POTENTIAL APPLICATION OF ULTRA-HIGH PERFORMANCE FIBER-REINFORCED CONCRETE WITH WET-MIX SHOTCRETE SYSTEM IN TUNNELING

By

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Abstract

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SYSTEM IN TUNNELING

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In the tunneling industry, shotcrete has been used for several decades. The use of shotcrete or wet-mix spray-on methods allows the application of this method in complex underground profiles and shapes. The need for time efficient spraying methods and constructability for lining coverage opens the door for technologies like steel and synthetic fiber reinforced shotcrete to achieve a uniform and a good quality product. An important advantage of the application of fiber reinforced concrete in shotcrete systems for tunneling is that almost no steel fixing is required. This leads to several other advantages including safer working conditions during excavation, less cost, and higher quality achieved through the use of this new technology. However, there are still some limitations. This research presents an analysis and evaluation of the potential application of a new R&D product, ultra-high-performance fiber-reinforced concrete (UHP-FRC), developed by UTA associate professor Shih-Ho (Simon) Chao. This research will focus on its application to tunnel lining using a wet-mix shotcrete system. The objectives of this study are to evaluate the potential application of UHP-FRC with wet-mix shotcrete equipment. This is the first time UHP-FRC has been used for this purpose; hence, this thesis also presents a preliminary evaluation of the compressive and tensile strength of UHP-FRC after application with shotcrete equipment, and to identify proper shotcrete procedures for mixing and application of UHP-FRC. A test sample was created with the wet-mix shotcrete system for further compressive and tensile strength analysis and a proposed plan was developed on the best way to use the UHP-FRC in lining systems for the tunneling industry. As a result of this study, the viscosity for pumpability was achieved for UHP-FRC. However, the mixer was not fast enough to efficiently mix this material. After 2 days, material strength showed 7,200 psi, however, vertical shotcrete was not achieved due to the flowability of the material. Further research with dry-mix shotcrete is recommended.

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Chapter 1

Introduction and Background

This chapter presents a brief introduction and background of the innovative research conducted to demonstrate ultra-high performance fiber-reinforced concrete (UHP-FRC) as a viable material for shotcrete systems and the current applications of shotcrete in the different concrete industry segments. It presents the research needs, objectives, methodology, and results of this investigation. It also presents a brief introduction to the shotcrete system as a potential application with the ultra-high performance fiber-reinforced concrete (UHP-FRC) and how this material will benefit the shotcrete systems for tunneling lining.

1.1 Introduction to Concrete

Concrete is a simple mixture of aggregates (fine and coarse) with a paste. Portland cement and water create the paste which covers the surface area of fine and coarse aggregates. Once hydration with water occurs through a chemical reaction, the mixture hardens and becomes strong enough to form the rock-like material mass commonly known as concrete. This process creates remarkable mechanical properties such as plasticity and malleability when mixed, and strength and durability when it hardens. These properties have made concrete essential to modern day construction.

1.1.1 Concrete Composition

The quality of the concrete depends on the proper proportioning of filler (fine or coarse aggregate) and binder (cement paste) If the mixture lacks the consistency needed to fill all the voids between fine and coarse aggregates, it will have low workability, and once it hardens it will produce a concrete with rough surfaces, a lot of voids, lack of tensile strength and can even become brittle. If the mixture has an excessive amount of paste, it will have a great workability while fresh and with smooth surface when it hardens; but it will be very expensive and with a high probability of cracking. In the case of concrete developed with Portland cement, the chemical hydration reaction happens in the presence of water. Cement and water combines to make a paste which covers all the surface area of each particle of fine and coarse aggregates. The cement in concrete needs moisture to cure or harden. When the hydration stops, the concrete stops gaining strength. Hence, when cement paste hardens and gains strength, the process is called hydration.

Concrete's quality depends largely on the quality of the cement paste, which depends on the proper proportion of the water-cement ratio. Water-cement ratio is the ratio of the weight of mixing water to the weight of the cementitious material. The concrete with a better quality comes from a low water-cement ratio without sacrificing workability of the concrete while fresh. Concrete needs to be properly placed, consolidated, and cured in order to obtain a good quality of hardened concrete.

A good concrete with good quality, workability while fresh, and strength with durability while hardened is due to a proper and proportioned mix design. Usually, a mix design is composed by 10 to 15 percent cement, 60-75 percent aggregates, 15-20 percent water, and 5-8 percent entrained air (Portland Cement Association, 2016). Regarding of the water used for concrete, any drinkable water that has no odor or taste can serve as mixing water for concrete. When water has an excess of impurities it can affect the process of hydration and strength while hardening. In the long term, water with impure elements could cause efflorescence, staining, corrosion of reinforcement, volume instability and, therefore, a reduction in durability. The specifications and standards for concrete mix designs will provide tolerances and limitations on the amount of chlorides, sulfates, alkalis, and solid particles in water. If a water test is performed, the reliability of the concrete is more accurate thereby proving the effect of impurities on hardened concrete.

1.1.2 Concrete Materials Selection

When selecting aggregates, the type and size of aggregates will depend of the thickness and purpose of the concrete. Aggregates make up 60-75 percent of the total volume of concrete (Portland Cement Association, 2016). This means that the selection of aggregates has an important role in the strength and durability of concrete. When a thin layer of concrete is required, the coarse aggregate will most likely be small. Aggregates up to six inches in diameter are used in large infrastructures such as dams or large columns. A proper gradation of particle size is recommended for an efficient use of cement paste. The deleterious materials or contamination in aggregates with other elements besides aggregates can tremendously affect the quality of concrete.

1.1.3 Mechanical Properties of Concrete

After mixing the main elements of concrete: aggregates, cement, and water, the mixture starts its hydration process and hardens. Portland cements are hydraulic cements which harden due to a chemical process called hydration. While hydration occurs, the microstructure of concrete forms when a node from a cement particle links up to another node adhering with that node and to the adjacent aggregates (Kendall et al. 1983). Before the concrete hardens completely, the concrete should be thoroughly mixed and placed. While placing the concrete, a process called consolidation helps concrete to eliminate air pockets or air voids, compacting and consolidating concrete monolithically. When concrete is used in slabs, concrete will have a surface finish once the moisture film disappears from the top surface; then a wood or metal hand float is used to smooth the concrete surface. The process of floating the concrete surface creates a relatively even surface with a slightly rough texture. The texture is used according to the purpose of the slab of concrete; a smooth or hard surface requires steel troweling.

While curing, the hydration process of cement continuously gains strength to harden concrete. Curing methods are used by sprinkling water fog, or by using moisture-retaining fabrics, such as burlap mats. Another curing method uses a curing membrane, which is a coating to eliminate the evaporation of water during hydration. Other curing methods used to improve hydration include sealing the surface plastic membranes or spraying curing compounds.

When weather conditions impact the process of curing, special techniques are used to protect the concrete from the effect of temperature variations without affecting the curing process. Moisture in concrete while curing helps to develop a strong, more durable concrete. The rate of the hardening speed depends on the fineness of the cement and the overall composition including proportioning of the mix design as well as moisture and temperature conditions while curing. Concrete gains strength while aging, which continues throughout the first month, but hydration will continue at a slower rate for many years.

1.2 Background

Ultra-high performance fiber-reinforced concrete (UHP-FRC) is a type of ultra-high performance concrete (UHPC), which is a class of advanced cementitious materials with improved strength and durability properties when compared to normal strength conventional concrete. The American Concrete Institute (ACI) defines ultra-high performance concrete (UHPC) as “concrete that has a minimum specified compressive strength of 150 MPa or 22,000 psi (ACI-239 UHPC, 2015) with specified durability, tensile ductility and toughness requirements; fibers are generally included to achieve specified requirements". The American Concrete Institute currently has an Ultra High Performance Concrete Committee (UHPC)-ACI 239, whose mission is to develop and report information on ultra-high performance concrete (UHPC) and its advances, in order to create the standardization process, QC/QA, certification, and ASTM testing procedures of ultra-high performance concrete (UHPC).

Ultra-high performance concrete (UHPC) shows elastic-plastic or strain-hardening characteristics under uniaxial tension and has very low permeability due to its dense mass. Ultra-high performance concrete (UHPC) typically has cement, silica fume, fine quartz sand, superplasticizers and fibers with water/binder-ratios ranging between 0.15 and 0.25 (American Concrete Institute, ACI-239 Committee-UHPC, 2015). Recently, UHPC has been developed with the addition of different cementitious materials, and other larger coarse aggregates. The new formulations on mix design sometimes contribute to an enhancement of one mechanical property of concrete, but at the same time could jeopardize other abilities of concrete.

The main characteristics of UHPC are reached through the following three principles (Richard and Cheyrezy 1995):

1. Homogeneity improves by eliminating coarse aggregates in concrete mass.
2. Density increases by optimizing the packing density of the concrete mass. This is achieved through optimizing gradation and mix proportions of concrete mass ingredients.

3. Ductility improves by introduction of fibers: When concrete too dense, it becomes very brittle; fiber reinforcement is added to obtain elastic-plastic or strain-hardening behavior in tension.

UHPC has more than two percent fiber volume fraction which is defined as volume of fibers/volume of composite. The maximum fiber content is a function of fiber aspect ratio and fiber shape as well as production issues such as workability. The UHPC study began when researching the behavior of high strength cement pastes with low water/binder-ratios of 0.20 to 0.30. It was found that cement pastes with low porosity will lead to compressive strengths of up to 200 MPa or 29 ksi and low strain deformations (Yudenfreund et al. 1972).

A literature search led to Roy et al. (1972) investigating strength enhancement by hot pressing techniques. This team of researchers was the first to apply hot pressing, and their results showed compressive strengths up to 680 MPa or 98 ksi with the use of superplasticizers (Roy et al.1972). By the 1980s, strength improvement was obtained by pozzolanic admixtures such as silica fume. By 1985, polymer modified cementitious materials called Macro-Defect-Free (MDF) concretes with a very dense matrix were developed, but were susceptible to water with a high creep (Alford and Birchall 1985). By 1987, densified small particle concrete (DSP) was being used to interact with superplasticizers and silica fume to decrease the porosity and increase strength. Dense small particle concrete (DSP) was the basis for UHPC (Bache, 1987). As stronger UHPC was developed, so did its brittleness; hence, various combinations of steel and synthetic fibers were used to increase ductility (Richard and Cheyrezy 1995).

The very first commercial applications of Ultra High Performance Concrete (UHPC) began in the 1990s in Europe, and now it is used worldwide. Several major research programs on UHPC have been carried out worldwide, such as early research in France and Japan, resulting in code-style guidelines (AFGC 2002), (JSCE 2008), a large federally funded program in Germany (Schmidt, Michael et al. 2008) as well as several research programs in Canada and the United States (Russell and Graybeal 2013, Graybeal 2011) specifically in US programs such as the Accelerated Bridge Construction (ABC) by the Federal Highway Administration (FHWA).

Ultra-High Performance Concrete (UHPC) has been used in multiple applications, such as bridges and infrastructure, facades, buildings, concrete elements exposed to harsh weather conditions, and for security and blast resistance. Applications include new construction and rehabilitation, using both cast-in-place and precast UHPC components. UHPC in its present form became commercially available in North America in 2000s. Ultra-High Performance Concrete (UHPC) is not yet commonly used due to its high cost when compared to conventional concrete.

1.3 Introduction to Shotcrete Systems

The history of shotcrete starts back in 1910 when a double-chambered cement gun based on a design developed by Carl Akeley, to make a cast from his animal shaped frames. According to the Kraemer Gunite, Inc. website (2013)**:** “He placed a dry plaster mix into a chamber, that resembled a pressure cooker, and used compressed air to push the powder thru a hose to a nozzle where mixing water was added.” A patent based o Akeley’s design was registered that same year whereby a double chamber “Cement Gun” was introduced to the construction industry in 1911. The sand-cement product created by this equipment has been registered under several trademark names including Guncrete, Pneucrete, Blastcrete, Blocrete, and Jetcrete. The terms “pneumatically applied mortar or concrete” and “sprayed concrete” were used to describe these systems’ new process. By

1930, the term “shotcrete” was coined by the American Railway Engineering Association to describe the Gunite process. In 1951, the American Concrete Institute started using the name “shotcrete” to describe the dry-mix process.

It is now also applied to the wet-mix process and has gained widespread acceptance in the United States and around the world. By 1950, the introduction of dry-mix guns was applied to mixtures containing coarse aggregate. Shotcrete technology also includes wet-mix shotcrete equipment such as a rotary gun and a continuous feed device. Consecutively, many more improvements were made to wet-mix equipment and materials in the 1970s and 1980s. These improvements allowed pumping low-slump concrete longer distances at greater volumes. These innovations enhanced the utility, flexibility, and general effectiveness of the process as noted in the American Concrete Institute Guide to Shotcrete. (ACI Guide to Shotcrete, 2005).

Recently, sprayed concrete has overcome the traditional methods of lining tunnel shapes and has become very important to the stabilization of excavated tunnel sections. Modern tunneling without sprayed concrete is considered unsafe, and unconceivable. Sprayed concrete is a single term that describes three components of a complete technology:

1. The material sprayed concrete.
2. The sprayed concreting process.
3. The sprayed concrete system.

These three components define a complete technology, which has a long tradition, a vast potential for innovation, and a great future. The material sprayed is a concrete mix design that is determined by the requirements of the application and specified parameters. Therefore, its maximum particle grading goes from 8 to 16 mm with an increase in binder content. Special sprayed concrete admixtures are used to control the properties of the material. Sprayed concrete was used for the first time in 1914 and has been permanently developed and improved over recent decades (Schlumpf et al. 2004).

There are now two different sprayed concrete processes: 1) the dry-mix process sprayed concrete and 2) the wet-mix process sprayed concrete. The main shotcrete requirements focus on workability (pumping and spraying applications) and durability. The requirements are (Schlumpf et al. 2004):

1. High early strength.
2. Good pump ability (dense-flow delivery).
3. The correct set concrete characteristics (initial setting).
4. Good spray ability (pliability or flexibility).
5. User-friendly workability (long open times).
6. Minimum rebound, or bouncing of material.

The sprayed concreting process will determine the type of installation. After the concrete mix is mixed according to design, the concrete is transported by conventional means to the process equipment. Sprayed concrete or sprayed mortar is fed to the point of use via excess-pressure-resistant sealed tubes or hoses and is sprayed on and compacted. The following methods are available for this stage of the process:

1. Dense-flow process for wet sprayed concrete.
2. Thin-flow process for dry sprayed concrete.
3. Thin-flow process for wet sprayed concrete.

Before the spraying process, the concrete passes through the nozzle at high speed. The jet is formed and the other relevant constituents of the mix are added, such as water for dry sprayed concrete, compressed air for the dense-flow process and setting accelerators when required.

The prepared sprayed concrete mix is then projected onto the substrate at high pressure which compacts so powerfully that a fully-compacted concrete structure is formed instantaneously. Depending on the setting acceleration, it can be applied to any elevation, including vertically overhead. The sprayed concrete process can be used for many different applications. Sprayed concrete and mortar is used for concrete repairs, tunneling and mining, slope stabilization and even artistic design of buildings. Sprayed concrete construction has various advantages:

1. Applications amenable to any elevation because sprayed concrete adheres immediately and bears its own weight.
2. Applications amenable to uneven substrates.
3. Good adhesion to the substrate.
4. Totally flexible configuration of the layer thickness on site.
5. Applications amenable to reinforced sprayed concrete (mesh/fiber reinforcement).
6. Achievement of rapid load-bearing skin without forms (shuttering) or long waiting times.

Sprayed concrete is a flexible, economic and rapid construction method, but it requires a high degree of mechanization, and highly trained specialists are essential for successful application of the shotcrete process. (Schlumpf et al. 2004)

1.4 Shotcrete

Shotcrete is a popular construction technique. Due to its research and development in materials, equipment, and construction procedures, there are periodical changes in the current industry practice. Shotcrete work orders are managed according to the process used (wet-mix or dry-mix) and the size of aggregate used (coarse or fine).

