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Developing Ultra-High Performance Concrete (UHPC) with Locally Available Materials

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Developing Ultra-High Performance Concrete (UHPC) with Locally Available Materials

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Civil Engineering

by

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ABSTRACT

Ultra-High Performance Concrete (UHPC) can enhance the durability and resilience of concrete structures. The use of local materials is a fundamental step to save energy and reduce the cost of concrete. The main focus of this research was to develop a UHPC with compressive strength of 150 MPa using locally sources materials. In this study, the effect of fine materials, binder type and content, type of mixer, steel fibers and curing regimes on concrete's compressive strength were investigated. The relationship between compressive strength and elastic modulus was also studied. This study synthesizes all relevant experimental data in the literature to propose a new equation for predicting the modulus of elasticity (MOE) at different ages. A number of UHPC mixtures were developed to verify the accuracy of the proposed equation. With an error of ±10%, the proposed equation provides a reasonable prediction for the UHPC mixtures containing local materials. The final part of the dissertation focuses on developing economical UHPC mixtures by reducing the amount of binder content by using of ash. Costs were compared with the UHPC mixtures that are available in the market, indicating \$283/m^3 compared to approximately \$200/m^3 with current products.

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DEDICATION

I dedicate this dissertation to my parents and my inspiration, Imam Ali Ibin Abi Talib with love.

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CHAPTER 1: INTRODUCTION AND RESARCH OBJECTIVES

1.1 INTRODUCTION

Technological advancement was made in the concrete field within the past two centuries. With the advent of chemical additives, a producer of concrete can influence the setting time, slump, and even air entrainment of a mix. For example, the use of superplasticizers (SP), which are also known as high range water reducers (HRWRs), can make concrete flow and consolidate due to its own self-weight. Other options, apart from the use of chemical admixtures, are available as well. Concrete's weight can be reduced or enhanced with a change in aggregates. Lightweight aggregates may be necessary for specific applications. The use of such aggregates can reduce the unit weight of concrete, making slabs and wall sections thinner. Heavyweight concrete containing steel and iron aggregates can create a unit weight in excess of 300 pounds per cubic foot. Such concrete is useful in nuclear reactor walls [1]. Even though strength is always a concern as architects, engineers are pushing the boundaries of design continually with bridges that span longer distance, and with taller buildings. With these advanced, the concrete must be stronger, more flexible, and more durable.

The concrete industry for many years were aiming to develop high performance materials that can sustain the server environments. Attempts and efforts were made on maximizing the ultimate strength of the cement-based material besides the durability, which are the main important properties of the concrete based on design standpoint. These efforts were completed by producing a new class of portland cement-based material, which is known as Ultra-High Performance Concrete (UHPC). With this new technology, High-Performance Concrete (HPC) is no longer the strongest and most durable material properties compared to UHPC.

1.2 BACKGROUND

The development of UHPC has taken quite a few years due to its complexity. To start with, the development of UHPC can be outlined back to about the 1930s. During this time, Eugene Freyssinet understood that if one were to apply pressure to concrete during the setting process, the result would be to increase the compressive strength of material. Later in the 1960s, applying pressure to the concrete was used in combination with a curing regimen that included a heat source and a water-saturated environment. In 1970s, compressive strength of 230 MPa (33 ksi) was achieved by using a vacuum mixing procedure [2]. Also, a 510 MPa (74 ksi) was obtained by using a pressure of 50 MPa (7.25 ksi) and extremely high temperature (200°C) [3].

UHPC was first recognized as Reactive Powder Concrete (RPC) due the fact that it contained only very fine materials [4]. Ultra-High Performance concrete can be defined as a cement-based composite with a very high compressive strength of approximately 150 MPa (21.75 ksi) and high tensile strength 6.2 to 11.7 MPa (0.90 to 1.7 ksi) compared to the conventional concrete due to the existence of the short discontinuous steel fibers [5]. If steel fibers are added to the paste in order to decrease brittleness and increase energy absorption capacity, the term Ultra-High Performance Fiber Reinforced concrete, (UHP-FRC) is used in the literature [4 – 7].

The major principle of developing UHPC is to create a homogeneous and dense matrix. One of the main differences between UHPC and the conventional concrete is the removal of coarse aggregate particles to eliminate the effect of the interfacial transition zone between cement paste and aggregate, which contains the micro-cracking [4, 8]. Therefore, aggregate materials used with UHPC are sand (not larger than 600 – μm) and quartz flour. Another requirement to produce strong paste is the use of large amount of cementitious materials [9 – 11]. Pozzolanic materials replacement, especially silica fume (SF) are required for the high strength and durability due to the pozzplanic reaction, which produce more calcium silicate hydrates (C-S-H) and accompanied with less voids. Several researches reported that the replacement ratio of portland cement by silica fume is up to 25% [8, 12].

The low water to cementitious materials ratio (w/cm) is a must to obtain high strength and durability. With the new generation of HRWR of polycarboxylate base, one can reduce the w/cm up to 0.14 or less [8]. Because of the large dosages of superplasticizer, UHPC mixes may take a while to set up. Therefore, to combat this potential problem, an accelerator may be employed to aid reduce the set time. Because of the high binder content, the UHPC tends to have a brittle failure in an explosive manner and a tendency toward micro cracking, which are related to the high autogenous shrinkage. That is why steel fibers are added to the mixture design [13 – 15].

Steel fibers are the only non-liquid or granular components in the mixture of UHPC. Even though fibers are not important for achieving a homogenous mixture, they are influential on the concrete in macro and micro level. They improve the tensile and flexural strengths of concrete. Normally, steel fibers are cylindrical in shape. Each fiber can have hooked or straight ends and experience the same principal modes of failure such as pullout and rupture [17]. In general, fiber content influences the ductility of UHPC. As fiber content increases in UHPC mixture, there is an increase in ductility. Typically, the diameter of most fibers is approximately 0.15 to 0.2 mm (0.006 to 0.008 in) and 13 mm long (0.5 inches). When they are added to the UHPC, the length of the fiber is usually the biggest concern. Fiber length can not only influence how effective the fiber is at holding tension cracks together, but the workability of a fresh concrete mixture as well. In general, when short fibers are added, the mix is more workable.

1.3 MOTIVATION

UHPC possesses superior properties when compared to Conventional concrete. Higher strength allows for smaller section and longer spans. UHPC also has rheological properties similar to Self-consolidated Concrete (SCC). Most UHPC mixture require rare and expensive constituent materials. Therefore, developing UHPC with locally available materials is the main motivation for conducting this research to increase the use for different applications. UHPC is a new material and there is a lack of information and design codes for members cast with UHPC. The conducted research focuses on advancing our knowledge of UHPC, especially the mixture proportions so that it can be easier for individuals and ready-mix companies to produce UHPC with local materials and already existed techniques.

1.4 RESEARCH OBJECTIVES

The objectives of the research project are as follows:

1. To develop UHPC by using locally available materials in Arkansas and without using of superior approaches.
2. Investigate the effect of supplementary cementitious materials (e.g. silica fume; fly ash) on compressive strength.
3. Examine different curing regimen (e.g. moist curing, heat curing) on UHPC strength.
4. Inspect the effect of different steel fibers addition by fracture volume on compressive strength and modulus of elasticity of UHPC mixtures.
5. Develop modulus of elasticity equation for UHPC. The equation is developed based on the all possible date that collected from literature. The equation is also compared with research data that are conducted in this research.

6. Examine the effect of two different mixers on UHPC compressive strength.
7. Investigate the cost of UHPC mixtures. This is conducted by a comprehensive study that considered different materials, several curing regimens.
8. Develop economical UHPC mixtures and the cost has been compared with most available commercial UHPC mixtures.

1.5 DISSERTATION ORGANIZATION

This dissertation is a compilation of three articles which were written to support the main idea of the research. This dissertation is organized in five chapters. Chapter 2 describes the development of Ultra-High Performance Concrete with locally available materials. Chapter 3 evaluates the modulus of elasticity of UHPC and develops MOE equation based on the data collected from literature. Chapter 4 focuses on the cost of UHPC mixtures and develops economical mixtures as compared with the commercially available UHPC products. Finally, conclusions, contributions of the research, and recommendations for further research in this area are presented in Chapter 5.

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CHAPTER 2: DEVELOPMENT OF ULTRA-HIGH-PERFORMANCE CONCRETE WITH LOCALLY AVAILABLE MATERIALS

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Abstract:

Ultra-High Performance Concrete (UHPC) is an advanced type of concrete that can enhance the durability and resilience of concrete structures. The use of local materials is a fundamental step to save materials and energy and reduce the cost of concrete. In this study, the effect of sand gradation, binder type and content, and curing regimens on concrete's compressive strength were examined. Results indicated a 90-day strength of 155 MPa was achieved with a replacement of 5% of silica fume without heat curing. Curing regime of 2 days at 60°C followed by 3 days at 90°C resulted in the highest strength.

KEYWORDS: Ultra-High Performance Concrete; silica fume; fly ash; compressive strength

2.1 INTRODUCTION

The development in mineral admixtures (e.g., silica fume and fly ash) and chemical admixtures [e.g., high-range water reducer (HRWRA)] leads to the introduction of several types of high-quality concrete. These types of concrete typically include high-strength concrete, high-performance concrete, and fiber-reinforced concrete. The further advancement in concrete technology has resulted in a new type of concrete called Ultra-High Performance Concrete (UHPC). UHPC is a cement-based composite with a compressive strength of 150 MPa and tensile strength of 6.2 MPa [1 – 3]. The age at which UHPC achieves these strengths has not been specified. The benefits of using UHPC in the design of precast, prestressed concrete structures have been confirmed in a number of projects in United States, Germany, Canada, France, and Australia. In the United States, UHPC is mainly used for bridge applications that include precast, prestressed bridge girders, precast waffle panels, and as a jointing material between precast concrete deck panels and girders [4 – 7].

In 1990s, UHPC was first known as reactive-powder concrete since it contained only very fine materials [8]. A typical UHPC mixture proportion consists of cement, supplementary cementitious materials (e.g., silica fume, fly ash, and slag cement), fine sand, quartz or glass powder, HRWR, steel fiber, and a low water content [1,9,10]. Coarse aggregate is excluded in many UHPC mixture proportion. This exclusion reduces the micro-cracks that are present in the coarse aggregate and in the interfacial transition zone between the paste matrix and coarse aggregate. These micro-cracks can increase the permeability of concrete [11]. In addition, when the concrete resists external loads, mechanical cracks tend to occur at the existing micro-cracks and propagate through the paste matrix and coarse aggregate which can lead to failure of the concrete. Therefore, the exclusion of coarse aggregate is necessary to improve the strength and durability of UHPC.

In terms of placement procedures, UHPC can reduce the time and the labor related to placement. UHPC tends to exhibit rheological behaviors similar to self-consolidating concrete. Therefore, the casting efforts are reduced, but additional form preparation is possibly needed [12]. The use of HRWR is one of main contributing factors to the high workability of UHPC while a low water content is necessary to achieve a high compressive strength [2,9,11]. Researchers have found that the water to binder ratio (w/b) of UHPC can be decreased to 0.12 [13]; where binder is the total content of cement and supplementary cementitious materials. However, the required water to cement (w/c) ratio for full hydration of cement is 0.32 [11]. For conventional concrete with a typical w/c ratio of 0.4, the degree of hydration increases from 80% to 100%. For UHPC, the water content is so low that all the cement particles are not hydrated [14].

UHPC is available as a premix in many markets [5]. The premix requires special attention during mixing, casting, curing and testing. For example, a high-shear mixer is typically necessary for the mixing UHPC and a heat-curing technique can be used to achieve a high compressive strength. Ductal® is a marketed form of UHPC that was developed by the participation of three companies: Lafarge, Rhodia, and Bouygues. Quartz powder with a diameter of 10 μm is used in the UHPC premix as a micro-filler material, and the premix also contains high tensile strength fibers (tensile strength of 2600 MPa) [13,15]. The use of these materials increases the cost of the premix. Commercially available UHPC is about 20 times more expensive than conventional concrete, which is about $\$100/yd^3$. This UHPC price includes the material costs of the proprietary blend and the fiber reinforcement, and the costs associated with the development and delivery of said material [15].

A potential solution to reduce the UHPC cost is to use a sand that has an average diameter of 150–600 μm or a natural sand as a filler material. However, the concrete's compressive strength can decrease when the diameter of the filler material increases. In this study, the authors investigate the effect of using a natural sand on the concrete's compressive strength. The use of a local sand not only reduces the cost of UHPC but also eliminates the time and labor necessary to produce the ultra-fine sand which has an average diameter less than 600 μm. The optimal use of supplementary cementitious materials, typically including silica fume and fly ash, additionally reduces the concrete cost. It is anticipated that UHPC can replace conventional concrete in various structural applications, including precast and cast-in-place concrete applications, due to its improved structural durability and extended service life. Therefore, there is a need to develop UHPC using local materials, which enables engineers to use UHPC when necessary without significant increases in cost.

2.2 LITERATURE REVIEW

A number of studies have developed the mixture proportions and evaluated the mechanical properties of UHPC since 2000s. In the United States, the Federal Highway Administration is one of many organizations that have investigated the development and applications of UHPC [1,13,15,16]. In the literature, there are two major trends in the UHPC research. The first trend focuses on the enhanced UHPC mechanical properties, typically including compressive strength, tensile strength, shear strength, and durability related properties. These improved properties are achieved by optimizing the UHPC mixture proportion. The second trend concentrates on applications for UHPC and aims at promoting its use in the design and construction of concrete structures. In the current state-of-the-art, UHPC has shown unique advantages for long-span bridge applications [17]. The development of UHPC using local materials can create additional opportunities for the UHPC applications in building and underground structures. In the following paragraphs, the contribution of the constituent materials to the mechanical properties is discussed. This will lead to the development of simplified UHPC mixture proportions as presented in the experimental program.

Table 2-1 shows a typical mixture proportion of UHPC premix that is available [6,10,13]. A large amount of binder is necessary to produce UHPC with a minimum compressive strength of 150 MPa. For the mixture shown in **Table 2-1**, the binder accounts for almost 40% of the total mass of the mixture. Silica fume accounts for 25% of the binder, which could be as high as 30% of the binder according to Ma and Schneider [18]. The use of silica fume is required to achieve a high compressive strength and durability. Silica fume accelerates the pozzolanic reactions that produces additional calcium silicate hydrates (C-S-H) and fills the voids in the paste matrix [11]. However, the improved properties associated with the addition of silica fume do come with a price; in the current market, silica fume is 4 –7 times more expensive than Portland cement. Wang et al. [19] stated that a UHPC mixture with a minimum compressive strength of 138 MPa at 28 days and 150 MPa at 56 days can be produced with 10% of the binder replaced by silica fume. Likewise, El-Hadj Kadri et al. [20] concluded that the effect of silica fume on the concrete's compressive strength is minimal when used at a replacement rate greater than 10% of the binder. The concrete mixtures using silica fume at replacement rates of 20% and 30% had lower compressive strength when compared to the mixtures containing 10%. The effect of silica fume and any other pozzolanic materials can depend on the curing conditions. In this study, the authors determine the most effective silica fume content for developing UHPC using the locally available materials, which not only provides an adequate compressive strength but also minimizes the cost of UHPC. Ground quartz is another filler material that accounts for 8.4% of the total weight of the mixture shown in **Table 2-1**.

Table 2- 1– Typical UHPC mixture proportion [6,10,13].

Material	Amount (kg/m^3)	Percentage by weight	Average diameter (μm)
Binder (Portland cement and silica fume)	943	37.8	n/a
Portland cement	712	28.5	15
Silica fume	231	9.3	<10
Filler material (ground quartz and fine sand)	1,231	49.2	n/a
Ground quartz	211	8.4	10
Fine sand	1,020	40.8	150 to 600
Water	109	4.4	n/a
Superplasticizer	30.7	1.2	n/a
Accelerator	30	1.2	n/a
Steel fibers	156	6.2	200

(Note: n/a = not applicable).

Ground quartz has an average diameter slightly less than the diameter of portland cement, which enables this material to fill the possible voids between sand, unhydrated cement particles, and the hydration products which creates a denser paste matrix. A denser concrete matrix increases the compressive strength and decreases permeability. However, the use of ground quartz may not be necessary due to a substantial portion of unhydrated Portland cement which fills the voids and produces a dense paste matrix. Velez et al. [21] found that the stiffness of unhydrated cement particles is greater than the other components in the paste matrix. Therefore, the w/b can be decreased as long as there are enough hydration products to bind all concrete components into a solid matrix. This allows the quartz powder to be excluded from the mixture proportions for an additional reduction in the UHPC cost.

The size of the filler materials generally influences the compressive strength of UHPC. The Ductal® premix shown in **Table 2-1** uses fine sand (150 – 600 μm) to ensure the homogeneity of the concrete and improve the strength. Park et al. [22] evaluated the effect of sand gradation on the concrete's compressive strength. The first and second sand type had an average grain size of 300 – 500 μm and 170–300 μm, respectively. The experimental investigation showed that the mixture proportion in which the fine aggregate was composed of 70% of the 300 – 500 μm sand and 30% of the 170 – 300 μm produced the highest compressive strength. Gerlicher et al. [23] used sand that had grain sizes of 125 – 500 μm for the development of UHPC that had 28-day compressive strength of up to 188 MPa. However, Ma et al. [23] concluded that the grain sizes of sand had no significant effect on the concrete's compressive strength. They used two types of sand that had different grain sizes to develop non-fiber reinforced, self-compacting UHPC. The fine sand had grain sizes of 300 – 800 μm, and the coarse sand has grain sizes of 2 – 5 mm. The 28-day compressive strengths ranged from 150 to 165 MPa with water curing at 20°C and approximately 190 MPa with heat treatment at 90°C.

A HRWRA is necessary for UHPC to achieve the desired workability, but the dosage and effects of the HWRWRA can vary. Gerlicher et al. [23] determined that 35 kg/m3 of superplasticizer is suitable to produce a slump flow of 360 mm. This amount of HRWR is slightly greater than the amount used in the Ductal® premix, which is 30.7 kg/m^3 as presented in **Table 2-1**. However, the setting time of UHPC using large dosages of superplasticizer may be extended. In order to solve this potential problem, an accelerator may be employed to reduce the setting time. The accelerator disperses the cement particles in water that accelerates the reaction, decreasing the setting times of the concrete. According to Lafarge, an accelerator dosage of 30 kg/m^3 is recommended for UHPC when using a substantial amount of superplasticizer [6].

Depending on the composition of UHPC, failure can be explosive due to its high compressive strength and brittle nature. The use of steel fibers can eliminate this type of brittle failure [24 – 26]. Steel fibers also improve the flexural capacity and performance of UHPC. Different percentages (by volume) of steel fibers are used in UHPC, and this percentage generally ranges from 0 to 5% as reported by Kazemi et al. [27]. Also, the researchers recommended a fiber content of 3% in UHPC, which resulted in a compressive strength of 151 MPa and 172 MPa at 28 and 42 days of age, respectively. The incorporation of steel fibers also enhances the overall performance of UHPC, particularly in increasing the concrete's tensile strengths and decreasing autogenous shrinkage. Hegger et al. [28] concluded that steel fibers have minimal effect on the ultimate compressive strength but increase the concrete stiffness, which is represented by the concrete modulus of elasticity. The measured stress–strain curves indicated the concrete shows a linear-elastic behavior up to 90% of the ultimate strength. This property is particularly beneficial in reducing the deformation and deflection when the concrete structure resists external loads. For conventional concrete, the concrete stiffness nonlinearly decreases when the compressive stress is greater than 45% of the ultimate compressive strength.

Temperature and moisture are important factors when curing of UHPC. Graybeal [10,13], Habel et al. [29], and Prem et al. [30] concluded that the curing regime influences the mechanical properties of UHPC. For example, a heat-curing regime can increase the early age compressive strength and enhance the ultimate compressive strength. A typical curing regime of UHPC consists of two stages. In the first stage, the concrete is placed in a suitable temperature while avoiding moisture loss until final set. In the second stage, the curing temperature may increase to accelerate compressive strength gain [13]. In the current practice, different curing regimes are implemented on the marketed premix products, including (1) 96 h at 90°C with a relative humidity of 95%, (2) 48 h at 90°C with a relative humidity of 95%, and (3) moist curing (e.g., lab environment) [9,28]. Heinz and Ludwig [31] showed that a curing temperature between 65°C and 180°C can produce a compressive strength of 280 MPa at 28 days of age. At a curing temperature of 20 C, the concrete can achieve compressive strengths of 178 – 189 MPa. In addition, these compressive strengths are achievable at 48 h of age when using heat curing. The researchers also found that the concrete that is cured at 90°C produces no danger of delayed ettringite formation.

In summary, a number of UHPC mixtures have been proposed with various amounts and types of filler material, steel fibers, HRWR, and accelerator. For UHPC, filler material is a significant component that occupies approximately 50% by weight. The type of filler material directly affects the cost and compressive strength of UHPC. The use of local materials can reduce the cost and promote using UHPC in practice, but depending on the locality, using local materials may reduce strength. In this study, the researchers develop UHPC mixtures using locally available river sand as a filler material. The quantities of the constituent materials are based on the recommended values in the literature. The developed UHPC mixtures have a 90-day compressive strength of 150 MPa. The paper begins by the investigation of the effect of curing regimes on the concrete's compressive strength at different ages. The authors then present the experimental procedures and results of a number of UHPC mixtures. Finally, the authors discuss the research findings that lead to a new technique in developing UHPC using local materials.

2.3 EXPERIMENTAL INVESTIGATION

2.3.1 Materials

For this research program, the binder consists of portland cement (Type I), densified micro-silica (silica fume), and Class C fly ash. The properties of cement, silica fume and fly ash are presented in **Tables 2-2**, **2-3**, and **2-4**. Three gradations of the Arkansas River sand were used for the development of UHPC. Sand-1 had a natural gradation (**Figure 2-1a**) that was distributed from the No. 4 (4.75 mm) sieve to the No. 200 (75 μm) sieve. Sand-2 had a smaller particle size, which ranged from passing the No. 30 (600 μm) sieve and to being retained on that No. 50 (300 μm) sieve (**Figure 2-1b**). Another type of sand (Sand-3), which passed sieve No. 200 (75 μm), was used to evaluate the effect of curing regimens on the concrete's compressive strength (**Figure 2-1c**). The three types of sands are shown in **Figure 2-2**. The HRWR admixture was carboxylate-based, and the steel fibers had a diameter of 0.2 mm and a length of 12.7 mm. The steel fiber content was 3% by volume.

Table 2-2– Cement properties.

