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M.Sc. in Civil Engineering

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UNIVERSITY OF GAZİANTEP

GRADUATE SCHOOL OF

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EXPERIMENTAL AND COMPARATIVE INVESTIGATION OF FLEXURAL BEHAVIOR OF BASALT AND STEEL FIBER REINFORCED CONCRETE BEAM

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DUAA ZUHER FADIL

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Experimental and Comparative Investigation of Flexural Behavior of Basalt and Steel Fiber Reinforced Concrete Beam

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Supervisor

Assoc. Prof. Dr. Nildem TAYŞİ

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Duaa Zuher FADIL

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Duaa Zuher FADIL

ABSTRACT

EXPERIMENTAL AND COMPARATIVE INVESTIGATION OF FLEXURAL BEHAVIOR OF BASALT AND STEEL FIBER REINFORCED CONCRETE BEAM

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M.Sc. in Civil Engineering
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Concrete is a widely used material in structural engineering construction in different ways, whereas concrete has a low tensile strength and fails in a brittle manner. These shortcomings are generally overcome by using several technics. One of them was the inclusion of fibers into the concrete. The experimental study in this thesis is achieved to show the improvement gained by the addition of basalt, steel, and glass fibers to the concrete mix on the flexural performance of reinforced concrete beams. Thirteen different beams were tested and the results are compared. All beams with an effective span of 1300 mm were tested until failure under 4-point flexural test. The beams were designed as a balance-section. All beams are the identical size of "1500 x 150 x 200 mm" and divided into four groups. Group A consists of three beams strengthened with different volumetric ratios (0.5, 1.0, and 1.5 %) of basalt fiber. Group B consists of three beams strengthened with different volumetric ratios (0.5, 1.0, and 1.5 %) of steel fiber. Group C consists of three beams (0.25-0.75, 0.5-0.5, and 0.75-0.25 %) of basalt and glass hybrid fibers. Group D consists of three beams (0.25-0.75, 0.5-0.5, and 0.75-0.25 %) of steel and glass hybrid fibers, and the last one is a control beam. The concrete mixtures was designed for high strength concrete. For each mix three-cubes and three cylinders are cast to obtain the effect of the fibers on concrete compressive and tensile strength.

Very few researchers were presented in literature on the hybrid effect of steel, glass and basalt fibers in reinforced concrete beams. This thesis presents the effect of hybrid fiber on the compressive, tensile and flexural strength of concrete. Basalt fiber concrete usually has a high tensile strength but slightly smaller than steel fiber. The flexural strength of basalt fiber reinforced concrete increased with increasing fiber content in a gradual fashion. It is observed from the test results that there is a negative effect of fiber inclusion on the compressive strength of concrete.

Keywords: Basalt fiber, hybrid fibers, flexural performance.

ÖZET

BAZALT VE ÇELİK FİBER TAKVİYELİ BETONARME KİRİŞLERİN EĞİLME DAVRANIŞININ İNCELENMESİ İÇİN DENEYSEL VE KARŞILAŞTIRMALI ÇALIŞMA

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61 sayfa

Beton, mühendislik yapılarında yaygın olarak kullanılan bir malzemedir, oysa beton düşük bir çekme mukavemetine sahiptir ve kırılgan bir şekilde göçer. Betonun bu eksiklikler genellikle çeşitli teknikler kullanılarak aşılmaktadır. Bunlardan biri elyaf liflerin betona dahil edilmesidir. Bu tez çalışmasında, bazalt, çelik ve cam elyafların beton karışımına katılmasıyla elde edilen betonarme kirişlerin eğilme performansına olan gelişmelerinin gösterilmesi amaçlanmıştır. Bu araştırmada, onüç farklı betonarme kiriş test edilmiş ve sonuçlar karşılaştırılmıştır. Tüm kirişler1300 mm'lik etkili açıklığa sahip olup, 4-noktalı eğilme testi yüklemesi altındaki göçene kadar test edilmiştir. Kirişler dengeli olarak tasarlanmıştır. Tüm kirişler "1500 x 150 x 200 mm" lik aynı büyüklüktedir ve dört gruba ayrılmıştır, Grup A, farklı hacimsel oranlarla (0.5, 1.0 ve % 1.5) basalt elyaf ile güçlendirilmiş üç kirişten oluşmaktadır. B grubu, farklı hacimsel oranlarla (0.5, 1.0 ve % 1.5) çelik elyaf ile güçlendirilmiş üç kirişten oluşur. Grup C, üç (0.25-0.75, 0.5-0.5 ve 0.75-0.25 %) bazalt ve cam hibrit kirişlerden oluşur. D grubu ise çelik ve cam hibrit üç kiriş (0.25-0.75, 0.5-0.5 ve 0.75-0.25%) den oluşur ve son olarak elyafsız kontrol kirişi mevcuttur. Ayrıca, her bir karışım için üçer küp ve silindir numune ile fiberlerin beton basınç ve çekme mukavemetleri üzerine etkisi incelenmiştir. Tüm beton karışımları, yüksek mukavemetli olarak tasarlanmıştır.

Literatürde çelik, cam ve basalt elyafın hibrit olarak betonarme kirişler üzerindeki etkileri çok az sunulmuştur. Bu tez, hibrit liflerin betonun çekme, basınç ve eğilme mukavemetlerine etkilerini sunmaktadır. Basalt elyaflı beton, çelik elyaflıdan az olsa da genellikle yüksek bir çekme mukavemetine sahiptir. Lif içeriğinin artmasıyla basalt elyaflı betonarme kirişin eğilme mukavemeti giderek artmaktadır. Test sonuçları göstermektedir ki, elyaf eklenmesi betonun basınç mukavemetini olumsuz olarak etkilemektedir.

Anahtar Kelimeler: Basalt elyaf, Hibrit lifler, eğilme davranışı.

To all who are in the universe after Allah and His Messenger, My Parents. They always support me, strength me, encourage me and they always are my shelter after Allah. From them, I learned to withstand, no matter what the difficulties. I am grateful to Allah for having parents like you. To whom always give me the most beautiful life, to those who are closest to my soul, My Sisters. To My Friends, to everyone provided me with assistance, facilities, ideas, and information during my years of studies.

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LIST OF SYMBOLS/ABBREVIATIONS

ASTM	American Society for Testing and Materials
BFRC	Basalt Fiber Reinforced Concrete
ACI	American Concrete Institute
CB	Control Beam
FRC	Fiber Reinforced Concrete
RC	Reinforced Concrete
BF	Basalt Fiber
SFRC	Steel Fiber Reinforced Concrete
SF	Steel Fiber
GF	Glass Fiber
GFRC	Glass Fiber Reinforced Concrete
HF	Hybrid Fibers
HYFRC	Hybrid Fibers Reinforced Concrete
P_y	Yielding Load
P_{cr}	First Cracking Load
P_u	Ultimate Load
δ_{cr}	First Crack Deflection
δ_y	Yielding Deflection

CHAPTER 1

INTRODUCTION

1.1 General

In civil engineering construction, concrete is a major construction material used all over the world. Concrete is widely adopted as building materials despite the fact that it is not as strong as steel because of its relatively low cost. These construction materials have inherently brittle in nature and have some of the dramatic demerits are overcome such as poor deformability of concrete and weak crack resisting properties. Is also weak in tensile strength parameter and flexural strength is relatively low as compared to their compressive strength. The mechanical characteristics may be enhanced through the introduction of reinforcing fibers that have the high tensile strength and ductility (Faruk, et al., 2012). In recent years, by combining two or more kinds of fibers as a reinforcing material of conventional Reinforced Concrete (RC), fibers are used extensively, and a new material called Hybrid Fibers Reinforced Concrete (HYFRC) was used.

1.2 Background

In history, much effort has been made to enhance concrete structural performance. Several researchers who tested concrete with fibers and other materials to improve the behavior of concrete emphasize bending stiffness, compressive strength, shear strength, ductility and other properties. In the past few decades, various studies (Patil, et al., 2014), (Wlodarczyk, et al., 2016), (Krassowska, et al., 2013), (Branston, et al., 2016) have focused on the properties and applications of fiber RC. It has been found that the addition of fibers to concrete can improve the tensile and shear strength, fracture toughness, crack resistance and energy dissipation capacity of concrete structures. The most common fibers are steel, glass, carbon, aramid, polypropylene, and Basalt Fiber (BF). Thanks to limited dimensions, the fibers have a remarkable structural integrity (Kizilkanat, et al., 2015). However, Steel Fiber (SF) is the most common one.

The first experimental test to improve the properties of concrete by using reinforcing elements, for example, the nails segments were done in 1910 ACI 544.1 R, (2002). Nevertheless, it was until 1963 ACI 544.1 R, (2002) that the main experiment to improve concrete characteristics using actual SF ACI 544.1 R, (2002) was done. BF is often reported to provide the best mechanical characteristics, more economical, friendly manufacturing process. These properties are remarkably excellent, and the manufacturing process dates back to 1923 (Jamshaid , et al., 2015), but use it was very limited in the Fiber Reinforced Concrete (FRC) industry.

1.3 Advantages and Disadvantages of Concrete

Concrete is one of the most conventional construction materials. Concrete has several advantages such as formability, durability and desired mechanical strength which gives it an edge over the other conventional building materials but it has disadvantages such as low tensile strength (Jiang, et al., 2014), (Faiz, 2013), (S. T. Tassew and A. S. Lubell, et al., 2014).

1.4 Fiber Reinforced Concrete

1-In general, areas of improvement in FRC over plain concrete including tensile strength, compressive strength, modulus of elasticity, fatigue life, durability, crack resistance, control the crack, shrinkage, resistance the impact and abrasion, thermal effects, resistance the fire and expansion (ACI Committee544 1996).

2-The fibers are effective in restricting the development of cracks, and as a result, preventing sudden, potentially catastrophic, brittle failures because of the low tensile strength and strain capacity of plain concrete.

3-FRC great uses because of high corrosion resistance, high flexibility, and durability

4-Fibers are given at least a relatively higher tensile strength (200% - 300%), a higher coefficient of elasticity and a much higher elongation in the tension compared to the normal concrete and having appropriate bond properties with a cement matrix, lead to the best FRC function.

5-The fibers reduce the permeability of concrete and thus reduce bleeding of water.

6-All the fiber concretes yield higher toughness compared to control concrete.

7-The fibers conserve the residual loading capacity after the alkali-silica reaction (Giaccio, et al., 2015).

8-Shear reinforcement can be completely eliminated in the shear span if fibers are provided. Due to the bridging action of fiber, post-peak strength could also be improved.

9-FRC construction is more economical than traditional construction.

10-FRC reduce workability and accelerated stiffening of the fresh concrete mixture.

1.5 Basalt Fiber

1-BF is available in the commercial market.

2-BF can be manufactured with conventional processes and equipment, and less energy, which offers an economic advantage (fiore V, et al., 2015).

3-BFs are considered 100% natural, have no toxic reaction with air or water, to be more environmentally friendly (Jamshamid, et al., 2015).

4-BF its unique physical and chemical properties, such as high elastic modulus, high strength, corrosion resistance, high-temperature resistance, and lightweight, make it a better solution to many engineering problems (Jamshamid, et al., 2015).

5-Increased splitting tensile strength.

6-Increased flexural strength.

7-BF improved the performance of concrete with respect to crack resistance and ductility.

8-Improved shear capacity.

9-No significant effect of BF on compressive strength and concrete elasticity coefficient.

1.6 Steel Fiber

1-SF in plain concrete improved the mechanical properties of the concrete structure.

2-Steel Fiber Reinforced Concrete (SFRC) increased toughness and reduction in cracking severity (Dupont, et al., 2002).

3-Increased first-crack strength with SFRC are relatively small (Bentur, et al., 2014).

4-Increased tensile flexural strength.

5-Improved shear capacity.

6-SFRC improved flexural fatigue endurance, flexural toughness, and impact resistance (ACI Committee 544, et al., 2009).

7-Hıgh cost, the cost of SF at a modest dosage of 1% (by volume) can double the material cost of the concrete (Van Chanh and N, 2004).

8-SF is susceptible to corrosion due to the ingress of water and chlorides.

9-SF increased the dead load of the structure.

10-The effect of SF on the compressive strength is not significant.

1.7 Aim and Objectives of the Thesis

This thesis aims to present the comparative study of effect of BF and SF on the flexural and mechanical behavior of RC. Moreover, this study has been concentrated on the load-deflection behavior of FRC beams. The size of BF is 12 mm and SF is 30 mm. For flexural strength tests, all beams are divided into four groups. Group A consists of three beams strengthened with different volumetric ratios (0.5, 1.0, and 1.5) % of BF. Group B consists of three beams strengthened with different volumetric ratios (0.5, 1.0, and 1.5) % of SF. Group C consists of three beams (0.25-0.75, 0.5-0.5, and 0.75-0.25) % of basalt and glass Hybrid Fibers (HF), and Group D consists of three beams (0.25-0.75, 0.5-0.5, and 0.75-0.25) % of steel and glass HF. Studies on compressive, tensile, and bending strength are carried out in comparison with Control Beam (CB), plain concrete does not contain fiber.

The objective of this thesis is investigation of the structural behavior of beam specimens with an experimental work on the Basalt Fibers Reinforced Concrete (BFRC), SFRC, HYFRC and plain concrete beams. For this purpose, mechanical properties of concrete types and load-deflection curves of beams were obtained. The experimental results of FRC beams were compared numerically and graphically with CB.

1.8 Outline of the Thesis

This thesis is divided into five chapters include an introduction. Some background information regarding FRC, BF, SF and its advantages and disadvantages. This chapter also explains the objectives of the research.

The second chapter explains the literature review for BFRC, SFRC, and HYFRC and their properties and usage.

The third chapter gives a detailed explanation of the experimental work of this thesis.

The fourth chapter discusses the results of the contents obtained from the previous chapter and presented the materials and structural results regarding the beam test.

