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M.Sc. in Civil Engineering
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INVESTIGATION OF DUCTILITY BEHAVIOR OF PVA FIBRE REINFORCED BEAMS

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IN

CIVIL ENGINEERING

BY

MUKHTAR HAMID ABED

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Investigation of Ductility Behavior of PVA Fiber Reinforced Beams

M.Sc. Thesis

in

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Supervisor

Assoc. Prof. Dr Nildem Tayşi

By

Mukhtar Hamid ABED

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Mukhtar Hamid ABED

ABSTRACT

INVESTIGATION OF DUCTILITY BEHAVIOR OF PVA FIBER REINFORCED BEAMS

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Polyvinyl Engineered Cementations Composites (PVA-ECC), had been extensively investigated by many researchers. However, adding PVA to the normal concrete has not been much investigate the mechanical and structural characteristics in concrete beams. This research aimed to investigate the mechanical properties of the fibrous concrete reinforced with conventional reinforcement. The tested parameter was the volume fraction of the fiber (V_f %), and reinforcement ratio (ρ) on the conventional concrete beam. To achieve this aim, a set of experiments were carried out. Concrete mixes containing different PVA fiber volume fractions ranging between 0.5 % and 1.5 % with different conventional reinforcement ratio ranging from 0.5 % to 1.0 % were prepared and tested. Material tests are done for compressive strength (f'_c), tensile strength (f_{sp}) and modulus of elasticity of fiber reinforced concretes. And also beams are tested under 4-point monotonic test, to assess their structural behaviors. The results showed that the PVA fibers is significantly enhanced the compressive strength up to 44 % and improved the beam ultimate strength up to 10 %. Moreover, the inclusion of PVA increases the beam ductility factor up to 130 %. These improvements also affect the initiations of the first crack and its depth in the tension zone, where the load resistance of the compression zone is increased with increasing the fiber percentages.

Key Words: PVA fiber reinforced concrete, ductility of fiber reinforced beams.

ÖZET

ELYAFLI BETONARME KİRİŞLERİN SÜNEKLİĞİNİN İNCELENMESİ

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PVA elyaf takviyeli mühendislik özellikleri geliştirilmiş çimento bazlı kompozitlerin malzeme özellikleri üzerine bugüne kadar birçok araştırma yapılmıştır, fakat mekanik ve yapısal özellikleri pek fazla araştırılmamıştır. Bu çalışmanın amacı, PVA hacim fraksiyonunun (V_f %) ve donatı takviye oranının (ρ) geleneksel betonun mekanik ve yapısal özelliklerine katkısını deneysel olarak incelemektir. Bu amaca ulaşabilmek için bir dizi deney yapılmıştır. % 0.5 ila % 1.0 arasında değişen geleneksel donatı oranı ile % 0.5 ila % 1.5 aralığında değişen farklı PVA lif hacim fraksiyonlarını içeren beton karışımları hazırlanmış ve test edilmiştir. Lif takviyeli betonların basınç dayanımları (f 'c), gerilme mukavemeti (fsp) ve elastisite modülü için malzeme testleri yapılmıştır. Ayrıca bu kirişlerin yapısal özelliklerini değerlendirmek için 4 nokta testi yapılmıştır. Sonuçlar, PVA elyaflarının basınç mukavemetini belirgin bir şekilde % 44'e kadar arttırdığını, bunun sonucunda da kirişin nihai dayanımının % 10'a kadar arttırdığını göstermektedir. Bunlara ek olarak, PVA'nın dahil edilmesi, kiriş süneklik faktörünü % 130'a kadar arttırmaktadır. Bahsedilen iyileştirmeler, elyaf yüzdelerinin artmasıyla çekmedeki ilk çatlağın başlama yükünü arttırıp çatlak derinliğini azaltırken sıkışma bölgesinin yük direncini de arttırmaktadır.

Anahtar Kelimeler: PVA lif takviyeli beton, lif takviyeli kirişlerin sünekliği.

To My Parents, I am grateful to God for having parents like you. Your unconditional love and support made my every achievement possible.

