

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

**MECHANICAL AND FRACTURE PROPERTIES OF
ULTRA HIGH STRENGTH CONCRETE REINFORCED
WITH HIGH VOLUME MICRO STEEL FIBERS**

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

**BY
BARHAM HASSAN MOHAMMED**

JUNE 2016

**Mechanical and fracture properties of ultra high strength
concrete reinforced with high volume micro steel fibers**



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

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

**By
Barham Hassan MOHAMMED**

June 2016



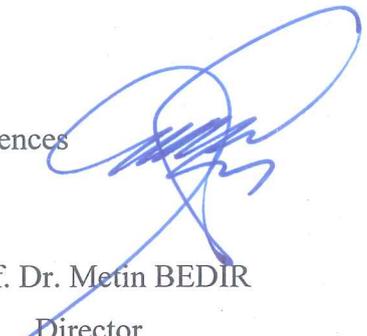
© 2016 [Barham Hassan MOHAMMED]

REPUBLIC OF TURKEY
UNIVERSITY OF GAZİANTEP
GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES
CIVIL ENGINEERING DEPARTMENT

Name of the thesis: Mechanical and fracture properties of ultra high strength
concrete reinforced with high volume micro steel fibers

Name of the student: Barham Hassan Mohammed
Exam date: 16/06/2016

Approval of the Graduate School of Natural and Applied Sciences


Prof. Dr. Metin BEDİR
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of
Master of science.


Prof. Dr. Abdulkadir ÇEVİK
Head of Department

This is to certify that we have read this thesis and that in our consensus/majority
opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master
of Science


Assoc. Prof. Dr. Mehmet GESOĞLU
Supervisor

Examining Committee Members:

Assoc. Prof. Dr. Mehmet GESOĞLU

Assoc. Prof. Dr. Erhan GÜNEYİSİ

Assist. Prof. Dr. Kasım MERMERDAŞ

Signature


.....
.....
.....

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by this rules and conduct, I have fully cited and referenced all material and results that are not original to this work.



Barham Hassan MOHAMMED

ABSTRACT

MECHANICAL AND FRACTURE PROPERTIES OF ULTRA HIGH STRENGTH CONCRETE REINFORCED WITH HIGH VOLUME MICRO STEEL FIBERS

MOHAMMED, Barham Hassan

M.Sc. in Civil Engineering

Supervisor: Assoc. Prof. Dr. Mehmet GESOĞLU

June 2016, 62 pages

An investigational work was implemented to reveal the effects of high-volume micro-steel fibers (MSF) on the mechanical properties and ductility of Ultra High Performance Fiber Reinforced Concretes (UHPFRCs). The aspect ratio and tensile strength of the MSF used were 37.5 and 2250 MPa, respectively. At water - binder ratios (w/b) of 0.12 and 0.14, two groups of UHPFRCs containing 1%, 1.5%, 2%, 2.5%, 3%, 3.5 and 4% of micro steel fiber by volume and tested for the compressive strength, splitting tensile strength, modulus of elasticity, flexural strength, load-displacement behavior, fracture energy, and characteristic length. The experimental results showed that all mixtures with 4% of MSF demonstrated a compressive strength of greater than 160 MPa, splitting tensile strength higher than 12 MPa, and modulus of elasticity of greater than 43 GPa. On the other hand, the mixes with 4% of MSF exhibited a strain hardening. were achieved with the same range of fiber content and 0.12 w/b,. load- displacement behavior with enhanced ductility and all other fracture parameters well improved significantly.

Keywords: Ultra High Performance Concrete, Micro Steel Fiber, Water-Binder Ratio, Fresh Property, Mechanical Properties, Fracture Parameters

ÖZET

YÜKSEK ORANDA MİKRO ÇELİK LİFLERLE GÜÇLENDİRİLEN ÇOK YÜKSEK DAYANMLI BETONLARIN MEKANİK VE KIRILMA ÖZELLİKLERİ

MOHAMMED, Barham Hassan
Yüksek Lisans, İnşaat Mühendisliği Bölümü
Tez Yöneticisi: Doç. Dr. Mehmet GESOĞLU
Haziran 2016, 62 sayfa

Hacimce yüksek oranda çelik mikrofiberin ultra yüksek mukavemetli fiberli betonların (UHFRC) sünekliği ve betonların özellikleri üzerine etkisini incelemek amacıyla bu çalışma yapılmıştır. Çelik mikrofiberlerin en-boy oranı ve çekme gerilmesi değerleri sırasıyla 37.5 ve 2250 MPa dır. UHFRC lar su-bağlayıcı oranı 0.12 ve 0.14 olan iki grupta hacimce fiber içerikleri %1, %1.5, %2, %2.5, %3, %3.5 ve %4 olarak üretilmiş ve basınç dayanımı, yarma çekme dayanımı, elastisite modülü, eğilme dayanımı, yük-deplasman davranışı ve kırılma enerjisi ölçülmüştür. Deneysel sonuçlar su-bağlayıcı oranı 0.12 ve 4% çelik microfiber içeren betonların 160MPa dan daha fazla bir basınç dayanımına sahip, 12 MPa dan fazla yarma çekme dayanımı ve 43GPa dan fazla elastisite modülüne ulaştıklarını göstermektedir. Öteyandan, %4 çelik microfiber içeren karışımlarda pekleşme davranışına benzer eğilimler gözlemlenirken, yük-deplasman davranışı ile birlikte sünekliği ve diğer tüm kırılma parametreleri de önemli ölçüde geliştirilmiştir.

Anahtar kelimeler: Ultra Yüksek Mukavemetli Beton, Çelik Mikro Fiber, Su Bağlayıcı Oranı, Taze özellikler, Mekanik Özellikler, Kırılma Parametreleri
Mechanical Properties, Fracture Parameters.



To My Parents

ACKNOWLEDGEMENTS

First of all, thanks to great God for giving me patience and determination to accomplish this study.

I would like to give my sincere thanks to my honorific supervisor, Assoc. Prof. Dr. Mehmet GESOĞLU, for all his help, patience, valuable advices, always providing and guiding me in the right direction. I'm very grateful and proudest to work under his academic guidance. It is not enough to express my appreciation with only a few words.

Thanks and appreciation also extended to committee-members for their comments and suggestions.

My appreciation and acknowledgement for Dr. Diler ASAAD, for his valuable help and guidance, without his support and assist this research wouldn't have been possible, thanks again for their generous assistance. Thereafter, I would like also to thanks research asst. Serkan ETLİ who is directly or indirectly involved in the process of producing this research report.

My special thanks to my beloved parents, Mom, my wife Nawras, brother, and sisters. Their faith, moral support, and love without any complaint encouraged me to work hard and to continue pursuing a M.Sc. project abroad. I'm proud of my family, they form the backbone and origin of my happiness.

Finally, my sincere appreciation also extends to my friends and those who took part in completion of this thesis.

TABLE OF CONTENTS

ABSTRACT	V
ÖZET.....	VI
ACKNOWLEDGEMENTS	VIII
TABLE OF CONTENTS	IX
LIST OF FIGURES	XII
LIST OF TABLES	XIV
LIST OF SYMBOLS/ ABBREVIATIONS	XV
CHAPTER 1	1
INTRODUCTION	1
1.1 General	1
1.2 Research Significance	2
1.3 Thesis Organization.....	3
CHAPTER 2	4
LITERATURE REVIEW.....	4
2.1 Definition of UHPC.....	4
2.2 Types of UHPC	6
2.3 Applications of UHPC.....	7
2.4 Composition of UHPC	11
2.5 Advantages of UHPC	12
2.6 History and Development of UHPC.....	12
2.7 Principles of Developing UHPC	14
2.8 Mechanical Properties	21
2.8.1 Compressive Strength	21

2.8.2 Modulus of Elasticity	21
2.8.3 Splitting Tensile Strength	21
2.8.4 Flexural Strength and Toughness	22
2.9 Durability Performance	24
2.9.1 Porosity.....	24
2.9.2 Chloride Ion Penetration.....	25
2.10 Effect of Curing Method	25
CHAPTER 3	28
MATERIALS AND MIXTURE PROPORTIONS.....	28
3.1 Materials	28
3.1.1 Cement.....	28
3.1.2 Type of Silica fume.....	29
3.1.3 Superplasticizer.....	29
3.1.4 Micro Steel Fibers.....	30
3.1.5 Quartz Powder	31
3.2 Concrete mixture proportioning, casting and sample preparation.....	33
3.3 Slump Flow Test	35
2.4. Testing methods	35
CHAPTER 4	39
DISCUSSION AND RESULT	39
4.1. Fresh Properties of UHPFRC	39
4.2. Compressive Strength.....	40
4.3. Splitting Tensile Strength	41
4.4. Modulus of Elasticity	43
4.5 Modulus of Rupture.....	44
4.6 Load-Displacement Curves	45
4.7 Fracture Energy	48

4.8. Characteristic Length, l_{ch}	49
CHAPTER 5	51
CONCLUSIONS.....	51
REFERENCES.....	53



LIST OF FIGURES

Figure 2.1 Attributes of HPFRC (Roy, 2011)	5
Figure 2.2 Classification of FRC composites (Naaman and Reinhardt, 2006).....	6
Figure 2.3 UHPC Example: Sherbrooke Footbridge (Resplendino and Petitjean, 2003).	8
Figure 2.4 UHPC Footbridges (a) Footbridge of Peace in Seoul, South Korea at night (Behloul and Cheyrezy 2002a); (b) during the day (Lafarge in Searls 2007); (c) perforated hollow UHPC bridge girder (Tanaka et al. 2002); (d) resistant of fire UHPC footbridge in Rhodia, France; (e) Gartnerplatz Bridge - Kassel, Germany....	10
Figure 2.5 UHPC Construction Examples (a) UHPC panels on Joppa clinker silo (b) 54 ft UHPC columns in Detroit, (Behloul and Cheyrezy 2002a).	11
Figure 2.6 Stress-strain diagrams of concrete illustrating: increasing brittleness with increased strength (a) using external confinement; (b) using fiber reinforcement (Shah and Weiss, 1998) cracking in tension was further discussed in details by Rossi (2001).....	17
Figure 2.7 Splitting tensile strength test procedure, (Prabhat Ranjan Prem et al 2013).	22
Figure 2.8 Typical flexural strength test curves of four types of concrete (Lukasik, 2005).	23
Figure 2.9 Effect of curing temperature on the compressive strength of RPC (Shaheen and Shrive, 2006).	26
Figure 3.1 Micro steel fibers.	30
Figure 3.2 Type of Quartz (Large 1.2 -2.5).....	32
Figure 3.3 Type of Quartz (medium 0.6 – 1.2)	32
Figure 3.4 Type of Quartz (small 0-0.4)	32
Figure 3.5 Slump test	35
Figure 3.6 Views of a) experimental setup for three point bending test and b) dimensions of the notched beam specimen c) fracture test device	38
Figure.4.1 Super plasticizer amount versus different MSF content of UHPFRC with 0.12 w/b, and (b) 0.14 w/b	39

Figure.4.2 Compressive strength of UHPFRC at different ages: (a) 0.12 w/b, and (b) 0.14 w/b.....	41
Figure 4.3 Splitting tensile strength of UHPC versus different volume of MSF fiber at 28 days	42
Figure 4.4 Modulus of Elasticity of UHPC versus different volume of MSF at 28 days	44
Figure 4.5 Net flexural strength of UHPC versus different volume of micro steel fiber at 28 days	45
Figure 4.6 Load versus displacement curves of UHPFRC with respect to steel fiber content: (a) 0.12 w/b (b) 0.14w/b group.	47
Figure 4.7 Fracture energy versus different steel fiber rate of UHPFRC at 28 days:	49
Figure 4.8 Characteristic length versus different steel fiber rate of UHPFRC at 28 days.	50

LIST OF TABLES

Table 3.1 Chemical composition and physical properties of Portland cement and silica fume.	28
Table 3.2 Physical and mechanical properties of Portland cement, silica fume	29
Table 3.3 Properties of superplasticizer	30
Table 3.4 Physical properties of ultrafine quartz powder used for UHPFRC.....	31
Table 3.5 Compound compositions of ultrafine quartz powder used for UHPFRC	31
Table 3.6 Mix proportions (kg/m^3).	34
Table 4.1 Load - displacement test results	46

LIST OF SYMBOLS/ ABBREVIATIONS

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BS	British standard
CH	Calcium Hydroxide
C-S-H	Calcium-Silicate-Hydrate
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

Ultra-high performance concrete (UHPC) is a new type of concrete developed by selecting the particle sizes and gradation of the constituent materials in micro-scales, targeting the highest possible packing. In UHPC, a high proportion of cement is used compared to that of normal strength (NS) and high-performance concrete (HPC) (Schmidt and Fehling 2005). A very low w/b is used in UHPC mixtures due to which, only part of the total cement hydrates in UHPC, and the un-hydrated cement can be replaced with crushed quartz (Richard and Cheyrezy 1995, Yazıcı 2007, Soutsos et al. 2005). The reduced workability of UHPC due to its very low w/b can be resolved by adding an effective superplasticizer (SP) (Tue et al. 2008). Moreover, the addition of silica fume can improve the workability of UHPC and fill voids between coarser particles due to its finer size and spherical shape, thus enhancing the strength properties through pozzolanic reactions (Ma and Schneider 2002, Neves 2005). Using fine aggregate such as quartz powder (instead of coarse aggregates) plays an important role in reducing the maximum paste thickness. Consequently, in spite of very brittle failure mode of plain UHPC, the stiffness and strengths of the interfacial transition zone (ITZ) enhanced as recently reported by authors (Gesoglu et al. 2016).

Regardless to its types and dimensions, adding fibers will play an important role to enhance resistance to cracking, ductility and toughness properties of plain UHPC to form superior more quality of a concrete named as Ultra-High Performance Fiber Reinforcement Concrete (UHPFRC). UHPFRC usually incorporates discrete fibers to encourage strain hardening behavior in tension and to avoid sudden failure (Yu et al. 2016, Yoo et al. 2016). Thus, high fracture parameters enable design of more efficient structures with reduced weight and material consumption.

Many researchers trying to test the performance of UHPFRC around the world to determine the optimum fiber properties, like; fiber type, volumetric content, distribution homogeneity, and length (Park et al. 2014, Kang et al. 2016). Tran et al. (2016) investigated the enhancement of fracture parameters of UHPFRC by adding 1-1.5% fibers. They concluded that smooth fibers exhibited higher fracture strength and specific work-of-fracture at high rates than twisted fibers. Beglarigale and Yazıcı (2015) studied the effect of parameters like hooked or smooth end and water/binder ratios on reactive powder concretes. The fiber–matrix bond characteristics improved more as the smooth fibers used besides decreasing water/binder ratios improved the bond strength, increased the pull-out peak load and debonding toughness in the all curing conditions. Aydın and Baradan (2013) investigated drying shrinkage behavior and the mechanical properties of mortars that reinforced with 0.5%, 1.0%, 1.5% and 2.0% of volume fractions and two different lengths of 6 mm and 13 mm of steel fibers. The mechanical properties of mortars developed intensely respecting to the increase of fiber length from 6 to 13 mm. Furthermore, the drying shrinkage of mortars reduced via increasing fiber dosages.

Nonetheless, In UHPFRC systems, micro steel fibers (MSF) due to their micro sized have the best consistency with the other concrete cementations since they have all in the level of micro sized. Thus, it has been found that the micro steel fibers in UHPC in the form of randomly distributed synthetic fibers, which results in enhancing all mechanical properties. For example, Markovic (2006) drew the orientation of short micro steel fibers inside concrete (Fig. 1). He found that short steel fibers may still rotate in three directions and the positive influence higher than that of long fibers.

1.2 Research Significance

The goal of the present study is to develop UHPFRC by adding gradually high volume of micro steel fibers up to 4% with very low water/binder ratios of 0.12 and 0.14 via supporting new generation of super plasticizers and ultra-fine micro silica particles for compensating loss of workability. Most important mechanical properties like; compressive strength, tensile strength, modulus of elasticity, flexural strength, load displacement curve, fracture energy, and characteristic length were studied to evaluate enhancements of Strengths, Strains, Stiffness, Toughness, Ductility, etc. of UHPFRCs

1.3 Thesis Organization

Chapter 1 Introduction: Main objective and aim of this thesis are briefly introduced.

Chapter 2 Is a background and review of literature on the properties of UHPCCs as well as on the internal sulfate attack of ordinary mortars and concretes

Chapter 3 Experimental study: Includes materials, mixtures, casting, curing conditions, as well as the test method description according to British standards and ACI codes.

Chapter 4 Test results and discussion: Provides the study results and discussions with related Figures.

Chapter 5 Conclusions: Gives the conclusion of this thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Definition of UHPC

Ultra high performance concrete (UHPC) is a material that has been developed to meet the needs of high resistance to corrosion agents infiltrate such as chloride. Mix the water ratio UHPC include a water-to-cementations material ratio less than 0.25, fiber strengthen internal behavior its crisps, Binder content with high total. Furthermore, UHPC can cruise up the proper characteristics, in spite of the very low water content; there are granular packaging and high-range water-reducing admixtures enough (Graybeal, 2007a). Nevertheless, the use of the micro-reinforcement and the density of UHPC result in result in advanced mechanical properties and additional superior durability. Important testing has been implemented worldwide to determine optimum fiber properties; Volumetric ratio, such as the type and length of fiber, as well as homogeneity and distribution. Superior mechanical properties such as very high compressive and tensile strengths, high ductility, and resistance to fatigue was found as a result of using micro reinforcement in UHPC , through random distribution of steel synthetic fibers. Typically the part of standard production of precast members are heat and steam curing of UHPC mixes.This controls at an early age shrinkage while encouraging higher mechanical properties. Pressing force UHPC offers 150-400 Mpa and tensile strengths passion of 30-40 Mpa. Fiber reinforced concrete (FRC) is a ‘concrete made primarily of hydraulic cements, aggregates, and discrete reinforcing fibers as defined by ACI 544.1R (Report on Fiber Reinforced Concrete). Various kinds of FRC are produced by using different types of fibers. Steel, glass, carbon, and organic polymers are used for producing the most common types of fibers (synthetic fiber).

As reinforcement organic fibers and naturally occurring asbestos fibers are used. Normally, the diameter and length of fiber for the production of FRC does not exceed 1 mm (0.04 inches) and 76 mm (3 inches), respectively (ACI 544.1 R).