The fifth chapter explains how the previous chapters are related, general conclusions.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

FRC is a new constructional material established through broad research and progress during the last two decades. Their effect on the structural and mechanical properties of different types of fibers on concrete and cement composites has been extensively studied. BF and SF properties are introduced and then the effect of these fibers on the structure and mechanical properties of the concrete is described in detail.

2.2 Fiber reinforced concrete

One area of research that has expanded over the past few decades is to use discrete, randomly distributed fibers to produce composite materials called FRC. The FRC term is defined by AC1 544.2R. Many natural fibers have been used to improve the properties of concrete, as discussed in the last few years (Chen and Liu, 2005). The use of FRC has been investigated to obtain positive results on the durability of concrete (Hanseth and Lyytinen, 2010). Usage is not a new idea that the Egyptians used for the first time. At present, many kinds of fibers are used in civil engineering projects. Other recruitment FRC is used in structured fields, especially military and naval fields. For example, fortified structures, the explosion-proof structure, offshore platforms, Submarine oil mining (underground oil exploitation) expanded by (Sharqui et al., 2002). In addition, FRC has been widely used in the construction of industrial floors, bridge surface overlays, airport runways, highway docks, tunnel linings, fluid corridors, dams, slope installation and many ready-made products. Additive fibers to concrete can improve concrete properties such as tensile, bending, impact, fatigue, abrasion strength, deformation capacity, toughness, and load-bearing capacity after cracking (Jiang, 2014).

According to (Johnston, 1974) found that adding 1.5% fiber improves the compressive strength of concrete by 15%. The regular slope in the descending part of the FRC stress-strain curve shows an improvement in splitting strength, ductility, and toughness.

However, the effect of fibers addition on the compressive strength of concrete is still under argumentation as some researcher 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). Several investigators (Banthia and Gupta, 2004) and (Hsu and Hsu, 1994) concluded that the addition of fibers had no significant impact on compressive strength.

Moreover, the flexural toughness, compression toughness index and shear toughness of ceramic concrete showed a considerable increase with an increase in the fiber content, which was true regardless of the type of matrix or fiber length (S.T.Tassew and A. S. Lubell, et al., 2014).

However, the physical and mechanical properties of the fiber are not the only aspects to consider in assessing their potential use in the FRC. Factors such as the chemical durability of the fiber in an alkaline environment and the difficulty of working with fresh FRC also need to be carefully considered in choosing the type of fiber most suitable for a particular application. For example, when using different concrete mixtures or manufacturing methods, the effect of the fiber on fresh concrete properties (e.g. workability) changes. In addition, due to the uncertainties in accelerating the test, many years of field observation is required to evaluate the durability of the fiber or the durability of the entire FRC composite. It can be difficult to evaluate benefits of adding fibers are justified in the long term. The following subsections describe the basic mechanisms of FRC and typical applications of BF and SF.

2.3 Basic Mechanics of Fiber Reinforced Concrete

The main draw of using FRC is the enhancement of post-cracking behavior by limiting the growth of cracks. As a result, fiber addition has two major beneficial effects (Bentur, et al., 2014):

- Increasing the strength of the composite by transferring stress through the cracks. This behavior is characterized by an ascending stress-strain curve after the first-crack or strain hardening.
- By providing an energy absorption mechanism, the toughness of the composite material is increased. The mechanism is the result of gradual pullout of the fiber, which is reflected in the descending part of the stress-strain curve, or strain softening.

The behavior of the composite following the first-crack is dependent on the load-bearing capacity of the fiber. After cracking, several results are possible, depending on the material used. For example, using fibers with an elastic modulus and tensile strength higher than concrete (matrix) will increase pre-cracking strength depending on fiber-matrix bond strength and then increase toughness post-cracking.

However, if the elastic modulus of the fiber is lower than the elastic modulus of the matrix, the fiber deforms with the matrix and does not increase the first-crack strength. On the other hand, fibers with poor bonds with matrix are pullout shortly after cracks occur and do not increase toughness much**.** These types of variations in behavior are illustrated in Figure 2.1.

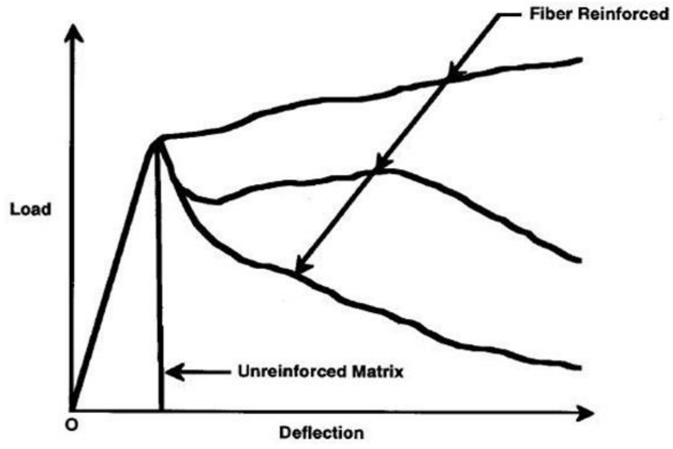
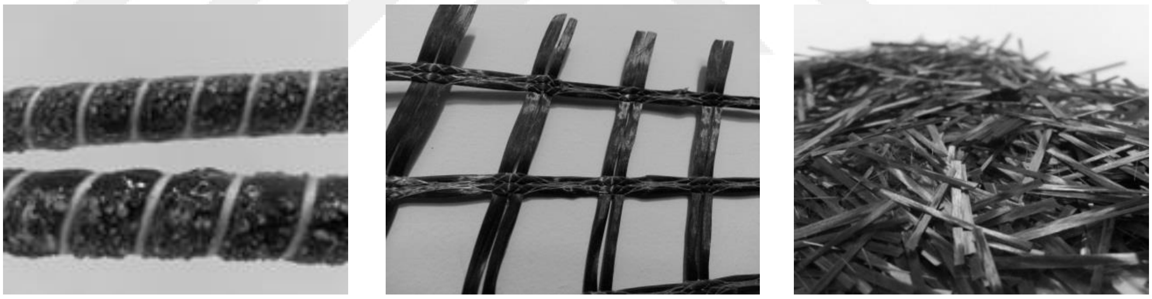


Figure 2.1 Typical post-cracking behavior of FRC (ACI 544.1R-96, 1996)

Apart from the use of different materials, the behavior of FRC composites can be modified in many ways. Behavior post-cracking can be improved by modifying the fiber-matrix contact area. This can be accomplished by changing the length or diameter (aspect ratio) of the fibers or by introducing mechanical anchorage through different geometric shapes (e.g., fibrillated or hooked end fibers). The load-bearing capacity of the composite can be improved by increasing the amount of fiber (without adversely affecting consolidation) or by a preferred orientation of the fiber (e.g. spray-up process versus random orientation from traditional mixing). Finally, the behavior can also be changed by changes to the matrix, such as using different cement, aggregate, material ratio, and production method. Regardless of these methods, the behavior of the composite is expected to change over time as well. The material properties of concrete changes due to on-going curing and environmental interactions and the load-bearing capacity of the fibers can vary depending on the chemical stability in an alkaline concrete environment.

2.4 Basalt Fiber Reinforced Concrete

Basalt is an igneous rock, which was abundantly discovered all over the world. Basalt rock is crushed, loaded into a furnace and liquefied. Next, drawing the basalt filaments through platinum-rhodium bushings. As the filament cools, the filaments are coated with a sizing agent. Sizing agents are necessary to prevent abrasion during transport. However, it also provides manufacturers with a means to differentiate themselves from their competitors. Figure 2.2 shows some common BF products developed for reinforcing concrete.



(a) Rebar (c) Mesh (c) Chopped fiber

Figure 2.2 Basalt fiber products developed for concrete reinforcing

The mechanical behavior of BFRC was evaluated by four basic characteristics: compressive strength, split tensile strength, bending force, and shock resistance. BF has recently gained popularity as a potential competitor in concrete reinforcing applications because of its excellent mechanical properties and an environmentally friendly manufacturing process (Composites World, 2006).

The research of BFRC mainly focuses on the basic mechanical properties: compressive, split-tensile, and bending strength. In the case of BF, the research shows a general agreement between the addition of beneficial fibers up to about 0.3 to 0.5%

by volume and detrimental after that (Borhan and TM, 2013), (Iyer, et al., 2015), (Jiang, et al., 2014).

The effect of BF on compressive strength has been shown to increase by as far as 31% with filament dispersion BF (Iyer, et al., 2015), but it is typically not important (Borhan and TM, 2013), (Iyer, et al., 2015), (Jiang, et al., 2014), (Dias DP, et al., 2005), (Ayub T, et al., 2014), (Adhikari and S, 2013), (Lipatov, et al., 2015), (Ramakrishnan V, et al., 1998).

The main benefit of BF in concrete under compression is the transition from brittle failure mode to more ductile mode (Jiang, et al., 2014), (Ayub T, et al., 2014), (Adhikari and S, 2013), (Ramakrishnan V, et al., 1998).

BF has been shown to significantly increase the tensile strength of concrete (Borhan and TM, 2013), (Iyer, et al., 2015), (Jiang, et al., 2014), (Dias DP, et al., 2005), (Ayub T, et al., 2014), (Adhikari and S, 2013), (Lipatov , et al., 2015). However, it is difficult to evaluate the magnitude of the increase in tensile strength, due to the discrepancies of values derived from direct tension, split tensile and bending test.

Furthermore, (Jiang, et al., 2014) found the beneficial effects of BF diminished significantly after 90 days.

BF has been shown to increase the flexural toughness of concrete (Jiang, et al., 2014), (Dias DP, et al., 2005), (Adhikari and S, 2013), (Ramakrishnan V, et al., 1998). However, because the results are based on different test methods, it is difficult to evaluate the relative merit of each product.

The researchers found by using the ACI Committee 544 recommended the drop-weight test for impact resistance (ACI Committee 544, 1988) that BF can significantly improve performance after cracking (Ramakrishnan V, et al., 1998).

The investigator showed the effects of elevated temperatures on the residual compressive strength and failure behavior of FRC. Two types of short fibers are used in this study e.g., SF and BF. They have reported that the residual compressive strength capacity of SFRC is higher than unreinforced concrete at both elevated temperatures and BFRC, on the other hand, have lower strength retention capacity than the control unreinforced concrete (Shaikh, et al., 2015).

Experimental results showed that the inclusion of BF and Glass Fiber (GF) in the concrete mixture reduces the workability of the concrete mixture. BFRC showed the highest compressive strength with 0.5% addition and Glass Fiber Reinforced Concrete (GFRC) showed maximum compressive strength with 0.75% addition (Kizilkanat et al., 2015).

The studies demonstrated that the beneficial effect was observed for concrete tensile strength, SFs added in a 1.5 % volume ratio showed a 40 % increase in tensile, flexural strength. The inclusion of 20 kg/m3 of BF 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 RC 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 (Krassowska, et al., 2013).

Researchers presented a comparative study of the effect of basalt, glass and SF on compressive strength and flexural strength of M40 grade concrete. The fibers were randomly placed in concrete (0.25%, 0.5%, 0.75%, and 1%) of the total volume of the concrete. The test results show that the flexural strength of BFRC is (19.16%, 31%, 9.8%, 1%) respectively higher than CB for every percentage of BF (0.25%, 0.5%, 0.75%, 1%) respectively. Similarly, for each percentage of GF, the flexural strength of GFRC is 9.08%, 17.1%, 4.24%, 0.2% respectively more than the reference beam. In addition, for each proportion of SFs, the flexural strength of the SFRC is 13.14%, 24.3%, 8.7%, and 2.29% respectively higher than the CB. The results showed a maximum flexural strength of 0.5% volume fraction of each type of fibers (Patil, et al., 2014).

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

Usage of BF in pavement concrete slabs is a good practice to enhance the properties of concrete or RC elements. As well, basalt filaments can be used to reinforce polymers to produce fiber reinforced polymer rebar. A similar technique has recently been applied on a smaller scale to produce basalt minibars (Reforce Tech, 2015).

Furthermore, the practicality of RC was assessed by BF through the repair of the concrete bridge structure (square turret), which was built sometime between the 1950s and 1960s. Patching repairs on supporting walls and snorkeling were made using cement-based mortars reinforced with BF. Approximately one cubic meter of degraded concrete at the end of the bridge surface was replaced with RC made of BF cast in situ. The measurements were made after one year by visual comparison between basaltic reinforced areas versus those that were not.

2.5 Steel fiber Reinforced Concrete

Concrete is intrinsically strong in pressure but weak in tension. The traditional way to overcome this shortage is to provide iron bars to carry the tensile strength once the concrete is broken or pre-stressed so that most of the concrete remains under pressure. That is why this insertion of SFs may essentially increase the tensile strength of the matrix to a moderate level but increases the rigidity largely. This has mainly inspired researchers to study the mechanical properties of iron-RC under different load conditions.

The most useful properties of SFRC are the improvement of flexural toughness, flexural fatigue endurance and impact resistance (ACI Committee 544.1 R - 96, 1996). As a result, SFs can completely or partially replace conventional steel rebar in many applications such as industrial flooring and pavements. However, SFRC poses several problems such as increased dead load, reduced workability, fiber balling at high dosages, and susceptibility to corrosion.

Using the SFRC can bring great benefits to the construction industry that savings during construction and labor were the most important .Additionally, SFs improve the cracks control, especially when acting with a reinforcing bars. However, there is still little consensus on the principles that must be adopted in the design. Several different test methods are currently used to determine the material properties of SFRC, but there is no agreement on which method is best. As a result, SF suppliers claim for the similar fibers with different properties, that confusing among designers, and in some cases insufficient structural performance.

The mechanical strength properties of SFRC were closely related with fiber parameters, matrix strength, and interaction. However, the strength of the matrix fiber interaction has not been considered in previous studies. Fiber matrix interaction is an important factor that implies strengthening because of fiber bridging in all micro-cracks in concrete matrix.

In earlier studies (Ghosh et al., 1989), (Agrawal et al., 1996), (Gao et al., 1997), (Padmarajaiah and S. K., 1999), (Song and Hwang, 2004), the improvement in mechanical properties in concrete due to the addition of SFs.