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LIST OF SYMBOLS/ABBREVIATIONS

A_s	cross-sectional area of reinforcement
ASTM	American Society for Testing and Materials
ACI	American Concrete Institute
A_{sc}	cross-sectional area of compressive reinforcement
A_{st}	cross-sectional area of longitudinal tensile reinforcement
A_{st}	cross-sectional area of longitudinal tensile reinforcement
E_c	Modulus of elasticity for concrete
LWC	Light Weight Concrete
LVDT	Linear Variable Displacement Transducers
RC	Reinforced Concrete
FRC	Fiber Reinforced Concrete
b	width of a rectangular cross-section
HSC	High Strength Concrete
NSC	Normal Strength Concrete

FR	Fiber Reinforcement
NFRC	Natural Fiber Reinforced Concrete
SNFRC	Synthetic Fiber Reinforced Concrete
SFRC	Steel Fiber Reinforced Concrete
HSC	High Strength Concrete
$^{l_f}/_{d_f}$	Aspect ratio of fiber
f'_c	compressive strength of concrete
V_f	Fiber volume fraction
f_{ct} , f_{sp}	Tensile strength for concrete
f_y	Yield stress of steel
δ	Displacement
δ_u	Deflection at ultimate
δ_y	Deflection at yielding
δ_{pcr}	Deflection at first crack
P_y	Yield load
P_u	Ultimate load
ρ	Reinforcement ratio
ρ_s	longitudinal tension reinforcement ratio (Ast/bd)
d	Effective depth
μ	Ductility factor

CHAPTER 1

INTRODUCTION

1.1 General

Concrete is characterized by its brittle behavior, low tensile strength; however, concrete has high compressive strength, thus, shows no post peak behavior. In fact, many catastrophic failures and deteriorations catastrophic failures without a noticeable warning in the concrete structure because of the brittle nature of these materials [1]. There is a large need to strengthen concrete structures around the world and there can be many reasons for strengthening. The deficiencies are usually the results of deterioration caused by exposure and age to the adverse environment, weightier traffic brought about by a functional change or growing society such as higher required permit load. As a result, a large number of concrete highway bridges need replacement or rehabilitation.

An approach introduced to enhance the post peak behavior and ductile performance of concrete is using fibers as intrinsic reinforcement. The use of short fibers randomly distributed to improve the physical properties of concrete or other brittle materials is an old concept. The straw-reinforced mud brick was used in the middle east about 10000 years ago. In 1400 BC, straw-reinforced grilled bricks were used to build a 57-meter-high hill near of Aqar Quf near Baghdad [2].

Native people also used mud bricks (a mixture of clay , sand, and straw) for a long time in the Americas, particularly in Southwest America and in parts of South America [3]. In 1900s the construction industry are pointed as a first using the fibers as asbestos cement. Moreover, the Fiber Reinforced Concrete (FRC) had conducted for academic research in many countries as a good option for improving the ductility of the concrete. The researches on the fibers was continued in the early of 1970s, particularly on, glass and steel fiber [4].

In the mid-1980s, several geometry and type of fiber have been produced, which produced in many technic to enhance the toughness of the FRC and the peak load resistance due to controlling the cracks [5]. As per the terms adopted by the American Concrete Institute (ACI) Committee 544, Fiber Reinforced Concrete, there are four classes of FRC based on fiber material typ. These are SFRC, for steel fiber, GFRC, for glass fiber, SNFRC, for synthetic fiber, including carbon fibers; and NFRC, for natural fiber. From amongst the several kinds of synthetic fibers used in SNFRCs and cementations composites PVA fiber is a comparatively new inclusion. the high mechanical properties of the mentioned fiber such as the tensile strength that ranging between 0.9 and 1.6 GPA, moreover, the high modulus of elasticity that ranging between 23 and 40 GPA, are characterized the modern synthetic fibers. Also the hydrophilic surface give an advantages in the chemically bond with the cementation material [6]. The high tensile strength of the PVA and the well bonding cement matrix lead to the controlling the initiation the cracks. Moreover, uniformly transferring the stresses between the two edges of the cracks.

1.2 Ductility Significance

The essential principles behind good reinforced concrete design are:

1) Beams must be weaker than the columns.

2) The failure have to be ductile rather than brittle.

3) Preventing the early joint failure.

4) The ductile failure come from flexural failure, while the brittle failure come from shear.

