AUGUST 2017 M.Sc. in Civil Engineering MAAN ABDELHAKEAM ALBAYATI

UNIVERSITY OF GAZİANTEP

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EXPERIMENTAL STUDY FOR FLEXURAL BEHAVIOUR OF HIGH STRENGTH RC BEAMS WITH HYBRID FIBERS

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Experimental Study for Flexural Behavior of High Strength RC Beams with Hybrid Fibers

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Supervisor

Assoc. Prof. Dr. Nildem TAYŞI

by

Maan Abdelhakeam ALBAYATI

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Maan Abdelhakeam ALBAYATI

ABSTRACT

EXPERIMENTAL STUDY FOR FLEXURAL BEHAVIOR OF HIGH STRENGTH RC BEAMS WITH HYBRID FIBERS

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An experimental program is achieved in this study to show the enhancement gained from addition of steel, basalt, and glass fibers to the concrete mix on the flexural performance of reinforced concrete beams. Ten different reinforced concrete beams are tested and results are compared. First one is a control beam, group A consist of three beams strengthened with different volumetric ratios (0.5, 1.0, and 1.5 %) of steel fibers. Group B consist of three beams (0.25-0.75, 0.5-0.5, and 0.75-0.25) % of steel and basalt hybrid fibers, and group C consist of three beams (0.25-0.75, 0.5-0.5, and 0.75-0.25) % of steel and glass hybrid fibers. Moreover, 30 standard concrete cubes are tested to show the effect of the fibers on concrete compressive strength, and 30 standard concrete cylinders are tested to show the difference in split strength. Test and comparison results show that group A beams give enhancement in first crack load values, which means enhancement in tension zone characteristic with maximum values of 60 % increase in cracking load for the beam with 1.0 % addition of steel fibers. Yield load is also, enhanced by (9.0 %, 0.4 %, and 5.0 %) increase for beam 1.0 % and 1.5 % volumetric ratios of steel fibers, and (0.5-0.5) % volumetric ratios of steel-glass hybrid fibers, respectively. Ultimate loads are enhanced by 0.6 %, and 2 % for beams with volumetric ratios of 1 % steel fibers and (0.5-0.5) % steel-glass hybrid fibers additives, respectively. Extending this experimental program to study different beam cross sections, deep beams, hybrid beams and creep-shrinkage effect are suggested as future work.

Keywords: Fiber reinforcement, Hybrid fibers, Flexural performance.

ÖZET

HİBRİT ELYAFLI YÜKSEK GERİLİMLİ BETONARME KİRİŞLERİNİN ESNEKLİK DAVRANIŞLARININ İNCELENDİĞİ DENEYSEL BİR ÇALIŞMA

ALBAYATI, MAAN ABDELHAKEAM
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Bu çalışmada, betonarme kirişlerin eğilme performansı üzerinde, çelik, bazalt ve cam elyaflarının beton karışımına eklenmesinden elde edilen güçlenmeyi göstermek için deneysel bir program yürütülmüştür. On farklı betonarme kiriş test edilmiş ve sonuçlar karşılaştırılmıştır. İlk kiriş elyafsız kontrol kirişidir, grup A çelik elyafların farklı hacimsel oranlarda (% 0,5, 1,0 ve 1,5) katkısı ile güçlendirilmiş üç kirişten oluşmaktadır. Grup B çelik ve bazalt hibrit lifli (0.25-0.75, 0.5-0.5 ve 0.75-0.25) üç kirişten ve grup C, çelik ve cam hibrit lifli (0.25-0.75, 0.5-0.5 ve 0.75-0.25) üç kirişten oluşmaktadır. Ayrıca, 30 standart küp beton numunesi, liflerin beton basınç dayanımı üzerindeki etkisini göstermek üzere ve 30 standart silindir beton numunesi, yarmada çekme mukavemetindeki değişimi göstermek için test edilmiştir. Test ve karşılaştırma sonuçları, A grubundaki kirişlerin ilk çatlak yük değerlerinde iyileşme sağladığını göstermektedir; bu da % 1'lik çelik lif eklenmesinde kiriş için çatlama yükünde % 60'lık maksimum değer ile gerilme bölgesi karakteristiğinde artış anlamına gelmektedir. Akma yükü, sırasıyla, % 1.0 ve % 1.5 hacimsel oranlı çelik lifli ve (% 0.5-0.5) hacimsel oranlı çelik-cam hibrit lifli kirişler için sırasıyla (% 9.0,% 0.4 ve% 5.0) artış ile iyileştirilmiştir. Maksimum yükler sırasıyla % 1 çelik ve (% 0.5- 0.5) çelik-cam hibrit elyaf katkılı kirişler için 0.6 % ve 2 % ile arttırılmıştır. Bu deneysel çalışmayı, farklı kiriş kesitlerini, derin kirişler, hibrit kirişler ve sünme-büzülme etkisini incelemek üzere genişletmek gelecekteki çalışmalar olarak önerilebilir.

Anahtar Kelimeler: Elyaflı güçlendirme, Hibrit betonarme, Eğilme performansı.

To My Family, they should receive my greatest appreciation for their enormous love. They always respect what I want to do also give me their full support and encouragement over the years.

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TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

LIST OF SYMBOLS

BF	Basalt Fiber
BFRC	Basalt Fiber Reinforced Concrete
σ	Compressive Strength
F	Flexural Strength
FRC	Fiber Reinforced Concrete
P_{cr}	First Cracking Load
Δ_{cr}	First Crack Deflection
GF	Glass Fiber
GFRC	Glass Fiber Reinforced Concrete
HYFRC	Hybrid Fiber Reinforced Concrete
SF	Steel Fiber
SFRC	Steel Fiber Reinforced Concrete
RC	Reinforced Concrete
T	Tensile Strength
P_y	Yielding Load
P_u	Ultimat Load
Δ_y	Yield Deflection

CHAPTER 1

INTRODUCTION

1.1 General

Concrete is broadly adopted as an essential material of construction in spite of the reality that it is neither as strong nor as tough as steel because of its relatively low cost. Plain. Concrete is brittle in nature and has a small tensile strength and strain ability to upon loading, which results in restricted resistance to tensile strain and cracking. The mechanical characteristics of concrete may be enhanced through the introduction of reinforcing fibers that have high tensile strength and ductility. Recently fibers have been significantly used by combining two types of fibers or more as a reinforcing materials in traditional Reinforced Concrete (RC), and this new material called Hybrid Fibers Reinforce Concrete (HYFRC).

1.2 Historical Background

Historically, much effort has been made in order to enhance the concrete structure performance. Flexural, compressive, shear strength, ductility, and other properties have been the focus of several researchers who have tested concretes with added fibers and other materials to improve the concrete behavior. The concept of adding fibers to improve inelastic material response is ancient, for example, the Mesopotamians used a straw to reinforce sunbaked bricks. This old technology is still used to improve concrete characteristics. Nowadays, fibers are produced from different materials such as steel, glass, basalt, carbon, and synthetic material. Each one of these fibers has its specific benefits. However, steel fiber is the most common one. It has been reported that the first experimental trial to improve concrete characteristics using discontinues steel reinforcing elements, such as nails segments were done in 1910 (ACI544.1R, 2002). However, it was not until 1963 (ACI544.1R, 2002) when major experiments were done to improve concrete characteristics using a real steel fiber (ACI544.1R, 2002). Experiments using glass fibers have been conducted in the United States since the early 1950's as well as in the United Kingdom and in Russia (Ashour et al., 1997). Applications of fibers reinforced concrete investigated since the mid-1960's have included road and floor slabs, topping layers, refractory materials, and some precast concrete products. Glass fibers are primarily used for Glass Fibers Reinforced Concrete (GFRC) (Ashour et al., 1997).

1.3 Literature Review

According to (ACI544.1R, 2002), steel fiber additives to the concrete mix may have a variable impact on compressive strength. What is certain is that steel fiber can improve the post-peak the concrete compressive strength. In other words, using steel fiber increases the toughness and energy observation. This feature is useful to prevent a sudden explosive failure of concrete, therefore is successfully used to improve high strength concrete.

(Johnston, 1974) found that an adding of 1.5 % fibers improves the concrete compressive strength up to 15 %. A regular slope in the descending portion of the FRC stress-strain curve indicates enhanced spalling strength, ductility, and toughness.

(Khaloo and Kim, 1996) studied that using 1.5 % volumetric ratio of steel fibers can increase the compressive strength by 37 %. On the other hand, another study (Thomas and Ramaswamy, 2007) showed that using the same previous ratio of steel fibers increases the peak compressive strength by less than 10 %.

(Shaikh and Taweel, 2015) found that the inclusion of steel fibers has more effect on the capacity of residual compressive strength for reinforced concrete than un reinforced concrete at elevated temperatures. The BFRC, furthermore , presented lower strength retention capacity relative to the control (without fibers). However, they observed that adding hybrid steel-basalt fibers reinforcement improved the deficiency of BFRC, but still slightly lower than the control and SFRC.

(Kizilkanat et al., 2015) noticed from the experimental results that the inclusion of basalt fibers and glass fibers in the concrete mix reduced the workability of concrete mix. BFRC presented the highest compressive strength at 0.5 % addition, while

GFRC presented the highest compressive strength of at 0.75 % addition.

(Lee et al., 2015) demonstrated that after arriving SFRC concrete samples to their compressive strength gave ductile behavior. On the other hand , thes samples showed a reduction in elastic modulus. While , these samples were shown an increase in the strain at the compressive strength with an increase in the fiber volumetric percentage ratios and fibers aspect ratio, in general.

(Dias and Thaumaturgo, 2005), (Borhan, 2013) reported that the slightly higher compressive strength in steel fibers reinforced concrete was referred to the bringing of micro-cracks by the steel fibers, which increased the maximum failure load in compression. otherwise, the BFRC concrete showed an opposite trend, where about 10 % decrease in compressive strength was noticed compared to the control concrete. In the case of basalt fibers reinforced concrete was 0.5 % (by vol.). Also, they reported, when a hybrid incorporation of both steel and basalt fibers are utilized, the adverse impact of basalt fibers in the compressive strength overcomes with a slight increase in compressive strength compared to control concrete.

However, the impact of fibers addition on the compressive strength of concrete is still under discussion as some investigator noticed an increase in the compressive strength with fibers addition whereas some reported a reduction in the compressive strength (Yao et al., 2003), (Song and Hwang, 2004), (Thomas and Ramaswamy, 2007), and (Atiş and Karahan, 2009). Some researchers (Banthia and Gupta, 2004), and (Hsu and Hsu, 1994) even concluded that the fibers addition has an insignificant effect on the compressive strength.

(Rathi et al., 2014) observed the result of adding glass fibers to concrete mix. The enhancement in split tensile strength was found to 11.88 %. The addition of 0.75 % volumetric percentage ratios of glass fibers showed the highest split tensile strength.

(Wiliamson, 1974) discovered that an adding 1.5 % volumetric percent of steel fibers additives increases up to 40 % of concrete direct tensile strength.

(Kizilkanat et al., 2015) observed the experimental study results that the splitting tensile strength of BFRC increased with increasing fibers content by 40 % at fibers addition of 1.0 %. However, no improve in strength for GFRC was observed after a dosage of 0.50 %.

(Mondal and Roy, 2015) found that the combination of steel fibers in reinforced concrete beams presented to be effective in improving the shear strength capability. It has also been detected that the strength increases with the use of varying depth of steel fibers. Beam strengthened using this scheme has given 20 % increase in shear strength and ultimate load when compared to the controlled beam.

(Biolzi and Cattaneo, 2017) studied an experimental test into the behavior of high-performance concrete beams applied to shear. From the study, the incorporation of steel fibers in high-strength concrete beam gives a remarkable enhance in shear strength. Also, from experimental results, the inclusion 1 % volumetric percentage ratio of steel fiber may be substitutional to shear reinforcement.

(Domański and Czkwianianc, 2004) investigated a double-span beam with steel fibers and polypropylene fibers reinforcement analyzing the effects of deformations in shear zones. (Sahoo and Sharma, 2014) studied the behavior of beams with steel fibers on the shear strength of simply supported beams. Studies have shown beneficial effects of hooked steel fibers at 0.75 % by volume.

(Krassowska and Lapko, 2013) demonstrated that the beneficial effect was observed for concrete tensile strength. Steel fibers added in a 1.5 % volume ratio showed a 40 % increase in tensile, flexural strength. The inclusion of 20 kg/m^3 of basalt fibers resulted in about 60 % increase of tensile, flexural strength compared to plain concrete tensile strength (without fibers). An improvement of flexural capacity was observed as compared to control reinforced concrete beams without fibers. The results of these tests clearly showed the improvement of failure behavior of SFRC and BFRC beams under load without brittle destruction due to a quasi-plastic characteristic of concrete.

(Patil and Kulkarni, 2014) presented the comparative study of effect basalt, glass and steel fibers on the compressive and flexural strength of M40 grade concrete. The fibers were put in concrete randomly by (0.25 %, 0.5 %, 0.75 %, and 1 %) of their total volume of concrete. Test results showed that for every percentage of basalt fibers i.e. 0.25 %, 0.5 %, 0.75 %, 1 % the flexural strength of BFRC which are (19.16 %, 31 %, 9.8 %, 1 %) more than control beam. Similarly, for every percentage of glass fibers, the flexural strength of GFRC which is higher than reference beam by 9.08 %, 17.1 %, 4.24 %, 0.2 % respectively. Also, for each ratio of steel fibers the flexural strength of steel which is higher than control beam by 13.14 %, 24.3 %, 8.7 %, 2.29 %. The results showed the maximum flexural strength for 0.5 % volume fraction of each type of fibers.

(Patil and Kulkarni, 2014) studied seven full-scale steel fibers reinforced self-consolidating concrete beams to find the impacts of macro steel fibers on the flexural performance of reinforced self-consolidating concrete beams. The maximum flexural strength of reinforced self-consolidating concrete beams increased significantly with increasing of fibers contents, and the impact of steel fibers was more pronounced for beams compared to lower reinforcement ratio. Steel fibers played a substantial role in decreasing the steel reinforcement strain relative to the beams without steel fibers at the same load value. Including of 50 kg/m^3 steel fibers in the beam with reinforcement ratio 0.76 % made better than a beam with reinforcement ratio 0.96 % in terms of yielding and ultimate load. It is showed that adding 50 kg/m^3 steel fibers in reinforced self-consolidation concrete beam could be replaced reinforcement ratio by about 0.2 %.