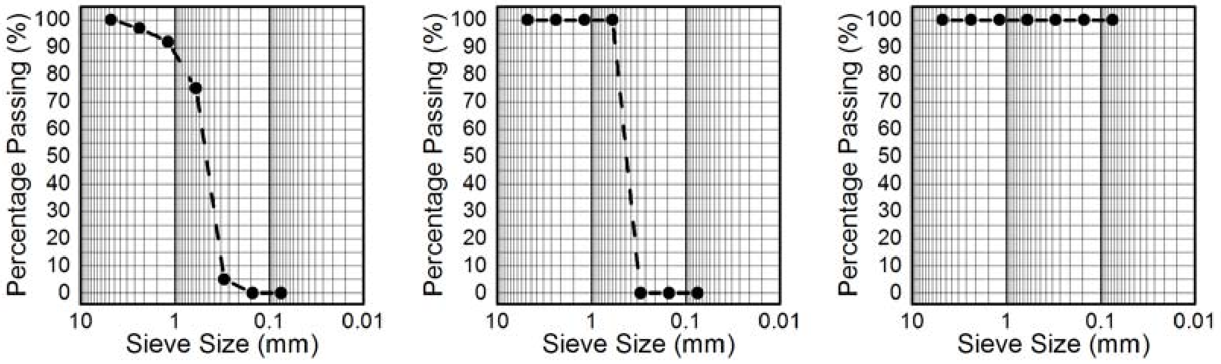
Item	Description
Chemical	
SiO_2	20.11%
Al_2O_3	5.07%
Fe_2O_3	3.80%
CaO	64.15%
MgO	0.98%
SO_3	3.23%
Loss on ignition	2.39%
Na_2O	0.18%
K_2O	0.56%
Insoluble Residue	0.40%
CO_2	1.09%
Limestone	2.80%
$CaCO_3$	88.23%
Potential compounds	
C_3S	55%
C_2S	14%
C_3A	7%
C_4AF	11%
$C_3S + 4.75\ C_3A$	88%
Physical	
Air content of mortar (volume)	8%
Fineness	4.5 m^2/g
Autoclave expansion	-0.01%
Mortar Bar Expansion	0.00%

Table 2-3 – Fly ash properties.

Item	Description
SiO_2	36.73%
Al_2O_3	21.49
Fe_2O_3	5.68%
CaO	22.70%
Na_2O	1.48%
K_2O	0.57%
MgO	4.30%
∑ Oxides	63.90%
∑ Alkalis	29.05%

Table 2-4 – Silica fume properties.

Item	Description
Chemical	
SiO_2	95.25%
SO_3	0.08%
CL^-	0.11%
Total Alkali	0.42%
Moisture Content	0.52%
Loss on Ignition	1.88%
pH	8.06%
Physical	
% retained on 45 µm sieve (wet sieved)	0.49%
Density (specific gravity)	2.24
Bulk Density (per ASTM)	696.71 kg/m^3
Specific Surface Area	24.49 m^2/g
Accelerated Pozzolanic Activity Index - with Portland Cement	124.44%



(a) **(b)** **(c)**

Figure 2-1. Gradation of sands used

Figure 2-2. **Three types of sand used in the experimental program**

2.3.2 Testing procedure

Cube specimens, 50 x 50 mm, were cast to measure the concrete's compressive strength at 1 day of age and at 7, 28, 56, and 90 days of age. The compression test was conducted according to ASTM C109/C109M [32]. The applied load rate was 1.0 MPa/s [10]. The concrete was mixed using a laboratory Hobart 19 L (20 quart) pan mixer. Cement, sand, silica fume, and/or fly ash were mixed for 10 min, and then water and HRWR admixture were added gradually. The mixing time was 15 – 20 mins for all mixtures due to the low w/b ratio and high binder content. The concrete was then placed in steel molds without vibration. The cubes were demolded after one day and then moist cured at of 21°C until testing. The flowchart shown in **Figure 2-3** summarizes the mixing procedures. The rheology of the UHPC mixtures was evaluated through the flowability of the fresh UHPC mixtures. The flow test was conducted according to ASTM C1437 [34] using a flow table test. This test is proposed for use with the mortar that presents plastic to flowable performance, and therefore, it is applicable for the fresh UHPC mixtures [15]. The results are presented in **Appendix 2A**.

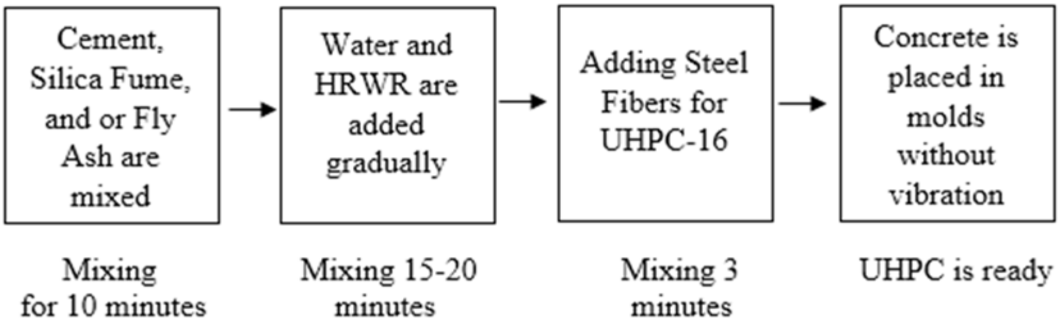


Figure 2-3. Flow charts for mixing procedure

Table 2-5 summarizes the mixture proportions. The content of binder, silica fume, fly ash, and sand were the variables in the development of the first 15 UHPC mixtures. Silica fume was used in different percentages (0, 5, 10, 15, and 20% by weight) of the total binder content to study the effect of silica fume on concrete's compressive strength. This wide range of silica fume replacement would determine the most effective silica fume content for UHPC. The authors considered the maximum replacement to be 20% of the binder since most of UHPC mixture proportions stated the range to be from 20 to 25% by the weight of the binder [18]. The fly ash content was 0, 20, 30, and 40% by weight of the total binder content. The maximum replacement was limited to 40% since high volume fly ash requires activated alkaline solution. The w/b was constant for all mixtures to reduce the number of concrete mixtures in the testing matrix [33].

Table 2-5 – Mixture proportions.

Mixture	Binder (kg/m^3)	*w/b*	Silica fume (%)	Fly ash (%)	Steel fiber (%)	HRWRA kg/m^3	Sand	Curing regimes
UHPC-1	890	0.2	0	0	0	30.2	Sand-1	A
UHPC-2	890	0.2	0	0	0	30.2	Sand-2	A
UHPC-3	890	0.2	5	0	0	30.2	Sand-1	A
UHPC-4	890	0.2	10	0	0	30.2	Sand-1	A
UHPC-5	890	0.2	15	0	0	30.2	Sand-1	A
UHPC-6	890	0.2	20	0	0	30.2	Sand-1	A
UHPC-7	890	0.2	5	0	0	30.2	Sand-2	A
UHPC-8	890	0.2	0	20	0	30.2	Sand-1	A
UHPC-9	890	0.2	0	30	0	30.2	Sand-1	A
UHPC-10	890	0.2	0	40	0	30.2	Sand-1	A
UHPC-11	890	0.2	5	20	0	30.2	Sand-1	A
UHPC-12	1,009	0.2	0	0	0	34.2	Sand-1	A
UHPC-13	1,009	0.2	0	0	0	34.2	Sand-2	A
UHPC-14	1,009	0.2	5	0	0	34.2	Sand-2	A
UHPC-15	1,009	0.2	5	20	0	34.2	Sand-2	A
UHPC-16-I	1,363	0.2	21	0	0	46.2	Sand-3	A, B, C, and D
UHPC-16-II	1,363	0.2	21	0	3	46.2	Sand-3	A, B, C, and D

Also shown in **Table 2-5** are the curing regimens. Curing regimen A was used for all of UHPC mixtures. This curing regimen consisted of moist curing at 21ºC until the day of testing. Mixtures UHPC-16 I and II were subjected to three additional curing regimens B, C, and D. For regimen B, the specimens were cured at 90ºC and 100% RH for the first three days after casting and then tested. Curing regimen C consisted of heat curing at 100% RH for the first 5 days after curing. The first two days was at 60ºC and the last three days at 90ºC. For the final curing regimen, D, the specimens were cured at 21ºC and 100% RH for the first 7 days after casting and were then subjected to 3 days at 90ºC at 100% RH. The graphical cycles for the curing regimens are illustrated in **Figure 2-4**.

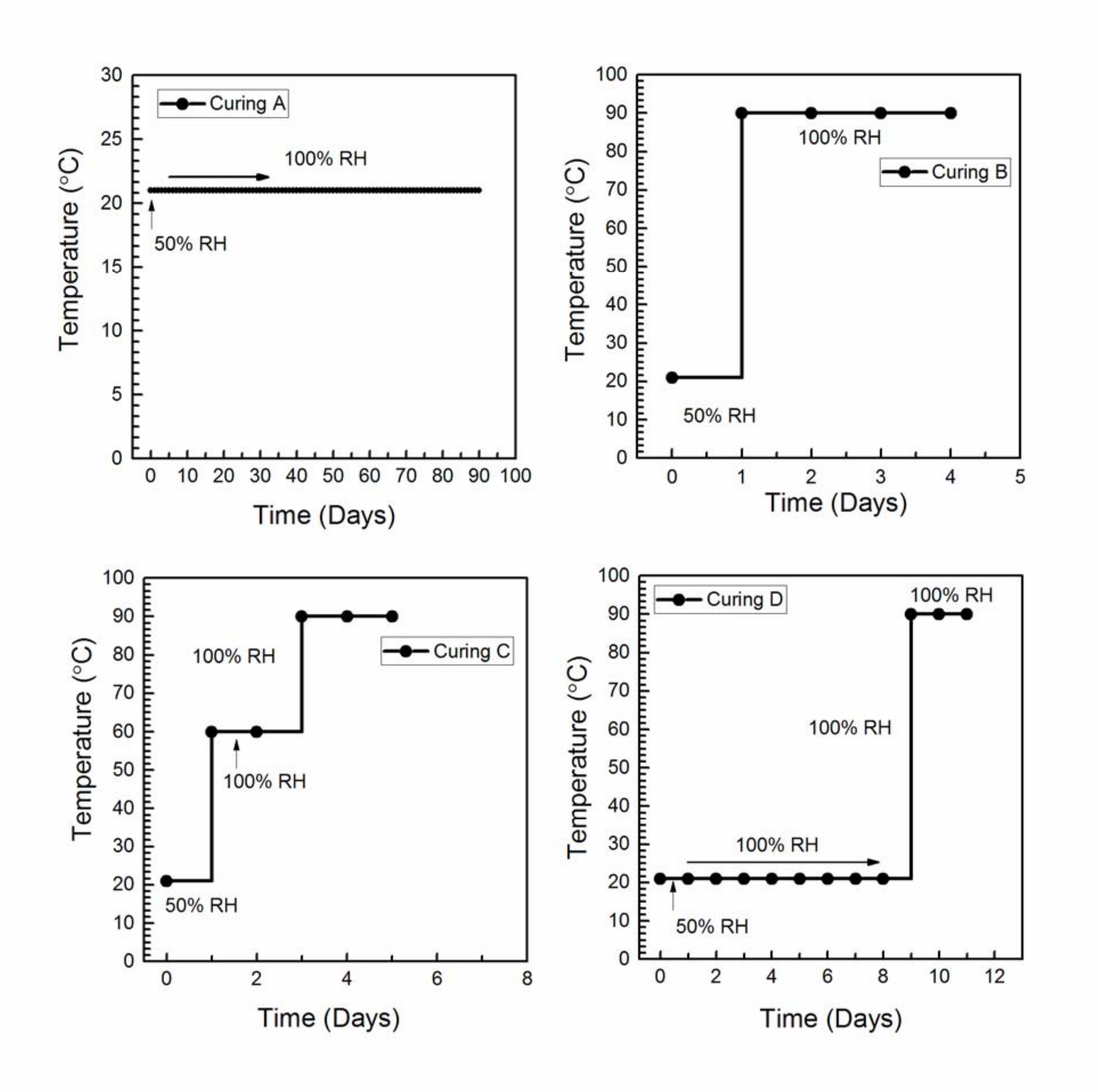


Figure 2-4. **The graphical cycles of curing regimens**

(Note: RH = relative humidity)

As previously noted, mixtures UHPC-16-I and II were developed to examine the four different curing regimens. Another variable examined in these two mixtures was the addition of steel fibers. These two mixtures also contained more binder and Sand-3, which had the smallest particle size among the three types of sand used in this study. In addition to cube specimens, a number of cylinders, 75 x 150 mm, were cast to evaluate the UHPC 16's compressive strength. The testing procedure of the cylinders was similar to that of the cube specimens [35]. After demolding the samples at 1 day of age, the cylinders were placed into an end-grinder to remove any surface irregularities and to ensure a plane surface for compressive strength testing. **Figure 2-5** shows the end-grinder and the water bath used for the heat curing.

Figure 2-5. End-grinder and water bath used for heat curing

2.4 EXPERIMENTAL RESULTS AND DISCUSSION

The compressive strengths for mixtures UHPC-1 to UHPC-15 are summarized in **Table 2-6**. Each compressive strength value presented in the table is an average of 3 samples. The compressive strengths at 1, 7, 28, 56, and 90 days of age are summarized in **Appendix 2B**. Since some of the mixtures contained supplementary cementitious materials, the compressive strength was measured up to 90 days of age. For the majority of the mixtures, the increase in strength from 56 to 90 days of age was minimal. The average increase is approximately 7%. Therefore, it is expected that the 90-day compressive strength represents the ultimate compressive strength of the UHPC mixtures.

Table 2-6 – Compressive strengths of the cube specimens at different ages.

Mixture	Concrete's compressive strength (MPa)					Standard deviation of 90-day strength
	1 day	7 days	28 days	56 days	90 days	
UHPC-1	59.0	95.7	106.3	108.8	114.1	1.0
UHPC-2	70.7	97.4	113.2	113.8	118.1	2.2
UHPC-3	73.2	105.7	117.2	120.1	125.4	0.9
UHPC-4	75.7	102.6	118.6	127.4	127.6	1.0
UHPC-5	70.5	96.8	118.0	120.1	120.9	1.5
UHPC-6	62.1	95.9	111.0	117.2	118.6	0.7
UHPC-7	77.8	106.1	116.6	124.1	126.2	0.9
UHPC-8	53.7	99.2	109.9	110.3	117.5	1.6
UHPC-9	24.6	101.2	114.8	117.2	119.3	1.4
UHPC-10	4.1	75.8	102.6	110.9	119.1	2.2
UHPC-11	52.8	92.8	112.8	113.8	119.7	2.3
UHPC-12	72.8	102.8	113.8	126.2	139.3	1.7
UHPC-13	73.2	102.3	115.2	129.3	149.7	1.8
UHPC-14	80.1	102.8	115.4	129.0	155.2	1.8
UHPC-15	53.1	101.5	114.5	131.7	152.1	5.6

Figure 2-6 presents the effect of silica fume on concrete's compressive strengths. This figure includes the test results of UHPC-1 (0% of silica fume), UHPC-3 (5% of silica fume), UHPC-4 (10% of silica fume), UHPC-5 (15% of silica fume), and UHPC-6 (20% of silica fume). All of

these mixtures contained Sand-1; therefore, the comparison is relevant. In general, the use of silica fume increased the strength at all ages, regardless of the replacement rate. Mixture UHPC-4 had the greatest compressive strength at 1 day, and at 28, 56, and 90 days. The 90-day compressive strength of UHPC-4 was higher than the strengths of UHPC-1, UHPC-3, UHPC-5, and UHPC-6 by 12, 2, 6, and 8%, respectively. However, the compressive strength of UHPC-4 was slightly greater than the strength of UHPC- 3 at 1, 28, 56, and 90 days. Since results showed a slight difference in the compressive strength of mixtures containing 5% or 10% silica fume, a silica fume content of 5% was chosen for this research program. By choosing 5%, the overall cost of the UHPC would be less when compared to mixtures containing more silica fume; the cost of silica fume where the research was being conducted is in the range of $700–$800 per ton. **Figure 2-6** also shows the necessity of using silica fume for UHPC mixture proportion. The compressive strengths of UHPC-1 (the control mixture containing no silica fume) are lower than the strengths of UHPC-3, UHPC-4, and UHPC-5 at all ages. However, the use of an excessive amount of silica fume also had a negative effect on the concrete's compressive strengths. The compressive strengths of UHPC-6 were greater than UHPC-1 but lower than the other mixtures. Several researchers have shown an increase in compressive strength as silica fume content increases [36,37]. Curing conditions are a possible factor contributing to this deviation when compared to the other studies in the literature. The rate of pozzolanic reactions in a moist-curing condition is slower than that in a heat-curing condition. Since all of the mixtures in this series had a low w/b and were cured at 21°C and 100% RH until the day of testing, a portion of silica fume remains unhydrated when large percentages of silica fume are used. When a large content of silica fume is used, the silica fume cannot react with all available calcium hydroxide.

Therefore, the extra portion of silica fume serves as a filler material without contribution to pozzolanic reactions [38,39].

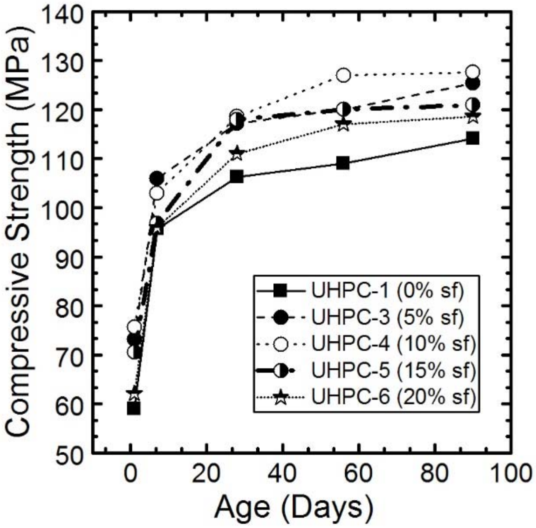


Figure 2-6. **Effect of silica fume on the concrete's compressive strengths at different ages**

(Note: sf = silica fume)

Figure 2-7 shows the effect of using different sand gradations on the concrete's compressive strengths. This figure includes the results of UHPC-1 (Sand-1, 0% of silica fume), UHPC-2 (Sand-2, 0% of silica fume), UHPC-3 (Sand-1, 5% of silica fume), and UHPC-7 (Sand-2, 5% of silica fume). When comparing the results of UHPC-1 and UHPC-2, when a finer sand was used (Sand-2), concrete compressive strength was increased, particularly at the later ages. For UHPC-2, the maximum-particle size in the paste matrix is 600 μm, which is 8 times less than that of UHPC-1. The paste matrix of UHPC-2 is denser than that of UHPC-1 that leads to greater compressive strengths [22,23,39]. However, the sand had minimal effect on the compressive strengths if the mixtures contained 5% of silica fume. The effect is apparent in the results of mixtures UHPC-3 and UHPC-7. This observation is due to silica fume possibly filling the voids caused by using larger sand particles (Sand-1) and making the paste denser. The 90-day compressive strengths of these two mixtures were similar (125.4 and 126.2 MPa). For the four mixtures, the difference in the maximum-particle sizes of the sand is insignificant.

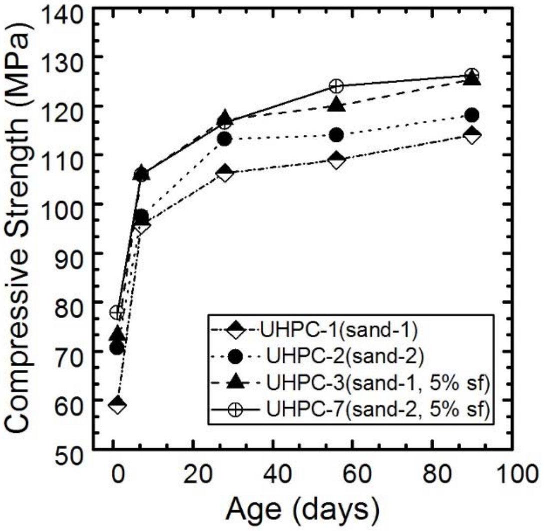


Figure 2-7. **Effect of the Sand-1 and Sand-2 on the concrete's compressive strengths**

(Note: sf = silica fume)

Shown in **Figure 2-8** are the compressive-strength results for the mixtures containing Class C fly ash. The mixtures presented in the **Figure 2-8** are UHPC-1 (0% of fly ash), UHPC-8 (20% of fly ash), UHPC-9 (30% of fly ash), UHPC-10 (40% of fly ash), and UHPC-11 (20% of fly ash and 5% of silica fume). As shown in **Figure 2-8**, when the fly ash content is greater than 20%, the compressive strength is less than that of mixtures with a lower fly ash content. When compared to UHPC-1, the 1-day strengths of UHPC-8, UHPC-9, UHPC-10, and UHPC-11 decreased by 9%, 58%, 93%, and 11%, respectively. The use of fly ash decreases the heat generated in the hydration process at early ages and consequently decreases the strength. At later ages, the concrete mixtures that contain fly ash experience a significant gain in compressive strength. The pozzolanic reactions of fly ash with calcium hydroxide additionally generate C-S-H that strengthens the paste matrix. At 28 days of age, the compressive strengths of UHPC-8 and UHPC-9 are 3% and 8% greater while the strength of UHPC-10 is slightly less than the strength of UHPC-1. As expected, the 90-day compressive strengths of UHPC-8, UHPC-9, and UHPC-10 were 3%, 5%, and 5% greater than the strength of UHPC-1.

As shown in **Figure 2-8**, a fly ash content of 30% (UHPC-9) produced the highest compressive strengths at 7, 28, 56 and 90 days of age. The use of UHPC-9 mixture proportion would be suitable for the concrete structures in which the 1-day compressive strength is not a concern or where heat curing was an option. The 1-day compressive strength of UHPC-8 was 9% lower when compared to UHPC-1 (the control mixture), but the 90-day compressive strength was 3% greater. In addition, when comparing mixture UHPC-8 (20% fly ash) and mixture UHPC-11 (20% fly ash, and 5% silica fume), the additional silica fume of 5% in UHPC-11 had minimal effect on the concrete’s compressive strength even though the results of UHPC-3 indicated the positive effect of silica fume. The 20% content of fly ash was sufficient to achieve the pozzolanic reaction without the need of silica fume. The compressive strengths of UHPC-11 were similar to those of UHPC-8 (**Table 2-6**). The simultaneous use of fly ash and silica fume in UHPC mixture proportion can lessen the influence of each component. Under the same curing condition, the generated calcium hydroxide of UHPC-11 and UHPC-8 is expected to be similar since these mixtures had the same water content. Therefore, the amount of C-S-H generated from the reactions with fly ash in UHPC-8 or with both fly ash and silica fume in UHPC-11 is the same, which is responsible for the similar concrete strengths.

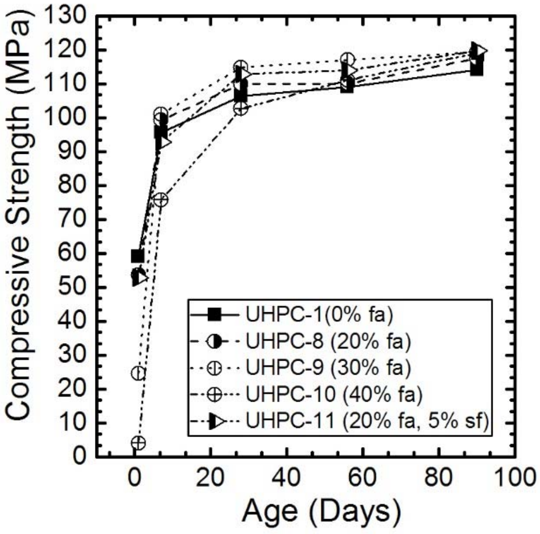


Figure 2-8. **Effect of fly ash on the concrete's compressive strengths**

(Note: sf = silica fume, fa = fly ash)

Shown in **Figure 2-9** is the relationship between the binder content and the concrete's compressive strength. This figure includes the results of UHPC-1 (Sand-1, 890 kg of binder, and 0% of silica fume), UHPC-12 (Sand-1, 1009 kg of binder, and 0% of silica fume), UHPC- 2 (Sand-2, 890 kg of binder, and 0% of silica fume), UHPC-13 (Sand- 2, 1009 kg of binder, and 0% of silica fume), UHPC-7 (Sand-2, 890 kg of binder, and 5% of silica fume), and UHPC-14 (Sand-2, 1009 kg of binder, and 5% of silica fume). As shown in the figure, concrete's compressive strength increases as the total binder content increases regardless of the silica fume content and the type of sand. The increase in binder content produces more C-S-H, and therefore the paste matrix is stronger and can resist greater compressive stresses. In addition, with the low w/b of 0.2, not all cement particles were hydrated; and therefore, the unhydrated cement particles increased the packing factor. For the concrete mixtures using Sand-1, the compressive strengths of UHPC-12 at 1 day and at 7, 28, 56, 90 days were 23, 7, 7, 16, and 22% greater than those of UHPC-1, respectively. Once again, the only difference between the two mixtures was the binder content. For the concrete mixtures using Sand-2 and with or without silica fume, as binder content increased, the compressive strength also increased. UHPC-14 achieved the highest 90-day compressive strength due to the use of a high binder content, Sand-2, and 5% of silica fume.