Dry-mix process consists of ingredients that are thoroughly mixed. A cementitious-aggregate mix is entered into a mechanical feeder called the delivery equipment and then introduced into a shotcrete hose by a pumping device such as a feed wheel, rotor, or feed bowl. Most of the time, the material is pushed by compressed air through the hose to a nozzle. The nozzle body is fitted inside with a water ring where water is introduced under pressure and thoroughly mixed with the other ingredients. The material is jetted from the nozzle at high velocity to shotcrete the area of work.

Wet-mix process consists of a process where all ingredients are thoroughly mixed. Then, the mortar or concrete is introduced into the pump to be pushed into the hose and conveyed by compressed air to a nozzle. Compressed air is injected at the nozzle to increase velocity and improve the shooting pattern. The mortar or concrete is jetted from the nozzle at high velocity to the area of work. Any of these processes produce shotcrete suitable for normal construction requirements. Equipment maintenance costs, operational issues, and placement properties will vary as mentioned in table 1-1; hence, different applications are required for different processes. According to the specific method, features associated with the shooting process such as compaction, rebound, and fiber orientation may affect the shotcrete properties. Water cement ratio is the most important factor for wet-mix shotcrete, as is the initial cement-aggregate ratio for dry-mix shotcrete.

The reduction of water to cement ratio improves the shotcrete strength, permeability, and durability. Accelerators, silica fume or other pozzolans modify physical properties, especially permeability and durability.

Table 1-1 Comparison of Dry-Mix and Wet-Mix Processes*

DRY MIX PROCESS	WET MIX PROCESS
Instantaneous control over mixing water and consistency of the mixture at the nozzle to meet variable field conditions.	Mixing water is controlled at the mixing equipment and can be accurately measured.
Better suited for placing mixtures containing lightweight aggregates or refractory materials.	Better assurance that the mixing water is thoroughly mixed with other ingredients.
Capable of being transported longer distances.	Less dust and cementitious materials lost during the shooting operations.
Delivery hoses are easier to move.	Normally has lower rebound resulting in less water.
Lower volume per hose size.	Higher volume per hose size.

* from Guide to Shotcrete (ACI Guide to Shotcrete, 2005).

The use of fibers will improve flexural strength and toughness. Proper curing is important and always improves the mechanical and physical performance of shotcrete. High-performance shotcrete is an innovative material-based system which develops high compressive strength, low permeability, high durability, and heat or chemical resistance.

The compressive strength of *dry-mix* shotcrete depends to a large extent on the cement aggregate ratio. Compressive strengths up to 12,000 psi (85 MPa) can be produced while strengths of 6,000 to 7,000 psi (40 to 50 MPa) are common. The reduction of water cement ratio using high-range water-reducing admixtures can produce high-strength in *wet-mix* shotcrete. Strengths over 14,000 psi (100 MPa) have been reported for *dry-mix*. Usually the strength of *wet-mix* shotcrete is between 4,000 and 7,000 psi (30 to 50 MPa). Early strength is critical in rehabilitation work, tunnels, and underground supports. Accelerators are used to accelerate the curing process, but they also affect the long term strength (ACI Guide to Shotcrete, 2005).

Nowadays, flexural properties are affected by steel or synthetic fibers. Fiber reinforcement develops durability and load-bearing capacity after cracking. It also helps control restrained shrinkage cracking and improves impact resistance. Bond strength is affected by the receiving surface, which usually bonds well with concrete, masonry, rock, steel, and many other materials. Bond strength is usually measured by shear or direct tension using a pull-off test. Shotcrete needs minimum tensile bond strength of 100 psi (0.7 MPa). Another parameter to pay attention to is shrinkage since it can lead to potential cracking and will incur costs, mainly in repairs. Shrinkage is greater in shotcrete than most conventional concretes due to a decrease of coarse aggregate and more cementitious material and water. Resistance to freezing and thawing depends on the water to cement ratio and encapsulation process or entrained-air-void.

Absorption and permeability are largely influenced by the water to cement ratio. The absorption value and the volume of permeable voids are useful in identifying poorly compacted shotcrete or shotcrete with a weak or damaged permeable voids or low absorption values. Low absorption values are an indication of a good quality shotcrete. High values of permeable voids or absorption usually indicate poor quality and a reduced durability of the in-place shotcrete.

1.4.1 Shotcrete Equipment

Shotcrete requires properly operated and maintained equipment. Equipment is selected for a project after a careful evaluation of the specifications, size and character of the work, job-site conditions, availability and quality of local materials, labor, and time available. The equipment consists of a gun or pump, a compressor, a mixer, nozzles, and miscellaneous hoses. First, the supervisor must know what process will be used, wet or dry mix process.

For dry-mix process, a gunite applicator is used (commonly called a gun). Shotcrete and gunite applicators may be divided into two distinct types: pressure vessels (batch) for dry mix application of shotcrete and rotary or continuous-feed guns for dry mix application of gunite. Guns are divided into batch guns or double chamber guns. Batch guns operate by placing a charge of material into the chamber and closing and pressurizing the chamber, causing the material to feed into a delivery pipe or hose. Double chamber guns allow for continuous operation by using the upper chamber as an airlock while operating. About rotary guns, there are two types: the barrel and the feed bowl. They are primarily dry-mix guns, but some types may be used for wet-mix applications.

For wet-mix process, a shotcrete system that pushes the concrete mixture through the delivery hose is needed while still fresh. A squeeze pump is used and uses mechanical rollers to squeeze the concrete through a tube into a delivery hose. These pumps now have been largely replaced by positive-displacement piston pumps with a hydraulically powered valve. The pressure in this pump is between 500 to 1,000 psi (3.5 to 6.9 MPa) for placement rates of 8 to 16 yd^3/h (6 to 12 m^3/h). The diameter of the outlet housing on most shotcrete pumps is 5 in. (125 mm). The ACI Guide to Shotcrete tells us that wet-mix shotcrete equipment is used where high volumes of concrete are needed (ACI Guide to Shotcrete, 2005).

Table 1-2 Compressor Capacities and Hose Diameters*

Material hose inside diameter, inches (mm)	Compressor Capacity	
	ft^3/min at 100 psi	m^3/min at 0.7 MPa
1 (25)	350	10.0
1-1/4 (32)	450	12.5
1-1/2 (38)	600	17.0
2 (51)	750	21.0
2-1/2 (64)	1000	28.0

* Guide to Shotcrete (ACI Guide to Shotcrete, 2005).

To select an appropriate hose for the material delivery depends on the material, and process to be used. Hose size and operating pressures should be analyzed and evaluated when selecting the appropriate hose as referred in table 1-2. A hose should be free of obstruction and have a minimum amount of joints for a proper delivery of material. Dry-mix equipment usually uses threaded and half-turn connectors. When an air hose is used in the shotcrete gun, the nozzle in the wet-mix process controls the pressure needed in the pipe to jet the materials. The air hose should be large enough to ensure a proper volume of air to operate the equipment. Air hoses should be capable of withstanding at least twice the operating pressure, and have an oil-resistant additive for kinking and abrasion. In the dry-mix process, the inside diameter of the air supply hose from the compressor to the gun should be at least as large as the inside diameter of the material hose. The water hose is used for supplying water to the booster pump, mixer, and nozzle.

Figure 1-1 Dry-mix Nozzle—from Guide to Shotcrete
(ACI Guide to Shotcrete, 2005).

The material delivery hoses are available in several different sizes and shapes for both dry- and wet-process shotcrete applications. The internal hose diameter should be three times the size of the largest aggregate particle in the mixture. Material hose diameter for steel fiber-reinforced shotcrete should be a minimum of one-and-a-half times the fiber length; for synthetic fibers, the multiple should be at least one. The material delivery hose in dry-mix should be lightweight and flexible, have an abrasion-resistant tube and cover, be non-collapsible, and resist kinking. Steel tubing 10 ft (3 m) long and 3 to 5 in. (75 to 125 mm) in diameter is frequently used in wet-mix shotcrete applications.

The sections of pipeline have the same type ends and use the same type couplers as the flexible material hose. Steel pipelines have less internal friction so the amount of force required to pump through a steel line is about 1/3 that required of a flexible line. The discharge nozzles consist of a nozzle body and nozzle tip and are attached to the end of the material delivery hose to inject water or air into the moving stream of materials. The nozzle also permits the addition of premixed water and solids and provides uniform distribution of the mixture.

The dry-mix nozzles should pattern the discharge as a uniform inner cone consisting primarily of solids and some water spray surrounded by a thin outer cone, which is mainly water spray. The nozzle tip size should not exceed the diameter of the hose and is often smaller. For the dry-mix nozzle a nozzle tip, water ring, control valve, and water body is needed as depicted in Figure 1-1.

The tip can be made of rubber, elastomer material, or metal with a rubber liner. In wet-mix, compressed air is injected in the nozzle to increase the exit velocity of the mixture as depicted in Figure 1-2. A typical wet-mix nozzle consists of a rubber or special plastic nozzle tip, an air injection ring, a control valve, and the housing.

Figure 1-2 Wet-mix Nozzle
--from Guide to Shotcrete (ACI 2005).

1.4.2 Shotcrete Plant Layout

The equipment should be placed as close to the work as possible to minimize the length of the material hose required. If the work is spread over a considerable area, the plant should be centrally located to reduce the number of equipment moves required to complete the project. To avoid duplicate material handling, the plant should be positioned so that material suppliers have easy and direct access to the mixer or pump. Proper maintenance of the equipment is a key requirement for producing high-quality shotcrete on a regular basis. Inspecting and cleaning each piece of equipment at least on a daily basis is imperative. Equipment should be greased, oiled, and generally maintained on a regular schedule. A preventive maintenance program should be established. Meetings should be held regularly to teach operators on the proper use and maintenance of their equipment. Adequate backup equipment and spare parts should be readily available to minimize downtime.

The crew should wear goggles, dust masks, or respirators. The crew should wear long-sleeve shirts to protect against cement burns. All guards and screens should be in place whenever any equipment is operating. The operator should relieve air pressure before opening any chamber or hose, and relieve pump pressure before opening the material line or pipeline. The operator should follow the manufacturer's operational recommendations and safety precautions. The crew should not insert shovels, bars, rakes, or other objects near or in moving parts of mixers. A shotcrete crew consists of a foreman, a nozzle operator, a finisher or rodman, an assistant nozzle operator, a gun or pump operator, a mixer operator, and laborers as shown on Figure 1-4. Some duties may be combined by having one person perform more than one operation. Other items to take into consideration in the layout plan is the control of mixing water, especially in the dry-mix process, where it could develop sagging, puddling, or dropouts in vertical and overhead applications. The Impact velocity of the material is an important factor in determining the ultimate properties of the shotcrete and to adequately encase reinforcement. The nozzle technique and proper manipulation is a must. Nozzle technique for wet-mix and dry-mix processes is generally similar, both requiring considerable attention to detail. Because the capabilities of wet-mix and dry-mix procedures and equipment are different, expertise from the nozzle operator is required. The mixture thickness and position of the work must be considered. Overhead work is typically gunned in layers just thick enough to prevent sagging or dropouts. Vertical surfaces may be applied in layers or as a single thickness, while horizontal or flat surfaces are usually gunned in a single thickness.

The shooting technique builds up several passes of the nozzle over a section of the work area. Whenever possible, sections should be gunned to their full design thickness in one layer, thereby reducing the possibility of cold joints and laminations.

Also, encasing reinforcement interrupts the material stream, so the area behind the bar is not compacted by the following stream of shotcrete material. This area behind reinforcement needs to be filled either by material that flows around the bar or by having the stream directed behind the bar. Multiple layers should be applied, first, by allowing a slight hardening or stiffening of the very first layers. Then all loose, uneven, or excess material, glaze, laitance, and rebound should be removed by brooming, scraping, or other means. Sandblasting or water blasting should remove any undesirable surface deposits that have taken a final set. Rebound and overspray are two of the undesirable issues in shotcrete. Both can be somewhat controlled or minimized by a nozzle operator with proper expertise. Overspray is light material carried away from the receiving surface and has similar characteristics in both the wet-mix and dry-mix processes. It adheres to round wire, shooting strips, forms, reinforcing steel and other projections, leaving an unconsolidated thickness of low-quality shotcrete. Rebound losses may be higher or lower depending on the expertise of the individual nozzle operator and the factors mentioned previously. Figure 1-3 describes the correct way for a thick shooting.

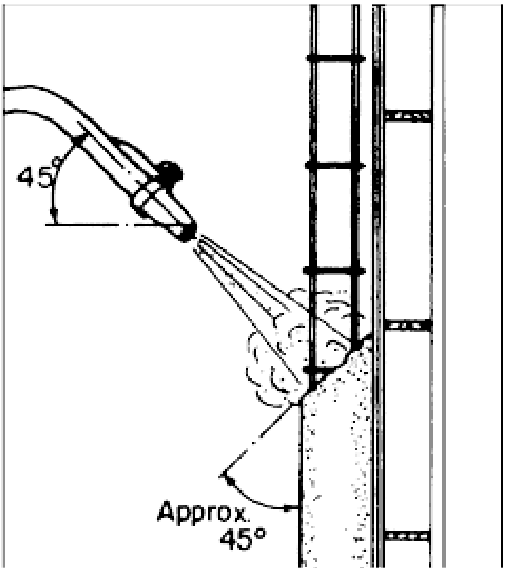


Figure 1-3 Correct Shooting Thick Applications
—from Guide to Shotcrete (ACI 2005).

Figure 1-4 Correct Shooting Position—from Guide to Shotcrete (ACI 2005).

1.5 Tunneling and Segmental Lining

Several tunnel concepts for design have been used throughout history. This is a summary of the most common methods used in tunneling systems.

1.5.1 Single Shell or Double Shell

The single shell method is a jointless construction method with many advantages. The term *“single shell sprayed concrete method”* does not refer to the placing of a single sprayed concrete layer but to the interaction of several layers as a single shell. No shear reinforcement is foreseen at the joints. The bond performance of the individual layers is, therefore, very important. A 5% fractile of the bond strength of 0.6 MPa or 87 psi is required. As no waterproof membrane is placed, several measures have to be taken to realize a watertight sprayed concrete and to minimize the tendency to crack (Harshol et al. 2007), (Vandewallen 2005).

The double shell method includes a geotextile and a plastic waterproofing membrane between the initial sprayed concrete support and the final in-situ concrete lining. Concrete is a permeable material through which water can seep. Water even finds an easier path through shrinkage cracks. Once these leaks start, they are difficult to eliminate. They cause an unsightly mess in the short term maintenance and durability problems in the long term. Leaks are also a potential safety hazard should the water ingress freeze on the road in winter conditions. Conventionally, tunnels constructed using sprayed concrete have been based on a temporary sprayed concrete lining to stabilize the opening after excavation and to contain short- to medium-term loads. When this lining has fully stabilized, a permanent cast in-situ concrete lining is installed to contain long-term loads and provide durability and water tightness. Water tightness is achieved by use of a waterproof membrane between the temporary and permanent linings as shown in Figure 1-5 (Selmer-Olsen, R. 1977).

Once the temporary sprayed concrete lining has been fully stabilized, a permanent cast-in situ concrete lining is installed to contain long-term loads, and provide durability and water tightness. This cast in-situ concrete lining is influenced from the ground pressures of dead load, relaxation, creep, swelling, landslips, earth subsidence, earthquake, water pressure, and chemical actions as a result of aggressive water or aggressive subsoil components. This cast in-situ concrete lining is also influenced by activities during construction such as removal of heat of hydration, shrinkage, transport activities for precast elements (segments), and jacking forces. Other deteriorating effects on the cast in-situ concrete lining while it is being used can come from temperature or chemical attacks from gases, sewage, deicing salt, traffic influences, transport of rubble stones in case of excess water pressure in tunnels and fire, which can happen in a transport tunnel. This tunnel’s final lining can be built using different techniques to create a shell made up of plain or reinforced concrete by spraying unreinforced shotcrete or reinforced shotcrete segments (Thomas, A., and Pickett, A. 2013).