Depending on the intended use of the final product the concrete matrix in FRC may be normal concrete, mortar, or special type of mix (such as, self-consolidating concrete). HPFRC is a special class of FRC, which exhibits high ductility and energy absorption capacity, high compressive and flexural strength, high durability, and high modulus of elasticity. The attributes are shown in Figure 2.1.

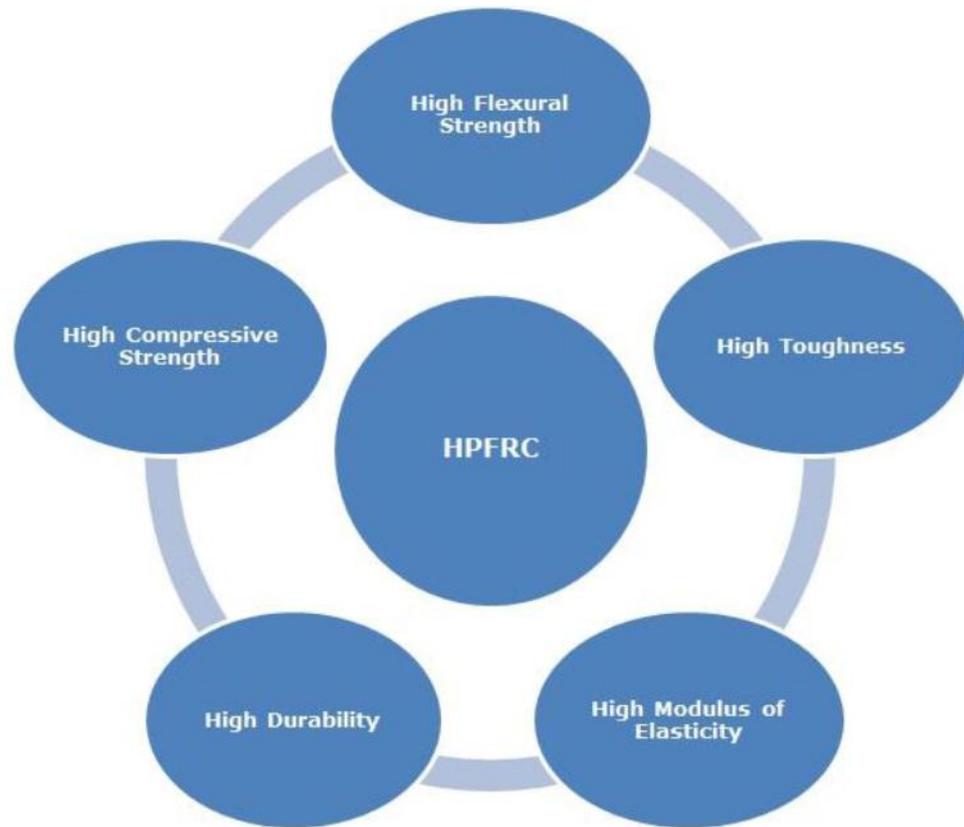


Figure 2.1 Attributes of HPFRC (Roy, 2011)

In comparing to conventional FRC, the HPFRC has superior flexural strength and much improved ductility. It shows deflection hardening behavior after first crack, when loaded in flexure. More deflection and multiple cracking occurs by increasing the load after first crack until the load reaches the peak load (maximum value).

After the peak load deflection softening starts and with the increase in deflection the load decreases. Based on stress-strain response in tension FRC is classified to tensile strain softening FRC and tensile strain hardening FRC and further classification of tensile strain softening FRC into deflection softening FRC and deflection hardening FRC are explained elsewhere (Naaman and Reinhardt 2006). Figure 2.2 shows the classification of FRC based on tensile stress-strain response.

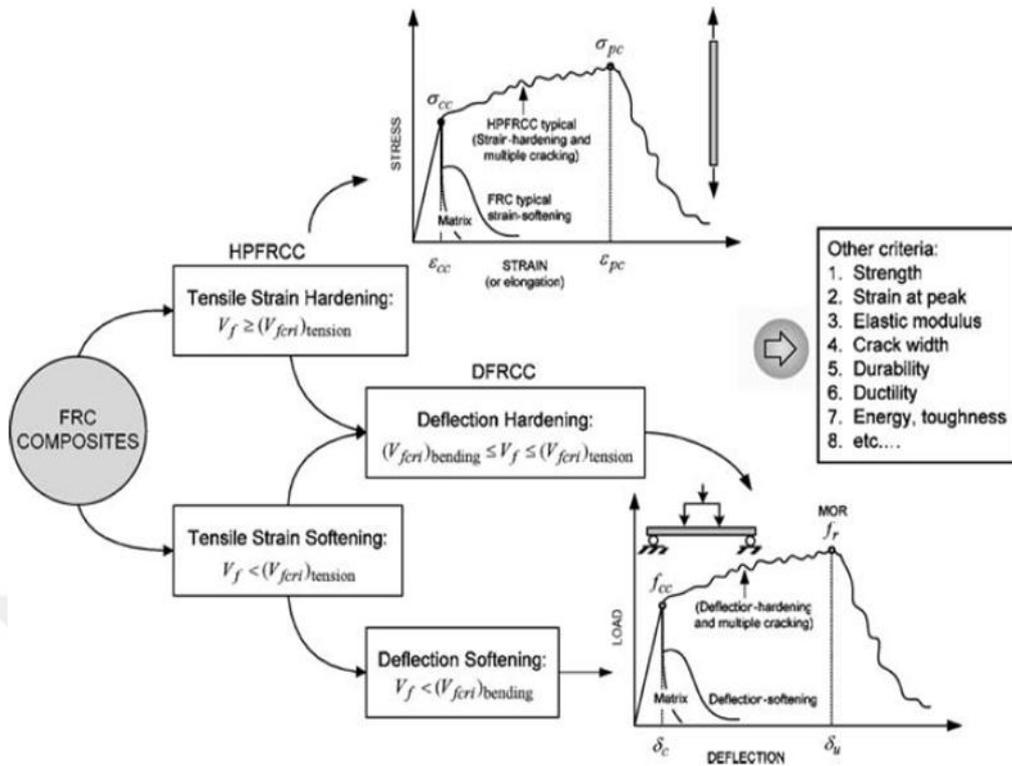


Figure 2.2 Classification of FRC composites (Naaman and Reinhardt, 2006).

UHPFRC has flexural strength similar to engineered cementitious composites (ECC) and high performance fiber reinforced cementitious composites (UHPFRCC) and much higher than high performance concrete (HPC) and deflection hardening FRCC (DHRCC). Its compressive strength is lower than ultra high performance concrete (UHPC) but is superior to that of DHRCC, HPC, HPRCC and ECC. It has better bonding property than conventional FRC and latex modified concrete (LMC). ECC is another special class of FRCC that has superior ductile property (Li 2003). It also strain-hardens after first cracking rather than strain-softens (Li and Kanda 1998). This high ductility is achieved by tailoring the micromechanical parameters of the constituents, namely, the matrix, the fiber-matrix interface and the fibers (Li and Leung 1992, Li 1993, Kanda and Li 1999).

2.2 Types of UHPC

There is a significant work up in Europe to develop many new types of UHPC materials. Those that have been developed include BSI®, Ductal®, and CEMENTEC (Ahlborn et al. 2003) that are marketed by Eiffage Group, Lafarge and Laboratoire of Central des Ponts et Chaussées of France, respectively. In North

America ductal® has been promoted by the Lafarge North America group and is the brand of UHPC studied in this report. The various UHPC materials are slightly differ in composition, and many new UHPC materials are in the process of being developed, its a priority for the U.S. to understand the behavior of UHPC material and its potential implementation.

2.3 Applications of UHPC

Because of development in UHPC, the proper market is need to be discovered to utilized its increased strength, flexural capacity, durability. To date this versatile material has been used in acoustical panels, precast elements, artwork, precast elements, few highway bridges and pedestrian bridges. In the U.S. utilization of UHPC has been limited, but also it is used for different applications in Europe, Australia, Canada, and Asia. Many of applications of UHPC have been related to industry of transportation, this innovative material is discovered not for only its strength benefit, but also durability UHPC. Only a short overview of UHPC applications in the world are discussed here, however, more and more detailed investigations about these uses can be found in other sources (Behloul and Cheyrezy 2002a and 2002b; Schmidt and Fehling 2005; Kollmorgen 2004).UHPC was developed in early 1990's, and the first structure that made of UHPC was in 1997, in Quebec, Canada, the Sherbrooke pedestrian bridge, was constructed. The 197 foot long structure is a post tension open space truss (Figure 2.3). Six match cast segments compose the main span. Among many other benefits, improved mechanical properties of UHPC allowed to use only the top surface of 1.2 in. thick (Semioli 2001). To develop an understanding of how to work UHPC in actual applications, also it has been implemented a long-term monitoring program on the bridge to monitor deviations forces in the prestressing tendons.



Figure 2.3 UHPC Example: Sherbrooke Footbridge (Resplendino and Petitjean, 2003).

UHPC was used to replace steel beams in the cooling towers of the Cattenom power plant, in France in 1997 to test its durability. Because the environment is corrosive that is why UHPC was chosen because of its durability property. No deterioration of the UHPC was observed when an AFGC-SETRA working group visited the site after three years (Resplendino and Petitjean 2003). Other transit applications in South Korea, Japan, France, and Germany was constructed it was footbridges. In Seoul, South Korea the Footbridge of Peace (Figure 2.4a and Figure 2.4b), is an arch-bridge with height of only 49 ft, a span of 394 ft, and a thickness varying anywhere between 1.2 in. and 4 in. (Brouwer 2001). Sakata-Mirai footbridge, In Japan, (Figure 2.4c) was completed in 2002 and demonstrated how a perforated webs in a UHPC superstructure can both reduce weight and be aesthetically pleasing (Tanaka et al. 2002). France utilized UHPC's high load carrying properties and fire resistant capabilities to construct highly fire resistant footbridge (Figure 2.4d) at a Chryso Plant in Rhodia (Behloul and Cheyrezy 2002a). Most recently, in Kassel, Germany the Gärtnerplatz Bridge was completed (Figure 2.4e) (Fehling et al., 2008).



(a)



(b)



(c)



(d)



(e)

Figure 2.4 UHPC Footbridges (a) Footbridge of Peace in Seoul, South Korea at night (Behloul and Cheyrezy 2002a); (b) during the day (Lafarge in Searls 2007); (c) perforated hollow UHPC bridge girder (Tanaka et al. 2002); (d) resistant of fire UHPC footbridge in Rhodia, France; (e) Gartnerplatz Bridge - Kassel, Germany.

In France, the Bourg Les Valence Bridge was the first vehicle bridge constructed by using UHPC in 2001. It spans about 145 feet with two equal spans consisting of 5 π -shaped prestressed elements. The π -shaped elements were connected by casting UHPC in situ (Resplendino and Petitjean 2003). In Australia UHPC was used to carry four lanes of traffic over a skewed (16°) single span of 49 ft. while reducing the dead weight by over half (Rebentrost and Cavill 2006). In 2001 UHPC made the transition to the United States with the creation of the roof of a clinker silo (Figure 2-5a) in Joppa, Illinois (Perry 2003). Using UHPC is a time gain and labor as the roof was constructed faster and with fewer workers than the two companion metal roofed silos. The 24 wedge-shaped precast panels with a thickness of 0.5 in. covered the 58 ft. diameter silo. In Detroit, Michigan UHPC has been used to construct columns with a smaller cross section in a cement terminal (Figure 2-5b) which allows for five more feet of truck width clearance for the three loading bays (Lafarge North America 2006a).



(a)



(b)

Figure 2.5 UHPC Construction Examples (a) UHPC panels on Joppa clinker silo (b) 54 ft UHPC columns in Detroit, (Behloul and Cheyreyz 2002a).

2.4 Composition of UHPC

UHPC usually consists of Portland (generally up to 800-1000 the fibers kg / m³) and quartz sand, quartz powder, silica, and micro steel and superplasticizers. Quartz powder is an important source of pressurized steam Treatment (sterilization) as they contribute to the formation of tobermorite structure, leading to high mechanical performance (Yazici et al., 2013). On the other hand 7 On the one hand, and the silica powder used in UHPCC has three main functions (Long et al., 2002; Aitcin 2003 :) (1) Filling the spaces between the larger particles the following categories, namely cement. (2) improve the flow of fresh concrete characteristics of lubricating effect It follows full core particles spherical; (3) develop secondary hydrate by reacting Buz and utensils with lime Resulting cement water main. Agents to reduce large-scale water (HRWR) -based chemistry carboxyl And used in accordance with ASTM C494 specification, F, normally because they offer the best Dispersion of cement particles dispersion due to steric hindrance mechanism that Compared to

other types of HRWR (Yanni, 2009). Using a high dose of HRWR it is possible to produce UHPCC with low water / cement (w/c) ratio (usually less 0.2). However, UHPCC called, in some cases, the reaction of the powder concrete (RPC), and was Modified in different ways. Different types of fine aggregates such as KORUND, basalt, I've been using limestone, bauxite and sintered, and granite as substitutes for quartz sand, without a major change in the mechanical properties of UHPCC (Aydin et al, 2010; Corinaldesi and Moriconi, 2012). Use of certain industrial products Such as ground granulated blast furnace slag (GGBS) and ash (FA), and UHPCC alternative materials in cement possible (Yazici et al 2008; Yazici et al. 2010; Hassan et al, 2012). Some waste materials such as rice husk ash (Tuan et al. God. 2011; Van and the like. 2014), as well as palm oil fuel ash (Aldahdooh et al., 2013.2014), has I also used. In literature, he said proportionality mixture UHPCC different. Table 2.1 Relations describe the confusion UHPCC proposed various investigators (Richard and Cheyrezy, 1995; Sahin and confession, 2006; Yazici et al, 2013).

2.5 Advantages of UHPC

The most fundamental mechanical property difference between normal concrete (NC) and H is the superior ductile property exhibited by UHPC. NC without any reinforcement, by virtue of its brittle nature, shows no significant post-cracking ductility. Fibers are added to normal concrete in order to bridge across the cracks as they begin to open once the concrete matrix has cracked. In a nutshell, fibers provide the post-cracking ductility to the material. Load vs. deflections curves for unreinforced matrix and FRC are shown in Figure 2.3. The magnitude of these post-elastic property changes depends on upon a type of matrix, strength of matrix, size of aggregates, type of fiber, fiber content, fiber aspect ratio, strength and modulus of fiber, fiber orientation, and surface bonding characteristic of fiber. Other advantages of HPFRC are the superior compressive and flexural strength, high modulus of elasticity, high durability, and low permeability.

2.6 History and Development of UHPC

Utilization of fibers to strengthen otherwise brittle building materials, dates back for a long time before. Historically, to reinforce sun-dried mud bricks (adobe) haulm was used and to reinforce masonry mortar and plaster horse hair was used. The reinforcement used to make the resulting product better resistant to cracking and

fragmentation that occur as a result of repetitive changes in humidity and temperature (Namaan 1985). In Romans horse hair added to concrete in order the concrete to be at the lower risk for cracking. Joseph Lambot in 1847, added fibers in the form of wire meshes or wire to concrete in order to create a new building material (Namaan 1985). This product cause the development of ferrocement, that it is known today. Labor cost is higher in placing continuous fibers that led to seek for discrete fibers that can be added to the mixer like admixtures or aggregates.

The first registered patent (1874) on FRC was the idea of A. Berard to use discontinuous fibers in the form of granular waste iron in concrete mix (Namaan 1985). In the following years, a lot of patents on various types of fibers were registered in many countries. In early 1900 asbestos fibers were the first that used in cement matrix. Overall the world asbestos based cemenitious products have been widely used in industry of construction. Using of alternative fibers instead of asbestos fibers is mandatory because of the health risk that asbestos fibers have. By the 1960s, glass, steel, and other synthetic fibers were used in concrete and continuously there is search for finding new fibers.

Polypropylene fibers were used in concrete as early as 1970 in England as reported by Krenchel and Shah (1985), the performance of concrete reinforced with steel and glass fibers were better than the performance of the resulting cement composite. lower elastic modulus of polypropylene fibers and the inferior bond between cement matrix and the ordinary polypropylene fibers are the main reasons behind the poor performance of polypropylene fibers. Later, an improvement was occur in polypropylene fiber by increasing tensile strength, higher elastic modulus and better bonding characteristic and this was developed in Denmark (Krenchel and Shah 1985). Since the mid-1960s, significant progress in the field of FRC has been reported because of the following advances in cement and concrete industry (Naaman 2007):

- a. Commercial introduction of superplasticizers each new generation,
- b. Enhancing use of active or inactive micro-fillers, such as, fly ash, silica fume and their significant effect on durability, strength and matrix porosity.

- c. Presence of various kinds of fibers for use in concrete, that can add significant effect on the ductility, toughness and strength of the resulting composite.
- d. Utilization of polymer addition to concrete for better bonding between matrix and fibers and;
- e. Creation in production processes (such as self-compacting or self-consolidation) to reduced effects on the porosity of the matrix and produce uniform mixing of high volumes of fiber.

Significant progress has also been made in modeling the behavior of FRC (Bentur and Mindess 1990, Balaguru and Shah 1992, Hannant 1978, Brandt et al. 2000 and Karihaloo 1997). These factors are the reasons behind the development of 'high performance fiber reinforced cement composite' as it is known today.

2.7 Principles of Developing UHPC

As it is known the strength of concrete (it is a brittle material) depends on the porosity of that material. It is observed that by decreasing porosity, significant increase in the strength will occur (Mindess and Young, 1981). Reducing the water-cement ratio is the key behind providing proper compaction with reduced porosity and high strength (Powers and Brownard, 1948). To alter attraction forces between the cement particles improving the fluidity of cementitious systems, reducing the size of voids and better dispersing the cement particles, the water-reducing admixtures should be use (Dodson, 1990). Improving the homogeneity, enhancing the microstructure of regular concrete and increasing the dry-compacted density are The main principles of development of UHPC matrices. This has been achieved either by: (1) modified with polymer cement (macro defect free, MDF), or 2. Condensation with a micro-fine particles in addition (Shah and Weiss, 1998). Macro-defect free (MDF) materials are polymer that water-soluble such as PVA (typically less than 5%), and has a low w/c (less than 0.2). The reduction in pore size that occurs as a result of processing causes very high tensile strength of MDF (200 MPa (29,000 psi) approaching that of steel).As noted by the recent work, crosslinking between cement and polymer cause important increase in the strength(Poyola et al., 1990). As a result, to produce the mechano-chemical reaction between the mineral and polymer phases high shear mixing process is required for MDF mixtures ((McHugh and Tan,

1993). Condensation with micro-fine particles is depend on the concept of particle packing and is the approach that used frequently. Superplasticizers let the cement particles to pack more uniformly, as previously mentioned, thereby increasing strength, and reducing the porosity of conventional concrete. The particle-packing idea can be further used by adding silica fume (submicron particles) that fill remaining void space, resulting in a strong material, and a dense.

