Behavior of Steel-Polypropylene Hybrid Fiber Reinforced Concrete

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We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Civil Engineering.

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ABSTRACT

Since ancient time, fiber reinforced concrete has been replaced with plain concrete which is brittle material. Although, the inclusion of single type fiber may improve mechanical properties of concrete, the hybridization can compensate the disadvantages of two fiber types and represent their advantages.

This thesis explores the effect of using steel fiber and polypropylene fiber for reinforcing the concrete to quantify the mechanical properties of concrete matrix. For this purpose, 45 specimens of fiber reinforced concrete which contains different fibers dosage were casted. All mixes were tested for slump and VeBe test in fresh state, and 28 days compressive strength, flexural strength and impact resistance tests were carried out in hardened state. According to the test results, the regression analysis was carried out to predict the value of compressive strength, flexural strength and impact resistance.

The experimental results show that the hybrid form of fiber has slight effect on compressive values, while it causes increase in modulus of rupture, toughness and impact resistance values.

Keywords: Fibers, hybrid fiber reinforced concrete, compressive strength, flexural toughness energy and impact energy.

ÖZ

Çok eski zamanlardan beridir yapılan uygulamalar ile kırılgan olan betona elyaf eklenerek bu kırılganlık azaltılmaktadır. Tek tip elyafın beton üzerine mekanik davranış avantajları olmasına rağmen, birden fazla değişik tip elyafın betondaki kullanımı ile tüm olumsuz davranışlar ortadan kaldırılabilmektedir.

Bu bilimsel çalışmada çelik elyaf ve polipropilen elyaf birlikte beton içerisinde kullanılmıştır. Bundan dolayı, 45 adey numune hazırlanmış ve bu numunelerin her birinde farklı oranlarda iki tip elyaf (hibrit) kullanılmıştır. Tüm karışımlar için taze halde ve sertleşmiş halde deneylere tabii tutulmuştur. Taze beton deneyi olarak çökme ve VeBe deneyleri, sertleşmiş beton için ise 28 günlük basınç mukavemeti, basmada çekme dayanmı ve darbe dayanımı deneyleri yapılmıştır.

Yapılan deney sonuçlarına göre hibrit karışımların betonun basınç mukavemetine az miktarda olumlu etkikisi olduğu görülmesine rağmen basmada çekme tokluk enerjisine ve darbe enerjisine olumlu etkisi olduğu gözlemlenmiştir.

Anahtar Kelimeler: Elyaf, hibrit elyaflı beton, basınç dayanımı, basmada çekme tokluk enerjisi, darbe enerjisi.

DEDICATION

I would like to dedicate this study to them as an indication of their significance in this study as well as in my life.

To My Beloved Parents and Family

ACKNOWLEDGMENT

I would like to extend my deepest gratitude to my research supervisor, Prof. Dr. Özgür Eren, whose scientific guidance and advice motivated me to make this research possible. I am also grateful for his invaluable support and scientific enthusiasm throughout my research. I will be forever thankful to him.

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Finally, I take this moment to express my never ending love and respect towards my family for their concern and tremendous support. I would like to dedicate this study to them as an indication of their significance in this study as well as in my life.

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LIST OF ABBREVIATIONS

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BS	British Standards
FRC	Fiber Reinforced Concrete
HyFRC	Hybrid Fiber Reinforced Concrete
HyF	Hybrid Fiber
MOR	Modulus of Rupture
PPF	Polypropylene Fiber
PPFRC	Polypropylene Fiber Reinforced Concrete
SF	Steel Fiber
SFRC	Steel Fiber Reinforced Concrete
USF	Ultimate Strength Failure

LIST OF SYMBOLS

A, B, C, D, E	Regression coefficients
V_f	Volume fraction
f_c	Compressive strength
V_{fs}	Steel fiber volume fraction
V_{fpp}	Polypropylene fiber volume fraction
F_e	Flexural strength
T_f	Toughness index
I_c	Impact resistance
R	Coefficient of multiple determination

Chapter 1

1 INTRODUCTION

1.1 General

Concrete is the most widely used construction material which is characterized by its low tensile strength and strain capacity. Historically, reinforcement in the form of iron rods were used initially, while continuous steel reinforcing bars and stirrups which improve one or more properties of concrete for a number of structural systems, are used at present time.

At one extreme, the former which was placed at appropriate location endure the imposed tensile and shear stress, while the latter are not efficient to endure the tensile stress [1]. At another extreme, fiber with randomly distributed tend to be more closely than conventional reinforcement bars [1]. Therefore, fibers of different size and type play an important role for bridging the cracks in the matrix which can prevent or control the initiation, propagation and coalescence of cracks leading to better concrete performance.

Generally, “FRC can be regarded as a composite material with two or more phases in which concrete represents the matrix phase and the fiber constitutes the inclusion phase [2].” Composite material consist of two or more components with different molecular level, mixed purposefully result in new material with new properties in comparison with single component [3]. Moreover, reinforcement of concrete with two or more types of fiber referred to the concept of hybridization. Therefore, the presence of one fiber provide a suitable condition for other fiber to use its potential properties [1].

1.2 Objectives

The objective of this research is to evaluate and compare the mechanical properties of FRC with the use of hybrid fibers compared to single type fiber composites. The mechanical properties examined include compressive strength, modulus of rupture (MOR), toughness (energy absorption) and impact resistance of various FRCs. In addition to this, the parameters that affect mechanical properties will be analyzed. Research results provide recommendation for fiber volume fraction to achieve a highly workable fiber reinforced concrete having high performance in compressive and flexural strength as well as impact resistance.

1.3 Scope

This research comprises experimental research that was performed at Eastern Mediterranean University. It is organized into the following chapters.

The literature of fiber reinforced concrete is reviewed in chapter 2. This chapter also covered the characteristics of the material used in this study. Chapter 3 contains the details of test method, as well the selection of materials, mix design and test equipment. The test results and discussion of the data are covered in chapter 4. Conclusion and recommendation are summarized in chapter 5.

Chapter 2

2 FIBER REINFORCED CONCRETE

2.1 General View of Fibers

Since ancient time, fibers have been used for reinforcing the brittle materials. The efficiency of fiber reinforcement is apparent in accordance with enhancement of two criteria: strength and toughness of matrix. Now, in modern days, different types of reinforced concrete were produced with discontinuous short fibers which have gained immense popularity. The modules and geometrical size of fiber affect the performance of FRC. Therefore, usage of suitable type and percentage of fibers improves overall mechanical performance of concrete.

Generally, fibers have different classification based on elastic modulus and origin of the material. Some of them have low modulus and some others have high modulus in comparison with cement matrix. Polypropylene, nylon, and cellulose are in first category, while steel, glass, carbon and asbestos belong to the second one [2]. Table.1 presents properties of common fibers dominating various industries [1].

These days, the applications of FRC are as varied as the types of fibers which are produced in various forms, bars, cables and different cross section, stirrups, sheets, channels and angles.

Since concrete is a complex material, a single type of fiber may affect properties to a limited level of fiber reinforced concrete. In order to overcome most weaknesses of concrete, the concept of hybridization which implies using two or more different types of fibers can eliminate concrete deficiency and present a synergetic response.

As Banthia et al [4] stated, "There are currently 200,000 metric tons of fibers used for concrete reinforcement". Table. 1 shows the existing commercial fibers and their properties. Steel fiber remains the most used fiber of all (50% of total tonnage used) followed by polypropylene (20%), glass (5%) and other fibers (25%)." Hence, in this research steel and polypropylene fibers are chosen for scientific investigation.

Table 1. Typical properties of fibers [1].

Fiber	**Diameter** (μm)	**Specific gravity**	**Modulus of elasticity (GPa)**	**Tensile strength (GPa)**	**Elongation at break (%)**
Steel	5-500	7.84	200	0.5-2.0	0.5-3.5
Glass	9-15	2.60	70-80	2-4	2-3.5
Asbestos:					
Crocidolite	0.02-0.4	3.4	196	3.5	2.0-3.0
Chrysotile	0.02-0.4	2.6	164	3.1	2.0-3.0
Fibrillated	20-200	0.9	5-77	0.5-0.75	8.0
Polypropylene:					
Aramid (Kevlar)	10	1.45	65-133	3.6	2.1-4.0
Carbon (high strength)	9	1.90	230	2.6	1.0
Nylon	-	1.1	4.0	0.9	13.0-15.0
Cellulose	-	1.2	10	0.3-0.5	-
Acrylic	18	1.18	14-19.5	0.4-1.0	3
Polyethylene	-	0.95	0.3	0.7×10^{-3}	10
Wood fiber	-	1.5	71.0	0.9	-
Sisal	10-50	1.50	-	0.8	3.0
Cement matrix (for comparison)	-	2.50	10-45	3.7×10^{-3}	0.02

2.2.1 Steel, Polypropylene and Hybrid Reinforced Concrete

2.2.1.1 Steel Fiber Reinforced Concrete (SFRC)

In 1950's and 1960's, the major theoretical studies of FRC initiated by Roumaldi, Batson, and Mandel [5] leading to use of steel fiber for reinforcing the concrete. In that time, round and smooth steel were common used fiber type which were cut or chopped to the required length. While adding straight steel fibers can increase toughness and ductility which are important issues in concrete structure, it causes some problems for mixing leading to lower workability. Therefore, using fibers with different length and geometrics properties paved platform to overcome problems and reaching expected purpose (Figure.1).

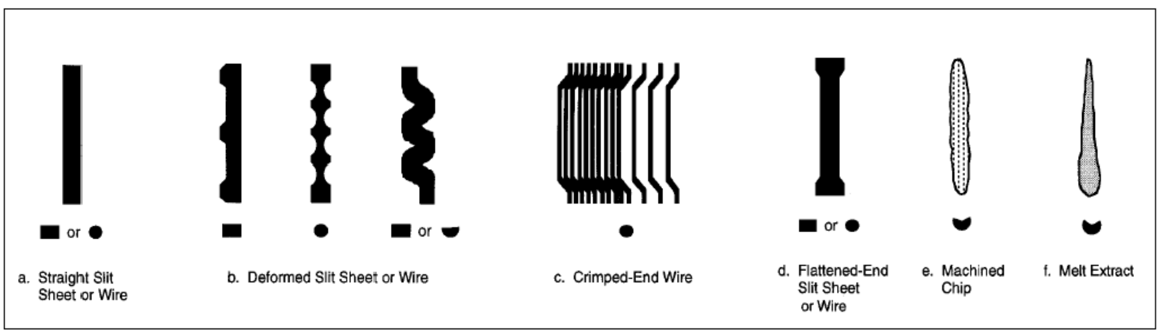

Figure 1. Various steel fiber geometries [6].

According to Benthur et al [1], the application of steel fibers are more common in pavement, dams and shotcrete. Various steel fibers are manufactured with lengths from 12.7 mm to 63.5 mm and their equivalent diameter is from 0.45 mm to 1 mm which is based on cross sectional area [7]. Typically, steel fiber properties; type of fiber; aspect ratio (L/D); size and shape are impressive factors on mechanical performance of steel fiber reinforced concrete (SFRC).

2.2.1.1.2 Mechanical Properties of SFRC

Steel fibers with high elastic modulus and stiffness, increase the toughness and compressive strength of concrete [8]. Moreover, the main life cycle benefits of using steel fiber are as follow:

- Increased fatigue, impact and absorption resistance;
- Increased tensile and flexural strength;
- Increased ductility; and
- Control the crack propagation and ability to retain load after cracking.