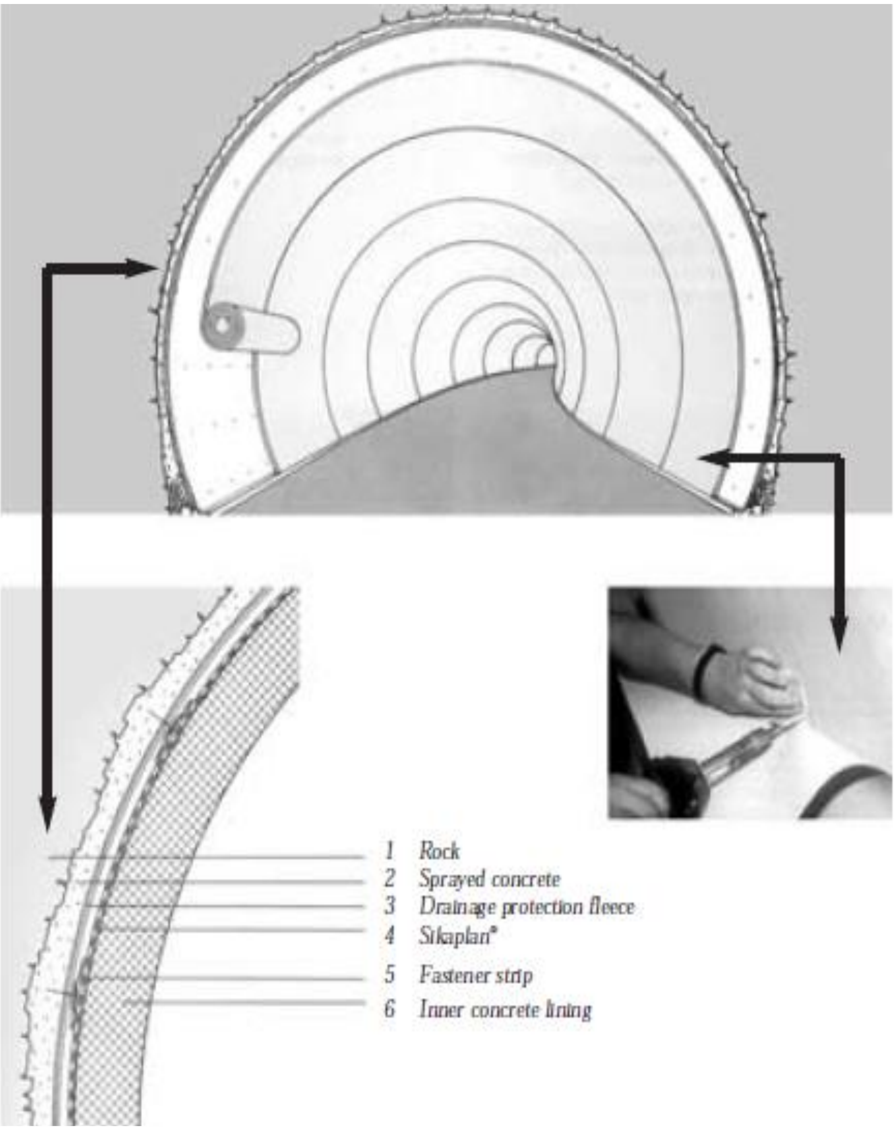


Figure 1-5 Tunnel Lining System from Vandewallen 2005.

1.5.2 New Austrian Tunneling Method (N.A.T.M.)

NATM may be defined as a method of producing underground space by using all available means to develop the maximum self-supporting capacity of the rock or soil to provide stability in the underground opening. The main principle of NATM can be explained as transforming the rock surrounding the tunnel profile from a load-exerting to a load-carrying member of the system. With modern support elements available such as (reinforced) sprayed concrete and rock bolting, and with the adoption of the right sequence of excavation and supporting procedures, the composite action between tunnel lining and rock mass can be largely achieved. Rabcewicz, who must be considered the main inventor of NATM, once compared the American method of “tunneling with steel supports” to the NATM method, which is described as “tunneling with rock supports.”

NATM is based on the principle of a two-shell design. While driving a tunnel, the existing, primary balance of forces in the rock mass will be changed into a new secondary and also stable state of balance. This can only be achieved through a succession of intermediate stages accompanied by various stress distribution processes. Rock deformation control is the first and primary issue. On the one hand, deformation should be kept to a minimum so that the primary state of stability and the compressive strength of the rock are not weakened more than is inevitable. On the other hand, deformation is actually wanted to the extent that the rock formation itself forms an overall ring-like support, minimizing costs for excavation and support.

A thin sprayed concrete lining is applied to establish a new state of equilibrium, which is recognized by checking the deformation process. The rock-mechanical function of a thin sprayed concrete lining has to be emphasized for its effects of a quick sealing of cracks and preventing the rock from disintegrating. NATM is classified as an observational method. The NATM philosophy aims at allowing a controlled deformation to take place, so that the support system carries a minimum load (Vandewallen, M. 2005).

1.5.3 Norwegian Method of Tunneling (NTM)

In the Norwegian Method of Tunneling, great emphasis is placed on the description of geological and geotechnical aspects of the project. Although the high level of experience in the Norwegian tunneling community has allowed “rules of thumb” and much “previous experience” to dictate a lot of support estimates, more and more companies are realizing the value of a documentation method such as the Q-system for regulating the description of rock mass conditions and support recommendations. The Q-system is an empirical method based on the RQD method of describing drill core and five additional parameters, which modify the RQD-value for the number of joint sets, joint roughness and alteration (filling), the amount of water, and various adverse features associated with loosening, high stress, squeezing and swelling. The rock mass classification is associated with support recommendations based on more than 2,000 case records.

The NMT appears most suitable for harder ground, where jointing and overreach are dominant, and where drill and blasting or hard rock TBM’s are the most usual methods of excavation. Bolting is the dominant form of rock support since it mobilizes the strength of the surrounding rock mass in the best possible way. Potentially unstable rock masses with clay-filled joints and discontinuities will need steel fiber reinforced sprayed concrete to supplement the systematic bolting (Vandewallen, M. 2005).

1.5.4 Tunnel Boring Machine (TBM)

Tunnel boring began close to the half of the 19th century, simultaneously yet independently in Europe and North America. A tunnel boring machine (TBM) can deliver economic tunnel excavation, reduce overreach and support, deal with difficult ground and complete on time projects. This method offers the advantage of constructing a constant tunnel cross section. Particularly in urban areas the use of a TBM proves to be very interesting as it provides a continuous support, even at a small overburden. The tunnel opening is lined immediately behind the TBM using mostly precast concrete segments. This of course reduces the risk for settlement of buildings in the neighborhood of the tunnel. The segments are precast at the job site or are brought in from a remote specialized precast concrete plant. The lining consists of concrete rings which are formed by putting several single pieces together. In a bolted lining the ring is formed by bolting the segments, in an expanded lining the ring is closed by using a keystone. In most ground conditions the segments forming a closed ring only have to resist normal compressive forces in their final position. However, these segments are subjected to different loading conditions before they get into their final place (Vandewallen, M. 2005).

The precast segments have to resist bending moments and flexural stresses when being demolded and transported to the storage facilities located outside the precast building. They have to resist tensile thermal stresses due to temperature changes at the storage area. The heaviest loading, however, takes place when the segments are being installed and have to resist the very high jack or ram loads of the TBM when moving forward. Cracking and spalling are the main problems of reinforced concrete segments. The heavy jack or ram loads are being applied at the outer unreinforced concrete skin of the segments. When spalling occurs a traditionally reinforced segment has to be repaired or even replaced for obvious reasons of durability concern. In Figure 1-6, a Tunnel Boring Machine is shown for reference.

1.5.5 Segmental Lining

In early times, tunnels were supported by timbers, shaped stones and bricks.

Later came steel girders, arches and ribs, often lagged by blocks and wood spacers. Smooth or corrugated bolted steel lining plates became popular, especially in the US, by virtue of low weight, predictable strength, fire resistance, ease of erection and suitability for back-grouting. Cast iron was first used to make segmental linings in the 19th century but has now generally been replaced by ductile spheroidal graphite iron.

During the 1930s concrete began to replace cast iron to make segments. Bolted concrete segments were used for the London Underground in 1936 and became available to build rings from 1.52 m (5 ft) to over 10 m (32.8 ft). Linings were developed to provide a smooth finish for sewer and water tunnels. Expanded wedge-block linings were introduced for use in cohesive clay, which could be excavated by shields to leave a smooth profile. The segments were placed directly against the clay surface and a wedge-shaped key provided compressive hoop stress to support the ring without the need for bolts or grouting. Many kilometers of wedge-block lining have been installed. Water tunnels constructed under London since 1991 have been lined with wedge-block rings with eight segments to a ring. Both single- and two-shell designs are possible in the case of segmental tunnel linings.

Two-shell tunnels have an outer lining with segments and an inner cast concrete shell as permanent lining. In the case of single shell construction, the segments act as the final lining so they have to comply with all the demands, resulting from construction conditions, the ground, groundwater conditions and tunnel use. The demands on the serviceability properties of segmental lining come from ground and water pressures. The need for higher concrete strength is governed both by construction (force transfer in the joints) as well as construction conditions (jacking forces, back up loads). Usually the segments are made of precast concrete as shown in Figure 1-7. Depending on the size of the tunnel and size of the segments themselves, reinforcement is introduced principally to withstand the stresses induced during the handling of the segments before installation and to resist the loads imposed by the rams of the TBM as it pushes off the lining as shown in Figure 1-8. Unreinforced segments are only used in the case of small tunnel cross-sections and low quality requirements (Abbas 2014).

Figure 1-6 Tunnel Boring Machine (TBM)
—from Vandewallen 2005.

The introduction of steel fiber reinforced concrete (SFRC) in tunnel linings is relatively recent. Steel fibers can be used to form a reduced standard reinforcement cage and under appropriate project conditions (diameter, underground), they can even serve as a complete substitution for a standard cage (Barták 2007).

Figure 1-7 Precast Segmental Lining
—from Vandewallen (2005).

Figure 1-8 Flatbed Trailer Loaded with Segments of Tunnel Lining
from Vandewallen (2005).

1.6 Ultra-High Performance Fiber-Reinforced Concrete (UHP-FRC)

Ultra-high performance fiber-reinforced concrete (UHP-FRC) is a type of ultra-high performance concrete (UHPC) with compressive strength of more than 150 MPa or 22 ksi with the addition of fibers. The fibers in UHP-FRC can cause brittleness to decrease that was developed due to high compressive strengths. Adding UHP-FRC can also increase the energy absorption capacity. UHP-FRC has high compressive strength, which was built into the concrete during the research stage using material science through the dense particle packing theory. This method allows higher durability, improves freeze-thaw resistance and has a higher penetration resistance to various chemicals (Palacios, G. et al. 2015).

UHP-FRC is not susceptible to alkali-silica reaction (ASR) due to the lack of coarse aggregates and the dense matrix in the mix design. These properties make the UHP-FRC structures durable, resilient, and blast and impact resistant. Other investigations developed compressive strengths between 120 to 250 MPa, or 17 to 36 ksi with the use of fibers. In 1995, a reactive powder concrete (RPC) was introduced and reported compressive strengths up to 800 MPa or 116 ksi, using a temperature of up to 400 °C or 750 °F with pressures of 50 MPa or 7.3 ksi, and 10% volume of steel fibers and steel aggregates (Richard and Cheyrezy 1995).

Methods with high temperature heat curing and pressure are considered impractical treatments for bulk applications by the concrete industry. Previous studies from Wille et al. (2011) demonstrated that by basic rules of mix design, the spread value in accordance with ASTM C230/C230M can be used as an indicator to optimize ultra-high performance cementitious paste, which consists of cement (C), water (W), silica fume (SF), glass powder (GP) and superplasticizer (SPL). Increasing the spread value by changing the type of material within its class, and/or by changing the materials. proportions indicates an improved particle packing while the amount of water is kept constant. The amount of water can be reduced while maintaining workability if we use this principle and reduce the water to cement ratio. Reducing the water to cement ratio will increase compressive strength. If the water to cement ratio is reduced without taking into consideration the packing density theory, it could lead to a decrease of workability and an increase in the amount of air voids in the matrix, which means that no improvements in compressive strength would be achieved (Wille et al. 2011).

Studies of Wille et al. showed that compressive strength can be related to the product (w/c x $air^{1/3}$) where air represents the percentage of ‘‘entrapped air.’’ It is also recommended that the most appropriate UHPC materials available on the US market use a UHPC mixture with compressive strengths over 190 MPa or 27.5 ksi after 28 days without special heat curing or pressure. The research design of a UHP-FRC calls for more than 200 MPa (29 ksi) in compressive strength, more than 10 MPa (1.45 ksi) in post-cracking tensile strength and an associated post-cracking strain capacity of at least 0.3% (which exceeds the yield strain of commonly used steel reinforcement). Tensile strengths in excess of the first cracking strength of the matrix are necessary to achieve multiple cracking, which is the key factor for a higher tensile strain at peak stress; therefore, more ductility is achieved. The proportions of the designed UHP-FRC mixtures are given in Table 3.

1.7 History and Current Applications of the Ultra-High Performance Fiber-Reinforced Concrete (UHP-FRC) to be Used

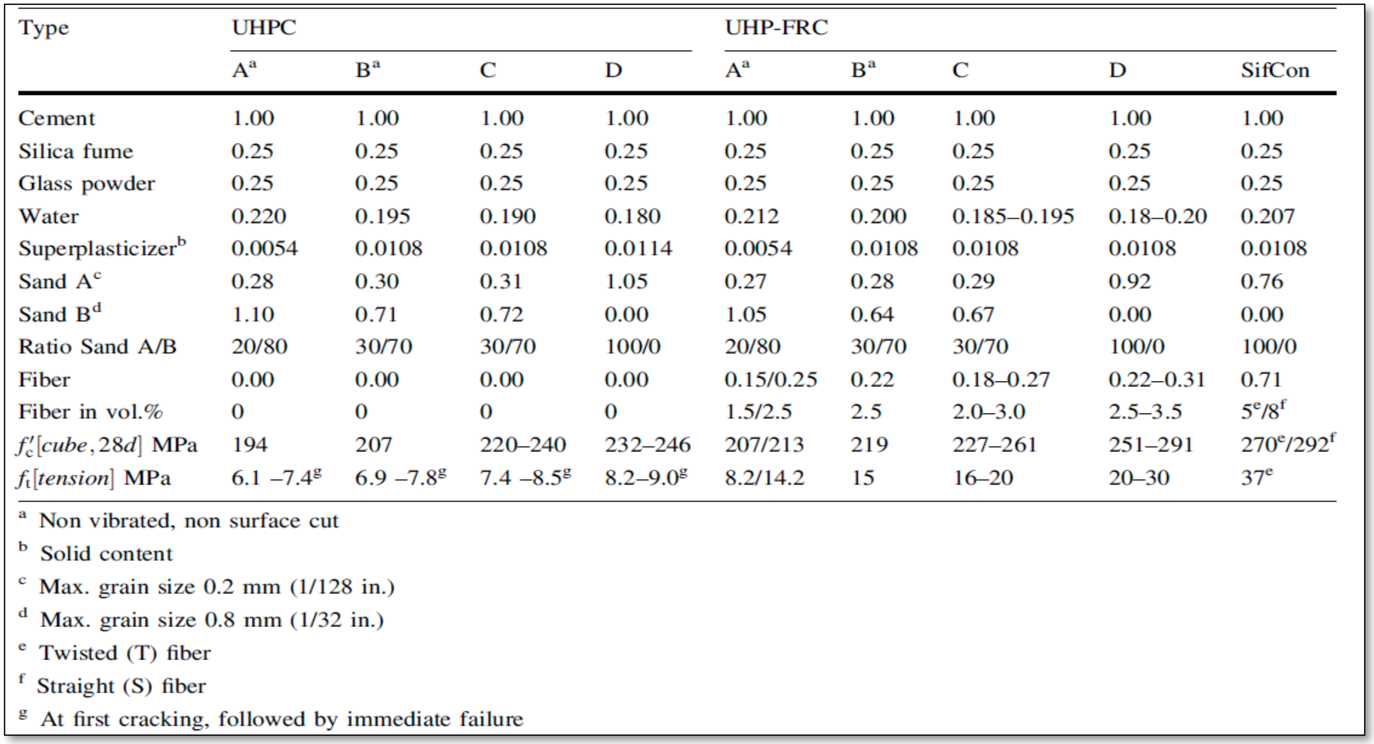
The ultra-high performance fiber-reinforced concrete (UHP-FRC) to be researched for application is a material developed by Dr. Shih-Ho (Simon) Chao at the

University of Texas at Arlington with a provisional patent UTA IPD #14-11. The UHP-FRC was developed initially in research for the Department of Defense grant, “Develop a Cost Efficient and Effective Method for Cast-In-Place Ultra High Performance Concrete (UHPC),” sponsored by the DOD Defense Threat Reduction Agency from 2012 to 2013. The DOD DTRA research project defined the development and proof-of-concept for UHP-FRC having high strength, i.e., >25 ksi (172 MPa) compressive strength and >0.72 ksi (4.96 MPa) post-cracking tensile strength.