At the turn of the 20th century, experimentation involving the use of SFs can be traced back as early as 1910 by (porter, 1910). It has been found that both compressive strength and tensile strength of concrete are significantly increased by including short steel pieces. Within the same publication (Porter, 1910) it was also foreseen that such reinforcement would be widely implemented in many structural applications.

SFs have a much smaller impact on the compressive response of SFRC than its tensile response. Research has shown that there is a small decrease in the Elastic Modulus of the concrete when SFs are added to the matrix (Neves, et al., 2005). This fact is attributed to the small voids introduced by the addition of the SFs.

However, the SFs introduce additional ductility in the overall compressive response (Kooiman, et al., 2000), (Lim and Nawy, 2005). This can prove beneficial in the case of a compressive failure (Barros and Figueiras, 1999), (Labib and W. A., 2008).

In 1974, Swamy et al. proposed a constitutive relationship for the estimation of the flexural strength of SFRC. Within the context of this publication, it was argued that the interfacial bond stress between the brittle matrix and its fibrous components was largely linear. A reasonable correspondence with the proposed relationship and previous experimental data was attained (Swamy, et al., 1974).

Studies have shown that the SFRC concrete samples after they reach their compressive strength give a ductile behavior. On the other hand, these samples showed a decrease in the elasticity coefficient. On the other hand, these samples generally showed an increase in the strain at the compressive strength with increased fiber volumetric percentage ratios and fibers aspect ratio (Lee, et al., 2015).

It was found that the addition of 1.5% volumetric percent of SF additives increased to 40% of the direct tensile strength of the concrete (Wiliamson and G. R., 1974).

The researchers studied the effect of concrete strength and fibers content ratio on the flexural strength of the SFRC. Three fibers volumetric percentage ratios, 0.25%, 0.375%, 0.5%, and three concrete compressive strength points, 25, 35 and 45 Mpa were considered for experiment. As a result, it was found that the equal flexural capacity ratio increases with increasing fibers volumetric percentage ratios but decreases with the increasing strength of concrete (Lee, et al., 2017).

It is well known that numerous parameters influence the tensile post-cracking response of SFRC. In addition, due to the non-homogeneous nature of SFRC and of concrete in general, significant variations (scatter) in its response can be observed (Kooiman, et al., 2000).

The influence of steel, glass and polypropylene fiber have been reported in an earlier investigation to improve the post-peak behavior of concrete. By increasing fiber content, ductility and toughness (energy absorption) are also increased (Fanella, et al, 1985).

SF additives to concrete mixtures can have various effects on compressive strength. It is certain that SF can improve post-peak concrete compressive strength. In other words, using SF increases toughness and energy observation. This feature is useful for preventing sudden explosive failure of concrete and is therefore successfully used to improve high strength concrete (ACI 544.1 R, 2002).

The study also reported that adding SF to traditional RC beams improves strength (ultimate load), ductility and stiffness under static loading (Bentur, et al, 1983).

Most of the prior theoretical and experimental studies on FRC beams are limited to SF reinforced RC beams. The results of these studies indicate that the addition of fibers to the mixture maintains structural stability and integrity and is effective in improving the ductile behavior of concrete beams (Bencardino, et al, 2013), (Swamy, et al, 1981).

The research showed that the combination of SFs in RC beams is effective for improving the shear strength capability. It has also been detected that the strength increases by using variable depth of the SF. The beam reinforced using this scheme increased shear strength and ultimate load of 20% compared to the controlled beam (Mondal, et al., 2015).

The researchers studied seven full-scale SFs reinforced self-consolidating concrete beams to find the impacts of macro SFs 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 SFs was more pronounced for beams compared to lower reinforcement ratio. SFs played a substantial role in decreasing the steel reinforcement strain relative to the beams without SFs at the same load value. Including of 50 kg/m3 SFs in the beam with a 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/m3 SFs in reinforced self-consolidation concrete beam could be replaced reinforcement ratio by about 0.2 %, (Patil, et al, 2014).

Although a variety of fiber reinforcing materials exist, FRC used for structural applications is most often made with SFs.

SFs have been used in concrete since the early 1900's. SFs are widely used applications of SFRC include highway pavement, airport runways, refractory concrete and concrete tunnel lining by spraying FRC.

SFs are also useful in flexural members as a secondary reinforcement, in which they can enhance resistance to dynamic loads (impact, fatigue, blast, and seismic loading) and changes in temperature and humidity (Bentur, et al., 2014).

In many ground floor slabs for both commercial and industrial applications, only a nominal amount of steel reinforcement is required to resist flexure and control cracking induced by the combined effects of loading and restrained shrinkage. Alternatively, some or all of the conventional reinforcement can be replaced with SFs.

The increasing demand of the construction industry for alternative construction methods has led to the development and implementation of SFRC in a wide variety of both industrial and commercial applications. Such applications include the design and construction of pile-supported and ground-supported floor slabs, pavements, and tunnel linings. This has triggered considerable developments, in more recent years, in SFRC constitutive modeling (Hillerborg, 1980), (Barros and Figueiras, 1999), (Bernard and E. S., 2000), (RILEM Technical Committee, 2002), (Soranakom, 2008).

2.6 Hybrid Fibers Reinforced Concrete

According to the composite material theory and other findings (Banthia et al., 2004). The addition of randomly distributed discrete fibers to the structural concrete increases its stiffness, while at the same time, ductility and load carrying capacity reduced crack development and propagation. Several carbon fibers, polyvinyl alcohol fibers, SFs, and asbestos fibers high modulus and high strength fibers can effectively increase the strength of concrete. However, their intrinsic brittle behavior does not enable ductility improvement. Low modulus strength fibers including polypropylene, basalt, and GFs are useful for improving ductility and reducing cracking (Soe et al., 2013), (Halvaei et al., 2016) and (Halvaei et al., 2015). Therefore, in order to obtain a cementitious composite having both improved strength and ductility, it is necessary to combine fibers having different chemical / mechanical properties. The active synergistic effects of different fibers complement each other, making it possible to create new composite materials with high performance and excellent economic benefits (Qian, et al., 2000), (Singh, et al., 2010). The use of two or more types of fibers in a suitable cementitious may potentially improve the overall properties of concrete and resulted in performance synergy (Hsie, et al., 2008), (Lawler, et al., 2005), (Jusoh, et al., 2017).

Three stages of crack formation can be distinguished of FRC composite from the crack evaluation: micro-crack formation before peak load, coalescence of fine micro-cracks into one micro-crack, and micro crack propagation after that (Rossi et al., 1987). By this evaluation, cementitious of different fiber types were proposed as reinforcement materials for cementitious materials. Since two or more combined fibers are used for cementitious composites, they provide different responses to the cracking process during various stages of loading. The resulting FRC comprising a cementitious of two or more fibers is often referred to as HYFRC. Therefore, HYFRC is designated to the cementitious matrix incorporating various types of fibers that provide hybrid performance that exceeds the sum of individual fiber performances (Banthia, 2004). Several investigators have concluded that hybridization of two or more different types of fibers produces cementitious composites with improved ultimate strength and strain capacity and strain hardening behavior (Ahmed and Mihashi, 2011) and (Nguyen et al., 2013). (Silva et al., 2013) and (Ahmed and Maalej, 2009) which involve mixing various lengths, diameters, modulus and tensile strength of the fibers as methods of hybridization. Since fibers size (length and diameter) are different, small size fibers bridge the micro cracks and thus control their coalescence, but the larger one is prevented macro cracks propagation. Controlling the micro crack and macro crack results in a higher strength and fracture toughness of the composite is substantially improved (Banthia, 2004). Because of this synergetic mechanism, the improvement in ductility depends mainly on long fibers (Marković and I., 2006). Figure 2.3 explains the effect of HF with different size in the concrete during applied load in the first and second phase.

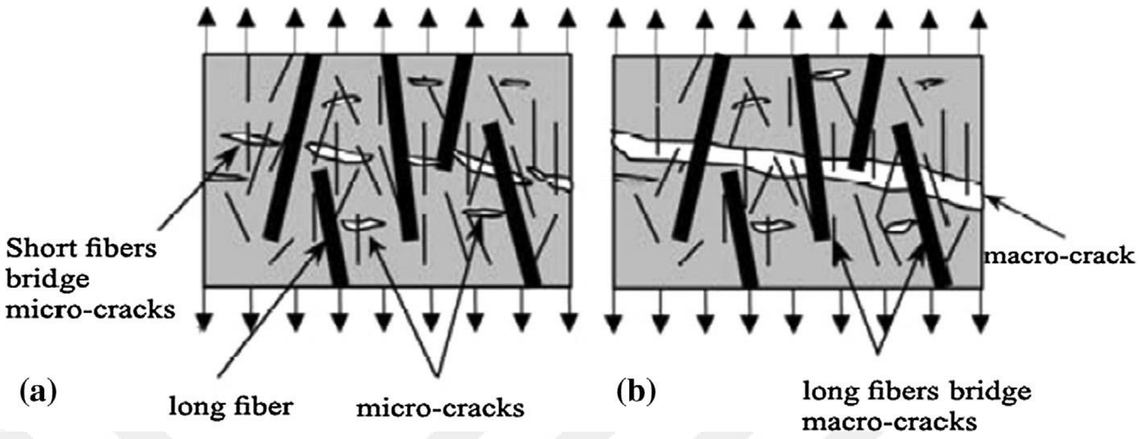


Figure 2.2 Effect of the HF of different size, (a) first phase, and (b) second phase of loading (Marković, 2006)

However, two fibers with different flexibility are used in the cementitious composite, stronger and stiffer fibers provide the first crack stress and the ultimate strength but the relatively flexible fibers improved toughness and strain capacity in the post-cracking region. In HF reinforcement, stronger and stiffer fibers can improve the strength of concrete because of the high modulus of elasticity and stiffness, but low modulus fibers can improve the ductility and toughness of HYFRC (Banthia et al., 2014). Some uses of HYFRC can be summarized in the fields of civil engineering: in Concrete Pavements, Construction of machine foundation, Rehabilitation of Bridge Deck, Tunnel Linings. Very few researches are present in the literature on the hybrid effect of BF, SF, and GF in RC beams. Therefore, in this study, a hybrid system was created by combining BF, SF, and GF. Since information on the ductile performance of HYFRC is insufficient, an attempt was made to investigate the ductility performance of HYFRC beams.

CHAPTER 3

EXPERIMENTAL PROCEDURE

3.1 Introduction

The present chapter describes the experimental program, which was undertaken to develop a better understanding of using BF, and combined BFs with GFs were mixed to enhance concrete properties. Accordingly, a detailed description such as the mix design, materials used, mixing and proportioning, casting and curing, preparation of formwork and the testing procedure are presented herein in this chapter. The aim of the present chapter is to acquaint the reader with the experimental methodology that was followed by testing simply supported beam specimens subjected to two concentrated equal loads. As well, the cylinder split tensile strength test, cube compressive strength test. The experimental work was carried out at the Structural and Materials Laboratory at Gaziantep University.

3.2 Mix Design and Material Properties

- Concrete mix design: The concrete mix was designed to use for plain concrete, BFRC, SFRC, basalt-glass HYFRC and steel-glass HYFRC. The details of the concrete mix design proportions that was chosen for the present study is presented in Tables 3.1- 3.4. For all mixtures, the water to cement ratio of the concretes was kept constant as 0.48.
- Cement: CEM II 32.5R Portland cement was used as cementitious materials. The chemical and physical features of the cement are presented in Table 3.5 and shown in Figure 3.1.
- Fine aggregate (Sand): A natural river sand was used and size interval was (0-4) mm.
- Coarse aggregate (Gravel): A river gravel was used with a maximum size is 10 mm.

Table 3.1 The details of mix proportion for Group A

Group		Concrete Mix	Cement Kg/m^3	Water Kg/m^3	Coarse aggregate Kg/m^3	Fine aggregate Kg/m^3	Super Plasticizer Kg/m^3	Fiber content by volume %		
								BF	SF	GF
CB		Control Beam	400	192	1110	600	1.80	-	-	-
A	A1	BF 0.50					2.45	0.50	-	-
	A2	BF 1.00					3.45	1.00	-	-
	A3	BF 1.50					3.80	1.50	-	-

Table 3.2 The details of mix proportion for Group B (Maan Albayati, 2017)

Group		Mix Concrete	Cement Kg/m^3	Water Kg/m^3	Coarse aggregate Kg/m^3	Fine aggregate Kg/m^3	Super Plasticizer Kg/m^3	Fiber content by volume %		
								SF	BF	GF
CB		Control Beam	400	192	1110	600	1.80	-	-	-
B	B1	SF 0.50					1.80	0.50	-	-
	B2	SF 1.00					1.80	1.00	-	-
	B3	SF 1.50					1.80	1.50	-	-

Table 3.3 The details of mix proportion for Group C

Group		Mix Concrete	Cement Kg/m^3	Water Kg/m^3	Coarse aggregate Kg/m^3	Fine aggregate Kg/m^3	Super Plasticizer Kg/m^3	Fiber content by volume %		
								BF	GF	SF
CB		Control Beam	400	192	1110	600	1.80	-	-	-
C	C1	BF 0.50 GF 0.50					3.55	0.50	0.50	-
	C2	BF 0.25 GF 0.75					3.45	0.25	0.75	-
	C3	BF 0.75 GF 0.25					3.63	0.75	0.25	-

Table 3.4 The details of mix proportion for Group D (Maan Albayati, 2017)

Group		Mix Concrete	Cement Kg/m^3	Water Kg/m^3	Coarse aggregate Kg/m^3	Fine aggregate Kg/m^3	Super Plasticizer Kg/m^3	Fiber content by volume %		
								SF	GF	BF
CB		Control Beam	400	192	1110	600	1.80	-	-	-
D	D1	SF 0.50 GF 0.50					1.80	0.50	0.50	-
	D2	SF 0.25 GF 0.75					1.80	0.25	0.75	-
	D3	SF 0.75 GF 0.25					1.80	0.75	0.25	-

Table 3.5 Cement features

Cement component	Calcium Oxide (Cao)	Silica (Sio_2)	Alumina Dioxide (Al_2O_2)	Iron Dioxide (Fe_2O_2)	Other
Percentage of component	63	22	7.7	3.3	4

Figure 3.1 Portland cement type 32.5R

- Fiber types: The mechanical properties of all fibers that used in this investigation were shown in Table 3.6. Figure 3.2 shows pictures of all the fibers used in the manufacturing of BFRC, SFRC, and HYFRC beams. The chopped BFs, SFs were hooked end shape and S-GFs were used in this investigation.