(Lee et al., 2017) studied the effects of concrete strength and fibers content ratio on the flexural strength of SFRC. Three fibers volumetric percentage ratios, 0.25 %, 0.375 %, and 0.5 %, and three concrete compressive strengths, 25, 35, and 45 MPa, were considered for the experiments. The results displayed that the equivalent flexural capacity ratio increased with the increase in the fibers volumetric percentage ratios but decreased with the increase in the concrete strength.

(Lee, 2017) tackled the direct residual flexural strengths of steel fibers reinforced concrete beams with various concrete strengths, 25, 35, and 45 MPa, and fibers volumetric percentage ratios, 0.25, 0.375, and 0.50%. The fibers reinforced concrete beams with a strength of 45 MPa displayed a higher increase in the residual flexural capacity immediately after concrete cracking, particularly for fibers volume fraction of 0.5 %. On the other hand, as concrete cracking propagated, the residual flexural strength and energy absorption capacity values rapidly decreased in the beams with a concrete strength of 45 MPa.

(Biolzi and Cattaneo, 2017) presented the inclusion of steel fibers enhances the mechanical behavior,I.e., flexural and shear capacities and the ductility of the flexural members.

1.4 Research Objectives

The aim of this thesis is studying the structural behavior of beam specimens by an experimental study on the SFRC, HYFRC and Control Beam CB beams. For this purpose, SFRC and HYFRC beams were tested in laboratory and load-deflection curve, mechanical properties were obtained. The experimental of SFRC, HYFRC results are compared numerically and graphically with CB.

1.5 Layout of the Study

Chapter one is a general introduction of FRC and a literature review and objectives of this research are also discussed in this chapter.

Chapter two, presents fiber types, fibers properties, use of fibers in reinforcing concrete and FRC.

Chapter three, gives a detailed descreption of the experimental work in this study .

Chapter four, covers the analysis of the experimental results and a discussion regarding the beam test .

Chapter five, dicusses the conclusions of this work and recommendations for future study.

CHAPTER 2

TYPES OF FIBERS

2.1 Potential Uses of Fibers Reinforced Concrete

An artificial stone material called concrete has been known to mankind for thousands of years. Despite high compressive strength, they have always the same problem - low resistance at the break and shrinkage cracks during solidification. Many builders are often faced with many challenges while working with concrete, such as dust, plastic shrinkage, and subsidence, the frost effect (at the early stage). Moreover, during further operation shows properties such as low resistance to freeze/thaw cycles, low shock resistance, abrasion liability, high penetration of water and chemicals. The ancient builders have beam with this, adding materials with higher strength and flexibility and materials that increase the uniformity of the curable mortars.

Fibers are used to improve the mechanical properties of concrete, especially the post cracking tensile resistant. Additionally, they have recently been used as an another engineering material instead of steel bars/steel stirrups in short-span concrete slabs. FRC construction is more economical than conventional construction. In addition to cost reduction, FRC have another beneficial property such as higher stiffness, higher ductility, lightweight, low repair costs, and better post-cracking and dynamic behavior. FRC has been used extensively in the construction of industrial floors, bridge deck overlays, airport runways, highway pavements, tunnel linings, spillways, dams, slope stabilizations, and many precast products. On the other hand, relatively little use of fibers reinforced concrete in the building structure is mainly due to the lack of design provisions in building codes. Fibers can improve the characteristics of hardened concrete. Fibers added concrete have been utilized at an expanding rate in several application (Behbahani, 2010) for instance :

Highway and Airfield Pavements: In the maintenance of damaging road way or in new road way erection can be utilized fibers by tied and un tied overlays to the slab beneath. The main benefits are: minimize of needed roadway thickness due to high flexural strength; the inclusion of steel fiber increases the strength to frequented and shock loading. The longitudinal and transverse joint intervals can be expanded. in the case of restricted shrinkage, fibers reduce the crack width less than the plain concrete due to high tensile strength capacity.

Hydraulic Structures: The main benefit of applying FRC in hydraulic constructions such as weir, and dams is its to avoid corrosion or cavitation impact by high-velocity water discharge.

Fibers Shotcrete: Fiber shotcrete were utilized in rocky slopes fixation, tunnel lining, and bridge maintenance. A fine cover of plain shotcrete used monolithically above the fibers shotcrete, can be used to stop surface smearing due to oxidizing. In addition to typical shotcrete benefits, the fiber is arranged in a plane by the technique of usage of the relatively fine cover.

Refractory Concrete: Fiber reinforced stiff concretes has been produced to be stronger than their corresponding unreinforced when applied to high thermal stress, mechanical abuse, thermal cyclic or thermal shock. The enlarged service spans are almost caused by the incorporation of crack limitation, improve toughness, the spall and erosion resistance transported by the fibers.

Precast Application: They are involved manhole covers, pipes made by concrete, machine foundation, and structures. Developed flexural and influence strengths may be permitted the applying of fibers concrete components in rough handling situations.

Structural Applications: The opportunities below can be represented for the usage of FRC in structural elements:

a) Fibers reinforcement can be provided an enhance influence strength to traditional reinforced beams and this, improvement resistance to local deterioration.

b) Fibers strengthening may prevent crack propagation and crack expansion; this can permit the utilize of high strength steel bar without redundant crack widths or deformations at applies loads.

c) Fibers strengthening gives ductility into traditional reinforced concrete elements, and hence, improves their constancy and solidity under earthquake and explosion loading.

d) Fibers strengthenin improves the shear risistence of plain concrete. As a effect, punching shear risistence of slabs is improved and unexpected punching failure can be converted to gradual ductile failure .

2.2 Different Types of Fibers

There are two ways in order to classifying fibers baced on their origin or their modulus of elasticity. The concept of the modulus of elasticity, fibers may be classified within two main classes, i.e., they are had a higher elastic modulus more than plain concrete (named tough involvement) and those with lower elastic modulus (named soft involvement).Glass, steel, and carbon have higher elastic moduli more than plain concrete, and vegetable fibers and polypropylene have the low modulus of fibers. High modulus fibers enhance both influence strength and flexural in the same time. While, low modulus fibers enhance the impact strength of plain concrete however do not assistance greatly to concrete flexural strength.

Based on the origin of fibers, fibers are categorized within three group of organic, mineral, and metallic. This system of categorization is commonly applied. Figure 2.1 provides the categorization of fiber. The communal kind of fibers are the stainless steel fibers, steel fibers, carbon fibers, steel fibers, and metallic stainless steel. Glass fibers are normal fibers in the group of mineral fibers. Organic fibers may be furthermore divided within human-made and natural fibers. Natural fibers may be divided into animal and sisal source or vegeyable source. For instance, leaf fiber and wood fiber are the vegetable origin, whereas silk and hair fiber is of animal source fiber. Industrial fibers may be categorized within two collections; they are synthetic fibers and a natural polymer. For example, cellulose and protein fibers are from a natural polymer, while nylon and polypropylene are synthetic fibers. Table 2.1 gives the specification of several kinds of fibers that are utilized in the civil engineering area.

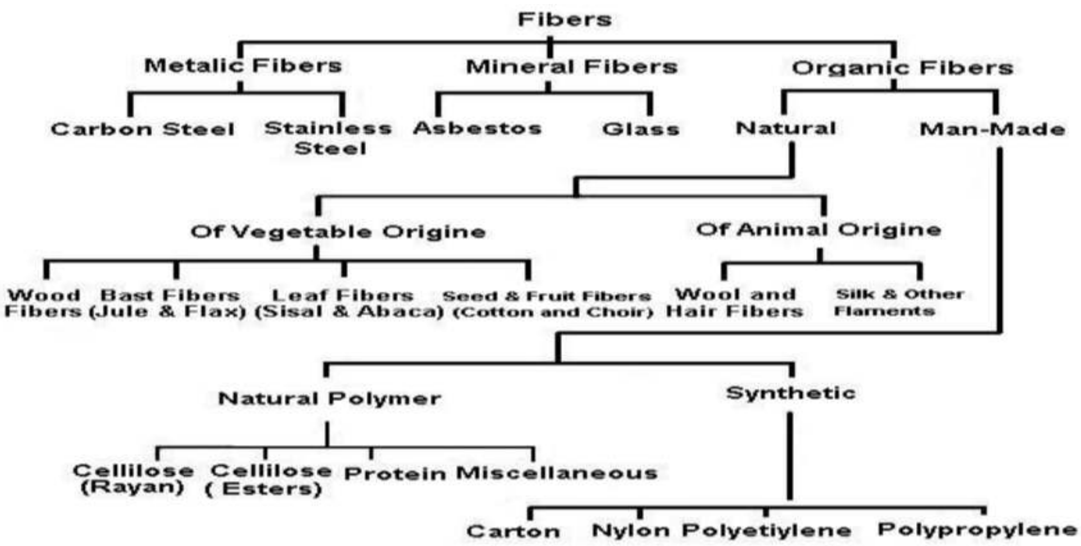


Figure 2.1 Shows fiber classifications (Behbahani et al., 2013)

Table 2.1. Present the typical properties of various types of fibers adopted from (Bentur and Mindess, 2006)

Type of Fibre	Diameter [μm]	Specific gravity [g/cm^3]	Tensile strength [MPa]	Elastic modulus [GPa]	Ultimate elongation [%]
Metallic					
Steel	5-1 000	7.85	200-2 600	195-210	0.5-5
Glass					
E glass	8-15	2.54	2 000-4 000	72	3.0-4.8
AR glass	8-20	2.70	1 500-3 700	80	2.5-3.6
Synthetic					
Acrylic (PAN)	5-17	1.18	200-1 000	14.6-19.6	7.5-50.0
Aramid (e.g. Kevlar)	10-12	1.4-1.5	2 000-3 500	62-130	2.0-4.6
Carbon (low modulus)	7-18	1.6-1.7	800-1 100	38-43	2.1-2-5
Carbon (high modulus)	7-18	1.7-1.9	1 500-4 000	200-800	1.3-1.8
Nylon (polyamide)	20-25	1.16	965	5.17	20.0
Polyester (e.g. PET)	10-8	1.34-1.39	280-1 200	10-18	10-50
Polyethylene (PE)	25-1 000	0.96	80-600	5.0	12-100
Polyethylene (HPPE)	-	0.97	4 100-3 000	80-150	2.9-4.1
Polypropylene (PP)	10-200	0.90-0.91	310-760	3.5-4.9	6-15.0
Polyvinyl acetate (PVA)	3-8	1.2-2.5	800-3 600	20-80	4-12
Natural - organic					
Cellulose (wood)	15-125	1.50	300-2 000	10-50	20
Coconut	100-400	1.12-1.15	120-200	19-25	10-25
Bamboo	50-400	1.50	350-50	33-40	-
Jute	100-200	1.02-1.04	250-350	25-32	1.5-1.9
Natural - inorganic					
Asbestos	0.02-25	2.55	200-1 800	164	2-3
Wollastonite	25-40	2.87-3.09	2 700-4 100	303-530	-

Many various kinds of fibers can be utilized in fibers reinforced concrete. Manufacturers produce fibers out of steel, polymers, and basalt, among others. Historically, there have also been employed numerous types of fibers of natural origin in buildings. One of these is asbestos. Asbestos was used as reinforcement in fibers cement wallboards (eternite or asbestos cement) in the middle of the last century. This is prohibited today because the material is carcinogenic (Olimb, 2012).

The behavior of fibers reinforced concrete is categorized within three groups based on the usage, fibers volumetric percentage ratios, and fibers efficiency. Such classifications lead to (Behbahani, 2010):

i. Small volumetric percentage ratios of fibers less than 1 %, that is utilized for several decades now for example pavement reinforcement or early-age plastic shrinkage control.
ii. Moderate volumetric percentage ratios of fibers existed between 1 % to 2 %, for example, used in each cast-in-place and construction elements for their enhanced fracture toughness, modulus of rupture, and impact resistance.
iii. High volumetric percentage ratios of fibers more than 2 % for critical purposes for example blast and impact strength constructions.

The Change of conventional reinforcing bars with fibers has the advantages presented below (Grzybowski, 1989; Rapoport et al., 2002; Grzybowski and Shah, 1990):

i. Fibers improve the tensile resistance of the concrete mix, thereby enhancing the shear resistances and flexural of concrete matrix.
ii. The bridging mechanism of fibers and its tendency to redistribute stress evenly throughout the concrete mix participate to post-cracking strength, inhibit crack.
iii. Developed and impart ductility to concrete mixture.
iv. FRC is more strong and useful than traditional reinforced concrete
v. Making and setting conventional rebar's needs time and costly labor. Thus, apply of fibers in concrete mix economies labor costs and time.

In 1910, Porter first suggested applying steel fibers in the concrete mix (Naaman, 1985). However, the first scientific test of FRC in the United States had been produced in 1963 (Romualdi and Batson, 1963). FRC is manufactured utilizing the conventional ordinary cement, fine and coarse aggregates, water and discrete discontinuous strengthing fibers. To improve the workability and constancy of FRC, superplasticizers (chemical addition) can be utilized within concrete mix. Fibers are commercially available and made of plastic, steel, glass and other naturalistic elements. Engineering limitations of fibers meet its shape, material, length, diameter, and kind of cross-section as shown in Figure 2.2. Steel fibers can be realized as discrete, short lengths of steel having ratio of their length to diameter (i.e. aspect ratio) in the range of 20 to 100 with any of the many cross section, and that are sufficiently small to be easily and randomly dispersed in fresh concrete mix using conventional mixing procedure (ACI544.1R, 2002).

