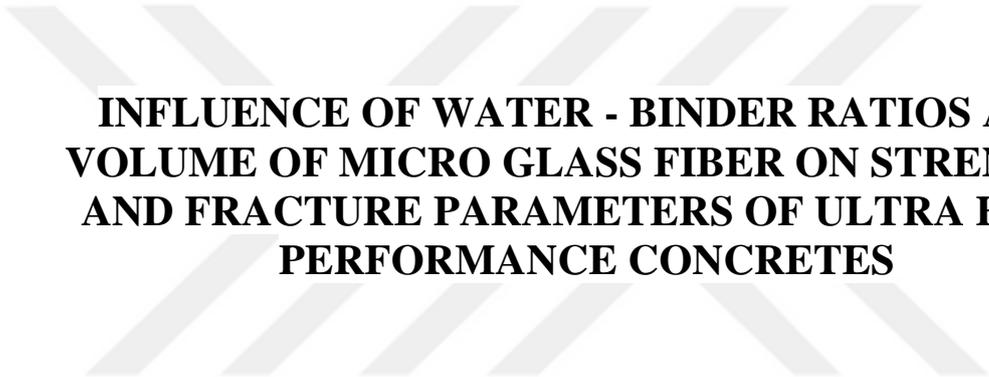


**GAZIANTEP UNIVERSITY  
GRADUATE SCHOOL OF  
NATURAL & APPLIED SCIENCES**



**INFLUENCE OF WATER - BINDER RATIOS AND  
VOLUME OF MICRO GLASS FIBER ON STRENGTH  
AND FRACTURE PARAMETERS OF ULTRA HIGH  
PERFORMANCE CONCRETES**

**M.Sc. THESIS  
IN  
CIVIL ENGINEERING**

**BY  
HAKAR HAMID QADIR  
MAY 2016**

**Influence of Water – Binder Ratios and Volume of Micro Glass Fiber on  
Strengths and Fracture Parameters of Ultra High Performance Concretes**

**M.Sc. Thesis  
in  
Civil Engineering  
University of Gaziantep**

**Supervisor  
Assoc. Prof. Dr. Mehmet GESOĞLU**

**By  
Hakar Hamid QADIR  
May 2016**



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**Hakar Hamid QADIR**

## ABSTRACT

### INFLUENCE OF WATER – BINDER RATIOS AND VOLUME OF MICRO GLASS FIBER ON STRENGTHS AND FRACTURE PARAMETERS OF ULTRA HIGH PERFORMANCE CONCRETES

QADIR, Hakar Hamid

M.Sc. in Civil Engineering

Supervisor: Assoc. Prof. Dr. Mehmet GESOĞLU

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An experimental work was carried out to investigate the effects of high volume micro-glass fibers on the mechanical properties and ductility of Ultra High Performance Fiber Reinforced Concretes (UHPFRCs). The aspect ratio and tensile values of the of micro-glass fibers were 722 and 2000 MPa, respectively. Depending on water per binder ratios (w/b) of 0.12 and 0.14, two groups of UHPFRCs containing 0%, 0.5%, 1%, 1.5%, 2%, 2.5%, and 3% fiber volumes were produced and tested for the compressive strength, splitting tensile strength, modulus of elasticity, flexural strength, load-displacement behavior, fracture energy, and characteristic length. The investigational results revealed that the mixes with 1.5% to 3% of micro glass fibers exhibited the best compressive strength of approximately 160 MPa as well as the highest splitting tensile strength. The results also showed that beyond 1.5 % volume fraction of fiber, the improvement of strength properties began to be constant. On the other hand, the mixes with 3% of micro glass fiber displayed a strain hardening, load- displacement behavior with enhanced ductility.

**Keywords:** Ultra High Performance Fiber Reinforced Concretes, Water – Binder Ratio, Glass Fiber, Mechanical Properties, Fracture parameters

## ÖZET

### SU BAĞLAYICI ORANI VE HACİMCE MİKRO-CAM FIBER MİKTARININ ULTRA YÜKSEK MUKAVEMETLİ BETONLARDA BASINÇ MUKAVEMETİ VE KIRILMA PARAMETRELERİNE ETKİSİ

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Yüksek hacimde mikro cam elyaf içeren ultra yüksek performanslı fiber takviyeli betonlardaki (UYPFTB) mekanik özellikleri ve sünekliği etkilerini araştırmak amacıyla bu deneysel çalışma gerçekleştirilmiştir. Mikro cam elyafların en-boy oranı ve çekme değerleri sırasıyla 722 ve 2000 MPa. UYPFTB lar su-bağlayıcı oranı 0.12 ve 0.14 olan iki grupta, hacimce % 0, % 0.5, % 1, % 1.5, % 2, % 2.5 ve % 3 fiber kullanılarak üretildi ve basınç dayanımı, yarmada çekme dayanımı, elastisite modülü, eğilme dayanımı, yük-deplasman davranışı, kırılma enerjisi ve karakteristik uzunluğu özellikleri için test edildi. Araştırma sonuçlarına göre mikro cam liflerinin % 1.5 ve % 3 oranında kullanıldığı karışımlar yaklaşık 160 MPa en iyi basınç dayanımı yanı sıra yüksek yarma çekme mukavemeti göstermiştir. Sonuçlar, aynı zamanda lif oranının hacimce % 1.5 dan sonra, mukavemet özelliklerinin iyileştirildiğini göstermektedir. Öte yandan, mikro cam elyafın % 3 olduğu karışımlarda pekleşme, yük-deplasman özelliği kazandırılmıştır.

**Anahtar kelimeler:** Ultra yüksek mukavemetli fiberli betonlar, Su-çimento oranı, cam fiber, Mekanik özellikleri, Kırılma parametreleri



To My Parents

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## LIST OF SYMBOLS/ ABBREVIATIONS

|            |   |
|------------|---|
| ACI        | American Concrete Institute                                   |
| ASTM       | American Society for Testing and Materials                    |
| BS         | British standard  |
| CH         | Hydroxide Calcium   |
| C-S-H      | Calcium-Silicate-Hydrate                                      |
| DRIFTS     | Diffuse Reflectance infrared Fourier Transformed Spectroscopy |
| E          | Modulus of Elasticity   |
| $f_{flex}$ | Flexural Strength   |
| FRC        | Fiber Reinforced Concrete                                     |
| $G_F$      | Fracture Energy   |
| HPC        | High Performance Concrete                                     |
| HPFRC      | High-Performance Fiber Reinforced Composites                  |
| ITZ        | Interfacial Transition Zone                                   |
| $l_{ch}$   | Characteristic Length   |
| LVDT       | Linear Variable Displacement Transducer                       |
| MGF        | Micro glass fiber   |
| RPC        | Reactive Powder Concrete                                      |
| RPCM       | Reactive Powder Composite Materials                           |
| RPM        | Reactive Powder Mortar  |
| SEM        | Scanning Electron Microscope                                  |
| SF         | Silica Fume   |
| TS         | Turkish Standard  |

|        |  |
|--------|--|
| UHPC   | Ultra High Performance Concrete                  |
| UHPFRC | Ultra-High Performance Fiber-Reinforced Concrete |
| w/b    | Water per binder ratio                           |
| w/c    | Water per cement ratio                           |



## CHAPTER 1

### INTRODUCTION

#### 1.1 General

The term “ultra-high performance concrete” was first used in a journal by De Larrard and Sedran in 1994 and in a similar development, Richard and Cheyrezy used the term reactive powder concrete (RPC) in 1995 (De Larrard and Sedran, 1994; Richard and Cheyrezy, 1995). Since the late 20<sup>th</sup> century the concrete technology had experienced, a major development led to production of ultra-high performance concrete (UHPC) or ultra-high strength concrete(UHSC), which has been the topic of most researchers through the world. UHPC’s durability and mechanical properties made it a supreme candidate to be used in several construction elements (Graybeal et al. 2011). UHPC as from its name is composed of very high binder content such as cement and silica fume, different types of fibers, and crushed quartz ranging between 10-2500  $\mu\text{m}$  used to give uniformity instead of using conventional coarser aggregates (Richard and Cheyrezy, 1995; Graybeal, 2005; Tue et al., 2008; Jiang et al., 2014; Uchida et al., 1995; Yoo et al., 2015; Sahin and Koksall, 2011). In addition, UHPC recognized by extremely low water per binder ratio with enough workability due to assist of a new generation of superplasticizers that controlled the permeability of concrete to be less, caused to improve in durability and strength (Wassermann et al., 2009; Dhir et al., 2004). For instance, Serelis et al. (2015) improved compressive strength from 119 MPa to 145 MPa via decreasing w/b from 0.28 to 0.22.

Ultra-high performance fiber reinforced concrete (UHPCFRC) is a composition of plain UHPC pregnant with different types of fibers leads to enhance the mechanical and fracture properties in an advanced manner. Various investigators proved that the addition of fiber to the matrix incredibly improves the properties of concrete such as toughness, flexural strength, fatigue resistance, impact and abrasion resistance, load bearing capacity after cracking and post-cracking capacity, deformation capability and tensile strength (Jiang et al., 2014; Uchida et al.,1995; Yoo et al., 2015; Sahin and

Koksal, 2011; Monteiro, 2006). Particularly, ultra-high performance fiber reinforced concrete (UHPFRC) denotes the highest advancement of ultra-high Performance Concrete (UHPC), and its ultimate compressive strength depends on the curing conditions; its value could rise up to 800 MPa (Richard and Cheyrezy, 1995).

Glass fibers are relatively lightweight, have the high-tensile strength, and they are cheap as well. There is a lack of study on incorporation of micro glass fiber (MGF) with UHPC in spite of some studies on their effect on ordinary concrete. Furthermore, researchers have shown when glass fibers added into a normal concrete matrix it had an ability to increase the flexural, and tensile strengths with improving the post-peak ductility in compression (Mirza and Soroushiann, 2002; Ali et al., 1975; Fanella and Naaman, 1985). In addition, Chandramouli et al. (2010) observed 20–25% rise in compressive strength with while 15–20% increase in flexural and splitting tensile strength when they reinforced the concretes using glass fiber. The same results were stated by Tassew and Lubell (2014) that with the increase of glass fiber volume fraction, the flexural strength value of concrete increased.

## **1.2 Research Significance**

Optimizing the volume fraction of glass fibers through investigating the mechanical properties of glass fiber reinforced ultra-high performance concretes is the main purpose of present study. Varying fractions of glass fiber at the rates of 0%, 0.5%, 1.0%, 1.5%, 2.0%, 2.5% and 3.0% were incorporated into two groups of UHPC with w/b of 0.12 and 0.14 to investigate the behavior of compressive strength, tensile strength, modulus of elasticity, flexural strength, load displacement curve, fracture energy, and characteristic length.

## **1.3 Outline of the Thesis**

**Chapter 1** This chapter consists of general introduction and the significance of the thesis.

**Chapter 2** This chapter focuses on the historical background on the compounds, application, and mechanical properties of UHPFRC.

**Chapter 3** this chapter covers highlights of the experimental test carried out in this study. The properties of the materials used, mixture design, mixing procedures, the preparation of samples, curing types, and testing procedures are mentioned.

**Chapter 4** The results obtained experimentally are presented and effect of using low water per binder ratio and different amount of glass fiber on the mechanical properties of UHPFRC are discussed in detail.

**Chapter 5** According to the results of comparative studies, conclusions are presented.



## CHAPTER 2

### LITERATURE REVIEW AND PREVIOUS WORKS

#### 2.1 UHPC - brief historical backgrounds and applications

According to Rossi (2000, 2008), UHPC can be defined as a concrete or cementitious composite with a relatively high binder ratio, a water to cementitious ratio (w/c) less than 0.2, and compressive strength of more than 21.8 ksi (150 MPa).

Concrete with nearly 800 N/mm<sup>2</sup> compressive strength was developed in the 1960s and produced under specific laboratory conditions. These products were well-compacted under high-pressure and treated thermally. In the early 1980s was the born of idea developing the fine grained concrete with very dense and homogeneous cement matrix prevent enhancement of micro-cracks inside the structure while it is loaded. As a result of limited grain size of not more than 1 mm high packing density considering the usage of different mineral additives termed as reactive powder concrete (Richard and Cheyrezy, 1995; Bache, 1981). At the same time, there was a wide range of formulas and the phrase "Ultra-High Performance Concrete" or - in brief - UHPC founded all over the world for concrete with a minimum pressure of 150 N/mm<sup>2</sup> force. Later, French investigators were the pioneer to write technical recommendations focusing on the design of UHPC in 2002 (SETRA, 2002). This report is known as the 'Interim Recommendations for Ultra-High Performance Fiber Reinforced Concrete'.

As regarded by Green et al. (2015) since the end of 1980 s Engineer Research and Development Center (ERDC) of the US Army carried out researches on ultra-high-performance concretes (UHPCs). The attention was mainly targeted the armed and civilian applications infrastructure works. The improvement of an UHPC material known as Cor-Tuf foundation was a part of their research, which includes several products including the patented material. The historical experience of ERDC with UHPCs, including component materials and invention on a laboratory scale, heat treatment, and the microstructure model, and paths to increase production. Case

investigations are introduced as well regarding current study purpose on the use of fiber reinforced UHPFRCs to retrofit and repair systems plate armor in the US Army Corps of Engineers (USACE) civilian works substructure of internal navigation and continuing on the long term durability field testing.

First research and development targeting the UHPC application in construction began in about 1985. Later after, numerous practical resolutions were enhanced one by one or concurrently, precast structures made of traditionally UHPFRC used in bridge decks, applications on-site for the rehabilitation of concrete bridges have weakened and floors of industrial (Buitelaar, 2004) fine grained reinforced with fiber ductile "reactive powder concrete" (RPC) such as "channels" manufactured by Lafarge located in France or producing Densit in Denmark (Acker and Behloul, 2004). With or without other reinforcements it is applied for precast components and other uses such as offshore bucked bases. Furthermore, the advancement of UHPC coarse-grained artificial or natural high strength aggregates, such as very high loaded columns and high-rise buildings (Schmidt et al., 2003)

As mentioned by Hajar et al. (2004) an increased domain of UHPC designs is existing these days and could be modified to accommodate the exact necessities of an individual design, architectural or construction methodology. The innovation applications were the unique first pedestrian bridge which was pre-stressed hybrid in 1997 located in Sherbrooke Canada as shown in Figure 2.1, steel parts surrogate of a tower used for cooling in Cattenom and two road bridges of 22.50 and 20.50 m in length utilized by lorries and cars in Bourg les Valence France constructed in 2001. For these constructions UHPC had been reinforced with nearby 2.5-3% volume of different types of steel fiber. Bridges in Bourg les Valence are pre-tensioned that consist of five precast beams. They had been set on site after that combined together with UHPC at the site.