Additional increase in strength may occur, if these particles are also pozzolanic. In addition, the increased density of these materials decreasing the penetrability to water, reduces the connected porosity and, thus increasing long-term durability. Graybeal (2005) it was uttered that most of the UHPC matrices are generally composed of cement with an average diameter of approximately 15 μm (0.00059-in), fine sand, between 150 and 600 μm (0.0059 and 0.0236-in), crushed quartz with an average diameter of 10 μm (0.000394-in), and silica fume that has a diameter small enough to fill the interstitial voids between the crushed quartz particles and the cement. Quartz particles can react with alkaline solutions Depending on the temperature, time, and particle size. Metamorphic quartz has been found to be reactive alkali, generally in reducing order of interaction (Mehta and Monteiro, 2005). Feylessoufi et al. (1997), and Richard and Cheyrezy (1995) said that further improvements to the cement matrix can be achieved by thermal treatment also is to stimulate a reaction of silica fume, and the average pore size reducing through the thermal treatment application. In a study by Cheyrezy et al. (1995)it was conducted that mercury intrusion with porosimetric analyses showed zero porosity in confined RPC specimens cured between 150°C (302 °F) and 200 °C (392 °F). Both swelling and shrinkage in RPC decreased upon applying steam curing as concluded by Collepardi et al. (1997).

Where heat curing at 90 °C (194 °F) was applied by Richard and Cheyrezy (1995) similar trends were observed. Also, in a study by Monosi et al. (2000) it was concluded that further strength increase with high pressure steam curing at 160 °C (320 °F), with respect to the RPC's that were steam-cured at 90 °C (194 °F). In brief, ultra-high strength matrix can be achieved by (1) low water-to binder ratio (typically below 0.2), and, using high dose of high-range water reducing agents (HRWR) typically based on polycarboxylate (PC) chemistry meeting the ASTM C 494 requirements for Type F high-range water reducing admixtures (Graybeal, 2005;

Ferron et al., 2007, and Habel et al., 2007) as as they provide better dispersion of cement particles due to the steric hindrance dispersion mechanism compared to other types of HRWR.), they provide better dispersion of cement particles due to the steric hindrance dispersion mechanism compared to other types of HRWR.), (2) aggregate containing only fine sand, (3) thermal treatment (curing), and (4) large quantity of fine particles (typically silica fume). When concrete is more homogenous, it has higher strength but will be more brittle than normal strength concretes. By comparing a cross section of a typical HSC with UHSC increased homogeneity can be noted. In the standard high strength system, aggregate particles and unreacted cement produce significant heterogenic, While the UHSC system is much more unified in the same range. As shown in Figure 2.6 how increased strength can changes the material performance by showing the stress-strain failure envelop of conventional, ultra-high strength concrete, and high strength. Material with ultimate failure strain and high stiffness can cause increase in compressive strength. But on the other hand, with high strength concrete show a sudden drop in load carrying capacity occurs after reaching a peak load(post-peak) (Shah and Weiss, 1998). By incorporation of short fibers in the concrete mix this problem could be solved. Fiber reinforcement of cement-based matrices are known to (1) improve the tensile or flexural strength, (2) control cracking, (3) alter the mode of failure by increasing post-cracking ductility. In most of the applications, fiber contents ranges from about 0.3 to 2.0% by volume, (4) change the rheology or the flow characteristics of the material in the fresh state, (5) improve the impact resistance or toughness. Reduction of the amount of prestressing strands needed and the achievement of longer spans is a significant beneficial effect of increase in tensile strength, in the precast prestressed industry. However, fiber-reinforced concretes differ from conventional concretes in having smaller size of coarse aggregate (10 mm (3/8-in) maximum size), and lower coarse aggregates content (350 to 750 kg/m³) (600 to 1250 lb/yd³) (Lankard, 1975; Swamy and Barr, 1989; and Banthia et al. 1999). fractured specimens of fiber-reinforced concrete shows that failure takes place primarily due to debonding or fiber pull-out, unlike plain 15 concrete, after initiation of the first crack fiber reinforced concrete specimen does not fail immediately as it is shown in a study by Shah and Weiss (1998). If the pull-out resistance of the fibers at the first crack is greater than the load at first cracking, the composite will carry increasing loads after the first cracking of the matrix as stated in Shah (1984) In explaining the toughening mechanism in fiber

reinforced composites. The fibers carry the entire load taken by the composite and the matrix does not resist any tension at the cracked section. The fibers will tend to transfer the added stress to the matrix through stresses bond, with an increasing load on the composite. Then there may be additional cracking in the matrix occur, if these bond stresses do not exceed the bond strength. Until either fibers fail or the accumulated local debonding will lead to fiber pull-out, this process of multiple cracking will continue.

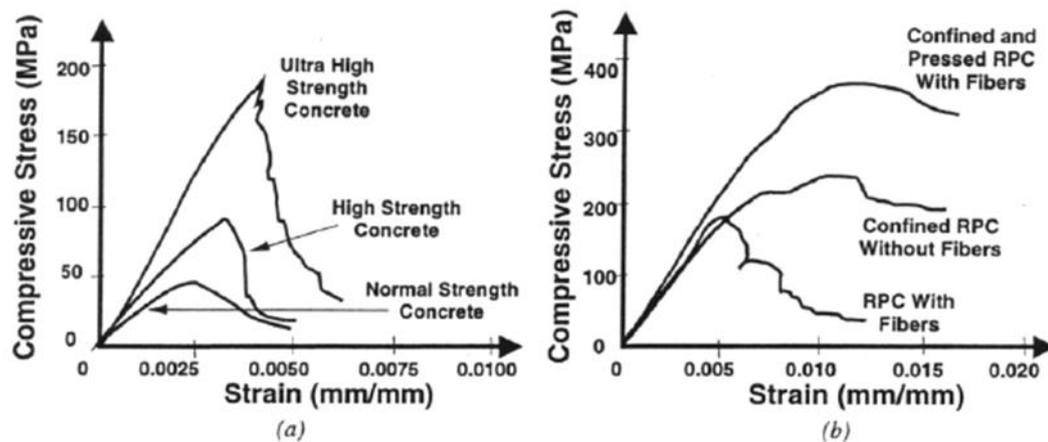


Figure 2.6 Stress-strain diagrams of concrete illustrating: increasing brittleness with increased strength (a) using external confinement; (b) using fiber reinforcement (Shah and Weiss, 1998) cracking in tension was further discussed in details by Rossi (2001).

There are three stages from the beginning of loading until failure:

(1) Throughout the entire volume of concrete, microcracks form randomly. (2) In this stage localized macrocracks will form by joining microcracks together, which affect the mechanical behavior. (3) Widening of one or more macrocracks causing the final failure. This scenario was also noted by Namaan and Homrich (1989). However, in resisting crack propagation according to their relative size, different fibers may be more efficient than others. Thus, the presence of a large number of fibers are spaced closely it seems that the most effective way to bridge the microcracks formed in the mixture through a first stage. By using short fibers (<5.08 mm (0.2 in) with small diameters the placement of a large number of fibers allowed without the presence of workability problems.

On the other hand, should the fiber used to be long enough (> 20 mm (0.79 in)) to bridge the macrocracks formed during the second and third stages.

However, the use of long fibers has always been associated with decrease workability and therefore usually limited to a volume fraction of 3%. They can overcome this problem by: (1) the use of increased amounts of superplasticizers (HRWRs) Several studies in the last few decades have focused on experimentally studying the influence of incorporating different types of short fibers on concrete performance, and (2) the use of two different types of fibers in the mixture: short fibers bridging microcracks, and long fibers bridging macrocracks. Fibers used to reinforce concrete divided into two main groups Hannant (1978), those with higher modulus such as steel, asbestos, carbon, glass, and Kevlar (aramid), and these with modulus lower than the cement matrix, such as nylon, cellulose and polypropylene. Considerable elongations or deflections may occur over a period of time in the low modulus organic fibers, if they are used to support permanent high stresses in a cracked composite. Thus, where the matrix is expected to be uncracked, they are more likely to be used. Generally the low modulus fibers have large values of Poisson's ratio and this combined with their low modulus, this is another problem with the low modulus fibers, it means that they contract diametrically much more than other fibers, if stretched along their axis. High lateral tensile stress at the fiber-matrix interface will occur as a result of this contraction, which is likely to cause pull out of fibers and a short aligned fiber to debond. On the other hand, to avoid pull out of fibers mechanical bonding may require for high short fibers. Still the most commonly used fibers of all the fibers are steel fibers For nonstructural and structural purposes, because they are produced with multiple cross-section commonly, and may have bent ends to provide anchorage with the cementitious matrix (Mehta and Monteiro, 2005 and Bissonnette et al., 2007). Thus, the only fibers that are considered to be used in the proposed study is steel fibers, incorporating short steel fibers has effect on the tensile performance of concrete and it is discussed here. There is the test by Krenchel (1974) on both plain and steel fiber-reinforced mortars which determine that incorporation of 0.9 and 2% fiber by volume of concrete cause increase in flexural strength by approximately 15 and 30%, respectively. Additionally, elongation at rupture site was 9 to 10 times of that of the unreinforced mortar this is noted in both cases. Potrzebowski (1983), did a study in which 2%

volume fraction of steel fibers, 40 mm (1.57-in) in length and 0.4 mm (0.016-in) in diameter were used in concrete of 10 mm (0.40-in) maximum size of aggregate (MSA) to detect the effect of fiber reinforcement on the splitting tensile strength. As in study showed that the splitting tensile strength directly change with the amount of fibers passing the crack plane, increasing tensile strength cause increase the amount of fibers passing the crack plane. Another study showed that incorporating round 1% volume fraction volume fraction of 0.5x50 mm (0.020x2.0-in) steel fibers cause increase in the load capacity in comparison to non-reinforced concrete. How the mechanical properties of fiber-reinforced concrete in uniaxial tension is affected by the strain rate on mechanical properties was studied by Kormeling and Reinhardt (1987). In this study, straight steel fibers, 25 mm (1.0-in) in length and 0.4 mm (0.016-in) in diameter were used at 1.5 and 3% volume fractions, the MSA was 8 mm (0.31-in). As shown in this study in fiber-reinforced concrete fiber-reinforced concrete was up to hundred times more than non-reinforced concrete. Multiple cracking pattern at low and intermediate load levels is produced by using of 12-14% volume fraction of hooked or deformed steel fibers, 30 mm (1.18-in) in length and 0.5 mm (0.020-in) in diameter in UHPC this is studied by Naaman and Hormich (1989). However, through opening of a single large tensile crack failure still occur. The tensile modulus of concretes with hooked fibers was lower than concretes with deformed fibers. The surface of texture is strongly determine the behaviors of fibers, matrix-to-fiber bond is better than hooked fibers because the surface texture of deformed fibers created at smaller strains(Bissonnette et al., 2007). Krstulovic-Opara and Malak (1997) studied that how the tensile behavior of slurry infiltrated mat concrete (SIMCON) is affected by using high strength steel fibers. In this study stainless steel fibers with 241.3 mm (9.5-in) in length and 0.334 mm (0.013-in) in equivalent diameter were used at 2.16-5.39% volume fraction and then direct tension tests were performed. This study shows that monotonic increase in toughness and tensile strength depends on increasing the fiber content. The toughness values varied between 0.124 and 0.29 MPa (17.98 and 42.05 psi) for 2.16 and 5.39% fiber volume fractions, respectively. In addition, the maximum strength of tensile it will change between 7 and 17 MPa (1015 and 2030 psi) for fiber volume fractions varying between 2.16 and 5.39%, respectively. In this study the value of strength, strains at maximum stress, and energy absorption capacity were reported respectively about one order, two orders, and three orders of magnitude larger than standard

unreinforced concrete. Previously, similar observations were also reported by Hannant (1978). The total energy absorbed in fiber debonding before complete separation of a beam might be about 10 to 40 times higher for fiber-reinforced concrete than for plain concrete, according to the ACI Committee 544. The Portland Cement Association (PCA) investigated the changes in mix proportion upon incorporating 0.254 x 0.056 x 25.4 mm (0.01 x 0.022 x 1-in) steel fibers in fiber-reinforced concrete mixture designed for highways and airport pavements and overlays (Hanna, 1997).

Based on this study, a chart was also developed to determine the increase in the cement content and the decrease in aggregate proportions for the fiber additions in the range 0.5 to 2% by volume. Using this chart, the mix proportions at a given water-cement ratio, the cement paste content had to be increased with a corresponding decrease in the proportion of aggregates to maintain adequate workability when 2% steel fibers were added to the plain concrete mixture. In result of this study, a chart was also developed to determine the decrease in aggregate proportions for the fiber additions in the range 0.5 to 2% by volume and increase in the cement content. There is a chart that shows how the cement paste content had to be increased with a corresponding decrease in the proportion of aggregates to maintain adequate workability when 2% steel fibers were added to the plain concrete mixture, at a given water-cement ratio. In addition, the maximum particle size of the matrix is important because it affect the distribution of fibers and the quantity which could be included in the composite of concrete. The size of particles should not greater than 20 mm (0.787-in), not greater than 10 mm (0.394-in) is preferable otherwise uniform fiber distribution becomes difficult to achieve (Hannant, 1978). There are various improvements in concrete performance associated with incorporating steel fibers, but also recent studies have shown that utilizing short steel fibers may have a negative effect on long-term tensile creep (tensile performance). Later, this effect is discussed in detail, but generally the effect was attributed to either the hypothesis that fibers are likely to act like course aggregate in a concrete mix, having a surrounding porous zone similar to the ITZ in the case of aggregates (Bissonnette et al., 2007), or increase in the void ratio fraction upon incorporating fibers (Bissonnette and Pigeon, 1995).

2.8 Mechanical Properties

2.8.1 Compressive Strength

Prabhat Ranjan Prem et al. (2013), investigated compressive strength of UHPC according to ASTM C109, Compression test on UHPC was carried out on cubic specimens of size (100x100x100) mm. The strength was recorded at 7, 14, 21 and 28 day. The average reading of tested four cubes was recorded as the strength at respective age. The compression test is carried out in compression testing machine of 3000 KN capacity. The load is applied at the rate 0.2 kN/sec. The ultimate strength is recorded after the specimens fail to resist any more loads. The compressive strength evaluated at 7, 14, 21 and 28 days. It is observed that the specimens attain 90% of the compressive strength around the age of 14 days. The mixes having same fibre volume irrespective of aspect ratio produced 25% increment in compressive strength, to that of the control mix. The results of compressive strength didn't depend too much on the reinforcement index of fibre. The specimens attain 90% of the compressive strength at the age of 14 days.

2.8.2 Modulus of Elasticity

In their study Gesoglu et al. (2016), they presented the effect of using binary and ternary blends of nanosilica (NS) and microsilica on the mechanical properties of low binder ultra-high performance cementitious composites (UHPCs). For this, two concrete groups were designed with and without silica fume by weight of cement with a constant water/binder ratio and total binder content. Commercially available NS was used in partial substitution of cement at 0%, 0.5%, 1%, 2% and 3% by weight. The results showed that UHPC exhibited a maximum modulus of elasticity equals to 44 GPa at 90 days.

2.8.3 Splitting Tensile Strength

According to BS 1881: (1983) splitting tensile test was carried on cylindrical specimen of 100 mm diameter and 200 mm height at the age of 28 days. Tensile strength is one of the basic and important properties of concrete. The results are required for the design of concrete structural elements subject to transverse shear, torsion, shrinkage and temperature effects. Its value is also used in the design of prestressed concrete structures, liquid retaining structures, roadways and runway

slabs. Diametric lines are drawn on each end of the specimen so that they are in the same axial plane. The specimen was placed on the plywood strip and aligned so that the lines marked on the ends are vertical and centered over the plywood strip. The second plywood strip and the bearing bar were placed longitudinally. The specimens were tested using a universal testing machine (UTM) of 1000kN capacity. The loading rate was kept constant until the splitting tensile stress failure occurs. For each mix, six cylinders were tested at the age of 28 days. It can be seen from the results that there is a good amount of enhancement in the tensile strength of the concrete upon addition of steel fibers. The value increased about 200% at the fiber volume of 2.5% when compared with control mix. Small fibres showed a lesser tensile strength than long fibres. One of the major objectives of adding the steel fibers in concrete is to enhance its tensile strength. The fibers used in this study have achieved the objective, according to Prabhat Ranjan Prem et al (2013).

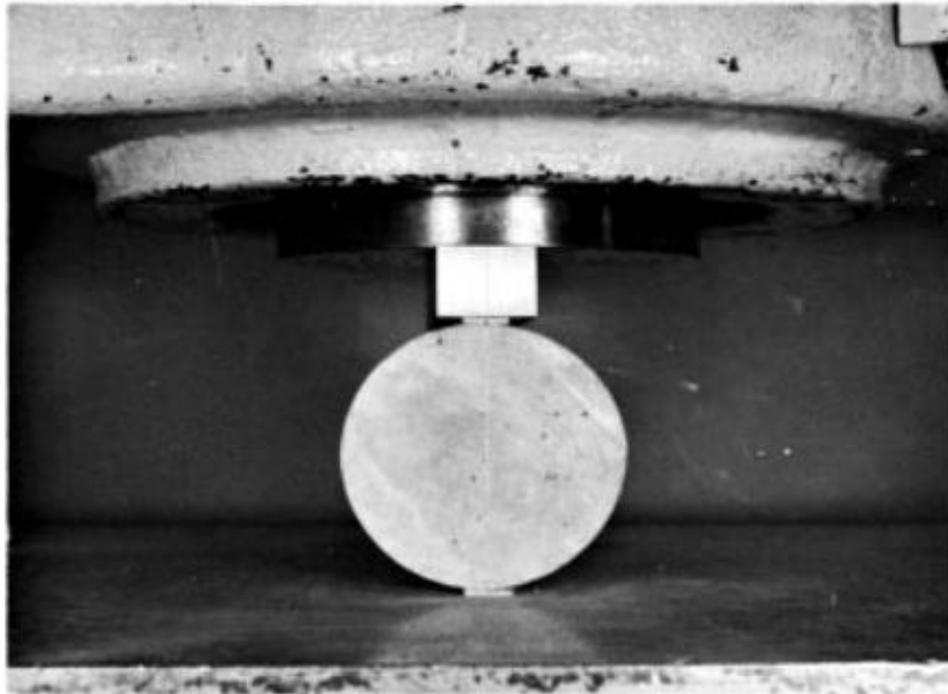


Figure 2.7 Splitting tensile strength test procedure, (Prabhat Ranjan Prem et al 2013).