The aim of the mentioned rules is to construct and design a structure with proper energy absorption areas within the structure to withstand the overload. Finally, ductile failure is required in order to avoid the series of following failure that causes a catastrophic collapse. Therefore, all the code of practice perceives the significance of ductility in the design. In the same manner, the ductile behavior of the structure allows to resist large plastic distortions with a slight decay in strength. Basis on premises, the main reason for the preferring the ductility is to construct a structure to that can resist the imposed load while the overload is experienced. Whereas the structure response is the main representing the overload case, rather than the single beam the ability to deform plastically. It is through the development of reinforced FRC beam, which displays these properties that the "ductile" rub enhancement beam has been developed. This study will examine the underlying philosophy behind the creation of a beam and demonstrate the results of first attempts to enhance the ductile.

The ability of the body to undergo the deformation and without decreasing the section flexural resistance can be termed as ductility [7]. In addition, the ductility can be defined in expression of energy or deformation. In the case of steel reinforced beams, where there is clear plastic distortion of steel at yield, elasticity can be calculated utilize deformity methods. It may be defined as the ratio of ultimate deformation to the deformation at yield. The deformations can be deflections, strains, or curvatures. In the case of FRC beams, where there is a clear plastic deformation of the steel in yield, the ductility can be calculated using deformation methods. It may be defined as the ratio of ultimate deformation to the deformation at yield. The deformations can be strains, deflections, or curvatures.

Ductility of reinforced structures is a desirable property where resistance to brittle failure during bending to ensure structural integrity [8]. Thus, it may be considered a criterion for determining feasible ranges of reinforcement percentages, between some minimum and maximum or balanced values. However, although reinforcement limitations are related to flexural ductility, they are not its direct expression or quantitative measure, but only reflect minimum ductility requirements implied by standard codes. Flexural ductility is a fundamental property of structural concrete sections [9], and it is an important property for seismic design. Several researchers have investigated the use of FRC to increase the flexural strength of concrete beams. This study aims to illustrate the ductility behavior of the concrete beams with fiber in flexural modes.

1.3 Research Objectives and Plan

In spite of that, many researches can be found in the literature on the effect of the fiber with cementations materials; however, there are a few researches are conducted on the structural behavior PVA fiber reinforced concrete (PVA-FRC). Most of the researches are concentrated on the ECC materials made from PVA. Therefore, the current research is aimed pay more attention to the PVA as a fiber to reinforcing the concrete. These include investigation the material mechanical properties and beam structural behavior. Accordingly, PVA fibers of same geometry and of length (12 mm) was selected to be investigated in order to evaluate their effect on hardened properties of concrete and concrete beam elements. Experimental investigations are categorized into two stages. Stage one can be referred to as “Material Testing” which mainly focuses on the mechanical properties of FRC. In this phase, FRCs with 12 mm fibers and volume fractions ranging from 0.5 % to 1.5 % are investigated to find out the optimum fiber content with regards to compressive strength, and tensile strength. Selected mix designs of previous investigations (material testing) are studied in second stage, which is categorized as “Structural Testing”. In this section, structural properties and behavior of PVA-FRC beams were assessed under the action of both monotonic. Herein, flexural capacities and ductility of different FRC beams are compared with Conventional Reinforced Concrete (CRC) beams.

1.4 Organization of the Thesis

This thesis is divided into five chapters include introduction. Some background information regarding FRC and its applications. The objectives of the research following some of the terminologies and concepts used in the thesis are summarized in Chapter 2. A review of previous investigations on RC beams reinforced with fibers is also covered within this chapter.

Chapter 3 introduce the analysis method used in the current work, and the materials properties that used in the laboratory work.

In Chapter 4 content results that obtained from previous chapter are discussed, materials and structural results were presented. The hardened properties (e.g. compressive, tensile and modulus of elasticity) of conventional and fiber reinforced concrete samples and structural testing results (4-point monotonic flexural tests on concrete beams) are discussed in details.

Finally, Chapter 5 is listed the conclusions obtained from the previous chapters.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this study, the concept of (FRC) and the function of fibers in a cement-based matrix are comprehensively explained. Different classes of fibers and their effect on structural and mechanical properties of concrete and cementations composite are broadly investigated. In addition, PVA fiber characteristics are introduced and the effect of this fiber on structural and mechanical properties of concrete and cementations composite is described in details.

2.2 Fiber Reinforced Concrete

The mechanical behavior of a structure is greatly affected by the constituent materials utilized. Based on tensile load-deformation response, most engineering materials can be classified into three groups; quasi-brittle, brittle and ductile (without or with strain-hardening) as illustrated in Figure 2.1.