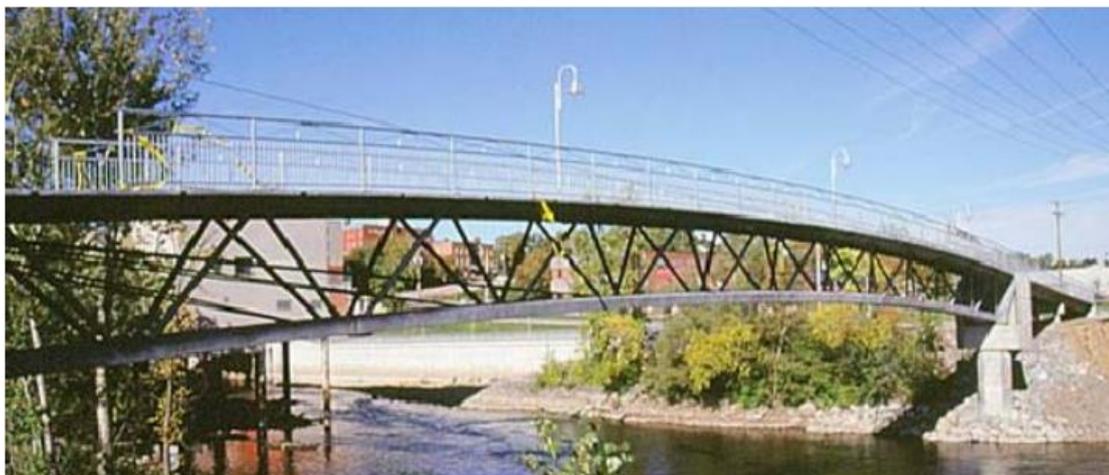


Figure 2.1 Sherbrooke footbridge, Canada, 1997 (Hajar et al., 2004)

Further pedestrian bridges with decks and/or other load-bearing constituents composed of fine-grained, fiber reinforced UHPC in Japan and Seoul Korea (Acker and Behloul, 2004).

Resplendino (2004) addressed a spectacular sample of architectural taking advantage of superior benefits of UHPC is the toll-gate build in Millau Viaduct in France. Figure 2.2 illustrates the elegant roof, 28 meters wide and 98 meters long with a thickness of 85 cm from center.

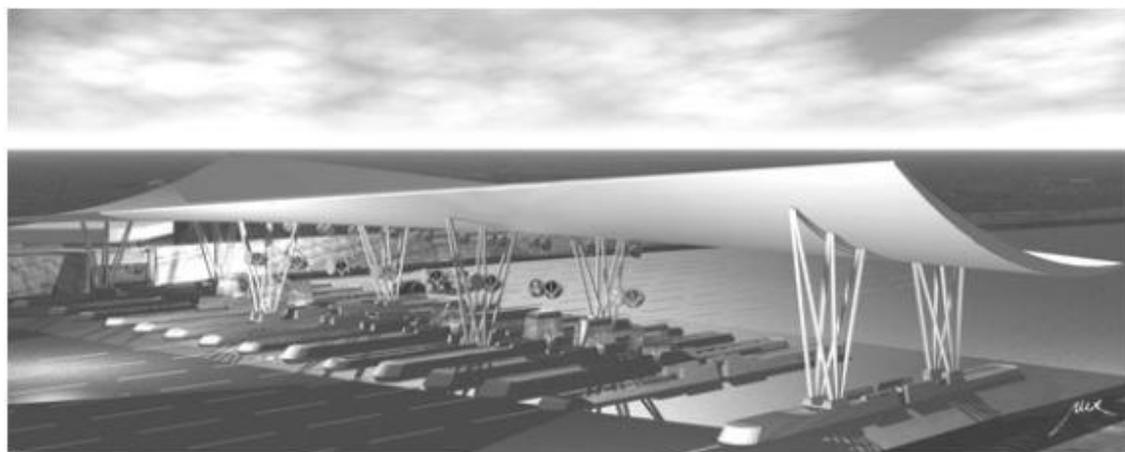


Figure 2.2 Roof of the Millau toll-gate (Resplendino, 2004)

As stated by Fehling et al. (2004) the first application of UHPC, a hybrid bridge for pedestrians and bicycles of nearly 135 m length and the maximum width of 40 m consists of prestressed precast chords and prefabricated deck elements of the bridge produced of UHPC with a grain size of 2 mm as maximum by using conventional

materials. The 4.50 x 2.00 x 0.08 m wide deck components of the bridge were prestressed diagonally. As an extra step to improve, it has been glued the load bearing elements of UHPC together without any further mechanical connection. This means another step towards the construction of suitable materials and economical technique for UHPC. Motivated by the former applications in South Korea, Canada, and Europe research and development efforts intensified in the various universities and cement, construction industries, the DAfStB developed state-of-the-art report on Ultra High Performance concrete (DAfStB UHPC 2003). DAfStB is a branch of German standardization organization (DIN) being in charge for all the technical requirements and standards relating to the production and applications of concrete and give the guidelines for the design of concrete constructions. The German state-of-the-art report explains technical know-how and UHPC experience published all over the world. It covers almost all existing applications so far - is based primarily on a mixture of commercially available UHPC - basic principles and standards of characteristic behavior, aspects of durability and fire resistance. Another part of the report mentions the adequate design and production of constructions by means of UHPC. The report conventionally is a first step in direction of a dependable technical recommendation and latter criteria for UHPC.

Zhang et al. (2010) established a new-engineered cementitious composite combined via poly vinyl alcohol. High ductility property of this new type of concrete make it suitable to be used in modify and repair of existing structures. The mixtures were tested for high early strength gain rate with different mixtures of a binder system. The micro mechanical model discovered that the quick deterioration in strain capacity, which was because of rapid drop of complementary energy and continuous rise of crack tip toughness.

The Sun-Yu Bridge in Korea, built in 2002, as presented in Figure 2.3 is the longest pedestrian bridge to use ultra-high-performance fiber-reinforced concrete in an arch form (Huh and Byun, 2005).



Figure 2.3 Seonyu Pedestrian Bridge (Huh and Byun, 2005)

Liu and Huang (2008) discovered a Reactive powder mortar (RPM) of compressive strength of 75 MPa and flow value 200% for rehabilitation and repair. Many tests such as, tensile tests, rebar pull-out, slant shear conducted and the test results compared with the repaired cylinders with epoxy resins. The strength of cylinders with RPM was higher, whereas the slant shear strength is almost equal to that of epoxy resin.

Lee et al. (2007) reported the application of RPC as a renovation material and assessed its bond and durability properties with existing reinforced concrete and high strength. They conducted many tests such as; compressive strength, bond strength, steel pull out strength and relative dynamic modulus of elasticity. The test results verified the dominance of RPC with respect to the other concretes used. The mechanical properties of RPC specimens were higher than that of the normal strength concrete by 200%.

## **2.2 UHPC – materials, mix proportions and design consideration**

According Randl et al. (2014) ultra high performance concrete (UHPC) is a substance emerging technological building that compared with the strength of ordinary concrete allows for more slenderness and increased durability when designing RC- structures. The environmental impact of the UHPC are affected by high cement content with more than twice the amount required in evaluation with ordinary concrete strength. Replacing cement in a mixture with less energy-intensive hydraulic additives observed for their impact on the specific characteristics and parameters calculated the environmental impact of different mixtures of UHPC.

As declared by Wille et al. (2011a) in a study of the type of cement suggested Type I Portland cement of low C3A content and a low-to-moderate fineness of 281,240 in.2/lb (4000 cm<sup>2</sup>/g) to be used in UHPC and UHP-FRC. The powder proportions (cement, silica fume, and glass powder) was then optimized by Wille et al. (2011a). Initially, they used the proportions of C:SF:GP of 1:0.18:0.53 recommended by Wille (2008), and then they achieved an increase of 13% in the spread value by changing it to 1:0.20:0.40. Next, changing these proportions to 1:0.25:0.30 resulted in an additional increase of 5% in spread value. A 2% increase in spread value was then obtained by further changing the proportions to 1:0.25:0.25. Although they observed very little influence on the compressive strength by changing these proportions, an improved packing density was achieved by increasing the spread values. Moreover, Wille et al. (2011a) also observed that improving the packing density of a paste can also lead to a reduction in the required HRWR amount. By optimizing the paste, they were able to reduce the required amount of HRWR from 8% by weight of cement to 1%, which was sufficient to obtain acceptable flowability along with high compressive strength. Later, they recommended a 1.4 to 2.4% range of HRWR by weight of cement to be the optimum range for UHPC and UHP-FRC.

Shi et al. (2015) reviewed the theoretic basics, methods of mixture designing, raw materials, and methods for preparation UHPC. Low porosity, enhancement in microstructure, improvement in homogeneity and increment in durability are four important principles for the design of UHPC. They observed in their study that the raw materials, the method of preparation, and curing type have a major impact on the UHPC properties. The use of supplementary cementitious materials that available on a large scale, such as slag and fly ash for part/complete cement and silica fume replacement, it can significantly decrease material costs without sacrificing strength. Applying high temperature curing causes improved performance and denser microstructure than room temperature treated does, however that obviously limits the applications of UHPC. Thus, the preparation of UHPC using obtainable raw materials on a large scale, common technology, such as the traditional casting and normal room temperature cure, are trends for the production of UHPC.

Schroefl et al., 2008 revealed that the type and amount of HRWR play a significant role in the fresh properties of UHPC and UHP-FRC. The most appropriate HRWRs

available on the market that is also commonly used are based on Polycarboxylate ether with various lengths of side chain. According to Stark and Mueller (2008), the required HRWR can be reduced by enhancing the packing density of fine sands.

As stated by Graybeal (2006) UHPC is generally composed of Portland cement, silica fume, ground quartz, fine sand, accelerator, superplasticizer, fibers, and water. The UHPC composition provided by Graybeal is presented in Table 2.1. The same results also predetermined by Richard and Cheyrezi in (1995). Ground basalt and other variations of these materials have been used in UHPC mix designs (Schmidt et al. 2008; Burkart and Müller 2009). Despite of that the constituents used in conventional concrete are similar to that used in UHPC, though the differences are in using fine aggregates and a great variation of material percentages.

Table 2.1 General composition of UHPC (Graybeal, 2006)

| Material         | Amount (lb/yd <sup>3</sup> ) | Percent by weight |
|------------------|------------------------------|-------------------|
| Portland cement  | 1,200                        | 28.5              |
| Fine Sand        | 1,720                        | 40.8              |
| Silica Fume      | 390                          | 9.3               |
| Ground Quartz    | 355                          | 8.4               |
| Superplasticizer | 51.8                         | 1.2               |
| Accelerator      | 50.5                         | 1.2               |
| Steel Fibers     | 263                          | 6.2               |
| Water            | 184                          | 4.4               |

Kowald and Trettin (2004) found that quartz fillers containing particles with a diameter of less than 5 micron are suspected to cause health problems. This led to intensive efforts to replace those particles by other mineral powders. Positive experiences have been gained with finely ground granulated blast furnace slag, the fine and glassy parts of ground or assorted fly ashes from stone coal power plants and with some high quality stone dusts e.g. produced from basalt. Ultra-fine slag particles are even

adequate to partly replace microsilica. Common limestone fillers are – as a rule – less beneficial. Research is done to further improve the rheological and the strength performance of UHPC by adding nanotubes.

Plawsky et al. (2003) found a different way to disperse the cement in sand to form dry premix with enhanced mechanical and physical properties. The issues in mixing the dry constituents and the water dispersal were introduced to the mixture. Additionally, they produced a dense-mortar by understanding of mixing process that led to design future generation equipment.

Staquet and Espion (2002) observed mechanical property of RPC. A compressive strength value without heat treatment can reach 180 MPa by changing type of the cement from CEM 42.5 to CEM 52.5 in RPC applications. Moreover, the concrete made with the white and light grey silica fume, respectively, had better workability than that prepared by the white-black silica fumes.

Yu et al. (2014) addressed the mix design and evaluation of the characteristics of ultra-high performance fiber reinforced concrete (UHPC). The concrete admixtures design is focused on target to achieve the densely compacted concrete matrix, and using them in Andreasen and Anderson particle packing adjusted model. A simple and effective method is utilized for the production of UHPC in their studies. They analyzed and measured workability, porosity, air content, compressive, and flexural strength of designed UHPC.

Dili and Santhanam (2004) improved RPC, which could be suitable for nuclear waste containment structures by preparing two mixture proportion of 200 MPa and 800 MPa strength. Workability, mechanical properties, durability of designed RPC mix were performed. The test that applied for durability of the RPC mixes with the flowability test in a range of 120mm-140mm, exhibited that the chloride ion and permeability of water is very low. The experimental results proved the appropriateness of the designed RPC mix for nuclear waste containment constructions.

Uzawa et al. (2005) implemented RPC steel fiber reinforced applications with 200 MPa compressive strength. They developed the existing RPC, and proposed a novel material which was accompanied by a simple method of curing. The suggested reactive powder composite materials (RPCM) have high toughness and compressive strength

despite ordinary curing techniques not like conventional RPC. The generated RPCM premix contains cement, quartz sand, water reducer and steel fiber having 1.33 aspect ratio. The results indicated that the reactive powder composite material in fresh state has an exceedingly high fluidity and excellent compatibility and when it reached the hardened state high levels of toughness and a compressive strength of about 200 MPa observed.

Dattatreya et al. (2007) examined a number of particle packing models to enhance a mix design of RPC. The granular packing of materials consists of cement, standard sand, quartz powder, and silica fume. The granular packing optimization of constituents was a significant reason for obtaining better properties of durability and mechanical, and the investigational results were matched with models of theoretic packing.

Almansour et al. (2008) studied on UHPC by increasing strengths and getting extremely low permeability for the application of bridges that have long life. The designs recommendation for producing UHPC used and considered concerning the Canadian Highway Bridge design code. Results attained to denote there is an important drop in concrete volume (49%-65%).

Bono and others. (1997) produced two RPC mixtures each of a different type in the University of Sherbrooke at a precast plant, one of the RPC was ready-mix, and the other was used in the ready-made factory. In ready-mixed concrete, the preparation of RPC samples was with and without steel fiber. The samples tested for compressive strength, modulus of elasticity, thawing and freezing, and scaling deicing salts resistant and chloride ion permeation. The experimental results revealed that mixes of RPC were able to resist freeze-thaw and under the scaling test, the mass loss was very low, chloride ion penetration under 10 Coulombs regarding steel fiber RPC samples.

Orgass and Klug (2004) observed influence of short and a hybrid consisted of long and short fibers on the mechanic properties, particularly on the effect of size and ductility of ultra-high performance concretes. The experimentations were executed for samples of different fiber volume like 0, 1, 2 % and variable grain size from 0.8mm to 5.0mm for RPC and UHPC, respectively. The modulus of rupture results and crack behavior denoted that there is a growth in strength with an increment in the steel fiber.

In the study of Hoang et al. (2008), the mechanical properties carried out for the UHPC using varying aspect ratios of steel fibers,  $L_f/d_f=17/0.2$  and  $L_f/d_f=35/0.5$ . The hybrid steel fibers caused high flowability, flexural strength and greater than 150 MPa compressive strength. Moreover, it was detected that the higher strength was achieved due to adding micro fibers by a volume higher than 1% as suggested. Furthermore, the ratio of silica fume and other filler powders should be about 20-25% for making self-compacting UHS concrete with a water to binder ratio of 0.2.