Compressive Strength: Adding steel fibers for concrete reinforcement has minor effect on enhancing the compressive strength of concrete. Figure. 2 presents the typical stress-strain curve for FRC with various percentage of steel fibers in comparison with plain concrete.

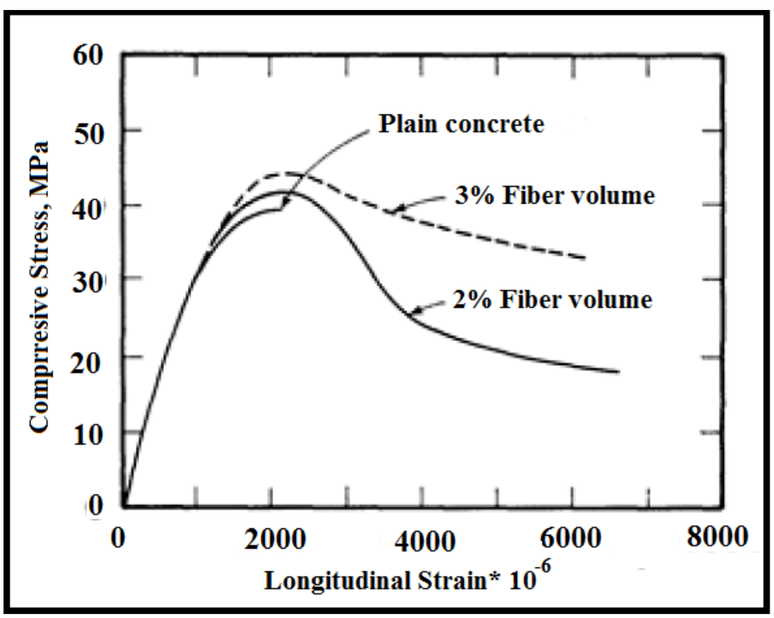

Figure 2. Stress-strain curves for steel fiber reinforced concrete under compression [1].

Flexural Strength (Modulus of Rupture): The addition of steel fibers for reinforcing the concrete, improves flexural strength of SFRC [9]. The extent of improvements in the flexural strength is sensitive to the type, quantity of fibers and the aspect ratio. Based on ACI 544 [6], “increases in the flexural strength of SFRC are substantially greater than in tension or compression because ductile behavior of the SFRC on the tension side of a beam alters the normally elastic distribution of stress and strain over the member depth.”

Toughness (Energy Absorption): Toughness is one of the concrete characteristic which is measured by the area under a complete load-deflection curve. Moreover, flexural toughness index is a function of the area under the load-deflection diagram for the SFRC up to first crack (the specified point at which the load-deflection curve becomes nonlinear). According to researchers [9], in FRC, the addition of fiber with high ultimate strain capacity provide toughening component which can bridge the macro cracks.

Durability: According to one research [10], “in the cracked section, the durability of the material depends on the performance of the bridging capacity of the fibers embedded in the concrete.” The fibers with high durability increased the strength and toughness [11].

Resistance to Corrosion: Typically, the harmful effect of steel bars in concrete reinforcement is corrosion emerged near the concrete surface, where the cover is quite small. In SFRC, the corrosion reduces the sectional area of embedded steel fibers leading to losses in strength and toughness.

2.2.1.2 Polypropylene Fiber Reinforced Concrete (PPFRC)

2.2.1.2.1 General

Synthetic fibers were used initially as construction material for reinforcement of cementitious materials in twentieth century. According to the report prepared by ACI 544 [6] on fiber reinforced concrete, synthetic fibers include: aramid, acrylic, nylon, carbon, polyester, polyethylene and polypropylene. In recent years, the large scale of using polypropylene as successful commercial application, has been started for reinforcing the concrete [12].

Polypropylene fibers are manufactured in various size and shape, and with different properties which are hair-like or made of plastic. Its chemical structure contains a long chain of individual molecules which is shown in Figure. 3.

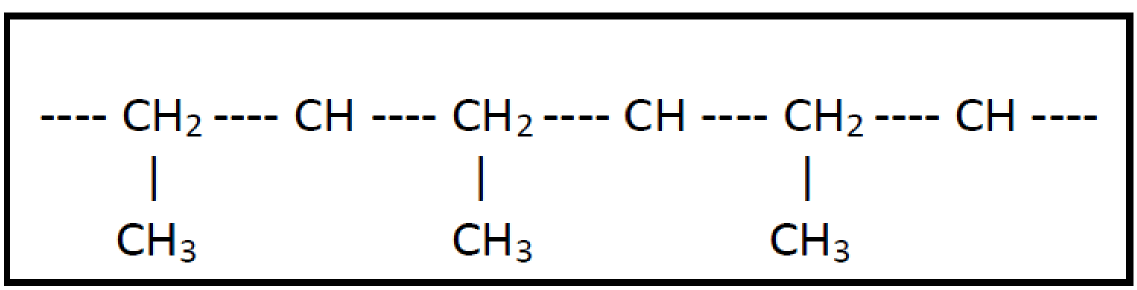

Figure 3. Chemical structure of polypropylene.

Priti et al [12] also claimed that polypropylene with unique properties are chemically inert and non-corrosive.

Typically, these fibers are manufactured with three different geometrics such as: monofilaments, film and extruded tape which the last two forms are used extensively for concrete reinforcement [1]. The polypropylene is a tough fiber with low tensile strength [13]. The main advantages of polypropylene fiber are its high melting point (165°C), alkali resistance and low cost of raw material [1]. Additionally, it is hydrophobic material, meaning water absorption is zero leading to preventing adhesion to the concrete [6]. On the other hand, polypropylene has some weakness points such as: sensitivity to oxygen and sunlight, poor fire resistance, low modulus of elasticity and poor bond with the matrix [1].

2.2.1.2.2 Mechanical Properties of PPFRC

The addition of randomly distributed short discrete polypropylene fibers has various effects on the properties of concrete. The efficiency of polypropylene fiber on compressive strength of concrete depends on its volume percentage. As Bentur et al [1] concluded, the compressive strength of PPFRC with low percentage of polypropylene fibers are not different considerably in comparison with unreinforced concrete. However, the compressive strength of PPFRC is affected by higher percentage of polypropylene fibers. Test result obtained by previous investigation has the similar results [13, 14].

Generally, the modulus of elasticity of polypropylene fiber is variable in hardened and plastic state of concrete. Although, the low elastic modulus and small length of polypropylene fibers improve the initial deficiency of PPFRC, it has adverse influence on compressive strength [14]. Although the presence of polypropylene fiber has no significant effect on compressive strength of concrete, it is effective in increasing flexural strength, splitting tensile, toughness index and durability parameter [15]. Moreover, the effect of short length polypropylene fiber is considerable in mitigating the crack propagation which is an effective reason for increasing the flexural toughness [1]. These short fibers with low modulus of elasticity enhance bond with concrete influencing load-deflection curve of PPFRC [1].

2.2.1.3 Hybrid Fiber Reinforced Concrete (HyFRC)

2.2.1.3.1 General

The term hybrid generally refers to composite combination and consists of material with multiple properties. Therefore, hybrid fiber reinforced concretes (HyFRC) are appointed to the matrix including different fibers with different percentage result in a suitable combination [16, 17]. Since no single fiber reinforced concrete has the perfect mechanical properties, the use of HyFRC improves the overall properties and optimizes the composite performance. On the basis of previous researches, the advantages of using steel fiber and polypropylene fiber in unit matrix are as follow[1, 2]:

1- The influence of fiber size is witnessed in micro cracks and macro cracks. The fiber with small size affect micro cracks and the larger ones arrest the propagating of macro cracks. Controlling the micro crack and macro crack results in a higher tensile strength and toughness of composite, respectively.

2- The hybrid reinforcement with flexible and ductile fibers improve toughness and strain in post cracking zone, while the stronger and stiffer fibers improve the first crack stress and ultimate strength.

3- The presence of fibers with various durable properties in hybrid reinforcement concrete has significant impact. The fibers with high durability increase toughness and strength relation after age, while the lower durable fibers guarantee the short term performance of the composite elements which are used in transportation and installation.

4- As Yao et al [9] concluded, “in the case of steel–polypropylene fibers, it slightly increased modulus of rupture (MOR) when compared to simple PP fibers, but decreased compressive strength when compared to simple steel fibers”.

Chapter 3

3 METHODOLOGY

3.1 Introduction

This chapter presents information for concrete material, mix preparation, casting, curing and testing which are described in details in the respective sections.

3.2 Materials

The properties of materials used in this research were obtained from local sources and are as follows.

3.2.1 Cement

The cement used in all concrete mix was a Portland Cement Type II. The type of cement is important for the water requirement and workability of concrete mix.

3.2.2 Water

In concrete mix, the water has significant impact on development of cement hydration. As Na jin [18] indicated, the addition of too much water causes higher prosperity and lower strength result from the increased distance between particles. As Wanielista et al [19] claimed, “the correct amount of water will maximize the strength without compromising the permeability characteristics of the pervious concrete.”

In present research, the water used in all mixes was local tap drinking water of Northern Cyprus. The determined required water-cement ratio used for this study was 0.5.

3.2.3 Aggregate

Since, aggregates occupy the volume of concrete, their size, shape and surface have significant impact on fresh and hardened properties of concrete [20].

In present research, the crushed limestone was used as aggregates which were extracted from Beşparmak Mountains (Cyprus). The aggregates were carefully sieved and meet ASTM C33 [21] grading requirements (Figure. 4). The maximum sizes of aggregates were 20 mm, 14 mm, 10 mm, and 5 mm.

3.2.3.1 Coarse Aggregate

The coarse aggregate used for concrete mix passing through sieve 20 mm and retained over sieve 5 mm. The maximum size is 20 mm with irregular shape and saturated surface dry condition. The grading results for the coarse aggregate, as obtained from tests undertaken in the laboratory was done according to ASTM C33 [21].

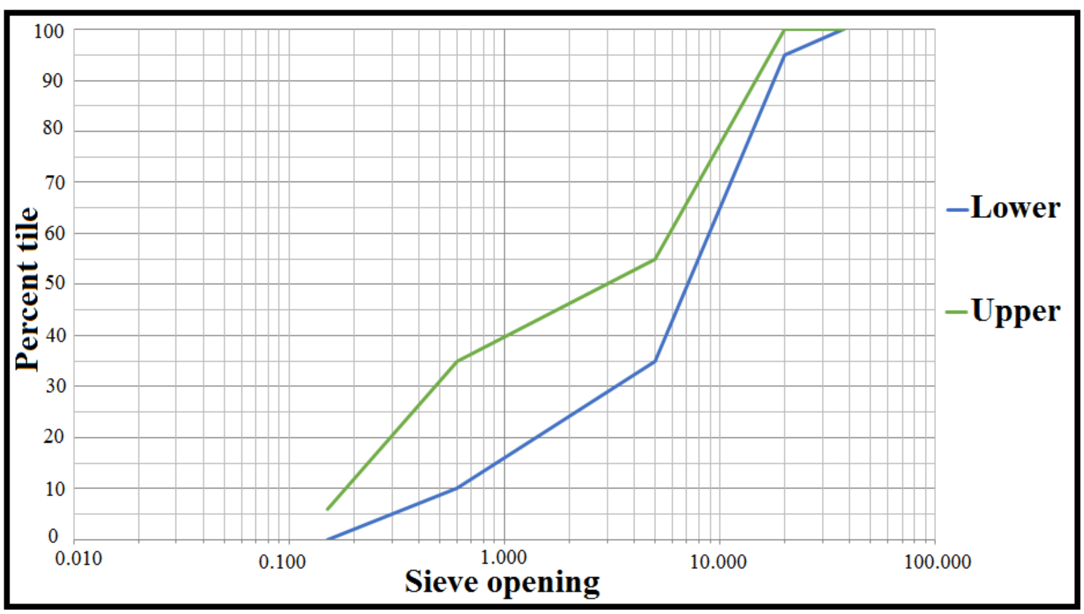

Figure 4. Standard particle size distribution limits of aggregates.

