22 (2022) and ASTM C496 (2017) / AASHTO T198 (2022), respectively. For traditional UHPC, cylinders were tested at 3, 7, and 28 days for compressive and split tensile strength. The loading rates for compressive strength and split tensile strength testing were 1,000 ± 50 lb/s and 500 ± 50 lb/s, respectively.

Compressive strength cylinders were tested with unbonded caps; however, ASTM C1231 (2023) specifically is not to be used when compressive strengths exceed 12,000 psi using 70 durometer neoprene pads. As such, 70 durometer pads were used, when appropriate, for lower strengths, particularly at early ages. Where strengths were expected to exceed 12,000 psi, 90 durometer pads were used. While these pads do not specifically meet the standard, the manufacturer qualifies them for use in excess of 15,000 psi.

Modulus of elasticity testing was conducted according to ASTM C 469 (2022) at 28 days for both types of UHPC mixes. The loading rate for modulus of elasticity testing was 500 ± 25 lb/s. At 28 days, cylinders were assessed for water absorption and permeable voids according to ASTM C642 (2021).

Drying shrinkage was measured according to ASTM C157 (2024) and ASTM C596 (2023). 1 x 1 x 11.25 inch specimens were prepared in triplicate. The specimens were cured in a moisture chamber for 1 day and then cured in limewater for another 1 day before subsequent storage at 50% RH.

Steel fibers were excluded from the mixes for surface resistivity (SR) measurements, as preliminary testing indicated that they adversely affected the results. To ensure accurate results, a separate UHPC batch without fibers was prepared, and three 4x8 inch cylinders were cast and cured in limewater for SR testing (per AASHTO T358 (2024)) at 28 days. A 4-point Wenner probe with a 1.5 inch probe spacing (Proceq Resipod) was used to obtain SR measurements, as illustrated in Figure 3-8.

A summary of all hardened property tests and associated standards is provided in Table 3-7.

Figure 3-8 Example surface resistivity measurement with 4-point Wenner probe.

Table 3-7 Summary of hardened property experimental tests with applicable ASTM and/or AASHTO standards.

Property Measured	*Test Method*
Compressive Strength	ASTM C39 (2024) / AASHTO T22 (2022)
Split Tensile Strength	ASTM C496 (2017) / AASHTO T198 (2022)
Modulus of Elasticity	ASTM C469 (2022)
Absorption	ASTM C642 (2021)
Permeable Voids	
Surface Resistivity	AASHTO T358 (2024)
Drying Shrinkage / Mass Loss	ASTM C157 (2024) and ASTM C596 (2023)

Chapter 4 Results and Discussion

4.1 High Early Strength (HES) UHPC

From the preliminary mix designs shown in Table 3-2, the original mix design containing one of the natural sands, NS1, was expanded to three different mixes as shown in Table 4-1. The cement-to-fine aggregate ratio was kept constant at 1:1 by mass. Fibers were dosed at a fiber volume fraction of 1% and are not typically included in the original mix design volumetric calculations.

The mixes only varied in the type of fine aggregate as a measure of mix design robustness, allowing TDOT to confidently use these mixes statewide regardless of fine aggregate type.

Table 4-1 Final mix designs for HES UHPC.

Mix	*HES-NS1*	*HES-NS2*	*HES-MS*
Cement (pcy)	1,900	1,905	1,950
Water (pcy)	342	343	351
Fine Aggregate, SSD (pcy)	1,900	1,905	1,950
Steel Fibers (pcy)	132	132	132
HRWR (oz/cwt)	12	12	12
Accelerator (oz/cwt)	45	45	45
Strength-Enhancing (oz/cwt)	3	3	3

Each of these mixes was initially assessed for slump flow and average compressive strength at 8 hours prior to performing a larger array of experimental tests. These initial quality indicators are shown in Table 4-2. As can be seen, all mixes exceeded the minimum slump flow of 21 inches and 8 hour compressive strength of 4,000 psi, indicating robustness. All mixes also exhibited maximum temperatures less than 160 °F when cured at 73 °F.

Table 4-2 Qualifying metrics for HES UHPC.

Property	*Mix*		
	HES-NS1	*HES-NS2*	*HES-MS*
Slump Flow (in)	25.75 ± 1.0	23.25 ± 0.25	27.0 ± 0.75
Compressive Strength at 8 hours (psi)	6,380 ± 90	6,500 ± 630	6,740 ± 60
Maximum Temperature (°F)	107	104	103

As each of these three mixes met or exceeded the initial qualifying criteria, further testing was conducted as described in Section 3.2.2.2. A summary of the fresh and hardened properties tested is shown in Tables 4-3 and 4-4.

Table 4-3 Summary of fresh concrete properties for HES UHPC mixes.

Property	*Mix*		
	HES-NS1	*HES-NS2*	*HES-MS*
Slump Flow (in)	25.75 ± 1.0	23.25 ± 0.25	27.0 ± 0.75
Air Content (%)	3.2	3.4	3.3
SAM	0.58	0.58	0.76
Unit Weight (pcf)	149.4	148.1	151.8
Maximum Temperature (°F)	107.4	104.4	102.7
Initial Setting Time (min)	115 ± 10	100 ± 5	95 ± 5
Final Setting Time (min)	200 ± 10	215 ± 10	260 ± 10

Table 4-4 Summary of hardened concrete properties for HES UHPC mixes.

Property	*Mix*		
	HES-NS1	*HES-NS2*	*HES-MS*
Compressive Strength at 8 hours (psi)	6,380 ± 90	6,500 ± 630	6,740 ± 60
Compressive Strength at 1 day (psi)	10,930 ± 650	11,060 ± 320	11,720 ± 170
Compressive Strength at 3 days (psi)	11,090 ± 70	12,040 ± 140	12,630 ± 120
Compressive Strength at 7 days (psi)	12,325 ± 165	12,825 ± 125	13,675 ± 365
Compressive Strength at 28 days (psi)	13,370 ± 520	14,680 ± 310	15,320 ± 630
Split Tensile Strength at 8 hours (psi)	710 ± 10	920 ± 130	930 ± 30
Split Tensile Strength at 1 day (psi)	1,000 ± 200	1,140 ± 60	1,265 ± 50
Split Tensile Strength at 3 days (psi)	1,145 ± 135	1,230 ± 160	1,425 ± 190
Split Tensile Strength at 7 days (psi)	1,470 ± 90	1,460 ± 75	1,345 ± 165
Split Tensile Strength at 28 days (psi)	1,500 ± 105	1,520 ± 60	1,635 ± 95
Modulus of Elasticity at 28 days (ksi)	5,760	5,610	5,920
Absorption (%)	2.99	3.16	3.11
Permeable Voids (%)	7.80	7.39	8.16
Surface Resistivity at 28 days	16	15	14
Drying Shrinkage at 28 days (%)	0.107	0.128	0.107
Mass Loss at 28 days (%)	1.95	2.30	2.41

4.2 Traditional UHPC

Initially, traditional UHPC mixes were trialed based on the information shown in Table 3-2 and further detailed in Table 4-1. Unfortunately, the compressive strength of the traditional UHPC mixes yielded compressive strengths at 28 days below 18,000 psi as shown in Table 4-5. Therefore, mix design modifications were needed to increase the 28 day strength of the mixes.

Table 4-5 Initial mix designs for traditional UHPC.