Rossi and Parant (2001) expanded Ultra-high performance concrete materials and characterized regular and constant activation of the multiscale fibers to reach the optimized strength. Additionally, the considered material being displayed as elasto-plastic samples with tensioned strain hardening. The outcomes showed that the new concrete was too sensitive to changes in the load rate as well as the rupture modulus values rises up to 25% in the quasi-static load range.

As recommended by Naaman (2008), utilization of the High Performance Fiber Reinforced Concretes (HPFRC) labeling them as having an arrangement of toughness-ductility and high strength as well. In another occasion, Naaman explained the strain-hardening FRC concretes distinctive tensile response and gave a theoretical formula in order to realize strain-hardening property when he demonstrated a study at IABSE conference in Paris in 1987. The phrases like high-performance and ordinary fiber-reinforced concrete were used instead of strain-hardening and strain-softening terms.

In their study Lai and Sun (2010) applied Hopkinson bars to find spalling strength of RPC. Prepared samples were exposed to impact of the projectile at the free end with different volume of steel fibers incorporated with RPC. Reflected tensile waves and the compressive also were noted. Moreover, a finite-element examination was implemented by simulating via material model 'JOHNSON HOLMQUIST CONCRETE'.

Jungwirth and Muttoni (2004) investigated the tensile behavior at the structural concrete laboratory of UHPCs members. As a result of the existence of steel fibers having high strength, the behavior was different and extremely high toughness of the component was recorded because of very high tensile stress and bond. Moreover, they

suggested pre-stressed cables UHPC and reinforcement to hold the utmost tensile strengths.

### 2.3 Mechanical properties of UHPC

Lubbers (2003) generated a table to compare general properties between ultra-high performance concrete and high strength concrete. Details presented in table 2.2.

Table 2.2 comparison between UHPC and HSC properties (Lubbers, 2003)

| Material characteristic | UHPC compared with HPC |
|-------------------------|------------------------|
| Compressive strength    | 2-3 times greater      |
| Flexural Strength       | 2-6 times greater      |
| Elastic Modulus         | 1.5 times greater      |
| Total Porosity          | 4-6 times greater      |
| Micro-porosity          | 10-50 times greater    |
| Permeability            | 50 times greater       |
| Water Absorption        | 7 times greater        |
| Chlorine Ion Diffusion  | 25 times greater       |
| Abrasive Wear           | 2.5 times greater      |
| Corrosion Velocity      | 8 times greater        |

Yu et al. (2014) in his study used a simple and effective method for the production of UHPFRC. He measured and analyzed air content, workability, porosity, compressive and flexural strength of UHPFRC. The results showed that by taking advantage of developed packing model, design of UHPFRC is conceivable when the amount of the binder is relatively low. In addition, the hydration degree of cement is measured for the UHPFRC. The outcomes showed that 28 days after curing, still there is huge volume of cement which is unhydrated in the matrix of UHPFRC, while it can be

substituted with more fillers in order to enhance workability and cost efficiency of UHPFRC.

Graybeal (2007) reported average 28-day steam-cured and normal cured compressive strength of 28.0 ksi (193 MPa) and 18.3 ksi (126 MPa), respectively, both associated with a standard deviation of 2.0 ksi (14 MPa) for UHP-FRC based on 3 in. (76 mm) in diameter and approximately 6 in. (150 mm) long cylinders. Also, an average 28-day steam-treated and untreated modulus of elasticity of 7,650 ksi (52.7 GPa) and 6,200 ksi (42.7 GPa), respectively, both associated with a standard deviation of 220 ksi (1.5 GPa) were also reported by Graybeal (2007). Strain at peak compressive strength of 0.41% and 0.35% with a standard deviation of 0.04% and 0.02% were reported for steam-treated and untreated cylinders, respectively (Graybeal, 2007). It was also noticed that the compressive strength of untreated UHP-FRC increases for at least 56 days after casting while it is basically stabilized after steam treatment for 48 hours (Graybeal, 2007).

Compressive stress-strain curves for untreated UHP-FRC cylinders at different ages are illustrated in Figure 2.4 based on which the pre-peak nonlinearity as well as the post-peak strain capacity decrease as the compressive strength increases (Graybeal, 2007).

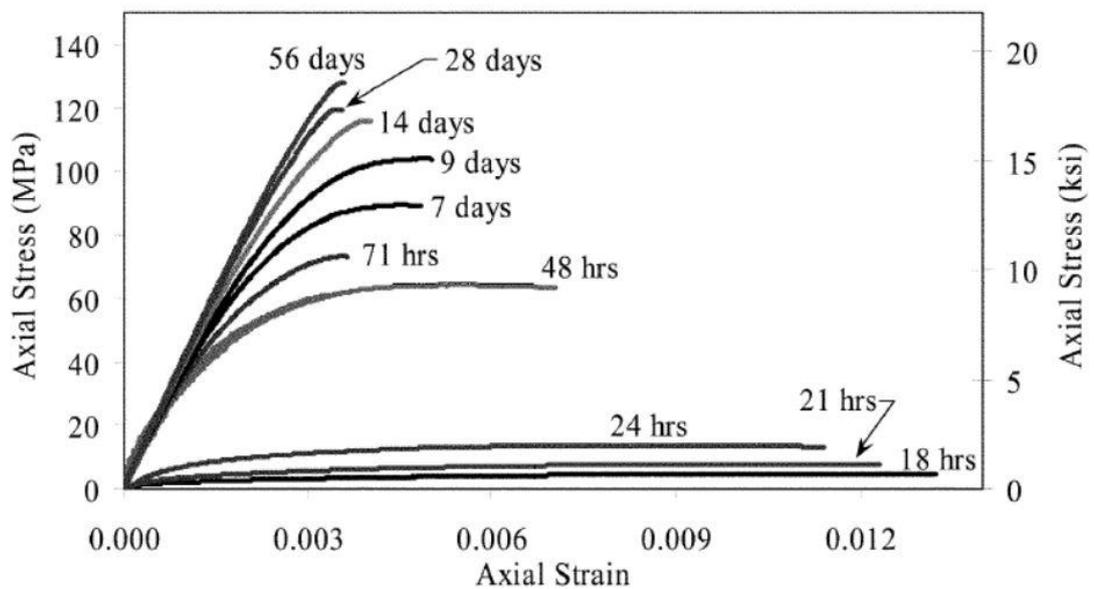


Figure 2.4 – Compressive stress – strain curves for normal cured UHPFRC cylinders (Graybeal, 2007)

According to Graybeal and Davis (2008), compressive strength of concrete can be determined through two standard testing methods based on failure of cylinder and cube specimens. They stated that testing machine capacity and end preparation of cylinder are the two main issues of compression testing methods of concretes with very high strength. Using smaller specimens and application of cube specimens are known to be the solutions of the first and second issues, respectively (Graybeal and Davis, 2008). However, they believed that deviation from the standard approach in the concrete industry by integrating the two solutions together might raise concerns regarding the exactness of the test results. Higher compressive strength is usually obtained from smaller specimens because the larger the specimen, the more it is likely to contain defects and low strength elements (Neville, 1996). Graybeal and Davis (2008) investigated the relationship between the compressive strengths of UHP-FRC based on three sizes of cubes (2 in. [51 mm], 2.78 in. [70.7 mm], and 4 in. [102 mm]) and three sizes of cylinders (2 in. [51 mm], 3 in. [76 mm], and 4 in. [102 mm]). Graybeal and Davis (2008) observed that the 2.78 in. (70.7 mm) and 2 in. (51 mm) cube specimens both resulted in very similar compressive strengths, which are equal to or higher than the compressive strength values obtained based on other specimen types. They also reported that the 4 in. (102 mm) and 3 in. (76 mm) cylinder specimens exhibited very similar compressive strengths while 2 in. (51 mm) cylinders led to lower compressive strengths compared with those exhibited by other specimen types. Coefficients for conversion of compressive strengths of different specimen types to compressive strengths based on 3 in. (76 mm) and 4 in. (102 mm) cylinder specimens that are more frequently used are summarized in Table 2.3 (Graybeal and Davis, 2008).

Table 2.3 – Coefficient for conversion of compressive strength results (Graybeal and Davis, 2008)

| Tested \ Desired | 76 mm diameter cylinder                | 102 mm diameter cylinder               |
|------------------|--|--|
| 100 mm cube      | Multiply by 1.00<br>( $R^2 = 0.9672$ ) | Multiply by 1.00<br>( $R^2 = 0.9791$ ) |
| 70.7 mm cube     | Multiply by 0.94<br>( $R^2 = 0.9857$ ) | Multiply by 0.93<br>( $R^2 = 0.9694$ ) |
| 51 mm cube       | Multiply by 0.96<br>( $R^2 = 0.9541$ ) | Multiply by 0.96<br>( $R^2 = 0.9472$ ) |
| 102 mm cylinder  | Multiply by 1.01<br>( $R^2 = 0.9853$ ) | —                                      |
| 76 mm cylinder   | —                                      | Multiply by 0.99<br>( $R^2 = 0.9839$ ) |
| 51 mm cylinder   | Multiply by 1.08<br>( $R^2 = 0.9645$ ) | Multiply by 1.07<br>( $R^2 = 0.9360$ ) |

Note: 1 in. = 25.4 mm.

Compressive strengths exceeding 30 ksi (200 MPa) were also achieved by implementing high particle packing density without using any pressure curing, heat curing, or specific mixer and by utilizing commercially available materials on the US market (Wille et al., 2011a; Wille et al., 2011b; Wille et al., 2011c). In these studies, the particle packing density of sand, silica fume, glass powder and cement were optimized by selecting ranges of particle sizes and changing the matrix proportions and compositions, and the spread value and the amount of entrapped air were measured for different mixtures.

Later Wille et al. (2012) investigated the tensile properties of UHP-FRC. If UHP-FRC mixes are designed to take a tensile stress in excess of the cracking strength of the matrix, tensile strain hardening followed by multiple cracking up to peak tensile stress (Figure 2.5) can lead to a very ductile tensile behavior (Wille et al., 2012).

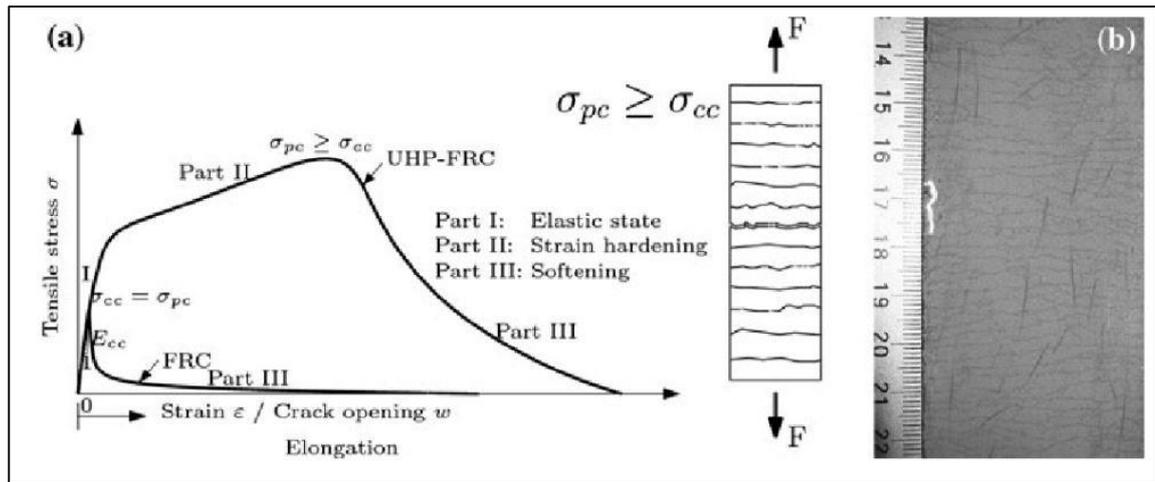


Figure 2.5 – (a) Tensile strain hardening behavior and (b) multiple cracking up to peak tensile stress (Wille et al. 2012)

Furthermore, Wille et al. (2011b) reported a tensile strength of 2.9 ksi (20 MPa) with a strain at peak tensile strength of 0.6% by using straight steel fibers with a volume fraction of 3%. By using a volume fraction of 1.5% 0.59 in. (15 mm) long twisted fibers, they achieved a tensile strength of 3.2 ksi (19 MPa). They also achieved a tensile strength of 2.3 ksi (15.9 MPa) associated with a strain at peak stress of 1% by adding 1% by volume of 0.87 in. (22 mm) long twisted fibers. Tensile strengths of 4.5 ksi (31.1 MPa) and 5.0 ksi (34.6 MPa) were obtained associated with strains at peak tensile stress of 0.72% and only 0.46% with the addition of long twisted fibers with volume fractions of 3% and 6%, respectively, by means of a fiber blend which allowed to have mixtures with such high volume fractions of long twisted fibers (Wille et al, 2011b). Based on these test results, Wille et al. (2011b) concluded that although using higher fiber content might result in a higher tensile strength, it may lead to a decrease in ductility.

Teutsch and Grunet (2004) reported a ductile fracture behavior in UHPC mixtures because of short fibers. Results of tensile tests revealed that adding of discontinuous short fibres leading to rise in loading capacity as well as fracture behavior, compared to UHPCs mixtures with no contribution of fibers. Higher loads were attained at equivalent displacements and a constant load carrying behavior because of an excellently dispersed improvement of crack was detected. Differences in the structure of the matrix of UHPC mixes with no-short fibers added, might not affect the bonding

characteristic considerably therefore no important variation in the advancement of the load-displacement curved obtained.

Shah and Daniel (1988) presented procedures for sample preparation and discuss testing of flexural strength, workability, absorption of energy and toughness. Recently advanced test methods are demonstrated for the first time for flexural toughness and impact strength. The possibility of following experimental tests to FRC studied: yield, air content, splitting tensile strength, compressive strength, unit weight, creep, modulus of elasticity, freezing and thawing resistance, shrinkage, abrasion resistance, cavitation, and erosion. The study applies to conventionally mix and placed FRC or fiber-reinforced shotcrete (FRS) using polymeric, glass, natural, and steel fibers.

Reineck and Greiner (2004) carried out tests for direct tension, noticed a slight rise in load after cracking first. Generally, the decline in load has happened, and it was very severe in some cases it seems clearly that the sample with a weak cross-section where the fiber positioned mostly perpendicular to the direction of load during the pouring of concrete. As a result, highest care should be given on the concrete casting and quality assurance generally. Flexural tensile strength of nearly 25-40 Mpa reported in their tests. The value of tensile flexural strength drops when depth of prism samples increased because of distinct size effect. Thus, the size of the prisms needs to mention when described these values. One of the main reasons of this effect of the size was the settlement of the fiber, which leads to the preferred orientation of the fibers parallel to the opposite surface to the pouring of concrete.