3.2.3.2 Fine Aggregate

According to ASTM C33 [21], fine aggregate shall consist of natural or other inert materials with similar characteristics which combines the hard, strong and durable particles. In this research, fine sand passing through sieve 5 mm and retained on sieve 0.075 mm was used as fine aggregate. The gradation results for the fine aggregate was obtained from tests undertaken in the laboratory according to ASTM C33 [21].

3.2.4 Admixture

According to ASTM C494 [22], superplasticizer is an effective type of water-reducing admixture which improves the concrete workability. In present research, the admixture used was BASF Glenium 27 which affects the cement particle separation leading to improvements in the concrete workability.

3.2.5 Silica fume

The silica fume used in this study was produced from silicon metal and ferrosilicon alloys which increased the concrete properties, both in the fresh and hardened state.

3.2.6 Reinforcement

As Bentur et al [1] claimed, "the efficiency of fiber reinforcement can be judged on the basis of two criteria: the enhancement in strength, and the enhancement in toughness of the composite, compared with the brittle matrix."

In order to investigate the influence of various fibers and their volume fractions in concrete matrix, two types of fiber "steel fiber" and "polypropylene fiber", were used. According to the purpose of present research, the optimum mix design achieved by Eren et al [23] which was taken as reference for concrete mixes.

3.3 Mix Design Consideration

Since the purpose of the study was to investigate the performance characteristic of FRC, six different combinations were considered. In each combination, the proportions of cement content, fine and coarse aggregate, water, admixture and silica fume were kept constant, while the corresponding fiber proportion by volume of concrete mix were different as given below:

- Mix 1: concrete reinforced individually with steel fibers (1.5% per volume of concrete)
- Mix 2: concrete reinforced individually with polypropylene fibers (0.15% per volume of concrete)
- Mix 3: concrete reinforced with 0.75% steel fiber per volume of concrete + 0.075% polypropylene fiber per volume of concrete
- Mix 4: concrete reinforced with 0.45% steel fiber per volume of concrete + 0.105% polypropylene fiber per volume of concrete
- Mix 5: concrete reinforced with 0.30% steel fiber per volume of concrete + 0.12% polypropylene fiber per volume of concrete
- Mix 6: concrete reinforced with 0.15% steel fiber per volume of concrete + 0.135% polypropylene fiber per volume of concrete

In the production of concrete matrix, the mixer with a capacity of 0.106 m^3 was used. Based on each mix design, constitute materials were weighed and placed in mixture. Figure. 5 presents the mix procedure which is obtained from previous research [11].

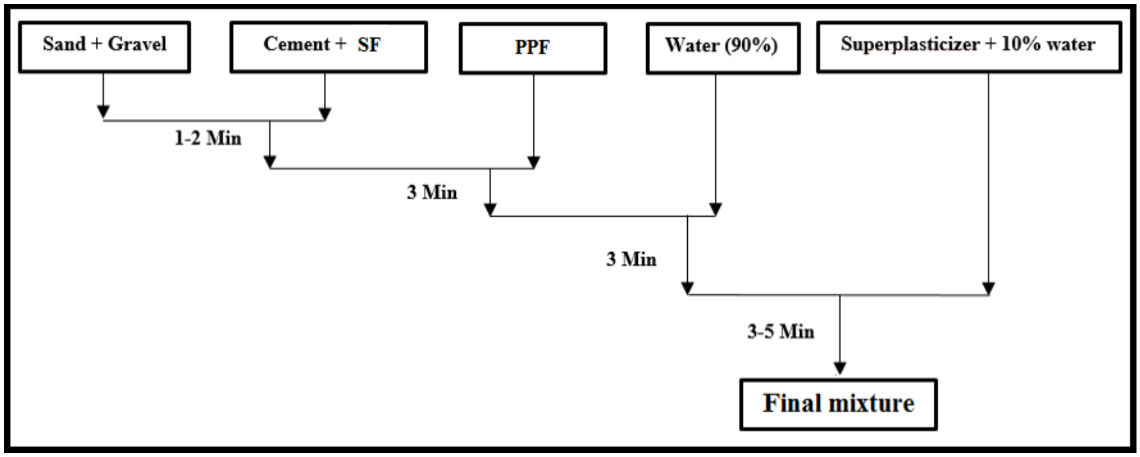

Figure 5. Mixing procedure for hybrid composite [11].

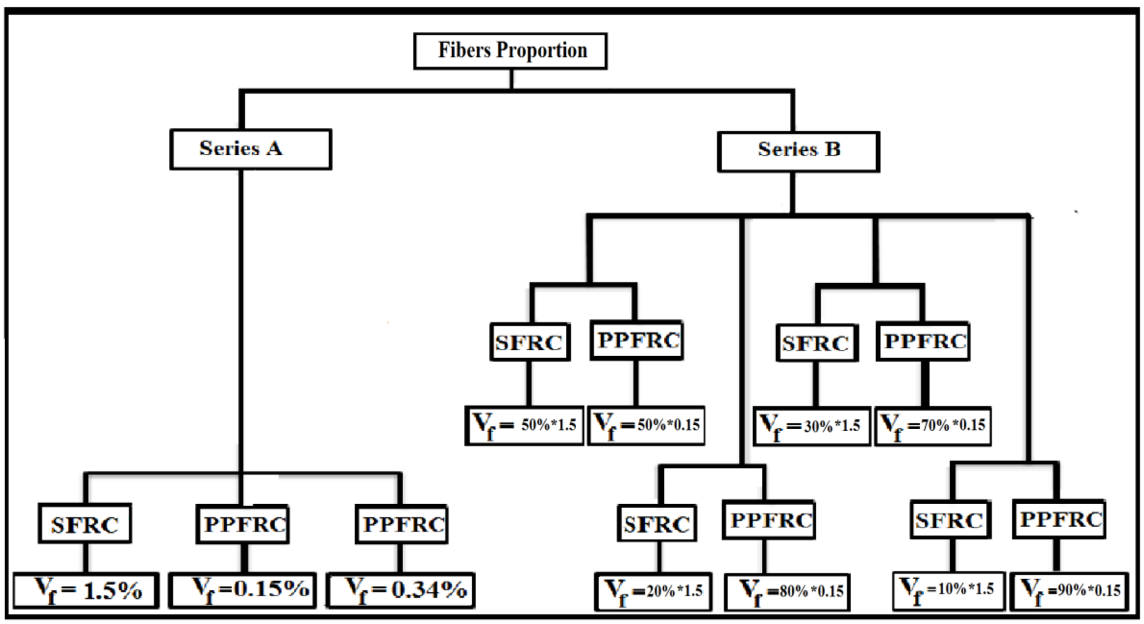

Figure 6. Fiber volume fraction used for reinforcing the composite.

Moreover, Figure. 6 illustrate the percentages of fiber types used for reinforcing the composites.

Altogether, materials were mixed for 3-5 minutes to ensure that the fibers can evenly disperse throughout the concrete. After completion of mix procedure and prior casting the concrete specimens, two tests (slump test and vebe test) on fresh concrete were carried out which were described in the following sections.

3.4 Casting and Curing

According to the goal of this study and related tests, the following specimens were cast from each mix:

- For evaluation of compression test: three 150 mm cubes
- For evaluation of flexural test: one 150 × 150 × 600 mm beam
- For evaluation of impact resistance test: one 150 × 600 mm cylinder

For each test, one specimen was made as the control one. After preparing the molds [24] concrete was placed in two layers vibrated with 50 Hz frequency leading to proper consolidation and concrete compaction. The specimens were cured in fog room with 22+2℃ temperature. In the following day, the specimens were extruded and cured in temperature controlled water tank until the date of testing (28 days).

3.5 Testing

In this research, all tests were conducted in accordance with the relevant ASTM and BS standards.

3.5.1 Experimental Details

In present study, all testes were considered to explore mechanical properties such as compressive strength, flexural strength and impact resistance of SFRC, PPFRC and HyFRC. The experimental program consists of laboratory tests on both fresh and hardened concrete.

3.5.2 Test on Fresh Concrete

In order to characterize the concrete workability which is defined by Neville [25] as amount of useful internal work necessary for full compaction [20], slump and vebe tests were performed immediately after mixing the batch of concrete. The procedure for slump and vebe tests were complied with BS EN 12350-2 [26] and BS EN 12350-3 [27], respectively.

According to European standard, the slump test is not suitable to concrete of which the maximum size of aggregate is greater than 40 mm and also the measurement of slump can be suitable between 10 mm and 210 mm [26]. Moreover, the vebe test is not applicable when the maximum size of aggregate exceeds 60 mm.

3.5.3 Test on Hardened Concrete

In the case of hardened concrete, the compressive, flexural and impact resistance tests were done for the assessment of fiber effect on mechanical properties of concrete.

3.5.3.1 Compressive Strength Test

This test covers the determination of 28 days compressive strength of cubic concrete specimens complied with BS EN 12390-3 [24]. In this test, the cube specimens (150 mm) were loaded in a testing machine under load control which is applied perpendicularly to the direction of casting. According to BS EN 12390-3 [24], the load was applied at the range of 0.6 ± 0.2 MPa/s ($N/mm^2 \cdot s$) until compressive failure of the cubic sample occurs. At failure point, the maximum load indicated in kN was recorded on the screen.

The relevant equation for compressive strength is as follows:

$$f_c = F/A_c$$

f_c: the compressive strength in MPa (N/ mm^2);

F: the maximum load at failure point in N;

A_c: the cross sectional area of the specimen (mm^2)

For each type of mix design, three specimens were tested and the results were recorded describing in Chapter 4.

3.5.3.2 Flexural Toughness Energy Test

This test covers the determination of flexural toughness energy of specimens under gradual load until failure. The test procedure and dimensions of beam specimens (150 × 150 × 600 mm) complied with ASTM C1609M [28].

For this test, the testing machine (Figure.7) with a controlled microprocessor was used to provide the graphical load-deflection diagram. The beam specimens were marked for proper placement in test machine which was placed on top of the support roller so that the LVDT's and thin steel plate were placed at measurement location and mid-span, respectively.

The load with constant cross-head displacement rate of 0.l mm/min was applied until the first crack appears and then the load was increased to 0.008 in/min for the remainder of the test. During the test, the force was recorded at least five times per second.