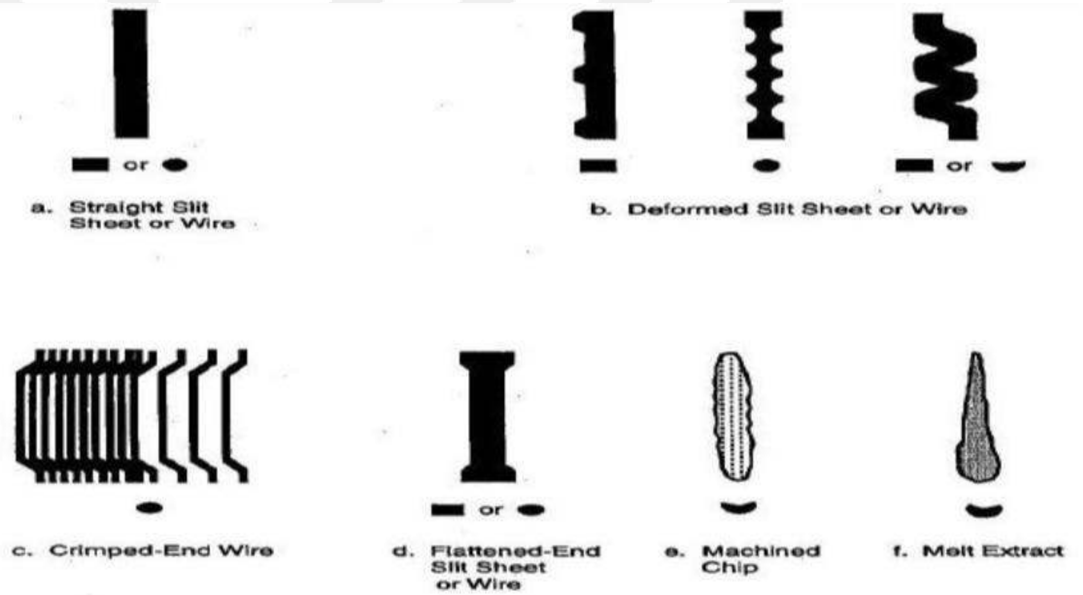


Figure 2.2 Different shapes of steel fibers (ACI544.1R, 2002)

2.1.1 Steel Fiber

The steel fibers may appear in different forms. Their cross sections contain circular, rectangular, half-round, and irregular or varying cross-sections. They can be straight or bent and come within different measures. An appropriate numerical parameter named the aspect ratio can be utilized to display the geometry. This ratio is the fiber length divided by the diameter. If the cross-section is not round, then the diameter of a circular section with the equivalent area is utilized. Standard limitation for steel fibers for FRC provides a classification of five common kinds of steel fibers according to their manufacturing process (ASTM et al., 2006); they are as follows:

1. Type I, cold-drawn wire
2. Type II, cut sheet
3. Type III, melt-extracted
4. Type IV, mill cut
5. Type V, modified cold-drawn wire

Type I fibers have tensile strengths ranging from 1000 to 3000 MPa, while Types II, III, IV, and V have a tensile strength as low as 350 MPa. Fibre shapes vary from round wires with deformed ends (Type I), rectangular or square rod shapes with dimples (Type II), triangular cross-section and twisted (Type V), or crescent cross-section and corrugated (Type V), as well as other shapes. They also come in different lengths, ranging from 5 mm to more than 50 mm. Longer fibers tend to perform better. However, they can be harder to mix well into the concrete. Figure 2.3 illustrates hooked end, waved, and straight fibers.

Figure 2.3 Fiber shapes (Ghoraishi et al., 2011)

2.1.2 Glass Fibres

The appropriate ASTM standard (C167-71) defines glass, as “an inorganic product of fusion which has cooled to a rigid condition without crystallizing.” Because glass is amorphous, it is isotropic and has a glass transition point rather than melting point. Its tensile strength in fibers form is approximately ten times more than in bulk form. Because of their high strength, high-performance capabilities, glass fibers are used as strength giving the material in structural composites such as rocket motor cases, pressure bottles, and aircraft parts. There are several characteristics of glass fibers come from their nature which makes them ideal reinforcements (Lubin, 2013). There are several types of glass fibers used in composites, the most widely used of which may be E-glass or electrical glass (Alsalihi, 2014). It has comparably low cost, and excellent strength and stiffness, but it is somewhat weak in impact endurance (Alsalihi, 2014). S-glass (also called R-glass or T-glass) is another type of glass fibers that possess high strength and high modulus, as well as a higher price in comparison to the E-glass (Alsalihi, 2014). Other types are A-glass (alkali resistant glass fibers) and C-glass (chemical resistance glass fibers) (Somboonsong, 1997), (Alsalihi, 2014). One of the disadvantages of glass fibers is their relatively low modulus compared with other types of fibers such as carbon or steel fibers (Sayed-Ahmed and Shrive, 1999). Other than their use in the structural field and in the aerospace industry, glass fibers are employed in the making of "thermal insulators, boat hulls, lightweight parts of automobiles, and rubber tires" (Somboonsong, 1997). Here are some properties of glass fibers (Lubin, 2013):

i. Superior Tensile Strength; glass fibers have very high tensile strength.
ii. Perfect Elasticity; glass fibers obey Hooke’s law. Typical glass fibers have a maximum elongation of 5 % at break.
iii. Attractive Thermal Properties; they have a low coefficient of thermal expansion and high thermal conductivity.
iv. Excellent Moisture Resistance; glass fibers do not absorb moisture.
v. Outstanding Dimensional Stability; glass fibers do not shrink or stretch.
vi. Excellent Corrosion Resistance; they resist all organic solvents and most acids and alkalis.
vii. Excellent Electrical Characteristics; glass fibers have high dielectric strengths and low dielectric constants.
viii. Low Cost; compared to other fibrous reinforcements, glass fibers have low cost.

2.1.3 Basalt Fibers

Basalt is a volcanic rock that has been flowed above the earth surface. Basaltic magma is widely produced by direct melting of the earth's mantle, the region of the earth below the outer crust. Basalt is composed mainly of silica and alumina with lime, magnesium oxide and ferric oxide noticed in lesser proportion (Ramakrishnan and Panchalan, 2005). Basalt fibers are made in a single-stage operation by melting pure raw material and are manufactured from very fine fibers of basalt. They are environmentally secure and non-toxic, possess high heat stability and insulating characteristics and have an elastic structure.

When utilized for combined materials, they give individual mechanical characteristics. It is recognized that basalt fibers have bested tensile resisters than E-glass fibers, maximal failure strain than carbon fibers as well as perfect strength to chemical attack, impact load and fire with less poisonous fumes (Sim and Park, 2005). Also, BFRC may hold big elastic deformations because basalt fibers do not have plastic deformation at elongation, and has better elasticity characteristics than steel fibers. The major properties of basalt reinforced concrete are its large durability in all cases of stress and the capability to endure big deformations in the elastic case. Physical and technical utility that may be reached by adding basalt fibers into the concrete element:

i. Low level of fine cracks.
ii. Improve concrete fatigue strength and resistance.
iii. Improve frost resistance.
iv. Improve water tightness.
v. Improve surface endurance of concrete.
vi. Reduction slivering of corners and edges.
vii. Provided an early compressive strength.

2.3 Disadvantage of Addition of Fibres into Concrete

The only disadvantages of FRC would be its reduced workability and accelerated stiffening of fresh concrete mixture cause the addition fibers. This increase construction labor and time due to the excessive vibration that is needed to make the FRC workable. The issue could be slightly overcome by the utilize of recently advanced high range superplasticizers that not only improve the workability of FRC but also keep the plasticity of the concrete mix for a longer time.

2.4 Hybrid Fibers Reinforce Concrete

All conventional fibers reinforced concrete materials include the utilize of a single fibers type. The single fibers can be active only in the limited range of strain and crack opening. Therefore, a given type of fibers can improve only strength or ductility of cementitious composites (Banthia and Gupta, 2004). Some of the high modulus and high strength fibers including carbon, polyvinyl alcohol, steel, and asbestos fibers can effectively increase the strength of concrete. However, their intrinsic brittle behavior does not allow for ductility improvement. Low modulus strength fibers including polypropylene, basalt, and glass fibers are more useful in ductility improvement and reduce cracking (Soe et al., 2013), (Halvaei et al., 2016), and (Halvaei et al., 2015). Therefore, to obtain a cementitious composite with both improved strength and ductility, combining fibers with different chemical/mechanical properties is necessary.

Three stages of crack formation can be distinguished from the crack evaluation of FRC composites: micro-crack formation prior to peak load, coalescence of fine micro-cracks into one micro-crack, and after that propagation of a micro crack (Rossi et al., 1987). By this evaluation, the combination of different fibers types as reinforcement in cementitious materials was proposed. Since two or more combined fibers are used in the cementitious composite, they provide different responses to cracking process during various stages of loading. The resulting fibers-reinforced concrete containing a combination of two or more fibers is often called HYFRC. Therefore, HYFRC are appointed to the cementitious matrix incorporating a various kind of fibers which result in hybrid performances which exceed the sum of individual fibers performances (Banthia and Gupta, 2004). The hybrid composite derives the benefits from each of the individual fibers and exhibits a synergetic response (Banthia and Soleimani, 2005), (Banthia and Nandakumar, 2003), and (Shu et al., 2015).

Some researchers have demonstrated that hybridization of two or more different types of fibers produces cementitious composites with improved ultimate strength, strain capacity and strain hardening behavior (Ahmed and Mihashi, 2011), and (Nguyen et al., 2013). The various methods of hybridization include mixing various lengths, diameters, modulus and tensile strengths of fibers (Silva et al., 2013), and

(Ahmed and Maalej, 2009). On this basis, the advantages of different ways of hybridization are as follows:

i. Hybrid based on fibers size (length and diameter): since the sizes of fibers are different, the fibers with small size bridges micro cracks and therefore controls their coalescence while the larger one is intended to arrest the propagation of macro-cracks Figure 2.4. Controlling the micro-crack and macro-crack results in a higher strength and a substantial improvement in the fracture toughness of composite, respectively (Banthia and Gupta, 2004). As a result of this synergetic mechanism, the ductility enhancement depends mainly on long fibers (Marković, 2006). Fibers dimensions are often described using the Specific Surface Area (SSA) which can be defined as the surface area for a unit mass (Banthia et al., 1995).

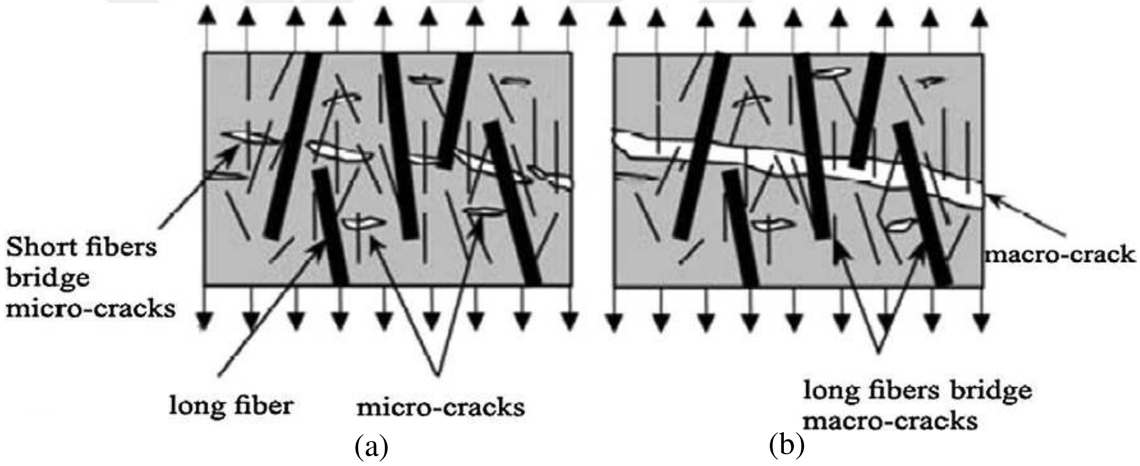


Figure 2.4 Action of the hybrid fibers with different size, (a) first phase, and B second phase of loading (Marković, 2006)

ii. Hybrid based on fibers modulus: since two fibers with different flexibility are used in the cementitious composite, stronger and stiffer fibers provide the first crack stress and ultimate strength while the relatively flexible fibers lead to enhanced toughness and strain capability in the post-cracking zone. In some recent research, hybridization of fibers in cementitious composite further was used to obtain higher strain capacity, durability enhancement and produce viable products in comparison to individual fibers reinforcement.

In hybrid fibers reinforcement, stronger and stiffer fibers can improve the strength of concrete due to the high elastic modulus and stiffness; while low modulus fibers can improve the ductility and toughness of hybrid fibers reinforced concrete (Banthia et al., 2014). The hybrid fibers reinforcement offers some additional benefits in the physical and mechanical properties compared to composites containing one type of fibers as shown in Table 2.2.

Table 2.2 Summarized data on physical/mechanical properties of HYFRC

Hybrid fibers								**Properties (effectiveness*-%)**	**Refs.**
Part A				Part B					
Type	L_f (mm)	D_f (μm)	V_f. (%)	Type	L_f (mm)	D_f (μm)	V_f. (%)		
Hooked end ST	30	800	0.73	PP	12	NR	0.2 5	Toughness = 17.43 N-m (-10) Equivalent flexural strength ratio = 0.53 (-7) Energy absorption in impact test = 18.45 (-18.2)	(Rashiddadash et al., 2014)
Hooked end ST	35	550	0.5, 1.0	Fibrillated PP	12	16	0.2 , 0.4	Compressive strength = 26.5 MPa (_8.3) Total energy = 0.28 MPa (+7.1) Tensile strength = 2.5 MPa (_39.0) Bulk density = 1880 kg/m3 (+0.5) Flexural strength = 7.3 MPa (+15.8) Total energy = 71,112 N.mm (+36.1)	(Libre et al., 2011)
Hooked end ST	30	500	0.38	PP PET	20 12	100 50	0.1 2	Compressive strength = 61.1 MPa (+3.2) Split tensile strength = 5.3 MPa (+1.9) Flexural strength = 6.72 MPa (+11.4) Flexural toughness = 22.67 N.m (+6.1)	(Sivakumar and Santhanam, 2007)
Hooked end ST	30	500	0.2	PP	15	100	0.3	Compressive strength = 45.3 MPa (_5.2) Modulus of rupture = 5.8 MPa (_15.5) Split tensile strength = 4.5 MPa (_7.0) Toughness index (I10) = 6.3 (_20.1)	(Yao et al., 2003)
Hooked end ST Deformed end ST	30	500	0.3 0.5	Cellulose	2.3	16	0.5	Compressive strength = 54–61 MPa (**) Flexural toughness factor = 4.9–5.7 MPa (*) Shear strength = 18.8–24.2 MPa (*)	(Banthia et al., 2014)
Hooked end ST	35	550	0.28	Straight ST	13	160	0.5 6	Compressive strength = 67.2 MPa (+17.5)	(Vandewalle, 2006)

* Effectiveness is calculated on the mono-fibers type FRC at the same fibers volume fraction.

** Detailed information about the mono-fibers reinforced concrete with same fibers volume fraction is not provided.

CHAPTER 3

DEFINITION OF EXPERIMENTAL TEST OF FRC AND HYFRC

3.1 Introduction

The details of the experimental works such as the materials used, mix design, mixing procedure, preparation of formwork and the testing process are presented in this chapter. The experimental program of this study provides a further understanding of using steel fibers and combined steel fibers with another type of fibers such as glass and basalt fibers were mixed to enhance concrete characteristics. The experimental program involved testing about simply supported beam specimens subjected to two concentrated symmetrical loads. Also, cylinder split tensile strength tests, cube compressive strength test.