As confirmed by Perry and Zakariassen (2004), one of supreme important properties of Ductal remains compressive strength of extremely high value. Lafarge North America claims that the compressive strength of Ductal after thermal treatment ranges between 158 and 228 MPa, which has been. The growth in compressive strength, over ordinary concrete or HPC, could be returned to the packing of particles and choosing specific components, and heat treatment of Ductal

Graybeal and Hartmann (2003) performed series of tests and found that the method of curing resulted in significant changes in the compressive strength, even a difference of 65% between the steam curing and ambient air curing. While different curing methods

can be adopted, and quality control on curing methods makes Ductal more convenient for precast operations.

As observed by Collepardi et al. (1997), conventional RPCs' mechanical properties with the coarser aggregates added RPC (modified). In modified RPC, natural graded aggregates with maximum size of 8mm utilized to be substitute of the fine sand and an amount of cementitious binder. The conventional and coarse aggregate RPC showed superior higher strengths and lowering shrinkage drying or creep strain when faced to high temperature curing reasonably than curing at normal room temperature.

Jungwirth and Muttoni (2004) conducted tests on material as well as UHPC on reinforced structural members with bars. Large-scale tests simulating the condition in structures were executed to know the behavior of UHPCs in real members. Three cases with 16 x 16 x 150 cm dimensions using different percentages of ribbed steel between 1.0 % and 4.8 % and having a yield stress of 556 MPa were tested. The behavior UHPC in tension shows a severe difference compared with that of ordinary concrete because of the existence of fibers and their influences.

Hoang et al. (2008) calculated the flexural behavior of fiber reinforced cement concrete with high-strength steel twisted, polyethylene of high weight of molecular spectra, steel hooked of high-strength, and PVA fibers. Two-volume fraction amounts of 1.2% and 4% were used. The T-fiber specimens showed greater mechanical properties whereas the PVA fiber concretes was the inferior once. However, the SP-fibers at maximum load, demonstrated the highest deflection. Both experimentally test results from were applied to study the new ASTM standard [C 1609/C 1609M-05], and little recommendations were made to improve the application of standard to the deflection for hardening of FRCCs.

Dallaire et al. (1998) described different mechanical properties of RPC materials used for building Sherbrooke pedestrian and bikeways Bridge inside their paper. Reactive powder concrete ductility is developed by restraining the material into a steel tube or adding steel fibers, "1.8% of volume and 12mm length." The chord member at bottom on a bridge made of two 320X380 mm prestressed beams with a box every 5 meter that related to the connection among the bottom beams and the diagonals. The

reinforcement rejection in the structures of Reactive powder concrete results of independence in form and shape of the members.

Resplendino (2004) in his study on the first commendations detected that the behavior of after peak for UHPC is very difficult to describe due to that they rely on the mixing as well as the pouring process. Because any flow throughout the concreting led to fiber alignment in the flow direction. Fibers alignment near wall normally are parallel to formwork's direction; this occurrence depends away from a distance from formwork in extra for the size of fibers. The nearer constituent thickness is to the length of fibers, and the larger is the result on the parts actual tensile strength. As a result of the normal property of fibers in the concrete liquid and viscous phase, preferential gravitational positioning of fibers can occasionally happen.

Bierwagen and Abu-Hawash (2005) studied on a multi-phase project of RPC beams; In phase I, a 71 ft long RPC beams were tested for flexural capacities and shear. In phase II, a 111 ft long RPC casted and examined. Depending on results, a part of web was decreased 1 inch in top flange but the bottom one decreased 2 inches. The design recommendations were taken from rules accessible from the reports existing in France and the construction was finished in 2005.

Dubey and Banthia (1998) reported the energy dispersion appliance of post peak along with a crack of RPC specimen. It shown that pullout of fibers caused the energy dissipation across the cracks. Additionally, the pozzolanic materials such as silica fume also increased the rate of brittle of the matrices. Increment in loads caused splitting and crushing of matrices, which by the way limiting the capability of fibers to do stresses transmission. Furthermore, it was recommended that the hardness of RPC could be enhanced by addition of metakaolin pozzolan to the mixture that play a vital role to increase the durability properties of RPC.

Habel et al. (2006) described the enhanced performance of Ultra-High Performance Fiber-Reinforced Concretes (UHPFRC) with cocktail fibers. This study also discovered that the micro steel fibers were contributing the strain hardening causing in bridging of micro cracks whereas as long fibers were responsible for transferring of forces in localized macro cracks. Consequently, the new improved concrete,

UHPFRC, resulted in greater stiffness and higher resistance to cracking with a hardening modulus of more than 45 Gpa preventing softening behavior.

Cwirzen et al. (2008) established a new Ultra high strength (UHS) mortar concrete for treated and non-treated ways in addition tested for frost durability properties. The compressive strength recorded at 28-day ranged from 170 to 202 MPa for concrete when treated thermally, and for non-heat treated concrete the strength values from 130 to 150MPa. Other tests were conducted for creep and shrinkage tests, which displayed enhanced when compared with ordinary concrete mixtures. Numerous examinations were implemented to form the bond between the mechanical properties, rheological, demand of water till time of wetting, and composition of the mix. The study of beam made of hybrid concrete showed the development of transition zone of small strength among Normal strength concrete and UHS.

Graybeal (2006) has studied direct tensile strength of UHPC using briquette specimens according to AASHTO T132. The dog bone-shaped briquette is of 25 mm square cross section and at middle length with 76 mm long. To guarantee uniform loading, special self-aligning grips permit for inert gripping of specimen inside test machine. The first crack strength ranged from 6.3-10.1 MPa while the post cracking strength ranged from 5.6-9.5 MPa. The toughness value ranged from 2-5.5, expressed as the ratio of post peak to pre-peak at areas. Strain-hardening Characteristics were not obvious in the majority of the cases.

Yoo et al. (2013) developed the ultra-high-performance-fiber-reinforced concrete (UHPFRC) getting the strengths of tensile nearly 10 MPa and compressive more than 180 MPa. The UHPFRC is not has only higher durability, strengths, and ductility but also decreases the self weight of members by reducing the required area of cross section, such as applied UHPFRC for the structural members. The elastic modulus and tensile strength were assessed from near the initial set by prediction models and tensile test machine for elastic modulus and tensile strength of UHPFRC were suggested. UHPFRC displays unlike material characteristic to high performance and also conventional normal concrete. For instance, it shows rapid surface drying as well as surface cracking, and high early age autogenous shrinkage due to having high fineness mineral admixtures and low w/b ratio. To accurately assess the basic properties of UHPFRC at the early age, ultrasonic pulse velocity (UPV), penetration resistance,

tensile, and shrinkage tests were conducted. The restrained shrinkage stress begins to start once the penetration resistance was reached 1.5 MPa. Thus, zero time is defined from subjective shrinkage measurements established UHPFRC, as when become resistant to penetration 1.5 MPa, this is 0.6 and 2.1 hours prior to setting of the initial and final, respectively. Finally, the proposed zero time UPVs, the initial and final sets, and was expecting very early age strength developments using UPV.

Redaelli (2006) reported the mechanical behavior using the real scale of UHPFRC reinforced with steel bars. It is verified that steel fibers enhanced the ductility of concrete, especially when the volumes of fibers were higher than 1.5%. Nevertheless, even a large volume of additional normal reinforcement cannot avoid a brittle failure and strain localization at the ultimate limit state. This study also unveiled that UHPFRC tensile members cannot be made fully ductile by introducing ordinary reinforcement as well as an alternative definition of the amount of minimum reinforcements to avoid brittle failure or UHPFRC tensile members were recommended.

In several researches (Graybeal, 2005; Soutsos et al., 2005; Heinz and Ludwig, 2004), The results reported for both normal and thermal cured Ductal, have shown that the compressive strength of Ductal generally appears to increase with increasing heat treatment temperature. The compressive strength of Ductal, when heat treated at 90°C, increases by about 33 percent of the strengths obtained for untreated specimens.

Several researchers have tried to describe the flexural strengths of Ductal with single or 2-point bending tests on somehow small prisms. Ductal North America claims that the flexural strength of Ductal after heat treatment ranges from 27–50 MPa. Research by Cheyrezy et al. (1995) shows that Ductal is capable of reaching a flexural strength up to 48 MPa and a toughness of 250 times that strength of normal concrete. As showed by Perry and Zakariassen (2004) UHPC exhibited flexural strengths ranging from 34–48 MPa which confirmed by Cheyrezy's findings as well. Dugat et al. (1996) reported also an ultimate flexural strength of 32 MPa. The attributed increase in behavior of flexure are the packing of particle and fiber addition that carry cement matrix together after cracking happened. UHPC with steel-fibers reveals ductility because as the specimen starts to micro-crack the fibers reinforced the matrices results in less and smaller destructive cracks to form (Graybeal and Hartmann, 2003).

The typical flexural strength test curves for Ductal and another three concrete types shown in Figure 2.1 indicates that the equivalent stress of Ductal is more than 47 MPa, compared to about 13 MPa for fiber reinforced concrete FRC 80 (Lukasik, 2005).

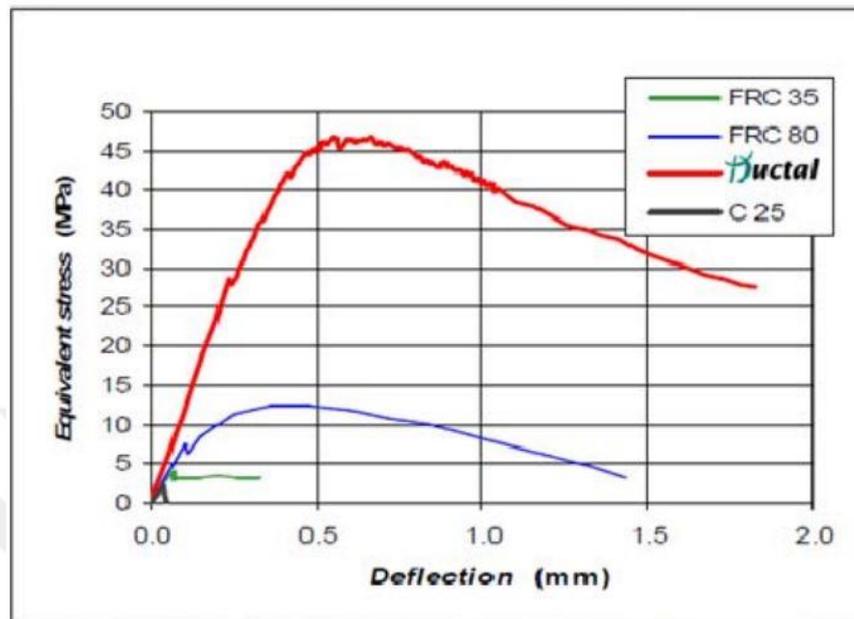


Figure 2.6 Typical flexural strength test curves of four types of concrete (Lukasik, 2005)

Graybeal (2005) conducted flexural testing of 71 specimens utilizing the procedure outlined in ASTM C 1018, which controls the rate of deflection of the prism. Specimens had span lengths of 6 in., 9 in., 12 in., and 15 in. with a cross section of 2 × 2 in. and a 12 in. span with a 3 × 4 in. cross section. Corrections were applied to calculate a more illustrative tensile strength from the first-crack strength. Ultimate load and toughness values based on the procedure outlined in ASTM C 1018 were reported. The flexural testing results appear to show that the flexural tensile strengths of Ductal depends heavily on the size of the prisms used in the test. The results of flexural strength of steam curing specimens was 35.4 MPa and that of untreated specimens of the same size was 29.9 MPa. Reineck and Greiner (2004) have reported the average values of flexural strength for a wider range of prism sizes, showing the size effect. The recorded higher strengths for smaller beams are largely due to local alignment of fibers in small prisms. The local alignment leads to relatively more fibers oriented parallel to the long direction of the prism, making a greater proportion of the fibers effective to bridge flexural cracks (VandeVoort et al., 2008).

Tanaka et al. (2002) reported that the bending fracture energy of Ductal is 36,000 J/m<sup>2</sup> compared to normal concrete ranging from 50 J/m<sup>2</sup> to 200 J/m<sup>2</sup>. This was supported by Cavill et al. (2006), who found the total fracture energy in the range of 20,000 J/m<sup>2</sup> to 30,000 J/m<sup>2</sup>. Elastic modulus development rate higher than the development rates of fracture energy, tensile and compressive strengths. This improvement is much expected to be as a result of the fact that fracture depends mainly on the strengths of the bonds, which are affected by elastic moduli and tensile strength of the mix (VandeVoort et al, 2008).

## **2.4 Durability and physical property of UHPC**

Ahlbom et al. (2008) defined concrete durability as the resistance of concrete against the attack of physical or chemical aggressive agents. Concrete can experience deterioration from either physical attack (abrasion, freezing and thawing, fire, or crystallization of salt) or chemical causes (chloride ingress producing corrosion of embed steel and sulfate attack, reaction of alkali silica, etc.).

Vodak et al. (1997) reported experimentations finding the linear coefficient of the thermal expansion of RPC, spreading of heat, and thermic characteristics of RPC concrete like thermal conductivity. The concrete utilized in French nuclear power plant were tested for vapor of water diffusivity at normal temperature, moisture diffusivity from 0 - 75% of extreme water saturation at normal temperature, specific heat of -30°C to 100°C, and a temperature range of 20°C to 200°C. A reasonable agreement for most of the considerations were found, when the results were compared with the other author results with similar concrete composition.

The improved microstructure of UHPC not only results in greater compressive strength but likewise causing superior durability properties. This results in a high strength plus a high performance material. The capillary porosity of UHPC, particularly low porosity, leads to great enhancements in the ultra-high-performance concrete durability properties. The superior durability characteristics of UHPC are due to the small and separated pore structure, which is produced as a result of the use of a combination of fine powder materials. Schmidt et al. (2003) and Acker (2001) stated that the total porosity of Ductal appears to depend on the curing process applied to the

substance. The total porosity ratios ranges from 4.0 percent to 11.1 percent for Ductal without heat treatment.

Zanni et al. (1996) studied the pozzolanic reaction and hydration by two specimens of RPC and at 20°C and 250°C heat treatment. The object of the testing was to study the effect of temperature on pozzolanic activity and hydration. The heat treatment led to the growth of the C-S-H length of series because of the pozzolanic action of quartz powder and silica fume. It was noticed that the leaking significantly affects the microstructure, especially in the paste; there was anhydrous grains of cement remained.

Herold and Muller (2004) reported that when the standard heat treatment is used, Ductal has total porosity ranging from 1.1 percent to 6.2 percent. Based on the work of Cheyrezy et al. (1995), the total porosity of the untreated Ductal in their study is approximately 8.4 percent, but heat curing decreases the total porosity of the UHPC specimen to only 1.5 percent. Literature review shows that there is a wide range in values reported. This is however not usual, as porosity depends to some extent on the preparation and curing.

Feylessoufi et al. (1996) reported a 230 MPa compressive strength with low temperature nitrogen adsorption desorption volumetric by diffuse reflectance infrared fourier transformed spectroscopy (DRIFTS). It was observed that RPC had pores like open network of several different diameters with high-level durability characteristics from the experiments conducted.