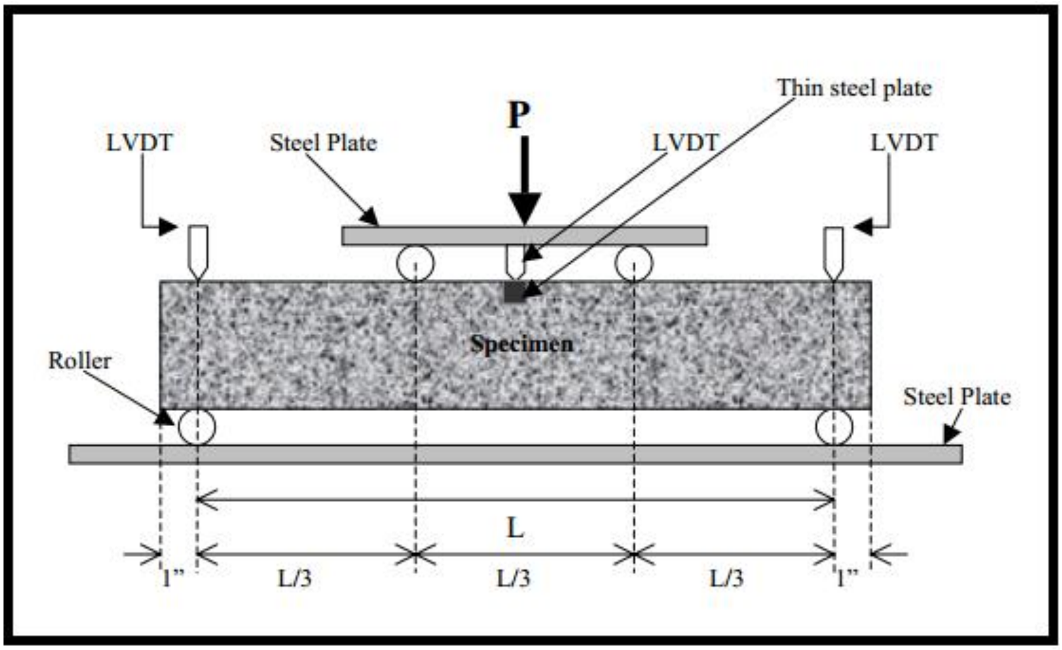

Figure 7. Test setup for flexural toughness test [29].

According to load-deflection diagram, the behavior up to the load at which first crack occurs was determined as first-crack strength:

$$f = PL/bd^2$$

f = first-crack strength or modulus of rupture (MOR), MPa,

P = the load, N,

L = the span length, mm

b = the average width of the specimen at the fracture, as oriented for testing, mm, and

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

The behavior there after, is defined by the toughness or energy absorption [29] which also reflects the post crack behavior:

$$\sigma b = \frac{\tau}{\delta tb} * l/bd2$$

σb = flexural toughness factor (kg/cm^2)

τ = flexural toughness (kg.cm)

δtb = deflection of (1/50) of span (cm)

b, d = width and depth of the beam under test.

As researchers [1] claimed, the load-deflection diagram can represent the fibers influence on the toughness of composite and its crack control potential.

3.5.3.3 Impact Resistance Test

According to researchers [30], different test methods measuring the impact resistance of FRC are complicated, expensive and time consuming. In general, fiber reinforcement can improve the performance of concrete under dynamic load that it mainly results from the higher strain capacity and load bearing capacity in the post cracking zone [1]. In this research, Drop Weight Impact test designed by ACI committee [6] has been used to measure the impact resistance of fiber reinforced concrete. The test was developed by modifying an aggregate impact test machine in accordance with BS 812: Part 112 Method of Determination of Aggregate Impact Value [31].

For this test, each type of fresh concrete was casted into the cylinder size of 150 × 300 mm (Diameter × Length). At 28 days age, the cylinder was sawed into four sections along the length (150 × 300 mm). The cylinder specimen was placed in machine and the load is transformed by dropping a hammer weighing 13.5 kg from a height of 30.0 cm which is placed on the top of the center of the cylindrical specimen (Figure.8).

As Eren [30] stated, “this method can be used for FRC, it is difficult to use it for SFRC due to the small weight of the hammer 4.54 kg. On the other hand, the number of blows is less if a larger mass 13.5 kg is used, which is more effective in transmitting impact loads”.

Number of impact values recorded was based on initial and ultimate failure. When the first crack was visible, the first measurement (impact times) was recorded, whereas the second values were measured as soon as the cracks propagate until the ultimate failure. In accordance to ACI committee, the full failure resulted from sufficient impact energy which was applied during the test and the average of impact resistance was taken from cylindrical discs for each variant.

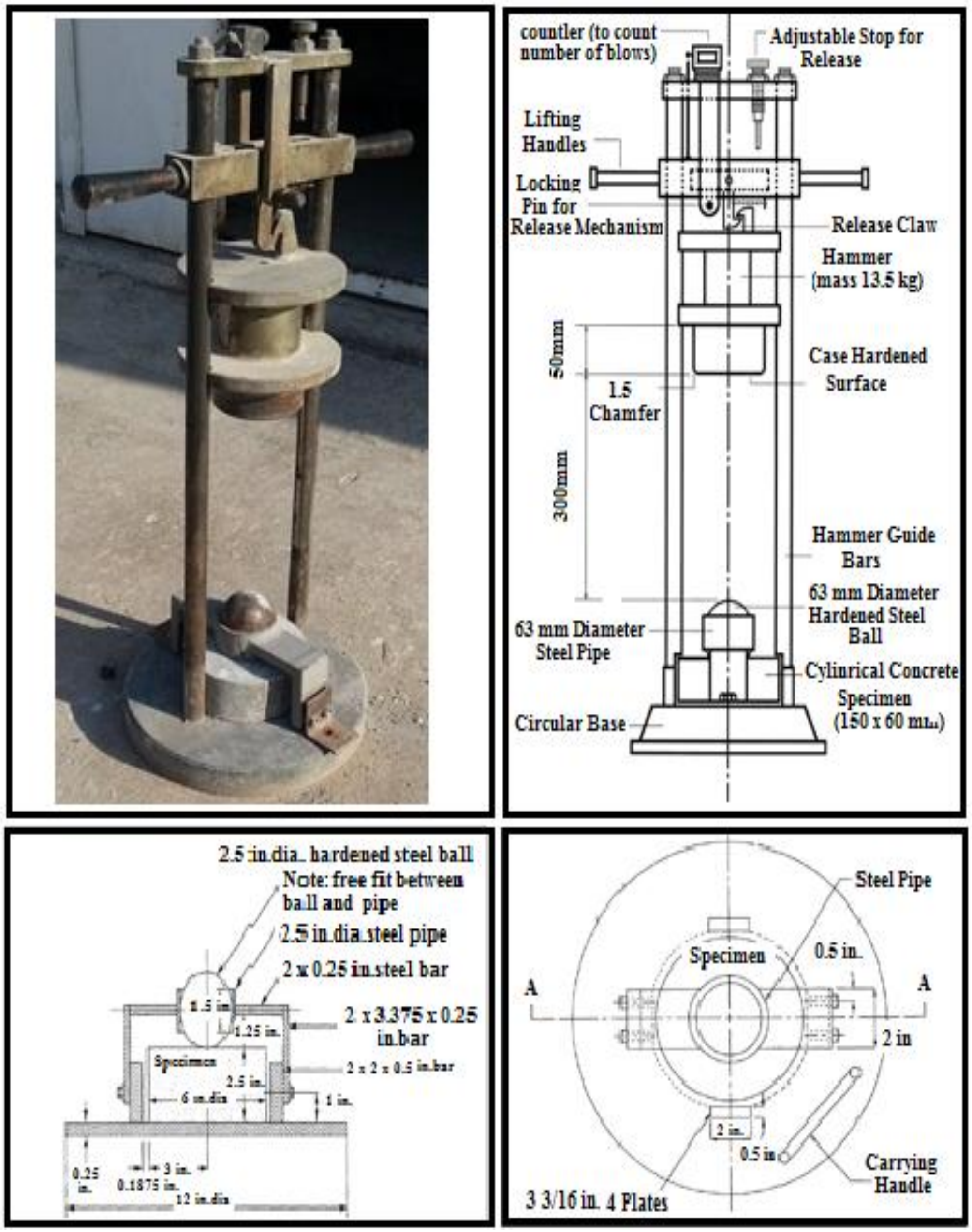

Figure 8. Impact test apparatus with the concrete disc in place [32].

Chapter 4

4 RESULTS AND DISCUSSION

4.1 Introduction

This chapter includes the analysis of the results, discussion and summary of findings on FRC specimens from test investigations. After analyzing, the corresponding results are compared with previous findings to make a conclusion as if any promotion is reached in concrete properties due to the addition of different types and dosage rate of fibers.

Moreover, the relations were found between compressive strength and fiber volume fraction, flexural strength and fiber volume fraction and compressive strength, toughness and fiber volume fraction and compressive strength, impact resistance and fiber volume fraction and compressive strength.

4.2 Results

4.2.1 Sieve Analysis

The term of sieving is referred to particle size distribution of fine and coarse aggregate by means of a mesh. According to ASTM C136 [33] , “this test method is used primarily to determine the grading of materials proposed for use as aggregates or being used as aggregates.” As pointed out in previous chapter, the grading for aggregates (fine and coarse) were complying with ASTM C33 [21].

Figure. 9 provides the size distribution of both fine and coarse aggregates. The obtained results from sieve test revealed that the maximum sizes of aggregates used were 20 mm, 14 mm, 10 mm, and 5 mm.

4.2.2 Slump Test

In order to investigate the consistence and workability of fresh concrete, the BS EN 12350-2 [26] specified a slump method. The result of slump test which was performed on SFRC in fresh state is around 6 cm. Inclusion of polypropylene fiber caused cohesion with matrix result in low slump. In present study, the concrete reinforced with 0.34 and 0.15 percentage of polypropylene fiber reached zero slump which is a result from the composites having low work abilities.

According to data from laboratory test, slump results losses ranging which is varying from a few centimeters to zero. One study [34] indicated the same results, slump reduction, when fibers were added to the concrete.

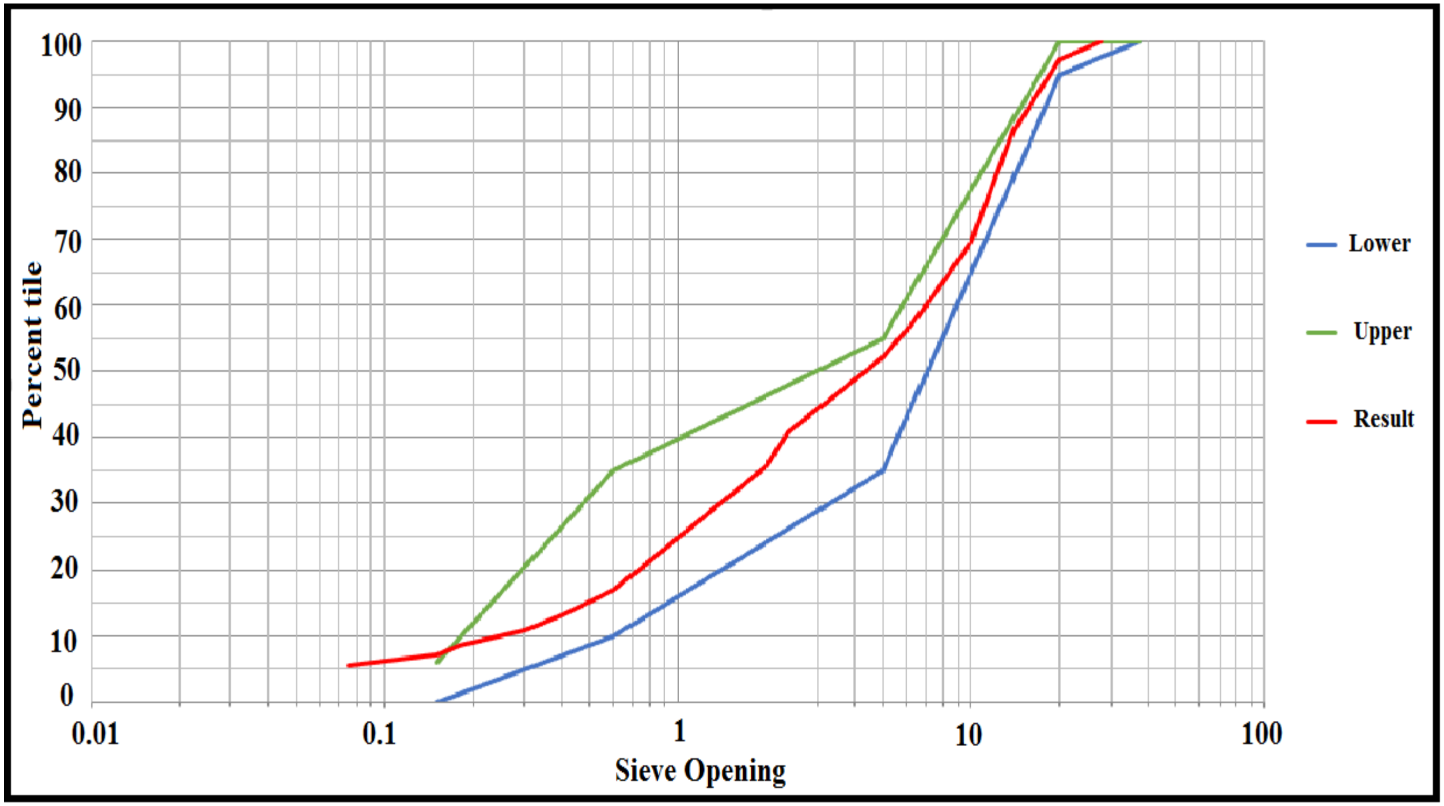

Figure 9. Particle size distribution of crushed limestone aggregates.