Additional grant-related requirements were feasibility for large-pour and cast-in-place, as well as workability for industrial application in future commercialization. The feasibility of large-pour and cast-in-place strongly relies on ease of mixing/curing process, i.e., no need for special mechanism and insensitivity to environmental conditions. The product quality can be reproducibly ensured only for such a case. The UHP-FRC was developed based on “High Packing Density.” In high packing UHPC, dense structure is accomplished by an optimized combination of different-sized particles, such as big and small aggregates, micro admixtures and pastes, and yielding high strength readily up to 30 ksi (206.8 MPa). Because the high packing density is accomplished by a self-compacting mechanism, it does not demand special heat treatment, pressure, vacuum, etc. for high strength achievement. High quality UHP-FRC can be reliably produced in field practice (Aghdasi et al. 2015). Consecutively, the National Science Foundation (NSF) sponsored this concrete technology under a program named “PFI: AIR-TT; Partnership for Innovation: Accelerated Innovation Research-Technology Transfer.” The overall objective of the PFI: AIR-TT program is to provide funding that will enable research discoveries to be translated onto a path toward commercial reality while engaging faculty and students in entrepreneurial and market-oriented thinking. The PFI: AIR-TT solicitation supports research to overcome technology barriers/knowledge gaps in the translation of NSF research to commercialization. It provides an opportunity for investigators to conduct the necessary research to develop a proof-of-concept prototype or scale-up of the prototype that addresses real-world constraints and provides a competitive value in a potential application space. A proof-of-concept is the realization of a certain method or idea to ascertain its scientific or technological parameters. A proof-of-concept should be understood sufficiently so that potential application areas can be identified and a follow-on working prototype designed. A prototype is a functional laboratory demonstration of the proof-of-concept that addresses a relevant application. The prototype should be understood well enough to identify performance parameters, design criteria, and functional limitations for scalability in a potential application area (NSF PF: AIR-TT, 2016).

In this National Science Foundation (NSF) programs of technology transfer, UTA’s UHP-FRC was awarded a grant under the name “Establishing Manufacturing and Large-Scale Casting Process and Structural Design Criteria for Ultra-High Performance Fiber-Reinforced Concrete (UHP-FRC)," from 2014 to 2016, which focuses on transferring concrete material science research to the marketplace through industry collaboration where it can fill the need for advanced next-generation construction materials. These next generation materials will enhance the sustainability of infrastructure, buildings, and bridges when subjected to environmental loadings. The project will result in a large-scale cast-in-place mixing procedure and high energy input mixers, as well as design recommendations and analytical models for the design and analysis of structural members UHP-FRC. UHP-FRC is important because the major problem of concrete is the considerable deterioration and consequent repair work needed due to its brittleness and limited durability.

Table 1-3 Recommended Mix Designs for UHPC-UHP-FRC*



Type	UHPC				UHP-FRC				
	A[a]	B[a]	C	D	A[a]	B[a]	C	D	SifCon
Cement	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Silica fume	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Glass powder	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Water	0.220	0.195	0.190	0.180	0.212	0.200	0.185–0.195	0.18–0.20	0.207
Superplasticizer[b]	0.0054	0.0108	0.0108	0.0114	0.0054	0.0108	0.0108	0.0108	0.0108
Sand A[c]	0.28	0.30	0.31	1.05	0.27	0.28	0.29	0.92	0.76
Sand B[d]	1.10	0.71	0.72	0.00	1.05	0.64	0.67	0.00	0.00
Ratio Sand A/B	20/80	30/70	30/70	100/0	20/80	30/70	30/70	100/0	100/0
Fiber	0.00	0.00	0.00	0.00	0.15/0.25	0.22	0.18–0.27	0.22–0.31	0.71
Fiber in vol.%	0	0	0	0	1.5/2.5	2.5	2.0–3.0	2.5–3.5	5[e]/8[f]
$f_c'[cube, 28d]$ MPa	194	207	220–240	232–246	207/213	219	227–261	251–291	270[e]/292[f]
$f_t[tension]$ MPa	6.1 –7.4[g]	6.9 –7.8[g]	7.4 –8.5[g]	8.2–9.0[g]	8.2/14.2	15	16–20	20–30	37[e]

[a] Non vibrated, non surface cut

[b] Solid content

[c] Max. grain size 0.2 mm (1/128 in.)

[d] Max. grain size 0.8 mm (1/32 in.)

[e] Twisted (T) fiber

[f] Straight (S) fiber

[g] At first cracking, followed by immediate failure

* Ultra-high performance concrete and fiber reinforced concrete: achieving strength and ductility without heat curing (Wille et al. 2011).

The consequence of concrete deterioration and short service life requires frequent repair and eventual replacement, which consumes more natural resources. The characteristics of UHP-FRC can significantly reduce the amount of repair-rehabilitation-maintenance work and give infrastructure a longer service life, all of which will eventually lower the environmental liability of concrete use and lead to enhanced sustainability, safety, performance, and economy of our future infrastructure. The project engages a small business partner, Bailey Tools Manufacturing (BTM), to develop the large-capacity high-shear mixers and high-performance fibers, as well as the Texas Manufacturing Assistance Center (TMAC), to guide commercialization aspects, in this technology transfer effort from research discovery toward commercial reality.

The objectives of the projects that the UHP-FRC went through were to address the following technology gap(s) as it translates from research discovery toward commercial application: 1) to develop a large-scale cast-in-place mixing design procedure and high energy input mixers; 2) to formulate design recommendations and analytical models for the design and analysis of UHP-FRC structural members. Experimental results will be used to formulate the major design aspects for UHP-FRC structural members. Once representative relationships are developed, systematic parametric evaluations will be carried out with particular attention paid to the flexural and shear design recommendations of UHP-FRC structural members. The potential economic impact is expected to be transformational, creating a more durable product with cost savings that will be clearly evident in the next 10 years. Implementation of the new equipment and technology will contribute to the U.S. competitiveness in the next-generation construction market and will reduce state funded concrete installation and repair costs by at least 25%.

Recently in 2015, the UHP-FRC team from UTA was awarded another National Science Foundation Project named “Innovation-Corps.” The NSF Innovation Corps (I-Corps™) is a set of activities and programs that prepares scientists and engineers to extend their focus beyond the laboratory and broadens the impact of select, NSF-funded, basic-research projects. While knowledge gained from NSF-supported basic research frequently advances a particular field of science or engineering, some results also show immediate potential for broader applicability and impact in the commercial world. Such results may be translated through I-Corps into technologies with near-term benefits for the economy and society (US NSF. 2016).

As part of the projects that the UHP-FRC went through, the scope of work was mainly to combine experience and guidance from established entrepreneurs with a targeted curriculum. However, I-Corps is a public-private partnership program that teaches grantees to identify valuable product opportunities that can emerge from academic research, and offers entrepreneurship training to student participants. UHP-FRC is currently under this project preparing for transitioning to the primary goal of the NSF I-Corps which is to foster entrepreneurship that will lead to the commercialization of technology that has been supported previously by NSF-funded research. The approach to entrepreneurship uses techniques developed to validate each commercial opportunity in a recognized, effective way: customer and business model development. The vehicle for commercialization activities will most often be start-ups founded by the I-Corps participants; successful I-Corps projects will be prepared for business formation. The I-Corps programs feed the NSF Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs (NSF I-Corps, 2016).

1.8 Objectives and Scope

The main objective of this thesis is to evaluate the potential application of UHP-FRC with the wet-mix shotcrete process. Other objectives of this thesis are:

1. Evaluate the potential application of UHP-FRC in tunnel lining systems using wet-mix shotcrete equipment.
2. Evaluate and analyze the compressive and tensile strengths of UHP-FRC applied with wet-mix shotcrete process.
3. Identify shotcrete process steps that could be helpful for further investigation and development of dry-mix shotcrete process.
4. Develop and validate a testing sampling process for compressive and tensile strength of UHP-FRC.

The scope of this thesis is limited to the wet-mix shotcrete process with a potential for additional future investigation of the dry-mix shotcrete process. This research focuses only on the application process with shotcrete equipment of wet-mix, and its potential use in tunnel lining systems.

1.9 Methodology

A thorough literature search was conducted to identify state-of-the-art technologies that are currently available in the world comparable to the study in this thesis paper. The sources used include government documents and published reports, books, journal articles, patents, conference papers, thesis and dissertations, and industry websites. Interviews and surveys with a couple of shotcrete companies, one from Texas and another one from Peru were performed to validate our research supporting the shotcrete industry.

A partnership with a U.S.-based shotcrete company was established in order to utilize their equipment for a proof-of-concept with the UHP-FRC. A trial test was conducted to simulate similar conditions and processes similar to the shotcrete wet-mix process for tunnel lining. The proof-of-concept of the UHP-FRC in wet-mix shotcrete systems in this study helps to evaluate the potential use of this material and further utilize it in tunnel lining. Part of the methodology is to define the needs of current shotcrete technologies and its limitations.

The formal steps for this study included identifying physical, environmental and operational indicators for selection of the most feasible equipment to be used for UHP-FRC. The selection of the equipment was based on the mixing strength required for the UHP-FRC mix design, since it is a denser concrete mix. Previous studies and UHP-FRC research helped to determine the consistency required for the gunite equipment.

A shotcrete mixer/pump ProCretor PC-3 from Airplaco Equipment Company was used. Airplaco is a division of Mesa Industries who were the forerunners of the dry-mix (Gunite) and wet-mix shotcrete equipment manufacturing industry from the very beginning of the invention process. Their technical support and staff will be collaborating to evaluate the workability of UHP-FRC with the ProCretor PC-3. All analysis of sample panels and evaluation of monitoring and material testing will be performed at the Civil Engineering Laboratory at the University of Texas at Arlington.

A visit to a contractor plant (Aggregate Industries, Inc.) in charge of the segmental lining systems for the River Supply Conduit 5 & 6 project in Los Angeles was used to collect data related to the process of constructability of the lining process and the potential application of the UHP-FRC. An interview with Harley Smith (Dramix-Bekaert, Steel Fibers-The World of Concrete-Las Vegas, NV) about the overview of the tunneling industry, and an interview with a gunite/shotcrete pool manufacturer (Prestige Gunite in Fort Worth, TX) was performed to understand the needs of the shotcrete industry. In collaboration with a National Science Foundation project (I-Corps), an interview with the leader of the shotcrete industry in Peru was conducted (Robocon S.A.-Lima Peru). The participation in the World Tunnel Congress (San Francisco) helped this author to gather the most updated information about new technologies in the tunneling industry, and to make a data analysis covering shotcrete lining issues and current solutions. Detailed methodology is provided in Chapter 3.

1.10 Expected Outcome

The outcomes of this thesis include:

1. An evaluation was made which supports our research objective to prove that UHP-FRC can be successfully applied in wet-mix shotcrete system equipment and used in tunnel lining.
2. An evaluation of compressive and tensile strengths of samples obtained from the wet-mix shotcrete process with UHP-FRC was analyzed and monitored.
3. A feasibility analysis of the shotcrete process using UHP-FRC was conducted and further investigative research was conducted to develop a dry-mix shotcrete process with UHP-FRC.

1.11 Research Needs

1. There are no known applications or studies done with UHP-FRC in wet-mix shotcrete systems in the world. This is statement is taken after a literature search and a review of the University of Texas at Arlington database to verify if previous studies with ultra-high performance fiber-reinforced concrete had been developed. An investigation in collaboration with the ACI committee UHPC 239, a

database search with the American Shotcrete Association, and verification with national researchers from the US Federal Highway Administration who are familiar with the applications of UHP-FRC was performed to validate the effectiveness of UHP-FRC.

2. Time of construction is a critical factor. The potential application of UHP-FRC, and validation of its successful application with the shotcrete system could have a tremendous impact on the speed of construction for lining systems, and the reliability of a resilient concrete material used in tunnels.
3. Ground water ingress through the rock substrate underlying the shotcrete layer created an issue with water percolating into the shotcrete lining layer, and even with high cement content, the shotcrete lining layer needs more than seven (7) days of undisturbed hydration to create non-continuous capillary pores. Application of a UHP-FRC with very low permeability, high ductility, and high early strength will solve that issue.
4. A need to design thinner layers of shotcrete lining is a necessity according to contractors of shotcrete systems who were interviewed from Texas (Prestige Gunite) and Peru (Robocon, S.A.) throughout this research.

1.12 Chapter Summary

Recent developments in the field of concrete materials for tunnel applications and techniques in shotcrete systems for tunnels provide new options for accelerated construction of underground systems. The shotcrete systems need lining systems with less material, more durability, and thinner lining layers. This study will be helpful in illustrating the applicability of an innovative technique and material for potential use in tunnel systems.

Chapter 2

Literature Research

2.1 Introduction

This chapter consists of a review of findings from a comprehensive literature search that was conducted as part of this research. As discussed in Chapter 1, a literature search was used as one of the means to understand existing research works on this topic and to gain a better knowledge of applicability of concrete materials similar to or equal to the Ultra-High Performance Fiber-Reinforced Concrete (UHP-FRC). The subjects searched include (i) fiber reinforced shotcrete concrete for tunnel linings, (ii) design of engineered cementitious composite suitable for wet-mixture shotcreting, (iii) real opportunities for ultra-high strength concrete in tunneling.

2.2 Fiber Reinforced Shotcrete for Tunnel Lining

The development of a high quality shotcrete in wet-mix application method allows challenging underground projects to be developed in the most difficult conditions. The need for rapid support on the ground and a durable sprayed material for permanent support gave way to a large range of spraying techniques and mix designs to be developed with the addition of synthetic fibers and steel fibers for a uniform and high strength concrete. All these conditions allow the tunneling industry to have a more efficient and safe construction (Zeidler et al. 2016).

Steel fibers in shotcrete system have been used for many years. The lack of design standard codes, the high cost of fibers, and the small amount of manufacturers of fibers who control this industry is the reason why most of the tunnels in Europe, the U.S. and Latin America are still reinforced with conventional bars reinforcement. Most of the benefits of using steel fibers are related to safety and quality of concrete. It is not required to have a proper placing and attachment like conventional rebar reinforcement, and it has safer environmental conditions during excavation. The consolidation of concrete has a better quality than bar reinforcement where there is a risk of bad encapsulation. The risk of spalling is reduced immensely and the reinforcement is throughout all thickness for a better multi-axial transferred load. The flaws on fiber concrete are the lower tensile strength, the weak mechanical properties post peak, and the lack of standard procedures. For a typical fiber concrete with 0.5 % vol. of steel fibers, the tensile strength is the same as plain conventional shotcrete. In larger fiber contents such as 2% of vol. the strength can be greater than the paste or mix design; this is due to the hardening behavior which is now connected through fibers (Zeidler et al. 2016).

The load distribution is uniform only where ground conditions prevail. In tunnel linings, the analysis of the stress strain relation with smaller bending moments and moderately increased axial forces compared to a linear elastic stress law can be reached. There are different ways to calculate the capacity of steel fiber shotcrete. The compression strength is considered with the same standard as reinforced concrete. For the design of tensile strength, it could be evaluated with flexural test results with the third point loading. The tensile strength is used as a strength value but rather reflects the toughness of the mix design as shown in Figure 2-1.

Steel fiber reinforced shotcrete lining cannot compete with a conventional bar reinforced concrete lining. However, steel fiber shotcrete mixture has some properties that could be applicable for tunnel lining, since tunnels are subject mainly to axial forces. If steel fiber reinforced shotcrete is more flexible compared to conventional bar reinforced lining, then it will be most likely that bending moments are reduced. The relative stiffness of ground and support govern the bending moment of the lining; hence, reducing the stiffness of lining will develop reduced bending moments (Zeidler et al. 2016).