Matte and Moranville (1999) reported the RPC that possesses a 25% total binder of silica fume content and 0.20 water to cement rate. The thermal curing method carried out after demolding at temperatures nearly 20°C to 400°C for improving the pozzolanic reactions and hydration. This procedure enhances the mechanic and microstructural properties. The addition of steel fibers resulted in compressive strengths of 200 MPa and 800 MPa thus this in turn develops the ductility of RPC.

Feylessoufi et al. (1997) discussed the effects of specimens cured with three different heating types. The results established the Xonolite creation when cured thermally, and the data presented that the kinetically controlled thermal curing had a control on crystallization and hydration.

Morin et.al. (2002) reported the capillar network of RPC by autogenous shrinkage and ultrasonic measures. The assessment of activation of unlike modes during the processes of hydration implemented. Division of sedimentary pores to take place because of the capillary network due to chemical re-action encouraged the C-S-H chains. This report from the capillary network is essential since it supplied information on the porosity and is an important parameter in the transport properties that relate to the durability of concretes.

Matte et al. (2000) carried out tests to calculate the pozzolanic reactivity of silica fume, long-term durability of RPC, mechanism of chemical reactions, pore structure, and the hydration rate of cement minerals. Therefore, the NIST micro structural model simulated the microstructure of RPC matrix, firstly. Then after the transference of Ca ions over penetrating water assessed via DIFFU-Ca, a model depending on equilibrium of local chemicals. These two models confirm the destruction process associated with an immediate dissolving of anhydrous cement silicates at the degradation while caused a connected pore space in a higher level, and was in good correlation with the experimentally program results. The study discovered that the RPC matrices was durable on condition that a sound zone perseveres. In view of only the concentration of calcium in investigational conditions of leaching, the degraded depth was 14-15 mm at 300 years for the RPC matrix. This value could be taken into consideration to determine the thickness of high integrity containers to be utilized for the waste storage of type B nuclear.

Yazici (2007) improved UHPCs by adding combined silica fume, granulated blast furnace slag, and fly ash with the Portland cement. In his study, Yazici brought many novels inside UHPCs; quartz powder and basalt were utilized as aggregate in mixture, Portland cement was substituted by fly ash and granulated blast furnace slag at specified ratios; High-strength concrete might be achieved with admixtures of mineral at high volume, and three different treatment ways, Standard, steam and autoclave treatment, were carried out for the samples with a compressive strength of these specimens greater than 170 MPa.

Yoo et al. (2013) studied the ultra-high-performance-fiber-reinforced concrete (UHPRFC). UHPRFC displays unlike material actions to high performance and conventional normal concrete. For instance, it shows rapid surface drying as well as

surface cracking, and high early age autogenous shrinkage due to having high fineness mineral admixtures and low w/b ratio. To accurately assess the basic properties of UHPFRC at the early age, ultrasonic pulse velocity (UPV), penetration resistance, tensile, and shrinkage tests were conducted. The restrained shrinkage stresses begin to start once the penetration resistance was reached 1.5 MPa. Thus, zero time is defined from subjective shrinkage measurements established UHPFRC, as when become resistant to penetration 1.5 MPa, this is 0.6 and 2.1 hours prior to setting of the initial and final, respectively. Finally, the proposed zero time UPVs, the initial and final sets, and was expecting very early age strength developments using UPV.

Harish et al. (2008) carried out the UHPCs at CSIR-SERC. It was detected that choosing of constituents and treatment methods showed a great character in the improved characteristics of UHPCs. It was observed that adding silica fume increased the concrete strengths as a result of its somehow high activity of pozzolanic. Furthermore, the types of curing methods “such as thermal water, thermal air, and normal water” was suggested to attain high mechanical parameters property. A mixture proportion has been reported utilizing an optimized curing regime and components volume to produce ultra-high strength concrete reaching 193 MPa.

Justs et al. (2015) employed an interior treatment by super absorbent polymers (SAP), to decrease shrinkage of autogenous and self-desiccation, which could cause an early cracking of the Ultra-High Performance Concrete (UHPC). UHPC and pastes of cement with a w/c ratio under 0.25, with or without SAP, were considered. SEM image analysis was used to determine the absorption capability of polymerized SAP solution on a hardened cementitious paste. They noticed that the SAP pores about to be partly filled with portlandite during the process of hydration of cement. Isothermal calorimetry indicated that SAP with water entrainment postpone the peak of key hydration, then after less than a week, it enhances the hydration degree in a manner like to increase the w/c percentage. Internal curing by SAP play an important role in decreasing the autogenous shrinkage and the internal relative humidity decrease. Furthermore, it is conceivable to achieve a compressive strength of up to about 150 MPa at 28 days by the effect of adding SAP.

Yoo et al (2015) described behaviors of ultra-high-performance-fiber-reinforced concrete (UHPFRC) influenced by admixtures those are reducing shrinkage (SRA)

using free and restrained autogenous shrinkage. Three varied reducer admixtures to cement volume percentages of 0%, 1%, and 2% and reinforcement with three varied percentages of 1.3%, 2.9%, and 8.0% measured. A greater SRA rate related to lower autogenous shrinkage and a little higher tensile strength. Additionally, a larger amount of SRA and a lesser reinforcement rate caused an improved restrained autogenous shrinkage performance, for example, lesser autogenous shrinkage strength as well as lower potential cracking. Consequently, it could be observed that utilizing of SRA or lesser reinforcement rate is more acceptable for refining the UHPFRC restrained shrinkage behavior.

Soliman and Nehdi (2014) explored the influence of adding shrinkage reducer admixtures (SRA) and/or wollastonite microfibers on the cracking potential and early age of ultra-high-performance-concrete (UHPC) shrinkage behavior. SRA was added at rates of 1% and 2% as fractional volume replacement for cement, whereas wollastonite microfibers were added at 0%, 4% and 12% by the cement weight. Results approved that the reinforcing effect made by wollastonite micro fibers improved the reduction in compressive strength caused by SRA. Adding of wollastonite micro fibers to SRA mix did not report an important change in the measured free shrinkage strain, but it improved the cracking resistance compared to that of mixes incorporating SRA only. Furthermore, addition wollastonite micro fibers reduced the leaching of SRA from concrete under submerged situations, therefore, leading to higher efficiency of SRA in reducing shrinkage.

## **2.5 Effect of fibers on UHPC properties**

### **2.5.1 Effect of Using Glass-Fiber on UHPC properties**

Chen and Cheminlard (2012) developed. a new UHPC based on the use of pozzolanic ultrafines and glass fibers. Through an optimization of particle packing and matrix/fiber interactions, this glass-reinforced UHPC (GF-UHPC) showed an unprecedented combination of self-placing behavior, deflection-hardening behavior in bending of thin plates, excellent resistance to wet aging, and a very low permeable matrix. A back analysis of the flexural data to extract the tensile strength of the GF-UHPC shows a highly efficient use of the 2.2 vol. % glass fibers to achieve tensile strengths of 9-11 MPa in the post-cracking regime. Microstructure characterization by

scanning•electron microscopy (SEM) and mercury-intrusion porosimetry (MEP) furthermore point to the high durability of the GF-UHPC.

Roth et al. (2010), showed a hardening of the deflection in ultra-high glass fiber reinforced concrete (GF-UHPC) with a matrix containing silica fume and fiberglass dosages of 3.0%. It was noted the presence of a large dispersion in the results of flexural, presumably due to, continuous gravity loading process of adding fibers to the UHPC. There were no reports on aging tests, and flow properties.

In their investigation Kizilkanat et al. (2015) relatively analyzed the use of glass and basalt fibers as reinforcement in high-strength concretes. They perceived from the results of the experimentally program that there was no important impact for the addition of fiber on the elastic-modulus and compressive stress of the mixture samples. Basalt fiber reinforced concrete (BFRC) splitting tensile stress of improved with adding larger amount of fiber, while no significant increment in the strengths of the glass fiber reinforced concrete (GFRC) detected behind the 0.50% dose of fiber. In the same direction to tensile strength, flexural stress of BFRC enhanced with adding more fiber content in a steady way, while did not notice any change for glass fiber reinforced concretes after 0.50% fiber volume. Fracture energy improved considerably beyond 0.25% ratio for each glass of and basalt reinforced concretes.

Tassew and Lubell (2014) research reported on tests conducted to determine the chopped glass fiber effect on the mechanical properties of ceramic concrete created by means of a binder of phosphate cement. Their study had two different types of ceramic concrete matrices, containing either sand or lightweight expanded clay aggregates. The examined fiber volume fractions were between 0% and 2%. They reported that inclusion of glass fibers into the ceramic concrete made a little effect on the compressive strength and elastic modulus, but resulted in a considerable increase in the flexural strength and direct shear strength, irrespective to the matrix type or the length of the fiber. The results also showed that compression, flexure and shear toughness improved with an improve in fiber content, while decreased workability. Overall, the results indicate that glass fiber-reinforced concrete ceramics can be produced with the workability and mechanical properties that are suitable for application in the construction of concrete elements.

### **2.5.2 Effect of Using Other types of Fibers on UHPC properties**

Naaman and Wille (2010) stated that a higher volume of paste phase is demanded when rigid fibers are added to the matrix due to an increased interaction between particles and fibers. Park et al. (2008) suggested an optimum sand to cement percentage of 1.1%. However, Wille et al. (2011a) increased this ratio to 1.4% in order to reduce shrinkage by decreasing the cement quantity.

Yu et al. (2015) observed and experienced UHPFRC with ternary fibers. Analyzing and measurements for flowability, flexural toughness and mechanical properties of the designed UHPFRC are carried out. The experimental outcomes approve that, depending on hybrid macro and micro fibers and the optimized particle packing, UHPFRC with low fiber ratio (Vol. 2%) and considerably low binder content (about 620 kg/m<sup>3</sup>) is possible to create. Furthermore, as a result of the combined effect between the applied fibers, the hybrid fiber reinforced UHPFRC showed an enhanced flowability and developed mechanical properties. However, hooked steel ratio affect the flexural strength of the UHPFRC. Due to the particular characteristics of UHPFRC, the JSCE SF-4 recommendation is chose to be more proper rather than ASTM C1018-97, to be used to evaluate the flexural hardness of UHPFRC.

Mufti et al. (1993) reported the suitability of using steel fiber concrete deck slabs with no contribution of steel reinforcement. Slab-girder bridges with polypropylene fibers developed by preparing four half-scale models with no involvement of steel reinforcement also to keep away from corrosion problems. The girder upper flanges must be connected with steel straps in crosswise directions to avoid deck slab curvature on the upper surface. This was simulated by presenting stiffener along edges by means of unconventional edge beams. Results proved that slab had major flexural rigidity in the horizontal plane, and proposed the introduction of shear jointers to ensure effective transfer of forces in the plane of the slab deck to the girder.

### **2.6 Effect of water per binder ratio on UHPC**

Ma et al. (2002), examined that the percentage of water to cement and workability of self-compacting concrete highly correlated. A lower water per cement ratio will reduce the cavities among the constituent parts and therefore the density of packing could be

improved, and this improvement maintains an effect on the reduction of the porosity of the cementitious matrix. A similar conclusion by Long (2002) was developed.

Serelis et al. (2015) investigated the relations between the w/c ratio and compressive strength, also to discover the best UHPC structure. Hence, they created four varied ultra-high-performance concrete (UHPC) compositions for the investigation, though the ratio of w/c ranged between 0.25% and 0.33%. It has been preserved that cement, quartz, and superplasticizer volume to be constant (at 735 kg/m<sup>3</sup>, 962 kg/m<sup>3</sup>, and 36.76 liters), respectively. Silica fume and glass powder used as binder. The glass powder optimal fineness was chosen by test of Chapelle. In their research, various arrangements of glass powder, silica fume, and quartz powder were used as micro-filler. It was obtained compressive strength of up to 160 MPa.

Wille et al. (2011a) studied the effects of w/c as well as the influences of the air content on the compressive strength of UHPC. The results of these studies are illustrated in Figure 2.1. They observed that in general, by decreasing the w/c ratio or the air content, the compressive strength of UHPC increases. However, they stated that neither w/c ratio nor air content is not the only influential parameter affecting the compressive strength of UHPC due to the spread observed in the data. Therefore, they investigated the combined effects of the w/c ratio and the air content on compressive strength of UHPC. This study is summarized in Figure 2.2. In a more comprehensive investigation of the influence of w/c ratio, Wille et al. (2011a) observed that reducing w/c leads to an increase in viscosity and paste yield stress of the matrix, thus decreasing the spread value. They stated that a higher volume of entrapped air is caused as a result of this reduction in w/c, which resulted in an almost no improvement in strength. Therefore, they concluded that increasing strength by decreasing w/c is not valid unless the spread value is enhanced by means of a better packing density. Furthermore, when packing density is improved, the volume of water trapped to fill voids is decreased, thus more water would be available to cover the surface of the particles, which leads to the reduction of the overall viscosity of the matrix and consequently better flowability (Wille et al., 2012). Later, they recommended a spread value between 8 to 15 in. (200 to 370 mm) based on which a w/c of 0.16 to 0.27 with an optimum value of 0.22 was then suggested.

## **CHAPTER 3**

### **EXPERIMENTAL STUDY**

The experimental program performed in the present study consisted of two stages. The first stage included the mix design of UHPFRC. The mixtures developed herein were of enough flowable in order to overcome the challenges during placing of UHPFRC in practice. In the second stage, the effects of using Glass fiber on various properties of plain and fiber reinforced UHPC were investigated with conducting different water per binder ratio of 0.12 and 0.14, respectively. The UHPFRC mixtures were designed with binary and ternary blends of Portland cement and silica fume.

The adopted curing regime in this study was standard curing. The specimens were tested for compressive strength, splitting tensile strength, modulus of elasticity, flexural strengths, load–displacement behavior, fracture energy and characteristic length.

#### **3.1 Raw Materials**

##### **3.1.1 Cement**

The cement used in the current work was ordinary Portland cement (CEM, I 42.5 R) meeting the requirements of the TS EN 197 (mainly based on the European EN 197-1). The chemical, physical, and mechanical properties of the cement are presented in Tables 3.1 and 3.2, respectively.

Table 3.1 Chemical properties of Portland cement and silica fume.

| Item                           | Cement | Silica fume |
|--------------------------------|--------|-------------|
| Fe <sub>2</sub> O <sub>3</sub> | 2.88   | 1.31        |
| SO <sub>3</sub>                | 2.63   | 0.41        |
| K <sub>2</sub> O               | 0.88   | 1.52        |
| CaO                            | 62.12  | 0.45        |
| MgO                            | 1.17   | -           |
| SiO <sub>2</sub>               | 19.69  | 90.36       |
| Na <sub>2</sub> O              | 0.17   | 0.45        |
| Cl                             | 0.0093 | -           |
| Al <sub>2</sub> O <sub>3</sub> | 5.16   | 0.71        |
| Free CaO                       | 1.91   | -           |
| Insoluble residue              | 0.16   | -           |
| Loss on ignition               | 2.99   | 3.11        |

### 3.1.2 Silica Fume

Silica fume (SF) was used as supplementary cementitious material. Chemical and physical properties of SF is presented in Tables 3.1 and 3.2, respectively.