4.2.3 VeBe Test

As pointed out in preceding chapter, vebe test is the method for determining the concrete workability and consistency which was specified by BS EN 12350-3 [27]. This test is applicable for the concrete with the maximum size of 63 mm. Results reported in Table. 2 and Figure. 10 are for vebe time of the different mixes.

Results from four studies [12, 23, 30, 35] show that fiber addition increases vebe time.

Table 2. Obtained vebe time.

Mix designation	Volume fraction %	VeBe time (sec)
SFRC 1.5%	1.5	3" 70
PPFRC 0.15%	0.150	7" 48
SFRC 50%*1.5 + PPFRC 50%*0.15	0.825	1" 26
SFRC 30%*1.5 + PPFRC 70%*0.15	0.555	2" 31
SFRC 20%*1.5 + PPFRC 80%*0.15	0.420	2" 53
SFRC 10%*1.5 + PPFRC 90%*0.15	0.285	3" 56

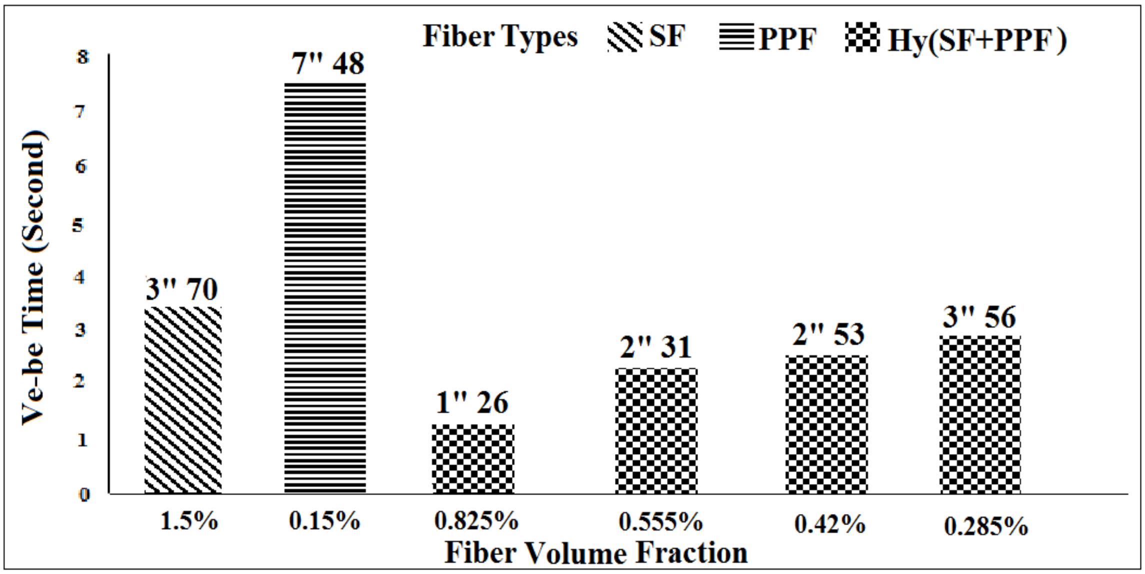

Figure 10. Influence of fibers volume fraction on vebe time

4.2.4 Compressive Test

This section highlighted the effect of fibers with various types and doses on compressive strength of composite. Twenty eight days compressive strength of each six mixes was specified in accordance with BS EN 12390-3 [24].

Regarding this, three cubes from each mix were tested which is subjected to a gradually applied load, until the compressive failure of the specimen occurs. Table. 3 shows the individual and average compressive strength for cube specimens. Also, a regression analysis obtained from the data was carried out to predict compressive strength of FRC.

4.1.4.1 Analysis of the Results

The obtained results which are shown in Table. 3 and Figure. 11, indicated that:

The compressive strength varied from 50.23 MPa to 20.43 MPa. Similar to other researcher's findings, this study showed that the inclusion of fibers can affect the compressive strength of the concrete depending on fiber types, volume fractions and its modulus of elasticity.

According to Figure.11, it can be concluded that steel fiber proved to be very effective in improvement of compressive strength. Since steel fiber is sufficiently strong, the inclusion caused sufficient bond to material resulting in sufficient transfer of stress across a crack and improved resistance of crack growth. Similar findings were reported by Bentur [1] and also Shah [7].

According to the test results, it is obvious that the addition of polypropylene fiber at very low volume percentage [1], has slight effect on compressive strength. The inclusion of polypropylene fiber, if it is clustered, will caused low workability and initial defect in concrete resulting in reduction of compressive strength. Also, this reduction attributed to air voids, compaction and consolidation problems. At the end, the HyFRC has lower compressive strength value than single type fiber reinforced concrete resulting from reduction in volume fraction of effective fiber which is steel one. So by increasing polypropylene fiber and decreasing steel fiber volume fraction, compressive strength decrease as well.

The maximum compressive strength obtained is 50.23 MPa for 1.5% steel fiber while a decrease in strength value was observed in hybrid composite. Moreover, according to Hsie, M [8], steel fiber has high module of elasticity which increase compressive strength.

In order to see the variation of compressive strength with volume fractions of fibers, Figure. 12 was drawn. The regression analysis provided nonlinear relation as given below:

$$Fc= A+ B*V_{fs}+ C*(V_{fs})^2+ D*(V_{fs})^3+ E*V_{fpp}$$

Where; f_c is compressive strength, V_{fs} is steel fiber (SF) volume fraction, V_{fpp} is polypropylene fiber (PPF) volume fraction, A, B, C, D and E are regression coefficients (Table. 4).

From the figure, the trend for compressive strength values is ascending by increasing the steel fiber volume fraction. On the other hand, the increase of polypropylene fiber volume fraction causes a slight growth in compressive values.

Table 3. Compressive strength values at 28 days of age.

Mix designation	**Volume fraction %**	***f*C 28 days age (MPa)**				***fc* AVE (MPa)**
SFRC	1.500	49.90	50.80	50.00	-	50.23
PPFRC	0.150	38.80	37.70	35.80	35.50	36.95
(50%*1.5 S+ 50%0.15 PP) FRC	0.825	28.90	32.30	30.10	-	30.43
(30%*1.5 S+ 70%*0.15PP) FRC	0.555	23.80	26.60	25.60	25.50	25.38
(20%*1.5 S+ 80%*0.15 PP) FRC	0.420	22.00	20.70	21.30	-	21.33
(10%*1.5 S+ 90%*0.15 PP) FRC	0.285	19.20	20.80	21.30	-	20.43

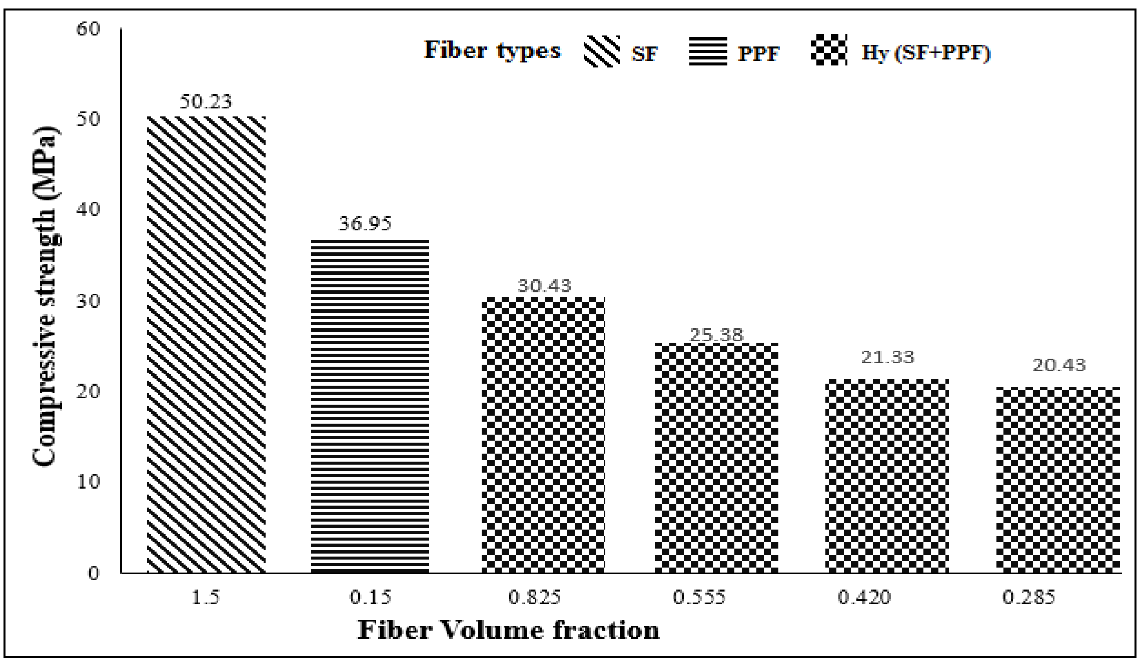

Figure 11. Copmression tests results.