Mix	*NS1*	*NS2*	*MS*
Cement (pcy)	1,900	1,905	1,950
Water (pcy)	342	343	351
Fine Aggregate, SSD (pcy)	1,900	1,905	1,950
Steel Fibers (pcy)	132	132	132
HRWR (oz/cwt)	13.01	15.31	16.08
Accelerator (oz/cwt)	0	0	0
Strength-Enhancing (oz/cwt)	0	0	0

Table 4-6 Qualifying metrics for traditional UHPC.

Property	*Mix*		
	NS1	*NS2*	*MS*
Slump Flow (in)	26.75 ± 1.0	24.5 ± 0.75	21.5 ± 0.5
Compressive Strength at 28 days (psi)	15,990 ± 380	14,150 ± 770	17,290 ± 260
Maximum Temperature (°F)	99	99	100

As a next step to increase the 28 day compressive strength, the UHPC mix with NS1 fine aggregate was modified by the addition of supplementary cementitious materials (SCMs). Silica fume (SF) or metakaolin (MK) subsequently replaced 10% of the Type IL cement by mass. These revised UHPC mix designs are shown in Table 4-7.

Table 4-7 Revised mix designs for UHPC using NS1 fine aggregate and SCMs.

Mix	*NS1-SF*	*NS1-MK*
Cement (pcy)	1,710	1,710
Silica Fume (pcy)	190	0
Metakaolin (pcy)	0	190
Water (pcy)	342	342
Fine Aggregate, SSD (pcy)	1,900	1,900
Steel Fibers (pcy)	132	132
HRWR (oz/cwt)	16.84	14.54
Accelerator (oz/cwt)	0	0
Strength-Enhancing (oz/cwt)	0	0

These mixes were then tested for compressive strength at 28 days. The qualifying results are shown in Table 4-8.

Table 4-8 Qualifying metrics for traditional UHPC With NS1 fine aggregate and SCMs.

Property	Mix	
	NS1-SF	NS1-MK
Slump Flow (in)	20.25 ± 0.25	25.5 ± 0.5
Compressive Strength at 28 days (psi)	17,300 ± 580	19,150 ± 550
Maximum Temperature (°F)	96	98

While silica fume did increase the compressive strength, the mix did not achieve the target compressive strength of 18,000 psi at 28 days. Silica fume also reduced the slump flow below the minimum target value of 21 in. On the other hand, the mix containing 10% metakaolin exceeded 18,000 psi at 28 days while maintaining adequate flow.

The mixes were subsequently repeated by changing out the natural sand (NS1) with the manufactured sand (MS). These new mix designs are shown in Table 4-9 with the resulting flow and 28 day compressive strengths shown in Table 4-10.

Table 4-9 Revised mix designs for UHPC using MS fine aggregate and SCMs.

Mix	MS-SF	MS-MK
Cement (pcy)	1,755	1,755
Silica Fume (pcy)	195	0
Metakaolin (pcy)	0	195
Water (pcy)	351	351
Fine Aggregate, SSD (pcy)	1,950	1,950
Steel Fibers (pcy)	132	132
HRWR (oz/cwt)	19.90	16.07
Accelerator (oz/cwt)	0	0
Strength-Enhancing (oz/cwt)	0	0

Table 4-10 Qualifying metrics for traditional UHPC With MS fine aggregate and SCMs.

Property	Mix	
	MS-SF	MS-MK
Flow (in)	21.0 ± 1.0	25.5 ± 0.5
Compressive Strength at 28 days (psi)	19,860 ± 680	21,090 ± 330
Maximum Temperature (°F)	99	98

While both mixes exceeded the 18,000 psi target for compressive strength at 28 days, the mix containing silica fume was right at the threshold for acceptable flow. Therefore, based on the results for flow and compressive strength presented thus far, it appears that mixes containing metakaolin performed better than mixes containing silica fume. Regardless, all four of the mixes presented in Tables 4-7 and 4-9 were subjected to the full battery of fresh and hardened property tests. Results for the fresh and hardened properties are shown in Tables 4-11 and 4-12.

Table 4-11 Summary of fresh concrete properties measured for traditional UHPC with SCMs.

Property	*Mix*			
	NS1-SF	*NS1-MK*	*MS-SF*	*MS-MK*
Flow (in)	20.25 ± 0.25	25.5 ± 0.5	21.0 ± 1.0	25.5 ± 0.5
Air Content (%)	5.3	5.2	3.9	4.0
SAM	0.54	0.24	0.64	0.70
Unit Weight (pcf)	145.5	146.7	150.7	153.5
Maximum Temperature (°F)	96	98	99	98
Initial Setting Time (min)	300 ± 15	125 ± 10	375 ± 15	135 ± 10
Final Setting Time (min)	410 ± 25	375 ± 25	520 ± 20	535 ± 20

Table 4-12 Summary of hardened concrete properties measured for traditional UHPC with SCMs.

Property	*Mix*			
	NS1-SF	*NS1-MK*	*MS-SF*	*MS-MK*
Compressive Strength at 3 days (psi)	12,190 ± 180	14,750 ± 300	12,940 ± 180	15,270 ± 170
Compressive Strength at 7 days (psi)	14,550 ± 260	15,810 ± 450	14,805 ± 480	17,390 ± 270
Compressive Strength at 28 days (psi)	17,300 ± 580	19,060 ± 420	19,860 ± 680	21,090 ± 330
Split Tensile Strength at 3 days (psi)	1,535 ± 205	1,355 ± 70	1,425 ± 245	1,500 ± 125
Split Tensile Strength at 7 days (psi)	1,515 ± 195	1,575 ± 215	1,490 ± 60	1,705 ± 40
Split Tensile Strength at 28 days (psi)	1,820 ± 55	2,065 ± 70	1,900 ± 75	2,030 ± 55
Modulus of Elasticity at 28 days (ksi)	6,270	6,800	6,180	7,130
Absorption (%)	1.11	1.76	1.03	1.42
Permeable Voids (%)	2.63	4.41	2.54	3.49
Surface Resistivity at 28 days	96	287	87	235
Drying Shrinkage at 28 days (%)	0.056	0.069	0.068	0.057
Mass Loss at 28 days (%)	1.61	1.55	1.89	1.82

4.3 Comparisons Between ASTM C1437 and ASTM C1611

The initial phase of this research started with small scale batch mixes in order to relatively quickly and easily develop UHPC mixes to meet certain performance metrics. One of the qualifying metrics was the flow, which was measured according to ASTM C1437 for the small batch mixes. It was originally estimated that a flow greater than 9 inches should correlate to adequate slump flow (i.e., greater than 21 inches) for larger batch mixes.

In order to retroactively assess the effectiveness of this original metric, all 7 mixes described in the previous sections were evaluated for flow according to the varying standards. A basic comparison is illustrated in Figure 4-1. With an intercept set to zero, there is a general correlation between the two flow values determined for the mixes used in this research. Ultimately, none of the original small batch mixes achieved a 9 inch flow when mixed with the large, high shear mixer. This is likely due to the lower mixing energy of the large batch mixer compared to the high precision, small batch mixer. Regardless, this comparison appears to indicate that an ASTM C1437 mortar flow of at least 8 inches would be sufficient to produce a UHPC mix with an ASTM C1611 slump flow of at least 21 inches, which is the lower limit generally accepted for self-consolidating concrete.