Table 3.2 Physical and mechanical properties of Portland cement, silica fume

| Item                                  | Portland cement  | Silica fume        |
|---------------------------------------|------------------|--------------------|
| Specific surface (m <sup>2</sup> /kg) | 394 <sup>a</sup> | 21080 <sup>b</sup> |
| Specific gravity                      | 3.15             | 2.2                |
| Initial setting time (min)            | 215              | -                  |
| Final setting time (min)              | 250              | -                  |
| Volume expansion (mm)                 | 1                | -                  |
| 1-day compressive strength (MPa)      | 18.2             | -                  |
| 2-day compressive strength (MPa)      | 29.5             | -                  |
| 7-day compressive strength (MPa)      | 42.0             | -                  |
| 28-day compressive strength (MPa)     | 50.2             | -                  |

<sup>a</sup> Blaine specific surface area.

<sup>b</sup> BET specific surface area

### 3.1.3 Superplasticizer

A new-generation superplasticizer (SP) that made of polycarboxilate type F in accordance with ASTM C 494 (2013) was utilized in different amounts to maintain the target workability for the mixtures. Table 3.3 provides the properties of the superplasticizer.

Table 3.3 Properties of the superplasticizer

| Properties               | Results                         |
|--------------------------|---------------------------------|
| Appearance               | Light brown to yellow liquid    |
| Specific gravity at 20°C | $1.08 \pm 0.02 \text{ gm/cm}^3$ |
| PH- value                | $7 \pm 1$                       |
| Alkali content (%)       | $\leq 1$                        |
| Chloride content (%)     | $\leq 0.1$                      |

#### 3.1.4 Quartz Sand Aggregates

Commercial quartz in three different size fractions of 1.2–2.5 mm, 0.6–1.2 mm and 0-0.4 mm with a specific gravity of 2.65 were used as fine aggregates. Figure 3.1 shows the three sizes of the aggregate used.



Figure 3.1 Sizes of Quartz aggregates

### 3.1.5 Glass fibers

Micro glass fibers of 13 mm length and diameter of 18 microns were used as a fiber reinforcement. The properties of micro glass fibers given by the producer are listed in Table 2. A photographic view of the GF is shown in Figure 3.2.

Table 3.4 Properties of glass fiber.

| Fiber type  | Length (mm) | Diameter ( $\mu\text{m}$ ) | Modulus of elasticity (GPa) | Elongation (%) | Tensile strength (MPa) | Aspect ratio (L/d) | Density ( $\text{g}/\text{cm}^3$ ) |
|-------------|-------------|----------------------------|-----------------------------|----------------|------------------------|--------------------|------------------------------------|
| Micro Glass | 13          | 18                         | 77                          | 2.56           | 2000                   | 722                | 2.60                               |



Figure 3.2 Photographic view of GF

### 3.2 Mixture Proportioning

The compositions of UHPFRC used in the present study were recognized by high volume of binder, non-existence of coarser aggregate, and extremely very low w/b ratio such as many other studies (Aydin et al., 2010; Corinaldesi and Moriconi, 2012; Yazici et al., 2008; Yazici et al., 2010). Two groups with w/b ratios of 0.12 and 0.14 each containing 7 mixtures were produced as shown in Table 3.5. In both groups, the amount of silica fume was kept constant to be 15% by weight of total cementitious materials. Micro glass fibers at volume ratios of 0%, 0.5%, 1%, 1.5%, 2%, 2.5%, and 3% for each group were added. The mixtures were designated regarding two parameters, namely volume of micro glass fiber and w/b ratios. For example, 0.12MGF0.5 indicates the mixture of 0.12 w/b and 0.5% volume of micro glass fiber.

Table 3.5 Mix proportions (kg/m<sup>3</sup>).

| Concrete mixture | w/b  | Cement (kg/m <sup>3</sup> ) | Silica fume (kg/m <sup>3</sup> ) | Water (kg/m <sup>3</sup> ) | SP (kg/m <sup>3</sup> ) | Glass fiber % | Quartz (kg/m <sup>3</sup> ) |
|------------------|------|-----------------------------|----------------------------------|----------------------------|-------------------------|---------------|-----------------------------|
| 0.12MGF0         | 0.12 | 998.8                       | 176.25                           | 141.0                      | 75.2                    | 0.0           | 1010.1                      |
| 0.12MGF0.5       | 0.12 | 998.8                       | 176.25                           | 141.0                      | 77.6                    | 0.5           | 991.1                       |
| 0.12MGF1         | 0.12 | 998.8                       | 176.25                           | 141.0                      | 78.7                    | 1.0           | 975.0                       |
| 0.12MGF1.5       | 0.12 | 998.8                       | 176.25                           | 141.0                      | 81.7                    | 1.5           | 954.5                       |
| 0.12MGF2         | 0.12 | 998.8                       | 176.25                           | 141.0                      | 81.1                    | 2.0           | 942.7                       |
| 0.12MGF2.5       | 0.12 | 998.8                       | 176.25                           | 141.0                      | 84.6                    | 2.5           | 920.8                       |
| 0.12MGF3         | 0.12 | 998.8                       | 176.25                           | 141.0                      | 88.2                    | 3.0           | 898.7                       |
| 0.14MGF0         | 0.14 | 998.8                       | 176.25                           | 164.5                      | 49.4                    | 0.0           | 1013.9                      |
| 0.14MGF0.5       | 0.14 | 998.8                       | 176.25                           | 164.5                      | 49.4                    | 0.5           | 998.0                       |
| 0.14MGF1         | 0.14 | 998.8                       | 176.25                           | 164.5                      | 50.5                    | 1.0           | 981.9                       |
| 0.14MGF1.5       | 0.14 | 998.8                       | 176.25                           | 164.5                      | 52.9                    | 1.5           | 962.9                       |
| 0.14MGF2         | 0.14 | 998.8                       | 176.25                           | 164.5                      | 54.1                    | 2.0           | 946.8                       |
| 0.14MGF2.5       | 0.14 | 998.8                       | 176.25                           | 164.5                      | 55.2                    | 2.5           | 930.6                       |
| 0.14MGF3         | 0.14 | 998.8                       | 176.25                           | 164.5                      | 62.3                    | 3.0           | 900.1                       |

### 3.3 Sample Preparation

For producing UHPC, a high speed, vertical axis mixing machine named Hobart mixer, having a maximum speed of 470 rpm was used (Figure 3.2). Firstly, binder and quartz were mixed in the machine at low speeds of 100 rpm for 3 min. After that three quarter of the water was added to the mixture and remixed for another 4 min at the same speed. Then the remained water and SP were added to the premixed materials and mixed for 5 min. At the end, micro glass fiber was added and mixed for the 2 min at 100 rpm speed and an extra 2 min at a speed of 470 rpm. The fresh mixtures were then poured into the molds and well compacted by using a vibrator machine.

(a)



(b)



Figure 3.3 Hobart mixer: (a) photographic view of the mixer, and (b) close view of the mortar in the mixer

### **3.4 Curing of Samples**

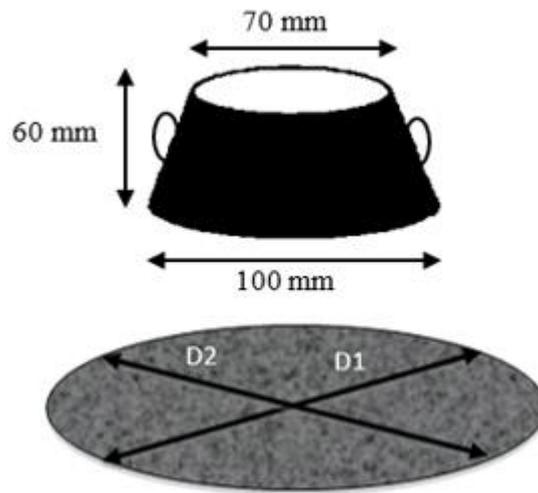
The specimens were covered with polyethylene sheets and left to cure under room temperature  $22 \pm 2$  °C. The molds of the specimens were removed one day after casting, after demolding all samples for mechanical properties were subjected to water curing at  $22 \pm 2$  °C until the test days.

### **3.5 Testing Procedures**

#### **3.5.1 Mini Slump Flow Test**

measurement for the UHPC flow was done using the mini slump flow test suggested by EFNARC (2002) as illustrated in Figure 3.3. After pouring fresh UHPC to the mini cone, the cone was lifted straight upwards to allow free flow for the fresh UHPCs on the plate. The flow value of the designed UHPC was calculated after 2 minutes as the average of two measured diameters of the mixture, i.e. D1 and D2. The UHPC mixtures had a flow values that controlled by using an adequate amount of superplasticizer as shown in Table 3.5.

(a)



(b)



Figure 3.4 Mini slump flow test: (a) dimensions, and (b) mixture flow

### **3.5.2 Tests on Mechanical Properties**

#### **3.5.2.1 Compressive Strength Test**

Compression test was carried out on 50 mm cubes at 3, 7, and 28 days, with respect to ASTM C39 (2003), at a rating load of 0.9 kN/s using a digital testing machine of 3000 kN capacity. Each result presented in this study is the average of three samples.

#### **3.5.2.2 Splitting Tensile Strength Test**

Splitting test of UHPCs was conducted on six 70 mm cubes at 28 days for each mix, according to BS 1881-117 (1983), and the average value was reported.

#### **3.5.2.3 Modulus of Elasticity Test**

Cubic specimens with dimensions of 150 mm were used for determining the static modulus of elasticity in accordance with BS EN 1352 (1997) three cube specimens were loaded up to 40% of the ultimate load determined from the compression test; corresponding stress was found from it, and the elastic modulus was reported as the average of the three sets of readings, using the stress–strain response E was measured as well.

#### **3.5.2.4 Fracture Energy Test**

Fracture energy behavior of UHPFRC was investigated according to specifications and recommendations of RILEM 50-FMC/198 Technical Committee (1985). The displacement was measured by a linear variable displacement transducer (LVDT) at mid-span. As shown in Figure 3.4, Instron 5500R closed-loop testing machine with a maximum capacity of 250 kN were used to applied load. The opening notch was achieved through reducing the effective cross section to 42 70 mm via a diamond saw to accommodate large aggregates in more abundance. Thus, the notch to depth ratios (a/W) of specimens was 0.4. According to RILEM (1985), the fracture energy,  $G_f$ , of a single edge notched beam can be calculated under three point bending test as:

$$G_f = \frac{W_0 + mg\delta_s \frac{s}{u}}{B(W-a)} \quad (3.1)$$



Figure 3.5 Photographic view of notched beam specimen

Where  $W_0$  is the area under the load–deflection curve;  $m$  is the mass of the beam;  $g$  is the acceleration due to gravity;  $\delta_s$  is the specified deflection of the beam, while  $S$ ,  $U$ ,  $B$ ,  $W$ , and  $a$  are span, length, width, depth, and notch depth of the beam, respectively. For each mixture, at least three specimens were tested at the age of 28 days. All the beams were loaded started at a constant rate of 0.02 mm/min.

### 3.5.2.5 Net Flexural Strength Test

In accordance with literature, the net flexural strength,  $f_{flex}$ , was calculated via equation 3.2 by assuming no notch sensitivity (Ravindra and Henderson, 1999; Akcay et al., 2012).

$$f_{flex} = \frac{3P_{max}S}{2B(W-a)^2} \quad (3.2)$$

Where  $P_{max}$ ,  $S$ ,  $B$ ,  $W$ , and  $a$  are ultimate load span, length, width, depth, and notch depth of the beam, respectively.

### 3.5.2.6 Characteristic Length

Characteristic length ( $l_{ch}$ ) as a measure of ductility was computed using Eq. (3) as a function of modulus of elasticity ( $E$ ), fracture energy ( $G_f$ ), and splitting tensile strength ( $f_{st}$ ) (Hillerborg1985).

$$l_{ch} = \frac{EG_F}{f_{st}^2} \quad (3.3)$$



## CHAPTER 4

### RESULTS AND DISCUSSIONS

#### 4.1 Fresh properties

Slump flow of the UHPFRC mixtures were fixed at  $18\pm 1$  cm. In order to maintain that flow ratio of superplasticizer was increased for any increase of micro glass fiber content, as shown in Figure 4.1. Moreover, the effect of lowering water per binder ratio from 0.14 to 0.12 is also detected, as it can be seen the rate of superplasticizer in the group of 0.12 w/b is higher than group of 0.14 w/b, to compensate the low water and obtain the desired workability for the UHPFRC mixtures.

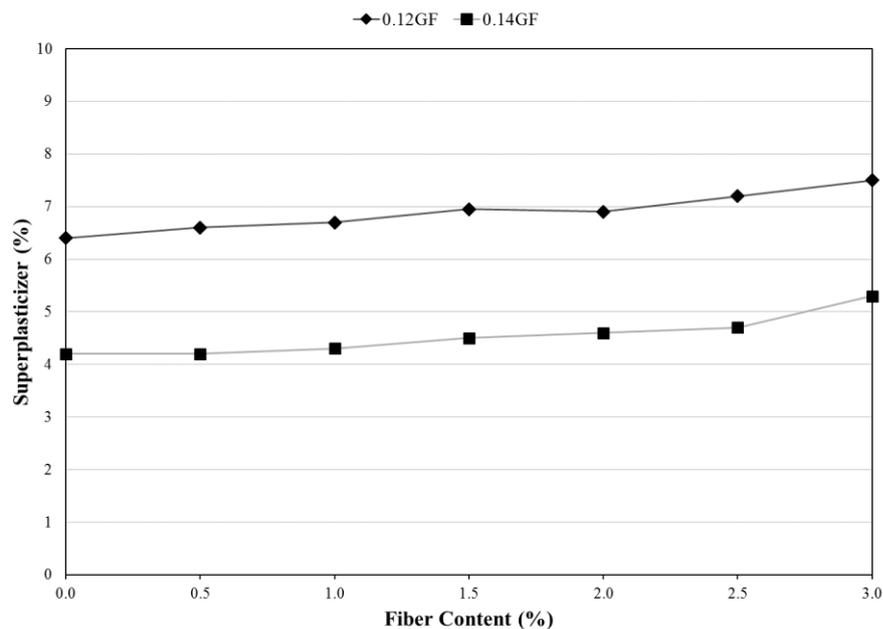


Figure 4.1 Superplasticizer ratio versus different volume of micro glass fiber

#### 4.2 Compressive strength

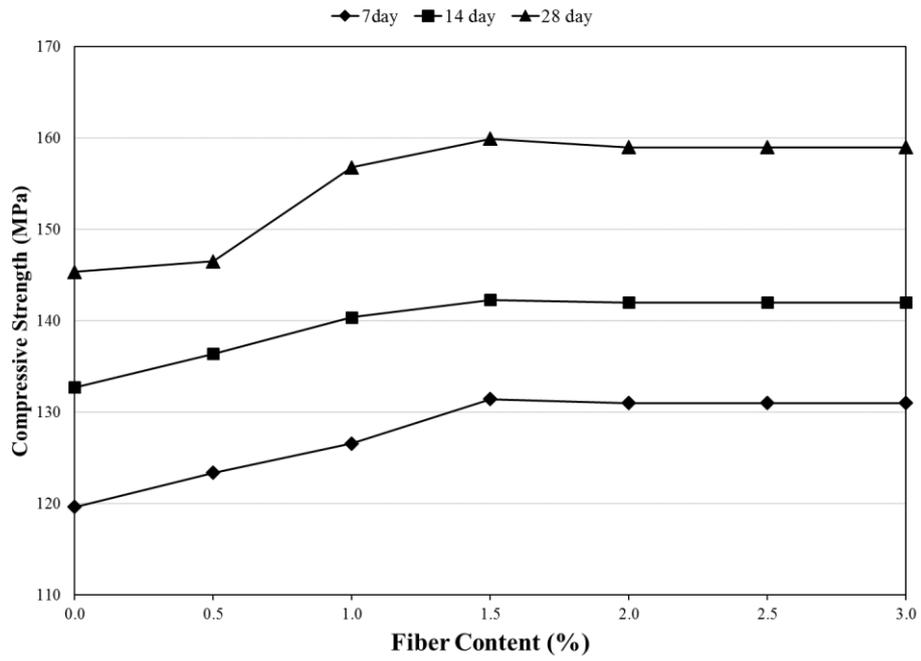
Variations in the compressive strength of UHPFRCs with different volume of micro glass fibers are illustrated in Figure 4.2, depending on the two water per binder ratios of 0.12 and 0.14. It was observed that there was a systematic growth on the strength

with increasing the fiber content until 1.5% and then started to be constant, irrespective to w/b and ages. When the fiber content was increased from 0% to 1.5%, the enhancement in compressive strength was as high as 10%, and 11.1% for concretes with 0.12, and 0.14 w/b, respectively. In addition, the results indicated a meaningless effect of increasing more micro glass fibers on the compressive strength which started directly after 1.5% to reach 3%. This behavior is probably because of the huge number of fibers per any percentage content. For example, the number of 3% of micro glass fibers is equal to  $24.36 \times 10^6$ , may much more than the volume necessary to improve the plain UHPCs and preventing the particles not to slip over each other.