3.2 Material

Fibres: The steel fibers used in this study was hooked end shape. The specifications of all fibers used in this study are shown in Table3.1. Figure 3.1 illustrates the photo of all fibers employed in the manufacturing of SFRC and HYFRC beams. Chopped basalt fibers and S-Glass fibers were used in this study, also.

Ordinary Portland Cement Type II: The cement type (Cem II/B-LL 32.5 R) was kept in humidity controlled place inside a mechanical division laboratory of Gaziantep University due to weather moisture and to protect cement in appropriate conditions. The physical and chemical features of the cement are presented in Table 3.2.

Figure 3.1 (a) basalt fibers, (b) glass fibers, and (c) steel fibers.

Table 3.1 Fibers specification

Fibers type	**D (µ mm)**	**L (mm)**	**L/D**	**Modulus of elasticity (GPa)**	**Specific of gravity (kg/m³)**	**Tensile strength (MPa)**
Steel fibers	55	30	55	-	7850	1500
Glass fibers	13	12	-	77	2600	3400
Basalt fibers	13-20	12	-	89	2800	4100-4800

Table 3.2 Cement features

Parameters	**Cement (%)**
CaO	63
Silica (SiO_2)	22
Alumina (Al_2O_2)	7.7
Iron oxide (Fe_2O_2)	3.3
Others	4

Coarse aggregate (gravel) and fine aggregate (sand): The gravel was 10 mm maximum size, and the sand used was natural river sand employed in this study.

Water: For mixing and placing concrete, domestic water was utilized, which in turn required for cement hydration process and give satisfied workability.

Water Reducer: To produce adequate workability of concrete mix, Superplasticizer grade 50 (1.8 kg/m3) was used because it has low water cement ratio and the existence of fibers.

3.3 Beam Fibers' Volumetric Percent

The experimental program consisted of ten beam specimens of the same size. The first one did not contain any fibers CB. The first group A specimens were reinforced with 0.5 %, 1 %, 1.5 % volumetric ratio of hooked-end steel fibers, the second group B specimens have been strengthened with 0.25 % steel fibers and 0.75 % basalt fibers, 0.5 % steel fibers, and 0.5 % basalt fibers, 0.75 % steel fibers and 0.25 % basalt fibers volumetric ratio, the third group C specimens were reinforced with 0.25 steel fibers and 0.75 % glass fibers, 0.5 % steel fibers and 0.5 % glass fibers.0.75 % steel fibers and 0.25 % glass fibers. Table 3.3 shows the detail of these specimens. The system used to identify the specimens was based on two parts. The first section of the specimen name refers to its fibers type in the sequence. The second part relates to the volumetric ratio system that was used such as SF0.50 which refers to steel fibers with 0.5 % volumetric ratio.

Table 3.3 The detail of the beams fiber's volumetric percent

Group	Concrete mix	GF by a volumetric ratio %	ST by a volumetric ratio %	BF by a volumetric ratio %
-	CB	-	-	-
A	SF 0.5	-	0.5	-
	SF 1.0	-	1.0	-
	SF 1.5	-	1.5	-
B	SF 0.75 BF 0.25	-	0.75	0.25
	SF 0.5 BF 0.5	-	0.5	0.5
	SF 0.25 BF 0.75	-	0.25	0.75
C	SF 0.75 GF 0.25	0.25	0.75	-
	SF 0.5 GF 0.5	0.5	0.5	-
	SF 0.25 GF 0.75	0.75	0.25	-

3.4 Beam Geometry

Nine FRC and CB with 1500 mm long are elected for the flexural experiments. Figure 3.2 shows the cross-section, loading and supporting of the beam. Beam reinforcement consists of four steel bars, two of them (8 mm diameter) used above neutral axes and the rest (10 mm diameter) under neutral axes. To obtain pure bending failure for longitudinal bars, shear reinforcement was calculated and placed. Fifteen stirrups made from 5 mm diameter bar of mild steel, were set at 100 center to center in the shear span. All beams with the same cross-sectional dimensions of 150 x 200, were provided. The geometry of beam layout depicted in Figure 3.2.

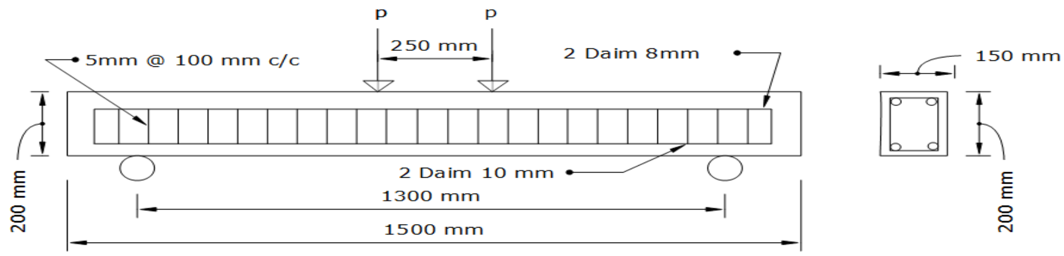


Figure 3.2 Beam geometry and reinforcement details

3.5 Mix Design

The standard mix design was used for control beam CB, SFRC, steel-glass fibers reinforced concrete and steel-basalt fibers reinforced concrete. The details of mix proportion for all beams are given in Table 3.4. For all mixes, water - cement ratio was maintained at 0.48.

Table 3.4 The details of mix proportion by (kg/m^3)

Group	Concrete mix	Cement	Water	Coarse aggregate	Fine aggregate	SP	GF	ST	BF
-	CB	400	192	1110	600	1.8	-	-	-
A	SF 0.5	400	192	1110	600	1.8	-	39.25	-
	SF 1.0	400	192	1110	600	1.8	-	78.5	-
	SF 1.5	400	192	1110	600	1.8	-	117.75	-
B	SF 0.75 BF 0.25	400	192	1110	600	1.8	-	58.875	7
	SF 0.5 BF 0.5	400	192	1110	600	1.8	-	39.25	14
	SF 0.25 BF 0.75	400	192	1110	600	1.8	-	19.625	21
C	SF 0.75 GF 0.25	400	192	1110	600	1.8	6.5	58.875	-
	SF 0.5 GF 0.5	400	192	1110	600	1.8	13	39.25	-
	SF 0.25 GF 0.75	400	192	1110	600	1.8	19.5	19.625	-

3.6 Fabrication of Specimens

Reinforcement cages were constructed at Gaziantep University Lab. First, the reinforcement bars were cut to the required length. Second, the formwork was built using plywood with 200 mm depth,150 mm width and 1500 mm length and the interior faces of the formwork were oiled before concrete placed. Figure 3.3 shows some examples of the laboratory site preparation. Type II cement, river sand, and river aggregate were used. The mix proportion used for this work is shown in Table 3.4. However, the required amount of each type of fibers was determined depending on the specific gravity. Table 3.4 illustrates the amount of fibers used one cubic meter. The mixing of the materials was done at Gaziantep University's Lab using 0.25 m^3 mixer. Fine and coarse aggregates were first mixed for two minutes.

Figure 3.3 Fabrication of reinforcement cages and formwork

Then cement was added and left to be mixed for another two minutes, then Superplasticizer and water were combined in water and added to the mix. Fibers were the last ingredient to be added. To ensure a sufficient mixing and distributing of fibers, the concrete was mixed for five minutes.

For casting the specimens, a fresh concrete mix was prepared as shown in Figure 3.4. It was transferred from the mixer machine to the beam formwork using a concrete transporter truck. The concrete was poured into a ready formwork with reinforcement. The vibration was applied to consolidate the mix. In order to have a uniform distribution of the fibers and prevent segregation occurrence. Figure 3.4 demonstrates the finishing of the surface to provide a smooth surface and avoid fibers stick-out. After casting on the following day of casting, formwork's of the beams were stripped. The curing of the beam specimens started on the second day. The beams were covered with a layer of waterproof material and kept moist for twenty-eight days. This method of curing is termed as membrane curing ASTM 156. For the cylinders and cube, concrete was cast in plastic test cylinders and cube. On the second day, they were opened and moved to the curing pool.

Figure 3.4 Proportioning, mixing and casting of beam specimens

3.7 Specimens Testing Procedures

3.12.1 Compressive Strength Test

Three cubical specimens were molded for each beam specimen. Therefore, each FRC beam specimen had at least three cubical specimens. In order to ensure a fibers distribution similar to the one in the beams, “100 x 100 x 100 mm” cubes were used. The cubes were sampled, compacted, cured and tested following the ASTM specifications (ASTM C172, 2007), (ASTM. C39/C39M, 2003), and (ASTM. C31/C31M, 2003). A plastic cubical mold that can be covered with a plastic lid was used in order to keep the moisture for more than one day. After one day the plastic molds were molded, and the cubes were moved to the curing room until the testing day. A BESMAK digital series compression machine, which is shown in Figure 3.5, was utilized to find concrete compressive strength. Load carrying capacity and strength (MPa) were recorded after the failure of the specimen.

Figure 3.5 Concrete compressive test machine

3.12.2 Splitting Tensile Strength Test

For each type of beam, three cylinders were sampled following (ASTM C172, 2007). Then they were cured based on (ASTM C31/C31M, 2003). The cylinders were taken out of the curing room after twenty-eight days. The splitting tensile test was conducted following (ASTM C496, 2007) as shown in Figure 3.6. A concrete compressive machine was used to apply the load.

Figure 3.6 Splitting tensile test machine

Standard cylinders of size 100 mm diameter and 200 mm long were utilized for casting and testing the specimens. The specimens were tested on a BESMAK digital series machine as shown in Figure 3.6.The rate of loading was 1.5 kN/min, and the ultimate load was written. Each concrete cylinder was laid in a horizontal position, and the load was applied to one of the long sides which creates uniform tensile stress in the cylinder. The specimen splitting tensile strength can be found out applying the equations (3.1):

$$T = 2P/\pi ld \tag{3.1}$$

Where:

T = splitting tensile strength, MPa

P = maximum applied load, N

d = diameter of the cylinder, mm

l = height of the cylinder, mm

3.12.3 Beam Flexural Strength Test

A load contains system was used to test the beam specimens. This system consists of a hydraulic actuator with 250-kn load capacity. The applied load on the beam specimens was determined by a load cell while a linear variable differential transformer (LVDT) determined the defection of the specimens. Figure 3.7 displays the beam inspection setup. Flexure test was conducted on the beams to study its flexure behavior. Standard specimens of dimension 1500 x 200 x 150 mm were poured. The casting and testing procedure as per the specifications provided by (ASTM C1609, 2007) were followed. The specimens were rested on the supports with a clear span of 1300 mm. The testing was performed on an INSTRON testing machine at an average rate of displacement 0.2 mm/sec as shown in Figure 3.7.

The flexural strength was calculated applying the following formula (3.2):

$$f = \frac{PL}{bd^2} \tag{3.2}$$

Where,

f = the strength, MPa,

P = the load, N,

L = the span length, mm,

b = the average width of the specimen at the fracture, as

oriented for testing, mm, and *d* = the average depth of the specimen at the fracture, as

oriented for testing, mm.

Figure 3.7 Flexural Beam test and beam failure

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 General

This section shows the overall results of experimental work of the research. These cover compressive and split tensile strength test and flexural strength test of the concrete with the increase of steel fibers, hybrid fibers (steel-glass, steel-basalt). To find the optimum volumetric ratios of fibers, and a detailed analysis of the fibers reinforced concrete beams considering the flexural performance of FRC beams and CB contain conventionally reinforced bars. Each is discussed separately to characterize the performance of the reinforced concrete beams by reviewing load versus deflection relationship and failure mode.

4.2 Mechanical properties

Table 4.1 summarizes the mechanical test results for each mix proportions used in this research. The twenty-eight day's cubic compressive strength (σ) of steel fibers and hybrid fibers are recorded in Table 4.1. The addition of fibers contributes in transforming the brittle characteristic of concrete to a ductile material. Furthermore, no important trend of enhancing compressive strength was recognized. For the first group A of the steel fibers additive with different volumetric ratios. Table 4.1, Figure 4.1, Figure 4.4 displays no important change in compressive strength, where the measured compressive strength of mix CB is 63.66 MPa, while the compressive strength of SF0.5 concert mix, which has 0.5 volumetric percentage ratio additive of steel fibers, is 61.71 MPa, which gives a reduction by 3 % when compared to the control concert mix CB, which has no fibers additives. Also, it can be seen that the addition of 1.0 % volumetric percentage ratio of steel fibers for concert mix SF1.0 gives of 62.89 MPa compressive strength, which shows a reduction by 1 % when compared to the mix CB. Concrete mix SF1.5, which has 1.5 volumetric percentage ratio of steel fibers additive, gives of 62.04 MPa compressive strength, also means a reduction by 3 % when compared to the control mix CB.

Table 4.1 Summary of compressive strength and split tensile strength result of tested cube and cylinder.