Table 3.6 Fibers properties

Fibers Types	Diameter (D) (μm)	Length (L) (mm)	Elongation (%)	Modulus of Elasticity (GPa)	Tensile Strength (Mpa)	Specific of gravity (Kg/m^3)	Density (g/cm^3)
Basalt Fiber	13-20	12	3.15	89	4100-4800	2800	2.8
Steel Fiber	750	30		210	1200	7850	7.85
Glass Fiber	13	12	2.56	77	3400	2600	2.6

Figure 3.2 (a) Basalt fibers, (b) Glass fibers, and (c) Steel fibers.

- Water: In order to mix and place concrete, we were used domestic water, it was necessary for the cement hydration process and give sufficient workability.
- Water reducer: By adding fibers into the concrete, reduce the workability of the concrete, to obtain a desired level of workability in the concrete, Polycarboxylate based Superplasticizer (SP) was used at varying dosages.

3.1 Description of Beam Specimens

3.3.1 Beam geometry

Twelve FRC beams and CB were selected for the flexural experiments. The flexural machine (INSTRON) in the Gaziantep University laboratory as shown in Figure 3.3 carried out the tests for beams. All specimens with the identical size of (1500 x 150 x 200) mm. All beams have identical reinforcement details including four longitudinal reinforcements two of them 10 mm diameter bars were used at the bottom (tension zone) of each beam, two of them 8 mm diameter bars were used at the top (compression zone) of each beam and stirrups reinforcement of 5.5 mm diameter at 100 mm spacing center to center as shown in Figure 3.4 with specimen details, loading and supporting of the beam.

Figure 3.3 Flexural test machine for beam

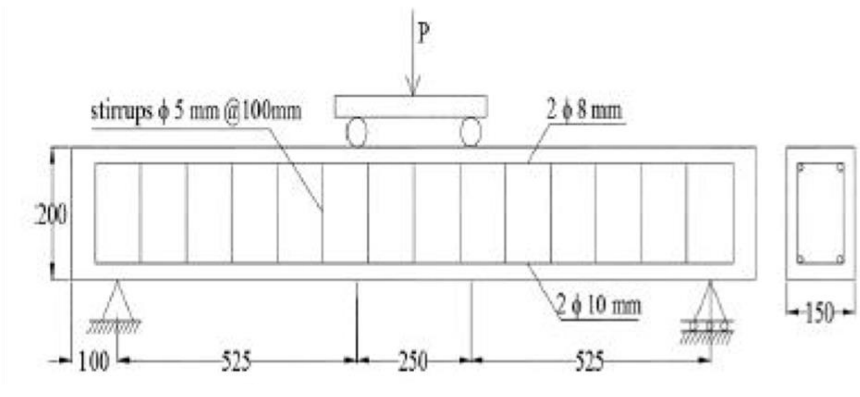


Figure 3.4 Loading and geometry of tested beam (all dimension in mm).

3.3.2 Beam volumetric fiber percent

The experimental study constructed thirteen RC beams and divided into four groups, Group A, B, C, and D. The reinforcement details and dimensions for all beams were the same but we used a different percentage of fibers. The first group A beams were reinforced with 0.5 %, 1 %, 1.5 % volumetric ratio of BFs, The second group B beams were reinforced with 0.5 %, 1 %, 1.5 % volumetric ratio of SFs, the third group C beams were reinforced with 0.5% BFs and 0.5% GFs, 0.25 % BFs and 0.75 % GFs.0.75 % BFs and 0.25 % GFs, the fourth group D beams were reinforced with 0.5% SFs and 0.5% GFs, 0.25 % SFs and 0.75 % GFs.0.75 % SFs and 0.25 % GFs and, the last beam has not contained any fibers CB. Table 3.7 shows the detail of these beams, which explains the beam name refers to its fibers type, and the volumetric ratio that was used such as BF0.50, which refers to BFs with 0.5 % volumetric ratio.

Table 3.7 The detail of the beams volumetric fiber percent

Group	**Concrete mixtures**	**BF Fiber content by volume (%)**	**SF Fiber content by volume (%)**	**GF Fiber content by volume (%)**
CB		-	-	-
A	BF 0.50	0.50	-	-
	BF 1.00	1.00	-	-
	BF 1.50	1.50	-	-
B	SF 0.50	-	0.50	-
	SF 1.00	-	1.00	-
	SF 1.50	-	1.50	-
C	BF 0.5 GF 0.5	0.50	-	0.50
	BF 0.25 GF 0.75	0.25	-	0.75
	BF 0.75 GF 0.25	0.75	-	0.25
D	SF 0.5 GF 0.5	-	0.50	0.50
	SF 0.25 GF 0.75	-	0.25	0.75
	SF 0.75 GF 0.25	-	0.75	0.25

3.4 Manufacturing of Specimens

3.4.1 Manufacturing of reinforcement cages and formwork

Reinforcement cages were performed in the laboratory of Gaziantep University. The formwork was performed using plywood with a depth of 200 mm, a width of 150 mm and a length of 1500 mm, and the inner surfaces of the formwork was cleaned and oiled before casting the concrete. The Figure 3.5 shows some examples of laboratory manufacturing for the specimens.

3.4.2 Proportioning and mixing

The concrete was mixed in a vertical rotations mixer that has four paddles for blending the materials by (80-100) liter capacity, which was done at Gaziantep University Laboratory as shown in Figure 3.6. The details of mix proportion for this work was shown in Table (3.1), (3.2), (3.3) and (3.4). As the first step the dry materials (river sand, river gravel, and cement Type II) were mixed for almost 5 minutes clockwise and counterclockwise to be homogeneous mixture before adding water. Then Super plasticizer and water were combined with each other and shacked well then added to the mixture for almost five minutes as shown in Figure 3.6. Fibers were added as the last step. In order to ensure adequate mixing and distribution of the fibers, the concrete was mixed for five minutes then mixture will be ready for casting.

3.4.3 Casting and curing process of specimens

When the mix is ready for casting the specimens, a fresh concrete mix was moved from the mixer machine to the mold by a concrete transporter truck as shown in Figure 3.7. The concrete was placed in three layers into a ready mold with reinforcement, and each layer was compacted by a vibrating machine to consolidate the mix and in order to prevent the occurrence of segregation as shown in Figure 3.7. Figure 3.7 illustrates the surface finish, it provides a smooth surface and to avoid fibers extend. Prepared three cubes and three cylinders' specimen for each beam as shown in Figure 3.8. A standard plastic test cylinder (100 x 200) mm and also a plastic test cube by dimension (100 x 100 x 100) mm were cast as three layers, the grading process for each layer was done by a rod carefully as shown in Figure 3.8.

Figure 3.5 Manufacturing of tested beam (a) reinforcement cages, (b) formwork (c) reinforcement with mold

After casting concrete into the mold, the surface of the concrete was flattened and smoothed using a trowel. The cubes and cylinders were sampled following ASTM C172, (2007). The cylinders were used to evaluate the tensile strength fct of the concrete and cubes were made to evaluate the compressive strength fc' of the concrete. We were Cast three samples to get an accurate test reading.

After casting, for the beams, all samples were cured at room temperature for 24 hr. After demolding, the beam specimens were cured by covering with a layer of waterproof material and kept moist for 28 days as shown in Figure 3.9. This curing method is called as membrane curing (ASTM C156-05, 2005).

For the cylinders and cubes, after one day of casting, all samples were opened and placed in the curing pool with an average temperature of 23 ℃ for 28 days of curing as shown in Figure 3.10. The cubes and cylinders were cured based on (ASTM C31/C31M, 2003).

Figure 3.6 Proportioning and mixing of the specimen

Figure 3.7 Preparing and casting of the beam specimens

Figure 3.8 Preparing and casting of cubes and cylinders

Figure 3.9 Curing of beam specimen

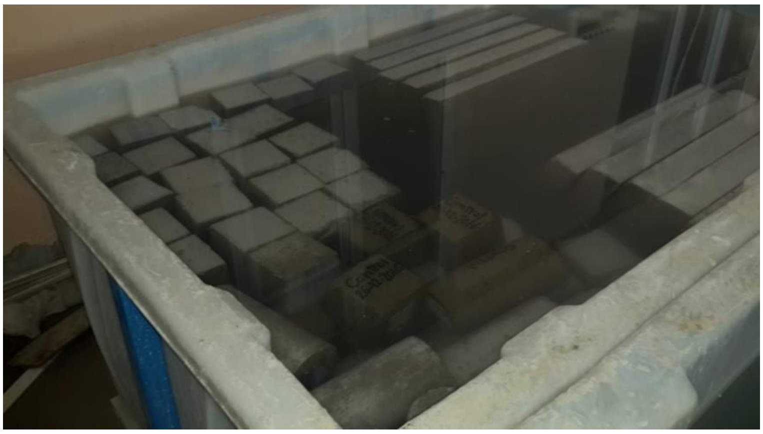


Figure 3.10 Pool curing for cube and cylinder

3.5 Test Set-up and Measurement Procedure of the Specimens

3.5.1 Compressive strength test

The compressive strength test is the most common test conducted on hardened concrete. It is a simple test to perform. Furthermore, many of the desirable properties of concrete are qualitatively related to its compressive strength. However, the main reason for the popularity of compression testing is the essential importance of compressive strength in concrete structural design (Neville and A. M., 1996). Concrete compressive strength depends on many factors such as water-cement ratio, cement strength, the quality of concrete material, and quality control during production of concrete…etc. Compressive strength test according to (ASTM. C39/C39M, 2003), was performed on cube specimens with dimensions of 100×100×100 mm. For each beam specimen, we prepared three cube specimens, in order to ensure the fibers distribution was similar to that in the beam, and average was reported from the test results in this study. A (BESMAK) digital series compression machine in the Gaziantep University laboratory as shown in Figure 3.11 carried out the test process for cubes. It was used to find a concrete compressive strength. Load carrying capacity (kN/sec) and strength (MPa) were recorded.

Figure 3.11 Compressive machine test for compressive strength test

3.5.2 Splitting tensile strength test

The Splitting tensile test (indirect test) is a simple and indirect way to determine the tensile strength of concrete, which give more consistent results than other tensile tests. The measured strength in the split test is close to the direct tensile strength of the concrete and is about 5 to 12 percent higher (Neville and A. M., 1996). The splitting tensile strength test was performed according to (ASTM C496, 2007), on three specimens of each mix. A load was applied using a concrete compression machine. The cylinders were tested using a (BESMAK) digital series compression machine as shown in Figure 3.12. The rate of loading was 1.5 kN/sec. The concrete cylinder was laid in a horizontal position, and the load vertically applied to one of the long sides, that create a uniform tensile stress in the specimen as shown in Figure 3.12. To determine the specimen splitting tensile strength can use the following equation (3.1):

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

Where, T is the splitting tensile strength in MPa and P is maximum applied load in N, also the d is the diameter of the cylinder in mm and l is the height of the cylinder in mm.

Figure 3. 12 Compressive machine test for split tensile strength test

3.5.3 Beam flexural strength test

The flexural strength test of concrete was conducted on the beams to study its flexure behavior. The specimens were installed as a simply supported condition and tested by two-point loading based on (ASTM C1018-92, 1992), with an effective span of 1300 mm between the supports, and the distance between loads was 250 mm. Each specimen was supported on roller assemblies and knife-edges to allow longitudinal motion and rotation. Figure 3.13 shows the test setup and instrumentations for the tested specimen. For test process utilized an INSTRON testing machine its consists of a hydraulic actuator with 250 kN load capacity and at an average rate of displacement 0.02 mm/sec. To find out the applied load on the beam specimens we used a load cell while a Linear Variable Differential Transformer (LVDT) was used to find out the deflection of the specimens. The beam specimens were loaded until they are broken, applied loads and deflections will record. However, the cracks of the specimens were mapped and test observations were recorded during loading and at the time of failure. Figure 3.13 presents the four-point flexural test of FRC and HYFRC beam specimen. To determine the flexural strength, we used the following equation (3.2).

$$\mathcal{F} = \frac{\mathrm{PL}}{bd^2}ʃ \qquad (3.2)$$

Where, ʃ is the strength of the beam in MPa, and P is the load in N, L is the span length in mm, b is the average width of the beam at the fracture, as oriented for testing in mm and d is the average depth of the beam at the fracture, as oriented for testing in mm.

Figure 3.13 Flexural strength test machine for beam and beam failure

CHAPTER 4

EXPERIMENTAL RESULTS

4.1 General Remarks

This chapter shows the total results of experimental works done in this research. The compressive strength test, splitting tensile strength test and flexural strength test for the concrete with BFs, SFs, and hybrid (basalt-glass, steel-glass) fibers are explained. In order to find the optimum volumetric ratio of fibers, and a detailed analysis of FRC beams considering the flexural performance of FRC beams, HYFRC beams, and CB. Therefore, to characterize the performance of the RC beams they are discussed individually by examining the relationship between load and deflection, and failure mode.

4.2 Control Specimens for Mechanical Properties

4.2.1 General overview

Table 4.1, and Table 4.2 summarizes the mechanical test results for every mix proportions used in this research.