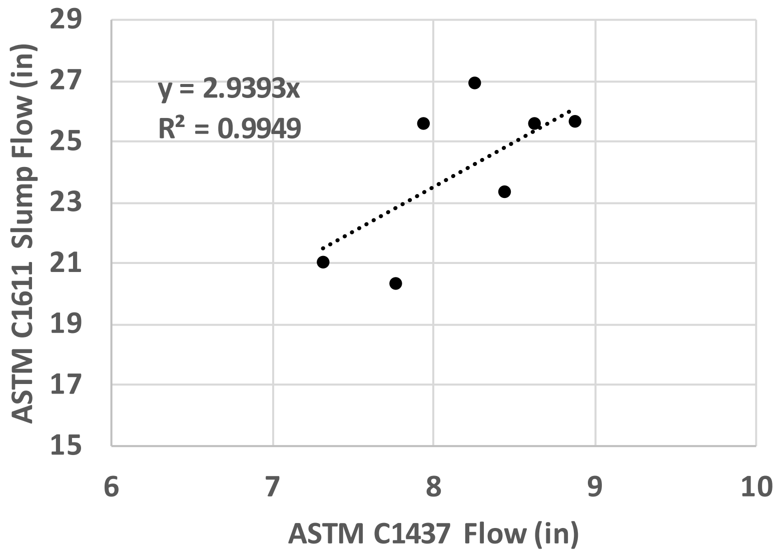

Figure 4-1 Comparison between ASTM C1437 and ASTM C 1611 flow values.

4.4 Compressive Strength – Modulus of Elasticity Relationships

The well-known relationship between compressive strength and modulus of elasticity is given in Equation 4-1 (AASHTO, 2015; ACI, 2022), for unit weights between 90 and 160 lb/ft^3.

$$E_c = 33 w_c^{1.5} \sqrt{f_c'} \quad (4\text{-}1)$$

where:

E_c = modulus of elasticity (psi),

w_c = unit weight (pcf), and

f_c' = compressive strength (psi).

However, Equation 4-1 is known to provides inaccurate estimates of modulus of elasticity with higher strength concretes. Therefore, the measured data were input in the equation to calculate an estimated E_c and compared to the measured E_c, as seen in Table 4-13.

Table 4-13 Comparison of measured and estimated modulus of elasticity at 28 days using Equation 4-1.

	Mix						
	HES-NS1	*HES-NS2*	*HES-MS*	*NS1-SF*	*NS1-MK*	*MS-SF*	*MS-MK*
Measured E_c (lsi)	5,760	5,610	5,920	6,270	6,800	6,180	7,130
Estimated E_c (ksi)	6,970	7,210	7,640	7,620	8,100	8,600	9,110
Difference	-21.0%	-28.5%	-29.0%	-21.5%	-19.0%	-39.2%	-27.8%

Overall, for the mixes tested in this research, the use of Equation 4-1 overestimates the modulus of elasticity for UHPC mixes by approximately 20-40%. This has also been seen in other research (ACI 362).

More recently, revisions to Equation 4-1 have been proposed (AASHTO, 2024), as seen in Equation 4-2.

$$E_c = 120{,}000 K_1 w_c^{2.0} f_c'^{0.33} \qquad (4\text{-}2)$$

where:

E_c = modulus of elasticity (ksi),

K_1 = correction factor for aggregate source (assumed 1.0 unless determined by physical test),

w_c = unit weight (kcf), and

f_c' = compressive strength (ksi).

Estimates of the modulus of elasticity using Equation 4-2 are shown in Table 4-14.

Table 4-14 Comparisons of measured and estimated modulus of elasticity at 28 days using Equation 4-2.

	Mix						
	HES-NS1	*HES-NS2*	*HES-MS*	*NS1-SF*	*NS1-MK*	*MS-SF*	*MS-MK*
Measured E_c (ksi)	5,760	5,610	5,920	6,270	6,800	6,180	7,130
Estimated E_c (ksi)	6,300	6,390	6,810	6,510	6,830	7,310	7,730
Difference	-9.4%	-13.9%	-15.0%	-3.8%	-0.5%	-18.2%	-8.5%

While the percent difference from measured modulus of elasticity is more accurate using Equation 4-2 compared to Equation 4-1, Equation 4-2 does still appear to overestimate the modulus by up to 18%. Since modulus of elasticity is partly a function of the stiffness of the aggregate in a concrete mix, it would appear that the absence of coarse aggregate in UHPC mixes may influence the strength-modulus relationship. Furthermore, the aggregate correction factor was taken to be 1.0 in this analysis, which may not be correct, though it was outside the scope of this research. More research is needed to further understand this relationship.

4.5 Compressive Strength – Split Tensile Strength Relationships

While there are some well established relationships between compressive strength and modulus of rupture (i.e., flexural strength), there is no universally accepted relationship between compressive strength and split tensile strength. While both flexural strength and split tensile strength are indirect measures of tensile strength, this research focused on split tensile strength due to ease of specimen preparation and testing. ACI 362 published Equation 4-3 based on prior research (ACI 362); however, the equation is generally applicable only for compressive strengths up to 12,000 psi. A comparison of the experimental and estimated split tensile strengths at 28 days is shown in Table 4-15.

$$f'_{sp} = 7.4\sqrt{f'_c} \qquad (4\text{-}3)$$

where,

f'_{sp} = split tensile strength (psi), and

f'_c = compressive strength (psi).

Table 4-15 Comparison of measured and estimated split tensile strength at 28 days.

	Mix						
	HES-NS1	*HES-NS2*	*HES-MS*	*NS1-SF*	*NS1-MK*	*MS-SF*	*MS-MK*
Measured f'_{sp} (psi)	1,500	1,520	1,635	1,820	2,065	1,900	2,030
Estimated f'_{sp} (psi)	855	895	915	975	1,020	1,035	1,075
Difference	+43.0%	+41.1%	+44.0%	+46.4%	+50.6%	+45.5%	+47.0%
f'_{sp} / f'_c Ratio	11.3%	10.4%	10.7%	10.5%	10.8%	9.7%	9.6%

As seen in Table 4-15, Equation 4-3 grossly underestimates split tensile strength based on compressive strength at 28 days for UHPC with strengths varying between approximately 13,000 and 21,000 psi. Even at the lowest compressive strength measured, the equation does not apply. Within the scope of this research project, there is not enough data to develop a statistically significant relationship based on these 7 mixes.

Otherwise, it is generally accepted that the ratio of split tensile strength to compressive strength is approximately 8-12%. As seen in Table 4-15, this particular relationship is still valid with ratios of 9.6-11.3% for UHPC tested at 28 days in this research.

4.6 Cost Comparisons

Material costs used in the calculation of mix design costs are shown in Table 4-16. It should be noted that these costs were obtained based on quantities used in this research. As such, costs may vary depending on quantities used. In other words, estimated costs may be expected to decrease with increasing quantities. Transportation and labor costs are not included in the cost estimations. Furthermore, steel fibers are the most expensive component of the UHPC mixes. This was the primary reason for only including 1% fibers by volume in most mixes.

Table 4-16 Material prices used for estimating mix design costs (as of April 2025).

UHPC Materials	*Cost ($/US Ton, unless otherwise specified)*
Type IL Cement	150.00
NS1 Sand	46.30
NS2 Sand	56.00
MS Sand	51.00
Silica Fume	450.00
Metakaolin	1,000.00
HRWR ($/Gallon)	14.50
Accelerator ($/Gallon)	8.75
Strength-Enhancing Admixture ($/Gallon)	17.60
Steel Fibers	5,100.00

For the two HES UHPC and four UHPC mixes developed in this research, estimated mix design costs are shown in Table 4-17. For the HES UHPC mixes, the costs per cubic yard of concrete ranged from $568 to $581. For the traditional UHPC mixes, costs ranged from $571 to $640 per cubic yard. Since the cost of metakaolin was approximately twice that of silica fume, the mixes containing metakaolin were approximately 10% higher than those containing silica fume. However, the metakaolin mixes had better performance (i.e., higher strength and improved workability), which may offset the additional cost compared to the mixes containing silica fume.