Group	Beam	σ (MPa)	FRC σ / CB σ	σ Change (%)	T (MPa)	FRC T / CB T	T Change (%)
-	CB	63.66	1	-	2.85	1	-
A	SF 0.5	61.71	0.97	- 3	6.85	2.40	140
	SF 1.0	62.89	0.99	- 1	7.03	2.47	147
	SF 1.5	62.04	0.97	- 3	6.94	2.44	143
B	SF 0.75 BF 0.25	50.37	0.79	- 21	3.66	1.28	28
	SF 0.5 BF 0.5	52.94	0.83	- 17	3.70	1.30	30
	SF 0.25 BF 0.75	49.15	0.77	- 23	3.89	1.36	36
C	SF 0.75 GF 0.25	58.72	0.92	- 8	5.56	1.95	95
	SF 0.5 GF 0.5	61.09	0.96	- 4	6.51	2.28	128
	SF 0.25 GF 0.75	55.42	0.87	- 13	4.42	1.55	55

For the second group B consist of composite fibers (hybrid) steel-basalt additive with the different volumetric ratio. From Table 4.1, Figure 4.2, and Figure 4.4 The compressive strength of concrete mix SF0.75BF0.25, which has 0.75 volumetric percentage ratio of steel fibers and 0.25 volumetric percentage ratio of basalt fibers, is 50.37 MPa,

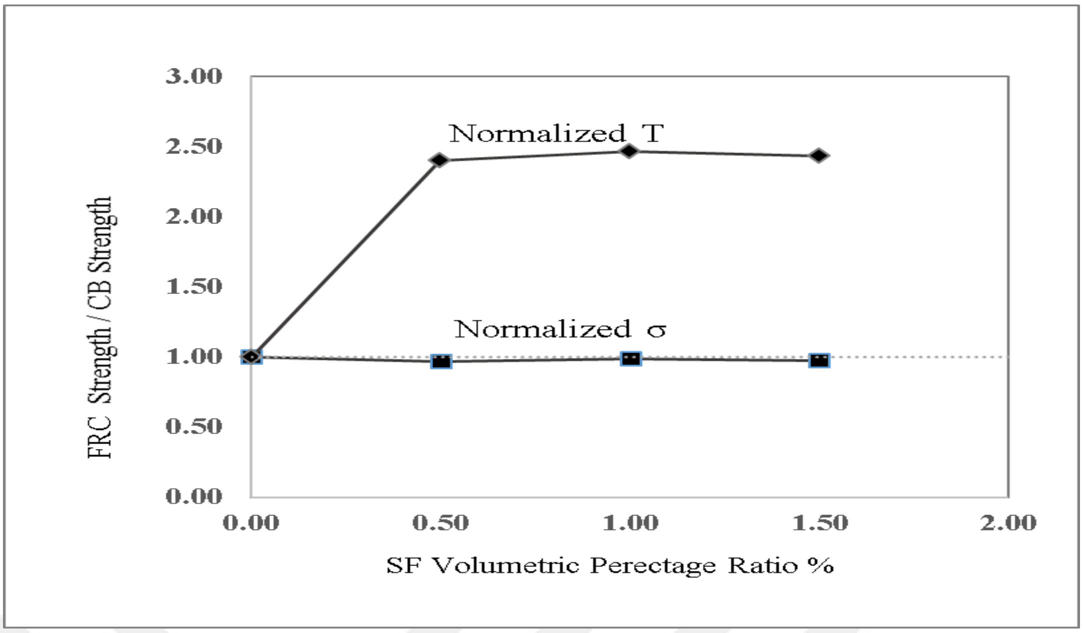


Figure 4.1 Effect of SF on concrete strength, compressive and splitting tensile strength as a unity for plain concrete

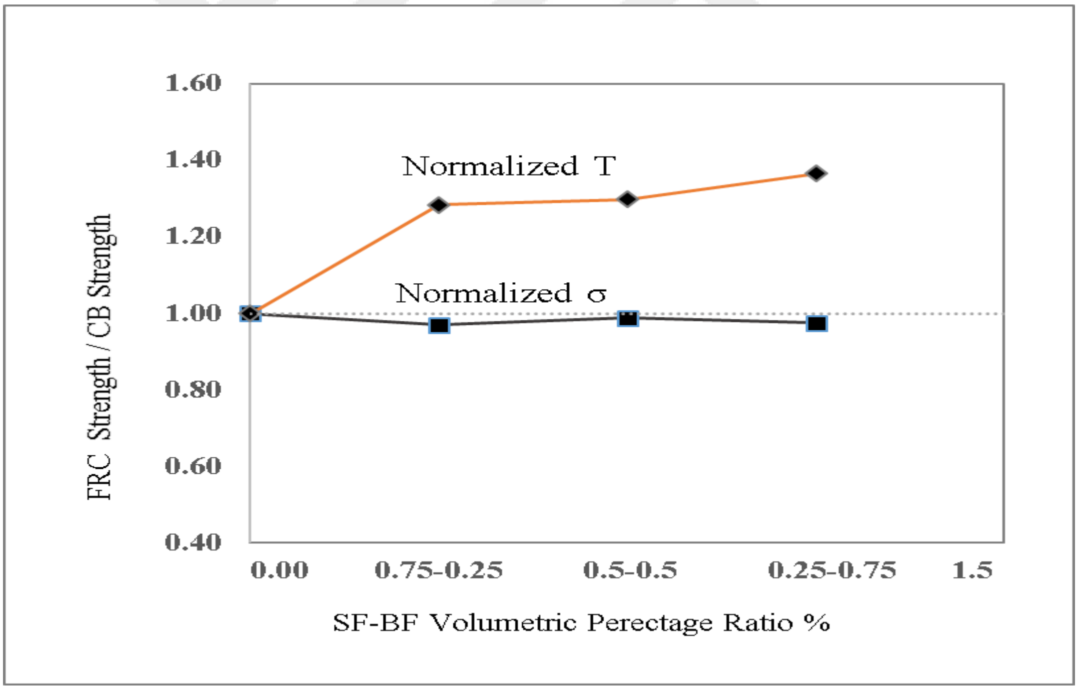


Figure 4.2 Effect of SF-BF on concrete strength, compressive and splitting tensile strength as a unity for plain concrete

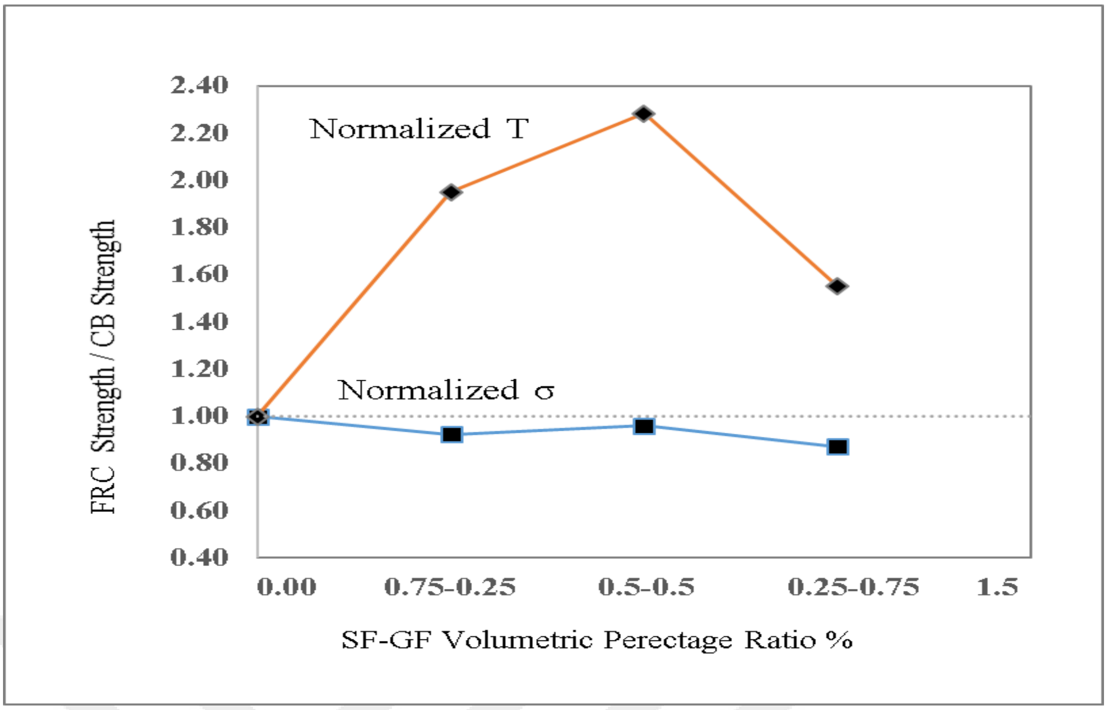


Figure 4.3 Effect of SF-BF on concrete strength, compressive and splitting tensile strength as a unity for plain concrete

which gives a reduction by 21 % when compared to the CB. Concrete mix SF0.5BF0.5 gives of 52.9 MPa compressive strength, which has 0.5 volumetric percentage ratio of each basalt fibers and steel fibers additive. SF0.5BF0.5 shows a reduction by 17 % in comparison to the CB. Furthermore, SF0.25BF0.75 concrete mix, which consists of 0.25 volumetric percentage ratio of steel fibers and 0.75 volumetric percentage ratio of basalt fibers additive, gives of 49.1 MPa compressive strength, which means the highest reduction in this group by 23 % compared to the CB. The group B result shows when reducing steel fibers additive and increase basalt fibers additive with the same value, the compressive strength decrease because of increasing basalt fibers additive reduces the density of concrete and increase the air void ratio in the concrete mix. While the cause for the decrease in compressive strength is not exactly clear, but the poor interface of basalt fibers with cement matrixes well as an increase in porosity due to the addition of basalt fibers in cement paste reported by (Jiang et al., 2014) could be the contributing factors. However, when a hybrid combination of both steel and basalt fibers are applied, the adverse effect of basalt fibers in the compressive strength is overcome. For the third group C of hybrid steel-glass fibers additive with the different volumetric ratio, Table 4.1, Figure 4.3, and Figure 4.4 give the compressive strength results. The compressive strength of concrete mix SF0.75GF0.25, which has 0.75

volumetric percentage ratio of steel fibers and 0.25 volumetric percentage ratio of glass fibers, is 58.72 MPa. This value gives a reduction of compressive strength by 8 % when compared to the CB.

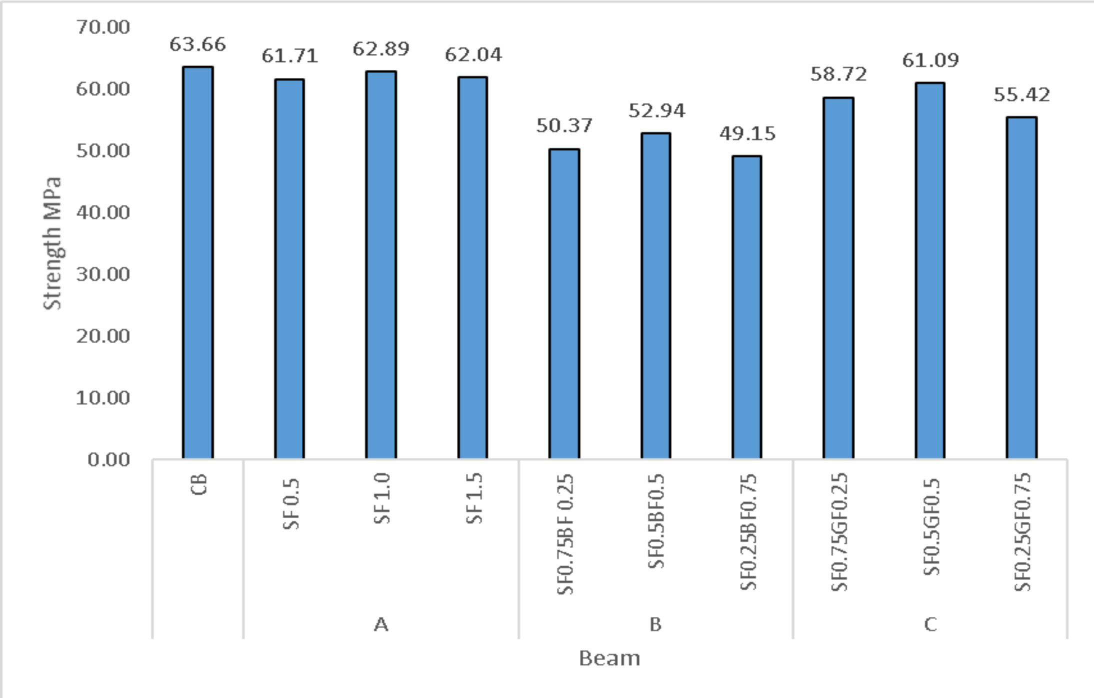


Figure 4.4 Compressive strength verse type of mixes with different percentage of steel fibers and hybrid fibers

Concrete mix SF0.5GF0.5, which has 0.5 volumetric percentage ratio for each type of additive fibers (steel and glass fibers), gives of 61.09 MPa compressive strengths. This concrete mix shows a reduction of compressive strength by 4 % when compared to the CB, while SF0.25GF0.75, consist of 0.25 volumetric percentage ratio of steel fibers and 0.75 volumetric percentage ratio of glass fibers, provides 55.42 MPa compressive strength, which shows a reduction of compressive strength by 13 % when compared to the CB. Also, there is no enhancement in compressive strength of the steel-glass additive. It is noticeable that an increasing of glass fibers and decreasing of steel fibers dosage in concrete mix started to decrease the compressive strength by occurring air void more than the control and decrease the density less than the control mix because of low specific gravity of glass fibers.

The results of the split tensile strength (T) test of concrete cylinders with the different volumetric ratio of steel fibers and hybrid fibers at 28 days are given in Table 4.1, Figure 4.1, Figure 4.2, Figure 4.3, and Figure 4.5. For the first group A of steel fibers additive with the different volumetric ratios. The results of the split tensile strength test display that addition of steel fibers up to 1.0 volumetric percentage ratio increased the split tensile strength of concrete, Where split tensile strength of concrete increased by 140 % and 147 %, with the concrete mix SF0.5 and SF1.0, respectively, which have 6.85 MPa and 7.03 MPa of split tensile strength respectively. Also, it observed that SF1.0 has the highest increase in split tensile strength. Also, when the addition of steel fibers is more than 1.0 % volumetric percentage ratio of steel fibers, the split tensile strength of concrete started to decrease as concrete mix SF1.5, which gives of 6.94 MPa split tensile strength. This provides an increase by 144 % compared to the CB.