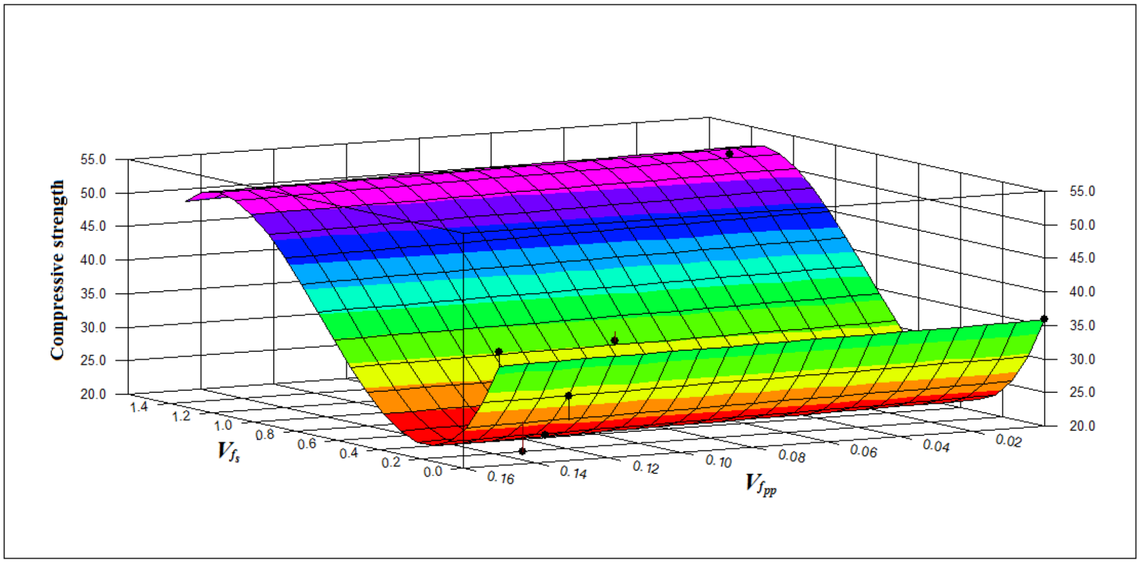

Figure 12. Effect of fiber volume fraction on compressive strength of concrete.

Table 4. Result of regression analysis for compressive strength versus fibers volume fraction.

Relation	**Equation**	**Regression values**					
		A	**B**	**C**	**D**	**E**	**R^2**
Compressive strength	$F_c = A + B*Vf_S + C*(Vf_S)^2 + D*(Vf_S)^3 + E*(Vf_{pp})$	35.84	-88.50	158.81	-62.305	-6.921	0.938

4.2.5 Flexural Test

According to ASTM C1609, the flexural performance of FRC can be obtained from load-deflection diagram by testing a beam which is supported by third-point loading. Also, the test results show the absorbed energy. At the test age, each specimen was tested with flexural test machine following process described in previous chapter.

Figure. 13 is representation of the load-deflection behavior of all FRC beams. As for the comparison, the load-deflection diagram is divided into three regions. The first region started from beginning of the loading until the occurrence of first crack. In this region, the curve is linear and reaches a maximum level at first crack occurrence. The second region is demonstrated area from ultimate load ending at a point in which the tensile strength is resisted by bond between fibers and concrete. The third region corresponds to the net deflection which is almost parallel to the horizontal axis.

Figure.13 shows the average load-deflection behavior of fiber reinforced beams. As stated before, the behavior of FRC can be determined by the first crack strength (MOR) and toughness (energy absorption) from load deflection curve which are discussed below. The Analysis was done separately as follow:

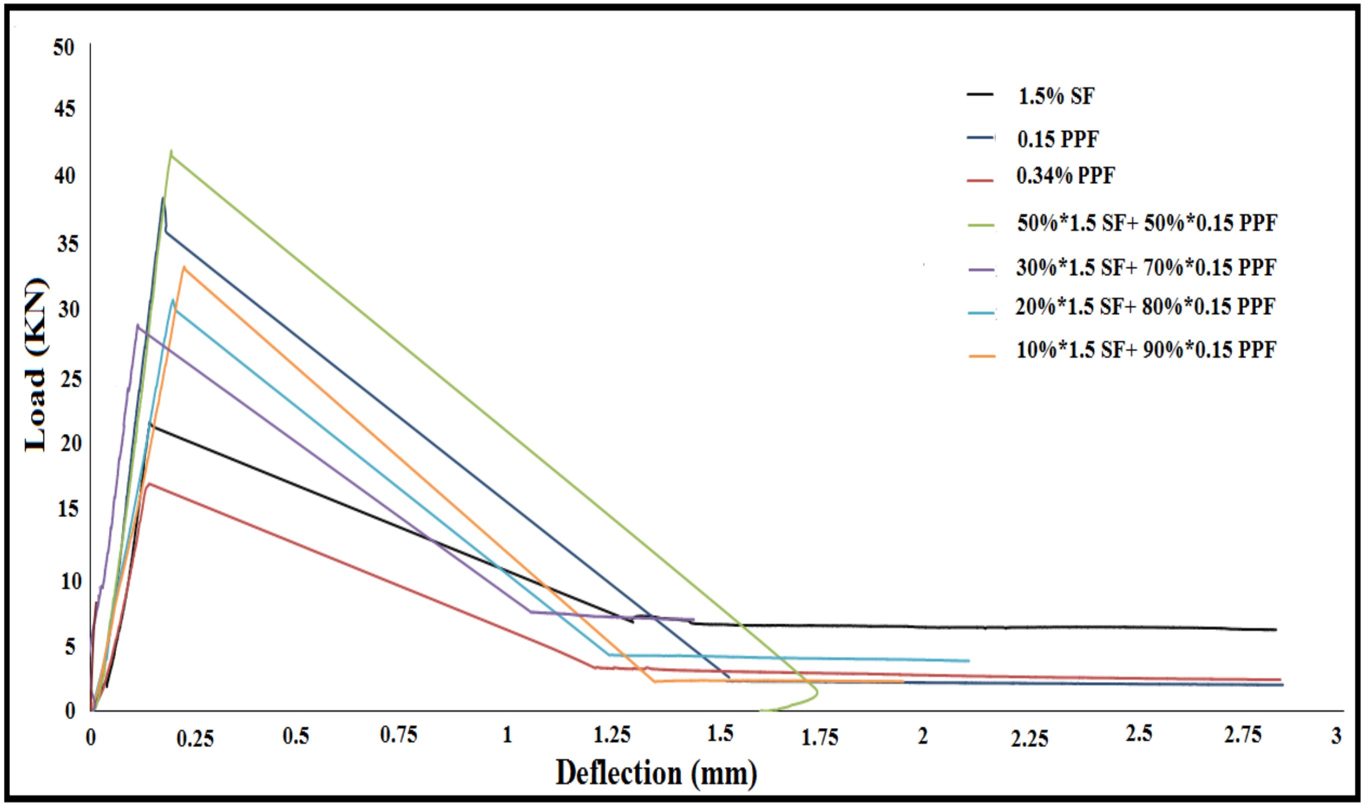

Figure 13. Load-deflection diagram.

4.2.5.1Analysis of the Results

4.2.5.1.1 Analysis of Flexural Strength (MOR)

The results reported in Table. 5 are showing the flexural strength values. In a broad view from Figure. 14, the highest flexural strength was obtained in HyFRC with 0.825% volume fraction of both steel and polypropylene fiber and the lowest value was obtained in SFRC with 1.5% steel fiber volume fraction. However, the fiber volume fraction of SFRC is 10 times greater than fiber volume fraction in PPFRC composite. This is a result from the ability of polypropylene to enhance the load bearing capacity in the post-cracking zone. Similar findings were also reported by Bentur et al [1]. In HyFRC, the combination of steel and polypropylene with half percentage of each single fiber have better function in first pick zone. In case of hybridization, the presence of steel fiber which is stronger and stiffer improves the first crack stress and presence of polypropylene which is smaller can bridge the stress and control the crack growth leading to better function in concrete composite compared to presence of single type fiber.

Table 5. Flexural strength test results.

Mix design designation	Volume Fraction (%)	Flexural Strength (MOR) MPa
SFRC	1.500	2.884
PPFRC	0.150	4.774
PPFRC	0.340	2.268
(50%*1.5 SF + 50%*0.15 PPF) RC	0.825	5.536
(30%*1.5 SF + 70%*0.15 PPF) RC	0.555	3.828
(20%*1.5 SF + 80%*0.15 PPF) RC	0.420	4.002
(10%*1.5 SF + 90%*0.15 PPF) RC	0.285	4.406

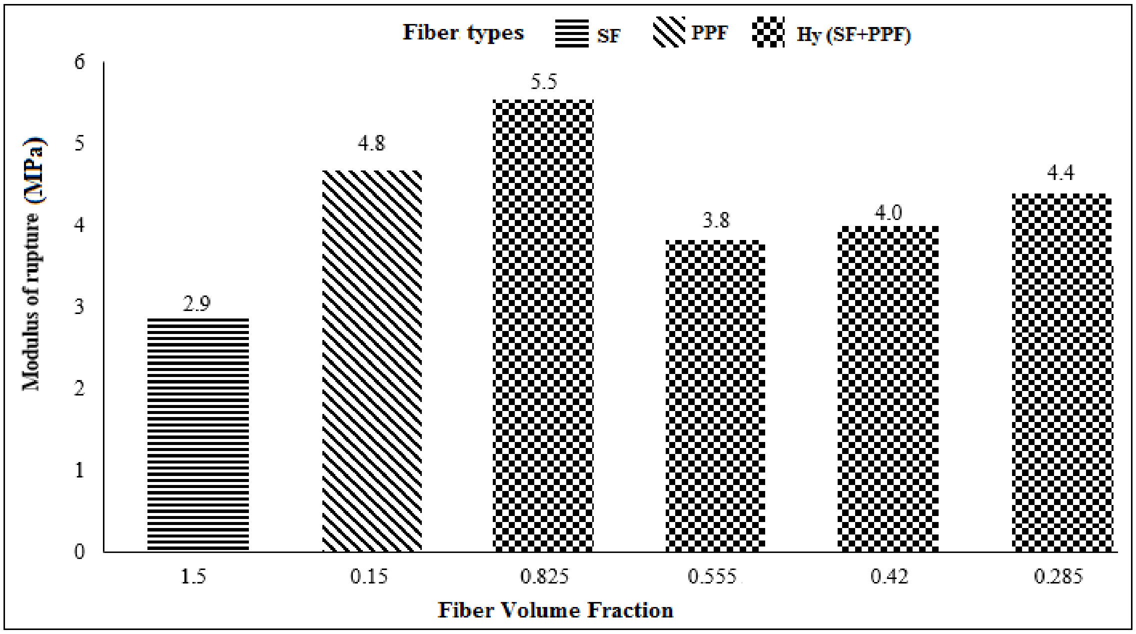

Figure 14. Flexural strength test results.

According to regression analysis, the relation between flexural strength (MOR) and volume fraction of fibers and compressive strength is nonlinear as given below:

$$F_e = A + B^* V_f + C^* f_c + D^*(f_c)^2$$

Where; F_e is flexural strength, V_f is fibers volume fraction, f_c is compressive strength of composites. A, B, C and D are regression coefficients.

The results of regression are shown in Table. 7 and Figure. 15. It represents the variation of flexural strength of fiber reinforced concrete as a function of fiber volume fraction and compressive strength. At one extreme, the flexural strength values decrease by increasing fiber volume fraction indicating slight effect of fibers on flexural strength. When compressive strength is around 30-35 MPa, the highest flexural strength value will be obtained.