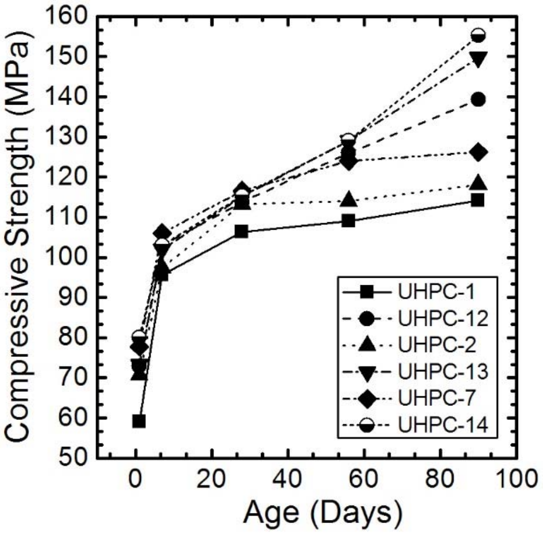


Figure 2-9. **Effect of binder content on the concrete's compressive strengths at different ages**

When compared to UHPC-14, UHPC-15 additionally contained 20% fly ash. The 1-day compressive strength of UHPC-15 was 34% less than the strength of UHPC-14 (**Table 2-6**). This difference is attributed to effect of fly ash delaying the strength development at early ages. The 90-day compressive strength of UHPC-15 was similar to UHPC-14 (152.1 vs 155.2 MPa). Similar to UHPC-9, the mixture UHPC-15 is suitable for the concrete structures in which the 1-day strength is not a concern but where a 90-day compressive strength in excess of 150 MPa is necessary.

Shown in **Table 2-7** are compressive strengths of UHPC-16-I and UHPC-16-II. The only difference between the two mixtures is the addition of steel fiber (3% by volume) in mixture UHPC-16-II. The compressive strength was measured once the curing regimen was completed. Each compressive strength result is an average of three samples. The four curing regimens (A, B, C, and D) were discussed in Section 3.2 and are also shown in **Table 2-7**. Also shown in **Table 2-7** are the differences in the compressive strength using cube specimens or cylinders for each mixture.

Table 2- 7 – Compressive strengths of UHPC-16-I and UHPC-16-II.

Curing regimen	Sample type	Compressive Strength (MPa)	
		UHPC-16-I (no steel fibers)	UHPC-16-II (3% of steel fibers)
A	Cube	125.9	137.0
	Cylinder	117.4	122.3
B	Cube	159.7	170.6
	Cylinder	145.9	152.6
C	Cube	165.8	179.0
	Cylinder	151.2	157.3
D	Cube	163.9	177.0
	Cylinder	149.0	156.4

(Note: curing regimen A is up to 28 days of age)

Shown in **Figure 2-10** is the influence of the curing regimens and steel fiber content on the compressive strengths. For the concrete without steel fibers (UHPC-16-I), curing regimen A resulted in the lowest compressive strengths (e.g., cube samples) while curing regimen C yielded the highest compressive strengths. This difference is attributed to the higher rate of the pozzolanic reactions which accelerates the C-S-H formation during the heat-curing regimen. The concrete's compressive strengths with the curing regimens B, C, and D were 27%, 32%, and 30% greater than the strength of curing regimen A. Based on the test results of UHPC-16-II mixtures, the use of 3% of steel fibers increased the concrete's compressive strengths for all curing regimens. The average increase in compressive strength was 8% for cube samples. However, the average increase for cylinders was 4%. This increase is possible because the steel fibers effectively delay the formation and propagation of cracks when the concrete is subjected to tensile or compressive stresses, and it prevents a sudden explosive failure of the cubes or cylinders as illustrated in **Figure 2-11**. Based on the test results of mixtures UHPC-16-I and UHPC-16-II, the use of steel fibers is unnecessary from only a compressive-strength standpoint. Fibers are necessary when increased ductility or increased tensile strength is needed.

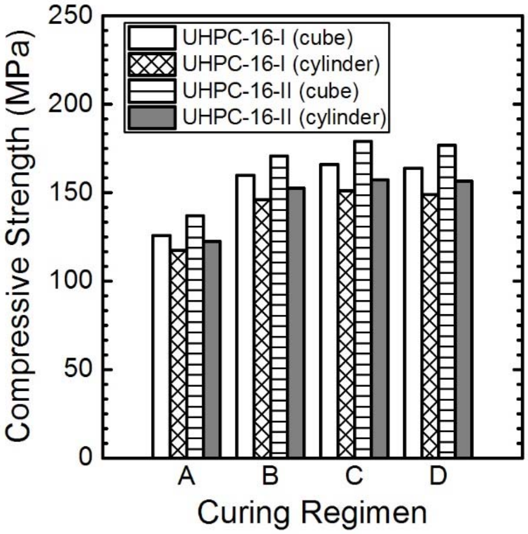


Figure 2-10. **Effect of curing regimes and steel fibers on the concrete's compressive strengths**

Figure 2-11. **Failure of cubes and cylinders with and without steel fibers**

The compressive strength data illustrated in **Figure 2-10** also indicates that the strength of cube specimens was greater than cylindrical samples. The compressive strength of the cylindrical specimens of UHPC-16-I were 93%, 91%, 91%, and 91% of the same cube specimens for curing regimes A, B, C, and D, respectively. These values were 89%, 89%, 88%, and 88% for UHPC-16-II. In average, the compressive-strength ratio of the cylindrical samples to cube samples for all mixtures and all curing regimes was 0.9. Similar ratios were found by Kazemi et al. [27] and

Graybeal [40]. Neville [41] reported a ratio of 0.86 for the concrete with a compressive strength in a range of 52 to 99 MPa, and the ratio tends to increase for higher concrete strength.

2.5 CONCLUSION

Based on the results of this experimental investigation, the following conclusions are drawn:

1. It is possible to develop UHPC mixtures containing locally available materials. A 90-day compressive strength of 155 MPa was obtained with a total binder of 1,009 kg/m^3, 5% of silica fume, and Sand-1. For this mixture, the replacement of 20% fly ash had minimal effect on the 90-day compressive strength.
2. The use of finer sand increases the compressive strength when compared to natural gradation sand. However, this effect is minimal when silica fume is incorporated.
3. The use of more than 10% of silica fume had minimal effects on the compressive strength. The concrete mixtures containing 5% and 10% of silica fume had similar 90-day compressive strengths.
4. Regardless of the silica fume content and the types of sand, the compressive strength increases as the binder content increases. A binder content of 1,009 kg/m^3 is recommended to achieve a minimum compressive strength of 150 MPa at 90 days of age.
5. A fly ash content of more than 20% decreased the concrete's compressive strengths at early ages but increased the strengths at later ages. A fly ash content of 30% produced the highest 90-day compressive strength, while a content of 20% had minimal effect on the strengths at all ages.
6. The use of 3% by volume of steel fibers increased the compressive strength by 4% and 8% based on the test results of cylindrical and cube samples, respectively.

7. The curing regimens influenced concrete’s compressive strength. Curing regime C, which was 2 days at 60°C followed by 3 days at 90°C, resulted in the highest compressive strengths.
8. As with conventional concrete, specimen size effects compressive strength. The compressive strength of cube specimens was approximately 11% greater than the compressive strength of cylindrical specimens cast with the same mixture.

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APPENDIX 2A

The flow of concrete is calculated using Eq. 2A1. The initial and final diameters measured in the flow tests are presented in Table A1.

$$Flow = \left(\frac{D_f - D_i}{D_i} \right) \times 100 \qquad \text{(Eq. 2A-1)}$$

where D_i and D_f are the initial and final diameters in the flow test, respectively.

Table2A-1 – Measured flow of UHPC mixtures.

Mixture	Initial Diameter D_i (mm)	Final Diameter D_f (mm)	Flow (%)
UHPC-1	185	210	14
UHPC-2	175	195	11
UHPC-3	180	210	17
UHPC-4	180	200	11
UHPC-5	180	210	17
UHPC-6	175	190	9
UHPC-7	175	200	14
UHPC-8	190	215	13
UHPC-9	190	210	11
UHPC-10	195	220	13
UHPC-11	190	215	13
UHPC-12	190	215	13
UHPC-13	180	210	17
UHPC-14	180	200	11
UHPC-15	195	215	10
UHPC-16-I	170	190	12
UHPC-16-II	165	185	12

APPENDIX 2B

The measured concrete's compressive strengths of cube samples are summarized in Table B1 to B5.

Table 2B-1 – Concrete's compressive strength at 1 day of age with standard deviation.

UHPC Mixture	1-day compressive strength MPa				
	Sample 1	Sample 2	Sample 3	Average	Standard Deviation
UHPC-1	58.2	59.4	59.4	59.0	0.7
UHPC-2	72.4	70.5	69.2	70.7	1.6
UHPC-3	72.6	73.6	73.4	73.2	0.5
UHPC-4	74.3	76.1	76.7	75.7	1.2
UHPC-5	72.0	69.4	70.1	70.5	1.3
UHPC-6	59.0	63.1	64.2	62.1	2.7
UHPC-7	76.5	77.3	79.6	77.8	1.6
UHPC-8	52.1	54.0	55.0	53.7	1.5
UHPC-9	22.3	25.1	24.6	24.6	1.5
UHPC-10	5.5	4.3	2.5	4.1	1.5
UHPC-11	53.7	52.0	52.7	52.8	0.9
UHPC-12	71.5	73.8	73.1	72.8	1.2
UHPC-13	70.4	75.8	73.4	73.2	2.7
UHPC-14	83.5	81.1	75.7	80.1	4.0
UHPC-15	51.8	53.7	53.8	53.1	1.1

Table 2B- 2– Concrete's compressive strength at 7 days of age with standard deviation.

UHPC Mixture	7-day compressive strength MPa				
	Sample 1	Sample 2	Sample 3	Average	Standard Deviation
UHPC-1	96.4	95.6	95.1	95.7	0.7
UHPC-2	97.1	97.4	97.7	97.4	0.3
UHPC-3	104.7	105.0	107.4	105.7	1.5
UHPC-4	101.6	102.7	103.5	102.6	1.0
UHPC-5	97.5	96.4	96.5	96.8	0.6
UHPC-6	95.8	96.0	95.9	95.9	0.1
UHPC-7	102.4	105.5	110.4	106.1	4.0
UHPC-8	100.1	96.2	101.3	99.2	2.7
UHPC-9	101.6	99.7	102.3	101.2	1.3
UHPC-10	72.8	76.5	78.1	75.8	2.7
UHPC-11	92.8	94.4	91.2	92.8	1.6
UHPC-12	100.6	103.5	104.3	102.8	1.9
UHPC-13	101.7	102.0	103.2	102.3	0.8
UHPC-14	103.0	100.4	105.0	102.8	2.3
UHPC-15	100.3	102.4	101.8	101.5	1.1

Table 2B- 3 – Concrete’s compressive strength at 28 days of age with standard deviation.

UHPC Mixture	28-day compressive strength MPa				
	Sample 1	Sample 2	Sample 3	Average	Standard Deviation
UHPC-1	105.7	105.1	108.1	106.3	1.6
UHPC-2	114.1	112.8	112.7	113.2	0.8
UHPC-3	116.0	118.0	117.6	117.2	1.1
UHPC-4	116.5	119.0	120.3	118.6	1.9
UHPC-5	118.0	118.5	117.5	118.0	0.5
UHPC-6	110.5	112.1	110.4	111.0	1.0
UHPC-7	116.7	118.1	115.0	116.6	1.6
UHPC-8	110.0	109.4	110.3	109.9	0.5
UHPC-9	114.1	113.8	116.5	114.8	1.5
UHPC-10	103.0	101.8	103	102.6	0.7
UHPC-11	113.1	112.8	112.5	112.8	0.3
UHPC-12	114.0	115.1	112.3	113.8	1.4
UHPC-13	114.0	114.7	116.9	115.2	1.5
UHPC-14	115.0	115.0	116.2	115.4	0.7
UHPC-15	113.8	114.3	115.4	114.5	0.8

Table 2B- 4– Concrete’s compressive strength at 56 days of age with standard deviation.

UHPC Mixture	56-day compressive strength MPa				
	Sample 1	Sample 2	Sample 3	Average	Standard Deviation
UHPC-1	108.8	107.8	109.8	108.8	1.0
UHPC-2	113.8	113.2	114.4	113.8	0.6
UHPC-3	120.3	119.8	120.2	120.1	0.3
UHPC-4	128.0	126.9	127.3	127.4	0.6
UHPC-5	120.1	119.5	120.7	120.1	0.6
UHPC-6	117.3	118.1	116.2	117.2	1.0
UHPC-7	124.3	124.2	123.8	124.1	0.3
UHPC-8	110.1	110.4	110.4	110.3	0.2
UHPC-9	117.1	116.8	117.7	117.2	0.5
UHPC-10	109.6	111.0	112.1	110.9	1.3
UHPC-11	112.9	113.8	114.7	113.8	0.9
UHPC-12	126.8	127.0	124.8	126.2	1.2
UHPC-13	128.9	129.0	130.0	129.3	0.6
UHPC-14	129.0	128.5	129.5	129.0	0.5
UHPC-15	130.5	132.0	132.6	131.7	1.1

Table 2B- 5– Concrete's compressive strength at 90 days of age with standard deviation.

UHPC Mixture	90-day compressive strength MPa				
	Sample 1	Sample 2	Sample 3	Average	Standard Deviation
UHPC-1	115.2	113.6	113.5	114.1	1.0
UHPC-2	117.8	116.1	120.4	118.1	2.2
UHPC-3	126.2	124.4	125.6	125.4	0.9
UHPC-4	128.3	128.1	126.4	127.6	1.0
UHPC-5	120.3	119.8	122.6	120.9	1.5
UHPC-6	118.4	118.0	119.4	118.6	0.7
UHPC-7	127.1	125.4	126.1	126.2	0.9
UHPC-8	115.7	118.4	118.4	117.5	1.6
UHPC-9	117.8	119.5	120.6	119.3	1.4
UHPC-10	119.8	120.9	116.6	119.1	2.2
UHPC-11	121.8	120.0	117.3	119.7	2.3
UHPC-12	138.2	141.2	138.5	139.3	1.7
UHPC-13	148.9	151.8	148.4	149.7	1.8
UHPC-14	156.5	155.9	153.2	155.2	1.8
UHPC-15	156.0	154.6	145.7	152.1	5.6

CHAPTER 3: EVALUATION OF MODULUS OF ELASTICITY OF ULTRA-HIGH PERFORMANCE CONCRETE

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Abstract:

Modulus of elasticity (MOE) is a significant parameter in the design of concrete structures. The use of local materials for developing ultra-high performance concrete (UHPC) is beneficial in saving energy and reduce the concrete cost. However, this practice possibly reduces the MOE of UHPC. This study synthesized all relevant experimental data in the literature to propose a new equation for predicting the MOE at different ages. A number of UHPC mixtures were developed to verify the accuracy of the proposed equation. With an error of ±10%, the proposed equation provides a reasonable prediction for the UHPC mixtures containing local materials.

KEYWORDS: UHPC; fly ash; local material; compressive strength; modulus of elasticity

3.1 INTRODUCTION

Ultra-high performance concrete (UHPC) is a recent development in the concrete technology. UHPC is a highly durable cement-based composite with a high compressive and tensile strength [1]. The enhanced mechanical properties lead to the increased flexural resistance, shear strength, and durability for concrete structures. Currently, UHPC is used for several concrete structures, typically including precast/prestressed bridge girders, precast waffle panels for bridge decks, and as a jointing material between precast concrete deck panels and girders [2, 3]. In the United States, the use of UHPC for highway infrastructure has begun since 2001. The replacement of conventional concrete by UHPC also saves materials, decreases installation, and labor costs [4]. However, these advantages have been not widely recognized because of special requirements in terms of material components used to produce UHPC mixtures (e.g., fibers, fine aggregates, or cementitious materials) and the high cost of UHPC.

Ductal® is a marketed premix of UHPC in the United States. Quartz powder with a diameter of 10 μm and steel fibers with a tensile strength of 2,600 MPa are essential components of Ductal® UHPC mixtures. Fine sand, with a diameter of 150 – 600 μm, is used as a macro-filler component [3, 5]. Currently, the UHPC premix is about 20 times more expensive than conventional concrete due to the additional costs of proprietary blend and fiber reinforcement, and the costs associated with the development and delivery of said material [6]. The replacement of the fine sand with a natural-gradation sand or fly ash can reduce the UHPC cost and widen the applications of UHPC to building, under-ground, or mass-concrete structures. Natural-gradation sand that is available locally is about \$8 per ton, and fly ash is approximately \$15 – \$40 per ton. The replacement of filler materials additionally reduces the required time and labor necessary to produce the fine sand with an average diameter less than 600 μm. However, the use of natural-gradation sand or fly ash possibly affects the concrete stiffness, particularly on the compressive strength and MOE, because of changes in concrete microstructures.

In concrete structures, the modulus of elasticity is a necessary parameter in design. This parameter directly relates to the shortening of concrete components under compressive stress and due to creep and shrinkage. The concrete shortening causes the redistribution of internal stresses between columns, beams, or walls in reinforced concrete structures. Concrete shortening also affects prestress losses in prestressed members. Finally, MOE is necessary when estimating the deflection of members to ensure that serviceability requirements are met. MOE can be determined through laboratory testing, or most often it is estimated based on compressive strength. Regardless of a number of MOE equations were developed for normal-strength and high-strength concrete, it is necessary to develop a new MOE equation which is applicable for UHPC mixtures consisting of various material components.

The objective of this study is to propose a relationship between compressive strength and MOE of UHPC based on the data collected from the literature, and to evaluate the MOE of UHPC mixtures that use locally available materials as a filler material. The replacement of fine sand with natural-gradation sand or fly ash can minimize the UHPC cost, but possibly affect the concrete stiffness. Understanding the effect of these local materials on the behavior of UHPC is a preliminary step to widen the applications of UHPC to different types of concrete structures. It has been expected that the superior mechanical properties of UHPC can extend the service life of concrete structures with a minimal maintenance cost [3].

3.2 LITERATURE REVIEW

A number of equations have been proposed to estimate the MOE of concrete as summarized in **Table 3-1**. Since the measurement of the MOE requires specific expertise, a correlation between the MOE and compressive strength is developed to assist engineers with the design of concrete structures when the test data is not always available. The equation proposed by ACI Committee 318-14 [**7**] is widely used to estimate the MOE of concrete. However, test data indicates that this equation over-estimates the MOE of high-strength concrete [8]. When the concrete's compressive strength increases, the MOE also increases, but it is not in the same trend of normal-strength concrete. Therefore, the ACI Committee 363 [8] proposed a new equation to predict the MOE of high-strength concrete. It has been anticipated that a new equation is necessary for UHPC since the compressive strength of UHPC is significantly greater and the concrete components are different when comparing to high-strength concrete.

Table 3-1 lists typical MOE equations found in the literature since 2000s. For example, Graybeal [16] developed a new equation that is in a similar form with the ACI 318-14 equation based on the test data of four curing regimens: (1) steam at 90 ºC and 95% of relative humidity (RH), (2) untreated laboratory control conditions, (3) tempered steam at 60 ºC and 95% RH, and (4) delayed steam at 90 ºC and 95% RH. This equation was revised when additional data was used to derive the fitting curve [17]. In general, the accuracy of the proposed equations is dependent on the size of the collected or tested data. In this study, the authors make the best effort in collecting all relevant test data to derive a new MOE equation and conduct necessary tests to evaluate its accuracy.

Table 3-1 – Proposed equations of MOE.

Committee or Researcher	Equation	Note
ACI Committee 318-14 [7]	$E_c = 4,730\sqrt{f'_c}$	Normal Strength Concrete, $f'_c \leq$ 41.4 MPa and $1440 \leq \omega \leq 2480$ kg/m^3
ACI Committee 363 R-10 [8]	$E_c = 3,320\sqrt{f'_c} + 6900$	High Strength Concrete, $f'_c \leq$ 83 MPa
FIP-CEB [9]	$E_c = 21,500\alpha_\beta \left[\frac{f_{ck}}{8}\right]^{\frac{1}{3}}$	$f'_c < 80$ MPa; α_β is a variable for the aggregate type, f_{ck} is the characteristic compressive strength of (150x300 mm)
	$E_c = 21,500\alpha_\beta \left[\frac{f_{cm}}{10}\right]^{\frac{1}{3}}$	$f'_c < 80$ MPa; $\alpha\beta$ is a variable for the aggregate type, f_{cm} is the compressive strength at 28 days of (150x300 mm) cylinder
Norwegian Standard NS 3473 [10]	$E_c = 9,500\left(f'_c\right)^{0.3}$	$25 \leq f'_c \leq 85$ MPa
Ma et al. [11]	$E_c = 19,000\left(\frac{f'_c}{10}\right)^{\frac{1}{3}}$	UHPC without coarse aggregates
	$E_c = 21,902\left(\frac{f'_c}{10}\right)^{\frac{1}{3}}$	UHPC with basalt coarse aggregates
Association Française de Génie Civil (AFGC) [12]	$E_c = 9,500\left(f'_c\right)^{\frac{1}{3}}$	Heat Cured Compressive Strength
Sritharan et al. [13]	$E_c = 4,150\sqrt{f'_c}$	UHPC (75x150) mm cylinders
Ma and Schneider [14]	$E_c = 16,365\ln\left(f'_c\right) - 34,828$	UHPC
Kollmorgen [15]	$E_c = 11,800\left(f'_c\right)^{\frac{1}{3.14}}$	$34 \leq f'_c \leq 207$ MPa
Graybeal [16]	$E_c = 3,840\sqrt{f'_c}$	$126 \leq f'_c \leq 193$ MPa
Graybeal [17]	$E_c = 4,069\sqrt{f'_c}$	$97 \leq f'_c \leq 179$ MPa

The MOE of the UHPC premix available in current markets varies from 55 to 59 GPa at 28 days of age [3]. Bonneau et al. [18], however, reported a lower MOE of 46 GPa for non-fibered UHPC. The addition of 2.0% of steel fibers by fraction volume increased the MOE by 6%. The MOE is anticipated to be decreased when the fine sand used to develop the UHPC premix is replaced by natural-gradation sand or fly ash. Therefore, the existing equations or reported MOE values may not accurately represent UHPC mixtures containing natural sand or fly ash as a fine material.