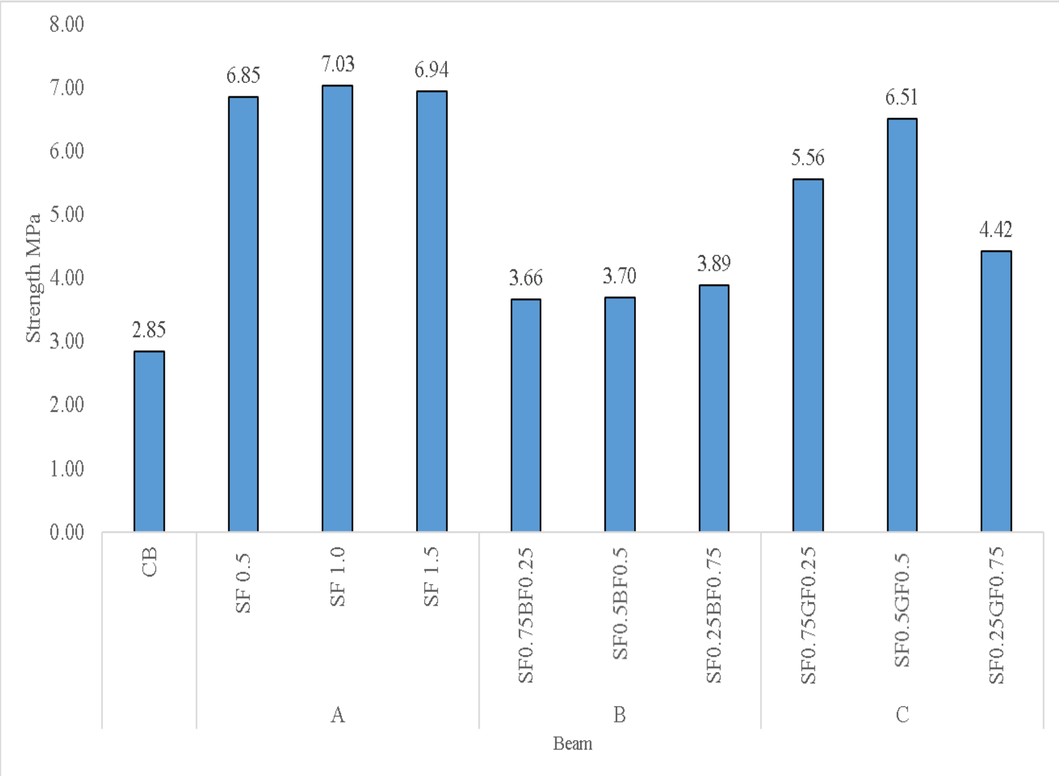


Figure 4.5 Split tensile strength verse type of mixes with different volumetric ratio percentage of steel fibers and hybrid fibers

For the second group B of steel-basalt fibers additives with different volumetric ratio. As displayed in Table 4.1, Figure 4.2, and Figure 4.5 the split tensile strength is of 3.66 MPa for concrete mix SF0.75BF0.25, which has increased by 28 % compared to the CB. While concrete mix SF0.5BF0.5 gives of 3.7 MPa, split tensile strength, which provides an increase by 30 % when compared to the CB. Also, concrete mix SF0.25BF0.75 provide an increase by 36 % with respect to the CB, which gives split tensile strength of 3.89 MPa.

For the third group of steel-glass hybrid fibers additives with the different volumetric ratios. As displayed in Table 4.1, Figure 4.3, and Figure 4.5 the split tensile strength of concrete mix SF0.75GF0.25 is 5.56 MPa, which gives an increase by 95 % when compared to the control concrete. In comparative with control concrete, the highest increased in the split tensile strength with the SF0.5GF0.5 concrete mix is 128 % when compared to the control concrete, which provides 6.51 MPa. It is noticeable that concrete mix SF0.25GF0.75 has a minimum improve in split tensile strength of 55 % compared to the CB, where has split tensile strength of 4.42 MPa. In general, adding hybrid (steel-glass) enhance the concrete mix, but the optimum adding with 0.5 percentage of each steel and glass fibers as shown previously.

4.3 Load-Deflection Response

All results concerned with the flexural performance of FRC beams with different volumetric ratios of steel fibers and hybrid fibers are given in Table 4.2, and Table 4.3. As shown in Table 4.2 and Figure 4.6, for the first group A of the steel additive with various volumetric ratios. The first cracking load (P_{cr}) of the CB is 17.6 kN, while the cracking load of beam SF0.5 is 19.4 kN, which gives an increase by 10 % when compared to the CB, as shown in Table 4.2 and Figure 4.6. Beam SF 1.0 gives a cracking load of 28.1 kN, and this provides an increase by 60 % when compared to the CB. This high percentage increase represents the optimum case when compared to the 13 % decrease in cracking a load of beam SF1.5, which has 15.4 kN. As shown in Figure 4.7 and Table 4.2, for the second group B of the steel-basalt additive with the different volumetric ratio, the cracking load of SF0.75BF0.25 is 18.9 kN. This gives an increase by 7 % compared to the CB, while beam SF0.5BF0.5 gives 17.4 kN, which gives a reduction 1 % relative to the control beam. Beam SF0.25BF0.75 gives a cracking load of 13.1 kN, which means a decline by 26 % compared to the control beam, and this improvement in cracking response is due to the additional steel fibers and basalt fibers which contribute in resisting crack formation and propagation. For the third group C of steel-glass fibers additives which have different volumetric ratios. Beam SF0.75GF0.25 gives 19.6 kN, which provides an increase by 11 % compared to the control beam, while beam SF0.5GF0.5, of 21.9 kN cracking load, drives an increase by 24 % and beam SF0.25GF0.75 of 23.9 kN, gives an increase 36 % relative to control beam. First cracking load of beam SF1.0, which is 28.1, shows the optimum increasing relative to the control beam 60 %, and this shows good agreement with the recommendation (ACI 544).

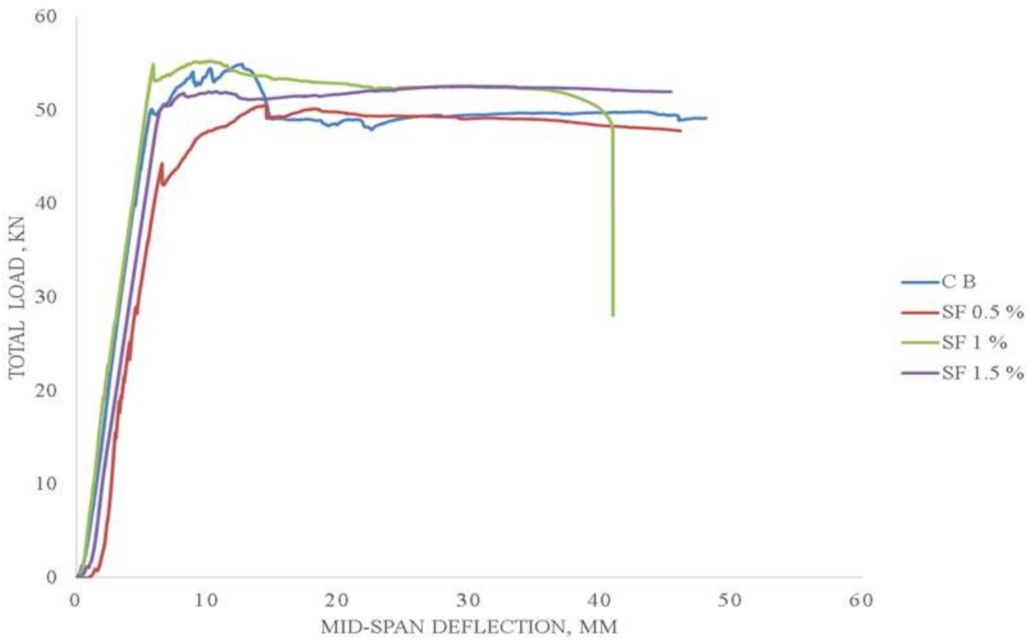


Figure 4.6 Load versus mid-span deflection for group A

Table 4.2 Load-deflection data of the tested beams compared with CB as a reference beam

Beam	P_{cr} (kN)	P_{cr} Change (%)	Δ_{cr} (mm)	Δ_{cr} Change (%)	P_Y (kN)	P_Y Chang e (%)	Δ_Y (mm)	Δ_Y Chang e (%)	P_U (kN)	P_U Change (%)
CB	17.6	-	2.5	-	50.09	-	5.73	-	54.86	-
SF 0.5	19.4	10	3.4	36	44.3	- 12	6.5	13	50.5	- 8
SF 1.0	28.1	60	3.1	24	54.76	9	5.86	2	55.2	0.6
SF 1.5	15.4	- 13	2.5	0	50.3	0.4	6.5	13	52.57	- 4
SF 0.75 BF 0.25	18.9	7	4.8	92	38.1	-24	8.15	42	40.26	- 27
SF 0.5 BF 0.5	17.4	-1	2.5	0	45.7	- 9	6.04	5	46.48	- 15
SF 0.25 BF 0.75	13.1	- 26	2.6	4	44.5	- 11	6.6	15	50.3	- 8
SF 0.75 GF 0.25	19.6	11	3.9	56	45.32	- 10	7.41	29	47.99	- 13
SF0.5 GF 0.5	21.9	24	3	20	52.37	5	6.54	14	55.8	2
SF 0.25 GF 0.75	23.9	36	4.2	68	47.35	- 5	7.17	25	49.98	- 9

Table 4.2, Figure 4.6, Figure 4.7, and Figure 4.8 show the first crack deflection (Δcr) and their percentage change relative to the control beam CB. For the first group A, the crack deflection of the control beam 2.5 mm, while the crack deflection of beam SF0.5 is 3.4 mm, which gives 36 % increase when compared to the CB. Beam SF1.0 provides a crack deflection of 3.1 mm, where this value shows an increase by 29 % relative to CB, while beam SF1.5 shows crack deflection of 2.5 mm which means same value with control beam. Group A indicates that the increase in a volumetric ratio of steel fibers concert beams reduces the crack deformation and propagation where appears in beam SF0.5 the optimum case.

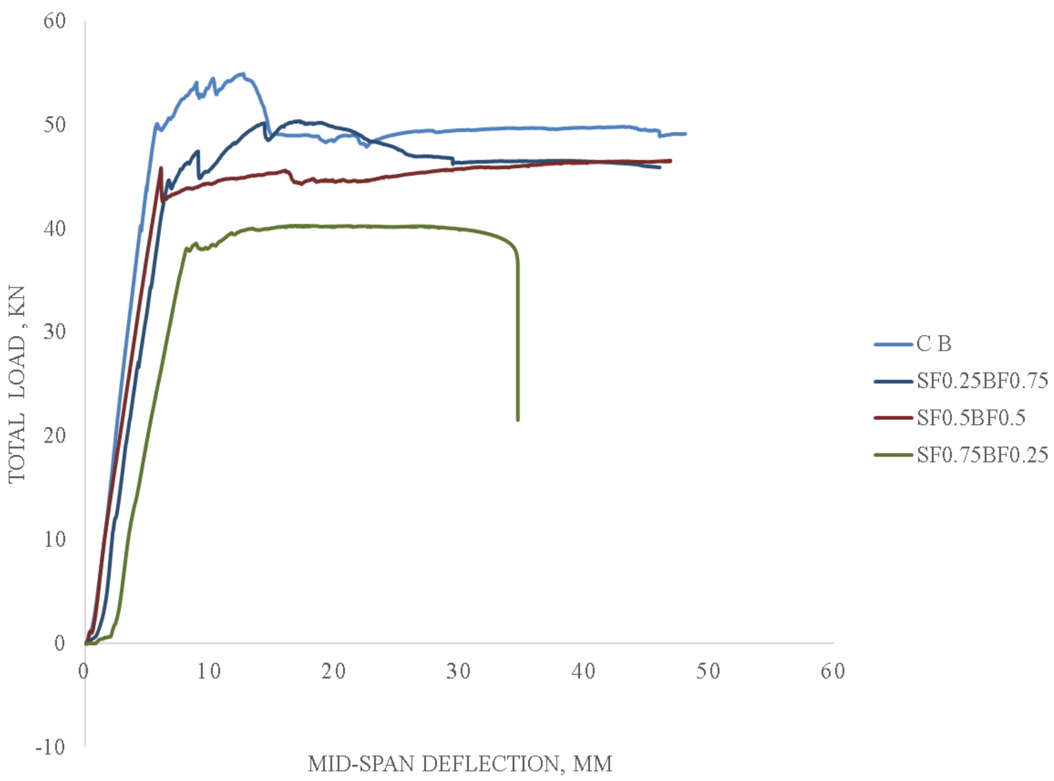


Figure 4.7 Load versus mid-span deflection for group B

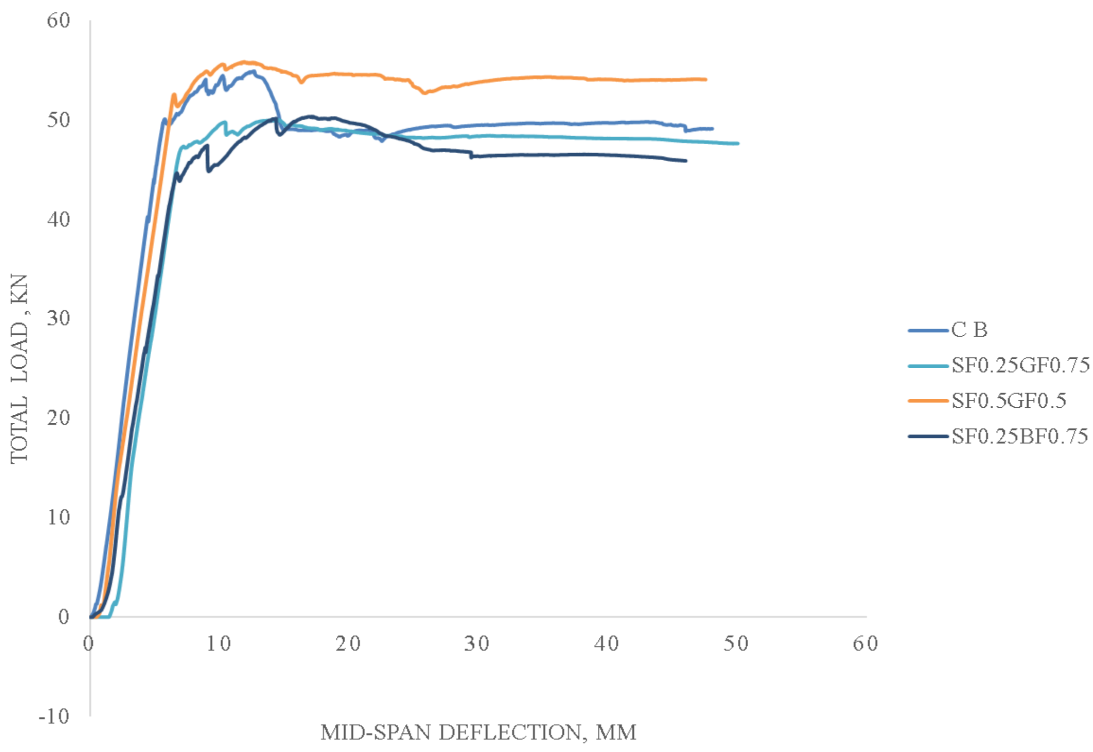


Figure 4.8 Load versus mid-span deflection for group C

For the second group B of the steel-basalt additive with the different volumetric ratio, the crack deflection of beam SF75BF25 is 4.8 mm, this gives an increase by 92 % when compared to CB, while beam SF0.5BF0.5 shows 2.5 mm crack deflection which means has the same crack deflection of CB. Beam SF0.25BF0.75 gives a crack deflection of 2.6 mm, which means no significant increasing by 4 % relative to CB. In the third group C steel-glass additive result shows, beam SF0.25GF0.75 gives the highest crack deflection of 4.2 mm, which means an increase by 68 % when compared to CB. Beam SF0.75GF0.25 gives of 3.9 mm crack deflection which means an increase by 56 %, while beam SF0.5GF0.5 shows the lowest crack deflection relative to the other beams in this group of 3 mm which gives an increase of 20 % relative to CB. First crack deflection provides a good indicator to fibers additive. From the Table 4.2 results show that mixing two type of fibers with different properties gives significant enhancement to resist initial crack occurs in the beams.