Overall, for comparison, as of 2019, proprietary UHPC mixes have been shown to cost more than $2,000 per cubic yard. (Stewart et al., 2022). As such, the non-proprietary mixes developed here can achieve similar performance at a much lower cost than proprietary mixes.

Table 4-17 Estimated cost for UHPC mixes (as of April 2025).

Mix	*Cost ($/cubic yard)*
HES-NS1	568.00
HES-NS2	577.80
HES-MS	581.00
NS1-SF	570.70
NS1-MK	628.70
MS-SF	581.20
MS-MK	639.60

Chapter 5 Future Research

Research presented in the previous chapters demonstrated the fulfillment of the two primary objectives. In summary, it is possible to develop both high early strength UHPC and traditional UHPC using locally available materials.

From a materials perspective, there are a variety of future avenues for research. This research used cement from only one manufacturer. Cement composition plays a role in the rate of chemical reaction and strength development, as well as workability, particularly in regard to tricalcium silicate (C_3S) content and cement fineness. With the use of ASTM C595 Type IL cements now, it is impossible to assess C_3S content due to the presence of additional calcium in the limestone addition. In other words, Bogue potential composition equations are not valid for Type IL blended cements. More research should be conducted utilizing several different cement sources to determine the extent of the impact cement type/source has on UHPC performance.

For the traditional UHPC mixes, silica fume and metakaolin were both shown to be effective at producing the required strengths. At the same time, there are a multitude of different combinations of cement and SCMs that may accomplish similar goals. The current research presented here purposely avoided fly ash due to its' inherent variability. However, in an effort to reduce UHPC costs, the use of fly ash (likely Class C) in a ternary blended mix could be considered.

Regarding mix designs, there are a large number of modifications that could be made to produce similar performance. Cement and aggregate contents could be somewhat modified along with further admixture optimization. With further research, it would be interesting to consider thresholds for performance. In other words, in this research 1,900 pounds per cubic yard of cementitious materials was consistent with all mixes, but what is the minimum cementitious content that would still produce acceptable strength results?

This research used a specific type of steel fibers from an out-of-state producer. There are a variety of steel fibers that could likely be used with minimal impact on compressive strength. Fibers are primarily added for post-cracking behavior. However, this research did not focus on any mechanical behavior, such as toughness and post-crack strength, which would be applicable in bending/flexural conditions. As TDOT expands the use of UHPC applications, this should be considered.

Also to be considered are the broader structural properties of UHPC that were outside the scope of this research. This research indicated that traditional relationships between compressive strength and other mechanical properties either under- or overestimated performance. This will be critical to understand more thoroughly for structural design. Other concerns such as development length and pull-out strengths should be considered.

Chapter 6 Conclusions and Recommendations

Locally available and non-proprietary materials were successfully used to develop UHPC mixes. The following conclusions and recommendations are drawn:

- A general UHPC mixing procedure has been developed that optimizes mixing time with simplicity. UHPC mixes should not be mixed for more than 10 minutes after the addition of water to the mix. A high shear mixer is required to ensure proper mixing energy and dispersion of materials.
- This is the first known research of non-proprietary UHPC that achieved a 4,000 psi compressive strength at 8 hours using an appropriate combination of chemical admixtures. Due to the extremely rapid early-age strength development, further strength development is limited. Therefore, typical UHPC compressive strengths on the order of 18,000 psi were not achievable at 28 days for these mixes.
- Setting times for the HES UHPC mixes were on the order of a couple hours. This indicates the need for on-site field mixing and rapid placement for adequate workability. Slump (flow) loss is a significant concern for these mixes.
- Traditional UHPC mixes with a compressive strength of 18,000 psi were achieved with the use of SCMs such as silica fume or metakaolin. Metakaolin performed better with regard to improved workability, compressive strength and surface resistivity.
- The costs of the UHPC mixes developed in this research project range from $568.00 per cubic yard to $639.60 per cubic yard. Steel fibers are the most expensive UHPC component, representing about 50% of the total materials cost. Compared to proprietary UHPC, the non-proprietary UHPC developed in this research is at least three times less expensive.
- Established compressive strength relationships with other mechanical properties, such as modulus of elasticity, are not applicable at the higher strengths of UHPC. Broader structural design considerations were outside the scope of this research but cannot be ignored for future UHPC usage.

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Appendix A Gradation of Aggregates

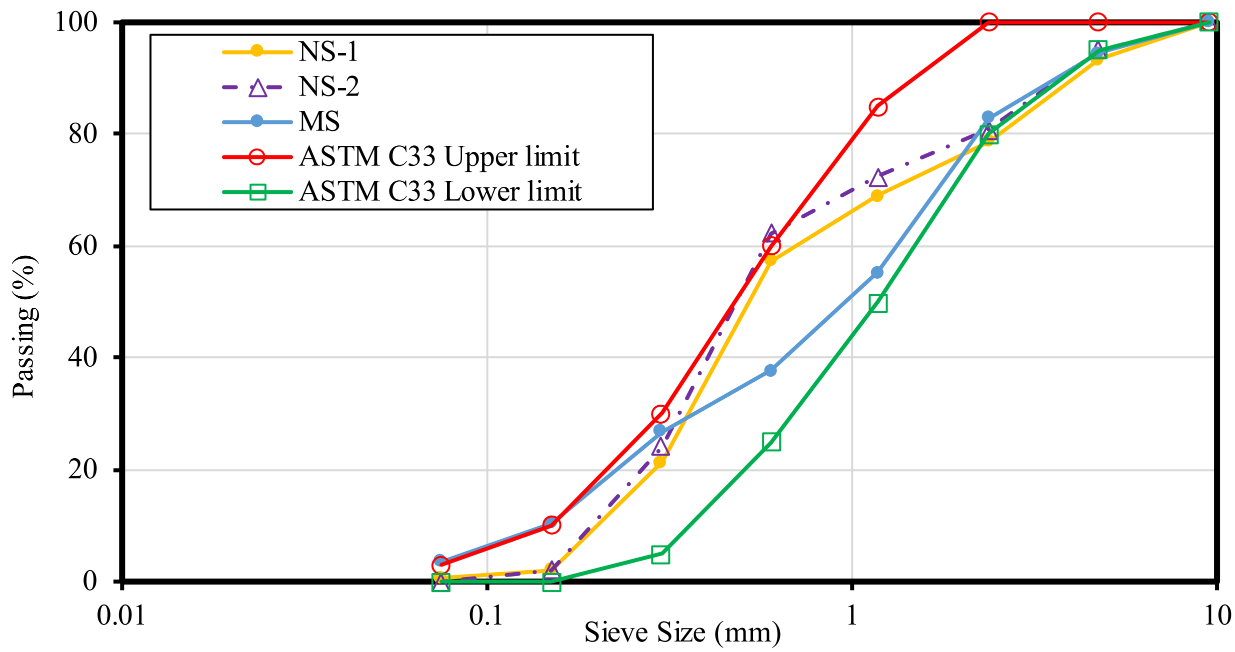

Figure A-1 Gradation of fine aggregates.

Appendix B Compressive Strength Individual Results

Table B-1 Compressive strength data for HES-NS1.

Age	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
8 hours	6,474	6,373	6,302	6,383	86
1 days	10,635	11,672	10,480	10,929	648
3 days	11,037	11,141	N/A	11,089	73
7 days	12,516	12,211	12,249	12,325	166
28 days	13,773	12,780	13,566	13,373	524

Table B-2 Compressive strength data for HES-NS2.