In this study, the authors measure the MOE of a number of UHPC mixtures that contain locally available materials and different contents of steel fibers. A new MOE equation is derived from all relevant test data found in the literature to minimize the inaccuracy due to inconsistent sample size. The accuracy of the derived equation is verified based on the measured MOE values.

3.3 EXPERIMENTAL INVESTIGATION

3.3.1 Relationship between concrete's compressive strength and modulus of elasticity

Concrete compressive strength has a strong correlation to the MOE. Researchers have proposed a number of equations to represent this correlation as discussed in previous sections. These equations were mainly developed based on the test results of an individual study or combined with the collected data of similar studies. The deviation of the proposed equations depends on the size and diversity of the collected samples. In this study, the authors collected 223 data points of compressive strength and MOE of UHPC from a number of studies in the literature [5, 15, 19 – 39]. These data points are summarized in **Appendix 3A**. The compressive strength and MOE range from 31 to 235 MPa and 25.0 to 68.3 GPa, respectively. The data points represent the concrete properties at different ages, and the lower bounds represent the properties at early ages. **Figure 3-1** illustrates the collected data and the best fitting curve that represents the correlation between the compressive strength and the MOE. The best fitting curve is expressed in **Eq. (3 – 1).**

$$E_c = 11{,}511\left(f_c'\right)^{0.3} \quad \text{(MPa)} \qquad \textbf{(3 – 1)}$$

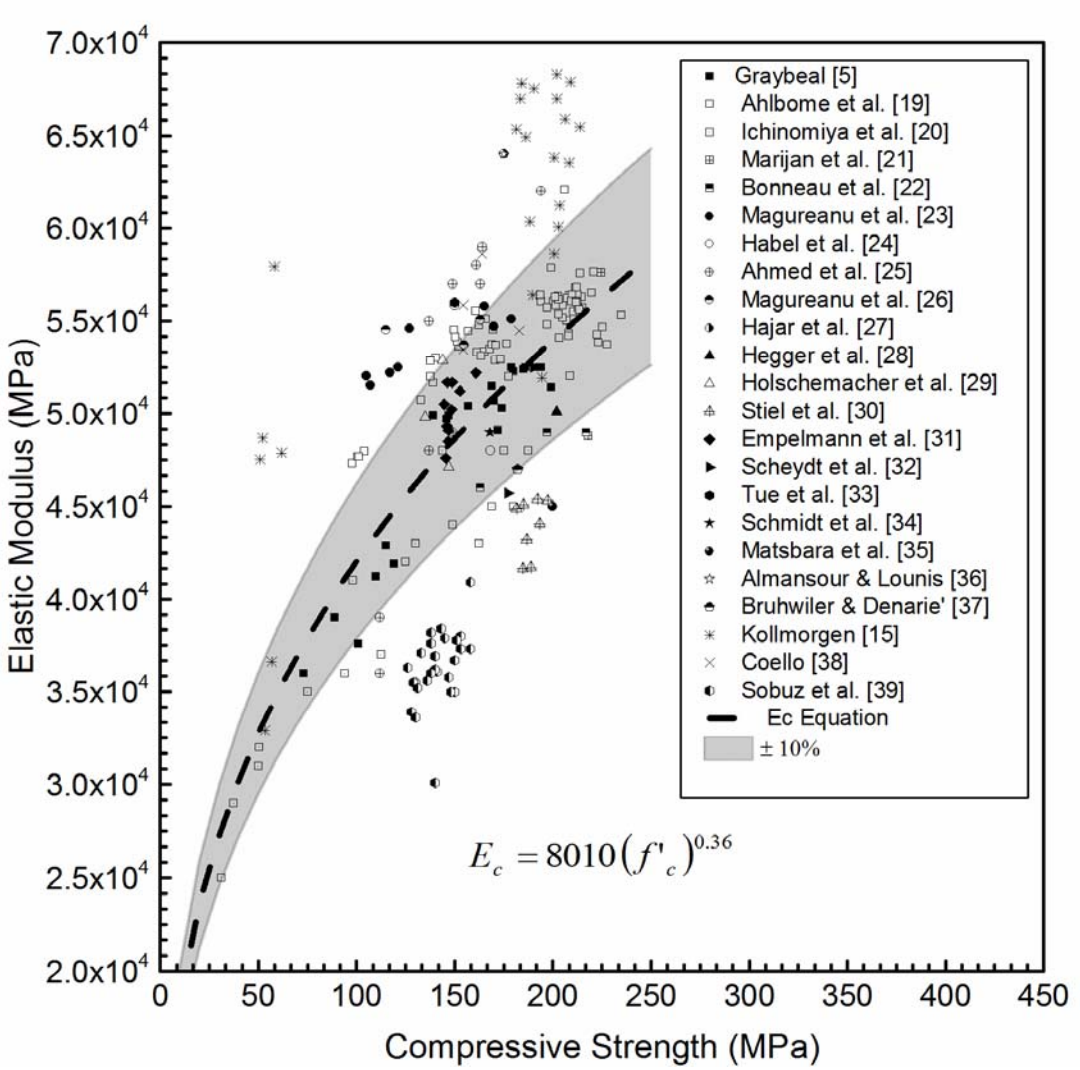

Figure 3-1. **Relationship between compressive strength and elastic modulus of literature data**

Eq. (3 – 1) has a similar form to the ACI 318 – 14 equation. However, the exponent of 0.36 indicates that the correlation between compressive strength and MOE of UHPC does not follow the same trend as normal-strength or high-strength concrete. This deviation is expected since the microstructure of UHPC is different from normal- and high-strength concrete. For normal- and high-strength concrete, the type and stiffness of coarse aggregates are significant parameters affecting to the MOE [40]. The behavior of the concrete matrix is complex and relies on the interaction between three phases of materials: cement matrix, coarse aggregate, and interfacial transition zone –a weak link between the cement matrix and the coarse aggregate. For UHPC, however, the coarse aggregate is generally excluded, and the interfacial transition zone may not exist in UHPC. The incorporation of steel fibers additionally changes UHPC behavior. All of these factors attribute to differences in the behavior of UHPC from the normal- and high-strength concrete.

The coefficient of determination R2 of **Eq. (3 – 1)** is 0.37 because of a high scatter of the reported experimental data. Given an error of ±10%, 56% of the data is in the expected range while 24% and 20% of the experimental data is under- and over-estimated, respectively. The use of special curing techniques (e.g., a combination of pressure and heat curing), which dramatically change the UHPC microstructure at the early ages, is the main reason attributing to the under-estimation of the derived equation. The derived equation, however, over-estimates the MOE of several UHPC mixtures that use locally available materials. It should be noted that the over-estimation of the MOE can result in problems when estimating the performance of UHPC structures. For example, the concrete structures may experience a deflection larger than expected, or prestressed concrete structures may experience prestress losses larger than the predicted values using existing codes.

3.3.2 Materials

For the UHPC developed in this study, the binder consisted of portland cement (Type I) and condensed silica fume. Two types of fine aggregates were used in the UHPC mixtures as shown in **Figure 3-2**. Fine-1 is the Arkansas River sand that has a natural gradation with 90% of the particles less than 1 mm as illustrated in **Figure 3-3**. The researchers additionally used Class C fly ash, which had an average particle size less than 75 µm, as the other fine aggregate **(Figure 3-3)**. The fly ash identified as Fine-2 in this study. Fly ash is a by-product from the coal combustion process. The use of fly ash can improve the workability, reduce internal temperatures during hydration process, and enhance the long-term durability of concrete structures. Fly ash reacts with calcium hydroxide, which is the most soluble hydration product and has a negative effect on the concrete mechanical properties [41]. The properties of cement fly ash, and silica fume are presented in **Tables 3-2, 3-3, and 3-4**.

Figure 3-2. Two types of fine materials used in the experimental program. Fine-1 is Arkansas River sand, and Fine-2 is Class C fly ash

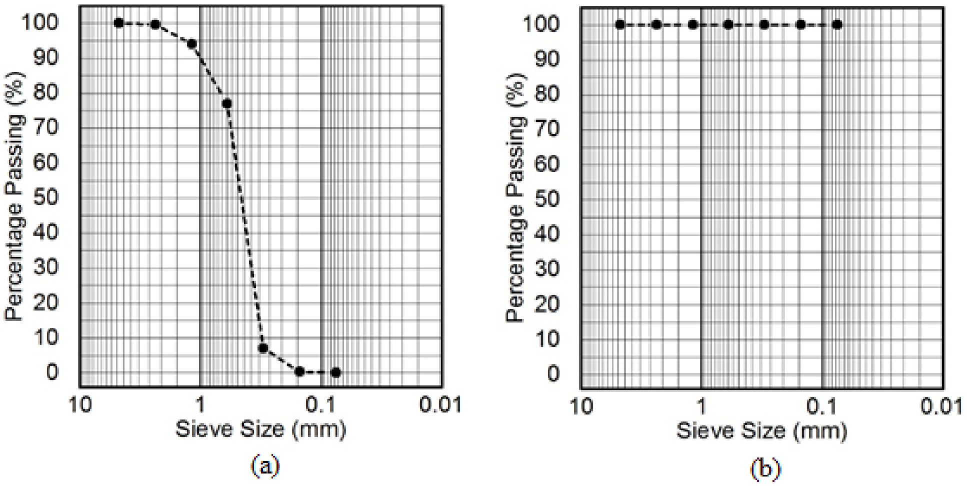

Figure 3-3. **The gradation of Fine-1 (left) and Fine-2 (right)**

Table 3-2– Properties of cement.

Item	Description
Chemical	
SiO_2	20.11%
Al_2O_3	5.07%
Fe_2O_3	3.80%
CaO	64.15
MgO	0.98
SO_3	3.23
Loss on ignition	2.39%
Na_2O	0.18%
K_2O	0.56%
Insoluble Residue	0.40%
CO_2	1.09%
Limestone	2.80%
$CaCO_3$	88.23%
Potential compounds	
C_3S	55%
C_2S	14%
C_3A	7%
C_4AF	11%
$C_3S + 4.75\ C_3A$	88%
Physical	
Air content of mortar (volume)	8%
Fineness	4.5 m^2/g
Autoclave expansion	-0.01%
Mortar Bar Expansion	0.00%
Specific gravity	3.15

Table 3-3 – **Fly ash properties.**

Item	Description
SiO_2	36.73%
Al_2O_3	21.49
Fe_2O_3	5.68%
CaO	22.70%
Na_2O	1.48%
K_2O	0.57%
MgO	4.30%
∑Oxides	63.90%
∑Alkalis	29.05%
Specific gravity	2.5

Table 3-4 – Silica fume properties.

Item	Description
Chemical	
SiO_2	95.25%
SO_3	0.08%
Cl	0.11%
Total Alkali	0.42%
Moisture Content	0.52%
Loss on Ignition	1.88%
pH	8.06%
Physical	
% retained on 45 µm sieve (wet sieved)	0.49%
Density - (specific gravity)	2.24
Bulk Density - (per ASTM)	696.71 kg/m^3
Specific Surface Area	24.49 m^2/g
Accelerated Pozzolanic Activity Index - with Portland Cement	124.44%

Steel fibers used in this study had a diameter of 0.2 mm and a length of 12.7 mm. The steel fibers were incorporated at 2%, 4%, and 6% by fraction volume in the UHPC mixtures to investigate its effect on the compressive strength and MOE. With the given fiber content, UHPC is expected to have high compressive strength and stiffness and a longer linear portion in the stress-strain curve. Hegger and Rauscher [42] indicated that the measured UHPC stress–strain curves are linear up to 90% of the ultimate compressive strength. This property is particularly beneficial in reducing and predicting the deflection of UHPC structures. For example, the MOE of conventional concrete decreases nonlinearly when the compressive stress is larger than 45% of the ultimate compressive strength [40]. For UHPC, the MOE may stay constant until 90% of the ultimate compressive strength, which allows for a better estimate of deflection when compared to the structures cast with conventional concrete.

3.3.3 Mixture Proportions

Sixteen UHPC mixtures were developed and investigated in this study. The mixture proportions are summarized in **Table 3-5**. The w/b ratio and silica fume replacement are constant in the testing matrix while the binder, steel fibers, HRWRA, and fine aggregates are variables. A 20% replacement of cement by silica fume satisfies the requirement of pozzolanic reactions and packing factor of UHPC mixture proportions [5]. Two binder contents were used. A high binder content is necessary to achieve a high compressive strength by accelerating hydration reactions using heat curing regimen. In the current practice, the typical binder content in UHPC mixture proportions ranges from 1,230 to 1,422 kg/m^3 [43 – 47]. The binder content can be as high as 1,620 kg/m3 [48]. It was observed that increasing the cement content increased the UHPC compressive strength; however, beyond a cement content of approximately 1,700 kg/m^3, the compressive strength tends to decline likely due to limited participation of aggregates [49].

Table 3-5 – UHPC mixture proportions.

Mixture	Binder (kg/m^3)	*w/b*	Silica Fume (%) by Mass of Binder	Steel fiber (%)	HRWRA (kg/m^3)	Fine Aggregate	Aggregate (kg/m^3)	Group
UHPC-1	1,365	0.2	20	0	30.26	Fine-1	647	A
UHPC-2	1,365	0.2	20	2	30.26	Fine-1	647	
UHPC-3	1,365	0.2	20	4	30.26	Fine-1	647	
UHPC-4	1,365	0.2	20	6	30.26	Fine-1	647	
UHPC-5	1,600	0.2	20	0	38.22	Fine-1	310	B
UHPC-6	1,600	0.2	20	2	38.22	Fine-1	310	
UHPC-7	1,600	0.2	20	4	38.22	Fine-1	310	
UHPC-8	1,600	0.2	20	6	38.22	Fine-1	310	
UHPC-9	1,600	0.2	20	0	77.22	Fine-1	310	C
UHPC-10	1,600	0.2	20	2	77.22	Fine-1	310	
UHPC-11	1,600	0.2	20	4	77.22	Fine-1	310	
UHPC-12	1,600	0.2	20	6	77.22	Fine-1	310	
UHPC-13	1,600	0.2	20	0	35.37	Fine-2	292	D
UHPC-14	1,600	0.2	20	2	35.37	Fine-2	292	
UHPC-15	1,600	0.2	20	4	35.37	Fine-2	292	
UHPC-16	1,600	0.2	20	6	35.37	Fine-2	292	

For the last 4 mixtures (Group D in Table 3), class C fly ash (Fine-2) was used as a fine aggregate. A number of advantages can be recognized from this replacement. The use of fly ash can reduce the cost of producing fine sand, which has an average diameter from 150 to 600 µm. Fly ash additionally contributes to reducing the calcium hydroxide content through the pozzolanic reactions. However, fly ash reduces the heat of hydration and consequently affects the strength development at early ages. The use of heat curing can overcome this issue and accelerate the development of compressive strength.

The first 8 mixtures (Groups A and B in **Table 3-5**) had the same amount of HRWRA (dosage per 100 kg of binder) to investigate the effect of binder content (from 1,365 to 1,600 kg/m3) on compressive strength and MOE. The amount of HRWRA for Group C was higher to increase the concrete flowability. The HRWRA content for last 4 mixtures (Group D), which contained a larger binder content than the first 4 mixtures, was reduced in order to maintain the same flow as the other mixtures.

3.3.4 Fresh concrete

The concrete was mixed using a laboratory Hobart 19 L (20 quart) pan mixer. Cement, fine aggregate, and silica fume were mixed for 10 minutes, and then water and HRWRA were incrementally introduced to the mixture. Steel fibers were then added slowly to the UHPC. After the fibers were added, the mixing continued for approximately 3 minutes to ensure that the fibers were well-dispersed. The mixing time was 15 to 20 minutes for all mixes due to the low w/b ratio and high binder content.

The rheology of the UHPC mixtures was evaluated through the flowability of the fresh UHPC mixtures. The flow test was conducted in accordance to ASTM C1437 [50]. This test is proposed for use with the mortar that presents plastic to flowable performance, and therefore, it is generally applicable for the fresh UHPC mixtures [6]. A fresh UHPC mixture was first placed in a short steel cone on an impact table as shown in **Figure 3-4a**. The cone was then lifted off slowly to allow the concrete to flow evenly about the table. The average of the initial diameter of the flow was taken at equally spaced locations. Next, the flow table was dropped 20 times for 20 seconds that allowed the concrete to settle as shown in **Figure 3-4b**. The average final diameter was recorded. The flow of the fresh UHPC mixture is calculated using **Eq. (3 – 2)**.

$$Flow = \left(\frac{D_f - D_i}{D_i} \right) \times 100 \tag{3 –2}$$

v

Figure 3-4. **Flow test**

3.3.5 Hardened concrete

Cylindrical specimens, 75×150 mm, were cast to measure the compressive strength and MOE. The samples were demolded at 1 day of age and were then placed into an end-grinder to remove any surface irregularities (**Figure 3-5a**) which was necessary when measuring compressive strength. The cylinders were then heat-cured at 100% relative humidity for five days (**Figure 3-5b**); two days at 60°C and three days at 90°C. The graphical cycles for the curing regimen are presented in Fig. 6. The cylinders used to measure the MOE were also sulfur capped to ensure the planeness of the specimens (**Figure 3-5c**) [51]. The authors measured the compressive strength at 6 and 28 days of age. The 6-day and 28-day strengths are almost identical. Hydration reactions begin after casting concrete and are accelerated by the heat-curing regimen for the first 5 days. Therefore, there are no expected reactions after the heat-curing period when the concrete samples were cured in an environmental chamber. In the following sections, the authors simply report the compressive strength and MOE at 28 days of age.

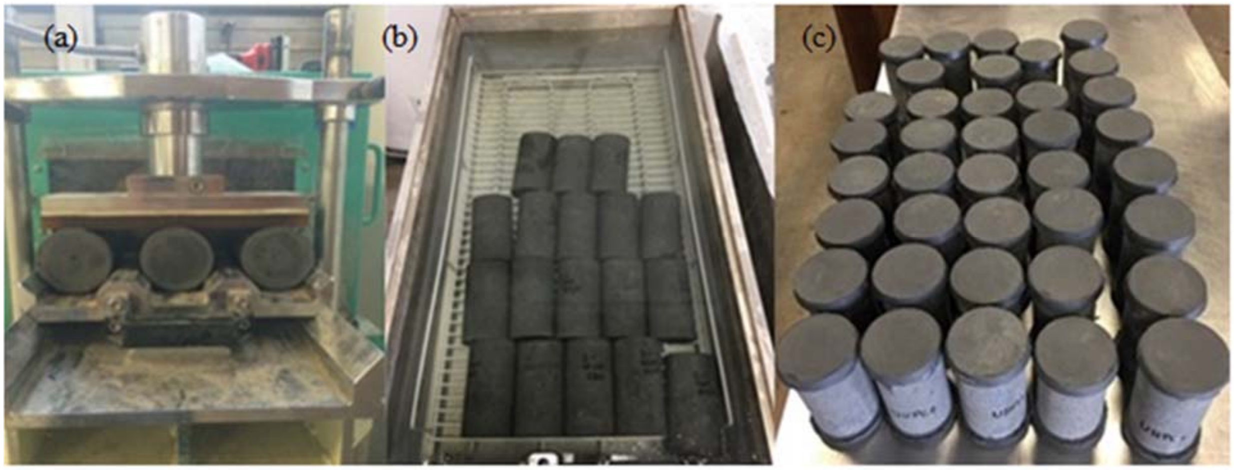

Figure 3-5. The end-grinding machine (5a), water bath (5b), and the sulfur capped cylinders (5c).

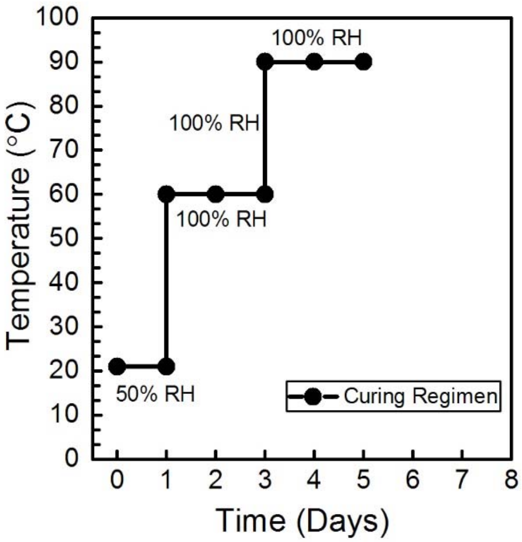

Figure 3-6. Curing regimen cycle. (Note: RH = relative humidity)

The compressive test was conducted according to ASTM C109 [52]. The applied load rate was 1.0 MPa/second due to the high compressive strength of UHPC [16]. The MOE test was performed according to ASTM C469 [53] with slight adjustments (**Figure 3-7**). Two extensometers were attached to the sample, and two strain measurements were recorded. The average strain from the two extensometers was used in determining the MOE. Three uni-directional strain gauges were attached randomly to several cylinders to compare with the strains obtained from the extensometers. Typical stress-strain curves of the two methods are presented in **Appendix 3B**.

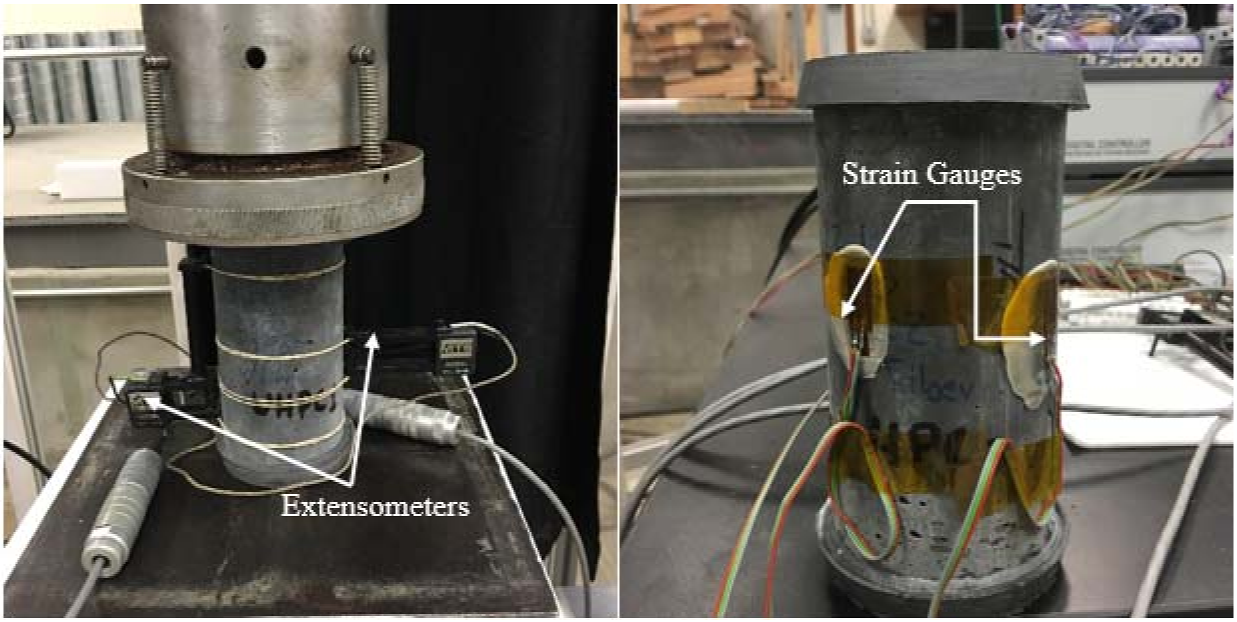

Figure 3-7. **Modulus of elasticity test procedure**

3.4 EXPERIMENTAL RESULTS AND DISCUSSION

3.4.1 Fresh concrete

The measured flows of the UHPC mixtures are summarized in **Table 3-6**. **Figure 3-8** illustrates the measured flows for the 16 UHPC mixtures. Group A and B had the same amount of HRWRA per 100 kg of binder materials, but the total HRWRA content of group B was higher because of the larger binder content. For a given fiber content, the flow increases when the binder content increases. For example, the flow of groups B and C are 2% and 4% larger than group A, respectively. The possible reason is that the binder lubricates the fine aggregate, and concrete with high cement content shows high cohesiveness.