To discuss yield load (P_Y) for the beams with and without fibers additive as shown in Table 4.2, Figure 4.6, Figure 4.7, and Figure 4.8. For the first group A with steel fibers additives, the addition of 1 % and 1.5 % as a volumetric ratio of steel fibers to reinforced concrete beam gives an increase of 9 % and 0.4 % for beam SF1 and SF1.5

of yield load 54.76 kN and 50.3 kN respectively to the CB. Beam SF0.5 shows yield load of 44.3 kN, which means a reduction by 12 % when compared to CB. For the second group B with the steel-basalt fibers additive with the different volumetric ratios. Yield load results gives of 38.1 kN, 45.7 kN and 44.5 kN for the beams SF0.75BF0.25, SF0.5BF0.5 and SF0.25BF0.75 respectively. Second group shows a decrees in yield load relative to the control beam by 24 %, 9 % and 12 % for the beams SF0.75BF0.25, SF0.5BF0.5 and SF0.25BF0.75 respectively. For the third group C with steel glass additives with the different volumetric ratio. Beam SF0.5GF0.5 gives of 52.37 kN yield load which shows an increase by 5 % when compared to CB, while beams SF75GF0.25 and SF0.25GF0.75 gives of 45.32 kN and 47.35 kN that means a reduction by 10 % and 5 %. This enhancement of yield load for the beams SF1.0, SF1.5 and SF0.5GF0.5 means the best volumetric ratio of steel fibers and hybrid steel fibers additives.

As shown in Table 4.2, Figure 4.6, Figure 4.7, and Figure 4.8. The yield deflection (Δ_Y) for the first group A of steel additive for the control beam is 5.73 mm, while the yield deflection of beam SF0.5 is 6.5 mm, which gives an increase by 13 % when compared with the CB. Beam SF1.0 shows yield deflection of 5.86 mm. This provides an increase by 2 % relative to the CB, while beam SF1.5 gives the same behavior relative to SF0.5 by an increase 13 % when compared to the CB. For the second group B of steel-basalt additives. Beam SF75BF0.25 gives 8.15 mm of yield deflection, which shows highest increasing by 42 % when compared to the control beam, while yield deflection of beam SF0.5BF0.5 is 6.04 mm. This gives lowest increased response by 5 % about the control beam. Yield deflection of beam SF0.25BF0.75 shows close behavior with beam SF0.5 and SF1.5 as shown in group A. In group C with steel-glass additives, the result of yield deflection is 7.41 mm and 7.17 mm for both beam SF75GF0.25 and SF0.25GF0.75, which gives an increase by 29 % and 25 % respectively for each one. This shows a similar effect in yield deflection behavior. Beam SF0.5GF0.5 gives of 6.45 mm yield deflection, which means an increase by 122 %. By referring to the Table 4.2 note that high decline lay in beam SF75BF0.25, SF0.75GF25, and SF0.25GF0.75. This volumetric ratio for this beams represent the worst case fibers additives, which means mixing steel-glass and steel-basalt was not enhance the yield behavior more than adding steel alone at yield behavior in beam element.

Ultimate load (P_U) is a good indicator of the structural behavior response in decreasing or increasing strength by adding fibers or hybrid fibers. As shown in Table 4.2 and Figure 4.6, for the group A with steel fibers additives. The ultimate load of the control beam is 54.86 kN, on the other hand, the ultimate load of SF0.5 is 50.5 kN, which gives a reduction by 8 % of strength when compared to the control beam. Beam SF1.0 keeps at the same level of force of 55.2, which provides no significant increasing by 0.6 % relative to the CB, while beam SF1.5 has an ultimate load of 52.57 kN, where shows a decrease in beam strength by 4 % when compared to the CB. By adding steel-basalt as shown in the group B. As shown in Table 4.2 and Figure 4.7 , the result shows a reduction in ultimate load in general, where beam SF0.75BF0.25 gives of 40.26 kN. This shows the lowest ultimate load appearing in the group B even another tested beam by reduction the ultimate load of 27 % relative to CB. Beam SF0.5BF0.5 gives of 46.48 kN of ultimate load, which gives a decrease by 15 % when compared to CB, while beam SF0.25BF0.75 gives of 50.2 kN. On the other hand, shows a decreasing by 8 % relative to CB. For the third group C of steel-glass additives. Beams SF0.75GF0.25 and SF0.25GF0.75 gives of 47.99 kN and 49.98 kN of ultimate load, which gives a reduction by 13 % and 9 % when compared to the CB, while beam SF0.5GF0.5 gives of 55.8 kN of ultimate load. This provides an enhancement by 2 % relative to the CB. Fiber and hybrid fibers additive for the strength concrete beam element gives a reduction in the ultimate strength in general

Table 4.3 provides a comparison between beam SF1.0 as a reference beam which has 1.0 % volumetric ratio of steel fibers additive and hybrid beams same proportion of 1.0 % as a total additive of hybrid fibers. Where, 1.0 % additive of hybrid fibers produced by replacing 25 %, 50 % and 75 % of steel fibers additive by basalt fibers or glass fibers each time.

Steel fibers reinforced concrete beam with 1.0 % volumetric ratio show better enhancement in first cracking load when compared with hybrid fibers reinforced concrete beams, Table 4.3 and Figure 4.9 Where, beams of steel-basalt fibers additive such as SF0.75BF0.25, SF0.5BF0.5, and SF0.75BF0.25 show a reduction by 33 %, 38 % and 53 % of cracking load respectively when compared with beam SF1.0 (control beam). Also as shown in Table 4.3 and Figure 4.10, beams of steel-glass additives such as SF0.75GFF0.25, SF0.5GF0.5, and SF0.25GF0.75 show a reduction in cracking load by 39 %, 22 %, and 59 % when compared with SF1.0, respectively.

In general, the increase in the volumetric ratio of the glass in the hybrid beams indicates an improvement in the resistance of the appearance first crack, but the hybrid beams, which contains basalt fibers, indicate that the increase in volumetric ratio of basalt fibers in the hybrid beams do not improve the resistance of the appearance of the first crack.

Table 4.3 Load-deflection data of the tested beams compared with SF1.0 as a reference beam

Beam	**P_{cr} (kN)**	**P_{cr} Change (%)**	**Δ_{cr} (mm)**	**Δ_{cr} Change (%)**	**P_Y (kN)**	**P_Y Chang e (%)**	**Δ_Y (mm)**	**Δ_Y Chang e (%)**	**P_U (kN)**	**P_U Change (%)**
SF 1.0*	28.1	-	3.1	-	54.76	-	5.86	-	55.2	-
SF0.75BF0.25	18.9	- 33	4.8	55	38.1	- 30	8.15	39	40.26	- 27
SF0.5BF0.5	17.4	- 38	2.5	-19	45.7	- 16	6.04	3	46.48	- 16
SF0.25BF0.75	13.1	-53	2.6	- 16	44.5	- 19	6.6	12	50.3	- 9
SF0.75GF0.25	19.6	- 39	3.9	26	45.32	-17	7.41	26	47.99	- 13
SF0.5GF0.5	21.9	- 22	3	- 3	52.37	- 4	6.54	12	55.8	1
SF0.25GF0.75	23.9	- 15	4.2	35	47.35	- 14	7.17	22	49.98	- 10

*SF1.0 reference beam

Figure 4.9 Load versus mid-span deflection comparisons between steel-basalt fibers group with SF1.0 as a control beam

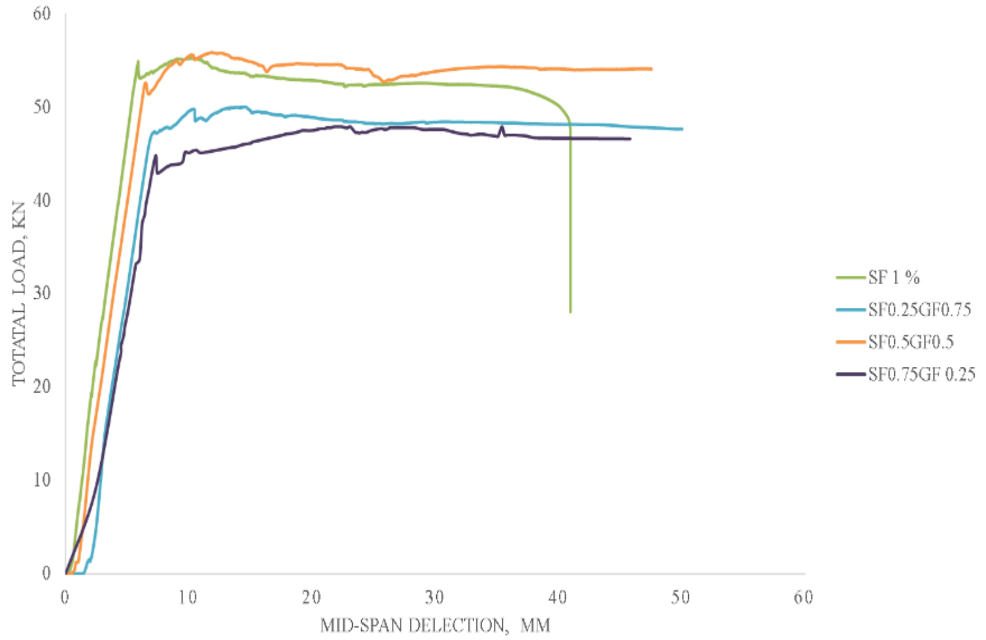


Figure 4.10 Load versus mid-span deflection comparisons between steel-glass fibers group with SF1.0 as a control beam

For the group of steel-basalt, the crack deflection of beam SF75BF25 is 4.8 mm; this gives an increase by 55 % when compared to the SF1.0, while beam SF0.5BF0.5 and beam SF0.25BF0.75 provides a crack deflection of 2.5 mm and 2.6 mm, which means reduction by 19 % and 16 %, respectively, relative to the control beam SF1.0. In the group of steel-glass additive result shows, beam SF0.25GF0.75 gives a crack deflection of 4.2 mm, which means an increase by 35 % when compared to the control beam SF1.0. Beam SF0.75GF0.25 gives of 3.9 mm crack deflection which means an increase by 26 %, while beam SF0.5GF0.5 shows the lowest crack deflection relative to the other beams in this group of 3 mm which gives a reduction by 3 % compared to the control beam SF1.0.

To discuss yield load for the beams with steel fibers additive only and steel hybrid fibers. For the steel-basalt fibers additive group. Yield load results gives of 38.1 kN, 45.7 kN and 44.5 kN for the beams SF0.75BF0.25, SF0.5BF0.5 and SF0.25BF0.75 respectively. This results show a decrees in yield load relative to the control beam SF1.0 by 30 %, 16 % and 19 % for the beams SF0.75BF0.25, SF0.5BF0.5 and SF0.25BF0.75 respectively. For the group with steel-glass additives beam SF0.5GF0.5 gives of 52.37 kN yield load which shows a decrease by 4 % when compared to the control beam SF1.0, while beams SF75GF0.25 and SF0.25GF0.75 gives of 45.32 kN and 47.35 kN which means a reduction by 17 % and 14 % relative to the control beam SF1.0.

Control beam SF1.0 shows yield deflection of 5.86 mm. For the group of steel-basalt additives. Beam SF75BF0.25 gives 8.15 mm of yield deflection, which demonstrates highest increasing by 39 % when compared to the control beam SF1.0, while yield deflection of beam SF0.5BF0.5 is 6.04 mm. This gives lowest increased response by 3 % when compared to the control beam SF1.0. Beam SF0.25BF0.75 gives 6.6 mm of yield deflection, which shows an increase by 12 % when compared to the control beam SF1.0. In the group of steel-glass additives, the result of yield deflection is 7.41 mm and 7.17 mm for both beam SF75GF0.25 and SF0.25GF0.75, which gives an increase of 26 % and 22 % when compared to the control beam SF1.0, respectively, which means close effect in yield deflection behavior. Beam SF0.5GF0.5 gives of 6.45 mm yield deflection, which means an increase by 12 %.

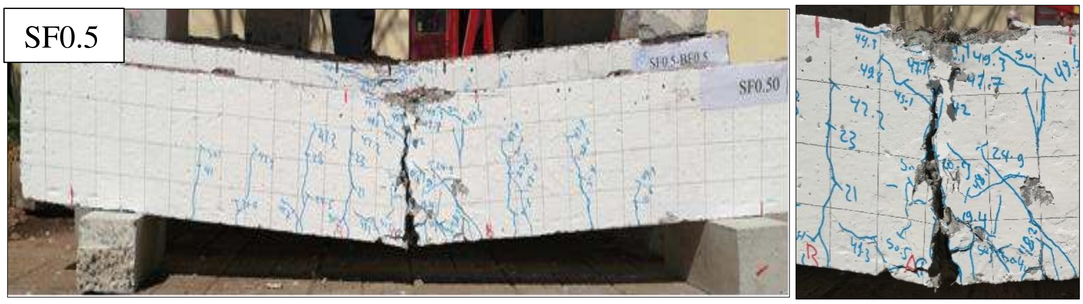
SF1.0 and hybrid beams are tested up to failure load. The recorded ultimate loads of the tested beams are presented in Table 4.3. For the tested beams of the steel-basalt group. Beam SF75BF0.25 gives a reduction in ultimate load capacity is about 27 % when compared with the conventional (reference) reinforced concrete beam SF1.0. While testing beams SF0.5BF0.5 and SF0.25BF0.75 provide a reduction by 16 % and 9 % of ultimate load capacity when compared to the reference beam SF1.0, which means by increasing the basalt content in the concrete mix enhances the ultimate load capacity. Further, for the tested beams of the steel-basalt group. Testing beam SF0.5GF0.5 an increase of about 1 % in ultimate load capacity over the conventional reinforced concrete beam SF1.0, which has the same level of strength. While beams SF0.75GF0.25 and SF0.25GF0.75 give a reduction by 13 % and 10 % when compared to the control beam SF1.0.