2.8.4 Flexural Strength and Toughness

Some of researchers have attempted to characterize the UHPC flexural strength with single or two-point bending tests on small prisms. UHPC North America claims that

the flexural strength of UHPC after heat treatment ranges from 27 - 50 MPa. Ductal is capable of reaching a toughness of 250 times that of normal strength concrete and a flexural strength up to 48 MPa, as studied in research by Cheyrezy et al. (1995). UHPC exhibited flexural strengths ranging from 34 - 48 MPa this noted by Perry and Zakariassen (2004) and confirmed by Cheyrezy's findings. Also, an ultimate flexural strength of 32 MPa was reported by Dugat et al. (1996). Increase in the UHPC flexural behavior attributed to the addition of fibers and the particle packing which hold the cement matrix together after cracking has occurred. UHPC with steel fibers has present ductility because after the formation of microcrack the small scale fibers reinforce the matrix causing less damaging, smaller cracks to form (Graybeal and Hartmann, 2003). Figure 2.8 show the typical flexural strength test curves for UHPC and another three types of concrete, and indicates that the equivalent stress of UHPC is more than 47 MPa, compared to about 13 Mpa for FRC 80.

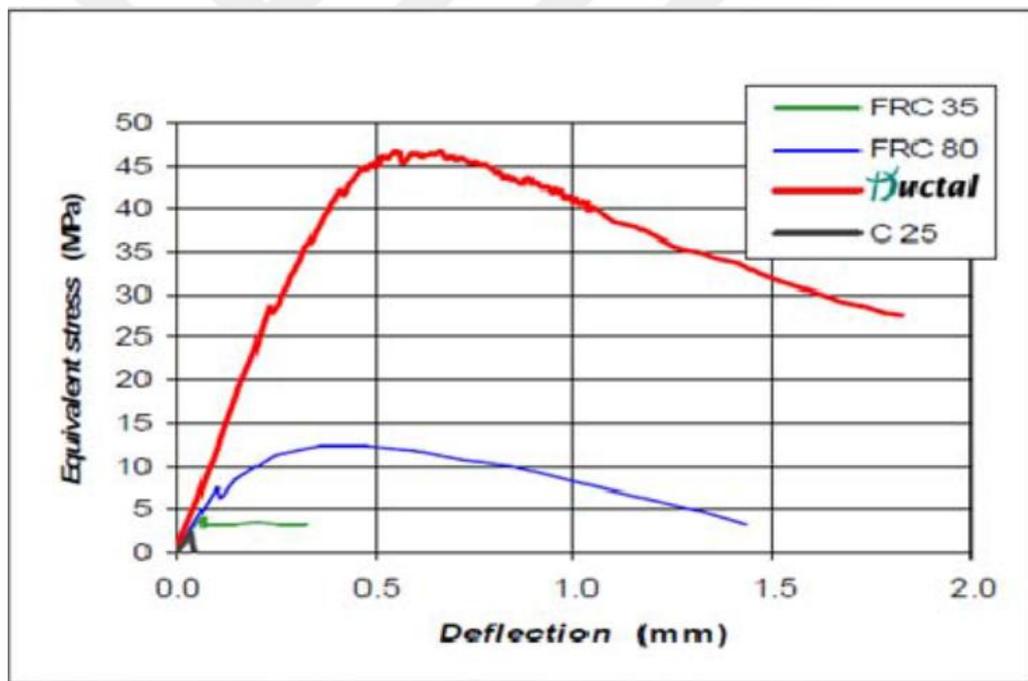


Figure 2.8 Typical flexural strength test curves of four types of concrete (Lukasik, 2005).

Graybeal (2005) conducted flexural testing of 71 specimens by using the procedure that outlined in ASTM C 1018, which controls the rate of deflection of the prism. Span lengths of Specimens were 6 in., 9 in., 12 in., and 15 in. with a cross section of 2 x 2 in. and a 12 in. span with a 3 x 4 in. cross section. Toughness values and ultimate load based on the procedure outlined in ASTM C 1018 were reported. The

result of flexural testing shows that the UHPC flexural tensile strength depends strongly on the size of the prisms used in the test. The results of flexural strength of untreated specimens were 29.9 MPa, and that of steam curing specimens of the same size was 35.4 MPa. The average values of flexural strength for a wider range of prism sizes was studied by Reineck and Greiner (2004) which showing the size effect. The smaller beams have higher strengths due to local alignment of fibers in small prisms as recorded. 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).

2.9 Durability Performance

Durability of concrete is defined as the resistance of concrete to the attack of physical or chemical aggressive agents. Concrete can experience deterioration from either physical attack (abrasion, freezing and thawing, fire, or salt crystallization) or chemical agents (alkali-silica reaction, chloride ingress causing corrosion of embedded steel and sulfate attack, etc.) (Theresa et al, 2008).

2.9.1 Porosity

The improved microstructure of UHPC not only results in higher compressive strength but also leads to superior durability properties. This makes UHPC both a high strength and a high performance material. The low porosity of UHPC, particularly capillary porosity, leads to great improvements in the durability properties of UHPC. The superior durability characteristics of UHPC are due to the low and disconnected pore structure, which is generated 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 UHPC appears to depend on the curing process applied to the material. Measurements of the total porosity range from 4.0 percent to 11.1 percent for UHPC without heat treatment. Cwirzen (2007) and Herold and Müller (2004) reported that when the standard heat treatment is used, UHPC 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 UHPC in their study is approximately 8.4 percent, but heat treatment reduces the total porosity of the UHPC sample 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.

2.9.2 Chloride Ion Penetration

The chloride ion penetration through concrete by means of capillary absorption, hydrostatic pressure, or diffusion is one of the most problematic durability issues associated with high permeability concretes (Stanish et al., 2000). The presence of chloride ions near metallic reinforcement is a major cause of corrosion. Roux et al. (1996) and Australian publications also reported chloride diffusion coefficient of UHPC to be around $2.0 \times 10^{-10} \text{ cm}^2/\text{sec}$ compared to $1.1 \times 10^{-8} \text{ cm}^2/\text{sec}$ for normal concrete.

Rapid chloride permeability test (RCPT) is another method to evaluate chloride ion permeability is by measuring the total electric charge passed through a test sample.

Additional research by Graybeal (2006a, b) demonstrated that measured 18 Coulombs as the total charge passed through a 51-mm thick UHPC sample subjected to the standard heat treatment and 360 Coulombs for an untreated UHPC sample (over a six-hour period). Bonneau et al. (1997) reported that the total charge passed through a 51-mm thick when thermally treated UHPC sample was 10 Coulombs. These amounts which are relatively small indicated relatively high chloride impermeability of UHPC.

2.10 Effect of Curing Method

Graybeal (2005) implemented four curing regimes on UHPCC samples, namely air treatment, steam curing at 90 °C for 48 h, delayed steam curing at 90 °C for 48 h which was not initiated until the 15th day after casting and tempered curing at 60 °C for 48 h. The corresponding 28-day compressive strength under above curing methods was 126, 193, 171, and 171 MPa, respectively. After steam curing the average tensile cracking strength was almost 9 MPa and about 6 MPa without any treatment. When using the elevated curing at 65 °C for 7 days instead of the moist curing at 23 °C, increase in the 28-day compressive strength of about 13 % and this was reported by Lee and Chisholm (2005). When high pressure steam curing at 160 °C and 0.7 MPa was applied, Further improvement in strength was observed. However, the results of both steam curing at 90 °C for 48 h and at 65 °C for 7 days

were comparable. The compressive strength of RPC significantly influenced by the curing temperature and this indicated by Work by Shaheen and Shrive (2006) . As seen in Figure 2.9, the strength increased quickly for temperatures between 23 and 150 °C due to acceleration of the hydration reactions. Because of acceleration of the hydration reactions, the strength increased quickly for temperatures between 23 and 150 °C, as seen in Figure 2.9.

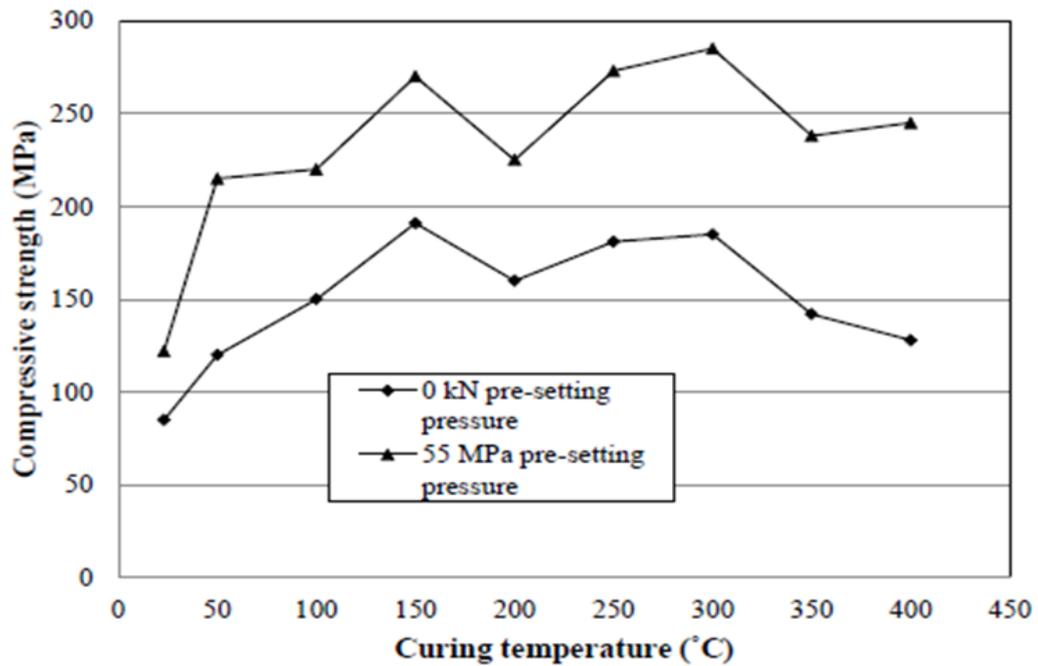


Figure 2.9 Effect of curing temperature on the compressive strength of RPC (Shaheen and Shrive, 2006).

However, the strength dropped between 150 and 200 °C due to rapid evaporation of internal water, causing incomplete hydration and increased porosity. Compressive strength raised again for the curing temperature ranging from 200 to 300 °C due to the accelerated pozzolanic reaction and subsequent formation of very dense C-S-H phases such as Xonotlite. At curing temperatures above 300 °C, the compressive strength started to go down due to the decomposition and evaporation of superplasticizer and its compounds which increased the micro-porosity. Figure 2.1 Effect of curing temperature on the compressive strength of RPC (Shaheen and Shrive, 2006) Contrary to the statements in the literature, the long-term study by Schachinger et al. (2008) showed that the compressive strength development after heat treatment didnot stop such that the strength gain at 8 years was as much as 30% in comparison with the strength at early ages of 1 to 5 days. This behavior was

contributed to the slow, but the continuous pozzolanic reaction of silica fume and the increase in the chain length of C-S-H phase. Their results also indicated that the samples subjected to delayed steam curing which started after the age of 3 days exhibited better longterm strength as compared to delayed steam curing which initiated after 1 day or 5 days or those subjected to water curing. The long-term study by Schachinger et al.(2008) noted that development of compressive strength after heat treatment did not stop so that the strength gain at 8 years was as much as 30% in comparison with the strength at early ages of 1 to 5 days, contrary to the statements in the literature. This behavior was contributed to the slow, but the continuous pozzolanic reaction of silica fume and the increase in the chain length of C-S-H phase. Their results also indicated that the samples subjected to delayed steam curing which started after the age of 3 days presented better long term strength in comparison with water curing, or delayed steam curing which initiated after 1 day or 5 days. Yazıcı et al. (2010) and Aydın et al. (2010) investigated the effects of curing conditions on the flexural behavior of RPC. They found that the compressive behavior was quite different from the flexural behavior of RPC. While the compressive strength under steam curing was higher than that under standard curing, the flexural behavior (flexural strength and fracture energy) showed a reverse trend. . The authors attributed this behavior to the weaker bond between the fibers and matrix after these curing regimes. In contrast, Yang et al. (2009) found that RPC cured at 20 °C was approximately 10% lower in flexural strength and 15% lower in fracture energy than that cured at 90 °C. Yazıcı et al. (2013) studied the compressive and flexural strengths of RPC under autoclaving in comparison with those under standard water curing. . Their results showed that the compressive strength enhanced appreciably under high-pressure steam curing in comparison with standard curing. Duration, autoclave temperature and pressure are factors of marked importance, such that for each temperature and pressure conditions there was a critical duration time beyond which the mechanical properties could be influenced negatively.

CHAPTER 3

MATERIALS AND MIXTURE PROPORTIONS

This chapter describes the materials and the mixture proportions those were used to develop HPFRC. Mixing procedures, casting procedures, and different curing conditions for HPFRC are also described in this chapter.

3.1 Materials

3.1.1 Cement

The cement used in the present work was ordinary Portland cement (CEM I 42.5 R). The chemical, physical and mechanical properties are presented in Tale 3.1.

Table 3.1 Chemical composition and physical properties of Portland cement and silica fume.

Item	Cement	Silica fume
Fe ₂ O ₃	2.88	1.31
SO ₃	2.63	0.41
K ₂ O	0.88	1.52
CaO	62.12	0.45
MgO	1.17	-
SiO ₂	19.69	90.36
Na ₂ O	0.17	0.45
Cl	0.0093	-
Al ₂ O ₃	5.16	0.71
Free CaO	1.91	-
Specific surface (m ² /kg)	394 ^a	21,080 ^b
Insoluble residue	0.16	-
Loss on ignition	2.99	3.11
Specific gravity	3.15	2.2

^a Blaine specific surface area.

^b BET specific surface area.

3.1.2 Type of 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 ² /kg)	394 ^a	21080 ^b
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	-

^a Blaine specific surface area.

^b BET specific surface area

3.1.3 Superplasticizer

A type F polycarboxylate-based superplasticizer (SP) in accordance with ASTM C494 (2013) was used to provide the desired workability. Table 3.3 provides the properties of the superplasticizer.

Table 3.3 Properties of superplasticizer

Properties	Results
Appearance	Light brown to yellow liquid
Specific gravity at 20 ⁰ C	1.08 ± 0.02 gm/cm ²
PH- value	7 ± 1
Alkali content (%)	≤ 1
Chloride content (%)	≤0.1

3.1.4 Micro Steel Fibers

Copper coated steel fibers used in 6 mm long, 0.16 mm diameter to provide steel fibres (Figure 3.1). Aspect ratio, specific gravity and tensile strength of fiber 37.5, 7.17 and 2250 MPa, respectively, as reported by the manufacturer.



Figure 3.1 Micro steel fibers.

3.1.5 Quartz Powder

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 3.2, 3.3 and 3.4 shows the three sizes of the aggregate used in Table 3.4 and 3.5 respectively.

Table 3.4 Physical properties of ultrafine quartz powder used for UHPFRC

Properties	Values
Specific gravity	2.65
Hardness (Moh's scale)	7

Table 3.5 Compound compositions of ultrafine quartz powder used for UHPFRC

Compounds	% by mass
SiO ₂	99.7
Al ₂ O ₃	0.12
Fe ₂ O ₃	0.021
TiO ₂	0.009
CaO	0.009
MgO , Na ₂ O , K ₂ O	<0.01 (each)
Loss on Ignition	0.1



Figure 3.2 Type of Quartz (Large 1.2 -2.5)



Figure 3.3 Type of Quartz (medium 0.6 – 1.2)



Figure 3.4 Type of Quartz (small 0-0.4)

3.2 Concrete mixture proportioning, casting and sample preparation

The compositions of UHPFRC used in the present study were recognized by high volume of binder and micro steel fibers, non-existence of coarser aggregate, and extremely very low w/b ratio like other studies (Corinaldesi and Moriconi 2012, Yazıcı et al. 2010). Two groups with a different w/b of 0.12 and 0.14 each of 7 mixes was produced as shown in Table 3.6 . In both groups, the amount of silica fumes was kept constant to be 15% by weight of total cementitious materials. Micro steel fibers at volume ratios of 1%, 1.5%, 2%, 2.5%, 3%, 3.5, and 4% for each group were added. The mixtures were designated on two parameters, which depended on different volume of micro steel fiber and w/b ratios. For example, 0.12MSF0.5 indicates the mixture of 0.12 w/b and 0.5% volume of micro steel fiber.

For producing UHPC, a high speed, vertical axis mixing machine having a maximum speed of 470 rpm was used. 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 steel 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 of varies sizes; three 50 mm cubes, six 70 mm cubes, three 150mm cubes, and three prisms of dimension's 70x70x280 mm to determine compressive strength, splitting tensile strength, modulus of elasticity, and flexural strength with fracture energy, respectively. Thereafter, the molds well compacted by using a vibrator machine then covered with polyethylene sheets and left to cure under room temperature. the molds of the specimens were removed one day after casting and cured by standard water curing until the test date.

Table 3.6 Mix proportions (kg/m³).