Table 4.1 The compressive strength and split tensile strength result of FRC and HF for tested cube and cylinder

<table>
<tr><td colspan="2" rowspan="2">Group</td><td>Concrete mixtures</td><td>Compressive strength (MPa)</td><td>Tensile strength (MPa)</td></tr>
<tr><td>CB</td><td>63.66</td><td>2.85</td></tr>
<tr><td rowspan="3">A</td><td>A1</td><td>BF 0.50</td><td>54.3</td><td>4.04</td></tr>
<tr><td>A2</td><td>BF 1.00</td><td>45.4</td><td>4.26</td></tr>
<tr><td>A3</td><td>BF 1.50</td><td>43.11</td><td>4.90</td></tr>
<tr><td rowspan="3">C</td><td>C1</td><td>BF0.50 GF0.50</td><td>57.42</td><td>3.96</td></tr>
<tr><td>C2</td><td>BF0.25 GF0.75</td><td>50</td><td>4.16</td></tr>
<tr><td>C3</td><td>BF0.75 GF0.25</td><td>58.82</td><td>5.06</td></tr>
</table>

Table 4.2 The compressive strength and split tensile strength result of FRC and HF for tested cube and cylinder (Maan Albayati, 2017)

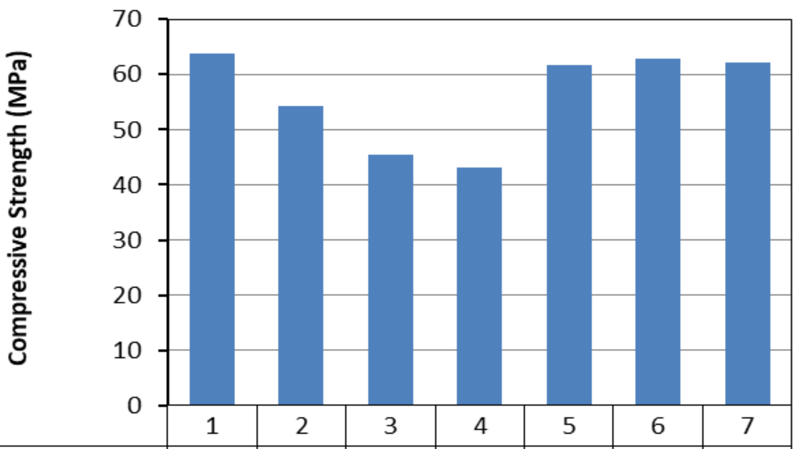
Group		Concrete mixtures	Compressive strength (MPa)	Tensile strength (MPa)
-		CB	63.66	2.85
B	B1	SF 0.50	61.71	6.85
	B2	SF 1.00	62.89	7.03
	B3	SF 1.50	62.04	6.94
D	D1	SF0.50 GF0.50	61.09	6.51
	D2	SF0.25 GF0.75	55.42	4.42
	D3	SF0.75 GF0.25	58.72	5.56

4.2.2 Compressive test for cubes

For the first Group (A) the compressive strength of concrete mixtures containing BF only was presented in Table 4.1 and Figure 4.1. Test results showed that for every percentage of BFs (0.5%, 1.0%, and 1.5%) the compressive strength of BFRC which was (14.7%, 28.7%, and 32.3%) less than control concrete. BFRC presented the highest reduction at this group in compressive strength at 1.5% addition. Table 4.1 and Figure 4.1 displays a negative change in compressive strength, where the BFs additive with a different percentage**.**

For the second Group (B) the compressive strength of concrete mixtures containing SF only was presented in Table 4.2 and Figure 4.1. Test results showed that for every percentage of SFs (0.5%, 1.0%, and 1.5%) the compressive strength of SFRC which was (3.1%, 1.2%, and 2.5%) smaller than control concrete. SFRC presented the highest reduction at this group in compressive strength at 0.5% addition. Table 4.2 and Figure 4.1 displays no important change in compressive strength, where the SFs additive with a different percentage.

Figure 4.1 shows the compressive strength of mixtures containing SF, BF only. It is evident from Figure 4.1 that fiber addition had a negative effect on the compressive strength of mixtures containing SF, BF only when compared with plain concrete. However, the influence in compressive strength was more prominent for SF when compared to BF mixes. The highest compressive strength was achieved for mix SF1.0 (62.89 MPa).

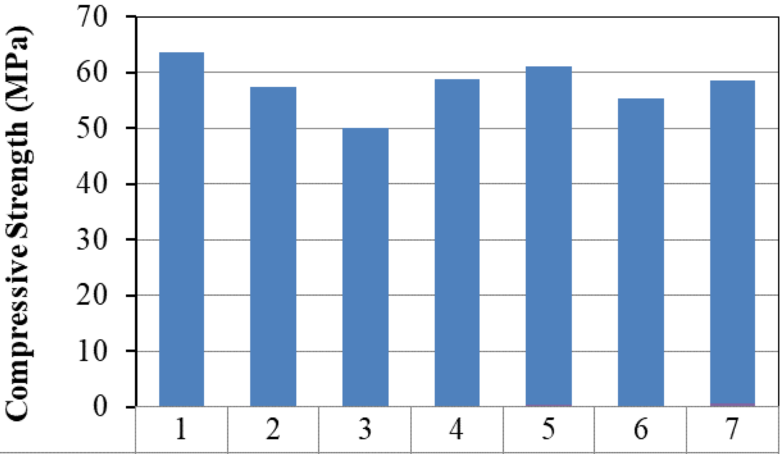


	1	2	3	4	5	6	7
Compressive strength	63.66	54.30	45.40	43.11	61.71	62.89	62.04
Steel Fiber Content (%)	0.00	0.00	0.00	0.00	0.50	1.00	1.50
Basalt Fiber Content (%)	0.00	0.50	1.00	1.50	0.00	0.00	0.00

Figure 4.1 Compressive strength of concrete mixtures with different percentage of steel fibers and basalt fibers

For the third Group (C) the compressive strength of concrete mixtures containing BF and GF was presented in Table 4.1 and Figure 4.2. Test results showed that for every percentage (0.5%BF and 0.5%GF, 0.25%BF and 0.75%GF, 0.75%BF and 0.25%GF) the compressive strength was (9.8%, 21.5% and 7.6%) respectively less than control concrete. BF additives to the hybrid basalt-glass fibers concrete mix may have a variable impact on compressive strength. The concrete with 0.25% BF and 0.75% GF showed the highest reduction at this group in compressive strength. However, fiber dosage with 0.75% BF and 0.25% GF resulted in the smallest reduction at this group in compressive strength. However, the negative effect of BF in the compressive strength of concrete is overcome with a slight increase in compressive strength compared to concrete with BF only, when a hybrid combination of both BFs and GFs are used.

For the last Group (D) The compressive strength of concrete mixtures containing SF and GF was presented in Table 4.2 and Figure 4.2. Test results showed that for every percentage (0.5%SF and 0.5%GF, 0.25%SF and 0.75%GF, 0.75%SF and 0.25%GF) the compressive strength was (4%, 12.9% and 7.8%) respectively less than control concrete. SF additives to the hybrid steel-glass fibers concrete mix may have a variable impact on compressive strength. The concrete with 0.25% SF and 0.75% GF showed the highest reduction at this group in compressive strength. However, fiber dosage with 0.5% SF and 0.5% GF resulted in the smallest reduction at this group in compressive strength. Also, there is no enhancement in compressive strength, where the SFs and GFs additive to concrete mix with a different percentage.



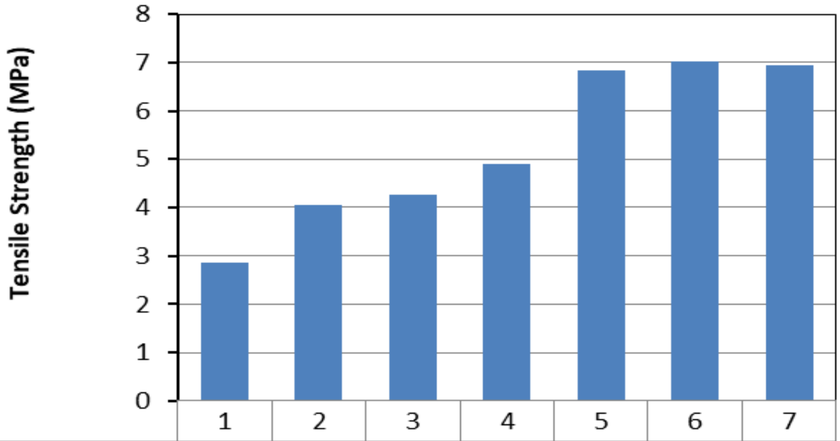
	1	2	3	4	5	6	7
Compressive strength	63.66	57.42	50.00	58.82	61.09	55.42	58.72
Basalt Fiber Content (%)	0.00	0.50	0.25	0.75	0.00	0.00	0.00
Steel Fiber Content (%)	0	0	0	0	0.5	0.25	0.75
glass Fiber Content (%)	0.00	0.50	0.75	0.25	0.50	0.75	0.25

Figure 4.2 Compressive strength of concrete mixtures with different percentage of HF

4.2.3 Tensile (splitting) test for cylinders

For the first Group (A) Table 4.1 and Figure 4.3 presents the splitting tensile strength (T) test results of concrete mixes containing BF only. BFs additive with the different volumetric ratios (0.5%, 1.0%, and 1.5%) the tensile strength of BFRC which was (41.8%, 49.5%, and 71.9%) more than control concrete. BFRC presented the highest tensile strength at 1.5% addition, while it has presented the lowest tensile strength at 0.5% addition. However, an important change in tensile strength of fiber inclusion was observed for the concrete with BFs additive at a different percentage.

For the second Group (B) Table 4.2 and Figure 4.3. Presents the splitting tensile strength (T) test results of concrete mixes containing SF only. SFs additive with the different volumetric ratios (0.5%, 1.0%, and 1.5%) the tensile strength of SFRC which was (140.3%, 146.7%, and 143.5%) more than control concrete. The results of the tensile strength test display that the addition of SFs up to 1% increased the tensile strength of concrete mix, where tensile strength of concrete increased significantly with the concrete mix SF0.5 and SF1.0. As well, it observed that 1%SF has the highest increase in tensile strength. However, when the addition of SFs is more than 1%, the tensile strength of concrete begins to decrease as 1.5% SF for concrete mix.

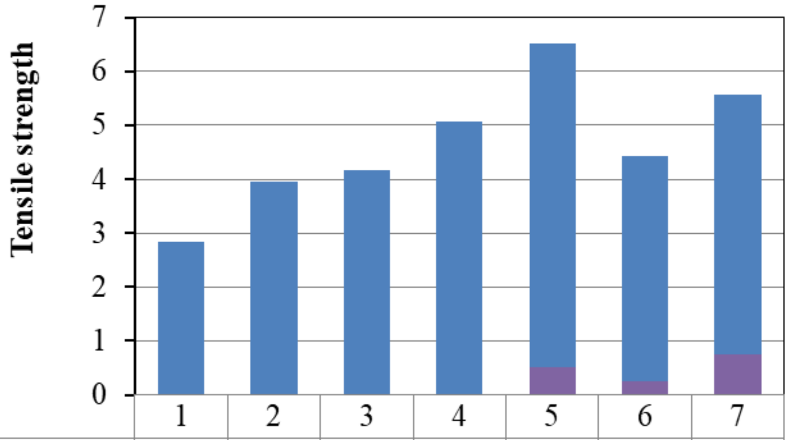


	1	2	3	4	5	6	7
Tensile strength	2.85	4.04	4.26	4.90	6.85	7.03	6.94
Steel Fiber Content (%)	0.00	0.00	0.00	0.00	0.50	1.00	1.50
Basalt Fiber Content (%)	0.00	0.50	1.00	1.50	0.00	0.00	0.00

Figure 4.3 Tensile strength of concrete mixtures with different percentage of steel fibers and basalt fibers

For the third Group (C) the splitting tensile strength of concrete mixtures containing BF and GF was presented in Table 4.1 and Figure 4.4. Test results showed that for every percentage (0.5%BF and 0.5%GF, 0.25%BF and 0.75%GF, 0.75%BF and 0.25%GF) the tensile strength was (38.9%, 46% and 77.5%) respectively more than control concrete. BF additives to the hybrid basalt-glass fibers concrete mix may have a variable impact on tensile strength. The concrete with (0.75% BF and 0.25% GF) showed the highest improvement at this group in tensile strength. Also, fiber dosage with (0.5% BF and 0.5% GF) resulted in the smallest improvement at this group in tensile strength. However, in a general manner adding a hybrid (basalt-glass) to the concrete mixture displays an important change in tensile strength.

For the last Group (D) The splitting tensile strength of concrete mixtures containing SF and GF was presented in Table 4.2 and Figure 4.4. Test results showed that for every percentage (0.5%SF and 0.5%GF, 0.25%SF and 0.75%GF, 0.75%SF and 0.25%GF) the tensile strength was (128.4%, 55.1% and 95.1%) respectively more than control concrete. SF additives to the hybrid steel-glass fibers concrete mix may have a variable impact on tensile strength. The concrete with (0.25% SF and 0.75% GF) showed the smallest improvement at this group in tensile strength. However, fiber dosage with (0.5% SF and 0.5% GF) resulted in the highest improvement at this group in tensile strength. However, in a general manner adding a hybrid (steel-glass) enhance the concrete mixture significantly.



	1	2	3	4	5	6	7
Tensile strength	2.85	3.96	4.16	5.06	6.51	4.42	5.56
Basalt Fiber Content (%)	0.00	0.50	0.25	0.75	0.00	0.00	0.00
Steel Fiber Content (%)	0	0	0	0	0.5	0.25	0.75
glass Fiber Content (%)	0.00	0.50	0.75	0.25	0.50	0.75	0.25

Figure 4.4 Splitting tensile strength of concrete mixtures with different percentage of HF

4.3 Load-deflection Responses of Beam

All the beams test result of the flexural performance of FRC beams of BFs and SFs and HF with different volumetric ratios was shown in Table 4.3, Table 4.4, Table 4.5 and Table 4.6. The beams were observed visually during the test. The cracks of the specimens were mapped and test observations were recorded during loading and at the time of failure. We used the CB to discuss and compare the results with other FRC and HYFRC beams.