Out of the two groups of UHPFRC mixes, the highest compressive strengths were obtained at the group of 0.12 w/b, even the differences were somewhat small, corresponding to fiber contents. Furthermore, the inverse relation between w/b and compressive strength is reported also by many scientists (Sekhar and Raghunath, 2014; Serelis et al., 2015; Trezos et al., 2014). Moreover, comparing with the cube samples at the age of 7 days, the highest rate of the strength increment due to 14 and 28 days of water curing were 8.3% and 21.7% for the first then 10.6% and 25.7% for the second groups, respectively. Furthermore, despite of using very low water per binder ratios in the present study those were smaller than the ratio chosen by the most other researchers, though good UHPCs flow of  $18 \pm 1$  cm were produced. Moreover, the strength reduction observed in the UHPCs with increasing w/b may be attributed to form further unwanted calcium hydroxide particles during the hydration process (Eq. 4.1).



(a)



(b)

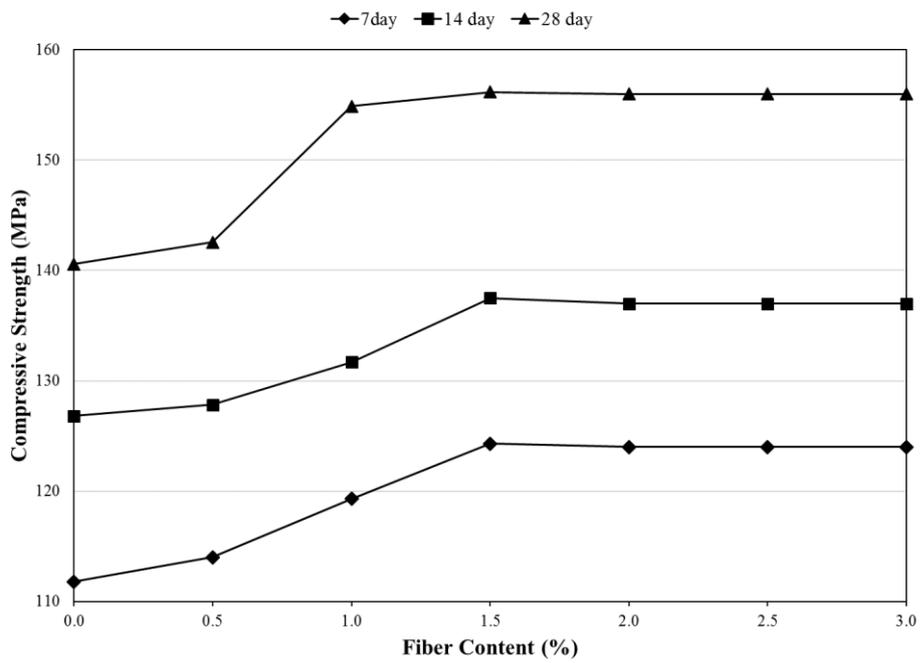


Figure 4.2 Compressive strength of UHPC of different ages: (a) 0.12 w/b, and (b) 0.14 w/b

### 4.3 Splitting tensile strength

The mechanism of failure in splitting tensile strength unlike compressive strength since former failed along the aggregates and cement paste rather than ITZ as a result of the strong bonds between them (Wang et al., 2006; Shehata, 2010). In addition, the tensile behavior of fiber reinforced concrete is divided into two categories: pre-cracking and post-cracking. The earlier behavior is generally affected by the elastic shear transfer mechanism between fiber and matrix and can be estimated by the rule of mixture. The latter one is expressed by the combined effect of fiber bridging and matrix tension softening behaviors (Kang and Kim, 2012).

The results of splitting tensile strength for the two groups of 0.12 and 0.14 w/b of UHPC containing various volumes of micro glass fibers given in Figure 4.3. The strength development for the splitting tensile strength is similar to that seen in the compressive strength. The splitting tensile strengths were obtained for the plain concretes were 9.2 MPa and 8.3 MPa, while adding 0.5%, 1%, 1.5%, 2%, 2.5%, and 3% of fibers induced an increase in the strength value by; 9.6 MPa, 10.2 MPa, 11.8 MPa, 11.8 MPa, 11.8 MPa, and 11.8 MPa also 9.17 MPa, 9.50 MPa, 10.53 MPa, 10.50 MPa, 10.56 MPa, and 10.5 MPa for the first and second groups, respectively. It was evident from the aforementioned figure the reality of the strength constant for UHPFRC containing more than 1.5% micro glass fibers, irrespective to water content. This behavior of glass fiber is may be related to dismantling properties of glass fibers during mixing process caused to form huge tiny particles as seen in Figure 4.4 However, these small particles will improve ITZ with a logic range after that they may not contribute to enhance it, when particles were much greater than the other concrete constituents, especially at fiber contents that laid between 1.5 to 3%.

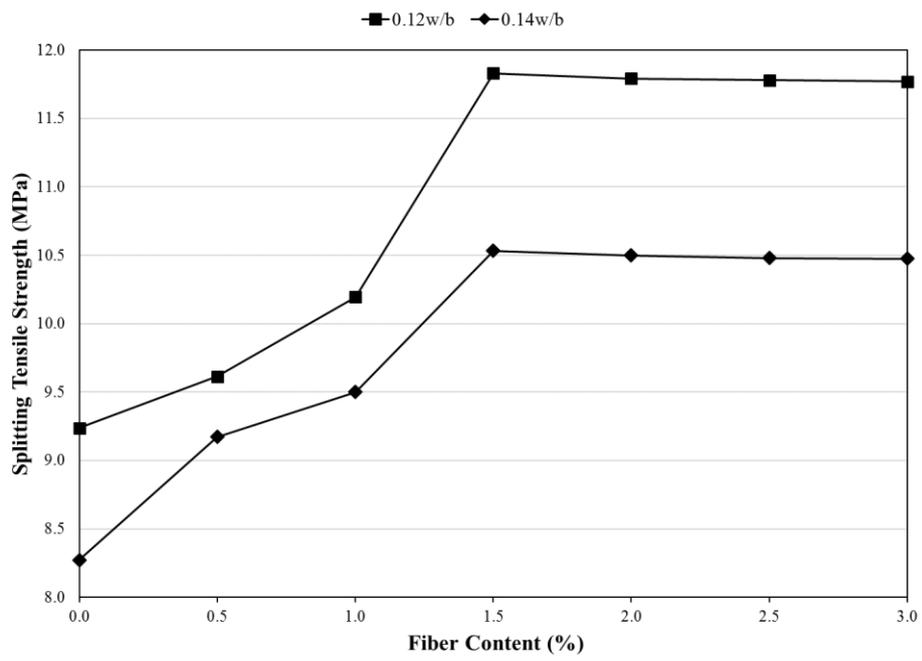


Figure 4.3 Splitting tensile strength of UHPC versus different volume of micro glass fiber at 28 days



Figure 4.4 Micro glass fiber

#### 4.4 Modulus of Elasticity

Indeed, modulus of elasticity is one of the supreme material properties used in the concrete design structures due to providing useful information about the ability of concrete to deform elastically. Investigators revealed that any amount of fibers giving an extension of the slope in the stress–strain relationship curve by redistribution localized strain and stress (Gesoglu et al., 2016).

The static elastic moduli of UHPCs for different volumes of micro glass fibers and two groups depending on water per binder ratios at 28-day of water cured were demonstrated in Figure 4.5. Regardless of water content, it was observed that adding micro glass fibers were to increase the static elastic moduli of the UHPCs continuously up to a volume of fiber inclusion after that steady results began. Precisely, the UHPFRC had improvement by 5.8% and 8.3% at 1.5%, comparing to their references for the first and second groups, correspondingly. These results approved that UHPFRCs with an optimized dosage of micro glass fibers had higher stiffness because of compactness of the aggregates with paste bond being enhanced. Moreover, the reason for the stable modulus of elasticity after adding of 1.5% micro glass fiber may be due to short particles of fibers (Figure 4.4), which played an important role of isolating the aggregate between each other and also the cement paste leading to the weak bonds. On the other hand, the reason of so close results to each other between the two groups of w/b, may be related to extremely small ratios of both water per binder that compensated by a new generation of superplasticizer and fineness of silica fume (see Table 3.1), which they together supported workability then flowability.

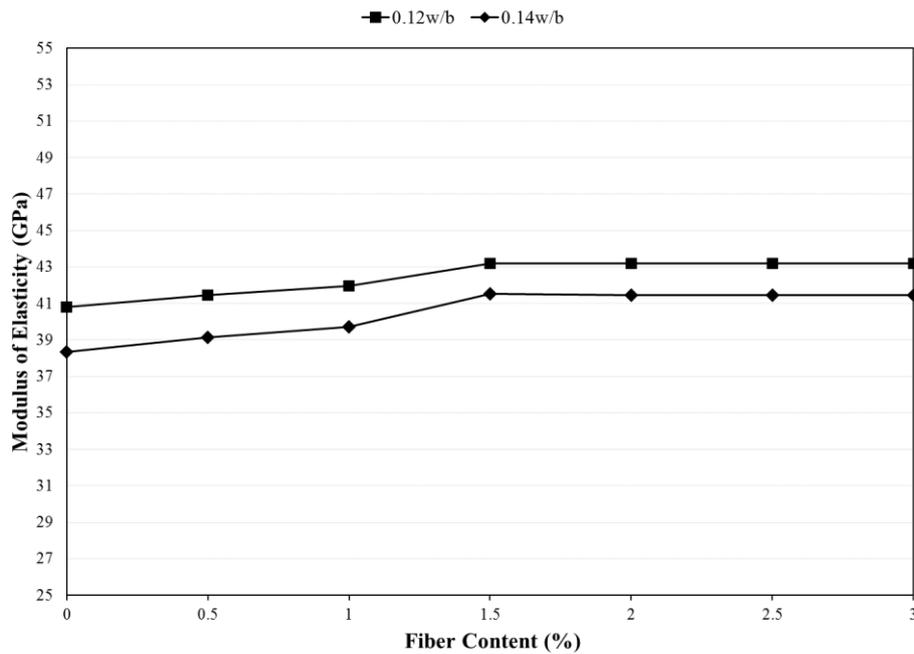


Figure 4.5 Modulus of Elasticity of UHPC versus different volume of micro glass fiber at 28 days

#### 4.5 Modulus of Rupture

Unlike that in many other types of failure of concrete structures, the flexural strength of concrete which characterizes the bending strength of beams, cannot be explained by energy release due to fracture, but the beam is considered to fail before any macroscopic cracks are formed.

The net flexural strength or moduli of rupture of UHPCs reinforced with micro glass fibers under three-point bending are presented in Figure 4.6. Indeed, there was relatively enhancement in the net flexural strength with increasing fibers to reach 17.7 MPa, and 16 MPa at 28-day for w/b of 0.12 and 0.14, respectively for UHPFRCs containing 3% of micro glass fiber. Improving in the modulus of rupture may be due to the improving the bond between aggregate and cement mortar by assisting of small dismantled glass fibers (Figure 4.4). Then, more energy is needed to make crack in UHPFRCs, because of the capacity of the high volume of glass fibers to absorb most energy under bending. On the other hand, the effect of increasing fibers much more than the influence of decreasing water content on the results. For instance, the average enhancement in the net flexural strength with adding 3% of fibers to plain UHPC was

60.1% for 0.12 w/b group, whereas decreasing of w/b from 0.14 to 0.12 cause an improvement by 10.7% for the same mixes containing 3% of micro glass fibers.

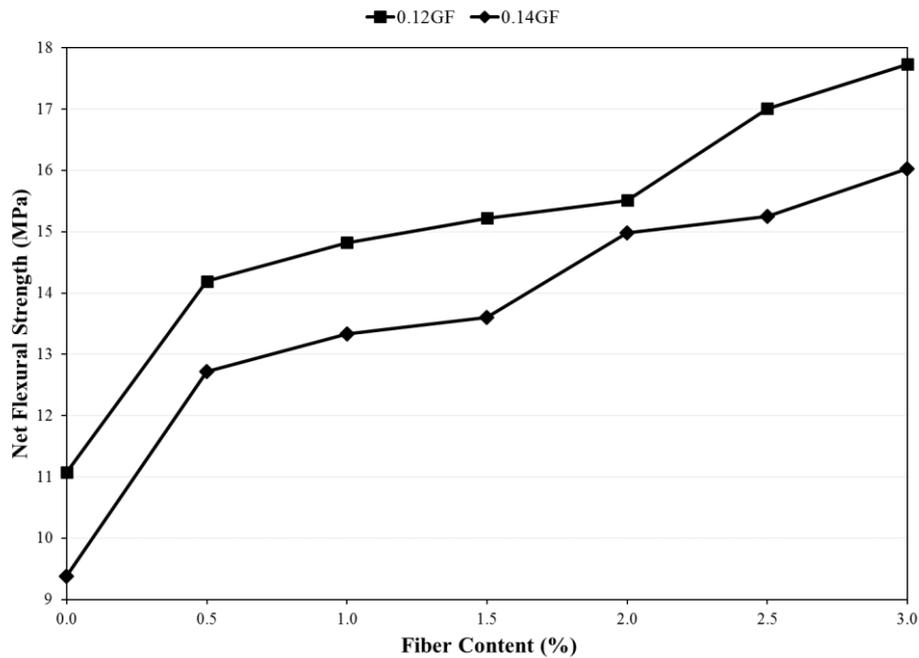


Figure 4.6 Net flexural strength of UHPC versus different volume of micro glass fiber at 28 days

#### 4.6 Load-displacement curves

The load-displacement curves for the notched UHPCs with 0%, 0.5%, 1%, 1.5%, 2%, 2.5% and 3% of micro glass fibers are shown in Figures 4.7 a&b for the groups of 0.12 and 0.14 w/b, respectively. In addition, Table 4.1 presented the effects of water content and different volume of fibers on some statements such as; pre-peak, post-peak, area under load-displacement curve, maximum displacement, and peak load. Besides to withstand a quantity of load by UHPCs, the fibers inside concrete would sustain more another part of the load this called 'peak load'. The first crack appeared and the applied load instantaneously reduced, when the UHPFRC matrix could not stand against the maximum applied load. This imputed to a load accompanying with potential energy imparted in fracturing the prisms (Gopalaratnam et al., 1984). Inasmuch of dismantling to an uncountable number inside concrete (see Figure 4.4), glass fibers made the slope of the pre-peak and post-peak of the curve to extent due to arresting occurring micro cracks of UHPCs.