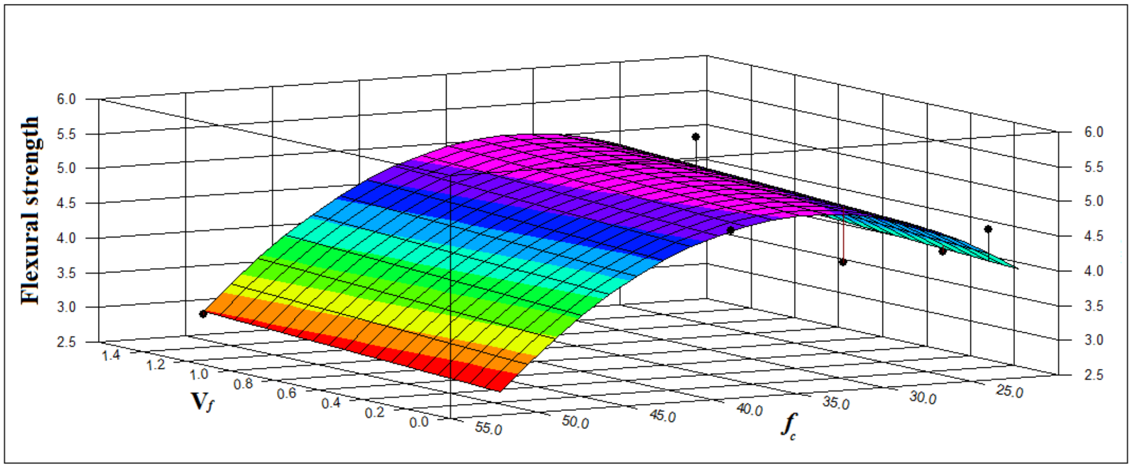

Figure 15. Effect of fiber volume fraction and compressive strength on flexural strength of concrete.

Table 6. Results of regression analysis for flexural strength versus fiber volume fraction and compressive strength values.

Relation	**Equation**	**Regression values**				
		A	**B**	**C**	**D**	**R^2**
Flexural strength	Fe= A + B*V_f + C*f_c+ D*(f_c)^2	-2.398	0.171	0.450	-6.972	0.710

4.2.5.1.2 Analysis of Flexural Toughness (Energy Absorption)

As mentioned in previous chapter, the area under the stress-strain curve represents the total energy absorbed prior to complete separation of the specimens. The results from flexural strength test with different percentage of fiber are given in Figure. 16.

From the figure, it is notable that the flexural strength test results with different percentage of fibers indicate that there is influential effect of fiber volume percentage on toughness. Table. 7 and Table. 8 indicate the effect of fiber volume fraction on toughness. The highest toughness index was obtained in hybrid fiber reinforcement.

According to the results, in single type fiber, SFRC has highest toughness index compared to PPFRC. The reason is because of the increase in fiber length and dosages result in arresting the crack propagation. Moreover, the addition of polypropylene fiber which is flexible and ductile and also concurrent presence of steel and polypropylene fiber result in highest toughness index.

Table 7. Toughness results of SF reinforced concrete.

V_f of SF (%)	Deflection at peak load δp (mm)	Toughness Index
1.5	0.14103	38.80
0.75	0.19554	39.72
0.45	0.11463	27.53
0.3	0.20317	25.61
0.15	0.22674	26.70

Table 8. Toughness results of PPF reinforced concrete.

V_f of PPF (%)	Deflection at peak load δp (mm)	Toughness Index
0.075	0.19554	39.72
0.105	0.11463	27.53
0.12	0.20317	25.61
0.135	0.22674	26.70
0.15	0.18218	37.25

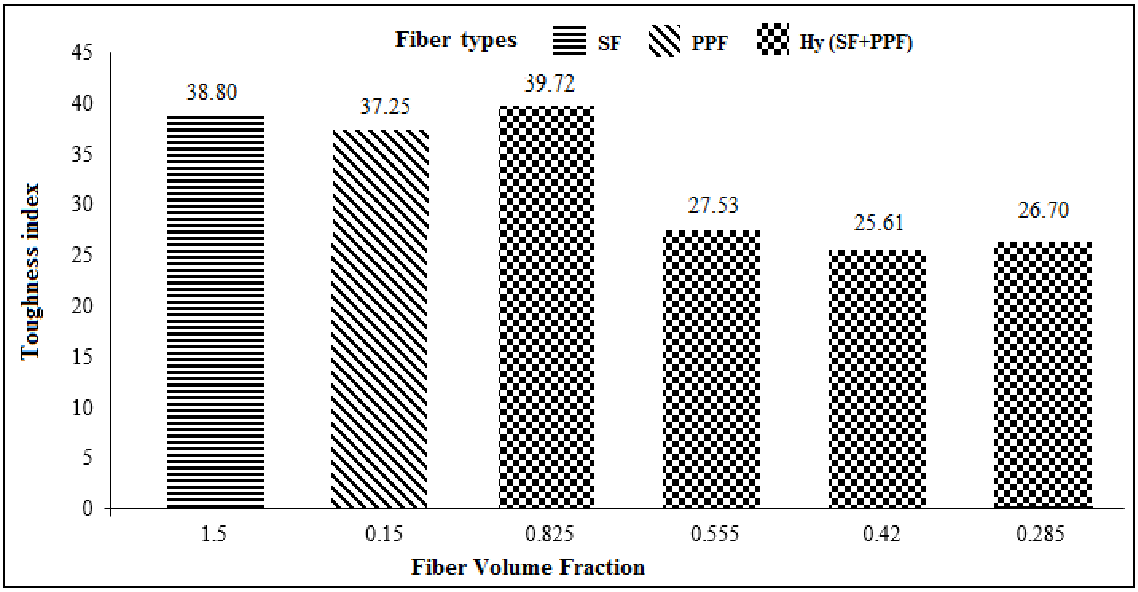

Figure 16. Flexural toughness test result.

In order to show the variation between concrete toughness and volume fraction of fibers and compressive strength, Figure. 18 was drawn and the relevant equation is given below:

$$T_f = A + B^*V_{fs} + C^* f_c$$

Where T_f is toughness index, V_{fs} is steel fiber volume fraction, f_c is compressive strength, A, B and C are regression coefficients (Table. 9).

As shown in Figure.17, the amount of fibers volume fraction has significant effect on toughness value. Increasing fiber amount enhanced the energy absorption.

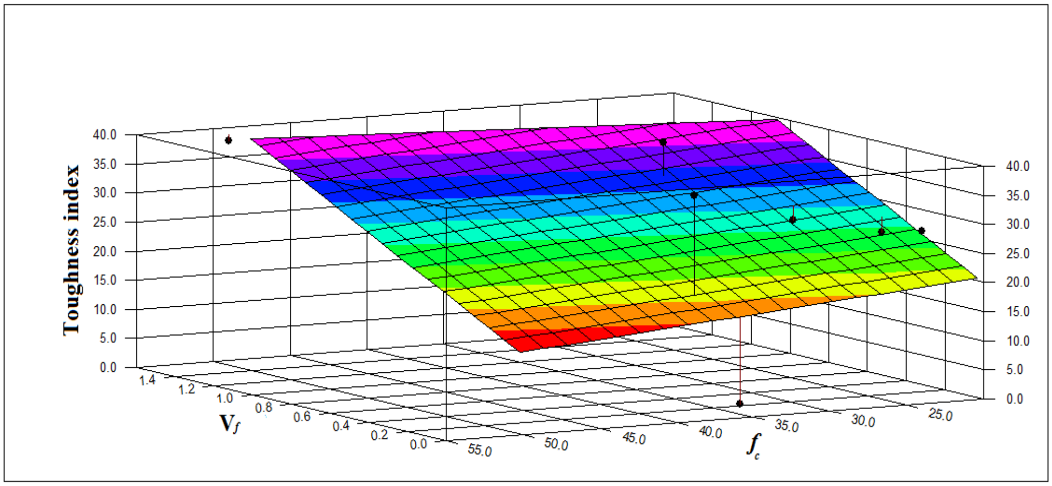

Figure 17. Effect of fiber volume fraction and flexural toughness of concrete.

Table 9. Result of regression analysis for flexural toughness versus fibers volume fraction.

Relation	Equation	Regression values			
		A	B	C	R^2
Flexural toughness	$T_f = A + B*V_{fs}+C* f_c$	25.41	18.6	-0.22	0.42

4.2.6 Impact Test

As explained in previous chapter, to specify the behavior of FRC under dynamic loading, impact resistance test could be carried out. This will represent the ability of concrete to endure repeated blows to absorb energy. Table. 10 presents the results of impact test carried out on cylindrical specimens. Moreover, the variation of impact resistance with volume fraction of fibers and compressive strength was investigated as shown below.

4.2.6.1 Analysis of the Test Results

Irrespective of fiber type, the impact energy is affected by fiber addition in concrete mixture. According to previous study, Pu et al [14] also reported the similar results. Moreover, fiber addition had no significant effect on first crack strength under impact test, but ultimate strength failure (USF) was greatly enhanced (Table. 10).

Based on test results, steel fiber were more efficient in increasing USF when compared with polypropylene fiber. In other words, the highest number of blows which caused highest impact energy was obtained with SFRC. It is due to the randomly distributed steel fiber in the matrix which were sufficiently strong for carrying stresses over strain. Figure. 21, 22 show the variation of impact resistance behavior in different mix design concrete. Consequently, the orientation permits the fiber for crack-bridging.

According to Figure. 18, among the composites with fiber combination (HyF), the highest USF was obtained in composite reinforced with 50% steel fiber and 50% polypropylene fiber volume fraction. Other hybrid fiber combination with various percentages resulted in decreased UFS values. This is due to the consequence of positive interaction between polypropylene fiber and steel fiber. Likewise, steel fiber has higher elastic modulus and tensile stress compered to polypropylene fiber, so in this case the steel fiber with higher volume fraction than polypropylene fiber in all mixes play an important role for the impact resistance. Moreover, steel fiber with long length affects the crack bridging and polypropylene fiber addition acting as rigid material to provide a great deal of energy absorption for crack resistance.

Consequently, regarding to fiber types and volume fraction, steel fiber had better performance in reinforcing the concrete to reach the highest impact resistance.

Table 10. Impact resistance values.

Mix design	Number of blows				Volume fraction (%)	Complete separation	Impact Energy (J)
	First Sample	Second Sample	Average	Approximate			
SF	8	7	7.5	8	1.5	28	618.36
PPF	6	3	4.5	5	0.150	8	176.67
SF + PPF	5	3	4	4	0.825	14	309.18
SF + PPF	4	6	5	5	0.555	12	265.01
SF + PPF	3	6	4.5	5	0.420	11	242.93
SF + PPF	2	2	2	2	0.285	6	132.51

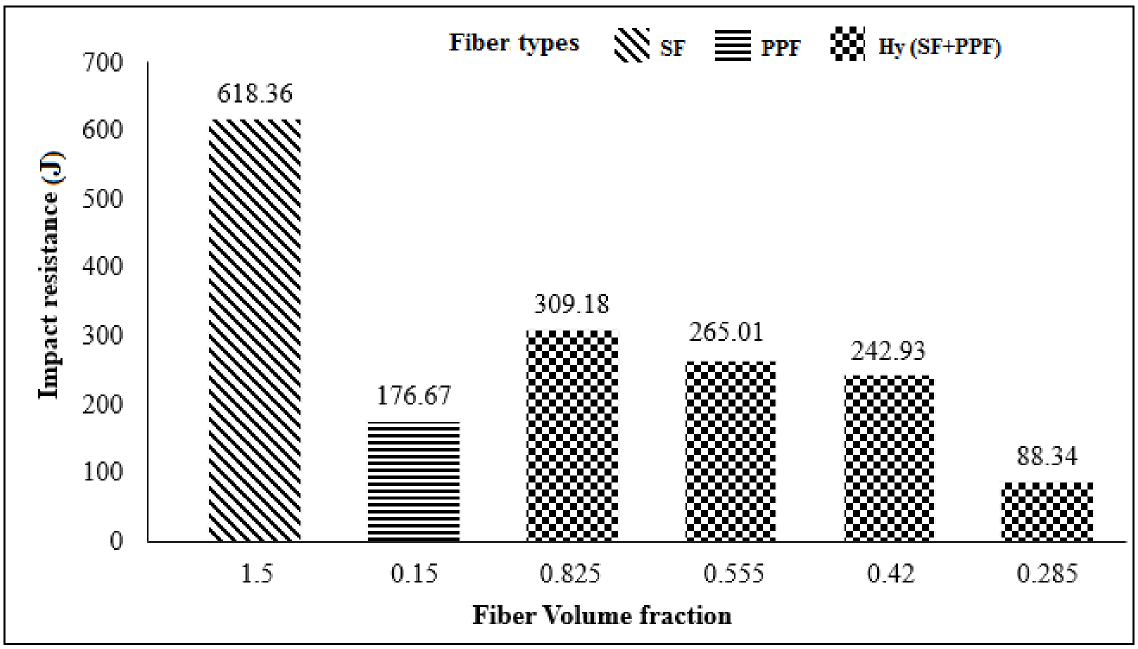

Figure 18. Impact resistance test results.