Concrete mixture	w/b	Cement (kg/m ³)	Silica fume (kg/m ³)	Water (kg/m ³)	SP (kg/m ³)	Steel fiber (%)	Quartz aggregate (kg/m ³)
0.12MSF1	0.12	998.8	176.25	141	64.6	1	1009.6
0.12MSF1.5	0.12	998.8	176.25	141	67.6	1.5	989.1
0.12MSF2	0.12	998.8	176.25	141	68.2	2	974.4
0.12MSF2.5	0.12	998.8	176.25	141	71.1	2.5	954
0.12MSF3	0.12	998.8	176.25	141	71.7	3	939.3
0.12MSF3.5	0.12	998.8	176.25	141	72.9	3.5	923.2
0.12MSF4	0.12	998.8	176.25	141	74	4	907
0.14MSF1	0.14	998.8	176.25	164.5	49.4	1	984.7
0.14MSF1.5	0.14	998.8	176.25	164.5	50.2	1.5	969.6
0.14MSF2	0.14	998.8	176.25	164.5	51.9	2	952.2
0.14MSF2.5	0.14	998.8	176.25	164.5	53.5	2.5	934.9
0.14MSF3	0.14	998.8	176.25	164.5	55.8	3	916.1
0.14MSF3.5	0.14	998.8	176.25	164.5	57.2	3.5	899.2
0.14MSF4	0.14	998.8	176.25	164.5	60.1	4	879

3.3 Slump Flow Test

Measurement for the UHPC flow was done using the mini slump flow test suggested by EFNARC (2002) as illustrated in Figure 3.5. 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.



Figure 3.5 Slump test

2.4. Testing methods

Compression test was performed on 50 mm cubes at 7, 14, and 28 days according to BS 1881-116 (1983). For this, three specimens were tested for each mixture, and average of them was reported. Splitting test was conducted with respect to BS 1881-117 (1983) on six 70 mm cubes at 28 days, and the average value was reported in this paper. 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.

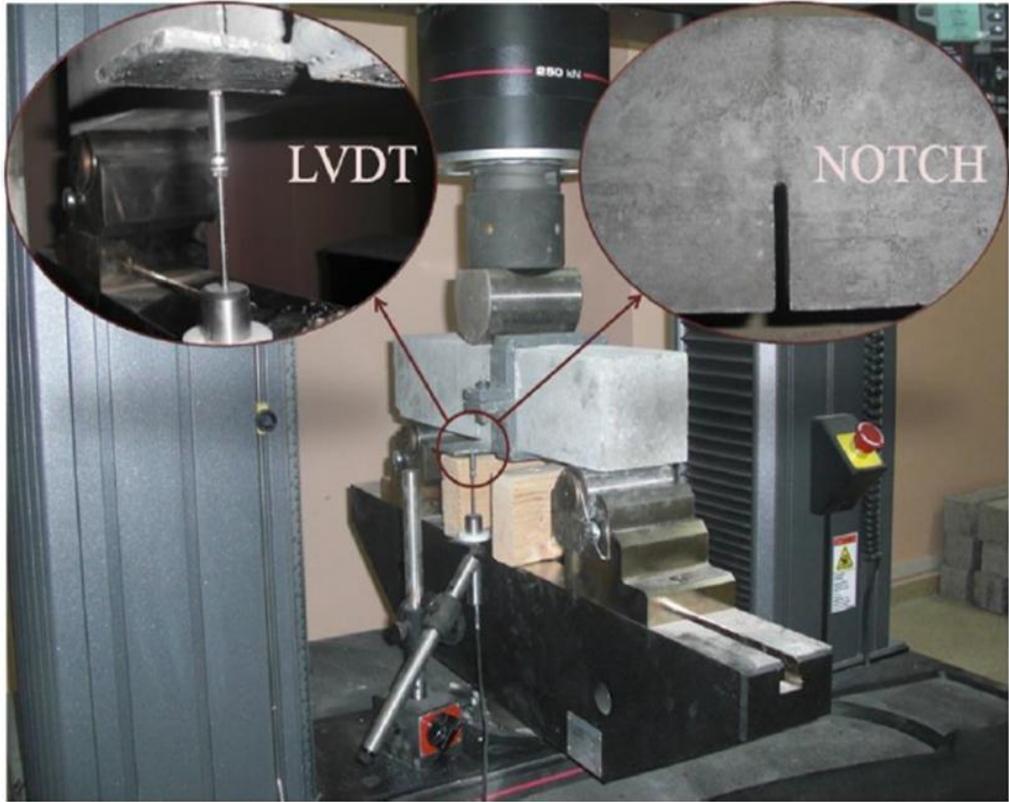
Fracture energy behavior of UHPFRC was investigated according to specifications and recommendations of RILEM 50-FMC/198 Technical Committee (1985). The displacement was measured by a linear variable displacement transducer (LVDT) at mid-span as shown in fig 3.6. Instron 5500R closed-loop testing machine 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:

$$G_f = \frac{W_0 + mg\delta_s \frac{S}{u}}{B(W-a)} \quad (1)$$

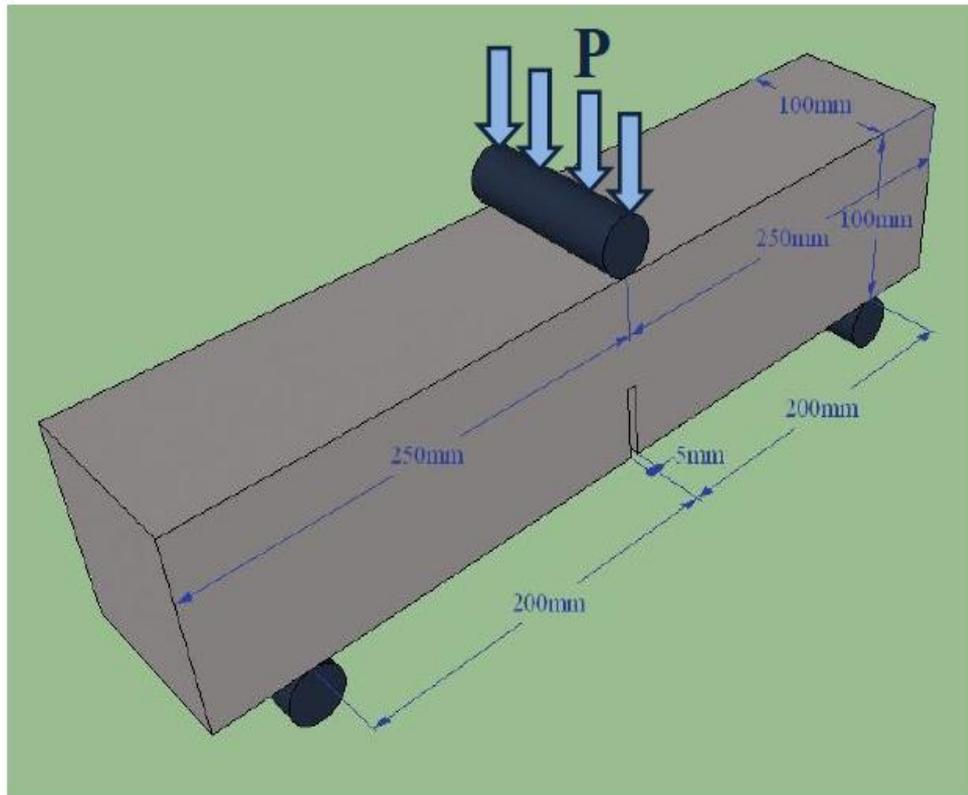
Where W_0 is the area under the load–deflection curve; m is the mass of the beam; g is the acceleration due to gravity; δ_s is the specified deflection of the beam, while S , U , B , W , and a are span, length, width, depth, and notch depth of the beam, respectively. For each mixture, at least three specimens were tested at the age of 28 days. All the beams were loaded started at a constant rate of 0.02 mm/min. In accordance with literature, the net flexural strength, f_{flex} , was calculated via Eq. (2) (P_{max} is the ultimate load) by assuming no notch sensitivity (Ravindra and Henderson 1999, and Akcay et al. 201). Moreover, 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).

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

$$l_{ch} = \frac{EG_f}{f_{st}^2} \quad (3)$$



(a)



(b)



(c)

Figure 3.6 Views of a) experimental setup for three point bending test and b) dimensions of the notched beam specimen c) fracture test device

CHAPTER 4

DISCUSSION AND RESULTS

4.1. Fresh Properties of UHPFRC

Assortment and use of superplasticizer (SP) are a critical for compensation of lack of flowability due to the condition of very low w/b for producing of high-quality UHPFRCs. In this study, the desired flowability for both groups of 0.12 and 0.14 w/b was attained as fixed as $12\pm 1\text{cm}$ by playing with the different amount of superplasticizer. Irrespective to water contents, it can be noticed from Fig.4.1 that any increase with the volume of fibers responded to the rise of the amount of super plasticizers. On the other hand, decreasing w/b from 0.14 to 0.12 needed an average of 15 kg/m^3 super plasticizer but when the fiber content increased from 1% to 4%, the demand of SP was increased to 9.4 and 10.7 kg/m^3 for the first and second groups, respectively, as compensation for the sake of keeping flow constant (see Fig 4.1).

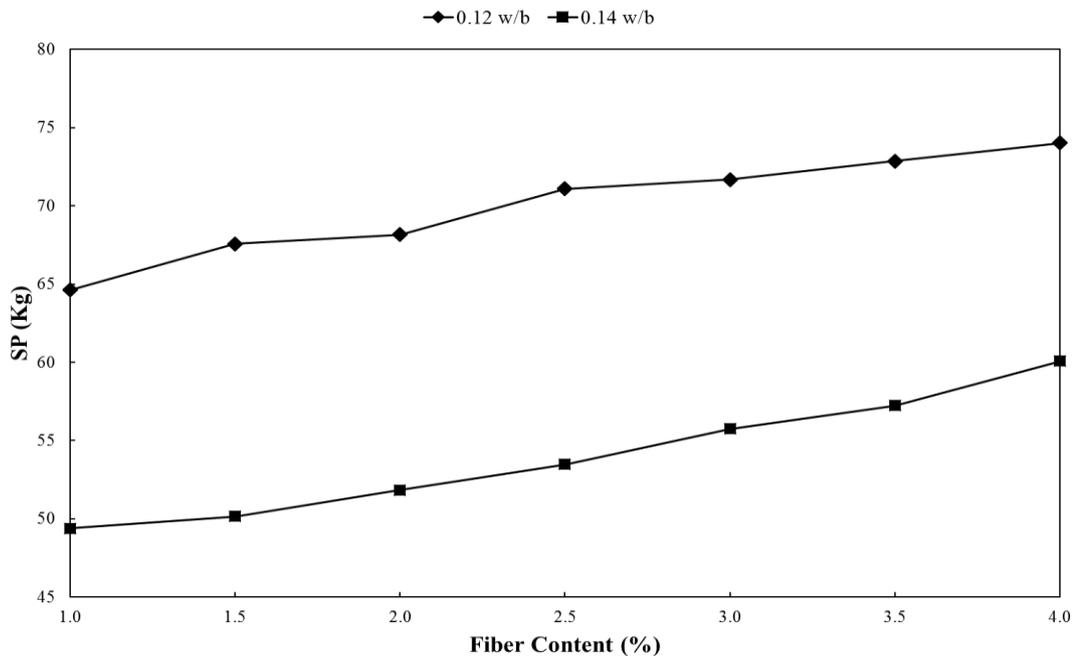
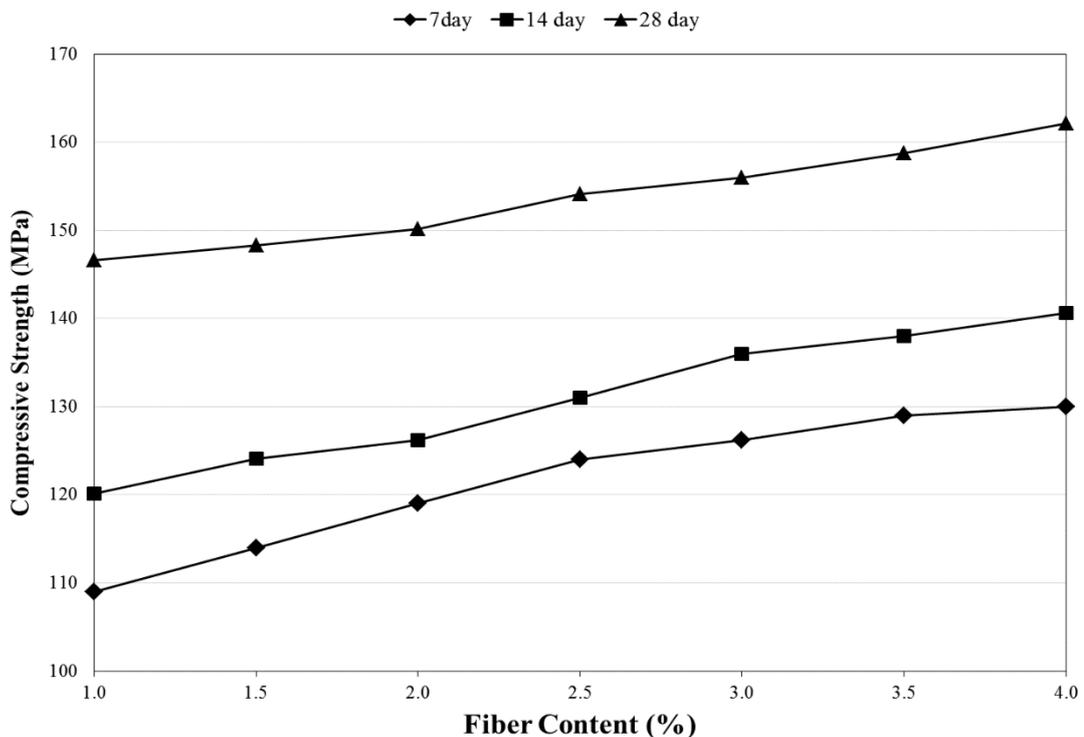


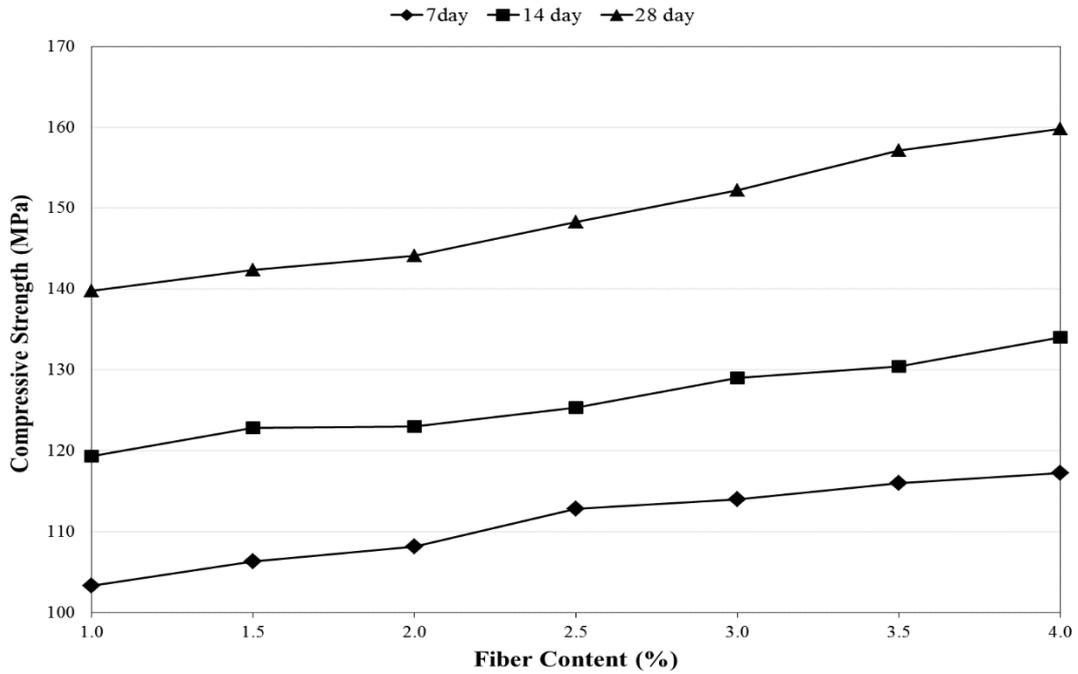
Figure.4.1 Super plasticizer amount versus different MSF content of UHPFRC with 0.12 w/b, and (b) 0.14 w/b

4.2. Compressive Strength

Variations in the compressive strength of UHPC reinforced with different volume of micro steel fibers, and ages are shown in Figs 4.2a and 4.2b. Very low water per binder ratios of 0.12 and 0.14 were preferred, which were smaller than chosen by the most other researchers. The highest compressive strengths were obtained from the mixtures of 0.12 w/b group with a small difference comparing to the group of 0.14 w/b; this may be due to both w/b ratios will give water to the system that near to the critical point for giving best results, irrespective to fiber contents. In contrast, the results indicated a meaningful effect of gradually increasing micro steel fibers on the growth of compressive strength regulatory. Precisely, when the fiber content was increased from 1% to 4%, the improvement in compressive strength was as high as 10.6%, and 14.3% for the groups of 0.12, and 0.14w/b, correspondingly. Furthermore, with any 0.5% addition of fibers at 28 days, the average increments of compressive strength were 2.6 for the first and 3.3 MPa for the second groups. The behavior of improving UHPFRC strengths is possibly due to affect that the micro steel fibers are much stricter than all surrounding cementitious cement paste, thus; on loading, the crack is not initiated quickly around the fiber particles in the mixture, which decelerates the failure of the steel fiber–UHPC matrixes.



(a)



(b)

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

4.3. Splitting Tensile Strength

The tensile performance of fiber-concrete is expressed into two classifications. First; pre-cracking, which is usually affected by the elastic shear transfer mechanism between matrix and fiber, can be assessed by the rule of the mix. Second; post-cracking is expressed by the combined effect of matrix tension softening behaviors and fiber bridging (Kang and Kim 2012).

The results of splitting tensile strength for the groups of 0.12 and 0.14 w/b of UHPC containing various dosages of MSF are given in Fig.4.3. The tensile strengths were obtained for the concretes contained 1% MSF were 10.8 MPa and 9.7 MPa, while adding 1.5%, 2%, 2.5%, 3%, 3.5, and 4% volume of fibers prompted an increase in the strength values by; 11 MPa, 11.2 MPa, 11.5 MPa, 11.7 MPa, 11.9 MPa, and 12.1 MPa also 9.7 MPa, 9.9 MPa, 10.7 MPa, 10.9 MPa, 11.0 MPa, and 11.4 MPa for the first and second groups, respectively. It can be noticed that there was faintly enhancement of the results due to adding micro steel fibers, this may be because of the failure in tensile strength is different than with compressive strength since the failure occurs along the paste and over the aggregates rather than interfacial

transition zone (ITZ), which improved via adding discrete fibers (Wang et al. 2006, Shehata 2010). Moreover, the reason for the increased splitting tensile strength may be due to some of the small particles of fiber played an important role to create good bonds between the aggregate particles between and the cement paste. On the other hand, in tensile strength of the concretes contains fibers the mechanism of failure is unlike plain concrete (Gesoglu 2015), since a uniform failure state occurs in fiber reinforced concrete, and the specimens did not separate after failing (see Fig. 4.3).