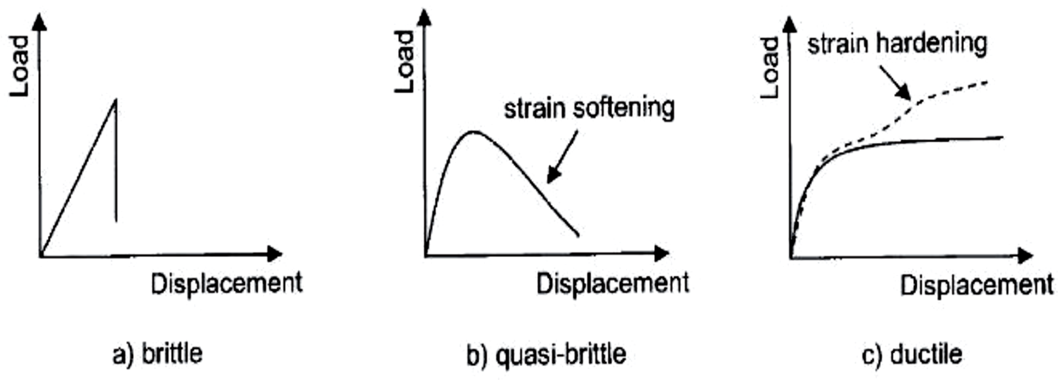


Figure 2.1 Three kinds of failure modes observed in materials [10]

Brittle failure can be observed that in hardened cement material[11]. Studied this type of failure, as shown in Figure 2.1, is described as a linear load-deflection curve followed by a drop in load at first cracking with an ultimate tensile strain in the order mentioned by 0.01 %. Quasi-brittle failure can be observed that in concrete and most Fiber Reinforced (FR) cementations composites, which is described as a linear stress-strain curve followed with a softening tail after first cracking. The quality of the softening part depends upon the matrix components. This softening mostly happens during bridging action of cement ligaments, aggregates and/or fibers. As graphically shown in Figure 2.2, conventional concrete, avoiding fiber, demonstrates limited strain softening behavior after peak load, however, a proper softening with an acceptable ductility can be observed in the case of FRC depending on fiber type and volume fraction. Ductile Strain-hardening materials (Figure 1- c), on the other hand, are capable of maintaining increasing levels of loading after first crack happens while undergoing large deformation [11]. This behavior can only be carried out by means of special matrix composition, appropriate fiber type and mostly high fiber volume fraction.

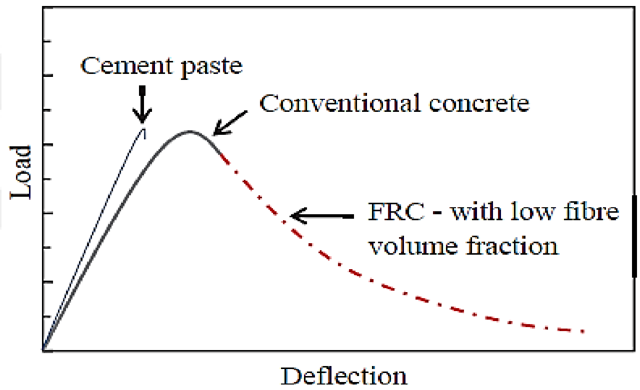


Figure 2.2 Schematic failure modes for concrete, cement and low fiber volume fraction fiber reinforced concrete

Accordingly, it can be said that fibers are added into a brittle-matrix composite to assist improve three main aspects, namely; strength, toughness and ductility (tensile) [12]. In addition to the improving the strength resistance, the main structural function of the fiber is to enhance the toughness of the members, this can be done by applying bridge like behavior between the two edges of the cracks, moreover, the energy absorbing is the other main improved parameter due to fiber pullout this will lead to initiate multiple cracking.

Fibers in a low volume fraction do not avail any structural function and are often used for plastic shrinkage crack control. The volume of moderate fiber is part of the FRCs, material that can be found in both cast-in-place and pre-cast structural members. These types of FRCs are characterized by improved fracture toughness, Modulus of Rupture (MOR), impact load resistance, fatigue resistance and other desirable mechanical properties [4]. Fiber in such FRCs secondary compounds is often considered secondary reinforcement used in combination with the main reinforcing steel. Many successful investigations have been reported for partial replacement of shear steel reinforcement [13], [15] and for crack width control [16], [17]. In recent years, new techniques have been successfully introduced in order to place large amounts of fibers into bulk structures such as beams, columns and joints. High fiber volume FRCs have demonstrated excellent strength properties, fracture toughness, and sometimes even appear to exhibit strain-hardening behavior. Due to the significant improvement in mechanical properties, these materials often share primary importance with the main reinforcements in a given structural member. Despite their high performance, when higher fiber volume fractions are used, wider applications of FRC might be hampered by special processing requirements. This concern often restricts the use of this material to precast members. Other important related concerns are the high cost and weight associated with high fiber volume fractions. These materials are usually restricted to steel fiber type.