4.3.1 First crack patterns

For the first group (A) the first cracking load ((P_{cr}) of concrete beams containing BF only was presented in Table 4.3 and Figure 4.5. Test results showed that for every percentage of BFs (0.5%, 1.0%, and 1.5%) the cracking load of BFRC beam that gives an increase by (3.4%, 11.4%, and 17%) when compared to the CB.

For the second Group (B) the first cracking load ((P_{cr}) of concrete beams containing SF only was presented in Table 4.4 and Figure 4.6. Test results showed that for every percentage of SFs (0.5%, and 1.0%) the cracking load of SFRC beam which gives an increase by (10.2%, and 59.7%) when compared to the CB. However, SFRC beams presented (12.5) % decrease in cracking load at 1.5% addition. Furthermore, it has presented the optimum case in beam SF1.0 at this group when compared to CB, and this shows a good agreement with the recommendation (ACI Committee 544, et al., 2009).

For the third Group (C) the first cracking load ((P_{cr}) of concrete beams containing BF and GF was presented in Table 4.5 and Figure 4.7. Test results showed that for every percentage (0.5%BF and 0.5%GF, 0.25%BF and 0.75%GF, 0.75%BF and 0.25%GF) the cracking load of the hybrid basalt-glass fibers concrete beam which gives an increase by (2.8%, 29.5%, and 24.4%) respectively when compared to the CB. This improvement in cracking response is due to additional BF and GF contributing to resist crack formation and propagation.

For the last Group (D) the first cracking load ((P_{cr}) of concrete beams containing SF and GF was presented in Table 4.6 and Figure 4.8. Test results showed that for every percentage (0.5%SF and 0.5%GF, 0.25%SF and 0.75%GF, 0.75%SF and 0.25%GF) the cracking load of the hybrid steel-glass fibers concrete beam which gives an increase by (24.4%, 35.8%, and 11.4%) respectively when compared to the CB.

In Table 4.3, Table 4.4, Table 4.5 and Table 4.6 shows the first crack deflection (δcr) of tested beams and the change in their percentage relative to the CB. For the first Group (A) the first crack deflection (δcr) of concrete beams containing BF only was presented in Table 4.3 and Figure 4.5. Test results showed that for every percentage of BFs (0.5%, 1.0%, and 1.5%) the crack deflection of BFRC beam that gives an increase by (32%, 56%, and 72%) when compared to the CB. We found that the increasing the volumetric ratio of BF concrete beams reduces crack deformation and propagation.

Furthermore, it has presented the optimum case in beam BF1.5 at this group when compared to CB.

Table 4.3 The detail of load-deflection data of tested beams for Group (A)

Flexural test Result	CB	BF 0.5	BF 1.0	BF 1.5
First crack load (P_{cr}) (KN)	17.6	18.2	19.6	20.6
First crack def. (δcr) (mm)	2.5	3.3	3.9	4.3
Yielding load (P_Y) (KN)	50.09	41.8	39.66	39.5
Yield def. (δY) (mm)	5.73	6.9	7.01	7.23
Ultimate load (P_U) (KN)	54.86	45.09	44.5	44.3
Ultimate def. (δ_u) (mm)	12.33	13.61	28.73	29.1
Failure load (KN)	49.2	43.5	44.1	42.6
Failure deflection (mm)	48.0	44.9	45.4	48.1

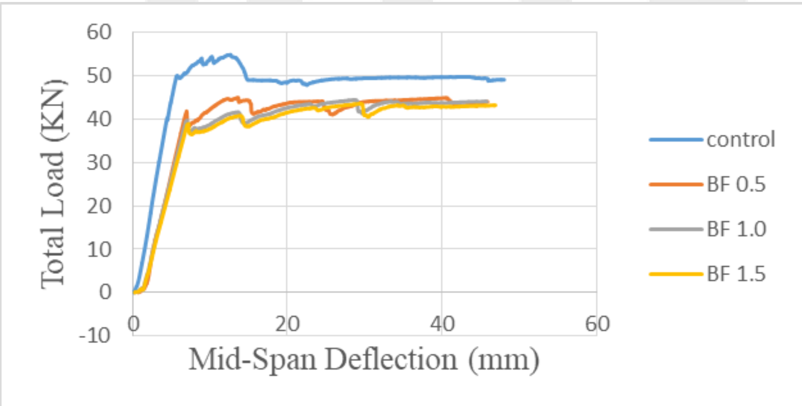


Figure 4.5 Load-deflection curves for flexural test of Group (A)

For the second Group (B) the first crack deflection (δcr) of concrete beams containing SF only was presented in Table 4.4 and Figure 4.6. Test results showed that for every percentage of SFs (0.5%, and 1.0%) the crack deflection of SFRC beam which gives an increase by (36%, and 24%) when compared to the CB. However, SFRC beams presented the same value with CB in crack deflection at 1.5% addition. We found that the increasing the volumetric ratio of SF concrete beams reduces crack deformation and propagation. Furthermore, it has presented the optimum case in beam SF0.5 at this group when compared to CB.

Table 4.4 The detail of load-deflection data of tested beams for Group (B) (Maan Albiyate, 2017)

Flexural test Result	CB	SF 0.5	SF 1.0	SF 1.5
First crack load (P_{cr}) (KN)	17.6	19.4	28.1	15.4
First crack def. (δcr) (mm)	2.5	3.4	3.1	2.5
Yielding load (P_{Y}) (KN)	50.09	44.3	54.76	50.3
Yield def. (δY) (mm)	5.73	6.5	5.86	6.5
Ultimate load (P_{U}) (KN)	54.86	50.5	55.2	52.57
Ultimate def. (δ_u) (mm)	12.33	14.47	10.39	10.8
Failure load (KN)	49.2	47.8	49.0	50.7
Failure deflection (mm)	48.0	45.8	40.6	45.3

For the third Group (C) the first crack deflection (δcr) of concrete beams containing BF and GF was presented in Table 4.5 and Figure 4.7. Test results showed that for every percentage (0.5%BF and 0.5%GF, 0.25%BF and 0.75%GF, 0.75%BF and 0.25%GF) the crack deflection of the hybrid basalt-glass fibers concrete beam which gives an increase by (20%, 36%, and 4%) respectively when compared to the CB.

For the last Group (D) the first crack deflection (δcr) of concrete beams containing SF and GF was presented in Table 4.6 and Figure 4.8. Test results showed that for every percentage (0.5%SF and 0.5%GF, 0.25%SF and 0.75%GF, 0.75%SF and 0.25%GF) the crack deflection of the hybrid steel-glass fibers concrete beam which gives an increase by (20%, 68%, and 56%) respectively when compared to the CB.

The first crack deflection provides a good indicator of fiber additives. The results showed that the mixing of two types of fibers with different properties greatly enhance the beams to resist initial crack occurs.

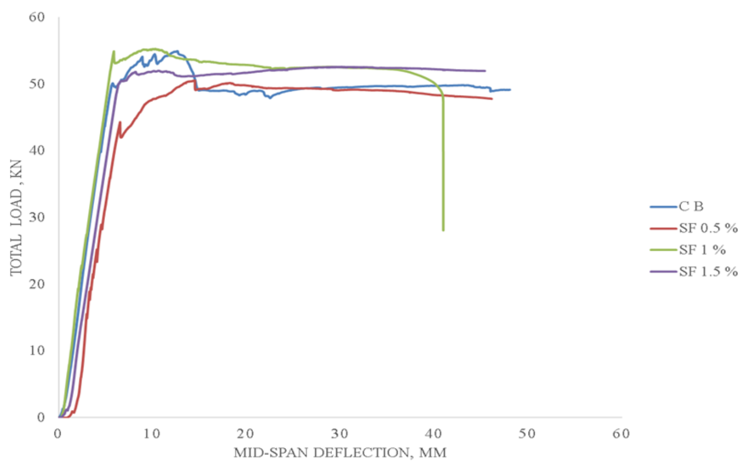


Figure 4.6 Load-deflection curves for flexural test of Group (B)

4.3.2 Yield patterns

It is evident at Table 4.3, Table4.4, Table 4.5 and Table 4.6 the yield load (PY) for FRC and HYFRC beams. For the first Group (A) the yield load of concrete beams containing BF only was presented in Table 4.3 and Figure 4.5. Test results showed that for every percentage of BFs (0.5%, 1.0%, and 1.5%) the yield load of BFRC beam which gives decrease by (16.6%, 20.8%, and 21%) when compared to the CB.

For the second Group (B) the yield load of concrete beams containing SF only was presented in Table 4.4 and Figure 4.6. Test results showed that for every percentage of SFs (1.0%, and 1.5%) the yield load of SFRC beam which gives an increase by (9%, and 0.4%) when compared to the CB. However, SFRC beams presented (11.6%) decrease in yield load at 0.5% addition.

For the third Group (C) the yield load of concrete beams containing BF and GF was presented in Table 4.5 and Figure 4.7. Test results showed that for every percentage (0.5%BF and 0.5%GF, 0.25%BF and 0.75%GF, 0.75%BF and 0.25%GF) the yield load of the hybrid basalt-glass fibers concrete beam which gives decrease by (33.9%, 2.4%, and 11.4%) respectively when compared to the CB.

For the last Group (D) the yield load of concrete beams containing SF and GF was presented in Table 4.6 and Figure 4.8. Test results showed that for every percentage (0.25%SF and 0.75%GF, 0.75%SF and 0.25%GF) the yield load of the hybrid steel-glass fibers concrete beam which gives decrease by (5.5%, and 9.5%) when compared to the CB. However, (0.5%SF and 0.5%GF) beam presented (4.6%) increase in yield load at this group.

The enhancement in yield load at the beams SF1.0, SF1.5 and SF0.5GF0.5 means the best volumetric ratio of SFs and hybrid SFs additives, but no enhancement in yield load of BFs and hybrid BFs additives.

In Table 4.3, Table 4.4, Table 4.5 and Table 4.6 shows the yield deflection (δy) for tested beams. For the first Group (A) the yield deflection (δy) of concrete beams containing BF only was presented in Table 4.3 and Figure 4.5. Test results showed that for every percentage of BFs (0.5%, 1.0%, and 1.5%) the yield deflection of BFRC beam that gives an increase by (20.4%, 22.3%, and 26.2%) when compared to the CB.

For the second Group (B) the yield deflection (δy) of concrete beams containing SF only was presented in Table 4.4 and Figure 4.6. Test results showed that for every percentage of SFs (0.5%, 1.0%, and 1.5%) the yield deflection of SFRC beam, which gives an increase by (13.4%, 2.3%, and 13.4%) when, compared to the CB.

For the third Group (C) the yield deflection (δy) of concrete beams containing BF and GF was presented in Table 4.5 and Figure 4.7. Test results showed that for every percentage (0.5%BF and 0.5%GF, 0.25%BF and 0.75%GF, 0.75%BF and 0.25%GF) the yield deflection of the hybrid basalt-glass fibers concrete beam which gives an increase by (1.2%, 22%, and 29%) respectively when compared to the CB.

For the last Group (D) the yield deflection (δy) of concrete beams containing SF and GF was presented in Table 4.6 and Figure 4.8. Test results showed that for every percentage (0.5%SF and 0.5%GF, 0.25%SF and 0.75%GF, 0.75%SF and 0.25%GF) the yield deflection of the hybrid steel-glass fibers concrete beam which gives an increase by (14%, 25%, and 29.3%) respectively when compared to the CB.

Table 4.5 The detail of load-deflection data of tested beams for Group (C)

Flexural test Result	CB	BF0.5GF05	BF0.25GF0.75	BF0.75GF0.25
First crack load ($P_{cr)}$ (KN)	17.6	18.1	22.8	21.9
First crack def. (δcr) (mm)	2.5	3.0	3.4	2.6
Yielding load ($P_{Y)}$ (KN)	50.09	33.1	48.9	44.4
Yield def. (δY) (mm)	5.73	5.8	7.0	7.4
Ultimate load ($P_{U)}$ (KN)	54.86	43.63	55.6	52.17
Ultimate def. (δ_u) (mm)	12.33	19.9	17.0	19.5
Failure load (KN)	49.2	34.8	49.4	45.6
Failure deflection (mm)	48.0	39.9	66.3	58.07

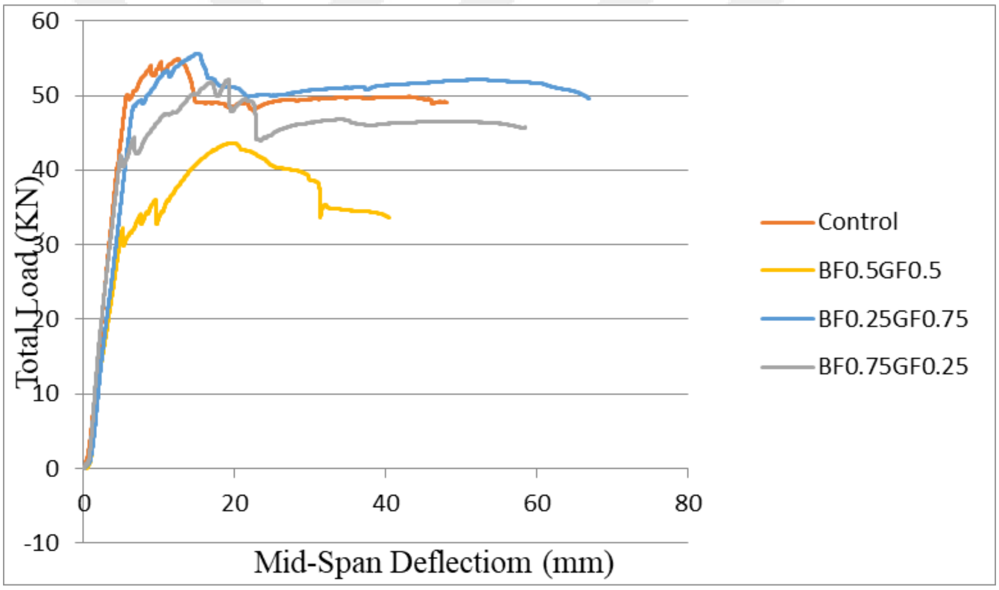


Figure 4.7 Load-deflection curves for flexural test of Group (C)

4.3.3 Ultimate beam strength

The ultimate load (Pu) was shown in Table 4.3, Table 4.4, Table 4.5 and Table 4.6. For the first group (A) the ultimate load (Pu) of concrete beams containing BF only was presented in Table 4.3 and Figure 4.5. Test results showed that for every percentage of BFs (0.5%, 1.0%, and 1.5%) the ultimate load of BFRC beam which gives decrease by (17.8%, 18.9%, and 22.9%) when compared to the CB. At last, the failure load for every percentage of BFs (0.5%, 1.0%, and 1.5%) was (43.5, 44.1, and 42.6) KN. Also, the maximum displacement in mid-span for every percentage of BFs

(0.5%, 1.0%, and 1.5%) was (44.9, 45.4, and 48.1) mm as shown in Table 4.3 and Figure 4.5.