The strength detraction observed in the UHPFRCs with increasing w/b may be attributed to form further unwanted calcium hydroxide (CH) particles during the hydration process (Eq. 4). Furthermore, the inverse relation between w/b and tensile strength is decided also by many researchers (Sekhar and Raghunath 2014, Šerelis et al. 2015)

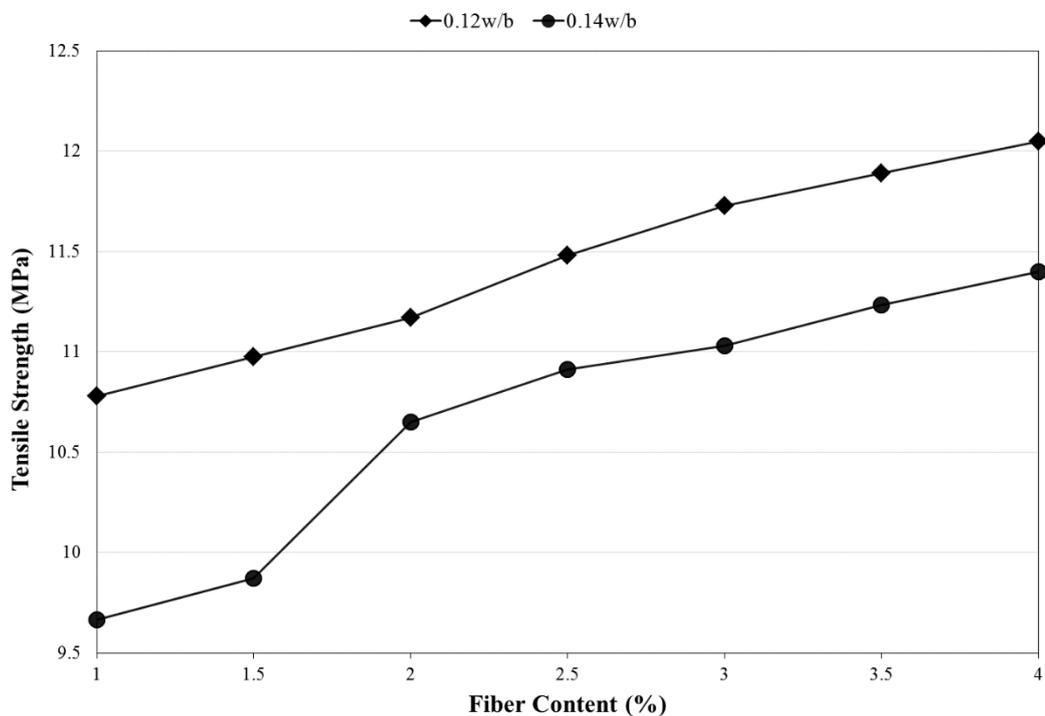


Figure 4.3 Splitting tensile strength of UHPC versus different volume of MSF fiber at 28 days

4.4. Modulus of Elasticity

The modulus of elasticity of concrete is important because of forecasting the deformability of structures. It can be determined using the secant line in a stated point on this curve and or using the tangent at the origin of the stress-strain curve. According to ASTM C469, cautions that the modulus of elasticity values will usually be less than the modulus derived under rapid load application and generally greater than values obtained under slow load application, when all other test conditions remain the same.

The moduli of elasticity of UHPC reinforced with different volumes of micro steel fibers and two groups of w/b at 28-day were shown in Fig.4.4. Irrespective to water content, it was observed that adding micro steel fibers responded to the increase of modulus of elasticity. Precisely, the UHPFRC had an enhancement by 22.7 % and 34.9 % at 4%, comparing to their control mixtures, which contains 1% of MSF for the first and second groups, respectively. These results approved that UHPFRCs with adding any dosage of MSF resulting of improvement stiffness due to compactness of the aggregates with paste bond and ITZ being enhanced. Irrespective to concrete types, increasing the modulus of elasticity using steel fibers was approved by many researchers (Kayali et al. 2003, Bilodeau et al. 2004).

Moreover, the reason of so close results to each other between the two groups, may interpret to extremely small water/binder ratios chosen that compensated by a new generation of superplasticizer and ultra-fineness of silica fume particles, which they together supported workability and flowability.

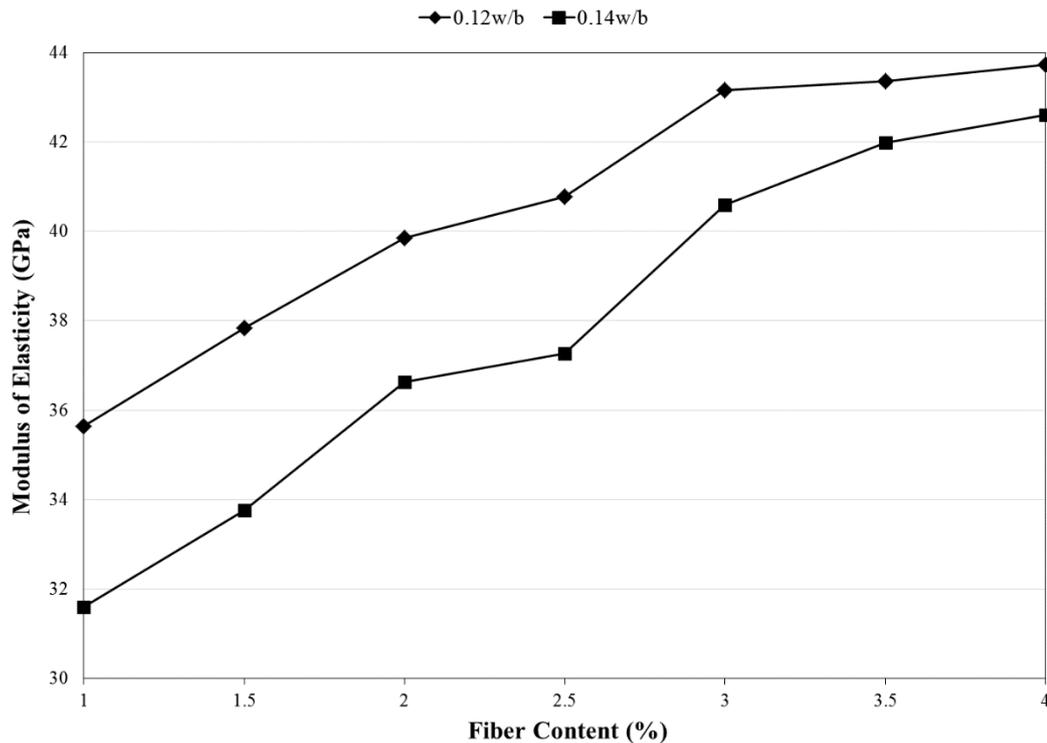


Figure 4.4 Modulus of Elasticity of UHPC versus different volume of MSF at 28 days

4.5 Modulus of Rupture

The moduli of rupture of UHPCs strengthened with different volume of micro steel fibers are presented in Fig 4.5. Actually, there was moderately an improvement in the net flexural strength with increasing fibers by 17.6 %, and 15.4 % at 28-day for w/b of 0.12 and 0.14, correspondingly for UHPFRCs having 4% of MSF. Improving in the modulus of rupture may be due to that; before cracking the matrix, the micro steel fibers will cover all the load until the loss of the bond between the matrix and fibers (Gao et al. 1997). Consequently, because of the efficient crack seizure by the discrete fibers, sudden failure is prevented resulted in growing the load carrying capability (Hassanpour et al. 2012). The capacity of reinforced UHPC with micro steel fibers to absorb the energy that tried to make a crack in concrete under bending detected and illustrated in Fig 4.5.

In contrast, the influence of adding fibers much more than the influence of decreasing water content of the results. For example, the average improvement in the modulus of rupture with adding 4% of steel fibers to UHPC was 36.8% for 0.12 w/b

group, but reducing w/b from 0.14 to 0.12 cause a development by 10.6% for the same mixture containing that 4% of MSF.

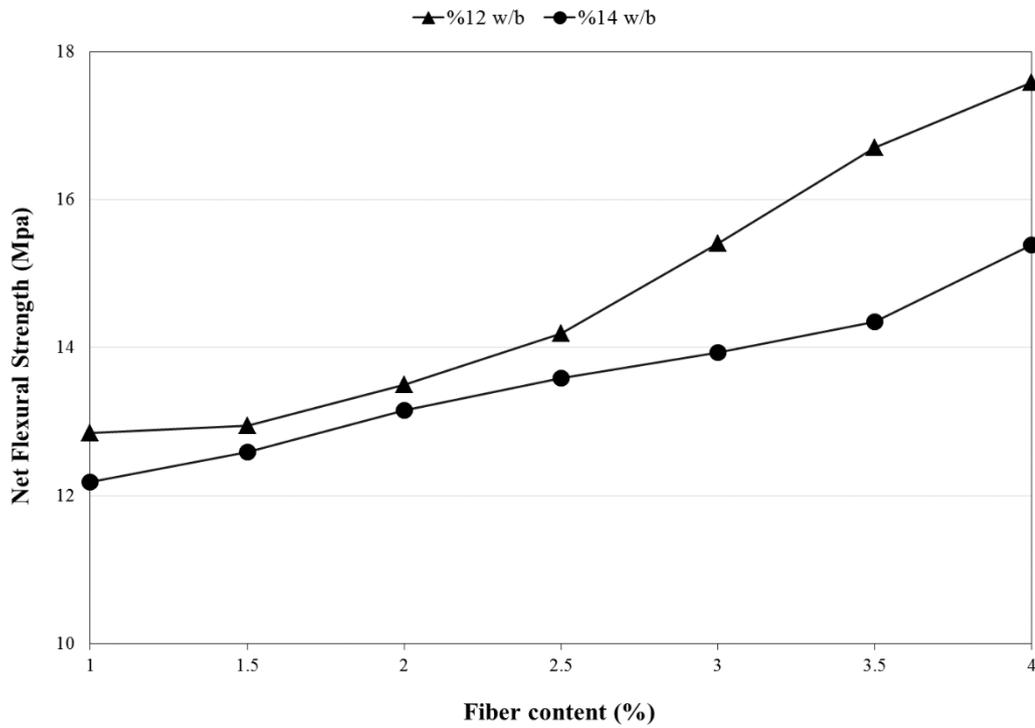


Figure 4.5 Net flexural strength of UHPC versus different volume of micro steel fiber at 28 days

4.6 Load-Displacement Curves

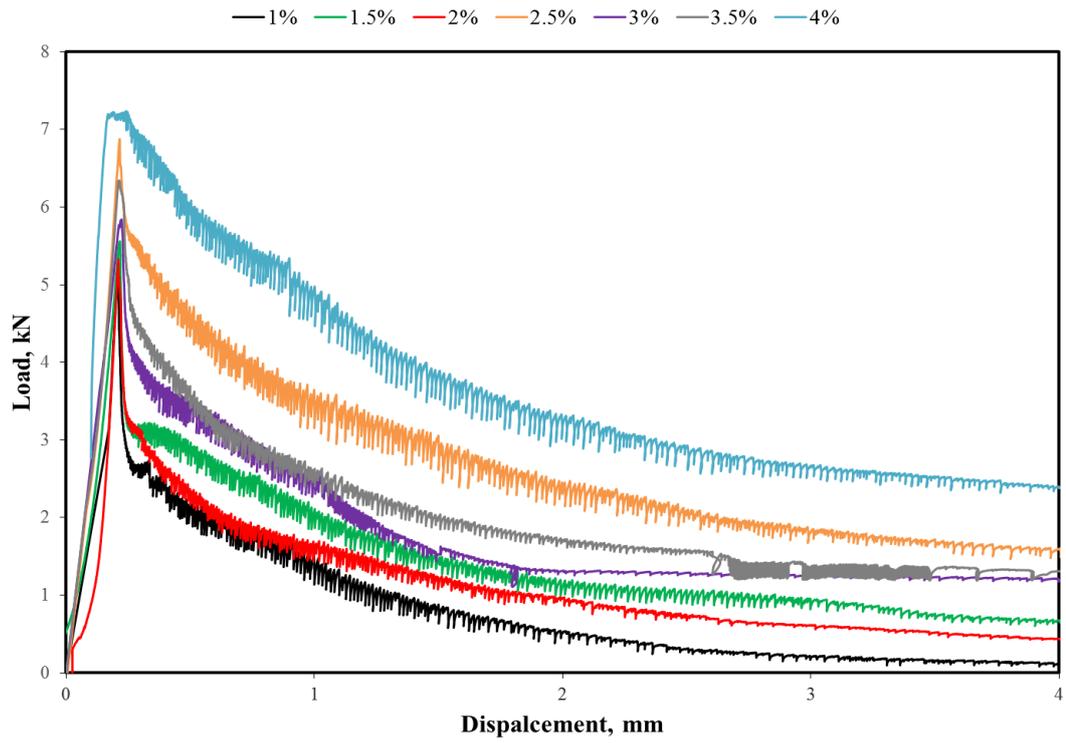
The load-displacement curves obtained from notched prismatic UHPC specimens subjected to three-point bending test with 1%, 1.5%, 2%, 2.5%, 3%, 3.5% and 4% of micro steel fibers, are presented in Figs.7&8 for the groups of 0.12 and 0.14 w/b, respectively. Also, Table 4.1 showed the effects of different volume of fibers and water contents on some properties of UHPFRC like; area under load-displacement curve, maximum displacement, and peak load. The UHPC containing 4% MSF with 0.12 w/b had an area under the curve, a maximum deflection, and a peak load of 8424.8 kN.mm, 5.4mm, and 7.2 kN, respectively, while these values reduced to 7253.7 kN.mm, 5.2mm, and 6.3 kN for additional 0.02 w/b (0.14 w/b) added to the mixes with the same fiber amount. The adverse effect of high w/b and its disturbing microstructure of concrete generally were also discussed by the others (Wang et al. 2015, Rong et al. 2014). These declined in the fracture parameters is due to that any extra water than the demand may play a passive role to restrict improving ITZ, de-

boning between aggregate and binder, and obstructing fibers to bridge the micro cracks.

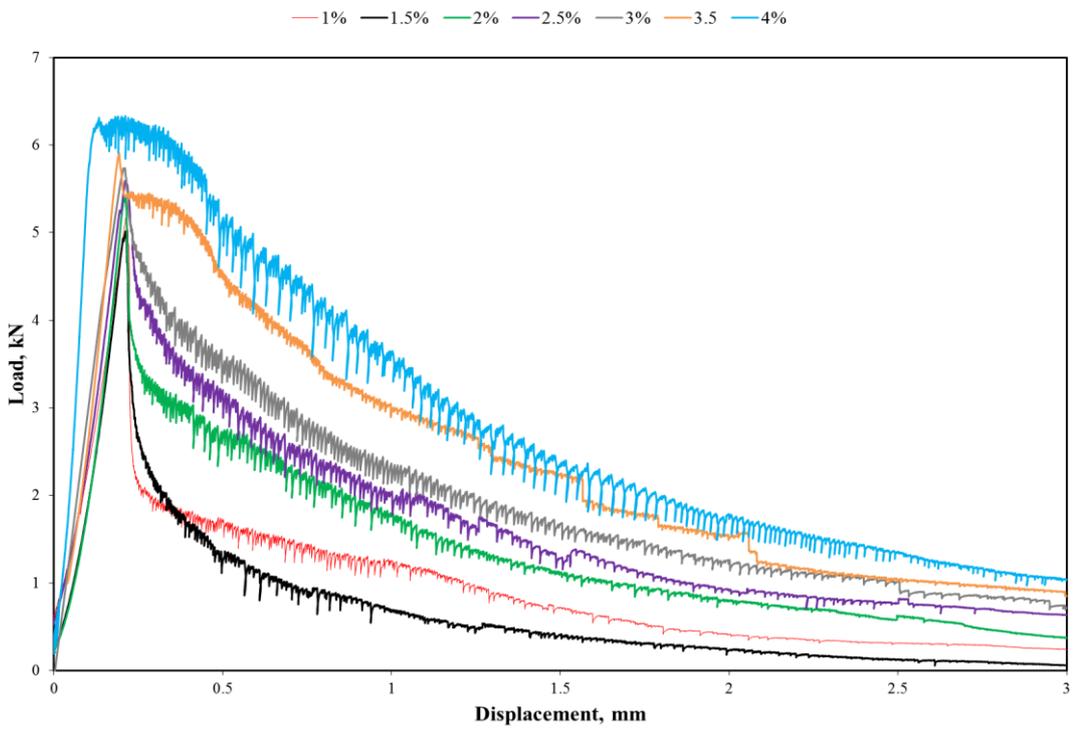
The fibers inside concrete sustained more part of the load that called ‘peak load’. Whenever the UHPFRC matrix could not stand against the maximum applied load, the first crack appeared then the applied load instantaneously reduced. Inasmuch of dismantling to an uncountable number inside concrete (see Fig. 4.6), micro steel fibers made the slope of the pre- and post-peak to extent due to arresting micro cracks occurring and enhancing bonding between aggregate and paste of UHPCs. Consequently, the above-mentioned figures showed that MSF affected transformation of UHPC from strain softening to hardening because of their great properties as illustrated in Table 4.1. 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 directly (Beygi et al. 2013). Whereas MSF content may play a direction and indirection role with the formal and later properties, respectively.