Table 3-6 – Measured flows of UHPC mixtures.

Mixture	Initial Diameter D_i (mm)	Final Diameter D_f (mm)	Flow (%)	Group
UHPC-1	165	195	18	A
UHPC-2	160	185	16	
UHPC-3	155	175	13	
UHPC-4	155	170	10	
UHPC-5	175	210	20	B
UHPC-6	170	200	18	
UHPC-7	170	195	15	
UHPC-8	165	185	12	
UHPC-9	190	230	21	C
UHPC-10	185	220	19	
UHPC-11	180	210	17	
UHPC-12	170	195	15	
UHPC-13	175	205	17	D
UHPC-14	175	200	14	
UHPC-15	175	195	11	
UHPC-16	165	180	9	

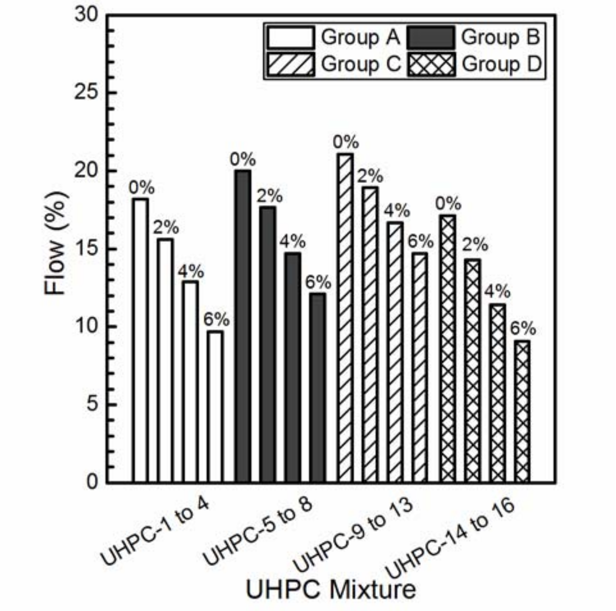

Figure 3-8. Measured flows of 4 UHPC groups. (Note: The values above columns indicate the steel fiber content)

When comparing the test results of groups B and C, the measured flows slightly increase when the amount of HRWRA increases. For example, the flows of mixtures UHPC-9 and UHPC-12 are 1% and 3% larger than those of mixtures UHPC-5 and UHPC-8, respectively. In fresh UHPC mixtures, HRWRA molecules tend to align themselves around cement particles to form a watery shell. These molecules instruct a strong negative charge that reduces the surface tension of the surrounding water; and therefore, enhances the fluidity of the system and reduces the plastic viscosity of the mixture [40].

For a specific group, the measured flows decrease when the fiber content increases (**Figure 3-8**). On average, the use of 2%, 4%, and 6% of steel fibers by fraction volume decreased concrete flowability. The increase in fiber content increases the specific surface area, which produces higher cohesive forces between the fibers and concrete matrix. In addition, the inter-connection of steel fibers within the paste matrix creates a stiff skeleton that inhibits the flowability of the

UHPC mixtures [54, 55]. These findings are consistent with those stated in the literature. Milan et al. [56] determined that the fiber content affects the workability of UHPC mixtures, in which the measured flows possibly reduce 10% when 4% of steel fibers by fraction volume are incorporated.

When comparing the test results of group B and D, the measured flows decrease due to the use of fly ash as a fine material, regardless of a minor difference in the HRWRA content. For example, the flows of mixtures UHPC-13 and UHPC-16 are 3% less than those of mixtures UHPC-5 and UHPC-8. The use of fly ash increases the surface area within the paste matrix and magnifies the cohesive forces between particles, which leads to a reduction in the measured flows.

3.4.2 Hardened concrete

The compressive strengths and MOE results of UHPC-1 to UHPC-16 are summarized in **Table 3-7**. Each value presented in the table is an average of three samples. The measured compressive strengths vary from 124 to 162 MPa, and the MOE ranges from 37 to 46 GPa. These values are lower than the reported results of UHPC premix. In UHPC premix, the use of fine quartz powder (average particle size = 1.7 μm) and ultra-fine sand (average particle size = 0.80 mm) produces a denser cement matrix with a minimum void ratio when comparing to the UHPC mixtures containing local materials [3]. This effect is particularly apparent in the compressive strength and MOE since these mechanical properties directly relate to the solidification of the concrete mixtures.

Table 3-7 – Measured compressive strength and modulus of elasticity.

Mixture	Compressive strength (MPa)	Modulus of elasticity (GPa)	Group
UHPC-1	136.4	43.4	A
UHPC-2	137.9	44.5	
UHPC-3	140.8	45.9	
UHPC-4	155.3	45.9	
UHPC-5	135.0	37.6	B
UHPC-6	135.9	40.3	
UHPC-7	143.2	41.0	
UHPC-8	145.7	43.4	
UHPC-9	124.1	37.2	C
UHPC-10	128.3	37.9	
UHPC-11	127.6	40.0	
UHPC-12	144.1	42.7	
UHPC-13	135.5	36.9	D
UHPC-14	146.8	38.3	
UHPC-15	144.7	39.3	
UHPC-16	162.4	43.1	

Figure 3-9 illustrates the test results presented in **Table 3-7**. For all groups, the use of 2% of steel fibers has a minimal effect on compressive strength and MOE. On average, the compressive strength increases from 1 to 8% while the MOE increases from 3 to 7%. Similar results are obtained for a fiber content of 4%. These results confirm the findings in the literature. It has been reported that steel fibers affect tensile strength while it is insignificant to the compressive strength [23, 42, and 57]. When a concrete matrix is subjected to tensile stresses, steel fibers effectively prevent the propagation of micro-cracks and transfer the stresses across the cracks. With a higher fiber content of 6%, the compressive strength and MOE are improved by 8 to 20% and 6 to 15%, respectively. However, steel fiber content is one of the main contributors to UHPC cost. Therefore, a large amount of steel fibers (≥ 4% by fraction volume) is used for special requirements for concrete toughness but seldom for concrete stiffness. In the

current practice, a fiber content of 2.5% is generally recommended to reduce the brittleness and increase the ductility of UHPC structures [3, 16].

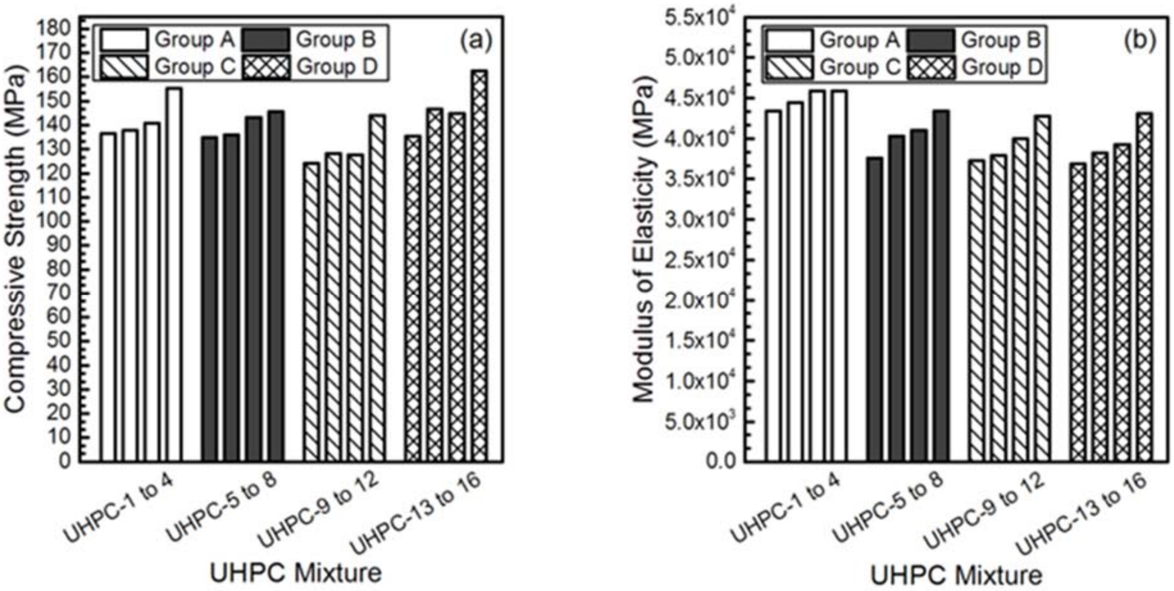

Figure 3-9. Measured compressive strengths and elastic modulus. (Note: The values above columns indicate the steel fiber content)

In comparison to group A, the binder of group B was increased from 1,365 to 1,600 kg/m^3 to evaluate the effect of binder content on concrete properties. As shown in **Figure 3-9**, the increase in binder content has minimal effect on compressive strength. In UHPC mixture, the water-cement ratio is low, and the mixing water is usually lower than the amount necessary for complete hydration. Therefore, a portion of binder gets hydrated that produces calcium silicate hydrate (C-S-H) –the main contributor to compressive strength. The un-hydrated binder cement particles serve as a filler material in the hardened concrete matrix. The MOE of group B, however, is slightly lower than group A. For the UHPC mixtures containing a higher binder content, the sand content is lower. In the hardened UHPC matrix, sand particles act as a skeleton that has a larger stiffness than the hardened cement matrix. Under compressive stress, this sand skeleton restrains the deformation of the concrete matrix, which results in the improved MOE of group A [58].

When comparing the test results of groups B and C, the increase in HRWRA has a negative effect on the compressive strength and minimal effect on the MOE. For example, the compressive strength of mixture UHPC-11 is 11% lower the UHPC-7. The increase in HRWRA increases the porosity of the hardened concrete matrix. The HRWRA used in this study contains 50% of water. Therefore, while HRWRA reduces the surface tension of water, which increases the concrete flowability as discussed previously, HRWRA also increases the water content in the UHPC mixture proportions. In addition, HRWRA generally tends to add entrained air during mixing process, which also increases to the porosity of the concrete mixtures [59]. According to the manufacture of the HRWRA used in this research, it adds approximately 2% of air compared to the mixture without HRWRA.

The behavior of UHPC mixtures containing fly ash as a fine material is possibly different from those containing natural sand. Technically, chemical reactions between the aggregate particles and cement matrix are not expected. Fly ash, however, engages in a number of pozzolanic reactions with cement hydration products, typically with calcium hydroxide and additionally generates C-S-H. The secondary C-S-H can strengthen the concrete matrix and improve the compressive strength and MOE, while the primary C-S-H generated during the cement hydration process is the main contributor to these concrete properties. However, the experimental results of groups B and D indicate that the use of fly ash as a fine material in the UHPC mixture proportions has no effect on compressive strength and MOE. The test results of mixtures UHPC-13 to 15 are almost identical to mixtures UHPC-5 to7. These results are a combination of two phenomena. The compressive strength and MOE of group D is improved because of the strengthening of the secondary C-S-H. However, the remaining un-hydrated fly ash particles possibly lessen the positive effect of the secondary C-S-H. The amount of the un-hydrated fly ash depends on the amount of generated calcium hydroxide from the hydration process of cement. In the UHPC mixture proportions, the amount of calcium hydroxide is limited since the entire cement content is not involved in the hydration process as discussed previously. In summary, the use of a large volume of fly ash in a UHPC mixture proportions has minimal effect on the compressive strength and MOE.

3.4.3 Validation of proposed equation

Figure 3-10 plots the proposed equation with an error of ±10% and experimental data achieved in this study. About 31% of the data are within the limits. This result indicates the over-estimation of the proposed MOE equation for the UHPC mixtures containing local materials in this study. The use of local materials can weaken the microstructure of the UHPC mixtures. In this study, natural sand was used in the UHPC mixture proportions without any kind of pretreatment or washing. Therefore, the concrete matrix may contain soft particles and different minerals on the particle's surface, which creates weak links in the matrix. When concrete is subjected to tensile stresses, cracks tend to form at the weak links and propagate to adjacent regions that reduce concrete stiffness. The sand used in premix UHPC generally contains less soft particles and minerals than the natural sand. In addition, the premix sand has smaller particle sizes, which scatters possible weak links and delays the interconnection of cracks when the concrete resists external tensile stresses. Therefore, the measured MOE of premix UHPC is larger than the mixtures containing local materials.

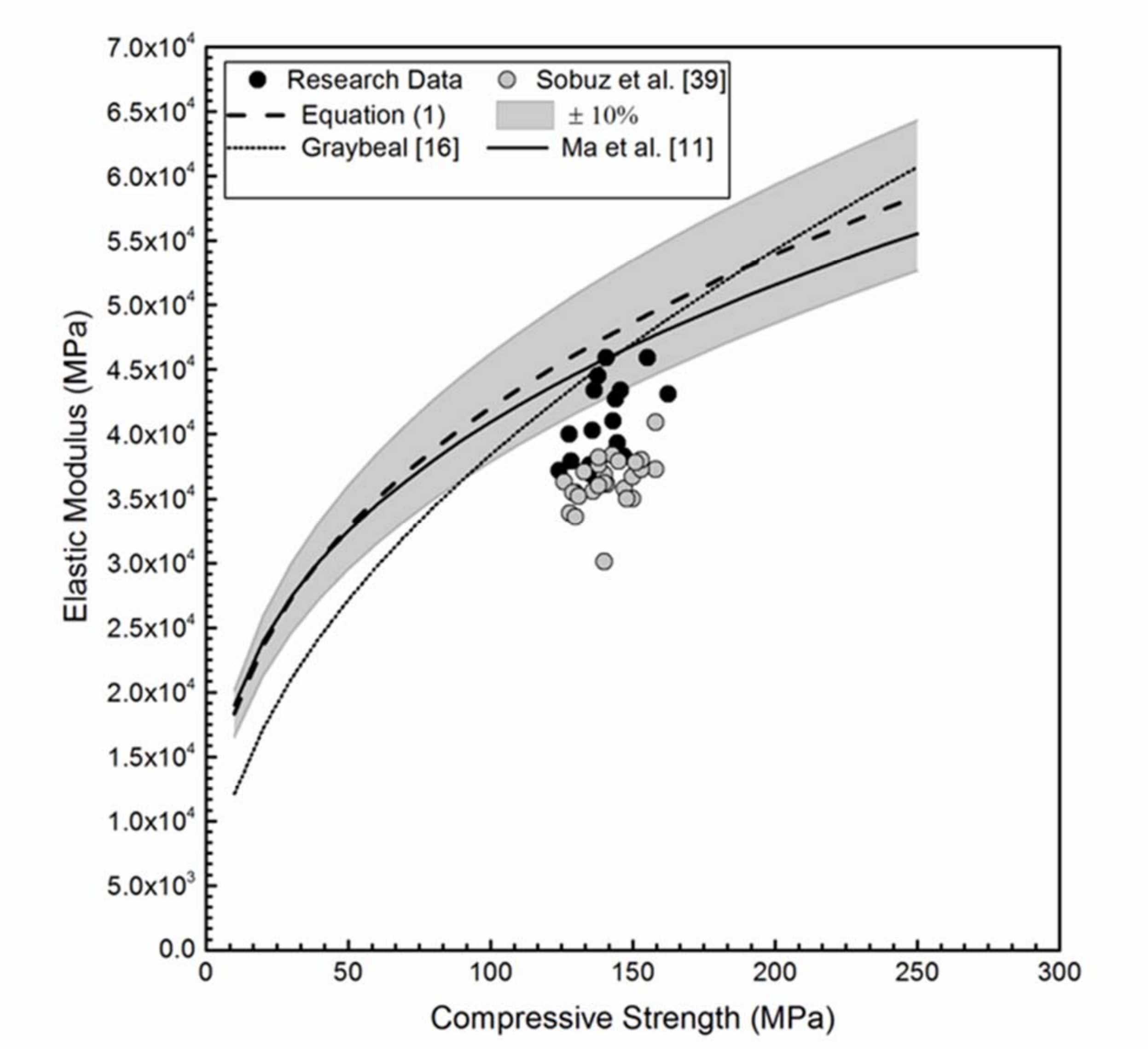

Figure 3-10. Modulus of Elasticity and Compressive Strength Relationship

In this study, there is no proposed equation for the modulus of elasticity of UHPC containing local materials. The achieved experimental data distribute in a limit range, which does not warrant the reliability of the proposed equation. Therefore, the authors used two typical equations proposed by Ma et al. [11] and Graybeal [16] to verify the experimental data. **Figure 3-10** also shows the over-estimation of these equations. About 69% of data points are in the lower region of the curves. These data show a trend similar to those reported by Sobuz et al. [39]. The use of conventional materials for developing mixture proportions in Sobuz et al.'s study possibly attributes to this similarity.

3.5 CONCLUSION

Based on the results of this experimental investigation, the following conclusions are drawn:

1. A new equation is proposed to predict the MOE of UHPC. With an error of ±10%, the proposed equation provides a reasonable prediction for the relevant data found in the literature.
2. Steel fiber content affects the flowability of the fresh UHPC mixtures. The flows decrease by about 2% as a fiber content increase of 2%. When fly ash is used as a natural fine material, the flowability decreases when compared to mixtures containing natural sand.
3. The use of natural sand or fly ash can reduce the MOE when comparing to a UHPC premix. The proposed equation over-estimates the measured MOE for the UHPC mixtures using local materials in this study.
4. The use of fly ash as a fine material has little effect on compressive strength and modulus of elasticity at 28 days of age in comparison to natural sand.

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APPENDIX 3A

Table 3A-1 - Collected concrete compressive strengths and modulus of elasticity.

Author (s)	Compressive Strength (MPa)	Modulus of Elasticity (GPa)
Graybeal [5]	169	51.5
	179	52.5
	180	52.3
	186	52.5
	185	52.4
	193	52.5
	199	51.4
	194	52.5
	73	36
	89	39
	101	37.6
	110	41.2
	119	41.9
	125	42
	139	49.9
	146	49.7
	147	49.9
	157	50.4
	115	42.9
	174	50.3
	170	50.7
	172	49.1
Michigan Tech [19]	98	47.3
	101	47.7
	104	48
	101	47.7
	141	53
	139	51.7
	138	52.9
	138	52
	133	50.7
	152	53.6
	157	54.5
	150	54.5
	152	53.9

Table 3A-1 - Collected concrete compressive strengths and modulus of elasticity. (Cont.)

Author(s)	Compressive Strength (MPa)	Modulus of Elasticity (GPa)
Michigan Tech [19]	150	54.1
	162	54.8
	170	54.5
	161	53.3
	161	55.6
	166	55.1
	165	53.4
	168	53.5
	176	53.8
	169	53.7
	177	52
	171	52.9
	174	52.9
	164	53.1
	210	55.5
	215	55.7
	208	54.3
	197	54.8
	211	56.2
	212	56.8
	208	56.4
	221	57.7
	207	56.2
	194	56.1
	200	56.1
	214	57.6
	214	56.3
	213	55.7
	212	56
	214	55.5
	220	56.5
	213	55.6
	228	53.8
	203	54.1
	208	54.2
	225	54.7
	235	55.3

Table 3A-1 - Collected concrete compressive strengths and modulus of elasticity. (Cont.)

Author(s)	Compressive Strength (MPa)	Modulus of Elasticity (GPa)
Michigan Tech [19]	206	62.1
	205	55.9
	197	55.7
	199	57.9
	212	56.4
	212	56.1
	210	56.4
	203	56.4
	201	55.8
	203	56.2
	210	56.1
	212	56.8
	171	53.7
	223	53.8
	223	54.3
	209	52
	207	55
	194	56.4
	212	56
	201	56.3
	205	55.2
	203	55.4
Ichinomiya et al. [20]	31	25
	38	29
	50	31
	50	32
	75	35
	94	36
	98	41
	112	37
	125	42
	130	43
	144	48
	149	44
	162	43
	169	45

Table 3A-1 - Collected concrete compressive strengths and modulus of elasticity. (Cont.)

Author(s)	Compressive Strength (MPa)	Modulus of Elasticity (GPa)
Ichinomiya et al. [20]	175	48
	180	45
	188	48
Marijan et al. [21]	218	49
	224	58
Bonneau et al. [22]	163	46
	217	49
	197	49
Magureanu et al. [23]	121	53
	105	52
	117	52
	107	52
	179	55
	170	55
	165	56
	127	55
Habel et al. [24]	168	48
Ahmed et al. [25]	149	49
	137	48
	112	36
	149	57
	137	55
	112	39
	163	57
	164	59
	161	58
	194	62
Magureanu et al. [26]	163	55
	155	54
	150	56
	115	55
Hajar et al. [27]	175	64

Table 3A-1 - Collected concrete compressive strengths and modulus of elasticity. (Cont.)

Author(s)	Compressive Strength (MPa)	Modulus of Elasticity (GPa)
Hegger et al. [28]	202	50
Holschemacher et al. [29]	135	50
	147	47
	144	53
Stiel et al. [30]	192	45
	193	44
	197	45
	185	42
	185	45
	187	43
	182	45
	189	42
Empelmann et al. [31]	161	52
	146	49
	145	51
	146	52
	149	52
	148	50
	147	49
	147	49
	153	51
	146	48
Scheydt et al. [32]	190	53
	177	46
Tue et al. [33]	150	56
Schmidt et al. [34]	168	49
Matsbara et al. [35]	200	45
Almansour and Lounis [36]	175	64

Table 3A-1 - Collected concrete compressive strengths and modulus of elasticity. (Cont.)

Author(s)	Compressive Strength (MPa)	Modulus of Elasticity (GPa)
Bruhwiler and Denarie' [37]	182	47
Kollmorgen [15]	57	37
	58	58
	53	33
	51	48
	62	48
	52	49
	186	65
	188	60
	202	68
	201	64
	214	65
	190	56
	184	68
	209	68
	194	52
	201	59
	190	68
	203	60
	183	67
	181	65
	203	61
	208	64
	206	66
	202	67
Coello [38]	183	54
	164	59
	154	56
	154	53
Sobuz [39]	141	36
	147	36
	150	35
	140	30
	148	35
	158	37
	143	38

Table 3A-1 - Collected concrete compressive strengths and modulus of elasticity. (Cont.)