4.4 Failure modes and visualizations

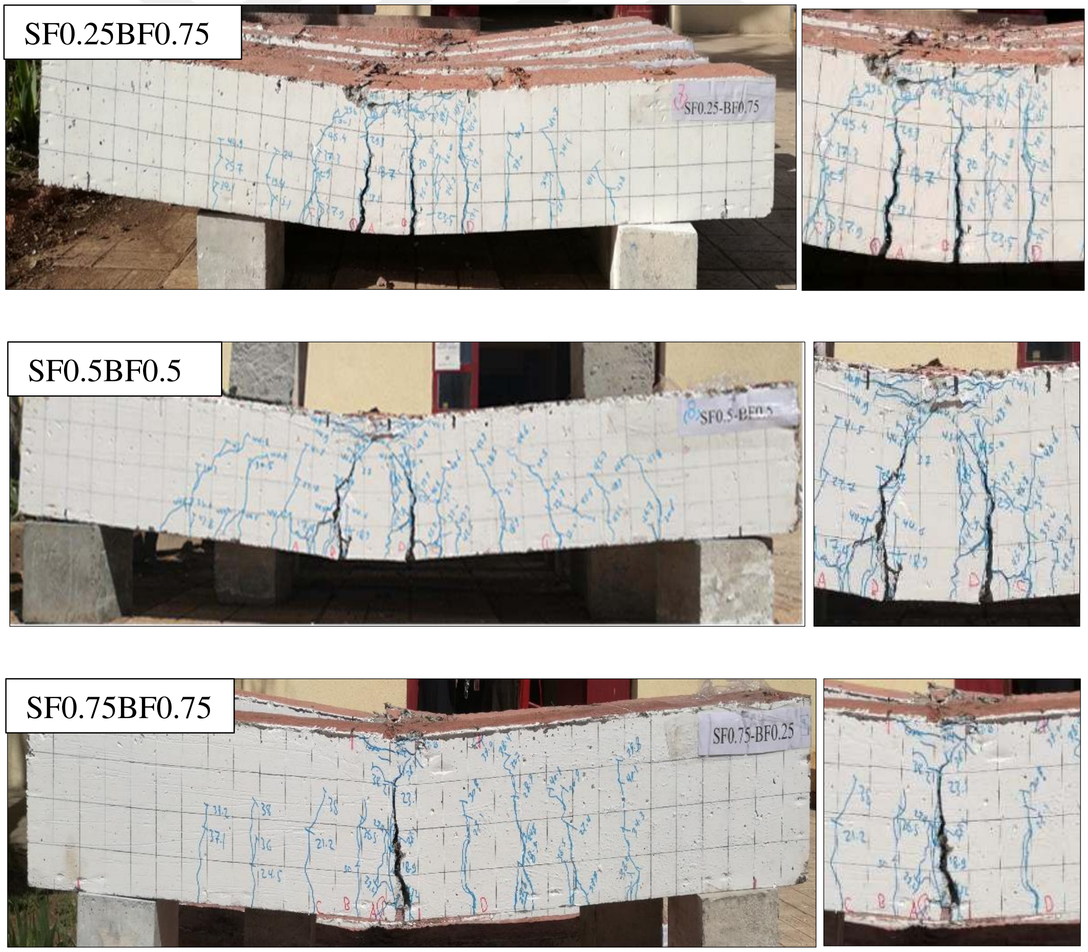
To well visualize the failure mode and crack pattern, the tested beams are painted with white emulsion and a grid of line made with a distance of 50 x 50 mm, as shown in Figure 4.11. The cracks initiation is shown in alphabetic order (i.e. . A, B, C, D, and E respectively). The propagation of these cracks are marked with multi-color pen and load is denoted on each stage of crack propagation.

The crack pattern of control beam CB, shown in Figure 4.11 indicates that the crack is initiated in the tension face at the middle of the beam. With load increment, other cracks are developed within the middle third of beam clear span. All the cracks show that the failure of this beam goes to be a flexural failure. The yield of bottom reinforcement happens before compression failure of the concrete. Before reaching ultimate load, compression concrete crushed successively and collapsed. The crack pattern for the group A, which is strengthed with steel fibers with the different volumetric ratio, show that the addition of steel fibers enhanced cracks formation and propagation, shown in Figure 4.11. The important note that visualized is that the first main crack, which was in the middle of the tested beam, is still propagation with a very limited formation of the another crack. The failure mode of this group was, also, by yielding tension steel reinforcement followed by concrete compression failure, but the compression concrete failure by delamination of multilayers. This noticeable type of concrete failure due to the addition of steel fiber , which enhanced the compression zone beside its contribution to tension zone. The crack pattern of group B, which is strengthened with steel-basalt fibers, with different volumetric ratios, show that the adding of this fiber, also enhanced the crack formation and propagation, showing in Figure 4.11. More than one main crack is formed and propagate as load increase. The failure mode of this group was, also, by yielding of tension steel reinforcement following by concrete compression failure in the forming of layer delamination as shown in Figure 4.11.

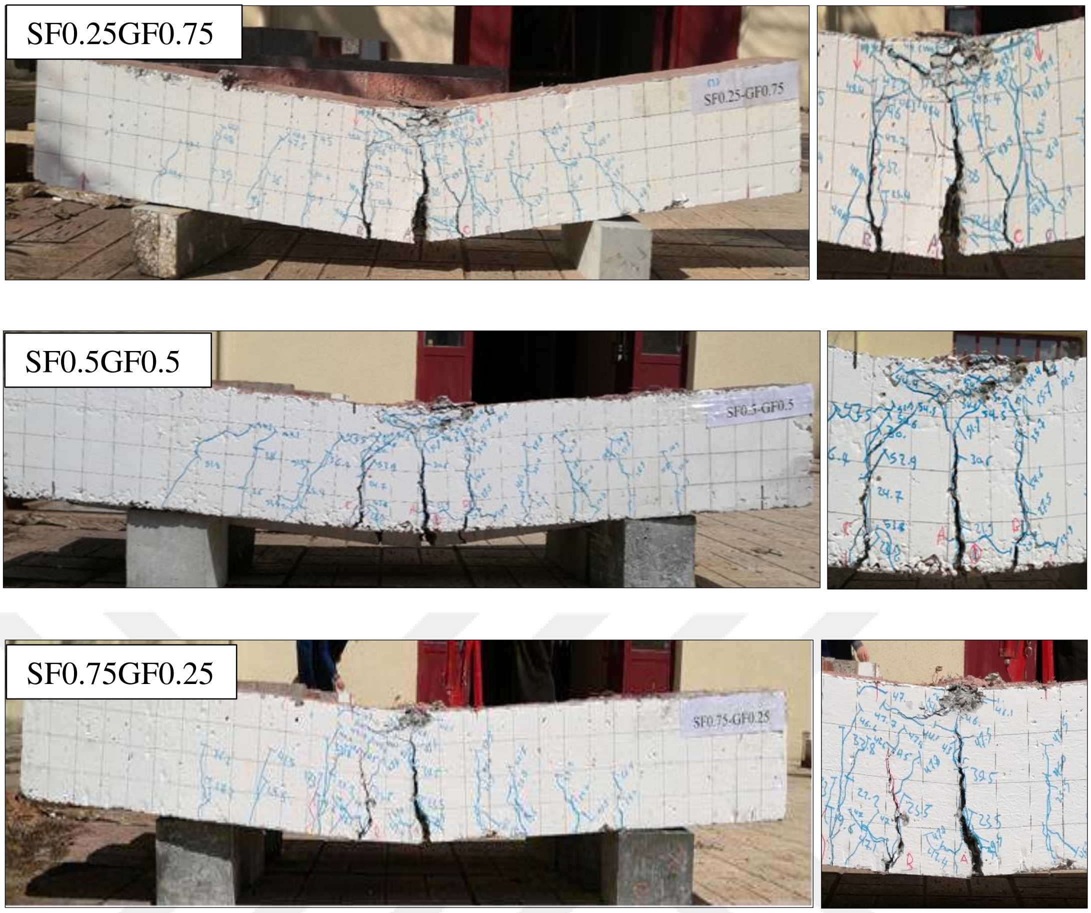
Crack pattern and failure mode for CB



(a) Crack pattern and failure mode for group A



(c) Crack pattern and failure mode for group B



(d) Crack pattern and failure mode for group C

Figure 4.11 Crack pattern and failure mode for tested beams (i.e., group A, B, C, and control CB)

As Figure 4.11 shows the third group C, which is strengthed with steel-glass fibers with the different volumetric ratio, the number of cracks increased for all additives percentage. Also enhanced the crack formation and propagation. More than one main cracks are formed and propagate as load increases, but still, the number of main cracks less than the control beam CB, while a number of fine cracks more than the control beam. The failure mode of the group C, also, by yielding of tension steel reinforced following by crushing compression zone of concrete failure in the forming of layers delamination as shown in Figure 4.11. Hence, it is noticeable that group B and C had more than one main cracks but still less than the control beam, on the other hand, group A had almost one large main crack. This type of the crack pattern due to the behavior of steel fibers beam and hybrid fibers beam, which are more ductile than the control and group A as explained previously.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusıons

Ten beams are tested one of them is the reference beam, and the others are fibers reinforced concrete beams classified as groups A, B and C. Group A represents steel fibers additive only, while group B and C are describing steel-basalt additives and steel-glass additives. Based on the result obtained from the experimental work and using four point load-deflection technique analysis for the fibers reinforced concrete beams, the following conclusions are presented ;

1. Steel, basalt and glass fibers may be used as additives to construct high strength reinforced concrete beams based on the percentage of (0.5, 1.0, and 1.5) % for steel fibers, (0.25-0.75, 0.5-0.5, and 0.75-0.25) % for steel-basalt hybrid fibers and (0.25-0.75, 0.5-0.5, and 0.75-0.25) % for steel-glass hybrid fibers.
2. The 28 days compressive strength is, in general, reduced when adding steel fibers only and hybrid fibers (steel-glass, steel-basalt) compared to the control mix.
3. Concrete compressive strength is slightly reduced for group A; which has steel fibers additive by (0.5, 1.0, and 1.5). The reduction is by (1.2-3) % only, which may be assumed as a negligible change in strength.
4. Concrete compressive strength for group B, which has steel, and basalt additive by 1.0 % a total amount of hybrid fibers gives a reduction by (17-23) %, and this is more than the reduction (4-13) % noticed for group C, which has steel fibers and glass fibers additives by 1.0 % total amount of hybrid fibers.
5. The 28 days split tensile strength is significantly increased when adding steel fibers, basalt fibers, and glass fibers compared to the control mix.
6. The optimum enhancement noticed in group A, which has steel fibers additives, by

7. (140-147) %. Also, significant enhancement has been noticed in group C, which has steel fibers and glass fibers, by (55-95) %.
8. The result of the second group B showed that increasing the volumetric ratio of basalt fibers increased the split tensile strength by (28, 30, and 36) % for the fraction (0.25, 0.5, and 0.75) % respectively. While the result of steel-glass additives is showed that the split tensile strength started to decrease after 0.5 % of glass fibers additives. Therefore it is considered the best additive of glass fibers compared to the other used ratios (0.25-0.75) %.
9. According to the observations through the beam tests. The presence of steel, basalt and glass fibers on the mix of tested beams delayed the formation and reduced the propagation of cracks. This led to an improvement the tension zone response prior to and beyond the first cracks
10. For the tested beams of the first group A, adding of steel fibers up to 1.0 % is enhanced the first cracking load up to 60 %.
11. For the tested beams for the third group C, increasing glass fibers volumetric ratio up to 0.75 % is caused an increase in the first crack flexural load by (11-13) %.
12. Groups A and C are enhanced in the first crack flexural load, while group B is enhanced in the first crack flexural load with 0.25 % fraction of basalt fibers additive by 7 %.
13. Varying results are obtained for tested beams . in a broad view, fibers and hybrid fibers are increased the value of the first crack flexural deflection by (0-36) %, (0-92) % and (20-56) % four group A, B, and group C, respectively.
14. For the tested beams strengthened with fibers and hybrid fibers are subjected to flexural load up to failure. The yield load is increased just only for three type of mix, which it is steel fibers additive for 1.0 % and 1.5 % volumetric fraction and steel-glass fibers additives with 0.5 % volumetric fraction, by (9, 0.4, and 5) %, respectively.
15. It has been seen that the result of the yield deflection also showed reversed effectively of adding fibers to concrete mix with an increase by (2-13) %, (5-42) % and (14-29) % for steel fibers, steel-basalt fibers, steel glass fibers additives, respectively.
16. For the tested beams strengthened with fibers and hybrid fibers are subjected to flexural load up to failure. For the ultimate flexure, the load is increased by (0.6, and 2) only for steel additives with 1.0 % volumetric fraction and for hybrid steel-

glass fibers additives with 0.5 % volumetric fraction for each one of them.

17. According to the observations through the beams test, the ultimate flexural load is decreased in general, and the worst case is noticed in steel-basalt additives with 0.75 % steel fibers and 0.25 % basalt fibers.
18. The additives of steel fibers and hybrid fibers are enhanced tension zone characteristic through less crack formation and propagation.
19. The failure mode of fiber and hybrid FRC are by yielding of tension steel reinforcement following by concrete compression failure in the forming of layer delamination.
20. It is noticeable that steel-basalt group and steel glass group had more than one main cracks but still less than the control beam, on the other hand, group A had almost one large main crack.

5.2 Recommendations for Future Work

A lot of research can be suggested for a better understanding of the effect of adding fibers and hybrid fibers in reinforced concrete beam on flexural and behavior of this fibers reinforced concrete beams. The following recommendations are suggested:-

1. Modeling the fibers reinforced concrete beam analytically to predict the flexural behavior.
2. This work can be further extended to study the effect of different concrete compressive strength.
3. The experimental program adopted in this research can be used to examine the effect of the torsional and shear behavior of the fibers and hybrid strengthened reinforced concrete beam.
4. The same experimental program can be used for fibers, and hybrid fibers reinforced concrete T-shaped or I-shaped beams. Also, the concept of hybrid sections can be considered for fibers and hybrid fibers additives.
5. Same adopted experimental program can be used with long term effect parameters (creep, shrinkage .....) to investigate the flexural behavior of fibers strengthened reinforced concrete beams. Also, the effect of fire on the fibers strengthen reinforced concrete beams subjected to flexural load can be included.
6. Adding of CFRP laminates in tension zone can be studied for these type of

beams with the same percentage additives.

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