Age	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
8 hours	6,276	7,204	6,007	6,496	628
1 days	11,093	10,721	11,366	11,060	324
3 days	11,912	12,027	12,191	12,043	141
7 days	12,964	12,729	12,783	12,825	123
28 days	14,376	14,988	14,769	14,682	310

Table B-3 Compressive strength data for HES-MS.

Age	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
8 hours	6,762	6,664	6,796	6,740	68
1 days	11,911	11,635	11,605	11,717	169
3 days	12,648	12,742	12,509	12,633	117
7 days	14,089	13,520	13,412	13,674	363
28 days	15,767	15,322	14,881	15,324	443

Table B-4 Compressive strength data for NS1-SF.

Age	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
3 days	12,102	12,395	12,062	12,186	182
7 days	14,451	14,365	14,846	14,554	256
28 days	17,059	16,878	17,963	17,300	581

Table B-5 Compressive strength data for NS1-MK.

Age	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
3 days	14,583	15,102	14,578	14,754	301
7 days	15,497	16,132	14,583	15,814	449
28 days	19,541	18,762	18,874	19,059	421

Table B-6 Compressive strength data for MS-SF.

Age	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
3 days	12,911	12,775	13,140	12,942	184
7 days	15,145	14,468	14,544	14,806	479
28 days	19,481	20,651	19,463	19,865	680

Table B-7 Compressive strength data for MS-MK.

Age	*Compressive Strength (psi)*			*Average Compressive Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
3 days	15,144	15,389	14,113	15,267	173
7 days	17,675	17,130	17,355	17,387	274
28 days	21,418	20,752	21,108	21,093	333

Appendix C Split Tensile Strength Individual Results

Table C-1 Split tensile strength data for HES-NS1.

Age	*Split Tensile Strength (psi)*			*Average Split Tensile Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
8 hours	720	706	696	708	12
1 days	1,234	872	895	1,000	202
3 days	1,099	1,044	1,300	1,147	135
7 days	1,389	1,569	1,448	1,469	91
28 days	1,603	1,398	1,498	1,500	103

Table C-2 Split tensile strength data for HES-NS2.

Age	*Split Tensile Strength (psi)*			*Average Split Tensile Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
8 hours	1,060	806	898	921	129
1 days	1,151	1,196	1,077	1,141	60
3 days	1,098	1,400	1,198	1,232	154
7 days	1,464	1,158	1,412	1,345	164
28 days	1,488	1,485	1,594	1,522	62

Table C-3 Split tensile strength data for HES-MS.

Age	*Split Tensile Strength (psi)*			*Average Split Tensile Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
8 hours	920	964	909	931	30
1 days	1,216	1,317	1,264	1,266	51
3 days	1,519	1,546	1,209	1,425	187
7 days	1,542	1,450	1,395	1,462	74
28 days	1,542	1,632	1,733	1,636	95

Table C-4 Split tensile strength data for NS1-SF.

Age	*Split Tensile Strength (psi)*			*Average Split Tensile Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
3 days	1,552	1,732	1,328	1,537	203
7 days	1,686	1,303	1,549	1,513	194
28 days	1,763	1,872	1,830	1,822	55

Table C-5 Split tensile strength data for NS1-MK.

Age	*Split Tensile Strength (psi)*			*Average Split Tensile Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
3 days	1,412	1,280	1,380	1,357	69
7 days	1,342	1,621	1,764	1,576	215
28 days	2,133	2,068	1,992	2,064	71

Table C-6 Split tensile strength data for MS-SF.

Age	*Split Tensile Strength (psi)*			*Average Split Tensile Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
3 days	1,305	1,266	1,710	1,427	246
7 days	1,535	1,450	1,492	1,492	43
28 days	1,970	1,908	1,821	1,900	75

Table C-7 Split tensile strength data for MS-MK.

Age	*Split Tensile Strength (psi)*			*Average Split Tensile Strength (psi)*	*Standard Deviation (psi)*
	Sample 1	Sample 2	Sample 3		
3 days	1,610	1,366	1,526	1,500	124
7 days	1,752	1,674	1,693	1,706	40
28 days	2,010	2,089	1,985	2,028	54

Appendix D Absorption and Permeable Voids Individual Results

Table D-1 Absorption and permeable voids data for HES-NS1 at 28 days.

ASTM C642 Identifier	Sample 1 (gram)	Sample 2 (gram)	*Average* (gram)
Oven-dried mass, A	1,630.7	1,610.3	1,620.5
Surface-dry mass after immersion, B	1,674.0	1,651.9	1,663.0
Surface-dry mass after immersion and boiling, C	1,681.1	1,656.7	1,668.9
Apparent mass in water after immersion and boiling, D	1,093.1	1,002.9	1,048.0

Table D-2 Absorption and permeable voids data for HES-NS2 at 28 days.

ASTM C642 Identifier	Sample 1 (gram)	Sample 2 (gram)	*Average* (gram)
Oven-dried mass, A	1,615.1	1,615.1	1,615.1
Surface-dry mass after immersion, B	1,653.0	1,660.9	1,657.0
Surface-dry mass after immersion and boiling, C	1,662.1	1,670.3	1,666..2
Apparent mass in water after immersion and boiling, D	971.9	977.2	947.6

Table D-3 Absorption and permeable voids data for HES-MS at 28 days.

ASTM C642 Identifier	Sample 1 (gram)	Sample 2 (gram)	*Average* (gram)
Oven-dried mass, A	1,630.3	1,640.5	1,635.4
Surface-dry mass after immersion, B	1,677.2	1,685.8	1,681.5
Surface-dry mass after immersion and boiling, C	1,681.5	1,691.0	1,686.3
Apparent mass in water after immersion and boiling, D	1,114.3	1,012.2	1,063.3

Table D-4 Absorption and permeable voids data for NS1-SF at 28 days.

ASTM C642 Identifier	Sample 1 (gram)	Sample 2 (gram)	Sample 3 (gram)	*Average* (gram)
Oven-dried mass, A	1,633.0	1,607.5	1,643.1	1,627.9
Surface-dry mass after immersion, B	1,649.1	1,625.7	1,661.2	1,645.3
Surface-dry mass after immersion and boiling, C	1,649.5	1,626.3	1,662.0	1,645.9
Apparent mass in water after immersion and boiling, D	998.2	908.0	974.0	960.1

Table D-5 Absorption and permeable voids data for NS1-MK at 28 days.

ASTM C642 Identifier	Sample 1 (gram)	Sample 2 (gram)	Sample 3 (gram)	*Average* (gram)
Oven-dried mass, A	1,622.2	1,631.5	1,635.9	1,629.9
Surface-dry mass after immersion, B	1,648.9	1,659.0	1,662.5	1,656.8
Surface-dry mass after immersion and boiling, C	1,650.6	1,660.8	1,664.2	1,658.5
Apparent mass in water after immersion and boiling, D	1,073.2	987.2	964.9	1,008.4

Table D-6 Absorption and permeable voids data for MS-SF at 28 days.

ASTM C642 Identifier	Sample 1 (gram)	Sample 2 (gram)	Sample 3 (gram)	*Average* (gram)
Oven-dried mass, A	1,701.8	1,709.5	1,676.2	1,695.8
Surface-dry mass after immersion, B	1,720.0	1,724.7	1,691.9	1,712.2
Surface-dry mass after immersion and boiling, C	1,721.1	1,725.5	1,693.3	1,713.3
Apparent mass in water after immersion and boiling, D	1,021.2	1,060.9	996.1	1,026.1

Table D-7 Absorption and permeable voids data for MS-MK at 28 days.