In order to see the variation of impact energy with fiber volume percentage and compressive strength, Figure. 19 was drawn. From this figure, it is obvious that for all SFRC, as compressive strength increases, impact energy decreases.

The relevant equation is as given below:

$$I_c = A + B*V_f + C*f_c$$

Where; I_c is impact energy, V_f is fibers volume fraction, f_c is compressive strength of composites. A, B and C are regression coefficients (Table. 11).

From the regression analysis, it can be seen that when the fiber volume fraction is 0.825 and the compressive strength is 30.43 MPa, the predictable impact energy will be 325.60 J, while its real value is 309.18 from the test result. Consequently, the error will be 5.31%.

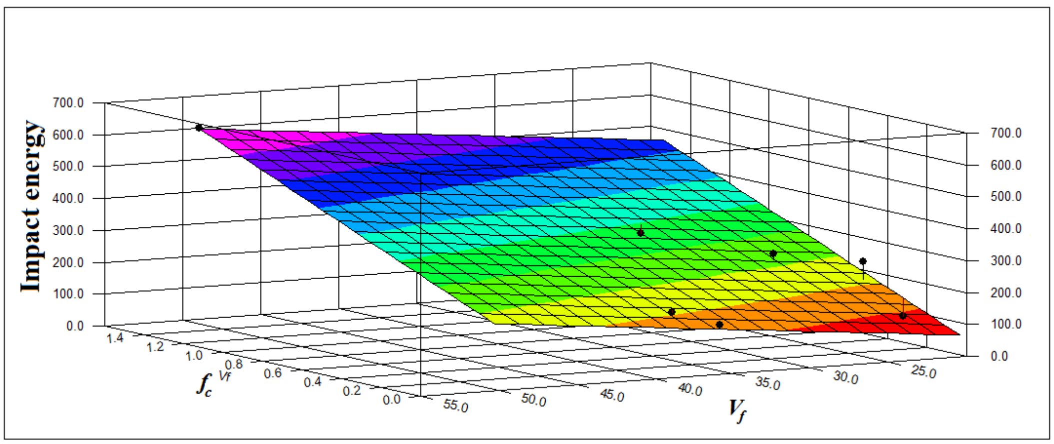

Figure 19. Effect of fiber volume fraction and compressive strength values on impact energy of concretes.

Table 11. Results of regression analysis for impact energy versus fibers volume fraction and compressive strength.

Relation	Equation	Regression values			
		A	B	C	R^2
Impact energy	$Ic=A+B*(V_f)+C*(f_c)$	-28.93	269.98	4.75	0.954

Figure 20. Single type fiber specimens after impact test.

Figure 21. Hybrid fiber specimens after impact test.

Chapter 5

5 CONCLUSION

Based upon the obtained results of this thesis, the following conclusion and recommendation are derived.

1. In general, the addition of fibers with different types and various amounts are achieved the desired improvements in mechanical behavior of reinforced concrete.

2. For the compressive strength, the better result was taken form single type fiber which is cased sufficient bond to material resulting in sufficient transfer of stress. So, the high volume percentage fibers has significant effect on compressive strength compered to low volume percentage. Therefore, in this case, the HyFRC with lower volume fraction of fibers than volume fraction steel fiber in SFRC has less compressive strength.

3. From the flexural test results, it has been concluded that the type and volume percentage of fiber have direct effect on MOR. Because in presence of fiber which is stronger result in improving the first crack strength. On the other hand, fibers with small size has better function in controlling the crack growth. Therefore, the HyFRC include 0.825% fiber volume fraction has highest MOR which is because of inclusion of steel fiber which is strong and inclusion of polypropylene which is

small. Therefore, in case of hybrid matrix, it can be concluded that the obtained results are sensitive, not only to amount of fiber, but also types of fiber used for reinforcing the composites.

4. According to the test results, it is obvious that the main properties influencing toughness and maximum loading of FRC are based on the type of fibers used, volume percent of the fiber. So regarding volume fraction, SFRC with higher fiber volume fraction comrade to PPFRC has highest toughness index. Among HyFRC, concurrent presence of steel fiber and polypropylene fiber with 0.825% volume fraction has highest toughness index compared to all mixtures.

5. The results show that the fiber addition increases impact resistance in all FRCs. Irrespective to fiber content, increasing of fiber amount result in growth rate of impact resistance. In high volume percentage of steel fiber, the high impact resistance result from the high elastic modulus and tensile strength of steel fiber. Moreover, fiber length is another reason for increasing the impact resistance of FRC. So among single type fiber, SFRC concrete regarding to fiber properties and high volume percentage of fiber has better performance for reinforcing the concrete. Likewise, HyFRC with highest fiber volume fraction (0.825%) has higher impact resistance value compared to other HyFRCs.

REFERENCES

[1] Bentur, A. and S. Mindess, Fibre reinforced cementitious composites. 2005, England: Taylor & Francis e-Library.

[2] Yurtseven, A.E., Determination of Mechanical Properties of Hybrid Fiber Reinforced Concrete, in Natural and Applied Sciences 2004, Middle East Technical University.

[3] Potyrała, P.B., Use of Fiber Reinforced Polymer Composites in Bridge Construction. State of the Art in Hybrid and All Composite Structures, in Enginyeria de la Construcció. 2011, politecnica de catalunya.

[4] Banthia, N. and M. Pigeon, Load Relaxation in Steel Fibers Embedded in Cementitious Matrices. November 1989, Journal of Cement Composites: UK.

[5] Roumaldi, J.P. and G.B. Batson, Mechanics of Crack Arrest in Concrete. 1963, Journal of Engineering Mechanics. p. 89: 147-168.

[6] Commitee, A., State-of-the-Art Report on Fiber Reinforced Concrete (ACI 544.1R-96). 2001: American Concrete Institute.

[7] Shah, S.P., et al., Guide for Specifying, Proportioning, Mixing, Placing, and Finishing Steel Fiber-Reinforced Concrete Aci Materials Journal, 1993. **90**(1): p. 94-101.

[8] Hsie, M., C. Tu, and P.S. Song, Mechanical properties of polypropylene hybrid fiber-reinforced concrete. Materials Science and Engineering a-Structural Materials Properties Microstructure and Processing, 2008. **494**(1-2): p. 153-157.

[9] Yao, W., J. Li, and K. Wu, Mechanical properties of hybrid fiber-reinforced concrete at low fiber volume fraction. Cement and Concrete Research, 2003. **33**(1): p. 27-30.

[10] Granju, J.L. and S.U. Balouch, Corrosion of steel fibre reinforced concrete from the cracks. Cement and Concrete Research, 2005. **35**(3): p. 572-577.

[11] Qian, C.X. and P. Stroeven, Development of hybrid polypropylene-steel fibre-reinforced concrete. Cement and Concrete Research, 2000. **30**(1): p. 63-69.

[12] Priti, A.P., K.D. Dr. Atul, and A.D. Dr. Jatin, Evaluation of engineering properties for polypropylene fiber reinforcement concrete. 2012, International Journal of Advanced Engineering Technology.

[13] Selvi, M.T., Studies on the Properties of Steel and Polypropylene Fiber Reinforced Concrete without any Admixture July 2013, International Journal of Engineering and Innovative Technology.

[14] Pu, W., et al., Performances of Hybrid Fiber Reinforced Concrete with Steel Fibers and Polypropylene Fibers. 2012, Civil Engineering and Urban Planning, ASCE.

[15] Bagherzadeh, R., A.H. Sadeghi, and M. Latifi, Utilizing polypropylene fibers to improve physical and mechanical properties of concrete. Textile Research Journal, 2012. **82**(1): p. 88-96.

[16] Bing, C. and J.Y. Liu, Residual strength of hybrid-fiber-reinforced high-strength concrete after exposure to high temperatures. Cement and Concrete Research, 2004. **34**(6): p. 1065-1069.

[17] Aydin, A.C., Self compact ability of high volume hybrid fiber reinforced concrete. 2007, J. Construction and Building Materials.

[18] Na Jin, B.E., Fly Ash Applicability in Previous Concrete, in Civil Engineering. 2010, Ohio State University.

[19] Wanielista, M. and M. Chopra, Performance assessment of Portland cement previous pavement. 2007: university of central Florida.

[20] Jamkar, S.S. and C.B.K. Rao, Index of Aggregate Particle Shape and Texture of coarse aggregate as a parameter for concrete mix proportioning. Cement and Concrete Research, 2004. **34**(11): p. 2021-2027.

[21] ASTM, Standard Specification for Concrete Aggregates in C33/C33M. 2013, American Society for Testing and Materials: United Sate.

[22] ASTM, Standard Specification for Chemical Admixtures for Concrete, in C494/C494M. 2013, American Society for Testing and Materials: United State.

[23] Eren, O. and K. Marar, Effects of limestone crusher dust and steel fibers on concrete. Construction and Building Materials, 2009. **23**(2): p. 981-988.

[24] BS, "Compressive strength of test specimens", in British Standards Institution, EN 12350-Part 3. 2009: British Standards Institution.

[25] Neville, A.M. and J.J. Brooks, Concrete Technology. 1987, Longman Scientific & Technical, Longman group UK Limited.

[26] BS, "Testing fresh concrete-Slump Test", in British Standards Institution, EN 12350-Part 2. 2009, British Standards Institution: London, 2000.

[27] BS, "Testing fresh concrete-VebeTest", in British Standards Institution, EN 12350-Part 3. 2009, British Standards Institution: London, 2000.

[28] ASTM, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete in C1609/C1609M. 2014, American Society for Testing and Materials: United States.

[29] SF-4, J., Method of test for flexural strength and flexural toughness of fiberreinforced concrete. 1984: Japan Society of Civil Engineers. p. pp. 58–66.

[30] Eren, O., K. Marar, and T. Celik, Effects of silica fume and steel fibers on some mechanical properties of high-strength fiber-reinforced concrete. Journal of Testing and Evaluation, 1999. **27**(6): p. 380-387.

[31] BS, Methods for Determination of Aggregate Impact Value, in British Standards Institution, EN 812-Part 112. 1997: British Standards Institution.

[32] Eren, Ö., Various Properties of High Strength Fiber Reinforced Concrete, in Civil Engineering Department. 1999, Eastern Mediterranean University.

[33] Materials, A.S.o.T.a., Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates, in ASTM C136 − 06. 2006.

[34] MALISCH, W.R., Polypropylene fibers in concrete

[35] Eren, O. and T. Celik, Effect of silica fume and steel fibers on some properties of high-strength concrete. Construction and Building Materials, 1997. **11**(7-8): p. 373-382.