In summary, the advantages and disadvantages of the application of steel fiber reinforced shotcrete in tunnel lining in comparison to reinforced concrete were demonstrated in this research. Several cases selected by this study show that steel fiber shotcrete is practical, versatile, and viable and will lead to lead a higher quality of tunnel structures.

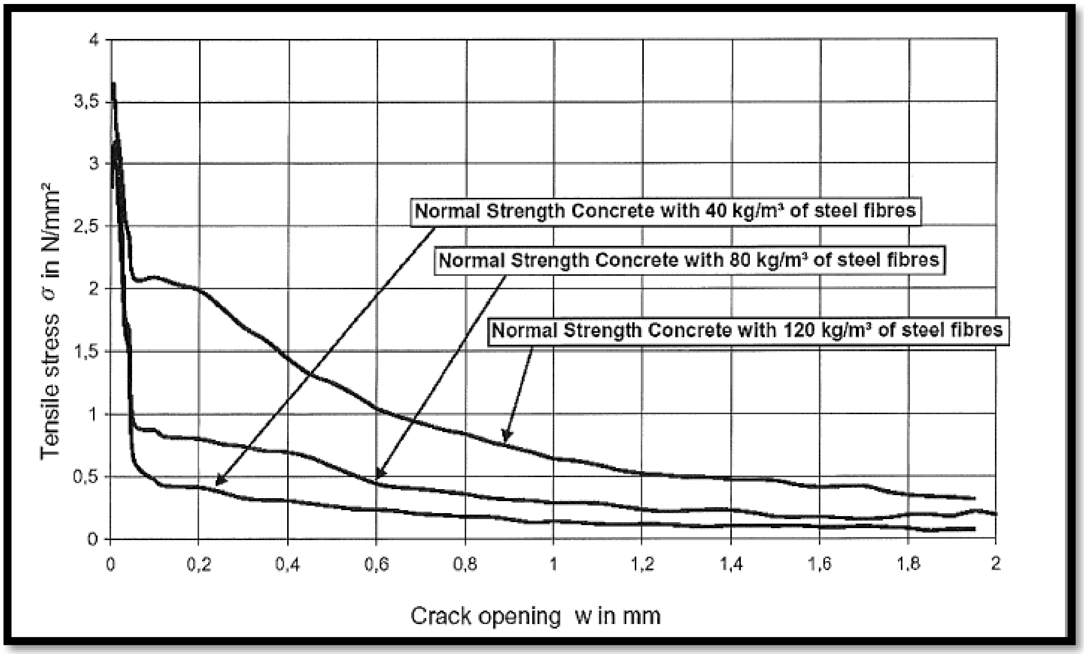


Figure 2-1 Post Cracking Behavior of SFRS (Zeidler et al. 2016).

2.3 Design of Engineered Cementitious Composite Suitable for Wet-Mix Concrete

A micromechanically designed cementitious composite that exhibits extreme tensile strain capacity while using a moderate amount of fiber was investigated. This cementitious composite was a sprayable engineered cementitious composite (ECC) with a special type of polyvinyl alcohol (PVA) fiber used as reinforcement. This study shows the fresh properties of the wet-mix shotcrete process with this cementitious composite accommodating the requirements of strain-hardening and micromechanical properties.

After test panels samples were subjected to spraying of the ECC mixture, the success of this fluid material's use in the shotcrete process was validated and a further uniaxial tensile test analysis shows that the strain-hardening behavior was feasible when compared with a cast sample of ECC with the same mix design. The applications of ECC will help repair the deteriorated infrastructures, providing a stronger and larger deformability in the spraying process. The ECC was flowable enough for a workable pumpability, so it was able to spray consistently in a fresh state. Therefore, the strain-hardening behavior was developed successfully using a micromechanical design.

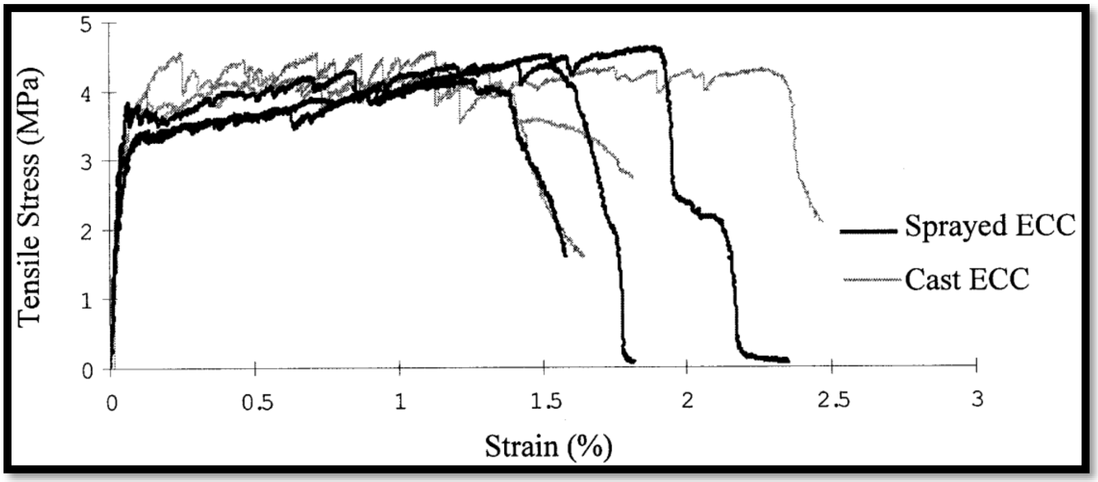


Figure 2-2 Uniaxial Tensile Stress (Li et al. 2003).

In conclusion, in this research the ECC was found in an optimal composition. The water cement ratio of 0.46 was used to obtain a matrix suitable to achieve the strain-hardening behavior. The diameter of PVA fiber was 39 micrometers with a length of 9 mm in a mixture with a volume fraction of 2% for proper pumpability and consistent distribution of fibers for the fiber-matrix interfacial properties while hardening (Li et al. 2003).

Fresh properties of flowability were obtained with the proper admixtures using HRWRA, HPMC, and CA particles. The mixing sequence and appropriate dosage of admixtures made a fresh mix with a desired rate and workable rheological properties. The desired rate of pumping was adjusted with a series of spraying tests.

The spraying results from the ECC mixtures depict that the maximum thicknesses obtained from samples of Mixture S-3 are 45 and 25 mm. These samples were sprayed on to a vertical surface and overhead surface, respectively. In another sample with another mixture with extensive rebound of sand, the thickness achieved was 10 mm. This was more likely due to the mix design with smaller particles of sand and lower stiffness of fiber (Li et al. 2003).

Finally, the uniaxial test results depict ultimate strain capacities from the sprayed sample in comparison with the cast sample as shown in Figure 2-2. The ECC wet-mixture shotcrete sample was found to have a higher tensile strain than the steel-fiber reinforced shotcrete (SFRS) by 100 times. The SFRS typical compressive stress is 40 MPa or 5.8 ksi in comparison with UHPC, which is 150 MPa or 21.7 ksi(Li et al. 2003).

2.4 Real Opportunities for Ultra High Strength Concrete in Tunneling

It is known that soft soil shield driven tunnels have a required thickness of lining proportionally related to the tunnel diameter, which should be 1/20th of the diameter. There are various structural mechanisms that influence the required thickness of tunnel lining. Steel fiber reinforced shotcrete allows the design of slender structures for bridges and roofs. This is a great market for the ultra-high performance concrete (UHPC) and its application in tunnel linings. Higher strength concretes could develop a more efficient

Figure 2-3 Double Deck Highway in 14.9 m (48.9 feet) Tunnel (Walraven et al. 2008).

tunnel system by reducing the thickness of the elements in the tunnel creating more space, and by reducing almost totally the amount of conventional reinforcement. This study depicts the influence of structural mechanisms on the lining thickness and focuses on discovering real opportunities for UHPC. Shield driven tunnels are mostly designed for trains or one-lane motorways. This means that the diameter of a two-lane tunnel for highway transportation will be larger than the tunnel diameter of tunnels designed for any other purpose. The larger size of this type of tunnel is very critical, since the concrete lining thickness is linearly related to the diameter of the tunnel. Increased cost of production and complex logistics of construction make large diameter tunnels very expensive.

If concrete lining thickness is reduced, construction will be more appealing as cost reduction would be significant in thinner lining production as shown in Figure 2-3. This study describes the potential influence of ultra-high performance concrete (UHPC-C180/210) in comparison with high strength concrete (C100/115), and conventional concrete (C35/45). The lining thickness control made possible by these different types of concrete offer great opportunities for UHPC application (Walraven et al. 2008).

The rule of thumb is to have 1/20th of the tunnel diameter as the thickness of lining, this is related directly and it has been applied in projects all over the world. For example, in the Netherlands at the Green Heart Tunnel, the lining thickness is 600 mm (23.6 in.) for a tunnel diameter of 13.3 m (43.6 ft). There is a lot of technical literature about the background of this rule of thumb, but there is not a fully proven physical explanation for this rule. The main reasons are related to the jacking forces from the tunnel boring machine (TBM) and the bending moments in the lining during grouting stages.

The lining thickness of the tunnel can be reduced drastically using UHPC. UHPC could potentially develop a thickness of 1/60th of the tunnel diameter. This analysis should also consider the construction stage as well as the bending moments and jacking forces. In order to develop a 1/60th thickness, a combination of fiber reinforced mix design and conventional reinforcement is necessary, adding the forces during construction to consider active buoyancy. While construction cracking may occur due to segmental lining torsion at the end of the TBM, it can also be prevented by adjusting the mix design or adding grouting at the end (Walraven et al. 2008).

The reduction of lining thickness will develop large deformations of the tunnel as well. Deformations typically exceed 100 mm (3.9 in.) if a 250 mm (9.8 in.) lining is used for this large diameter. Longitudinal joints receive more rotations and also over the ring joints. With these issues, more problems need to be faced and addressed when slender linings are applied. Decreasing the lining thickness should be considered given the acceptable limits for an optimal lining thickness.

2.5 Chapter Summary

Several methods and solutions have been studied to construct a safer and more cost efficient tunnel infrastructure. Different technologies have been developed; however, they are still not optimal and need an alternative solution. Comprehensive research on the available techniques, their capabilities to innovate with solutions to an unregulated industry like tunneling were presented in this chapter. The objective of this chapter was to present the characteristics of each of the potential issues and innovative technologies currently in use to enable a comparative study.

Chapter 3

Methodology

3.1 Introduction

This chapter discusses the methodology adopted for this research. An overview of the methodology was presented in Chapter 1. The primary interest is the potential application UHP-FRC in tunnel lining with a wet-mix shotcrete system. The evaluation of a UHP-FRC as a viable material for the wet-mix shotcrete system is needed for proof-of-concept to prove the benefit of potential application in tunnel lining; hence, proof-of-concept will validate this thesis's research showing that UHP-FRC is a viable product to apply to tunnel lining. For the purpose of this thesis, companies related to the shotcrete industry, contractors in the tunneling industry, and material supply companies were part of the source of this investigation. Table 3-1 shows the thesis methodology.

3.1.1 Literature Search

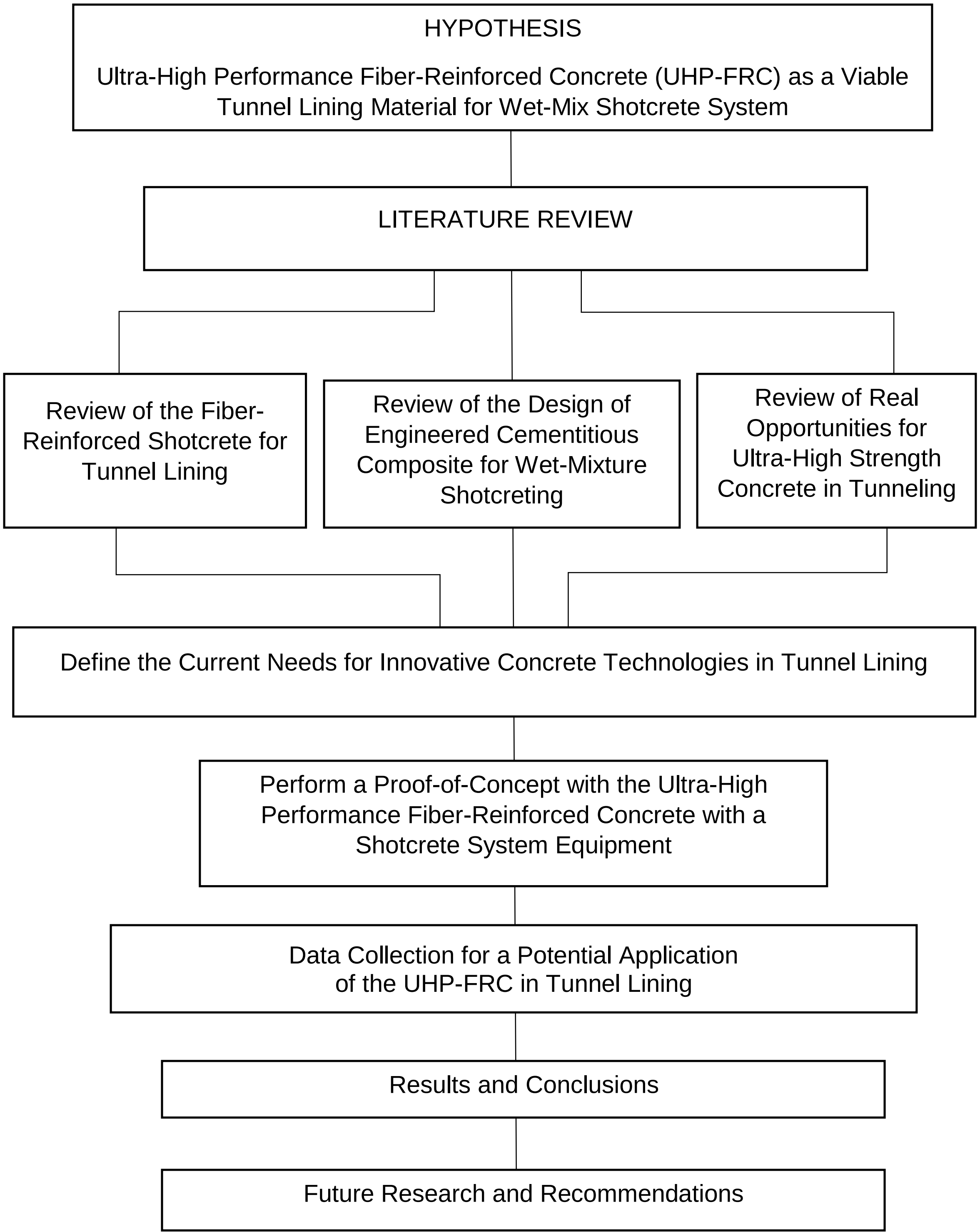
The literature review of the fiber-reinforced shotcrete for tunnel lining, the review of design engineered cementitious composites for wet-mix shotcreting, and the review of real opportunities for ultra-high strength concrete in tunneling gives us a good understanding of the needs and problems of the shotcrete industry, with an approach to the private industry and collecting information from first sources helped the author of this thesis to define current needs for innovation in concrete technologies applied to tunnel lining. Collecting data, preparing a summary, forming conclusions, and determining future research with recommendations were an important part of this research.

3.2 Shotcrete Equipment for The Experiment

In order to validate the potential application of UHP-FRC as a viable material for wet-mix shotcrete systems and eventually utilize this concrete material for tunnel linings, a proof-of concept process was performed at the University of Texas at Arlington. In order to validate the potential application of UHP-FRC as a viable material for wet-mix shotcrete systems and eventually utilize this concrete material for tunnel linings, a proof-of concept process was performed at the University of Texas at Arlington. The equipment used for the experiment was the ProCretor PC-3 from Airplaco Equipment Co., which is a U.S. based company leader manufacturer of concrete, shotcrete, slabjack, mudjack, and grout pumps, wet and dry mix batch plants, and gunite machines. Airplaco is also one of the divisions of Mesa Industries Inc. which manufactures products for refineries, storage tank facilities, and specialized construction industries.