Figure 2.3 is summarized the commercial produced fibers that adopted by ACI, according to the percentages of the fiber used. It is seen that the application, including three main percentages this is low which is less than 0.5 %, moderate percentages that ranging between 0.5 % to 5 %, and high amount percentages that is more than 5 %. It is worthy to mention herein that the fiber content less than 0.5 % are preferable to use in batch mix. While, higher percentages are utilized, more complicated or special mixing and placing techniques should be explored.

Nowadays, the mixing methods and placing process are, mixing the concrete as a batch, extrusion (through a stationary die), slip forming (moving-form extrusion), infiltrate slurry, and sheet using a pressure as a vacuum. Regards the production method, there are no limit constraint the geometry and the percentages of the fiber.

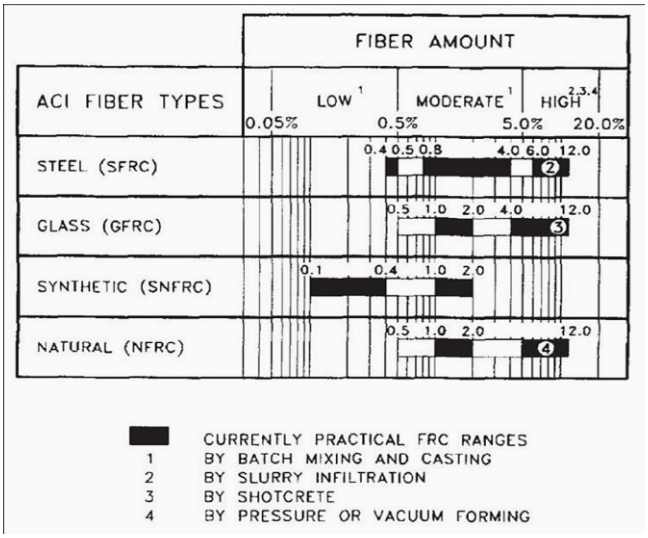


Figure 2.3 Fiber kinds and amount used by volume percent of matrix [5]

Nonetheless it is now well-known that composite properties rely upon three gatherings of constituent properties; the fiber, matrix and interface properties [11]. Fiber/matrix interaction plays an important role in controlling the material engineering properties and energy absorption capacities. Include many types of fiber / matrix interactions; the deboning interface, sliding friction, and tilt angle effects associated with random fiber orientations are also present, resulting in energy absorption in the fiber bridging zone of an FRC [18]. though the amount of energy related with each mechanism for a single fiber may not be considerably high, the large number of fibers bridging over an extended length can dramatically help with improving the toughness of the composite [19]. Figure 2.4, illustrates the mechanism of the activity of the fibers to control crack and the ability of the growth in energy absorbing. From left to right along the crack, the mechanism can be categorized as; fiber cutting, fiber slipping, fiber stress transforming through bridging activity, and deboning at the fiber/matrix interface, respectively.

Where bridging zone ends, fibers tend to being pulled out of the matrix, which is a type of polymer and steel fiber reinforced concrete. For compounds that contain brittle fibers like carbon, the end of the binding zone is connected with the fiber rupture. Fiber deboning involves the failure and breakdown of the material in the Interfacial Transition Zone (ITZ) due to interfacial shear created from the pulling out mechanism of a fiber bridging a crack [19] .