For the second Group (B) the ultimate load (Pu) of concrete beams containing SF only was presented in Table 4.4 and Figure 4.6. Test results showed that for every percentage of SFs (0.5%, and 1.5%) the ultimate load of SFRC beam which gives decrease by (8%, and 4.2%) when compared to the CB. However, SFRC beams presented (0.62%) an increase in ultimate load at 1.0% addition. At last, the failure load for every percentage of SFs (0.5%, 1.0%, and 1.5%) was (47.8, 49.0, and 50.7) KN. Also, the maximum displacement in mid-span for every percentage of SFs (0.5%, 1.0%, and 1.5%) was (45.8, 40.6, and 45.3) mm as shown in Table 4.4 and Figure 4.6.

For the third Group (C) the ultimate load (Pu) of concrete beams containing BF and GF was presented in Table 4.5 and Figure 4.7. Test results showed that for every percentage (0.5%BF and 0.5%GF, 0.75%BF and 0.25%GF) the ultimate load of the hybrid basalt-glass fibers concrete beam which gives decrease by (20.5%, and 5%) respectively when compared to the CB. However, (0.25%BF and 0.75%GF) beam presented (1.4%) an increase in ultimate load at this group. At last, the failure load for every percentage (0.5%BF and 0.5%GF, 0.25%BF and 0.75%GF, 0.75%BF and 0.25%GF) was (34.8, 49.4, and 45.6) KN. Also, the maximum displacement in mid-span for every percentage (0.5%BF and 0.5%GF, 0.25%BF and 0.75%GF, 0.75%BF and 0.25%GF) was (39.9, 66.3, and 58.1) mm as shown in Table 4.5 and Figure 4.7.

For the last Group (D) the ultimate load (Pu) of concrete beams containing SF and GF was presented in Table 4.6 and Figure 4.8. Test results showed that for every percentage (0.25%SF and 0.75%GF, 0.75%SF and 0.25%GF) the ultimate load of the hybrid steel-glass fibers concrete beam which gives decrease by (9%, and 12.5%) respectively when compared to the CB. However, (0.5%SF and 0.5%GF) beam presented (1.7%) an increase in ultimate load at this group. At last, the failure load for every percentage (0.5%SF and 0.5%GF, 0.25%SF and 0.75%GF, 0.75%SF and 0.25%GF) was (54.1, 48.1, and 46.5) KN. Also, the maximum displacement in mid-span for every percentage (0.5%SF and 0.5%GF, 0.25%SF and 0.75%GF, 0.75%SF and 0.25%GF) was (47.1, 47.3, and 45.8) mm as shown in Table 4.6 and Figure 4.8.

The ultimate load is a good indicator of structural behavior response in reducing or increasing strength by adding fibers or HF. For tested beams, Fiber and HF additives for strength concrete beam elements generally result in a reduction in ultimate strength.

In general, the test results showed that all the beam specimens behaved nearly linear up to the first crack in flexural test. After cracking, the area of effective concrete was reduced; Reducing the moment of inertia, and then the beam specimens behaved linearly but with less stiffness. Overall, the curves reveal that the post-cracking stiffness of the loading response has small differences between specimens.

Table 4.6 The detail of load-deflection data of tested beams for Group (D) (Maan Albiyate, 2017)

Flexural test Result	CB	SF0.5GF0.5	SF0.25GF0.75	SF0.75GF0.25
First crack load (P_{cr}) (KN)	17.6	21.9	23.9	19.6
First crack def. (δcr)(mm)	2.5	3.0	4.2	3.9
Yielding load (P_Y) (KN)	50.09	52.37	47.35	45.32
Yield def. (δY) (mm)	5.73	6.54	7.17	7.41
Ultimate load (P_U) (KN)	54.86	55.8	49.98	47.99
Ultimate def. (δ_u) (mm)	12.33	12.3	13.87	18.67
Failure load (KN)	49.2	54.1	48.1	46.45
Failure deflection (mm)	48.0	47.1	47.3	45.8

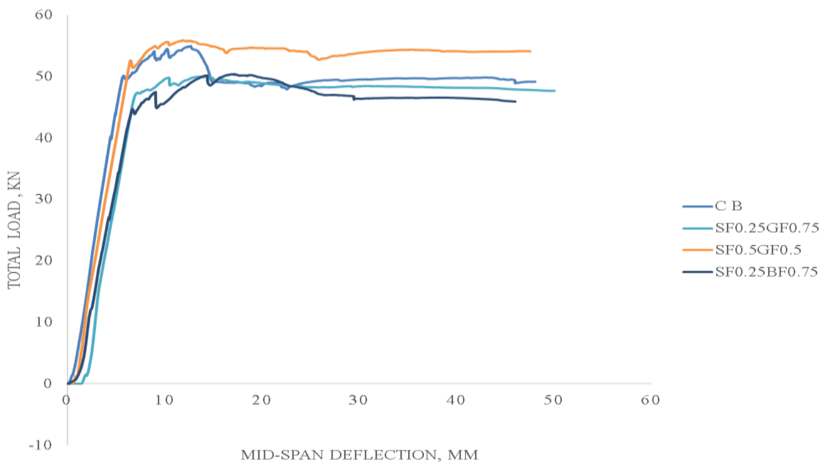


Figure 4.8 Load-deflection curves for flexural test of Group (D)

4.4 Failure Mechanism

To fully visualize the failure mode and the crack pattern, we painted the tested beams with a white emulsion and a grid of lines created at a distance of (50 x 50) mm, as shown in Figure 4.9- Figure 4.13. The propagation of these cracks was indicated with a multicolor pen and the load is denoted for each stage of crack propagation.

All beams failed in flexure test with cracking developed at the tension zone as shown in Figure 4.9- Figure 4.13. It was observed that all beams developed fine cracks from the end at the tension zone under a relatively small load of about 20 – 40 % of their ultimate load. The first noticeable crack was formed between the locations of the mid-span followed by two point loads in the area of the maximum bending moment, and we observed the main cracks and fine cracks for all beams under ultimate load.

The crack pattern of the CB shown in Figure 4.9 shows that the crack starts at the tension face at the middle of the beam. The cracks grew and extended in the middle third of beam clear span when load increment until failure occurred on the beam. All cracks indicated that this beam failure goes to be a flexural failure. The failure mode for control concrete beam was by yielding tension steel reinforcement followed by compression failure of concrete, compression concrete was successively crushed and collapsed before reaching ultimate load.

The crack pattern for the Group (A) reinforced with BFs at different volumetric ratios shows that the addition of BFs also improved the crack formation and propagation as shown in Figure 4.10. As the load increases, more than one main crack formed and propagate. The failure mode in this group was also, by the yield of bottom reinforcement (tension steel) happens before compression failure of the concrete, where the concrete compression failure in the forming of layer delamination, as shown in Figure 4.10.

The crack pattern of a Group (B) reinforced with SFs with different volumetric ratio shows that the addition of SFs improved the formation and propagation of cracks as shown in Figure 4.11. An important notice that is visualized was that the first main crack that was in the middle of the beams were tested is still propagating with a very limited formation of another crack. The failure mode for this group was also by yielding bottom reinforcement followed by compression failure of concrete, but the failure of compression concrete by multilayers delamination. This remarkable type of concrete failure due to the addition of SFs that improved the compression zone besides its contribution to the tension zone.

Figure 4.12 and Figure 4.13 showed the failure mode for the Group (C) and Group (D), which was strengthen with basalt-glass fibers and steel-glass fibers at a different volumetric ratio. We can summarize the crack pattern for these two groups, that was showed by combining fibers with different properties; they were more capable of resisting higher load and reduced crack opening at ultimate load. This ability was because of the bridging effect of HYFRC to arrest crack development and propagation during the early stage of concrete casting (wet) and hardening (dry) process improved the structural performance of the beam. Where the results showed significant enhancement in HYFRC beams by reducing the number of main cracks.

The failure due to the collapse of the bottom reinforcement was saw and a gradual concrete crushing detected as shown in Figure 4.12 and Figure 4.13.

From Figure 4.9 to Figure 4.13, showed that the number of cracks increased for all additives percentage. Generally, more than one main cracks are formed ad propagate as load increases, but there is still a number of main cracks less than the CB, however the number of fine cracks (linehair cracks) more than the CB. Also, summarized the number of total cracks, main cracks and fine cracks for all beams at ultimate load. For group A, it is noticeable that contain (1-3) main crack but still less than the CB, on the other hand For Group B, it is noticeable that had almost one large main crack. For Group C and D, it is noticeable that contain more than one main cracks but still less than the CB.

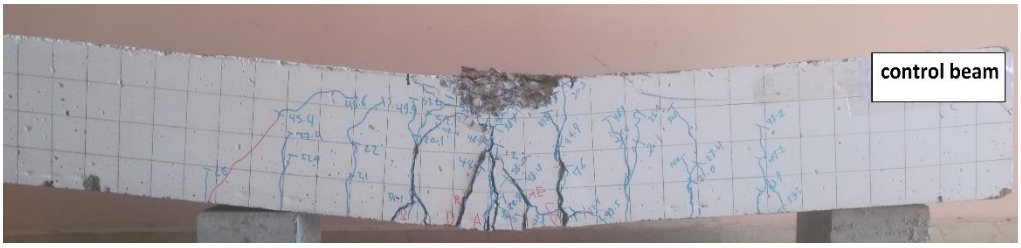


Figure 4.9 Crack pattern and failure mode of CB

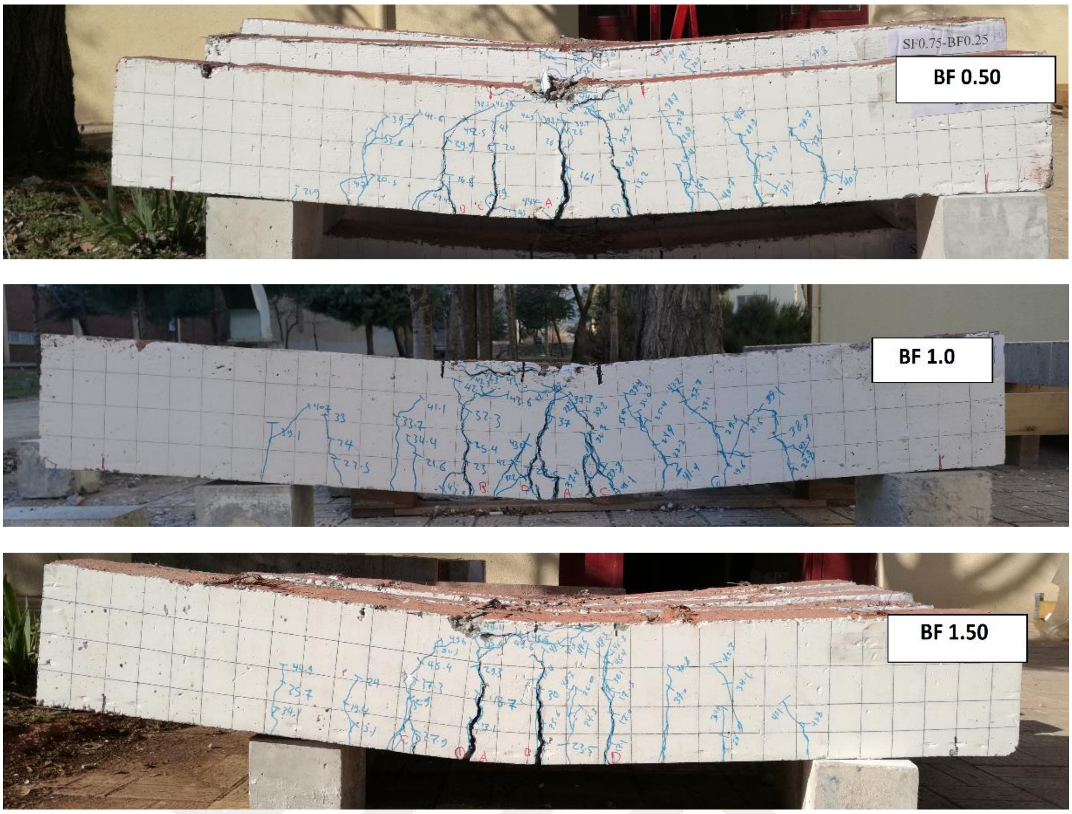


Figure 4.10 Crack pattern and failure mode of tested beams for Group (A)