The ProCretor PC-3 is an all-in-one grouting and shotcrete rig, with a high pressure and grout pump. This machine is mainly used for shotcrete material placement, concrete lifting, grout pumping, and concrete repair. The Procretor PC-3 features a diesel engine with a hydraulic mixer, a proxy switch for hydraulics, a dual set of cylinders, a swing tube valve, a high line pressure, and centralized controls. This wet-mix shotcrete and grout pump features a 10 ft^3 (0.28 m^3) mixer with a swing tube material valve. The output of the Pro-Cretor PC-3 is a maximum of 7 yd^3/hr or 5.3 m^3/hr. The pressure exerted by the pump is of 1,300 psi (88 bar), and it can host a maximum aggregate size of ¾ in. (19 mm) or less. The concrete dual piston cylinders push the material in a chamber that is 3 in. in diameter (76 mm). The length of the concrete piston cylinder stroke is 16 in. (406 mm). The full flow of material delivery hose through the S-tube is 3 in. in diameter (76 mm) and the discharge outlet size is 3 in. (76 mm). This machine has a diesel power source with 46 hp. The dimensions of the Pro-Cretor are 149 in. long × 79 in. wide × 53 in. deep. The approximated weight of the shotcrete machine is 3,770 pounds (lb) or 1,710 kilograms (Kg) as shown in Figure 3-1.

Table 3-1 Thesis Methodology



Pro-Cretor PC-3

Max. Output	7 cu yd/hr (5.3 m³/hr)
Pressure	1,300 psi (88 bar)
Max Aggregate Size	3/4″ minus (19mm)
Concrete Cylinders	Dual 3″ (76mm)
Concrete Cylinder Stroke	16″ (406mm)
Full Flow S-Tube	3″ (76mm)
Discharge Outlet Size	3″ HD (76mm)
Power Source	Diesel 46 hp
Dimensions	149 x 79 x 53 in.
Weight	3,770 lb (1710 kg

Maximum output and pressure cannot be reached simultaneously. Performance will vary depending on the operator, cycle rate, mix design and placement line.

Figure 3-1 Pro-Cretor PC-3 Technical Data (AIRPLACO, 2016).

3.3 UHP-FRC as A Potential Shotcrete Material

To validate the research objective of this thesis, which was to prove that ultra-high performance fiber-reinforced concrete is a viable material with a potential application in tunnel lining systems, a proof-of-concept was performed in order to demonstrate the delivery of this material through one the shotcrete delivery systems. For the purpose of this initial research, this study focused on the application of shotcrete material with a wet-mix process using the Pro-Cretor PC-3 from Airplaco. This proof-of-concept took place at the Civil Engineering Laboratory at the University of Texas at Arlington, in conjunction with Airplaco Equipment Co which provided the equipment and the technical assistance on the manipulation of the shotcrete equipment and the application onto the sample cast.

3.3.1 The Casting Process

The proof-of-concept was performed on April 6th, 2016, and the plan layout required the following tools: a 185 CFM-cubic feet per minute (314 CMH-cubic meter per hour) Air Compressor, the Pro-Cretor PC-3 shotcrete machine, a hopper bucket to carry all the dry-mix, buckets of water and the High Range Water Reducer (HRWR). Previously, two cast samples were fabricated according to the shotcrete nozzle main certification requirements as a standard for shotcrete sampling. The purpose of these samples is to core or saw samples for compressive and flexural testing. For the sake of completion, only data from samples of seven-day maturity were evaluated.

Regarding to the UHP-FRC a recent research shows that ultra-high-performance fiber-reinforced concrete (UHP-FRC) can be developed using dense particle-packing concept without special materials or treatments. The developed UHP-FRC is made of regular Type I cement with a water cement ratio of 0.26, silica fume, Sand 1 (500 μm or 0.019685 in.), Sand 2 (120 μm or 0.00472441 in.), glass powder (1.7 μm or 6.6929e-5 in.), and straight steel fibers 12.5 mm (0.49 in) long and 0.175 mm (0.0068897638 in.) dia., and it is a proprietary material patented by the University of Texas at Arlington under a provisional patent UTA IPD #14-11. The UHP-FRC is a type of UHPC with compressive strength more than 150 MPa or 22 ksi with the addition of fibers. UHP-FRC with the addition of fibers caused the brittleness that developed due to the high compressive strengths, which could decrease as well as increase the energy absorption capacity. UHP-FRC has high compressive strengths which were obtained using material science through the dense particle packing theory. This is the main reason for performing this proof-of-concept.

The plan layout was as follows: first of all, the mix design was weighed for a required volume of 0.25 yd^3 in order to efficiently utilize the capacity of the mixer of the Pro-Cretor PC-3. The dry-mix designed ready-to-mix product was conveyed by a hopper bucket attached to an overhead crane. For the sake of simplicity, the bucket was lifted with a forklift and placed just above the mixer for delivery and mixing of the raw material. When mixing time started, a previous priming with a cementitious slurry was processed through the shotcrete equipment system so the material running through would not be adhering to the inside walls of every part of the equipment. The mixing rate was 60 rpm and it was mixed one small batch at the time to keep the mixing in a constant motion without the reduction in the speed of mixer. After an approximated 15 minutes of dispensing raw material into the mixer, the last material for the mix design was included. A 2% of volume of steel fibers was added according to the mix design requirements.

The material pumping process was done taking in consideration that an approximated pressure of 1000 psi (6.9 MPa) or less in the pump and delivery hose was expected for conventional concrete in order to fulfill requirements of pumpability. The material was delivered to the nozzle at 600 psi (4.14 MPa) pressure which means a more flowable mix was being delivered. At the tip of the delivery hose is the nozzle from which the material is jetted to the surface of work. In the first attempt to shotcrete, approximately 10% of the sample was sprayed in order to fill the encapsulation of the steel conventional reinforcement rebars which were only for the purpose of holding the material sticking to the walls of the cast at all times. This technique of vertically placing the shotcrete sample is called the vertical method.

The flowability of the UHP-FRC was about 9-10 inches (228 - 254 mm) of slump according to ACI standards of slump testing, which validates the self-compacting consolidation mechanical property of the UHP-FRC. The flowability of the UHP-FRC did not allow shotcrete a built-up of material in the cast sample. The UHP-FRC maintained a stable and fluid consistency but it needed to have a reduced slump in order to be in the tolerance range of shotcrete. Then the nozzleman adjusted the end of the nozzle and to recirculate the concrete material back through the pump section, thereby recirculating the material until it gained a thicker consistency.

After 45 minutes of recirculation of the concrete material through the shotcrete system, the material did not gain any thicker consistency or the machine did not show any increased pressure in the delivery system as proof of the decrease in slump. It is important to depict the time of pumping and degree consistent in the mixer for a long period of time. No previous work had been completed whereby this process could be observed—not even with conventional concrete or with other specialty concretes. The decision was taken to cast the sample blasting concrete horizontally due to the flowability of the UHP-FRC.

3.4 Chapter Summary

This chapter presented the methodology that was used for this study. This methodology helped to understand and validate the research with different methods like literature search, interviews with contractors, suppliers and manufacturers of shotcrete materials and finally testing a shotcrete trial. The process of shotcrete was developed to collect data that led us to prove the potential application of UHP-FRC in the shotcrete tunnel linings. This project evaluated the critical parameters of compressive strength and flexural strength with the collection of sample cores.

Chapter 4

Results and Analysis

4.1 Introduction

This chapter presents the results and findings of this research as explained in Chapter 3.

4.2 Analysis of Results

According to the fiber reinforced shotcrete report (ACI Guide to Shotcrete, 2005), the flexural and compressive strengths for fiber-reinforced shotcrete for 8-day flexural strengths as determined from beam specimens vary from about 600 to about 1,500 psi (4.1 to 10.3 MPa) with typical values of 800 to 1,100 psi (5.5 to 7.6 MPa). These flexural strengths were determined using 4 x 4 x 14-in. (100 x 100 x 350-mm) beams sawed from test panels and tested on a 12-in. (305-mm) span in accordance with ASTM C 78.

For example, in previous investigation, the U.S. Bureau of Mines reported flexural strengths of 4,617 psi (31.9 MPa) for fibrous shotcrete and 2,244 psi (15.5 MPa) for the plain, control shotcrete using regulated-set cement and 2 percent by volume of fibers. These were 360-day strengths determined by ASTM C 78. Placement of the shotcrete tends to orient the fibers in a plane parallel to the surface being shot. This orientation is of benefit to the flexural properties of the shotcrete layer. Compressive strengths at 28 days from mixes have varied from about 4,200 to 7,500 psi (29 to 52 MPa) (ACI Guide to Shotcrete, 2005).

For the compressive strength test, samples were collected by sawing a cube 2.78" × 2.78" × 2.78” (70.6x70.6x70.6 mm). A peak force of 55,644.48 lbf (247.5 KN) was applied to the sample in compression. 2-days compressive strength data was collected to confirm the early high strength of this material with a 7,200 psi (49.6 MPa) result in the first 48 hours of concrete curing. More samples were obtained for 7 and 28 days curing of concrete. Note in Figure 4-1 that the strain creates an elongated curved which identifies and prevents a sudden failure of concrete due to the steel fibers in the mix design.

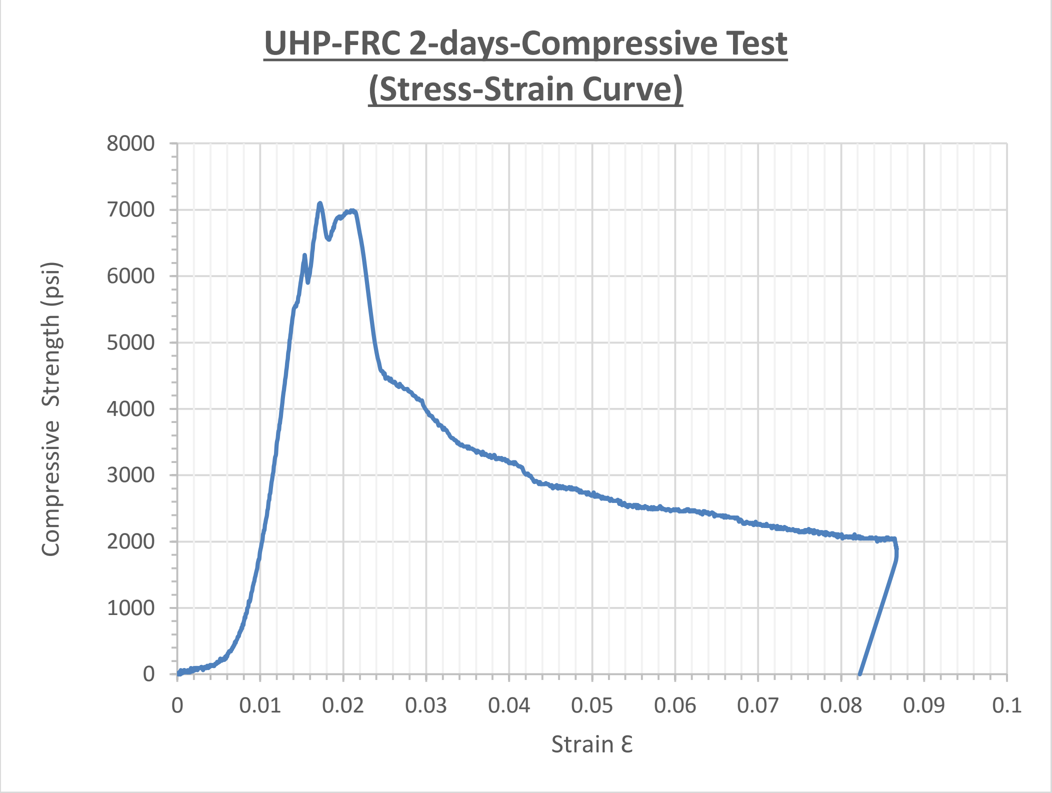


Figure 4-1 Stress-Strain Curve for a 2-days cured compressive test.
(Graph prepared by the research team at UTA CE Lab).

4.3 Analysis of Interviews

The time set apart for collecting data and researching the history of the shotcrete industry was also a time to meet important companies and people related to the tunneling, mining, shotcrete, and fibers industry. The following information was collected in these meetings through the participation and sponsorship of a National Science Foundation project.

4.3.1 INTERVIEW 1

Robocon S.A., a company from Lima-Peru was interviewed in March 2016. Mr. Enrique Sattler who is the President of Robocon, and this company is the shotcrete leader company in Peru with a production of 16,000 m^3 per month. They work in the Andes of Peru providing wet-mix shotcrete services to contractors that are in the tunneling business. Robocon uses SEMMCO Alpha 20 robotic arm shotcrete equipment to accelerate the process of concrete spraying. Sattler mentioned that he uses large fibers because they allow more safety in longer spans of tunnels and protect the lives of his workers. Mr. Enrique Sattler also stated that the tunneling industry in Peru is not regulated; it is only audited for safety procedures by the Peruvian government. Robocon uses Bekaert Steel Fibers to produce the 16,000 m^3(565,034.66 ft^3) of concrete per month, and he believes that if there is a material that could help him reduce the thickness of the tunnel lining with the same or greater strength, it would be very beneficial for the industry. This was a face-to-face meeting.

4.3.2 Interview 2

Aggregate Industries were interviewed from Las Vegas, NV in February 2016. Mr. David Wallis who is the Precast Plant Manager mentioned thatAggregate Industries produced precast segmental lining products for one of the most popular projects in California, the River Supply Conduit 5 & 6 project in Los Angeles. The plant is located just outside the city limits of Las Vegas, NV and they use steel fiber reinforced concrete (SFRC) for this project. This visit was made possible thanks to the invitation of one of their material suppliers, Bekaert. Wallis commented that the main reason of using SFRC is because it reduces the time it takes to insert rebars into precast segmental lining by almost 100%. However, the segmental lining still suffers a problem of spalling while jacking the pieces using the tunnel boring machine (TBM). Wallis’s experience in precast and residential construction makes him think that a faster curing concrete and stronger concrete could develop a slimmer product with more energy efficiency. This was a face-to-face meeting.

4.3.3 Interview 3

The company Bekaert was also interviewed at the The World of Concrete in Las Vegas, NV in February 2016. *Mr. Harley Smith who is theBusiness Development Manager*, and he stated that Bekaert is the largest provider of steel fibers in the world. The UHP-FRC for this research included Dramix which is a product of Bekaert. Smith's knowledge of the tunneling industry is vast. His business development work is focused on underground solutions, so his comments about the tunneling industry and its issues were very important for the development of this research. Smith emphasized that the US tunneling industry does not have standards defining the materials that are allowed for use in tunnel lining. He mentioned that in Europe different methods of innovation in concrete technologies are used in order to provide a safe construction environment with an accelerated process. He recommended we attend the largest tunneling systems conference in the world hosted by the International Tunnelling and Underground Space Association which was held in April in San Francisco. This was a face-to-face meeting.

4.3.4 Interview 4

Prestige Gunite of North Texas (Fort Worth, TX, March, 2016), *Mr. Gary Miller-President:* Prestige Gunite provides gunite services to the North Texas area. This company's customers are pool contractors, developers of underground infrastructures, and railroad tunnel developers. Miller's experience in the residential pool business is vast. He mentioned that the problems with materials that are delivered with concrete are not able to hold the pressures and changes of expansive soils. His gunite materials are of very poor quality in order to compete on prices. He mentioned that concrete delivery by shotcrete systems take many days to cure in order to obtain the strength necessary to proceed with construction. This was a phone interview.

4.3.5 Interview 5

Airplaco Equipment (Cincinnati, OH, April, 2016), *Mr. Greg Althammer-Southeast Regional Sales Manager:* Airplaco Equipment develops shotcrete equipment and grout pumps. Althammer mentioned the need for better products for their customers in conjunction with properly maintained equipment capable of performing cutting edge technology. Airplaco works with both systems, dry-mix (gunite) and wet-mix (shotcrete). They are currently working on a new innovative gunite technology which can accurately assess the water to cement ratio on the delivered mix while it is being jetted to the work surface. This new technology will provide their customers with a better quality of concrete and a more efficient monitoring system for strength and durability.