Table 4.1 Load - displacement test results

Concrete mixture	area under the curve (kN.mm)	maximum deflection (mm)	P max (kN)
0.12MSF1	3479.9	5.06	5.3
0.12MSF1.5	3597.6	5.1	5.3
0.12MSF2	4780.9	5.15	5.6
0.12MSF2.5	4969.2	5.2	5.8
0.12MSF3	5220.8	5.25	6.3
0.12MSF3.5	6278.4	5.3	6.9
0.12MSF4	8424.8	5.4	7.2
0.14MSF1	2877.5	4.81	5.0
0.14MSF1.5	3170.4	4.9	5.2
0.14MSF2	3270.8	4.94	5.4
0.14MSF2.5	3853.9	5.01	5.6
0.14MSF3	4513.4	5.06	5.7
0.14MSF3.5	5870.4	5.1	5.9
0.14MSF4	7253.7	5.2	6.3



(a)



(b)

Figure 4.6 Load versus displacement curves of UHPFRC with respect to steel fiber content: (a) 0.12 w/b (b) 0.14w/b group.

4.7 Fracture Energy

The fracture energy (G_f) is defined as the post-crack energy absorption ability of the material, and it represents the energy that the structure will absorb during failure or it can be expressed as an energy required to open a unit area of the crack surface. In the estimating of fracture energy, the weight of the beam was used as the energy supplied by the own weight of the prism, and the area under the curve was used as an indication of the energy supplied.

In the present research as showed in Fig. 4.7, the fracture energy of UHPFRC is depended on two important factors; volume fraction of MSF and w/b. It was illustrious from aforementioned figure; the UHPC with 4% micro steel fibers presented the highest value of the fracture energy, regardless of w/b. Precisely, adding 4% of MSF to UHPCs led to an enhancement of fracture energy by 137.5%, and 146.3% for 0.12 and 0.14 w/b groups, consequently, comparing to UHPFRC containing 1% MSF.

The huge performance of MSF may be related to their superior properties such as aspect ratio and high-tensile strength that made it need high energy necessary to fracture the beams because of arresting cracks by fibers. Furthermore, Prem et al. (2012) referred larger fracture energies of fiber-reinforced UHPCs due to an ability to bridge the cracks.

The rate of development of fracture properties is higher than other mechanical properties like compressive strength, tensile strength, and elastic modulus. This high improvement is may be due to the fact that fracture parameters mainly depends on bond strength and arresting cracks, which they improved by adding high volume of MSF, but the other tests strongly depended on enhancing ITZ that fibers indirectly shared to enhance it.

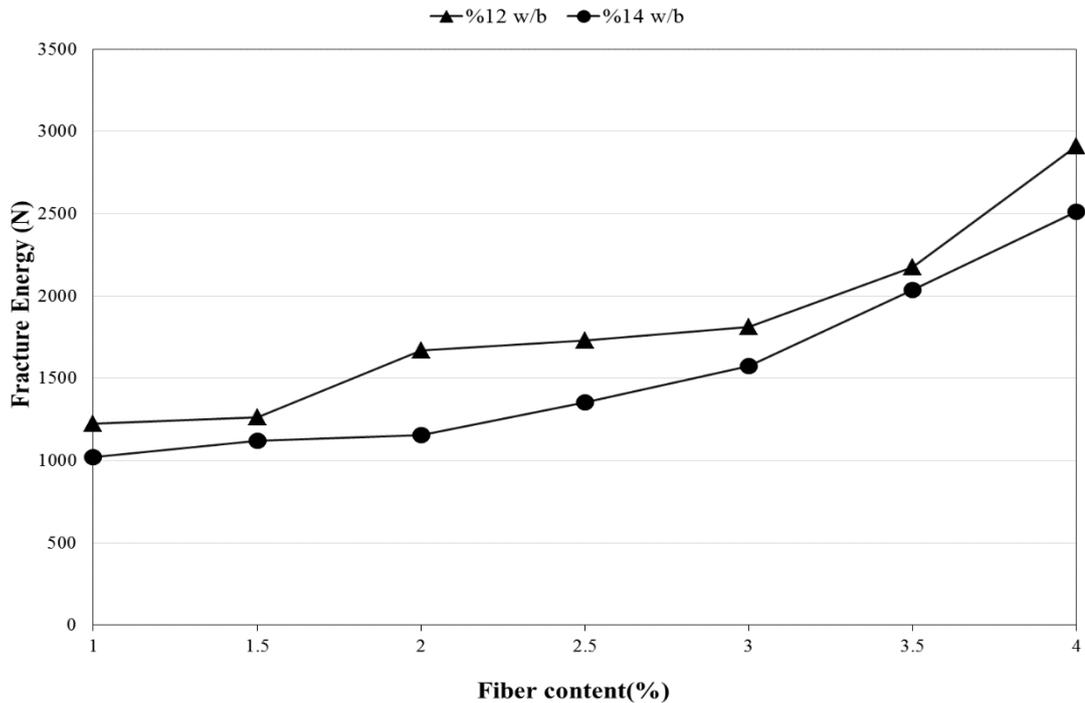


Figure 4.7 Fracture energy versus different steel fiber rate of UHPFRC at 28 days:

4.8. Characteristic Length, l_{ch}

The characteristic length is a measurement of brittleness; e.g. non ductile, it is mainly depending on the important mechanical properties of concrete like fracture energy, elastic modulus, and tensile strength. The concrete will be more ductile when the value of the characteristic length is higher.

The variations in the l_{ch} of UHPCs that reinforced with different volumes of MSF and two w/b contents of 0.12 and 0.14 are presented in Fig. 4.8. Comparing to high increasing of ductility by adding 4% volume of MSF, the enhancement due to decreasing w/b from 0.14 and 0.12 were somewhat small. This may be because of huge numbers of MSF at 4% volumes that reached 72×10^6 , which improved fracture energy (see Fig 4.7), which played very important role to enhance the characteristic length directly. Whereas decreasing w/b from 0.14 to 0.12 (the difference of water=0.02x binder), enhanced the ITZ rather than their effecting of the fracture properties.

Comparing to the study of Gesoglu et al. (2016) there is a big improvement of the brittleness of UHPC by adding MSF, decreasing w/b, and increasing binder content. The maximum value that they achieved was nearly 48 mm for the plain concretes

without fibers, with w/b of 0.2 and 800 kg/m³ binder. Precisely, in this study by adding 4% of micro glass fibers, and using 1175 kg/m³ of binders, the characteristic lengths of 978.8mm, and 736.5mm were recorded using prisms of the same dimensions of 70x70x280mm for 0.12 and 0.14 w/b groups, subsequently. In addition, many other researchers tried to investigate the characteristic length with other concrete types since there is lacked of studies with UHPC. For example, for compressive strength range of 40–80 MPa, Zhang et al. (2010) recorded the characteristic length between 412-235 mm, and Petersson (1980) measured it with the values of 200 and 500 mm. Additionally, for self-compacting high-strength concretes, Eskandari et al. (2010) found that l_{ch} ranged between 266 to 446 mm.

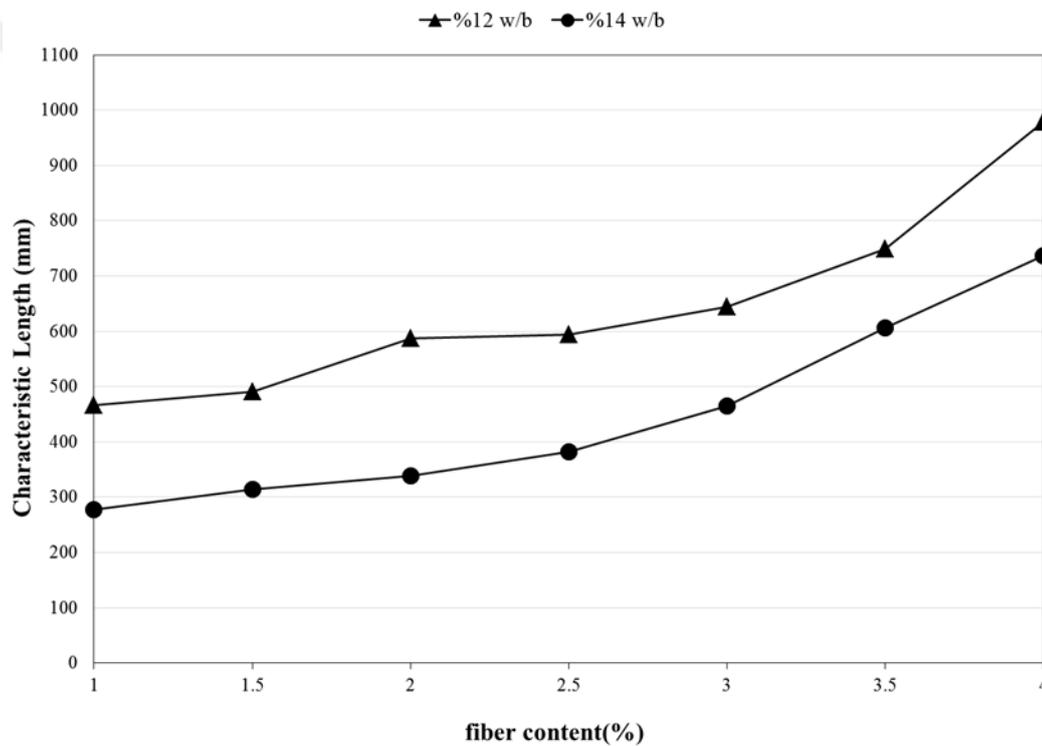


Figure 4.8 Characteristic length versus different steel fiber rate of UHPFRC at 28 days.

CHAPTER 5

CONCLUSIONS

1. Any increase in the volume of fibers responded to the rise of the amount of superplasticizers. Additionally, decreasing w/b from 0.14 to 0.12 needed an average of 15 kg/m^3 super plasticizer but when the fiber content increased from 1% to 4%, the demand of SP was increased to 9.4 and 10.7 kg/m^3 for the groups of 0.12 and 0.14 w/b, respectively.
2. The highest compressive strengths were obtained from the mixtures of 0.12 w/b group with a small difference comparing to the group of 0.14 w/b; this may be due to both w/b ratios will give water to the system that near to the critical point for giving best results. In contrast, the results indicated a meaningful effect of gradually increasing micro steel fibers on the growth of compressive strength regulatory. Precisely, When the fiber content was increased from 1% to 4%, the improvement in compressive strength was as high as 10.6%, and 14.3% for the groups of 0.12, and 0.14 w/b, correspondingly.
3. It can be noticed that there was faintly enhancement of the results due to adding micro steel fibers, this may be because of the failure in tensile strength is different than with compressive strength since the failure occurs along the paste and over the aggregates rather than interfacial transition zone (ITZ), which improved via adding discrete fibers.
4. The UHPFRC had an enhancement by 22.7 % and 34.9 % at 4%, comparing to their control mixtures, which contains 1% of MSF for the first and second groups. Moreover, the reason of so close results to each other between the two groups, may interpret to extremely small water/binder ratios chosen that compensated by a new generation of superplasticizer and ultra-fineness of silica fume particles, which they together supported workability and flowability.

5. The influence of adding fibers much more than the influence of decreasing water content of the results of flexural strength. For example, the average improvement in the modulus of rupture with adding 4% of steel fibers to UHPC was 36.8% for 0.12 w/b group, but reducing w/b from 0.14 to 0.12 cause a development by 10.6% for the same mixture containing that 4% of MSF.
6. The UHPC containing 4% MSF with 0.12 w/b had an area under the curve, a maximum deflection, and a peak load of 8424.8 kN.mm, 5.4mm, and 7.2 kN, respectively, while these values reduced to 7253.7 kN.mm, 5.2mm, and 6.3 kN for additional 0.02 w/b (0.14 w/b) added to the mixes with the same fiber amount.
7. Adding 4% of MSF to UHPCs led to an enhancement of fracture energy by 137.5%, and 146.3% for 0.12 and 0.14 w/b groups, consequently, comparing to UHPFRC containing 1% MSF.
8. The rate of development of fracture properties is higher than other mechanical properties like compressive strength, tensile strength, and elastic modulus. This high improvement is may be due to the fact that fracture parameters mainly depends on bond strength and arresting cracks, which they improved by adding high volume of MSF, but the other tests strongly depended on enhancing ITZ that fibers indirectly shared to enhance it.
9. Comparing to high increasing of ductility by adding 4% volume of MSF, the enhancements due to decreasing w/b from 0.14 and 0.12 were somewhat small. This may be because of huge numbers of MSF at 4% volumes that reached 72×10^6 that improved fracture energy, which played very important role to enhance the characteristic length directly. Whereas decreasing w/b from 0.14 to 0.12, enhanced the ITZ rather than their effecting of the fracture properties.

REFERENCES

- Aıtcin, P. C. (2003). The durability characteristics of high performance concrete: a review. *Cement and Concrete Composites*, **25(4)**, 409-420.
- Akcay B, Agar-Ozbek AS, Bayramov F, Atahan HN, Sengul C, Tasdemir MA(2012). Interpretation of aggregate volume fraction effects on fracture behavior of concrete. *Construction and Building Materials*.; **28(1)**, 437-43.
- Aldahdooh, M. A. A., Bunnori, N. M., & Johari, M. M. (2013). Development of green ultra-high performance fiber reinforced concrete containing ultrafine palm oil fuel ash. *Construction and Building Materials*, **48**, 379-389.
- Aldahdooh, M. A. A., Bunnori, N. M., & Johari, M. M. (2014). Influence of palm oil fuel ash on ultimate flexural and uniaxial tensile strength of green ultra-high performance fiber reinforced cementitious composites. *Materials & Design*, **54**, 694-701.
- Al-Rawi, R. S., Al-Salihi, R. A. W., & Ali, M. H. M. (1976). Effective Sulfate Content in Concrete Ingredients. *Magazine of Concrete Research*, **28(96)**, 130-142.
- ASTM C39. (2012). Standard test method for compressive strength of cylindrical concrete specimens. *Annual book of ASTM standard*.
- ASTM C469 / C469M-14, (2014). Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression, ASTM International, West Conshohocken, PA, 2014, www.astm.org.
- ASTM C494/C494M-13, (2013). Standard Specification for Chemical Admixtures for Concrete, ASTM International, West Conshohocken, PA., <www.astm.org>.
- ASTM C496. (2011). Standard test method for splitting tensile strength of cylindrical concrete specimens. Annual book of ASTM standard
- ASTM, C469. (2001). Standard test method for static modulus of elasticity and Poisson's ratio of concrete in compression. West Conshohochen: American Society for Testing and Materials. Aydın S, Baradan B. *The effect of fiber properties on high performance alkali-activated slag/silica fume mortars*. Composites Part B: Engineering. **45(1)**:63-9.
- Aydin, S., Yazici, H., Yardimci, M. Y., & Yiğiter, H. (2010). Effect of Aggregate Type on Mechanical Properties of Reactive Powder Concrete. *ACI Materials Journal*, **107(5)**.

- Balaguru, P. N., & Shah, S. P. (1992). Fiber-reinforced cement composites.
- Beglarigale A, Yazıcı H. (2015). Pull-out behavior of steel fiber embedded in flowable RPC and ordinary mortar. *Construction and Building Materials*. **75**:255-65.
- Behloul, M., & Lee, K. C. (2003). Ductal Seonyu footbridge. *Structural Concrete*, **4(4)**, 195-201.
- Bentur, A., & Mindess, S. (2006). *Fibre reinforced cementitious composites*. CRC Press.
- Bilodeau A, Kodur VK, Hoff GC(2004). Optimization of the type and amount of polypropylene fibres for preventing the spalling of lightweight concrete subjected to hydrocarbon fire. *Cement and Concrete Composites*; **26(2)**:163-74.
- Bini, L., Magi, B., Marzocchi, B., Arcuri, F., Tripodi, S., Cintonino, M., & Hochstrasser, D. F. (1997). Protein expression profiles in human breast ductal carcinoma and histologically normal tissue. *Electrophoresis*, **18(15)**, 2832-2841.
- Bini, L., Magi, B., Marzocchi, B., Arcuri, F., Tripodi, S., Cintonino, M., ... & Hochstrasser, D. F. (1997). Protein expression profiles in human breast ductal carcinoma and histologically normal tissue. *Electrophoresis*, **18(15)**, 2832-2841.
- Bissonnette, B., & Pigeon, M. (1995). Tensile creep at early ages of ordinary, silica fume and fiber reinforced concretes. *Cement and Concrete Research*, **25(5)**, 1075-1085.
- Bissonnette, B., Pigeon, M., & Vaysburd, A. M. (2007). Tensile creep of concrete: study of its sensitivity to basic parameters. *ACI Materials journal*, **104(4)**, 360.
- Brown, R., Shukla, A., & Singh, S. P. (2004). *Fiber Reinforcement of Concrete* (No. URITC FY 00-06,).
- BS 1881: Part 117 (1983). Testing concrete. Method for the determination of tensile
- Cheyrezy, M., Maret, V., & Frouin, L. (1995). Microstructural analysis of RPC (reactive powder concrete). *Cement and Concrete Research*, **25(7)**, 1491-1500.
- Corinaldesi, V., & Moriconi, G. (2012). Mechanical and thermal evaluation of Ultra High Performance Fiber Reinforced Concretes for engineering applications. *Construction and Building Materials*, **26(1)**, 289-294.
- de Larrard, F., & Sedran, T. (1994). Optimization of ultra-high-performance concrete by the use of a packing model. *Cement and Concrete Research*, **24(6)**, 997-1009.
- Dugat, J., Roux, N., & Bernier, G. (1996). Mechanical properties of reactive powder concretes. *Materials and structures*, **29(4)**, 233-240.

EFNARC, F. (2002). Specification and Guidelines for Self-Compacting Concrete. *Farnham, Surrey GU9 7EN, UK, website: www.efnarc.org, ISBN,953973344.*

Fehling, E., Bunje, K., Schmidt, M., Tue, N. V., Schreiber, W., & Humburg, E. (2007, January). Design of First Hybrid UHPC-Steel Bridge across the River Fulda in Kassel, Germany. In IABSE Symposium Report (Vol. 93, No. 9, pp. 1-8). International Association for Bridge and Structural Engineering.

Ferraris, C. F., Obla, K. H., & Hill, R. (2001). The influence of mineral admixtures on the rheology of cement paste and concrete. *Cement and concrete research*, **31(2)**, 245-255.

Ferron, R. P., Gregori, A., Sun, Z., & Shah, S. P. (2007). Rheological method to evaluate structural buildup in self-consolidating concrete cement pastes. *ACI materials journal*, **104(3)**, 242.

Feylessoufi, A., Crespin, M., Dion, P., Bergaya, F., Van Damme, H., & Richard, P. (1997). Controlled rate thermal treatment of reactive powder concretes. *Advanced cement based materials*, **6(1)**, 21-27.