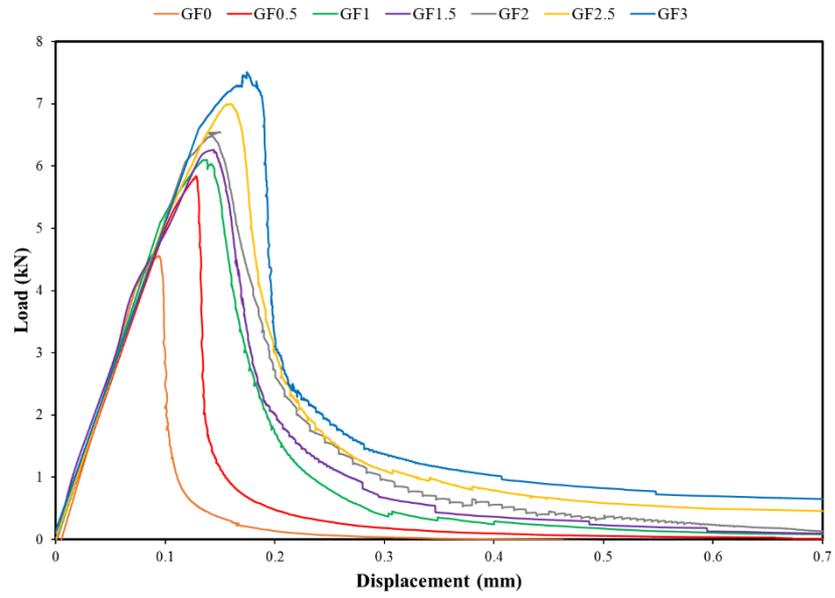
The UHPFRC containing 3% micro glass fiber with 0.12 w/b had an area under the curve, a maximum deflection, and a peak load of 1557.4 kN.mm, 1.5mm, and 7.3 kN, respectively, whereas these values decreased to 1315.7 kN.mm, 1.4mm, and 6.6 kN for additional 0.02 w/b (0.14 w/b) added to the mixtures with keeping the volume of fiber constant. These declined in the fracture parameters is due to; unnecessary addition of more water than the demand to complete the hydration process and giving enough workability, any extra water may play a passive role to restrict improving ITZ, de-bonding between aggregate and binder, and obstructing fibers to bridge the micro cracks. The significant of decreasing w/b and its affecting on the microstructure of concrete in general were also approved by the others (Gesoglu et al., 2013; Wang et al., 2015; Rong et al., 2014; Shi et al., 2015).

Consequently, the above-mentioned figures showed that glass fibers caused transformation of UHPC from strain softening to strain hardening because of their superior properties of maximum displacement, late post peak and in the general shape of the curve in addition to higher results mentioned above. These behaviors may be due to the pre- along with the early post peak regions in load–displacement curve largely depends on the micro-cracks and their expansion, but the declining slope at the end of the softening branch is highly related to mechanisms resulting from the aggregate interlock and other frictional effects (Beygi et al., 2013), whereas the glass-fiber content will play an indirection role to improve this relation.

Table 4.1 Load - displacement test results

| Concrete mixture | area under the curve (kN.mm) | maximum deflection (mm) | P max (kN) |
|------------------|------------------------------|-------------------------|------------|
| 0.12MGF0         | 261.2                        | 0.9                     | 4.6        |
| 0.12MGF0.5       | 364.2                        | 0.9                     | 5.8        |
| 0.12MGF1         | 460.6                        | 0.9                     | 6.1        |
| 0.12MGF1.5       | 629.5                        | 1.0                     | 6.3        |
| 0.12MGF2         | 895.5                        | 1.1                     | 6.4        |
| 0.12MGF2.5       | 1033.9                       | 1.2                     | 7.0        |
| 0.12MGF3         | 1315.7                       | 1.5                     | 7.3        |
| 0.14MGF0         | 471.7                        | 0.73                    | 3.9        |
| 0.14MGF0.5       | 592.7                        | 0.95                    | 5.2        |
| 0.14MGF1         | 888.0                        | 1.01                    | 5.5        |
| 0.14MGF1.5       | 1236.2                       | 1.02                    | 5.6        |
| 0.14MGF2         | 1350.6                       | 1.09                    | 6.2        |
| 0.14MGF2.5       | 1391.2                       | 1.12                    | 6.3        |
| 0.14MGF3         | 1557.4                       | 1.42                    | 6.6        |

(a)



(b)

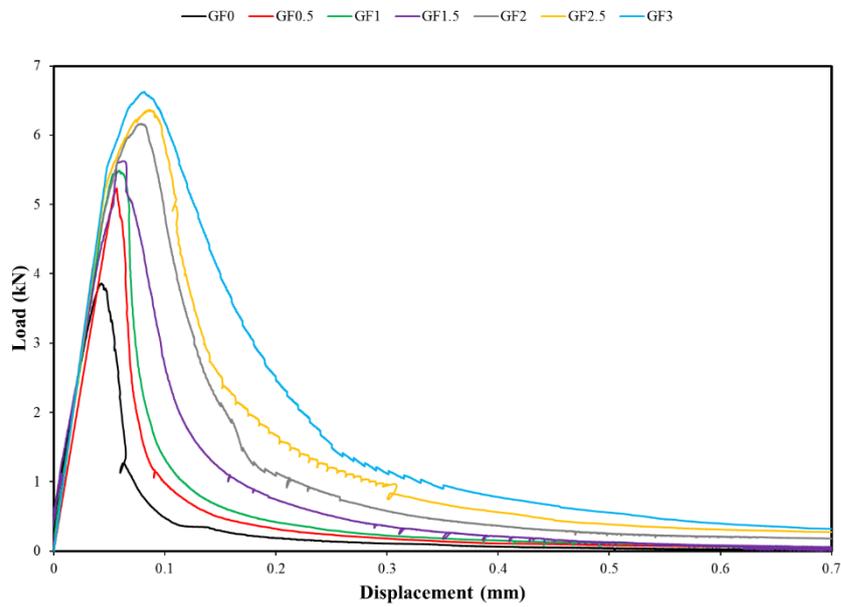


Figure 4.7 Load versus displacement curves of UHPFRC with respect to glass fiber content: (a) 0.12 w/b (b) 0.14w/b group.

#### 4.7 Fracture energy ( $G_f$ )

In spite of deserving a prime role in determining ultimate stress at the crack tip, fracture energy is a function of displacement and not strain. It can be expressed as an energy required to open the unit area of the crack surface. However, the fracture parameters specify ductility behavior of concrete, the higher the concrete ductility, the greater  $G_f$ .

In this study as presented in Figure 4.8, the total fracture energy of UHPFRC is depended on two significant considerations; w/b and volume fraction of the glass fibers. It was noted from above-mentioned figure; the UHPC with 3% micro glass fibers gave the highest value of the fracture energy, regardless of water content. Specifically, adding 3% of micro glass fibers to plain UHPCs led to an improvement of  $G_f$  by 211.4%, and 370.6% for 0.12 and 0.14 w/b groups, subsequently. The huge performance of micro glass fibers may be related to their main properties like high-tensile strength and aspect ratio as seen in Table 4, which made it need high energy necessary to fracture the prisms due to arresting cracks. Furthermore, authors verified that because of an ability to bridge the cracks, the fiber-reinforced UHPCs have larger fracture energies (Prem et al., 2012).

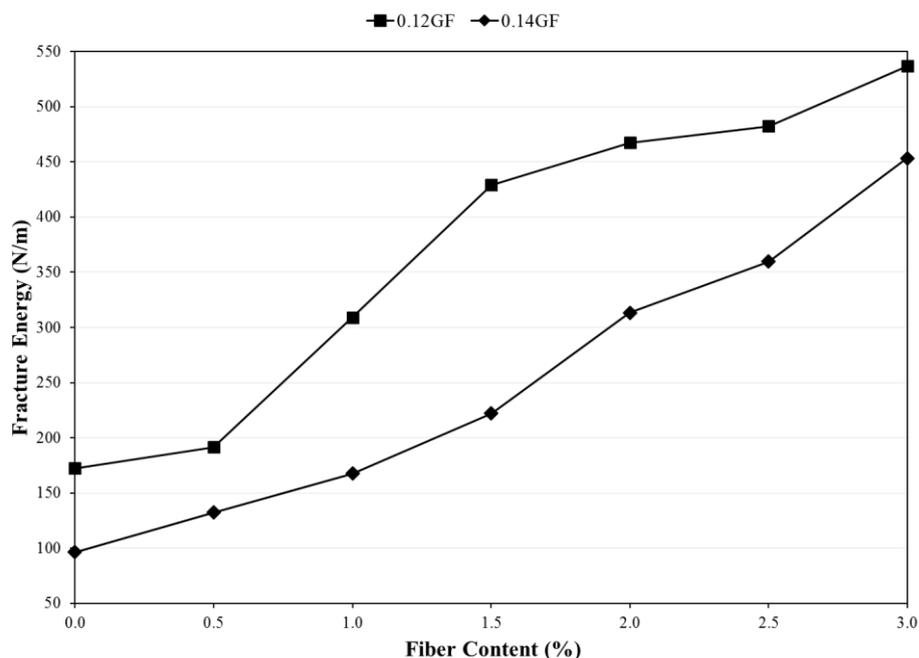


Figure 4.8 Fracture energy versus different glass fiber rate of UHPFRC at 28 days:

#### 4.8 Characteristic length

Whenever the value of characteristic length ( $l_{ch}$ ) is larger, the concrete will be less brittle, because it is a measurement of brittleness, e.g. non ductile. Additionally, according to Eq. 3, the characteristic length is mainly depending directly on the other important mechanical properties of concrete such as fracture energy with elastic modulus and inversely on the tensile strength.

The variations in the characteristic length of UHPCs reinforced with different volume of micro glass fibers and two water per binder contents of 0.12 & 0.14 are shown in Figure 4.9. Regardless of gradually enhancing the brittleness due to adding even small dosage of fibers, it is also noticed that the differences between the two groups were so small after adding 2% of glass fibers up to 3% if compared with UHPCs with lower fiber volumes (0-2%). This may be attributed to a huge number of fibers at high volumes, which will not let water to play an important role on effecting of ductility of UHPCs. However, comparing to the study of Gesoglu et al. (2016) there is a big improvement of the brittleness of UHPC by adding micro glass fibers. The maximum value that they achieved was nearly 48 mm for the plain concretes without fibers. Precisely, in this study by adding micro glass fibers, the characteristic lengths of 167.4mm, and 163mm were recorded using prisms of the same dimensions (70x70x280mm) for the first and second groups, consequently.

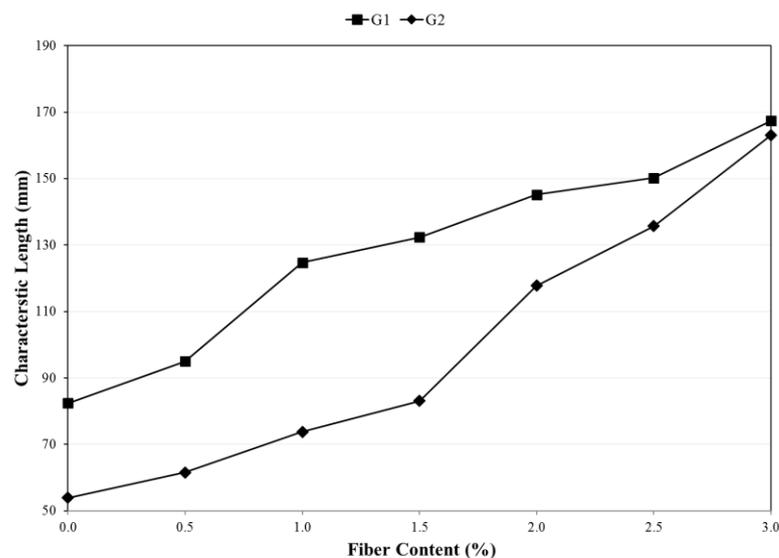


Figure 4.9 Characteristic length versus different glass fiber rate of UHPFRC at 28 days:

## CHAPTER 5

### CONCLUSIONS

1. It was observed that there was a systematic growth in the strengths with increasing the fiber contents up to 1.5% and then the results indicated a meaningless effect upon the results of compressive strength, splitting tensile strength, and modulus of elasticity.
2. Despite using very low water per binder ratios in the present study those were smaller than the ratio chosen by the most other researchers, though good UHPCs flow of  $18\pm 1$  was produced. The strength detraction observed in the UHPCs with increasing w/b may be attributed to form further unwanted calcium hydroxide particles during the hydration process.
3. The reason of so close results of modulus of elasticity to each other between the two groups, may be related to extremely small ratios of water per binder that compensated by a new generation of superplasticizer and fineness of silica fume, which they supported workability then flowability.
4. The effect of increasing fibers much more than the influence of decreasing water content on the results. For instance, the average enhancement in net flexural strength with adding 3% of fibers to plain UHPC was 60.1% for 0.12 w/b group, whereas decreasing of w/b from 0.14 to 0.12 cause an improvement by only 10.7% for the same mixes containing 3% of micro glass fibers.
5. Inasmuch of dismantling to uncountable number inside concrete, glass fibers made the slope of the pre-peak and post-peak of the curve to extent due to arresting occurring micro cracks of UHPCs.
6. The huge performance of micro glass fibers may be related to their main properties like high tensile strength and aspect ratio, which made it need high energy necessary to fracture the prisms due to arresting cracks.

7. Regarding to the characteristic length, the differences between the two groups of 0.12 and 0.14 w/b were so small after adding 2% of glass fibers up to 3% when compared with UHPCs of lower fiber volumes (0-2%). This may be attributed to huge number of fibers at high volumes that will not let water to play an important role on effecting of ductility of UHPCs.



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