4.4 Chapter Summary

This chapter presented interviews with leaders in the shotcrete industry as well as comments and suggestions based on recommendations for shotcrete use in Chapter 3. The results of compressive strength were limited by the curing age of samples and availability of research lab to test the specimen. Nevertheless, all efforts represent progress and hold promise for future investigations that could be extended and developed into new research devoted to improving the gunite/shotcrete industry. The analysis of data collected was plotted to have a better understanding of the mechanical behavior of UHP-FRC. The results of working with companies and people related to the industry were mainly for the purpose of researching potential applications of knowledge gained in a market-fit analysis for the shotcrete system.

Chapter 5

Conclusions and Recommendations

This chapter presents the conclusions drawn from the results and findings obtained in Chapter 4. It also includes recommendations that can be incorporated into further study of the same subject.

5.1 Conclusions

The conclusions for this research can be summarized as following:

1 This study represents the first proof-of-concept shotcrete testing using UHP-FRC.

2 After 45 minutes of continuous mixing directly exposed to the sunshine, the viscosity of UHP-FRC remained the same.

3 Current shotcrete mixer has approx. 60 rpm, which is not fast enough to generate the high shear required by UHP-FRC mixing procedure. In order to efficiently mix UHP-FRC, the shotcrete mixing machine must have a minimum mixing speed of 90 rpm.

4 UHP-FRC attempted high early strength, despite the loss of material in windy conditions. Room for improvement was noted here as pressure readings indicate UHP-FRC has potential for greater pumpability.

5 The mix design of UHP-FRC needs to be further optimized for vertical shotcrete application in order to provide a better bond.

5.2 Recommendations for Future Research

The recommendations for future study can be summarized as follows:

1. Include various types of trial mix designs of UHP-FRC with smaller batches and different water to cement ratios to achieve smaller concrete slumps.
2. Conduct survey with enough participants to be representative of the entire industry.
3. Include cost benefit analysis to compare different water to cement ratio mix designs and various fiber percentages in order to achieve a jetted material to adhere to the cast vertically placed.
4. Include a maintenance program for cleaning the hose and other parts of the shotcrete equipment with more efficiency.
5. Use a different type of material for the delivery hose such as a steel hose, so the fibers will not stick on the inside liner of the hose.
6. Identify gap between technologies by considering various high-risk distress indicators observing the current technologies available in the market.
7. The next opportunity for research should be the dry-mix method (gunite) in order to efficiently proof the concept since gunite requires less amount of batch volume of concrete material.
8. This research has a potential application in tunnel lining, but needs further research and funding provided by grants and companies related to the shotcrete industry. A consortium dedicated to shotcrete/gunite development needs to be developed where academia, industry, and federal funding agencies can join forces to create a better product using UHP-FRC.

Appendix A

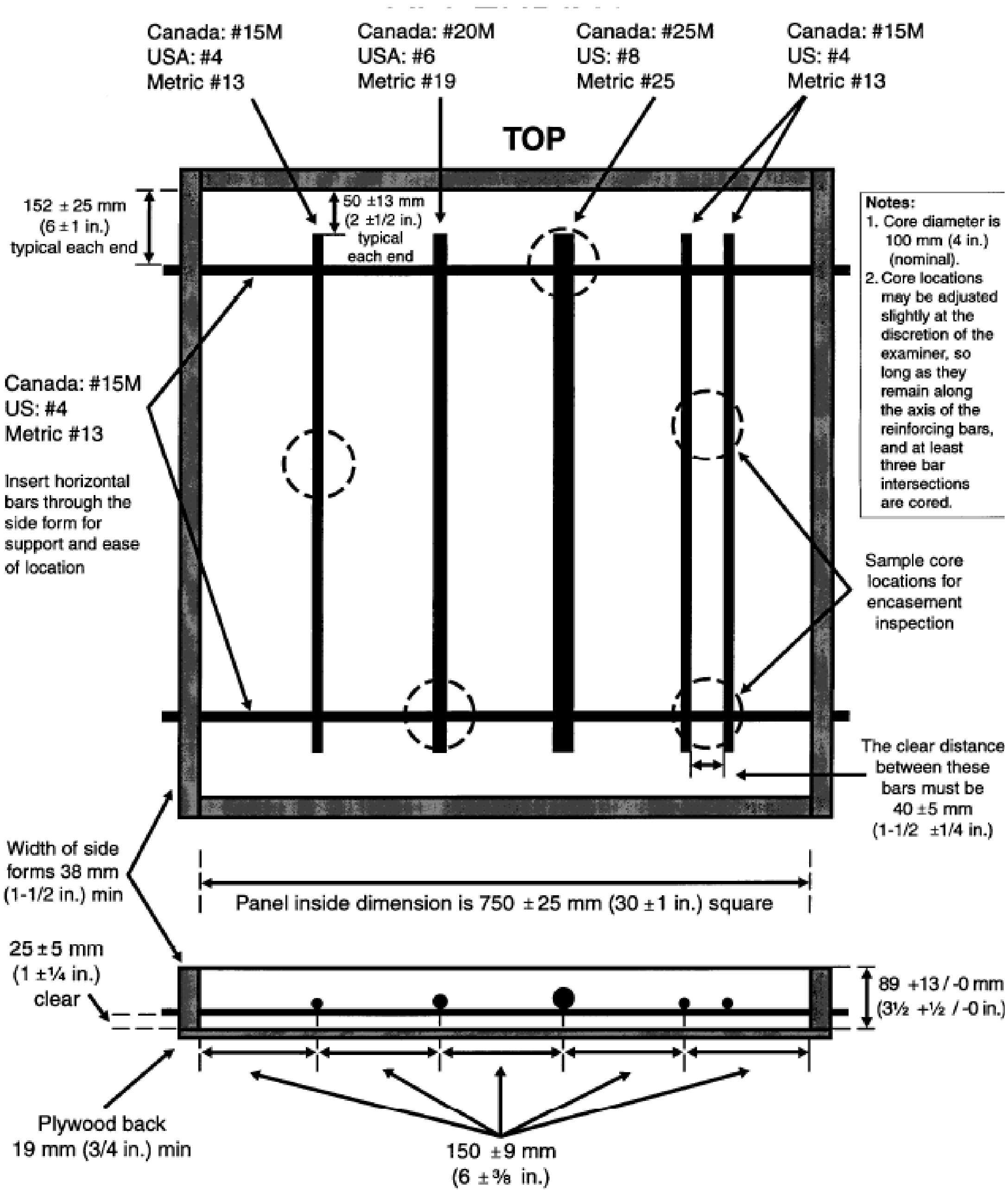
Photographs of Precast Segmental Lining

Visit to Precast Plant, Las Vegas, NV.

(Source: Aggregate Industries. February, 2016).

Appendix B

Shotcrete Trial



Proposed Construction Method for Shotcrete Cast (C 1140 – 03a, ASTM, 2003).

Sample Panels Cast.

Shotcrete Trial Experiment by Carlos Gamarra.

Shotcrete Experiment Setup by Carlos Gamarra.

Appendix C

The Shotcrete Equipment

SHOTCRETE MIXER/PUMP

AIRPLACO

AMERICAN OWNED-AMERICAN BUILT

10 cu ft Mixer

11 cu ft
Hopper with
Hydraulic Remixer

46 HP
Diesel Engine

Variable Volume
Control

Swing Tube
Material Valve

Shotcrete
Pressure Grouting
Concrete Levelling
Concrete Repair

photo courtesy of Russ Ringler

PRO-CRETOR PC-3

Max. Output	7 cu yd³/hr (189 ft³/hr)
Pressure	1,300 psi (88 bar)
Max Aggregate Size	3/4" minus (19mm)
Concrete Cylinders	Dual 3" x 16"
Concrete Cylinder Stroke	0 - 13/min
Hopper Capacity	11 ft³
Mixer	10 ft³ Hydraulic
Full Flow S-Tube	3" (76mm)
Discharge Outlet Size	3" HD (76mm)
Power Source	Diesel 46 hp
Dimensions	141" L x 79" W x 90" H
Weight	3,770 lb (1710 kg)
Tires	205/75R15 10 Ply
Axle	Single, 6,000 lb
Hitch	2" Ball
Brakes	Hydraulic Surge

Performance is relative to cycle rate, mix characteristics, line size and distance. Max output, line pressure and distance cannot be achieved simultaneously. Specifications are subject to change.

AIRPLACO Shotcrete Mixer/Pump Technical Data.

SHOTCRETE MIXER/PUMP

AIRPLACO

10 cu ft hydraulic mortar mixer for a self contained shotcrete and concrete repair trailer unit. Mixer features forward and reverse, mutli-blades, hinged clean-out door and hydraulic dumping into material hopper

PRO-CRETOR OPTIONS

- Hopper Vibrator
- Water Pump
- Clean Up Hose
- Operators Platform
- Air Compressor
- Water Suction Hose
- Hydraulic Outriggers
- Stroke Counter
- Wireless Remote
- Skid Mounting
- Chemical Pump
- Wheel Sizes
- Towing Hitch
- Paint Color

STANDARD FEATURES

- Self-Contained
- High Pressure
- Centralized Controls
- Proxy Switch Cycling
- Hard-Chrome Cylinders
- Full-Flow S-Tube
- Reversing Capability
- Heavy-Duty Trailer
- Water Meter

709512 Wet-Mix Shotcrete Nozzle

AP-PC-2013-REV1

AIRPLACO Shotcrete/Mixer Pump Technical Data.

Appendix D

Photographs of Applications of UHP-FRC

MuCEM Pedestrian Bridge, Marseille, France (American Concrete Institute, ACI-239 Committee-UHPC, 2015).

MuCEM general overview-net facade panels
(American Concrete Institute, ACI-239 Committee-UHPC, 2015).

Spent nuclear fuel dry storage casks
(American Concrete Institute, ACI-239 Committee-UHPC, 2015).

Pedestrian Bridge over Oveja's ravine, Alicante, Spain
(American Concrete Institute, ACI-239 Committee-UHPC, 2015).

General overview of Millau Viaduct
(American Concrete Institute, ACI-239 Committee-UHPC, 2015).

Appendix E

Compressive Strength of 2 Days Data

Scan Session: "Jean cube #2 2days"
Start Time: 4/8/2016 7:40:13 PM

Assignment:	Load	Front LVDT	Back LVDT
Reduction Method:	Calibrated V	Calibrated V	Calibrated Values

ID	SecondsEla	[01] lb	[16] in	[17] in	compressive strength (lb/in2)	strain		ID	SecondsEla	[01] lb	[16] in	[17] in	compressive strength (lb/in2)	strain		ID	SecondsEla	[01] lb	[16] in	[17] in	compressive strength (lb/in2)	strain
30	6	121.73769	-0.00001	-0.00004	15.7519914	-8.99281E-06		130	26	243.47539	0.0025	0.00277	31.503984	0.00094784		230	46	6695.57322	0.02311	0.02202	866.35956	0.00811691
31	6.2	243.47539	0	-0.00002	31.503984	-3.59712E-06		131	26.2	243.47539	0.00262	0.00291	31.503984	0.0009946		231	46.2	6573.83553	0.02322	0.02226	850.607568	0.00817986
32	6.4	-243.47539	-0.00001	-0.00002	-31.503984	-5.39568E-06		132	26.4	243.47539	0.00273	0.00301	31.503984	0.00103237		232	46.4	7060.78631	0.02336	0.02246	913.615536	0.00824101
33	6.6	0	-0.00001	-0.00002	0	-5.39568E-06		133	26.6	243.47539	0.00285	0.00312	31.503984	0.00107374		233	46.6	7060.78631	0.02352	0.02267	913.615536	0.00830755
34	6.8	0	0.00002	0	0	3.59712E-06		134	26.8	365.21308	0.00298	0.00326	47.2559754	0.0011223		234	46.8	7182.524	0.02364	0.02287	929.367528	0.00836511
35	7	-121.73769	-0.00002	-0.00002	-15.7519914	-7.19424E-06		135	27	365.21308	0.00309	0.0034	47.2559754	0.00116727		235	47	7669.47478	0.02379	0.02303	992.375496	0.00842086
36	7.2	121.73769	0.00002	0	15.7519914	3.59712E-06		136	27.2	243.47539	0.00319	0.0035	31.503984	0.00120324		236	47.2	7791.21248	0.02393	0.02328	1008.12749	0.00849101
37	7.4	121.73769	0.00002	-0.00002	15.7519914	0		137	27.4	486.95078	0.0033	0.00363	63.007968	0.0012464		237	47.4	7912.95017	0.02405	0.02348	1023.87948	0.00854856
38	7.6	243.47539	0.00001	-0.00002	31.503984	-1.79856E-06		138	27.6	243.47539	0.00344	0.00376	31.503984	0.00129496		238	47.6	8521.63865	0.02417	0.02368	1102.63944	0.00860612
39	7.8	0	0	-0.00001	0	-1.79856E-06		139	27.8	243.47539	0.00358	0.00391	31.503984	0.00134712		239	47.8	8399.90095	0.02432	0.02388	1086.88745	0.00866906
40	8	-243.47539	0.00002	0	-31.503984	3.59712E-06		140	28	365.21308	0.00375	0.00405	47.2559754	0.00140288		240	48	8521.63865	0.02448	0.02412	1102.63944	0.00874101
41	8.2	0	0.00001	-0.00002	0	-1.79856E-06		141	28.2	243.47539	0.00389	0.00421	31.503984	0.00145683		241	48.2	8765.11404	0.02459	0.02432	1134.14342	0.00879676
42	8.4	0	-0.00001	-0.00004	0	-8.99281E-06		142	28.4	486.95078	0.00405	0.00435	63.007968	0.00151079		242	48.4	9130.32712	0.02472	0.02454	1181.3994	0.00885971
43	8.6	121.73769	-0.00001	-0.00003	15.7519914	-7.19424E-06		143	28.6	243.47539	0.00418	0.0045	31.503984	0.00156115		243	48.6	9495.54021	0.02484	0.02473	1228.65538	0.00891547
44	8.8	121.73769	0.00001	-0.00004	15.7519914	-5.39568E-06		144	28.8	730.42617	0.00436	0.00468	94.511952	0.0016259		244	48.8	9617.2779	0.02496	0.02493	1244.40737	0.00897302