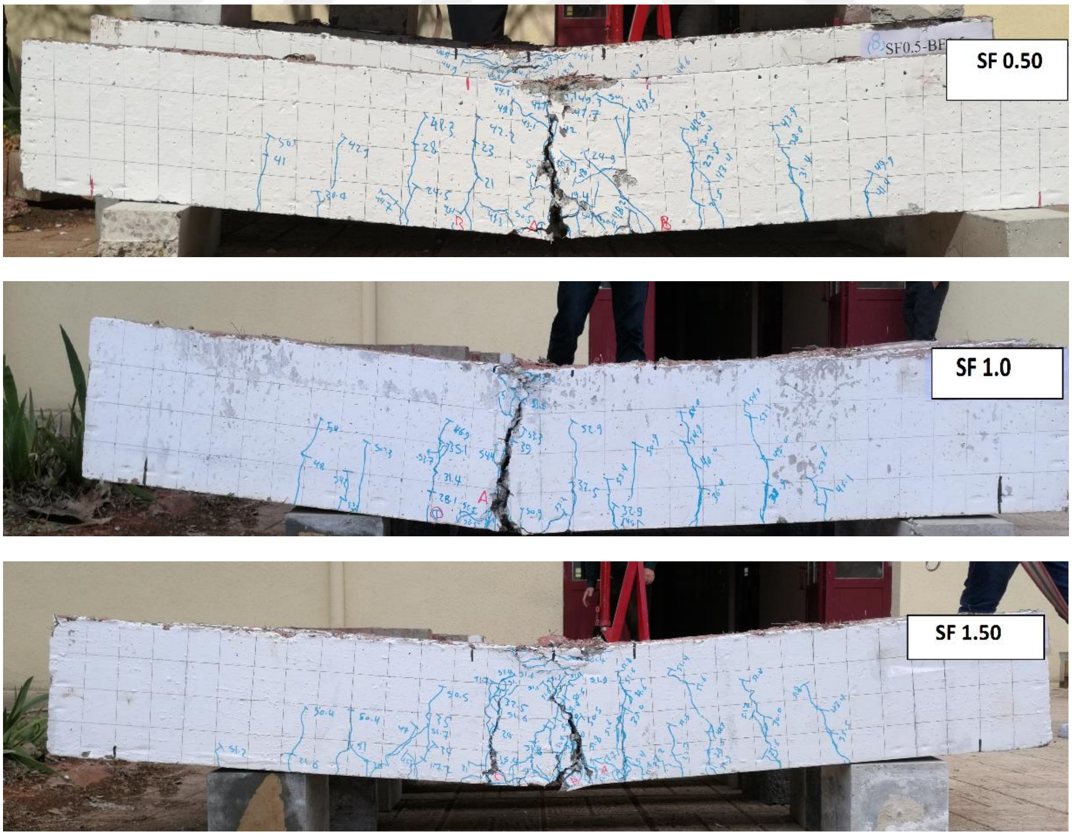


Figure 4.11 Crack pattern and failure mode of tested beams for Group (B)

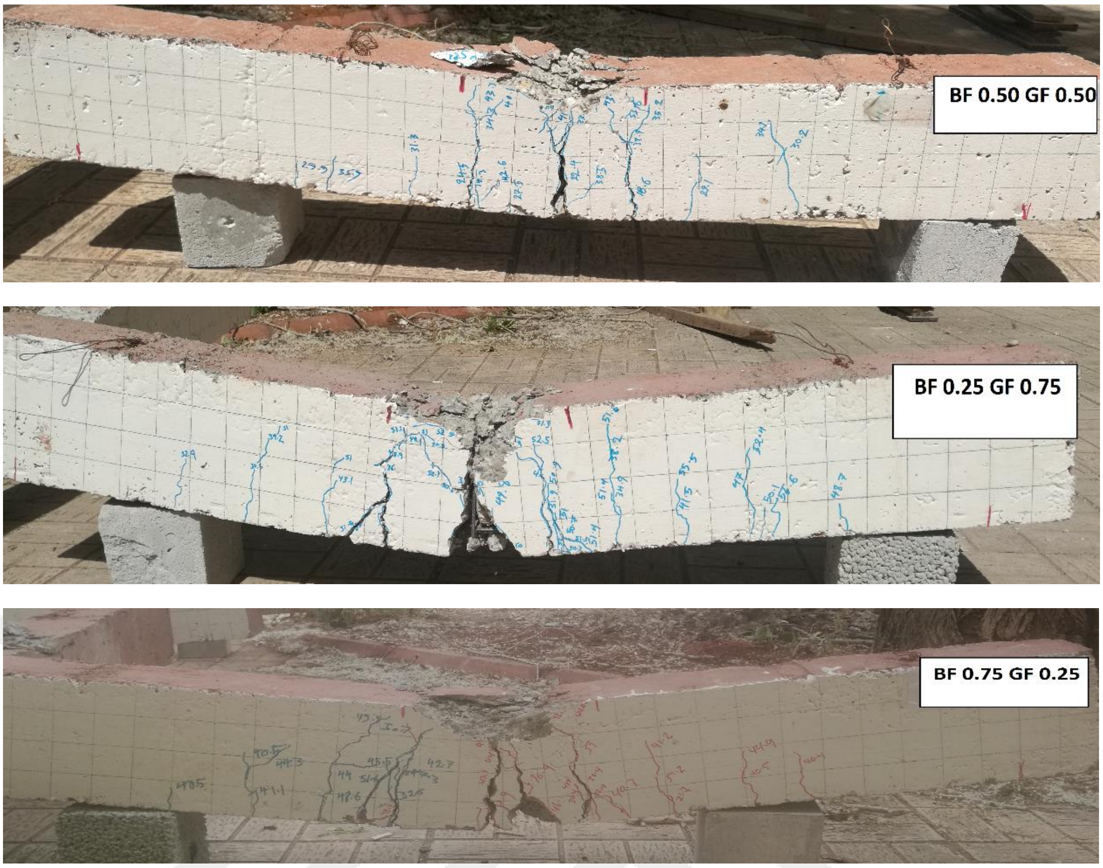


Figure 4.12 Crack pattern and failure mode of tested beams for Group (C)

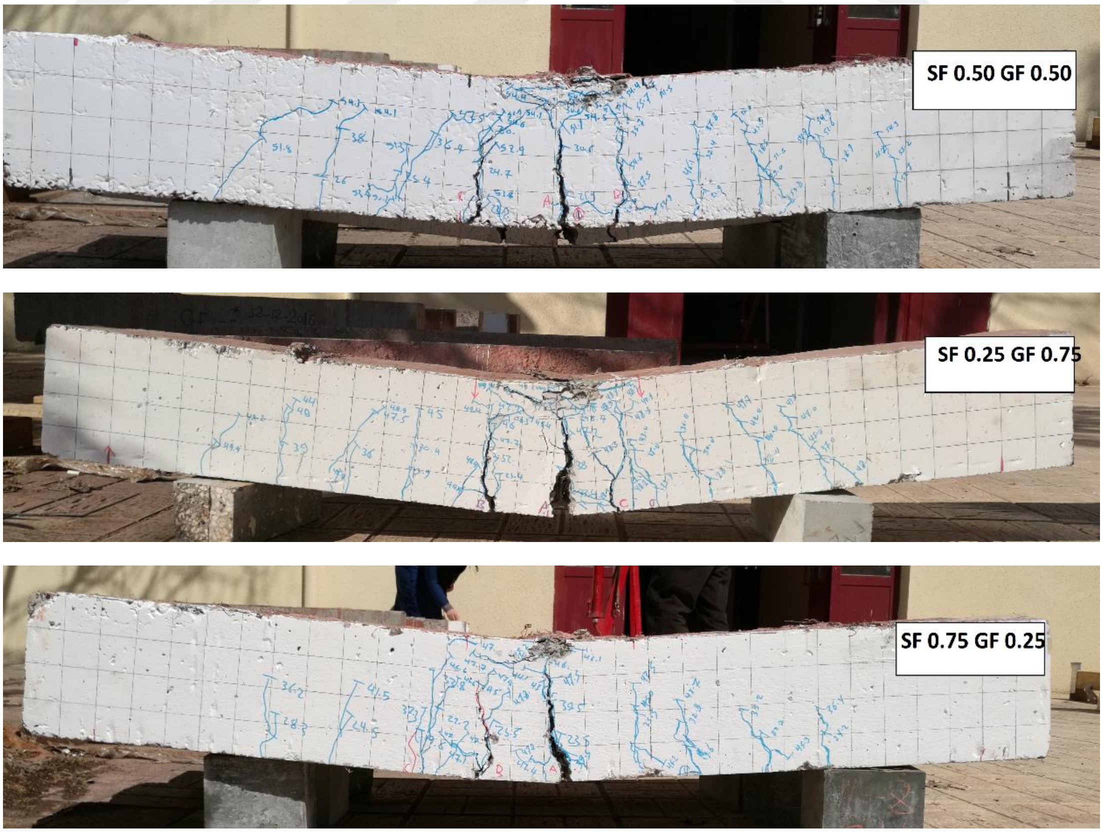


Figure 4.13 Crack pattern and failure mode of tested beams for Group (D)

CHAPTER 5

CONCLUSIONS

5.1 Conclusions

This study presents the experimental work of fibers concrete mixtures, HF concrete mixtures, and RC beams. Thirteen beams are tested, one of which is a reference beam (CB), the others are FRC beams classified as groups (A, B, C, and D) when group A represents BF additives only, while group B represents SF additives only. Groups C and D represent hybrid fiber additives, where two types of HF are used. These types are hybrid basalt-glass and hybrid steel-glass. The flexural and mechanical behavior of concrete reinforced with fibers and HF are compared.

The following conclusions can be stated based on the evaluation of results obtained from the experimental work of fibers concrete mixtures, hybrid concrete mixtures, and RC beams:

1. Generally, there is a decrease in workability when fibers were added to the concrete mixture.

2. The compressive strength generally decreases when fibers and HF are added compared to the control mixture.

3. The concrete compressive strength of group (A) has a negative effect. BFs additive by (0.5, 1.0, 1.5) which, decrease the strength with increasing fiber volume fraction, while the compressive strength of group (C) containing basalt and glass additives by 1.0 % a total amount of HF, it was decreasing when compared to the control mixture. However, the negative effect of BF in the compressive strength of concrete is overcome with a slight increase in compressive strength compared to concrete with BF only, when a hybrid basalt-glass fiber are used**.**

4. The concrete compressive strength of group (B) is slightly decreased. SFs additive by (0.5, 1.0, 1.5) which, the change in strength can be considered negligible. While the compressive strength of group (D) containing steel and glass additives by 1.0 % a total amount of HF, it was decreasing when compared to the control mixture.

5. The split tensile strength generally increased for the concrete with fibers and HF when compared to the control mixture.

6. For Group (A), an important change in tensile strength of fiber inclusion was observed for the concrete with BFs additive at a different percentage (0.5, 1.0, 1.5) it was increasing by (41.8, 49.5 and 71.9) %, which, increase the strength with increasing fiber volume fraction.

7. For Group (C) an important influence in splitting tensile strength for the concrete with basalt and glass fibers additives by 1.0 % a total amount of HF. It was increasing by (38.9-77.5) % when compared to the control mixture. The concrete with 0.75 % BF and 0.25 % GF showed the optimal enhancement in strength.

8. For Group (B) a significant change in tensile strength of fiber inclusion was observed for the concrete with SFs additive at a different percentage (0.5, 1.0, and 1.5) it was increasing by (140.3 - 146.7) %. It observed that SF1.0 has an optimum increase in strength.

9. For Group (D) a significant influence in splitting tensile strength for the concrete with steel and glass fibers additives by 1.0 % a total amount of HF. It was increasing by (55.1-128.4) % when compared to the control mixture. The concrete with 0.50 % SF and 0.50 % GF showed the optimal enhancement in strength.

10. From the tested results, the fibers and HF additives to the concrete mixture are given at least a relatively higher tensile strength (39% - 147%), a higher elongation in the tension compared to the control mixture, lead to the best FRC and HYFRC function.

11. Basalt, steel, and glass fibers can be used as additives for construct high strength RC beams of different percentage (0.5, 1.0, and 1.5) % for BFs and SFs, while the percentage of (0.25 and 0.75, 0.5 and 0.5, 0.75 and 0.25) % for hybrid basalt-glass fibers and hybrid steel-glass fibers.

12. From beam tests observations, showed that the presence of basalt, steel and glass fibers in the concrete mix for tested beams delayed the formation and reduced cracks propagation. This improved the response of the tension zone before and after the first crack.

13. For the first Group (A), the tested beams show that the first crack load improves by (3.4-17) % when BFs additive to concrete mixture. The first crack flexural load is increased with increasing the volumetric ratio of BFs.

14. For the third Group (C), the tested beams show that the first crack load increasing by (2.8-29.5) % when GF additive to hybrid basalt-glass mixture.

15. For the second Group (B) the tested beams, the first crack load improves up to 59.7% by the addition of SFs up to 1.0%.

16. For the last Group (D) the tested beams, the first crack load increasing by (24.4-35.8) % by the addition of GFs up to 0.75 %.

17. Different results are obtained for the tested beams. Generally, fibers and HF increase the value of the first crack deflection by (32-72) %, (0-36) %, (4-36) %, and (20-56) % for all Groups (A, B, C, and D) respectively.

18. From the tested beams, the yield load for the concrete with SF additives by (1.0 and 1.5) % and hybrid steel-glass fiber additives with 0.5 % volumetric fraction, it was increasing by (9, 0.4, and 4.6) % respectively when compared to the CB. A similar trend, the yield load is decreased for the concrete with BFs and hybrid basalt-glass fibers.

19. Generally, fibers and HF increase the value of the yield deflection by (20.4-26.2) %, (2.3-13.4) %, (1.2-29) %, and (14-29.3) % for all groups (A, B, C, and D) respectively.

20. From the tested beams, the ultimate flexural load for the concrete with SFs additives by 1.0 %, hybrid steel-glass fibers additives with 0.5 % volumetric fraction and hybrid basalt-glass fibers additives with (BF0.25GF0.75) % volumetric ratio, it was increasing by (0.62, 1.7, and 1.4) % respectively when compared to the CB. Generally, the ultimate load is decreased for the other types of concrete mixture with fibers and HF when compared to the CB.

21. For the tested beams reinforced with fibers and HF are subjected to flexural load up to failure, the failure due to the yield of tension steel reinforcement happens before crushing compression zone of concrete failure in the forming of layers delamination.

22. Generally, the beams with fibers and HF contains more than one main cracks but still less than the CB, while, SFs additive contain almost one large main crack.

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