Author(s)	Compressive Strength (MPa)	Modulus of Elasticity (GPa)
Sobuz [39]	140	37
	140	36
	136	36
	150	37
	158	41
	153	37
	153	38
	138	38
	151	38
	145	38
	126	36
	130	36
	128	34
	129	36
	130	34
	131	35
	133	37
	138	36
	138	38

APPENDIX 3B

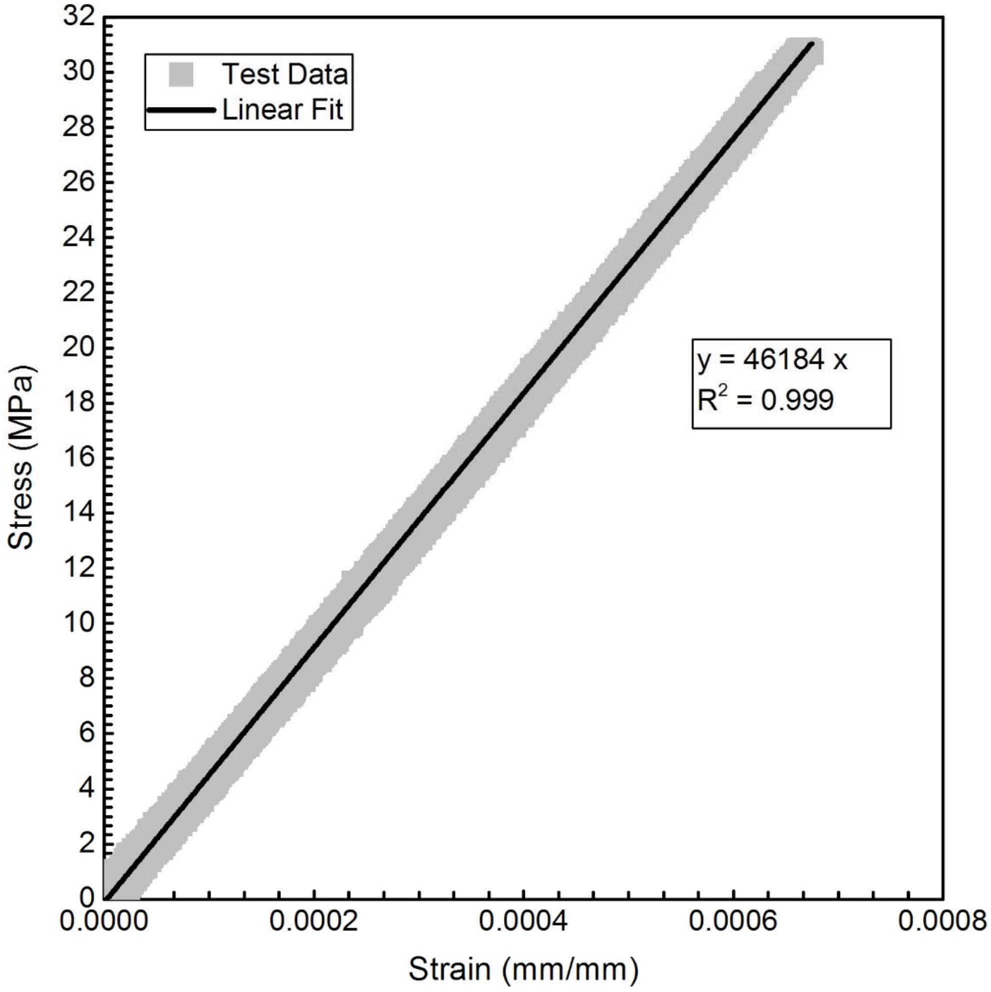

Figure 3B-1 – Stress–strain curve for UHPC-3 with two extensometers

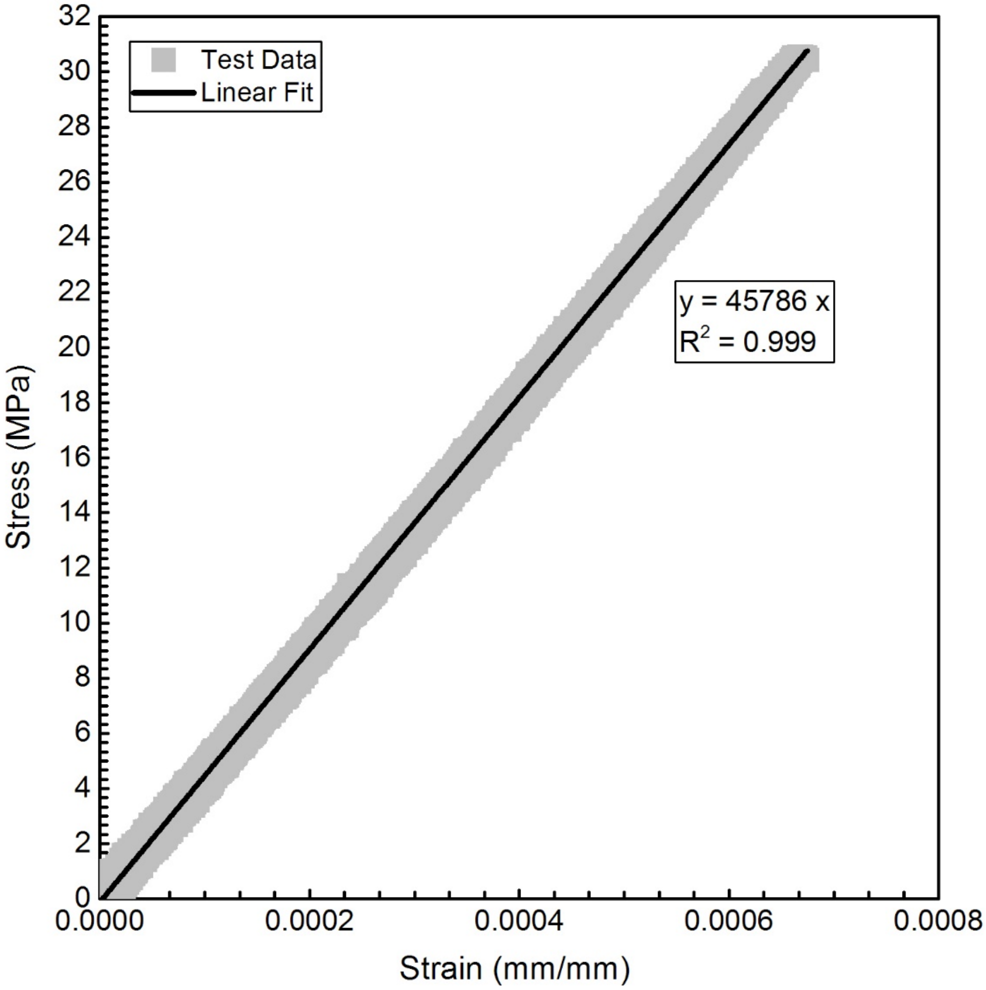

Figure 3B-2. **Stress–strain curve for UHPC-3 with three uni-directional strain gauges**

CHAPTER 4: DEVELOPMENT OF ECONOMICAL UHPC MIXTURES USING LOCAL MATERIALS

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Abstract:

Ultra-High-Performance Concrete (UHPC) offers innovative applications to concrete structures based on enhanced mechanical properties. The use of local materials is necessary to reduce the UHPC cost and save materials and energy. The research focuses on developing economical UHPC mixtures using locally available materials. The effects of different fine materials, steel fibers, curing regimes, and mixers on concrete compressive strength are evaluated. A minimum cost of $283 is achievable for a 150-MPa UHPC mixture.

KEYWORDS: Ultra-High-Performance Concrete; economical mixture; curing regiment; fly 23 ash; steel fiber; compressive strength

4.1 INTRODUCTION

Ultra-high-performance concrete (UHPC) is an advanced construction material that is highly durable and possesses enhanced mechanical properties (e.g., high compressive strength, tensile strength, and modulus of elasticity). UHPC can provide a cost-effective approach in design and construction of new concrete structures by reducing the size of structural members or extending the member spans [1], or in rehabilitation of existing structures [2 – 4]. A number of projects in the United States, Germany, Canada, France, and Australia have confirmed the advantages and benefits of using UHPC, including Shepherds Bridge in Australia, Wapello County Mars Hill bridge in Iowa (USA), and the Expressway bridge in Japan [5].

In the United States, UHPC is mainly used for bridge applications, including precast/prestressed bridge girders, precast waffle panels, and as a jointing material between precast concrete deck panels and girders [6]. It is anticipated that UHPC can offer a wide range of structural applications, not only for concrete structures but also for composite structures [7,8]. However, UHPC is 10 to 20 times more expensive than conventional concrete which has restricted its extensive use in the architecture, engineering and construction industry [9]. Therefore, additional research is needed to reduce the concrete cost, simplify UHPC mixture proportioning, and further understand the concrete behavior.

Table 4-1 presents different mixture proportions of commercially available, proprietary UHPC and their prices. Ductal® is a readily-available UHPC marketed by LafargeHolcim in the United States. This premix is delivered in three constituents: (1) dry materials that are pre-blended in bulk bags, (2) steel fibers that are packaged separately, and (3) chemical admixtures that are also packaged separately. The cost of this product is approximately $980/m3 for the materials, but cost can vary based on the amount being used [16]. Abbas et al. [9] reported that the cost of

UHPC ranges from $750 to $1,400/m3 in Europe and $1,000 to $2,620/m3 in North America. The price of UHPC depends on the specific requirements regarding concrete components, curing conditions, and the type of mixer required to batch UHPC. In the following sections, the effects of these factors on the concrete properties and possible solutions used to reduce the concrete cost are discussed in detail.

Table 4-1– Commercially available UHPC mixtures

Component	Ductal®	BSI®	CEMTEC ®	CRC®	BCV®	Cor-Tuf ®
Premix					2,115[c]	
Binder	1,154	1,283	1,318	920-940[b]	n/a	1,550
Cement	712	1114	1,050	n/a	n/a	758
Fine sand	1,020	1072	514	1,300-1,350	n/a	733
Silica fume	231	169	268	n/a	n/a	497
Ground Quartz	211	n/a	n/a	n/a	n/a	295
HRWRA	31	40	44	n/a	21	13
Accelerator	30	n/a	n/a	n/a	n/a	n/a
Steel fibers	156	234	470	150-300	156	140
Water	109	209	180	145-155		158
w/b	0.10	0.16	0.14	0.16	0.25	0.10
Price (dollar/m^3)	$2,600[a]	$1,632	$2,843	n/a	n/a	$1,496
Reference	[10]	[11]	[12]	[13]	[14]	[15]

Notes:

[a] The price includes the material costs of the proprietary blend and the fiber reinforcement, and the costs associated with the development and delivery of necessary concrete components;

[b] The binder includes cement, micro silica, and dry superplasticizer;

[c] The premix contains cement, silica fume, and fine filler materials;

n/a = not applicable.

4.2 SIGNIFICANT OF CONCRETE COMPONENTS

The use of silica fume is necessary to achieve the high compressive strength and durability of UHPC. Silica fume accelerates the pozzolanic reactions that produces additional calcium silicate hydrates (C-S-H) and fills the voids in the paste matrix [17]. As shown in **Table 4-1**, silica fume accounts for 13 to 32% of the total binder content. However, the price of silica fume is 4 to 7 times higher than cement. An optimized use of silica fume would reduce the UHPC cost without affecting the concrete properties. According to Graybeal [10] and Rossi et al. [12] (see **Table 4-1**), a 20% replacement of silica fume results in the highest concrete strength and durability. In this study, the 20% content will be used to develop the testing matrix as presented in the following sections.

Fine sand and other filler materials (e.g., quartz powder) are the main components in UHPC mixture proportions (**Table 4-1**). The size of the filler materials can influence the compressive strength of UHPC. The Ductal® premix contains fine sand (150 to 600 μm) to ensure the homogeneity of the concrete and improve the strength [18]. Park et al. [19] evaluated the effect of sand gradation on compressive strength. The study used two types of sand; one had an average grain size of 300 to 500 μm, and the other had an average grain size of 170 to 300 μm. The experimental results indicated that the mixture proportion in which the fine aggregate consisted of 70% of the 300 to 500 μm sand and 30% of the 170 to 300 μm sand produced the highest compressive strength. In the Gerlicher et al. [20] study, the use of ultra-fine materials having grain sizes of 125 to 500 μm resulted in a 28-day compressive strength of up to 188 MPa. However, Ma et al. [21] found that the particle sizes of fine aggregate had minimal effect on the compressive strength when developing non-fiber reinforced, self-compacting UHPC using two types of sand of different grain sizes: (1) fine sand with grain sizes of 300 to 800 μm, and (2) coarse sand with grain sizes of 2 to 5 mm. The 28-day compressive strengths ranged from 150 to 165 MPa with water curing at 20°C and about 190 MPa with heat treatment at 90°C. Based on the findings of these studies, researchers have further explored the use of fly ash or natural sand as a filler material to reduce the concrete cost [22]. By using a local sand, which has size ranging from 150 to 600 µm, the additional time and labor necessary to produce the ultra-fine sand is eliminated.

Temperature and moisture are important factors when curing UHPC. The mechanical properties of UHPC can be enhanced using heat curing regimens, which accelerates the early strength of concrete [23 – 25]. A typical curing regime of UHPC consists of two stages. In the first stage, the concrete is placed in a suitable temperature while avoiding moisture loss until final set. In the second stage, the curing temperature may increase to accelerate compressive-strength gain [18]. In the current practice, different curing regimes are implemented for UHPC, typically including (1) 96 hours at 90°C with relative humidity (RH) of 95%, (2) 48 hours at 90°C with RH of 95%, and (3) moist curing (e.g., lab environment) [26,27]. Heinz and Ludwig [28] specified that a curing temperature between 65°C and 180°C can yield a 28-day compressive strength of 280 MPa. The cement was chosen to achieve low water demand, low heat of hydration, excellent workability, favorable characteristics of hardening and reduction in the risk of delayed ettringite formation (DEF). At a curing temperature of 20°C, the concrete can achieve compressive strengths of 178 to 189 MPa. In addition, these compressive strengths are achievable at 48 hours of age when using heat curing.

When mixing UHPC, a high-shear mixer is recommended since the mixtures typically have high binder content and a low water/binder (w/b) ratio [29]. In addition, UHPC mixtures contain a high percentage of air voids that can influence its mechanical properties when compared to conventional concrete. The high percentage of air voids is due to the high amount of HRWRA. The UHPC air voids are not easily removed from the concrete mass, but when necessary, a vacuumed mixer can be used to overcome this issue [30]. However, many ready-mix companies do not possess a high shear mixer, making the desire to produce UHPC on a much larger scale less appealing. In addition, mixers can become highly taxed or overworked due to the increased unit weight and viscosity of UHPC, thus batch size must be decreased [31].

In summary, the use of UHPC is an avenue for building the next generation of infrastructure, building structures, and other facilities. The high cost and stringent requirements for the concrete components can be an obstruction for expanding the implementation of UHPC. It is necessary to develop economical and simple UHPC mixtures for practical use when applicable. This study develops and test a number of UHPC mixtures using locally available materials. The effect of binder content, high-range water reducer admixture (HRWRA), steel fiber, and mixer, and curing regimen on the compressive strength are examined.

4.3 EXPERIMENTAL INVESTIGATION

4.3.1 Materials

Cementitious materials (binder) consisted of portland cement (Type I), condensed silica fume, and Class C fly ash. The properties of the cement fly ash, and silica fume are presented in **Appendix 4A**. Seven types of locally available fine aggregates were used in this study. Fine-1 is a by-product material obtained from a quarry in Northwest Arkansas. Fine-2 is a river sand that was sieved and only the fraction that passed the No. 200 (75 μm) was used in the research program. Fine-3 is a combination of natural-gradation Arkansas River Sand and Fine-1 by a proportion of 1:1. Fine-4 consists of a natural-gradation sand (75%) and Fine-1 (25%). Fine-5 includes 25% of natural-gradation sand and 75% of Fine-1. Fine-6 is 100% of natural-gradation river sand. Finally, Class C fly ash was used as Fine-7. The gradation of all fine aggregates is presented in **Figure A4-1** of **Appendix 4A**. HRWRA was carboxylate-based admixture. Steel fibers had a diameter of 0.2 mm and a length of 12.7 mm, and were incorporated as 2% 4%, and 6% by fraction volume.

4.3.2 Mixture Design Testing Procedure

The mixture proportions are summarized in **Table 4-2**. Most of the mixtures had binder content of 1,305 kg/m^3. A high binder content is necessary to achieve a high compressive strength by accelerating hydration reactions using heat-curing regimen. For some mixtures, the binder content was increased to 1,424 and 1,543 kg/m^3 to examine its effect on the concrete compressive strength. It was observed that increasing the cement content increases compressive strength. However, beyond a cement content of approximately 1,700 kg/m^3, compressive strength tends to decrease likely due to the limited participation of aggregates. With a high cement content, the aggregates do not participate in UHPC compaction, and therefore the UHPC does not achieve the optimum packing factor [32].

Table 4-2 – Mix Proportions.

Mixture	Binder (kg/m^3)	*w/b*	Silica fume (%)	Fly ash (%)	Steel fiber (%)	HRWRA (kg/m^3)	Fine aggregate	Mixer type	Curing regimen
UHPC-1	1305	0.20	20	0	0	126.5	Fine-1	Pan	A
UHPC-2	1305	0.20	20	0	0	151.7	Fine-1	Pan	A
UHPC-3	1305	0.20	20	0	0	151.7	Fine-2	Pan	A
UHPC-4	1305	0.20	20	0	0	113.7	Fine-2	Pan	A
UHPC-5	1305	0.20	20	0	0	113.7	Fine-3	Pan	A
UHPC-6	1305	0.20	20	0	0	113.7	Fine-4	Pan	A
UHPC-7	1305	0.20	20	0	0	126.4	Fine-5	Pan	A
UHPC-8	1305	0.20	20	0	0	76.0	Fine-6	Pan	A
UHPC-9	1305	0.20	20	0	0	50.4	Fine-6	Pan	A
UHPC-10	1305	0.20	20	0	0	44.2	Fine-6	Pan	A
UHPC-11	1305	0.20	20	0	0	34.1	Fine-6	Pan	A
UHPC-12	1305	0.20	20	0	2	44.2	Fine-6	Pan	A
UHPC-13	1305	0.20	20	0	4	44.2	Fine-6	Pan	A
UHPC-14	1305	0.20	20	0	6	44.2	Fine-6	Pan	A
UHPC-15	1305	0.18	20	0	0	76.0	Fine-6	Pan	A
UHPC-16	1305	0.16	20	0	0	88.5	Fine-6	Pan	A
UHPC-17	1424	0.16	20	0	0	124.0	Fine-6	Pan	A

Table 4-2 - Mix Proportions. (Cont.)

Mixture	Binder (kg/m^3)	*w/b*	Silica fume (%)	Fly ash (%)	Steel fiber (%)	HRWRA (kg/m^3)	Fine aggregate	Mixer type	Curing regimen
UHPC-18	1424	0.20	20	0	0	48.2	Fine-6	Pan	A, B
UHPC-19	1543	0.16	20	0	0	134.1	Fine-6	Pan	A
UHPC-20	1543	0.20	20	0	0	52.2	Fine-6	Pan	A
UHPC-21	1543	0.20	20	0	2	52.2	Fine-6	Pan	A
UHPC-22	1543	0.20	20	0	4	52.2	Fine-6	Pan	A
UHPC-23	1543	0.20	20	0	6	52.2	Fine-6	Pan	A
UHPC-24	1543	0.20	20	0	0	89.7	Fine-6	Pan	A
UHPC-25	1543	0.20	20	0	2	89.7	Fine-6	Pan	A
UHPC-26	1543	0.20	20	0	4	89.7	Fine-6	Pan	A
UHPC-27	1543	0.20	20	0	6	89.7	Fine-6	Pan	A
UHPC-28	1305	0.20	20	0	0	48.1	Fine-7	Pan	A, B
UHPC-29	1424	0.20	20	0	0	51.2	Fine-7	Pan	A, B
UHPC-30	1543	0.20	20	0	0	49.4	Fine-7	Pan	A, B
UHPC-31	1543	0.20	20	0	2	49.4	Fine-7	Pan	A, B
UHPC-32	1543	0.20	20	0	4	49.4	Fine-7	Pan	A, B
UHPC-33	1543	0.20	20	0	6	49.4	Fine-7	Pan	A
UHPC-34	1305	0.20	20	0	0	44.2	Fine-6	Drum	A
UHPC-35	1305	0.20	20	0	0	50.4	Fine-6	Drum	A
UHPC-36	1305	0.20	20	20	0	50.4	Fine-6	Drum	A, B
UHPC-37	1305	0.20	20	0	2	50.4	Fine-6	Drum	A, B
UHPC-38	1305	0.20	20	0	4	63.2	Fine-6	Drum	A, B
UHPC-39	1305	0.20	20	0	6	69.5	Fine-6	Drum	A, B
UHPC-40	1543	0.20	20	0	0	59.5	Fine-7	Drum	A, B
UHPC-41	1543	0.20	20	0	2	59.5	Fine-7	Drum	A
UHPC-42	1543	0.20	20	0	4	59.5	Fine-7	Drum	A
UHPC-43	1543	0.20	20	0	6	59.5	Fine-7	Drum	A
Economical Mixtures									
UHPC-44	1163	0.20	5.5	0	0	39.41	Fine-6	Pan	A, B
UHPC-45	1163	0.20	5.5	0	2	39.41	Fine-6	Pan	A, B
UHPC-46	1163	0.20	5.5	30	0	39.41	Fine-6	Pan	A, B
UHPC-47	1163	0.20	5.5	40	0	39.41	Fine-6	Pan	A, B, C, D, E, F, G, H
UHPC-48	1163	0.20	5.5	50	0	39.41	Fine-6	Pan	A, B
UHPC-49	1163	0.20	5.5	30	2	39.41	Fine-6	Pan	A, B
UHPC-50	1163	0.20	5.5	40	2	39.41	Fine-6	Pan	A, B, F
UHPC-51	1163	0.20	5.5	50	2	39.41	Fine-6	Pan	A, B

The percentage of silica fume was constant to 20% for mixtures UHPC-1 to UHPC-43. This content was chosen based on previous UHPC research [17]. The HRWRA dosage rate ensured all mixtures had adequate flowability. The *w/b* were constant for most mixtures so that the researchers could investigate the effect of fine aggregate type and size, steel fiber content, and other variables on concrete compressive strength. Mixtures UHPC-15 to UHPC-17, and UHPC-19 had different *w/b* in order to investigate the effect of water content on UHPC.

Two concrete mixers were used in this study: (1) laboratory Hobart 19 L (20 quart) pan mixer and (2) drum mixer (0.06 m^3) as shown in **Figure A4-2** of **Appendix A4**. The purpose was to explore if a drum mixer can mix UHPC and examine its effect on UHPC compressive strength.

Mixtures UHPC-44 to UHPC-51 are called *Economical Mixtures*, which aim at minimizing the cost of UHPC. The amount of binder was decreased to 1,163 kg/m^3 for these mixtures, and the cost was further reduced using Class C fly ash at cement replacement rates of 30%, 40%, and 50%. In order to decrease costs, the silica fume content was limited to 5.5% of the total binder content, and the steel fibers were limited to 2% of the volume. Finally, for these eight mixtures, Fine-6 was the fine aggregate employed.

Eight curing regimens were employed to examine their effect on concrete compressive strength. Curing regimen A was selected based on previous research [22]. Regimen A consisted of 2 days cured at 60°C and 3 following days cured at 90°C. Curing regimen B was similar to the first one, but concrete samples were additionally cured in an environmental chamber for 21 days at 23°C after the heat-curing periods. The compressive strength was tested at 28 days of age. The remaining curing regimens C to H had a longer curing period, which was up to 28 days. The graphical representation of all curing regimens is showed in **Figure A4-3** of **Appendix A4.** While the use of heat curing can accelerate hydration, the pozzolanic reactions between calcium hydroxide and fly ash can be slow. Extending the heat-curing period can accelerate the pozzolanic reactions and increase the concrete compressive strength [33].

The rheology of the UHPC mixtures was evaluated using the flow test (ASTM C1437) [34] as shown in **Figure A4-4**. This test is recommended for use with the mortar that presents plastic to flowable performance, and therefore, it is applicable for the fresh UHPC mixtures [6]. The results are presented in **Table B4-1**.