ASTM C642 Identifier	Sample 1 (gram)	Sample 2 (gram)	Sample 3 (gram)	*Average* (gram)
Oven-dried mass, A	1,693.9	1,689.9	1,683.3	1,689.0
Surface-dry mass after immersion, B	1,721.8	1,715.6	1,691.5	1,709.6
Surface-dry mass after immersion and boiling, C	1,724.4	1,718.2	1,696.2	1,712.9
Apparent mass in water after immersion and boiling, D	1,041.3	1,031.8	1,008.4	1,027.2

Appendix E Surface Resistivity Individual Results

Table E-1 Surface resistivity data for HES-NS1.

Age (days)	*Surface Resistivity (kΩ-cm)*			*Average Surface Resistivity (kΩ-cm)*	*Standard Deviation (kΩ-cm)*
	Sample 1	Sample 2	Sample 3		
3	6.3	6.1	6.1	6.2	0.1
7	9.7	9.0	9.1	9.2	0.4
28	16.3	16.0	16.6	16.3	0.3

Table E-2 Surface resistivity data for HES-NS2.

Age (days)	*Surface Resistivity (kΩ-cm)*			*Average Surface Resistivity (kΩ-cm)*	*Standard Deviation (kΩ-cm)*
	Sample 1	Sample 2	Sample 3		
3	5.5	5.7	5.5	5.6	0.1
7	7.2	7.1	7.0	7.1	0.1
28	14.3	14.5	15.2	14.6	0.5

Table E-3 Surface resistivity data for HES-MS.

Age (days)	*Surface Resistivity (kΩ-cm)*			*Average Surface Resistivity (kΩ-cm)*	*Standard Deviation (kΩ-cm)*
	Sample 1	Sample 2	Sample 3		
3	5.7	5.5	5.7	5.6	0.1
7	7.4	7.3	7.2	7.3	0.1
28	13.8	13.3	13.9	13.7	0.3

Table E-4 Surface resistivity data for NS1-SF.

Age (days)	*Surface Resistivity (kΩ-cm)*			*Average Surface Resistivity (kΩ-cm)*	*Standard Deviation (kΩ-cm)*
	Sample 1	Sample 2	Sample 3		
3	16.3	15.1	16.8	16.0	0.9
7	21.3	20.8	21.0	21.0	0.3
28	95.2	95.6	96.2	95.6	0.5

Table E-5 Surface resistivity data for NS1-MK.

Age (days)	*Surface Resistivity (kΩ-cm)*			*Average Surface Resistivity (kΩ-cm)*	*Standard Deviation (kΩ-cm)*
	Sample 1	Sample 2	Sample 3		
3	7.9	7.8	7.7	7.8	0.1
7	54.8	57.6	55.8	56.1	1.4
28	288.5	281.3	290.5	286.8	4.9

Table E-6 Surface resistivity data for MS-SF.

Age (days)	*Surface Resistivity (kΩ-cm)*			*Average Surface Resistivity (kΩ-cm)*	*Standard Deviation (kΩ-cm)*
	Sample 1	Sample 2	Sample 3		
3	14.6	14.7	14.7	14.7	0.1
7	18.7	18.6	18.0	18.4	0.4
28	87.0	87.2	86.3	86.8	0.5

Table E-7 Surface resistivity data for MS-MK.

Age (days)	*Surface Resistivity (kΩ-cm)*			*Average Surface Resistivity (kΩ-cm)*	*Standard Deviation (kΩ-cm)*
	Sample 1	Sample 2	Sample 3		
3	7.1	7.1	5.4	6.5	1.0
7	49.8	53.0	51.1	51.3	1.6
28	222.0	227.0	255.3	234.8	17.9

Appendix F Drying Shrinkage Individual Results

Table F-1 Drying shrinkage data for HES-NS1.

Age (days)	*Offset Length (inch)*				*Average Length Change (inch)*	*Average Percent Length Change*	*Standard Deviation*
	Sample 1	Sample 2	Sample 3	Sample 4			
0	0.1889	0.1098	0.1862	0.1422			
1	0.1837	0.1050	0.1812	0.1372	-0.0050	-0.0425	0.0013
2	0.1828	0.1042	0.1804	0.1363	-0.0058	-0.0497	0.0017
3	0.1816	0.1021	0.1789	0.1347	-0.0074	-0.0633	0.0018
7	0.1795	0.1001	0.1768	0.1315	-0.0098	-0.0833	0.0054
14	0.1778	0.0989	0.1757	0.1305	-0.0111	-0.0939	0.0043
21	0.1774	0.0983	0.1749	0.1297	-0.0117	-0.0994	0.0047
28	0.1765	0.0972	0.1741	0.1289	-0.0126	-0.1071	0.0045

Table F-2 Drying shrinkage data for HES-NS2.

Age (days)	*Offset Length (inch)*			*Average Length Change (inch)*	*Average Percent Length Change*	*Standard Deviation*
	Sample 1	Sample 2	Sample 3			
0	0.1535	0.1274	0.1883			
1	0.1454	0.1198	0.1802	-0.0079	-0.0674	0.0023
2	0.1425	0.1169	0.1774	-0.0108	-0.0918	0.0021
7	0.1397	0.1142	0.1748	-0.0135	-0.1147	0.0024
14	0.1393	0.1138	0.1743	-0.0139	-0.1184	0.0024
21	0.1385	0.1129	0.1735	-0.0148	-0.1255	0.0020
28	0.1384	0.1125	0.1733	-0.0150	-0.1275	0.0008

Table F-3 Drying shrinkage data for HES-MS.

Age (days)	Offset Length (inch)			Average Length Change (inch)	Average Percent Length Change	Standard Deviation
	Sample 1	Sample 2	Sample 3			
0	0.1761	0.1831	0.0808			
1	0.1694	0.1766	0.0743	-0.0066	-0.0558	0.0009
2	0.1672	0.1741	0.0720	-0.0089	-0.0757	0.0005
7	0.1650	0.1718	0.0699	-0.0111	-0.0944	0.0013
14	0.1645	0.1713	0.0692	-0.0117	-0.0992	0.0008
21	0.1639	0.1708	0.0687	-0.0122	-0.1037	0.0005
28	0.1635	0.1705	0.0683	-0.0126	-0.1069	0.0000

Table F-4 Drying shrinkage data for NS1-SF.

Age (days)	Offset Length (inch)			Average Length Change (inch)	Average Percent Length Change	Standard Deviation
	Sample 1	Sample 2	Sample 3			
0	0.1945	0.1281	0.1564			
1	0.1919	0.1260	0.1543	-0.0023	-0.0193	0.0024
2	0.1908	0.1249	0.1531	-0.0034	-0.0289	0.0022
3	0.1903	0.1245	0.1526	-0.0039	-0.0328	0.0025
7	0.1889	0.1236	0.1511	-0.0051	-0.0436	0.0047
14	0.1883	0.1230	0.1504	-0.0058	-0.0490	0.0049
21	0.1879	0.1226	0.1501	-0.0061	-0.0521	0.0047
28	0.1876	0.1218	0.1498	-0.0066	-0.0561	0.0024

Table F-5 Drying shrinkage data for NS1-MK.