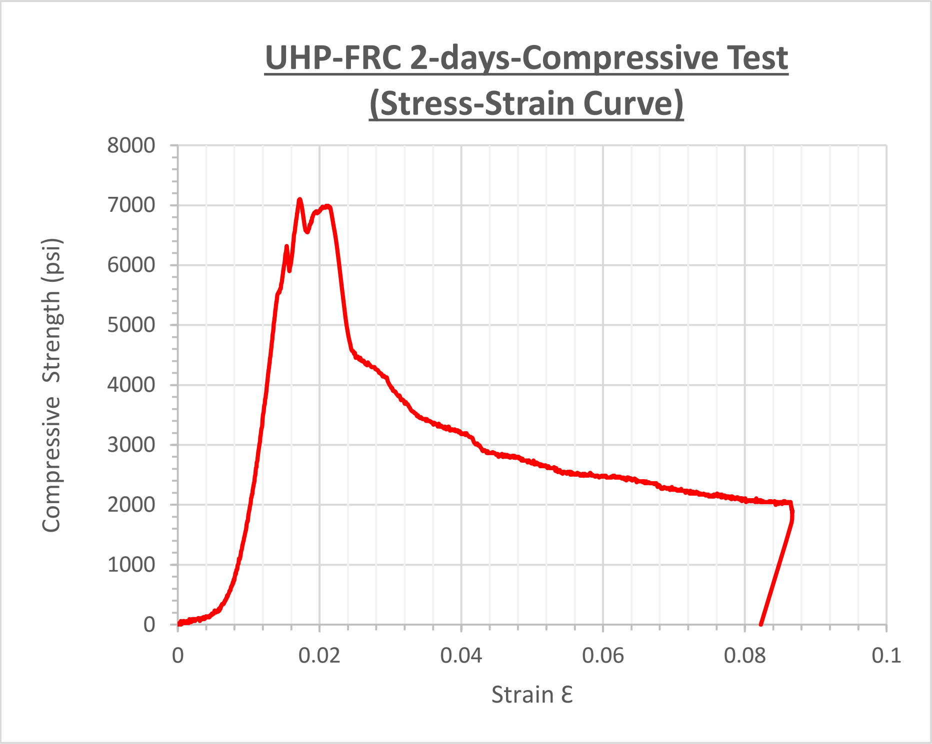
Beginning of 2-days Compressive Test

ID	SecondsElaj	[01] lb	[16] in	[17] in	compressive strength (lb/in2)	strain
330	66	39077.8001	0.03573	0.03976	5056.38943	0.013577338
331	66.2	39564.7509	0.03583	0.03994	5119.3974	0.013627698
332	66.4	39808.2263	0.03597	0.04004	5150.90138	0.013670863
333	66.6	40295.177	0.0361	0.04016	5213.90935	0.013715827
334	66.8	40660.3901	0.03619	0.04033	5261.16533	0.01376259
335	67	40903.8655	0.03631	0.04045	5292.66931	0.013805755
336	67.2	41269.0786	0.0364	0.04057	5339.92529	0.013843525
337	67.4	41634.2917	0.03652	0.04076	5387.18126	0.013899281
338	67.6	41877.7671	0.03665	0.04089	5418.68525	0.013946043
339	67.8	42242.9802	0.03673	0.04103	5465.94122	0.013985612
340	68	42608.1932	0.03687	0.04123	5513.1972	0.014046763
341	68.2	42729.9309	0.03701	0.04149	5528.94919	0.014118705
342	68.4	42851.6686	0.03712	0.04171	5544.70118	0.014178058
343	68.6	42973.4063	0.0373	0.04192	5560.45318	0.014248201
344	68.8	42851.6686	0.03744	0.04213	5544.70118	0.014311151
345	69	43216.8817	0.03758	0.04236	5591.95716	0.014377698
346	69.2	43338.6194	0.03777	0.04255	5607.70915	0.014446043
347	69.4	43338.6194	0.03791	0.04272	5607.70915	0.014501799
348	69.6	43825.5702	0.03805	0.04287	5670.71712	0.014553957
349	69.8	44069.0456	0.03816	0.04304	5702.2211	0.014604317
350	70	44190.7833	0.03831	0.04318	5717.9731	0.014656475
351	70.2	44555.9964	0.03844	0.0433	5765.22907	0.014701439
352	70.4	44921.2094	0.03864	0.04339	5812.48505	0.014753597
353	70.6	45286.4225	0.0388	0.04353	5859.74102	0.014807554
354	70.8	45651.6356	0.03895	0.04367	5906.997	0.014859712
355	71	45895.111	0.03907	0.04379	5938.50098	0.014902878
356	71.2	46260.3241	0.0392	0.04395	5985.75696	0.014955036
357	71.4	46503.7995	0.03935	0.0441	6017.26094	0.015008993
358	71.6	46747.2749	0.03948	0.04423	6048.76493	0.015055755
359	71.8	47234.2256	0.03962	0.04439	6111.77289	0.015109712
360	72	47721.1764	0.03977	0.04452	6174.78086	0.015160072
361	72.2	47964.6518	0.03987	0.04467	6206.28485	0.015205036
362	72.4	48086.3895	0.04002	0.04477	6222.03684	0.01525
363	72.6	48451.6026	0.04017	0.04491	6269.29281	0.015302158
364	72.8	48816.8157	0.04031	0.04507	6316.54879	0.015356115
365	73	45651.6356	0.04225	0.04509	5906.997	0.015708633
366	73.2	46016.8487	0.04249	0.04531	5954.25297	0.015791367
367	73.4	46260.3241	0.04267	0.04548	5985.75696	0.015854317
368	73.6	46503.7995	0.04288	0.04562	6017.26094	0.015917266
369	73.8	46747.2749	0.04302	0.04576	6048.76493	0.015967626
370	74	47234.2256	0.04318	0.04588	6111.77289	0.016017986
371	74.2	47477.701	0.04332	0.04605	6143.27688	0.016073741
372	74.4	47842.9141	0.04347	0.04615	6190.53285	0.016118705
373	74.6	48208.1272	0.0436	0.04627	6237.78883	0.016163669
374	74.8	48695.078	0.04377	0.04639	6300.7968	0.016215827
375	75	49182.0288	0.04389	0.04651	6363.80477	0.016258993
376	75.2	49547.2418	0.04404	0.04666	6411.06074	0.01631295
377	75.4	50155.9303	0.04419	0.04678	6489.8207	0.016361511
378	75.6	50399.4057	0.04432	0.04688	6521.32469	0.016402878
379	75.8	50642.8811	0.04448	0.04702	6552.82867	0.016456835
380	76	50886.3565	0.04462	0.04719	6584.33265	0.01651259
381	76.2	51373.3073	0.04476	0.04728	6647.34062	0.016553957
382	76.4	51616.7827	0.04492	0.04741	6678.84461	0.016606115
383	76.6	51981.9957	0.04506	0.04749	6726.10058	0.016645683
384	76.8	52347.2088	0.04524	0.04767	6773.35656	0.016710432
385	77	52590.6842	0.0454	0.04779	6804.86054	0.016760791
386	77.2	53077.635	0.04556	0.04789	6867.86851	0.016807554
387	77.4	53199.3727	0.04572	0.04802	6883.6205	0.016859712
388	77.6	53686.3235	0.04588	0.04813	6946.62847	0.016908273
389	77.8	53929.7989	0.04604	0.04827	6978.13245	0.01696223
390	78	54295.012	0.04623	0.04842	7025.38843	0.017023381
391	78.2	54781.9627	0.04638	0.04857	7088.3964	0.017077338
392	78.4	54781.9627	0.04661	0.04869	7088.3964	0.017140288
393	78.6	54903.7004	0.04693	0.04879	7104.14839	0.017215827
394	78.8	54538.4873	0.04742	0.04897	7056.89241	0.017336331
395	79	53686.3235	0.04816	0.0493	6946.62847	0.017528777
396	79.2	51738.5204	0.04921	0.04993	6694.5966	0.017830935
397	79.4	50886.3565	0.0498	0.0503	6584.33265	0.018003597
398	79.6	50764.6188	0.05032	0.05046	6568.58066	0.018125899
399	79.8	50642.8811	0.05067	0.05068	6552.82867	0.018228417
400	80	50642.8811	0.05095	0.05083	6552.82867	0.018305755
401	80.2	50886.3565	0.05121	0.05099	6584.33265	0.018381295
402	80.4	51008.0942	0.05145	0.05113	6600.08465	0.01844964
403	80.6	51129.8319	0.05166	0.05128	6615.83664	0.018514388
404	80.8	51616.7827	0.05195	0.05144	6678.84461	0.018595324
405	81	51616.7827	0.05215	0.05158	6678.84461	0.018656475
406	81.2	51738.5204	0.05242	0.05173	6694.5966	0.018732014
407	81.4	52103.7334	0.05264	0.05188	6741.85257	0.018798561
408	81.6	51981.9957	0.05292	0.05201	6726.10058	0.018872302
409	81.8	52468.9465	0.05313	0.05212	6789.10855	0.018929856
410	82	52590.6842	0.05335	0.05229	6804.86054	0.019
411	82.2	52834.1596	0.0536	0.05245	6836.36453	0.019073741
412	82.4	52955.8973	0.05385	0.05262	6852.11652	0.019149281

Peak of 2-days Compressive Test

ID	SecondsEla	[01] lb	[16] in	[17] in	compressive strength (lb/in2)	strain
1030	206	15825.9003	0.22362	0.22936	2047.75896	0.08147122
1031	206.2	15947.638	0.22382	0.22958	2063.51095	0.08154676
1032	206.4	16312.8511	0.22406	0.22981	2110.76693	0.08163129
1033	206.6	15947.638	0.22425	0.23005	2063.51095	0.08170863
1034	206.8	15825.9003	0.2245	0.23025	2047.75896	0.08178957
1035	207	15947.638	0.22473	0.23048	2063.51095	0.0818723
1036	207.2	15947.638	0.22494	0.23068	2063.51095	0.08194604
1037	207.4	16069.3757	0.22517	0.23091	2079.26294	0.08202878
1038	207.6	16069.3757	0.22539	0.23117	2079.26294	0.08211511
1039	207.8	15825.9003	0.2256	0.23137	2047.75896	0.08218885
1040	208	16069.3757	0.2258	0.2316	2079.26294	0.08226619
1041	208.2	15825.9003	0.22603	0.23184	2047.75896	0.08235072
1042	208.4	15825.9003	0.22628	0.23205	2047.75896	0.08243345
1043	208.6	15947.638	0.22648	0.23229	2063.51095	0.08251259
1044	208.8	15947.638	0.22669	0.23249	2063.51095	0.08258633
1045	209	15825.9003	0.22691	0.23274	2047.75896	0.08267086
1046	209.2	15825.9003	0.22713	0.23297	2047.75896	0.0827518
1047	209.4	15825.9003	0.22737	0.23317	2047.75896	0.08283094
1048	209.6	15825.9003	0.22761	0.2334	2047.75896	0.08291547
1049	209.8	15825.9003	0.22781	0.23363	2047.75896	0.08299281
1050	210	15825.9003	0.22806	0.23383	2047.75896	0.08307374
1051	210.2	15825.9003	0.22824	0.23411	2047.75896	0.08315647
1052	210.4	15825.9003	0.22848	0.23432	2047.75896	0.08323741
1053	210.6	15825.9003	0.22873	0.23455	2047.75896	0.08332374
1054	210.8	15825.9003	0.22896	0.23477	2047.75896	0.08340468
1055	211	15947.638	0.22917	0.23497	2063.51095	0.08347842
1056	211.2	15825.9003	0.22942	0.23522	2047.75896	0.08356835
1057	211.4	15825.9003	0.22964	0.23544	2047.75896	0.08364748
1058	211.6	15947.638	0.22987	0.23564	2063.51095	0.08372482
1059	211.8	15825.9003	0.23009	0.23587	2047.75896	0.08380576
1060	212	15825.9003	0.23031	0.2361	2047.75896	0.08388669
1061	212.2	15825.9003	0.23055	0.23629	2047.75896	0.08396403
1062	212.4	15825.9003	0.23078	0.23653	2047.75896	0.08404856
1063	212.6	15825.9003	0.23101	0.23675	2047.75896	0.0841295
1064	212.8	15947.638	0.23124	0.23697	2063.51095	0.08421043
1065	213	15704.1627	0.23144	0.23719	2032.00697	0.08428597
1066	213.2	15460.6873	0.23169	0.23743	2000.50298	0.0843741
1067	213.4	15825.9003	0.23192	0.23765	2047.75896	0.08445504
1068	213.6	15825.9003	0.23212	0.23786	2047.75896	0.08452878
1069	213.8	15825.9003	0.23236	0.23808	2047.75896	0.08461151
1070	214	15825.9003	0.23259	0.23831	2047.75896	0.08469424
1071	214.2	15582.425	0.23278	0.23853	2016.25498	0.08476799
1072	214.4	15704.1627	0.23304	0.23876	2032.00697	0.08485612
1073	214.6	15825.9003	0.23326	0.23896	2047.75896	0.08493165
1074	214.8	15825.9003	0.23347	0.23919	2047.75896	0.08501079
1075	215	15825.9003	0.23371	0.23941	2047.75896	0.08509353
1076	215.2	15825.9003	0.23391	0.23965	2047.75896	0.08517266
1077	215.4	15582.425	0.23412	0.23987	2016.25498	0.08525
1078	215.6	15704.1627	0.23436	0.24008	2032.00697	0.08533094
1079	215.8	15704.1627	0.23459	0.2403	2032.00697	0.08541187
1080	216	15947.638	0.23479	0.24051	2063.51095	0.08548561
1081	216.2	15704.1627	0.23501	0.24074	2032.00697	0.08556655
1082	216.4	15947.638	0.23523	0.24091	2063.51095	0.08563669
1083	216.6	15825.9003	0.23547	0.24116	2047.75896	0.08572482
1084	216.8	15704.1627	0.23568	0.24136	2032.00697	0.08579856
1085	217	15704.1627	0.2359	0.24158	2032.00697	0.0858777
1086	217.2	15704.1627	0.23613	0.2418	2032.00697	0.08595863
1087	217.4	15825.9003	0.23635	0.24203	2047.75896	0.08603957
1088	217.6	15825.9003	0.23657	0.24228	2047.75896	0.0861241
1089	217.8	15704.1627	0.23678	0.24249	2032.00697	0.08619964
1090	218	15825.9003	0.23701	0.24271	2047.75896	0.08628058
1091	218.2	15704.1627	0.23724	0.24291	2032.00697	0.08635791
1092	218.4	15825.9003	0.23743	0.2431	2047.75896	0.08642626
1093	218.6	15825.9003	0.23758	0.24324	2047.75896	0.08647842
1094	218.8	15460.6873	0.23766	0.24336	2000.50298	0.08651439
1095	219	15338.9496	0.23774	0.24341	1984.75099	0.08653777
1096	219.2	15338.9496	0.2378	0.24347	1984.75099	0.08655935
1097	219.4	15217.2119	0.23783	0.2435	1968.999	0.08657014
1098	219.6	15095.4742	0.23788	0.2435	1953.24701	0.08657914
1099	219.8	14973.7365	0.23792	0.24356	1937.49502	0.08659712
1100	220	15095.4742	0.23796	0.24358	1953.24701	0.08660791
1101	220.2	14973.7365	0.23799	0.24361	1937.49502	0.08661871
1102	220.4	14851.9988	0.23801	0.24363	1921.74302	0.0866259
1103	220.6	14851.9988	0.23802	0.24366	1921.74302	0.08663309
1104	220.8	14851.9988	0.23804	0.24366	1921.74302	0.08663669
1105	221	14851.9988	0.23807	0.24368	1921.74302	0.08664568
1106	221.2	14851.9988	0.23808	0.2437	1921.74302	0.08665108
1107	221.4	14851.9988	0.23809	0.24372	1921.74302	0.08665647
1108	221.6	14851.9988	0.23811	0.24372	1921.74302	0.08666007
1109	221.8	14730.2611	0.23813	0.24373	1905.99103	0.08666547
1110	222	14730.2611	0.23811	0.24376	1905.99103	0.08666727
1111	222.2	14851.9988	0.23813	0.24378	1921.74302	0.08667446
1112	222.4	14730.2611	0.23815	0.24375	1905.99103	0.08667266
1113	222.6	14608.5234	0.23817	0.24378	1890.23904	0.08668165
1114	222.8	14730.2611	0.23819	0.24378	1905.99103	0.08668525
1115	223	14486.7857	0.23819	0.24379	1874.48705	0.08668705
1116	223.2	14730.2611	0.2382	0.24377	1905.99103	0.08668525
1117	223.4	14608.5234	0.23821	0.24382	1890.23904	0.08669604
1118	223.6	14365.048	0.23821	0.2438	1858.73506	0.08669245
1119	223.8	13025.9334	0.23782	0.24346	1685.46314	0.08656115
1120	224	0	0.22645	0.23095	0	0.08226619

Failure of 2-days Compressive Test



UHP-FRC 2-days Compressive Test (Stress-Strain Curve)

Appendix F

Collaborators and the Author

AIRPLACO®

AMERICAN OWNED-AMERICAN BUILT

AGGREGATE
INDUSTRIES

ROBOCON
SHOTCRETE SERVICE

Prestige Gunite of North Texas Ltd

Phone: (817) 379-6871

Fax: (817) 431-0316

View Additional Phone Numbers

2828 Prestige Rd, Fort Worth, TX 76244

chpgitx@aol.com

On a scale of A+ to F

Reason for Rating

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Biographical Information

Jean Gamarra graduated in May 2015 with a Bachelor's Degree in Civil Engineering and Cum Laude Honors. He has continued to maintain a strong academic standing while pursuing a Master of Science in Civil Engineering degree with a concentration in Construction Engineering and Management. Mr. Gamarra has been working for the Federal Aviation Administration as a Civil Engineer/Program Manager, and at the same time he has been collaborating in a few research projects funded by the National Science Foundation as a research assistant and an entrepreneur lead for the University of Texas at Arlington. He has been the recipient of the Arthur R. Poor Civil Engineering Graduate Scholarship for Fall 2015, and the Charlie M. Moore Civil Engineering Graduate Scholarship for Spring 2015. Besides his Civil Engineering background, Jean Gamarra has been an entrepreneurial leader in his own construction business for more than fifteen (15) years, and he was recently accepted into the MBA program at West Texas A&M University beginning in Summer 2016.