All mixtures followed the same mixing procedure. The cement, sand, silica fume, and/or fly ash were mixed for 10 minutes, and then water and HRWRA admixture were added gradually. The mixing time varied from 15 to 20 minutes for the pan mixer and from 45 to 60 minutes for the drum mixer. The compressive strength was measured using cylindrical molds of 75×150 mm. All specimens were cast without vibration. After demolding the samples at one day of age, the cylinders were placed into an end-grinder to remove any surface irregularities. The samples were then cured in the storage area. The compressive test was conducted according to ASTM C39/C39M (2010) [35]. The researchers only concentrate the on the concrete compressive strength in this study. The other significant mechanical parameters, typically including tensile strength and modulus of elasticity, or durability-related properties, have a strong correlation to the concrete compressive strength and can be interpreted using analytical equations.

4.4 EXPERIMENTAL RESULTS AND DISCUSSION

Table 4-3 presents compressive strength results of UHPC mixtures. Each strength value is an average of three cylinders. The highest and lowest compressive strengths were 169.3 MPa and 79.7 MPa, respectively.

Table 4-3 – Compressive strength results of UHPC mixtures

Mixture	Heat Cured Compressive Strength (MPa)	28-day compressive strength (MPa)
UHPC-1	81.2	n/a
UHPC-2	79.6	n/a
UHPC-3	130.8	n/a
UHPC-4	158.0	n/a
UHPC-5	109.7	n/a
UHPC-6	113.6	n/a
UHPC-7	103.1	n/a
UHPC-8	143.2	n/a
UHPC-9	138.2	n/a
UHPC-10	143.3	n/a
UHPC-11	141.4	n/a
UHPC-12	144.8	n/a
UHPC-13	147.7	n/a
UHPC-14	162.2	n/a
UHPC-15	128.8	n/a
UHPC-16	141.8	n/a
UHPC-17	128.6	n/a
UHPC-18	141.4	138.0
UHPC-19	132.2	n/a
UHPC-20	141.8	144.9
UHPC-21	142.7	n/a
UHPC-22	150.1	n/a
UHPC-23	152.6	n/a
UHPC-24	131.0	n/a
UHPC-25	135.2	n/a
UHPC-26	134.5	n/a
UHPC-27	151.0	n/a
UHPC-28	132.0	128.6
UHPC-29	139.6	142.0
UHPC-30	142.3	159.6
UHPC-31	153.6	147.5
UHPC-32	151.5	151.7
UHPC-33	169.3	163.1
UHPC-34	136.1	n/a
UHPC-35	131.4	n/a
UHPC-36	107.0	125.7
UHPC-37	132.0	132.5
UHPC-38	126.9	126.2
UHPC-39	128.9	128.6
UHPC-40	145.1	151.9
UHPC-41	146.9	n/a
UHPC-42	151.0	n/a
UHPC-43	155.1	n/a

4.4.1 Effect of Fine Materials

Figure 1-4 shows the effect of fine materials on concrete compressive strength. The mixtures using Fine-1 (UHPC-1 and UHPC-2) had the lowest strength regardless of the HRWRA content. Fine-1 is an un-treated byproduct material from a local quarry, which possibly contaminated by weak minerals. The mixtures using Fine-2 (UHPC-3 and UHPC-4) had higher compressive strengths when compared to similar mixtures cast with Fine-1. Fine-2 is a material which was passes the No. 200 sieve. The use of fine sand is a key factor in producing UHPC that can improve the packing density of the mixture and produce a denser matrix [36]. Teichmann and Schmidt [37] reported that the packing density for non-UHPC concrete is approximately 0.68, and for UHPC it ranges from 0.71-0.87. For example, some proprietary mixtures contain sand having diameters ranging from 150 to 650 μm which are necessary to produce a minimum compressive strength of 150 MPa.

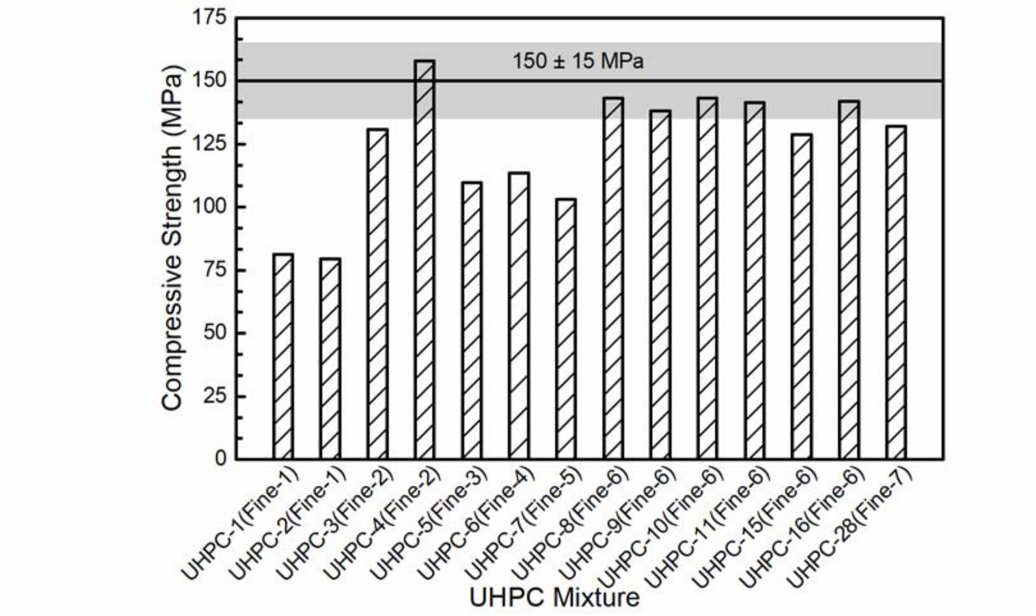

Figure 4-1. Effect of types of fine aggregate on concrete strength

As shown in **Figure 4-1**, all of mixtures including Fine-1, 3, 4, and 5 failed to produce the required strength of 150±15 MPa; where 150 MPa is the required UHPC compressive strength, and ±15 MPa is an assumed variation in measuring concrete compressive strength. Therefore, the use of these fines was eliminated for the further investigations. The incorporation of Fine-6 in mixtures UHPC-8 to 11, 15, and 16 improved the strength. The average compressive strength of these mixtures is 140 MPa. The use of different dosages of HRWRA and three *w/b* (0.20, 0.18, and 0.16) did not affect the strength considerably. The reduction in mixing water was offset by the additional water in HRWRA that resulted in similar total water content for above UHPC mixtures. Mixture UHPC-28 using Fine-7 (Class C flay ash) had compressive strength lower than the required strength. However, pozzolanic reactions between calcium hydroxide and the silica in the fly ash should continue to increase the long-term compressive strength. Alsalman et al. (2017) found that the 90-day compressive strength could be 30% higher than the strength at the end of heat-curing period.

4.4.2 Effect of Steel Fiber

Figure 4-2 illustrates the effect of steel fibers on concrete compressive strength. The use of 2% of steel fibers had a minor effect on the compressive strength. On average, compressive strength increased from 1% to 8%. The use of 4% fibers increased the strength from 3% to 6%. These results confirm the findings in the literature [38,39]. Steel fibers increase tensile strength; however, they have little effect on the compressive strength. When a concrete matrix resists to tensile stress, steel fibers effectively prevent the propagation of micro-cracks and transfer the stress crossing cracks. At a fiber content of 6%, the concrete compressive strength was increased by 7 to 19%. However, steel fibers are one of the main contributors to the high UHPC cost. A large amount of steel fibers (≥4% by volume) can increase concrete toughness but seldom used to increase for concrete stiffness. In the current practice, a fiber content of 2.0 to 2.5% is commonly recommended to reduce the brittleness and increase the ductility of UHPC structures [39,40].

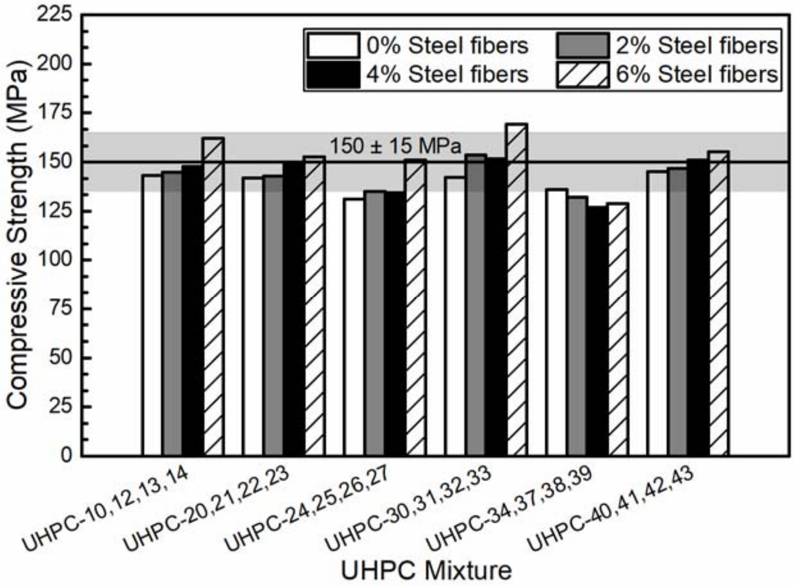

Figure 4-2. Effect of steel fibers on concrete strength

4.4.3 Effect of Binder Content and HRWRA

Figure 4-3a shows the effect of binder content on compressive strength. For UHPC mixtures using Fine-6, the increase in binder content had little influence on compressive strength. The use of low *w/b* is a possible factor attributing to this observation. When the water content is low, the amount of hydration products is limited. The remaining, unhydrated cement particles serve as a filler material in the matrix. For the mixtures using Fine-7, compressive strength increased with an increase in binder content. When binder content increases, the amount of fine aggregates decreases. During the heat-curing period, hydration reactions between cement and water are dominant in the paste matrix. The pozzolanic reaction between fly ash and calcium hydroxide generally occur at later ages. In other words, at the end of the heat-curing period, fly ash is possibly still inactivated and has minimal contribution to compressive strength when comparing to the unhydrated cement particles.

Figure 4-3b shows the increase in HRWRA content decreased compressive strength for the mixtures. HRWRA generally increases the *w/c* in the UHPC mixture proportions. In addition, HRWRA typically tend to add entrained air during mixing process, which also increases to the porosity of the concrete mixtures [41].

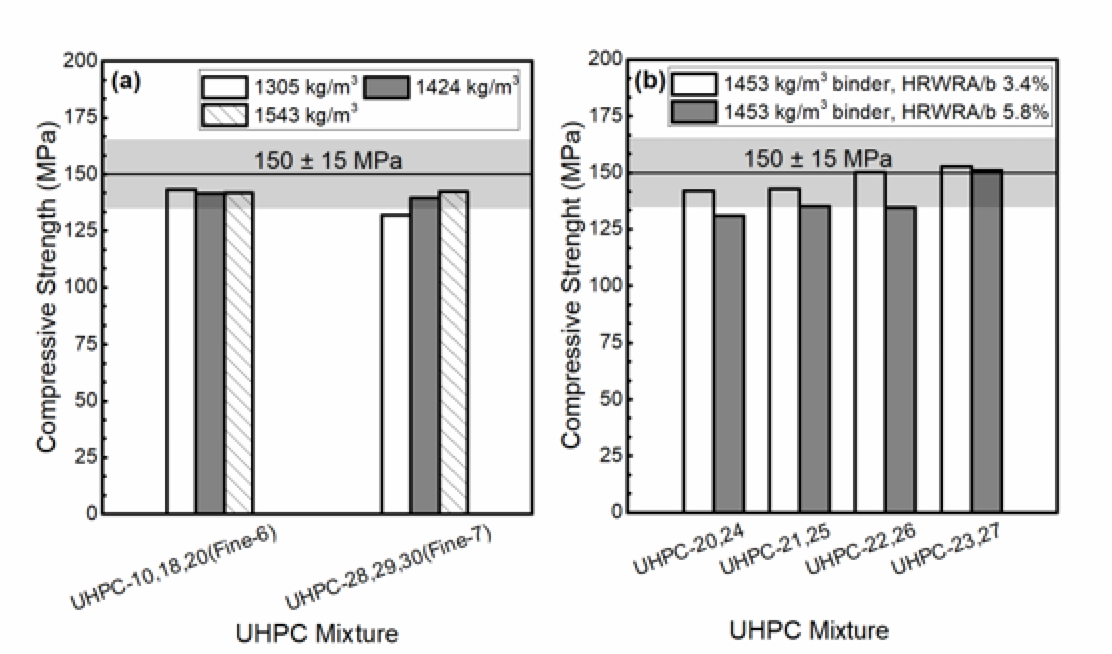

Figure 4-3 (a&b). **Effect of binder content and HRWRA on concrete strengh**

4.4.4 Effect of Mixer Type

Figure 4-4 presents the effect of mixer type on compressive strength. The mixtures batched using a pan mixer had higher compressive strengths when compared to the mixtures batched using a drum mixer. On average, the use of a pan mixer increased compressive strength by 8.3% higher when compared to the same mixture batched in a drum mixer. In addition, as fiber content increased, the difference in concrete strength was higher. The decrease in strength associated with the drum mixer can be attributed to the additional entrapped air in the concrete. The pan mixer provides a high shear action and reduces the amount of entrapped air in the concrete mixtures. In order to maintain the same concrete flows, most of the mixtures using the drum mixer had higher HRWRA content when compared to those batched using the pan mixer. Since the difference between strengths was relatively small, UHPC mixtures can be mixed with a regular drum rotating mixer; the average reduction in strength when using drum mixer is about 8.3%.

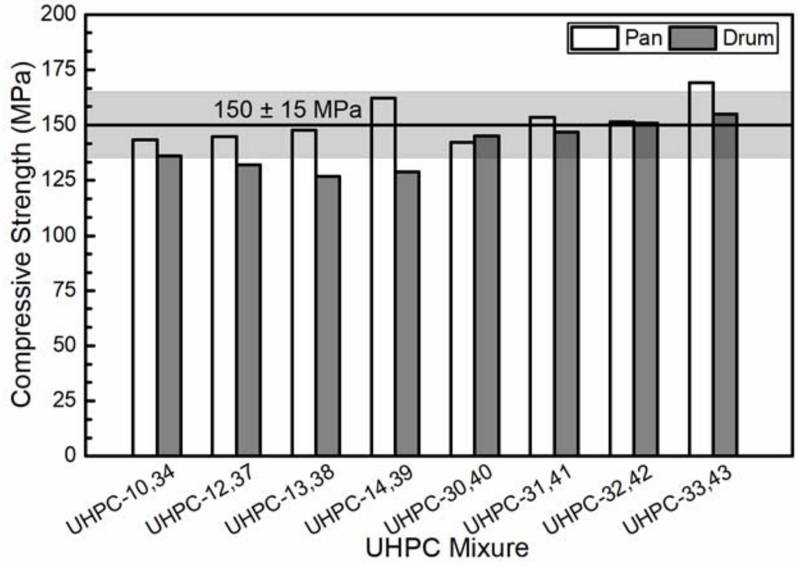

Figure 4-4. **Effect of types of mixers on concrete strength**

4.4.5 Effect of Additional Curing

Some of the UHPC mixtures were moist-cured after the heat-curing period to examine if the additional curing increased compressive strength. **Figure 4-5** compares the concrete strength of curing regiment A and B. For the curing regiment A, concrete samples were tested immediately after the 5-day heat-curing period. For curing regiment B, the samples were tested after the 26-day period, which included 5-day heat-curing period and 21-day moist-curing period. As shown in the figure, the additional 21-day curing period did not have a consistent effect on compressive strength. For some mixtures, the additional 21 days increased compressive strength when compared to the mixtures that were cured for only 5 days. For other mixtures, the opposite occurred.

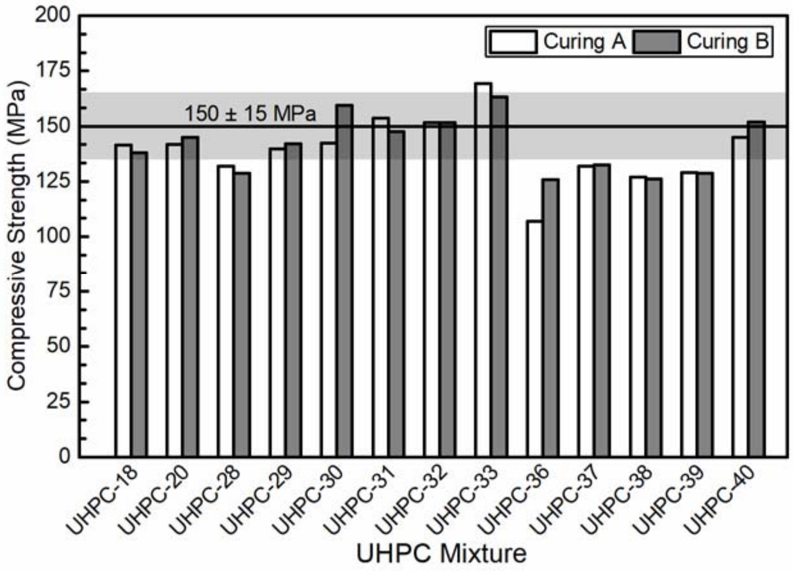

Figure 4-5. **Effect of additional moist curing on concrete strength**

4.5 ECONOMICAL MIXTURES

Table 4-4 presents the compressive strength of mixtures UHPC-44 to UHPC-51. For these mixtures, the binder content was reduced to 1,163 kg/m^3, and they contained Class C fly ash. This was done to reduce the cost of the UHPC (**Table 4-2**).

Table 4-4 – Compressive strength results of economical UHPC mixtures

Mixture	Curing regiments							
	A	B	C	D	E	F	G	H
UHPC-44	143.0	150.2						
UHPC-45	144.3	151.4						
UHPC-46	129.7	129.7						
UHPC-47	130.2	135.0	130.0	130.4	130	146.9	135.7	120.5
UHPC-48	82.0	111.1						
UHPC-49	132.7	131.1						
UHPC-50	133.4	136.6				149.7		
UHPC-51	86.3	110.3						

The compressive strength of mixtures UHPC-44, 46, 47, 48 and UHPC-10 shown in **Figure 4-6** indicates that the proposed reduction in binder content has minimal effect on the compressive strength. The incorporation of 30% or 40% of fly by weight of binder reduced compressive strength after the heat-curing period by approximately 9% when comparing to the mixtures containing no fly ash. For the concrete mixtures containing a high volume of fly ash, the fly ash reduced the early strength and did not affect by the heat curing (curing A). In particular, the compressive strength of UHPC-48 was 43% less than UHPC-44, which did not contain fly ash.

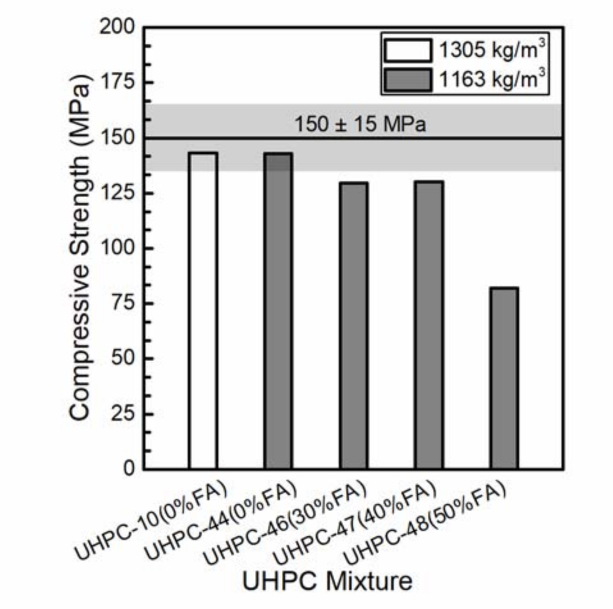

Figure 4-6. Effect of reduction in binder content and replacement of fly ash on concrete strength

A steel fiber content of 2.0% by volume was adopted from current commercially available UHPC mixtures. The premix UHPC from Ductal® and Cor-Tuf® UHPC mixtures typically contain 2.0 to 2.5% by volume of steel fibers. This amount of steel fibers aims to prevent a brittle failure. The experimental results shown in **Figure 4-7** indicate the minimal effect of steel fibers on concrete compressive strength. The UHPC mixtures containing 2% of steel fibers show a marginal increase in compressive strength when comparing to the mixtures containing no steel fibers. From the compressive-strength standpoint, steel fibers may be not necessary. Further research is needed to investigate the correlation between steel fiber content and failure mechanism of UHPC structures, which can lead to an optimal steel fiber content for UHPC mixture proportion.

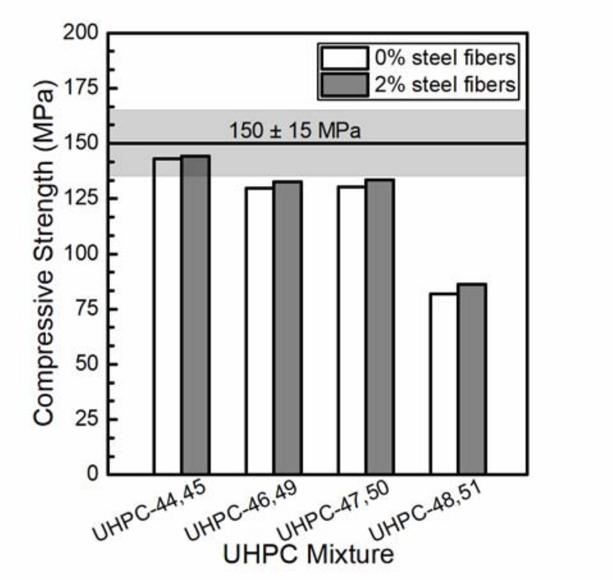

Figure 4-7. **Effect steel fibers on concrete strength**

Increasing fly ash content is a significant factor for further reducing UHPC cost. The experimental results shown in **Figure 4-8** indicate that the mixtures containing 50% fly ash (UHPC-48 and UHPC-51) had low compressive strength. On average, these mixtures achieved 84 MPa after the heat-curing period of 5 days, and the compressive strength increased about 30% after the additional moist-curing period of 21 days. However, the 28 day compressive strength was 25% lower than the proposed range of compressive strength for UHPC (150 MPa). For the concrete mixtures containing a large amount of fly ash, a longer curing period is needed for achieving the required strength [42]. For the concrete structures where the 28-day compressive strength is an important parameter for evaluating concrete quality, a Class C fly ash content of 50% may be not recommended.