Age (days)	Offset Length (inch)				Average Length Change (inch)	Average Percent Length Change	Standard Deviation
	Sample 1	Sample 2	Sample 3	Sample 4			
0	0.1759	0.2235	0.1706	0.2093			
1	0.1733	0.2206	0.1681	0.2068	-0.0026	-0.0222	0.0016
2	0.1724	0.2190	0.1665	0.2051	-0.0041	-0.0345	0.0035
7	0.1701	0.2173	0.1647	0.2032	-0.0060	-0.0508	0.0014
14	0.1690	0.2162	0.1633	0.2019	-0.0072	-0.0612	0.0018
21	0.1685	0.2156	0.1628	0.2015	-0.0077	-0.0654	0.0018
28	0.1680	0.2153	0.1624	0.2012	-0.0081	-0.0686	0.0011

Table F-6 Drying shrinkage data for MS-SF.

Age (days)	*Offset Length (inch)*			*Average Length Change (inch)*	*Average Percent Expansion*	*Standard Deviation*
	Sample 1	Sample 2	Sample 3			
0	0.1900	0.0760	0.1404			
1	0.1868	0.0724	0.1368	-0.0035	-0.0295	0.0021
2	0.1854	0.0711	0.1353	-0.0049	-0.0414	0.0023
3	0.1847	0.0707	0.1347	-0.0054	-0.0462	0.0020
7	0.1836	0.0692	0.1336	-0.0067	-0.0568	0.0022
14	0.1829	0.0685	0.1327	-0.0074	-0.0633	0.0028
21	0.1825	0.0684	0.1324	-0.0077	-0.0655	0.0023
28	0.1823	0.0680	0.1322	-0.0080	-0.0678	0.0023

Table F-7 Drying shrinkage data for MS-MK.

Age (days)	*Offset Length (inch)*			*Average Length Change (inch)*	*Average Percent Length Change*	*Standard Deviation*
	Sample 1	Sample 2	Sample 3			
0	0.1803	0.1375	0.1673			
1	0.1771	0.1346	0.1647	-0.0029	-0.0246	0.0025
2	0.1760	0.1335	0.1635	-0.0040	-0.0343	0.0021
3	0.1755	0.1329	0.1629	-0.0046	-0.0391	0.0017
7	0.1747	0.1320	0.1622	-0.0054	-0.0459	0.0023
14	0.1741	0.1314	0.1617	-0.0060	-0.0507	0.0027
21	0.1736	0.1312	0.1614	-0.0063	-0.0535	0.0034
28	0.1729	0.1308	0.1612	-0.0067	-0.0572	0.0055

Appendix G Mass Loss Individual Results

Table G-1 Mass loss data for HES-NS1.

Age (days)	*Mass (gram)*				*Average Mass Change (gram)*	*Average Percent Mass Change*	*Standard Deviation*
	Sample 1	Sample 2	Sample 3	Sample 4			
0	471.7	479.4	472.4	488.7			
1	468.3	476.0	469.0	485.3	-3.4	-0.7114	0.0117
2	467.6	475.4	468.4	484.6	-3.2	-0.8473	0.0155
3	467.3	475.0	468.0	484.2	-3.4	-0.9257	0.0075
7	466.1	473.8	466.9	482.9	-4.5	-1.1766	0.0121
14	463.8	471.5	464.7	480.6	-6.5	-1.6525	0.0187
21	463.0	470.6	463.8	479.6	-6.8	-1.8406	0.0174
28	462.5	470.1	463.3	479.1	-7.1	-1.9453	0.0161

Table G-2 Mass loss data for HES-NS2.

Age (days)	*Mass (gram)*			*Average Mass Change (gram)*	*Average Percent Mass Change*	*Standard Deviation*
	Sample 1	Sample 2	Sample 3			
0	468.3	441.0	456.5			
1	465.0	437.7	453.3	-3.3	-0.7180	0.0263
2	463.8	436.6	452.1	-4.4	-0.9742	0.0205
7	461.0	434.0	449.4	-7.1	-1.5671	0.0175
14	459.8	432.9	448.1	-8.3	-1.8306	0.0136
21	458.4	431.5	446.7	-9.7	-2.1383	0.0214
28	457.7	430.8	445.9	-10.5	-2.2995	0.0315

Table G-3 Mass loss data for HES-MS.

Age (days)	*Mass (gram)*			*Average Mass Change (gram)*	*Average Percent Mass Change*	*Standard Deviation*
	Sample 1	Sample 2	Sample 3			
0	487.5	479.3	477.9			
1	483.6	475.6	474.1	-3.8	-0.7890	0.0150
2	482.3	474.3	472.4	-5.2	-1.0869	0.0566
7	479.3	471.3	470.0	-8.0	-1.6681	0.0145
14	477.8	469.9	468.6	-9.5	-1.9657	0.0222
21	476.5	468.6	467.2	-10.8	-2.2426	0.0124
28	475.6	467.8	466.5	-11.6	-2.4086	0.0289

Table G-4 Mass loss data for NS1-SF.

Age (days)	*Mass (gram)*			*Average Mass Change (gram)*	*Average Percent Mass Change*	*Standard Deviation*
	Sample 1	Sample 2	Sample 3			
0	464.2	476.0	460.8			
1	461.7	473.3	458.1	-2.6	-0.5639	0.0239
2	461.0	472.6	457.5	-3.3	-0.7066	0.0150
3	460.6	472.2	457.1	-3.7	-0.7923	0.0147
7	459.3	470.9	455.7	-5.0	-1.0779	0.0262
14	457.9	469.4	454.3	-6.5	-1.3848	0.0268
21	457.4	468.8	453.7	-7.0	-1.5061	0.0384
28	456.9	468.3	453.2	-7.5	-1.6132	0.0385

Table G-5 Mass loss data for NS1-MK.

Age (days)	*Mass (gram)*				*Average Mass Change (gram)*	*Average Percent Mass Change*	*Standard Deviation*
	Sample 1	Sample 2	Sample 3	Sample 4			
0	468.0	483.2	472.9	478.8			
1	464.9	480.1	469.8	475.8	-3.1	-0.6465	0.0106
2	464.4	479.6	469.3	475.3	-2.8	-0.7516	0.0123
7	462.8	478.0	467.8	473.7	-4.3	-1.0827	0.0196
14	461.2	476.4	466.1	472.2	-5.5	-1.4192	0.0233
21	460.8	475.9	465.8	471.8	-5.5	-1.5031	0.0193
28	460.6	475.6	465.7	471.6	-5.5	-1.5451	0.0317

Table G-6 Mass loss data for MS-SF.

Age (days)	*Mass (gram)*			*Average Mass Change (gram)*	*Average Percent Mass Change*	*Standard Deviation*
	Sample 1	Sample 2	Sample 3			
0	488.5	482.0	482.6			
1	485.0	478.7	479.1	-3.4	-0.7088	0.0214
2	484.1	477.9	478.3	-4.3	-0.8808	0.0266
3	483.7	477.5	477.9	-4.7	-0.9634	0.0261
7	482.2	475.9	476.3	-6.2	-1.2869	0.0201
14	480.5	474.2	474.7	-7.9	-1.6310	0.0110
21	479.8	473.4	473.9	-8.7	-1.7893	0.0117
28	479.3	473.0	473.4	-9.1	-1.8856	0.0197

Table G-7 Mass loss data for MS-MK.

Age (days)	*Mass (gram)*			*Average Mass Change (gram)*	*Average Percent Mass Change*	*Standard Deviation*
	Sample 1	Sample 2	Sample 3			
0	484.6	489.1	489.6			
1	480.9	484.7	484.9	-4.3	-0.8744	0.1006
2	480.0	484.8	484.8	-4.6	-0.9363	0.0518
3	479.5	484.3	484.3	-5.1	-1.0388	0.0519
7	478.4	483.3	483.2	-6.1	-1.2575	0.0636
14	477.4	482.4	482.3	-7.0	-1.4489	0.0685
21	476.4	481.4	481.4	-8.0	-1.6471	0.0636
28	475.5	480.6	480.5	-8.9	-1.8248	0.0759

Appendix H Draft UHPC Special Provision

STATE OF TENNESSEE

SPECIAL PROVISION

REGARDING

ULTRA-HIGH PERFORMANCE CONCRETE (UHPC)

Description

This work consists of furnishing and placing a self-consolidating, high-strength cementitious material, herein referred to as ultra high performance concrete (UHPC).