Foy C, Pigeon M, Banthia N. (1988). Freeze-thaw durability and deicer salt scaling resistance of a 0, 25 water-cement ratio concrete. *Cement and Concrete Research*.; **18(4)**:604-14.

Gao J, Sun W, Morino K. (1997). Mechanical properties of steel fiber-reinforced, high-strength, lightweight concrete. *Cement and Concrete Composites*. **19(4)**:307-13.

Gesoglu M, Güneyisi E, Asaad DS, Muhyaddin GF. (2016). Properties of low binder ultra-high performance cementitious composites: Comparison of nanosilica and microsilica. *Construction and Building Materials*. **102**:706-13.

Gesoglu M, Güneyisi E, Hansu O, İpek S, Asaad DS. (2015). Influence of waste rubber utilization on the fracture and steel-concrete bond strength properties of concrete. *Construction and Building Materials*. **101**:1113-21.

González-Fonteboa, B., Martínez-Abella, F. (2008). Concretes with aggregates from demolition waste and silica fume. *Materials and mechanical properties. Build. Environ.* **43(4)**, 429–437

Graybeal, B. A. (2005). Characterization of the behavior of ultra-high performance concrete.

Graybeal, B. A. (2006). Material property characterization of ultra-high performance concrete (No. FHWA-HRT-06-103).

Graybeal, B. A. (2006). *Material property characterization of ultra-high performance concrete* (No. FHWA-HRT-06-103).

- Graybeal, B. A., & Hartmann, J. L. (2003). Strength and durability of ultra-high performance concrete. In *Concrete Bridge Conference, Portland Cement Association*.
- Graybeal, B., & Tanesi, J. (2007). Durability of an ultrahigh-performance concrete. *Journal of materials in civil engineering*, **19**(10), 848-854.
- Habel, K., & Gauvreau, P. (2008). Response of ultra-high performance fiber reinforced concrete (UHPFRC) to impact and static loading. *Cement and Concrete Composites*, **30**(10), 938-946.
- Habel, K., Denarié, E., & Brühwiler, E. (2007). Experimental investigation of composite ultra-high-performance fiber-reinforced concrete and conventional concrete members. *ACI Structural Journal*, **104**(1), 93.
- Hanle, L. J., Jayaraman, K. R., & Smith, J. S. (2004). CO2 emissions profile of the US cement industry. Washington DC: Environmental Protection Agency.
- Hanna, A. N. (1977). *Steel fiber reinforced concrete properties and resurfacing applications* (No. Bulletin RD049. 01P Monograph).
- Hannant, P. J. (1978). *Fibre cements and fibre concretes* (No. Monograph).
- Hannat, D. (1978). Fiber cements and fiber concretes. *John Wiley SOILS Ltd*.
- Hassan, A. M. T., Jones, S. W., & Mahmud, G. H. (2012). Experimental test methods to determine the uniaxial tensile and compressive behaviour of ultra high performance fibre reinforced concrete (UHPFRC). *Construction and Building Materials*, **37**, 874-882.
- Hassanpour M, Shafigh P, Mahmud HB. (2012). Lightweight aggregate concrete fiber reinforcement—a review. *Construction and Building Materials*. **37**:452-61.
- Hatta, R., Ito, K., Hosaki, Y., Tanaka, T., Tanaka, A., Yamamoto, M., ... & Tsuge, T. (2002). A conditionally dispensable chromosome controls host-specific pathogenicity in the fungal plant pathogen *Alternaria alternata*. *Genetics*, **161**(1), 59-70.
- Heinz, D., & Ludwig, H. M. (2004). Heat treatment and the risk of DEF delayed ettringite formation in UHPC. In *Proceedings of the International Symposium on Ultra-High Performance Concrete, Kassel, Germany, Sept. 13* (Vol. 15, pp. 717-730).
- Heinz, D., Urbonas, L., & Gerlicher, T. (2012). Effect of heat Treatment Method on the properties of UHPC. In *Ultra High Performance Concrete and Nanotechnology in Construction, 3rd Intl. Symp. on Ultra High Performance Concrete and Nanotechnology for High Performance Construction Materials*(pp. 283-290).

Hillerborg A. (1983). Concrete fracture energy tests performed by 9 laboratories according to a draft RILEM recommendation: Report to RILEM TC50-FMC. Report TVBM..

Hillerborg A. (1985). The theoretical basis of a method to determine the fracture energy G_F of concrete. *Materials and structures*. **18(4)**:291-6.

Hillerborg, A. (1983). Concrete fracture energy tests performed by 9 different laboratories according to a draft RILEM recommendation. *Report to RILEM TC50-FMC, Report TVMB-3015*.

Jolicoeur, C., & Simard, M. A. (1998). Chemical admixture-cement interactions: phenomenology and physico-chemical concepts. *Cement and Concrete Composites*, **20(2)**, 87-101.

Kang ST, Choi JI, Koh KT, Lee KS, Lee BY. (2016). Hybrid effects of steel fiber and microfiber on the tensile behavior of ultra-high performance concrete. *Composite Structures*.; **145**,37-42.

Kang ST, Kim JK. (2012). Investigation on the flexural behavior of UHPCC considering the effect of fiber orientation distribution. *Construction and Building Materials*. **28(1)**:57-65.

Kayali O, Haque MN, Zhu B. (2003). Some characteristics of high strength fiber reinforced lightweight aggregate concrete. *Cement and Concrete Composites*. **25(2)**:207-13.

Kollmorgen, G. A. (2004). Impact of Age and Size on the Mechanical Behavior of an Ultra-High Performance Concrete. *Michigan Technological University*.

Körmeling, H. A., & Reinhardt, H. W. (1987). Strain rate effects on steel fibre concrete in uniaxial tension. *International Journal of Cement Composites and Lightweight Concrete*, **9(4)**, 197-204.

Krstulovic-Opara, N., & Malak, S. (1997). Tensile behavior of slurry infiltrated mat concrete (SIMCON). *ACI Materials Journal*, **94**, 39-46.

Long, G., Wang, X., & Xie, Y. (2002). Very-high-performance concrete with ultrafine powders. *Cement and Concrete Research*, **32(4)**, 601-605.

Ma J, Schneider H.(2002);Properties of ultra-highperformance concrete. Leipzig Annual Civil Engineering Report (LACER). 7:25-32.

Markovic I. High-performance hybrid-fibre concrete – development and utilisation. Technische Universitat Delft, Ph.D. thesis; 2006.

McHugh, A. J., & Tan, L. S. (1993). Mechano-chemical aspects of the processing/property/structure interactions in a macro-defect-free cement. *Advanced Cement Based Materials*, **1(1)**, 2-11.

- Mehta, P. K. (1986). Concrete. Structure, properties and materials.
- Mohammed, H. (2015). Mechanical Properties Of Ultra High Strength Fiber Reinforced Concrete (Doctoral dissertation, The University of Akron).
- Mojumdar, S., Mazanec, K., & Drabik, M. (2006). Macro-defect-free (MDF) cements. *Journal of thermal analysis and calorimetry*, **83(1)**, 135-139.
- Monosi, S., Pignoloni, G., Collepardi, S., Troli, R., & Collepardi, M. (2000). Modified Reactive Powder Concrete with Artificial Aggregates. *ACI SPECIAL PUBLICATIONS*, **195**, 447-460.
- Naaman, A. E. (2003). Strain hardening and deflection hardening fiber reinforced cement composites. *High Performance Fiber Reinforced Cement Composites 4 (HPFRCC 4)*, 95-113.
- Naaman, A. E. (2007). High performance fiber reinforced cement composites: classification and applications. In *CBM-CI international workshop, Karachi, Pakistan* (pp. 389-401).
- Naaman, A. E., & Homrich, J. R. (1989). Tensile stress-strain properties of SIFCON. *ACI Materials Journal*, **86(3)**, 244-251.
- Naaman, A. E., & Reinhardt, H. W. (2006). Proposed classification of HPFRC composites based on their tensile response. *Materials and structures*, **39(5)**, 547-555.
- Naaman, A. E., Alkhairi, F. M., & Hammoud, H. (1993). Fiber Reinforced Concrete. *Contract*, *100*, 205.
- Nallathambi P, Karihaloo BL, Heaton BS. (1984). Effect of specimen and crack sizes, water/cement ratio and coarse aggregate texture upon fracture toughness of concrete. *Magazine of Concrete Research*. **36(129)**:227-36.
- Neves RD, Fernandes de Almeida JC. (2005) Compressive behaviour of steel fibre reinforced concrete. *Structural concrete*. **6(1)**:1-8.
- Norma, A. S. T. M. (2005). C39M. Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. *ASTM International*.
- Prem, P. R., Bharatkumar, B. H., & Iyer, N. R. (2013). Influence of curing regimes on compressive strength of ultra high performance concrete. *Sadhana*, **38(6)**, 1421-1431.
- Paillere, A., Buil, M., & Serrano, J. J. (1989). Effect of fiber addition on the autogenous shrinkage of silica fume concrete. *ACI Materials Journal*, **86(2)**, 139-144.
- Paivio, A., & Begg, I. (1981). *Psychology of language*. Englewood Cliffs, NJ: Prentice-Hall.

Park SH, Ryu GS, Koh KT, Kim DJ. (2014). Effect of shrinkage reducing agent on pullout resistance of high-strength steel fibers embedded in ultra-high-performance concrete. *Cement and Concrete Composites*, **49**:59-69.

Perry, V. H., & Zakariassen, D. (2003). Overview of UHPC technology, materials, properties, markets and manufacturing. In *Proceedings of the 2003 Concrete Bridge Conference* (pp. 1-38).

Perry, V., & Zakariassen, D. (2004). First use of ultra-high performance concrete for an innovative train station canopy. *Concrete Technology Today*, **25**(2), 1-2.

Potrzebowski, J. (1983). The splitting test applied to steel fibre reinforced concrete. *International Journal of Cement Composites and Lightweight Concrete*, **5**(1), 49-53.

Powers, T. C., & Brownyard, T. L. (1946). Studies of the physical properties of hardened Portland cement paste. *Bulletin*, 22.

Ravindra KD, Henderson NA. (1999). *Specialist Techniques and Materials for Concrete Production*. Thomas Telford Publishing, Thomas Telford Ltd.

Rebentrost, M., & Cavill, B. (2006). Reactive powder concrete bridges. In *AUSTROADS BRIDGE CONFERENCE, 6TH, 2006, PERTH, WESTERN AUSTRALIA*.

Recommendation, R. D. (1985). Determination of the Fracture Energy of Mortar and Concrete by Means of Three-Point Bend Tests on Notched Beames. *Materials and Structures*, **18**(106), 285-290.

Recommendation, R. D. (1985). Determination of the Fracture Energy of Mortar and Concrete by Means of Three-Point Bend Tests on Notched Beames. *Materials and Structures*, **18**(106), 285-290.

Reineck, K. H., & Greiner, S. (2004). Tests on ultra-high performance fibre reinforced concrete designing hot-water tanks and UHPFRC-shells. In *Proceedings of the International Symposium on Ultra High Performance Concrete, Kassel, Germany, Sept. 13* (Vol. 15, pp. 361-374).

Resplendino, J., & Petitjean, J. (2003). Ultra-high-performance concrete: First recommendations and examples of application. In *Proceedings of the Third International Symposium on High Performance Concrete* (p. 18).

Richard, P., & Cheyrezy, M. (1995). Composition of reactive powder concretes. *Cement and concrete research*, **25**(7), 1501-1511.

Richard, P., & Cheyrezy, M. H. (1994). Reactive powder concretes with high ductility and 200-800 MPa compressive strength. *Special Publication*, **144**, 507-518.

RILEM 50-FMC. (1985). Committee of fracture mechanics of concrete, Determination of fracture energy of mortar and concrete by means of three-point bend tests on notched beams, *Mater Struct.* **18** (106) 285–290.

Rong ZD, Sun W, Xiao HJ, Wang W. (2014). Effect of silica fume and fly ash on hydration and microstructure evolution of cement based composites at low water–binder ratios. *Construction and Building Materials.*;51:446-50.

Rossi, P. (2001). Ultra-High Performance Fiber-Reinforced Concretes. *Concrete international*, **23**(12), 46-52.

Rößler, C., Bui, D. D., & Ludwig, H. M. (2014). Rice husk ash as both pozzolanic admixture and internal curing agent in ultra-high performance concrete. *Cement and Concrete Composites*, **53**, 270-278.

Roy, M. (2011). Development and Evaluation of High Performance Fiber Reinforced Concrete as a Repairing Material. WEST VIRGINIA UNIVERSITY.

Schmidt M, Fehling E. (2005). Ultra-high-performance concrete: research, development and application in Europe. ACI Special publication. 1;228:51-78.

Sekhar NS, Raghunath PN. (2014). Influence of Water Binder Ratio on High Performance Concrete. *Open Construction and Building Technology Journal.* 8:18-21.

Šerelis E, Deligia M, Vaitkevičius V, Kerševičius V. (2015). Influence of Water to Cement Ratio with Different Amount of Binder on Properties of Ultra-High Performance Concrete. *Journal of Sustainable Architecture and Civil Engineering.* 10(1):78-86.

Shah, S. P., & Weiss, W. J. (1998). Ultra high performance concrete: a look to the future. In *Zia Symposium. ACI Spring Convention 1998.*

Shaheen, E., & Shrive, N. G. (2006). Optimization of mechanical properties and durability of reactive powder concrete. *ACI Materials Journal*, **103**(6), 444.

Shehata M. (2010). Optimizing the strength and permeability of pervious concrete. Ryerson University, Department of Civil Engineering.

Song, P. S., & Hwang, S. (2004). Mechanical properties of high-strength steel fiber-reinforced concrete. *Construction and Building Materials*, **18**(9), 669-673.

Soutsos MN, Millard SG, Karaiskos K. (2005). Mix design, mechanical properties, and impact resistance of reactive powder concrete (RPC). In *International RILEM Workshop on High Performance Fiber Reinforced Cementitious Composites (HPFRCC) in Structural Applications* (pp. 549-560).

Soutsos, M. N., Millard, S. G., & Karaiskos, K. (2005). Mix design, mechanical properties, and impact resistance of reactive powder concrete (RPC). In *International*

RILEM Workshop on High Performance Fiber Reinforced Cementitious Composites (HPFRCC) in Structural Applications(pp. 549-560).

splitting strength. British Standard Institutions, UK.

Structural applications of fiber reinforced concrete. ACI International, 1999.

Suaris, W., & Shah, S. P. (1982). Strain-rate effects in fibre-reinforced concrete subjected to impact and impulsive loading. *Composites*, **13**(2), 153-159.

Swamy, R. N., & Barr, B. (Eds.). (1989). *Fibre Reinforced Cement and Concretes: Recent Developments*. CRC Press.

Tran NT, Tran TK, Jeon JK, Park JK, Kim DJ. (2016). Fracture energy of ultra-high-performance fiber-reinforced concrete at high strain rates. *Cement and Concrete Research*. **79**,169-84.

Tue NV, Ma J, Orgass M. (2008). Influence of addition method of superplasticizer on the properties of fresh UHPC. In *Proceedings of Second International Symposium on Ultra High Performance Concrete*, University of Kassel, Germany (pp. 93-100).

Van Tuan, N., Ye, G., Van Breugel, K., Fraaij, A. L., & Dai Bui, D. (2011). The study of using rice husk ash to produce ultra high performance concrete. *Construction and Building Materials*, **25**(4), 2030-2035.

Vande Voort, T. L., Suleiman, M. T., & Sritharan, S. (2008). *Design and performance verification of ultra-high performance concrete piles for deep foundations* (No. IHRB Project TR-558).

Wang D, Shi C, Wu Z, Xiao J, Huang Z, Fang Z. (2015). A review on ultra high performance concrete: Part II. Hydration, microstructure and properties. *Construction and Building Materials*. **96**,368-77.

Wang K, Schaefer VR, Kevern JT, Suleiman MT. Development of mix proportion for functional and durable pervious concrete. In *Proceedings of the 2006 NRMCA Concrete Technology Forum—Focus on Pervious Concrete 2006 May 24*.

Wille, K., Naaman, A. E., El-Tawil, S., & Parra-Montesinos, G. J. (2012). Ultra-high performance concrete and fiber reinforced concrete: achieving strength and ductility without heat curing. *Materials and structures*, **45**(3), 309-324.

Yang, S. L., Millard, S. G., Soutsos, M. N., Barnett, S. J., & Le, T. T. (2009). Influence of aggregate and curing regime on the mechanical properties of ultra-high performance fibre reinforced concrete (UHPFRC). *Construction and Building Materials*, **23**(6), 2291-2298.

Yanni, G., & Youssef, V. (2009). Multi-scale investigation of tensile creep of ultra-high performance concrete for bridge applications.

Yazıcı H. (2007). The effect of curing conditions on compressive strength of ultra high strength concrete with high volume mineral admixtures. *Building and Environment*. **42(5)**,2083-9.

Yazıcı, H., Deniz, E., & Baradan, B. (2013). The effect of autoclave pressure, temperature and duration time on mechanical properties of reactive powder concrete. *Construction and Building Materials*, **42**, 53-63.

Yazıcı, H., Yardımcı, M. Y., Yiğiter, H., Aydın, S., & Türkel, S. (2010). Mechanical properties of reactive powder concrete containing high volumes of ground granulated blast furnace slag. *Cement and Concrete Composites*,**32(8)**, 639-648.

Yazıcı, H., Yiğiter, H., Karabulut, A. Ş., & Baradan, B. (2008). Utilization of fly ash and ground granulated blast furnace slag as an alternative silica source in reactive powder concrete. *Fuel*, **87(12)**, 2401-2407.

Yoo DY, Banthia N, Yoon YS. (2016). Flexural behavior of ultra-high-performance fiber-reinforced concrete beams reinforced with GFRP and steel rebars. *Engineering Structures*. **111**:246-62.

Yu R, Spiesz P, Brouwers HJ. (2016). Energy absorption capacity of a sustainable Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) in quasi-static mode and under high velocity projectile impact. *Cement and Concrete Composites*. **68**:109-22.

Yu, R., Tang, P., Spiesz, P., & Brouwers, H. J. H. (2014). A study of multiple effects of nano-silica and hybrid fibres on the properties of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) incorporating waste bottom ash (WBA). *Construction and Building Materials*, **60**, 98-110.