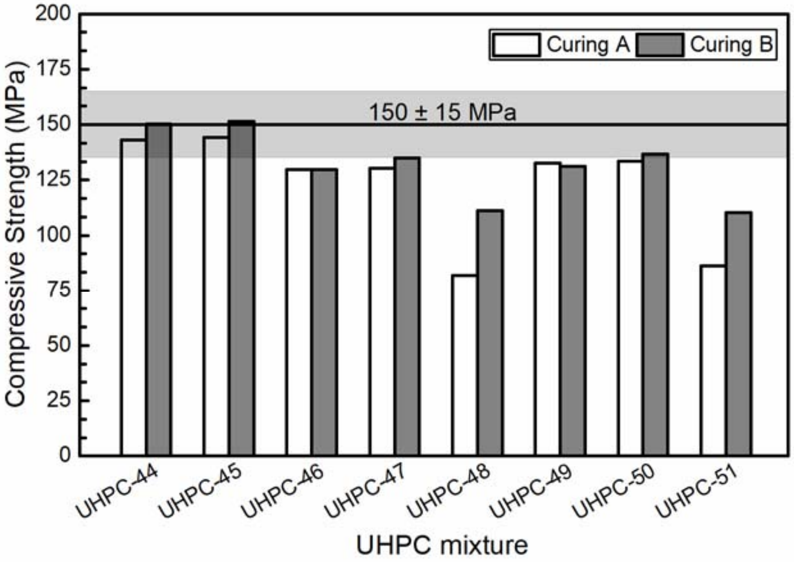

Figure 4-8. **Effect of additional moist curing on concrete strength**

The results of mixtures UHPC-46 and UHPC-47 show that the replacement of 30% to 40% of fly ash had minimal effect on the concrete compressive strength. Therefore, mixture UHPC-47 was further investigated using different curing regimens for cost optimization. **Figure 4-9** presents compressive strengths of mixture UHPC-47 subjected to different curing regimens (A, B, C, D, E, F, G, and H). There was little difference in compressive strength of curing regimens A to E. When the high-temperature curing period increases (curing regimen F), the strength increases about 12%. Under a higher curing temperature, the amount of hydration products increases. (Heinz, and Ludwig 2002). The standard curing regimen (curing regimen H) shows the lowest strength level (18% less when compared to curing regime F).

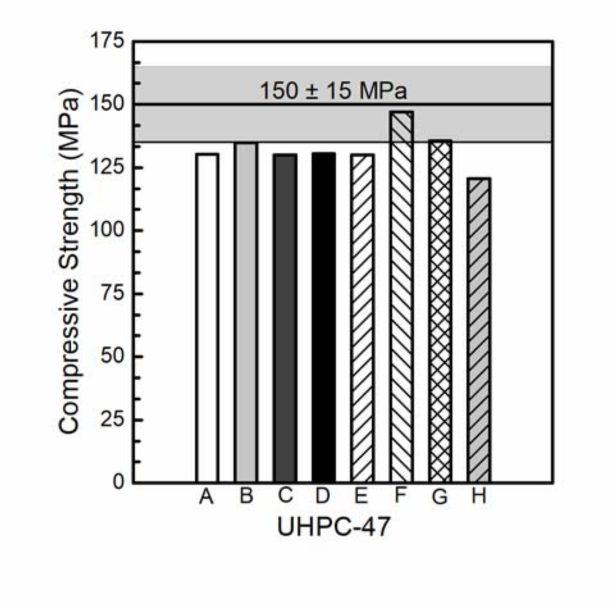

Figure 4-9. **Effect of different curing regimen on fly ash mixture. Note: The letters below columns represent different curing regiments presented in Figure 4A-3.**

4.5 COST ANALYSIS OF UHPC MIXTURES

Table 4B-2 in **Appendix B4** presents the cost of materials used in the research that are marketed in Arkansas, USA. **Table 4B3** summaries the cost of all UHPC mixtures per m^3. The highest cost is \$2,984 (UHPC-27) and the lowest is \$277 (UHPC-48). The addition of steel fibers is the main factor affecting the cost of UHPC mixtures. When finer materials were used, the cost increased due to extra amount of HRWRA. Using drum mixers increased the cost of UHPC mixtures due to the increase in HRWRA content. The reduction in binder content from 1,305 to 1,163 kg/m^3 and reducing the silica fume content from 20% to 5.5% decreased the cost by 32%. Additional reduction in cost was obtained by replacing a portion of the binder with fly ash. The minimum cost of a 150-MPa concrete mixture is \$307 (UHPC-44), which is 3 to 7 times less than the premix UHPC shown in **Table 4-1**.

Figure 4B-1 plots the cost versus compressive strength for UHPC mixtures that have achieved at least 150 MPa. The figure shows that there is no linear relationship between cost and strength; material selection plays a more important role. **Figure 4B-1** shows that UHPC-22, 44, and 50 achieved a compressive strength of approximately 150 MPa. The difference in their costs is noticeable due to binder content and steel fibers. UHPC-22 contains 4% steel fibers by volume, whereas, UHPC-44 and UHPC-50 contained 0%, and 2% fibers.

4.6 CONCLUSION

The following conclusions can be drawn:

1. UHPC mixtures were successfully developed using locally available materials found at AR, USA. The use of natural gradation sand was efficient in producing UHPC mixtures having compressive strength of 143 MPa.
2. UHPC mixtures were mixed by pan and drum rotating mixers. Mixtures batched in a pan mixer had compressive strengths 8% higher than mixtures batched in a drum mixer.
3. When Class C fly ash was used as a fine material, the highest compressive strength in the research project was achieved (169 MPa).
4. Mixtures with 1163 kg/m^3 of binder content achieved a strength of 150 MPa. This was achieved in mixtures with and without steel fibers.
5. By using a binder content of 1163 kg/m^3 and incorporating fly ash as a part of the binder, the cost was \$283/m^3 without steel fibers.

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APPENDIX 4A

Table 4A-1 – Cement properties

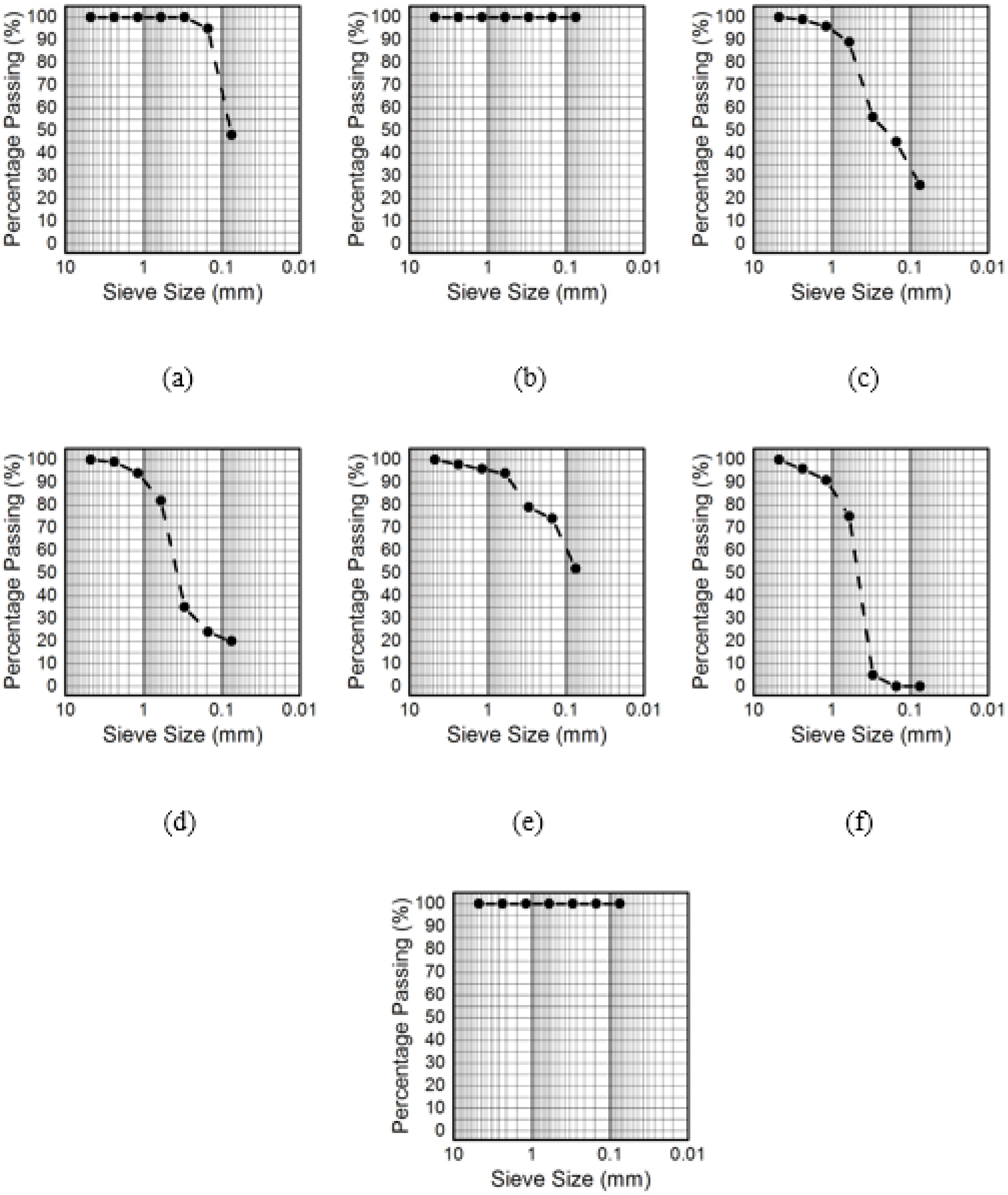
Item	Description
Chemical	
SiO_2	20.11%
Al_2O_3	5.07%
Fe_2O_3	3.80%
CaO	64.15
MgO	0.98
SO_3	3.23
Loss on ignition	2.39%
Na_2O	0.18%
K_2O	0.56%
Insoluble Residue	0.40%
CO_2	1.09%
Limestone	2.80%
$CaCO_3$	88.23%
Potential compounds	
C_3S	55%
C_2S	14%
C_3A	7%
C_4AF	11%
$C_3S + 4.75\ C_3A$	88%
Physical	
Air content of mortar (volume)	8%
Fineness	4.5 m^2/g
Autoclave expansion	-0.01%
Mortar Bar Expansion	0.00%

Table 4A-2– Fly ash properties

Item	Description
SiO_2	36.73%
Al_2O_3	21.49
Fe_2O_3	5.68%
CaO	22.70%
Na_2O	1.48%
K_2O	0.57%
MgO	4.30%
∑ Oxides	63.90%
∑ Alkalis	29.05%

Table 4A-3 – Silica fume properties

Item	Description
Chemical	
SiO_2	95.25%
SO_3	0.08%
Cl^-	0.11%
Total alkali	0.42%
Moisture content	0.52%
Loss on ignition	1.88%
pH	8.06%
Physical	
% retained on 45 μm sieve (wet sieved)	0.49%
Specific gravity	2.24
Bulk density - (per ASTM C1240 - 15)	696.71 kg/m^3
Specific surface area	24.49 m^2/g
Accelerated pozzolanic activity index - with Portland cement	124.44%



(a) (b) (c)

(d) (e) (f)

(g)

Figure 4A-1. Gradation of fine aggregates. Fig. A1a to A1g are corresponding to Fine-1 to Fine-7, respectively.

Figure 4A-2. Two types of mixers.

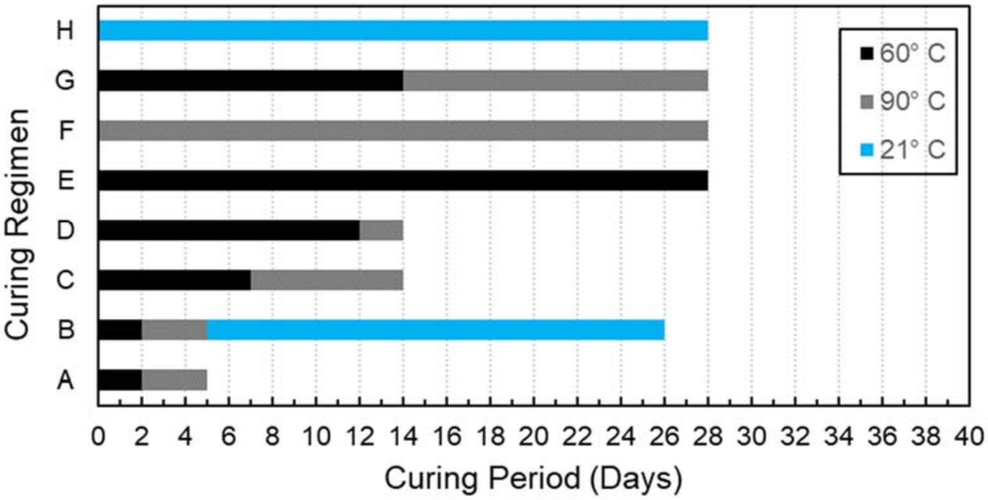


Figure 4A-3. Graphical representation of curing regimen

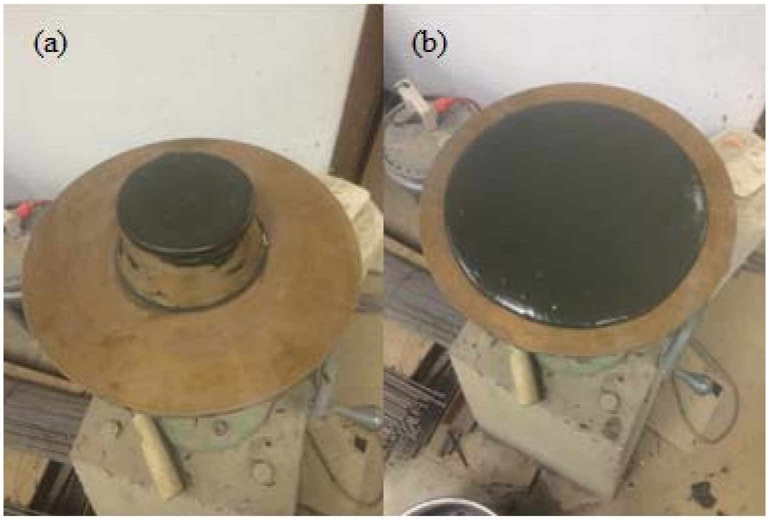


Figure 4A-4. Flow test procedure

APPENDIX 4B

The flow of concrete is calculated using Eq. B1. The initial and final diameters measured in the flow tests are presented in Table A1.

$$Flow = \left(\frac{D_f - D_i}{D_i} \right) \times 100 \qquad \text{(Eq. B1)}$$

where D_i and D_f are the initial and final diameters in the flow test, respectively.

Table 4B-1 – Flow results

Mixture	D_i (mm)	D_i (mm)	Flow (%)
UHPC-1	180	215	19
UHPC-2	185	230	24
UHPC-3	185	235	27
UHPC-4	170	200	18
UHPC-5	185	220	19
UHPC-6	185	225	22
UHPC-7	180	215	19
UHPC-8	180	220	22
UHPC-9	170	200	18
UHPC-10	165	195	18
UHPC-11	170	195	16
UHPC-12	160	185	13
UHPC-13	155	175	10
UHPC-14	155	170	15
UHPC-15	165	195	18
UHPC-16	165	190	15
UHPC-17	175	205	17
UHPC-18	180	215	19
UHPC-19	180	215	19
UHPC-20	175	210	20
UHPC-21	170	200	18
UHPC-22	170	195	15
UHPC-23	165	185	12
UHPC-24	190	230	21
UHPC-25	185	220	19
UHPC-26	180	210	17
UHPC-27	170	195	15
UHPC-28	165	190	15
UHPC-29	175	205	17
UHPC-30	175	205	17
UHPC-31	175	205	17
UHPC-32	175	200	14
UHPC-33	175	195	11
UHPC-34	165	185	12
UHPC-35	165	190	15

Table 4B-1 - Flow results. (Cont.)

Mixture	*D_i* (mm)	*D_i* (mm)	Flow (%)
UHPC-36	175	205	17
UHPC-37	160	180	13
UHPC-38	160	185	16
UHPC-39	165	190	15
UHPC-40	180	205	14
UHPC-41	175	195	11
UHPC-42	170	190	12
UHPC-43	165	180	9
UHPC-44	165	195	18
UHPC-45	160	185	16
UHPC-46	170	200	18
UHPC-47	175	210	20
UHPC-48	185	235	27
UHPC-49	170	200	18
UHPC-50	170	200	18
UHPC-51	180	225	25

Table 4B-2 – Cost of materials.

Material	Cost (per Ton)
Cement, Type I	$82
Silica fume	$800
Flay ash, Class C	$40
Ground quartz	$800
Steel fibers	$5,000
HRWRA	$3,400
Fine-1	$0[b]
Fine-2	$100 [a]
Fine-3	$23
Fine-4	$19.5
Fine-5	$6.5
Fine-6	$26
Fine-7	$40

Note: [a] Natural Gradation Sand (NGS) cost = $26/Ton
Cost of labor work to produce Fine-2 per hr. = $7.5
Required hours to produce a ton of Fine-2= 10 hours
Cost of Fine-2 = cost of a ton of raw materials ($26) + cost of labor (required hrs. x wage/hour)
= $26.0 + (10 hrs. x 7.5) = $101

[b] Fine-2 was obtained from a recycling plant with $0 cost

Table 4B-3 – Cost of UHPC mixtures.

UHPC Mixture	Price (USD/m^3)
UHPC-1	699
UHPC-2	780
UHPC-3	852
UHPC-4	730
UHPC-5	675
UHPC-6	672
UHPC-7	704
UHPC-8	554
UHPC-9	472
UHPC-10	452
UHPC-11	420
UHPC-12	1,232
UHPC-13	2,012
UHPC-14	2,792
UHPC-15	556
UHPC-16	597
UHPC-17	734
UHPC-18	488
UHPC-19	790
UHPC-20	524
UHPC-21	1,304
UHPC-22	2,084
UHPC-23	2,864
UHPC-24	644
UHPC-25	1,424
UHPC-26	2,204
UHPC-27	2,984
UHPC-28	465
UHPC-29	498
UHPC-30	515
UHPC-31	1,295
UHPC-32	2,075
UHPC-33	2,855
UHPC-34	452
UHPC-35	472
UHPC-36	460
UHPC-37	1,252
UHPC-38	2,073
UHPC-39	2,873
UHPC-40	554
UHPC-41	1,334

Table 4-B3 - Cost of UHPC mixtures. (Cont.)

UHPC Mixture	Price (USD/m^3)
UHPC-42	2,114
UHPC-43	2,894
UHPC-44	307
UHPC-45	1,078
UHPC-46	289
UHPC-47	283
UHPC-48	277
UHPC-49	1,087
UHPC-50	1,063
UHPC-51	1,057

Note: The cost of each concrete components is mentioned in **Table 4-B2**.

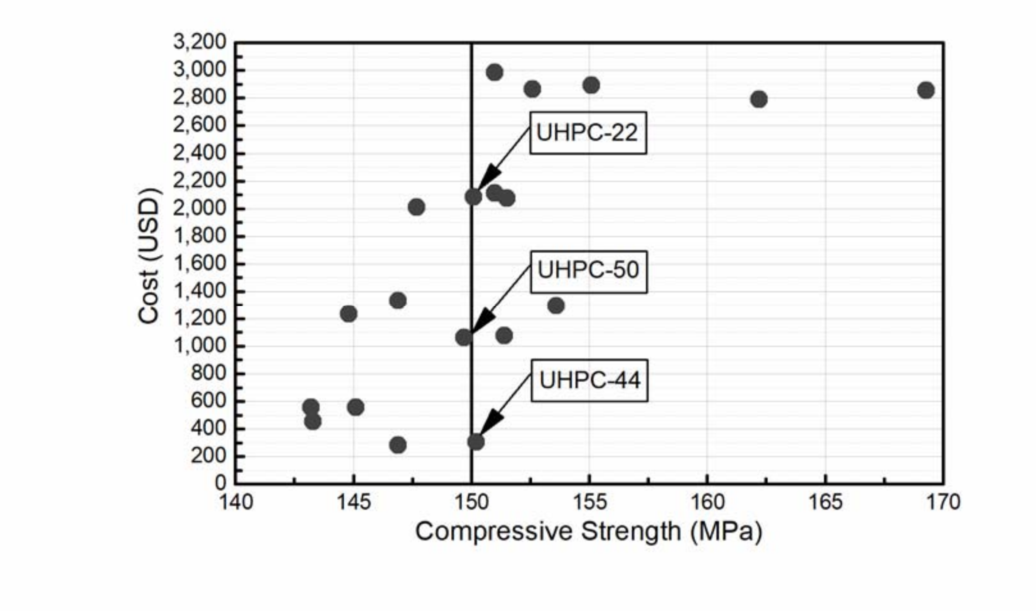


Figure 4B-1. Cost of UHPC

CHAPTER 5: CONCLUSIONS, CONTRIBUTIONS, AND FUTURE WOTK

5.1 CONCLUSIONS

The first objective of this dissertation was to develop Ultra-High Performance Concrete (UHPC) using locally available materials. The second objective was to develop an equation for predicting the elastic modulus of UHPC for a given compressive strength. Finally, the third aim was to minimize the cost of UHPC. The conclusions from the research program are listed below.

1. UHPC with a compressive strength of 155 MPa is successfully developed at 90 days of age with standard moist curing by using locally available materials in Northwest Arkansas.
2. The incorporation of ultra-fine sand enhanced the strength of UHPC compared to natural gradation sand; however, the effects minimal when silica fume is not incorporated.
3. Generally, incorporation of fly ash decreases UHPC strength at early ages but increases strength at later ages. A 30% incorporation of fly ash yields the highest strength at 90 days of age. 20% fly ash has minimal influence on strength at all ages.
4. Specimen size affects the strength of UHPC. The strength of cubed specimen is 11% greater than the strength of cylindrical specimens. The reason can be attributed to that contact area of cubes with the upper platen in the testing machine is more which results in more confinement.
5. An empirical equation to predict the elastic modulus of UPC is proposed by this research with an error of ±10%. The developed equation provided a reasonable prediction for elastic modulus for the data collected from literature. however, the proposed equation overestimates MOE for UHPC with local materials.

6. The replacement of natural gradation sand by fly ash can reduce the strength and the elastic modulus of UHPC mixtures.
7. Mixer type affects the strength of UHPC. Mixtures batched with a pan mixer had 8% higher strength compared with mixtures batched with a drum mixer.
8. By reducing the binder content to 1163 kg/m^3 and incorporation of fly as part of cementitious material, a UHPC mixture with a cost of \$283/m^3 is developed.

5.2 CONTRIBUTION TO THE BODY OF KNOWLEDGE

Number of studies has been carried out on developing of UHPC mixtures due to the need for a high strength and durable construction materials and several products have been introduced to the concrete market. However, there are no specifications and standards for mixture design. Therefore, this research provides simple guidelines for developing of UHPC mixtures. The following contributions are pointed out:

1. Development of UHPC by proposing mixture proportions can be made and mixed with locally available materials. The proposed mixtures consider the effect of multiple factors, such as binder content, supplementary cementitious materials, curing regimen, steel fibers, and mixture type.
2. Proposed an equation to estimate the elastic modulus of UHPC based on the most relevant and current data from literature (223 data points). The compressive strength and elastic modulus range 31 to 235 MPa, and 25 to 68.3 GPa, respectively.

$$E_c = 8,010\left(f_c'\right)^{0.36}$$

3. Reduce the cost of UHPC mixture compared to marketed premix, such as Ductal®. The research proposed a UHPC mixture with a cost of \$283/m^3. However, Ductal® costs approximately 2000/m^3.

5.3 FUTURE WORKS

Further experimental investigation may be considered for additional reduction in cost of UHPC. This can be achieved by using supplementary cementitious materials rather than silica fume. Another idea is produced green UHPC. Generally, mixture proportion of UHPC contains a high amount of portland cement. Cement production is one of the main sources of energy consumption and CO_2 emission. Therefore, future work may consider developing sustainable UHPC mixtures. Cement content can be optimized by using Vitrified Calcium Aluminio-Silicate (VCAS) pozzolans. VCAS pozzolans are green construction materials from industrial by-products and can alternatively replace cement at a ratio of 1:1. Also, by-product glass powder can be used as micro-filler material in sustainable UHPC mixtures. A complete testing matrix, with different percentages of glass powder, and VCAS, need to be considered for sustainable UHPC mixtures