Materials

The cement used shall be Type I or Type IL meeting the requirements of **901.01**.

Fine aggregate shall meet the requirements of **903.01**. No coarse aggregates are permitted.

Chemical admixtures shall meet the requirements of **921.06** and be approved by the Department. No air entraining admixtures shall be used.

Supplementary cementitious materials shall be approved by the Department.

Steel fibers shall be ½ inch long, and with a tensile strength greater than 300 ksi. Use 1% fibers by volume of mix after calculation of all other mix components. Fibers should be corrosion-resistant and have enhanced bonding through surface modifications.

Equipment

Furnish all materials, tools, equipment, transportation, necessary storage, access, labor, and supervision required for the proper application of the UHPC.

A high shear mixer will be required for on-site mixing. All dry materials (not including fibers) shall be mixed until homogenous. Water and chemical admixtures shall be mixed separately. The liquid solution shall be slowly added to the mixer. Once the mix has achieved adequate workability, the fibers shall be added to the mixer and mixed for an additional 2-3 minutes. Initial placement shall occur within 15 minutes, but no more than 30 minutes, after the addition of water to the mixer.

Proportioning Ultra-High Performance Concrete

The two general classes of UHPC delineated by slump flow and minimum compressive strength are given in Table 1. If the class of ultra-high performance concrete is not specified in the contract, the class to use shall be as directed by the Engineer. Example mix designs that have been demonstrated to achieve the required performance for each class are shown in Table 2. The Contractor may use these mixes or develop their own.

Table 1. CLASSES OF UHPC			
Class	ASTM C1856 Slump Flow, in	Minimum Compressive Strength, psi	
		8 hours	28 days
HES UHPC	> 21	4,000	12,000
UHPC	> 21	N/A	18,000

Table 2. EXAMPLE UHPC MIX DESIGNS		
Mix	HES UHPC	UHPC
Cementitious Materials: Fine Aggregate Ratio	1:1	1:1
Metakaolin	0	10% mass replacement
w/cm	0.18	0.18
Steel Fibers	1% by volume	1% by volume
HRWR (oz/cwt)	12	15
Accelerator (oz/cwt)	45	0
Strength-Enhancing (oz/cwt)	3	0

Note: HES = high early strength

Quality Control Sampling and Testing by the Contractor

Prior to the start of the project, perform trial batches. The trial batches shall be made using the same UHPC materials, equipment, and procedures as is to be used on the project. The Department will test the trial batch for slump flow and 4 x 8 inch test cylinders shall be made. Slump flow and strength results shall exceed those specified in Table 1. If the trial batch does not produce the required results, adjustments shall be made by the Engineer and a new trial batch shall be required. No direct payment will be made for the trial batching.

Construction Requirements

No vibration shall be used. Pour all succeeding UHPC placement into fluid UHPC.

Curing shall follow requirements of **501.18** and **604.23**.

The optimal ambient temperature for placement is 70-75 °F. Placement at lower temperatures may result in lower strengths, particularly for HES UHPC. Placement shall not occur at ambient temperatures above 85 °F. Temperature shall be continuously measured with at least two embedded thermocouples and shall not exceed 160 °F at any time.

Method of Measurement

The Department will measure UHPC by the number of cubic yards complete in place.

Basis of Payment

The Department will pay for accepted quantities, complete in place, at the contract unit price as follows:

Item No.	Description	Unit
XXX-01.01	UHPC	Cubic Yards

Such payment is full compensation for all materials, equipment, labor, and incidentals necessary for proportioning, mixing, delivery, storage, handling, surface preparation, installation, sampling, testing, repairs and curing of the UHPC to be included in the unit price bid for UHPC.

Appendix I Cement Mill Reports (for TDOT reference only)

Buzzi Unicem USA

Chattanooga Plant
P.O. Box 4304
1201 Suck Creek Road
Chattanooga, TN 37405
Phone: (423) 886-0800
Fax: (423) 886-4651

Mill Test Report

Cement Type: T-IL(10)
Manufacture Date: 10/31/2023
Silo Number:

From: October 1, 2023
To: October 31, 2023

Chemical	ASTM C-114
SiO2 (%)	18.3
Al2O3 (%)	4.4
Fe2O3 (%)	3.19
CaO (%)	64.1
MgO (%)	3.5
SO3 (%)	2.82
Total Alkali (Na2O + 0.658K2O)	0.50
Ignition Loss	5.3
Insoluble Residue	0.51
C3S (%)	79.7
C2S (%)	-7.6
C3A (%)	6.3
C4AF (%)	9.7
C3S + 4.75C3A	109.5
CO2 (%)	4.6
Limestone (%)	11.1
CaCO3 in Limestone (%)	87.6

Physical	ASTM C-150	
Time of Set (Vicat)		
Initial Set (min.)	108	
Final Set (min.)	225	
Compressive Strength	PSI	MPa
1 Day	2078	14.3
3 Day	3727	25.7
7 Day	4918	33.9
28 Day	6464	44.6
Cube Flow	117	
Fineness, Blaine	4114	
325 Mesh (%)	94.8	
Air Content (%)	6.0	
Normal Consistency (%)	25.0	
False Set (%)	75.3	
Autoclave Expansion (%)	0.09	
Specific Gravity	3.14	

This Portland-Limestone T-IL cement complies with ASTM C595 specifications.

Date 11/13/2023 11:25:22 AM

Buzzi Unicem USA

Chattanooga Plant
P.O. Box 4304
1201 Suck Creek Road
Chattanooga, TN 37405
Phone: (423) 886-0800
Fax: (423) 886-4651

Mill Test Report

Cement Type: Type III Low Alkali
Manufacture Date: October, 2023
Silo Number:

From: October 1, 2023
To: October 31, 2023

Chemical

SiO_2 (%)	20.1
Al_2O_3 (%)	5.0
Fe_2O_3 (%)	3.5
CaO (%)	64.1
MgO (%)	4.0
SO_3 (%)	2.6
Total Alkali (Na_2O + 0.658K_2O)	0.56
Ignition Loss	1.7
Insoluble Residue (%)	0.12
C_3S (%)	61.9
C_2S (%)	11.0
C_3A (%)	7.4
C_4AF (%)	10.6
C_3S + 4.75C_3A	96.9
CO_2 (%)	1.1
Limestone (%)	2.6
$CaCO_3$ in Limestone (%)	94.6

Physical

	PSI	MPa
Time of Set (Vicat)		
Initial Set (min.)	75	
Final Set (min.)	155	
Compressive Strength		
1 Day	3560	24.5
3 Day	5470	37.7
7 Day	7570	52.2
28 Day	-	-
Cube Flow	98	
Fineness, Blaine (cm2/g)	6118	
325 Mesh (%)	99.7	
Air Content (%)	6.7	
Normal Consistency (%)	30.2	
False Set (%)	83	
Autoclave Expansion (%)	0.12	

We certify that the above described cement, at the time of shipment, meets the chemical and physical requirements of ASTM C-150, AASHTO M-85, or ASTM C-91.

Date 11/13/2023 10:58:33 AM