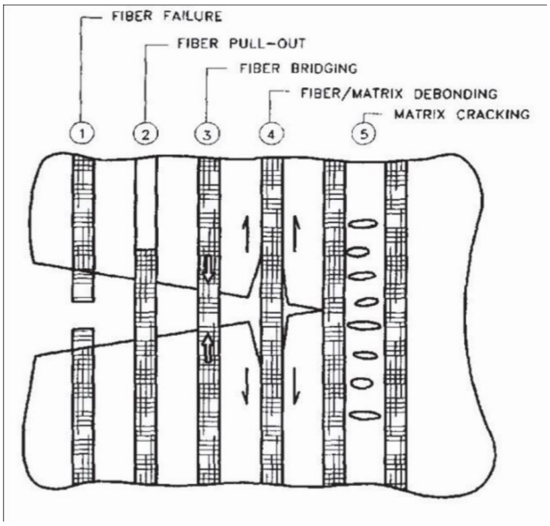
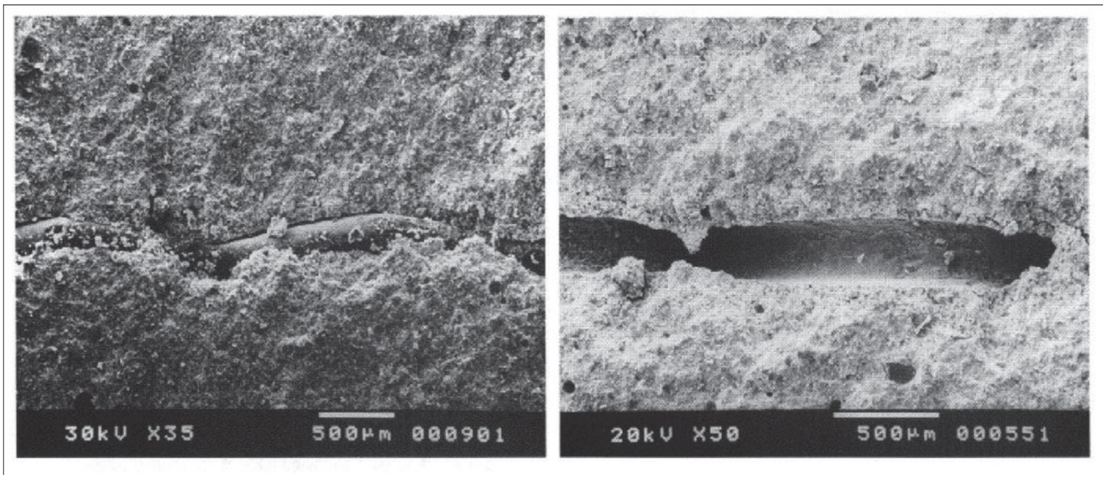


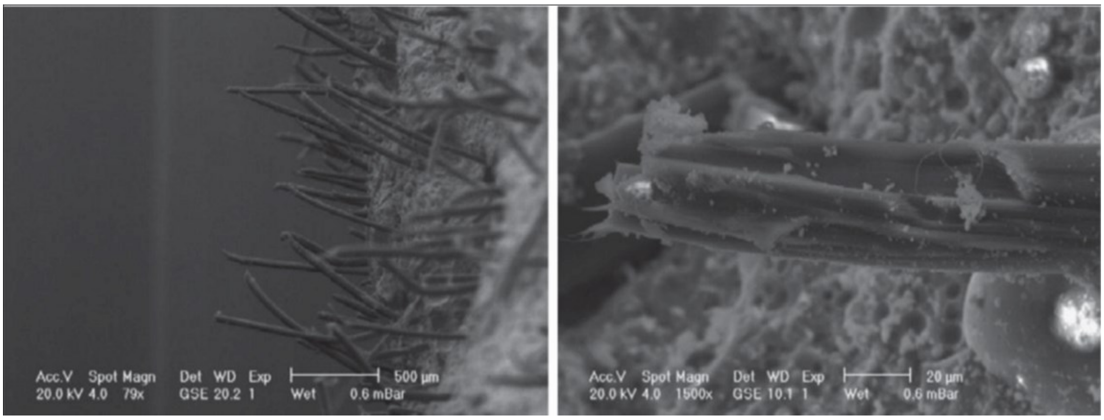
Figure 2.4 Energy-absorbing fiber/matrix mechanisms [20]

Commonly, fiber pull-out rather than rupture provides a larger ductility to the fiber reinforced composites [21], [22] . It is most desired to have composites showing strain-hardening behavior, which can be achieved through multiple cracking of reinforced matrix [23] Figure 2.5 and Figure 2.6 show some Scanning Electron Microscope (SEM) images of fiber rupture, and fiber pull-out. Figure 2.5 demonstrates the structure of a fiber in a cementations matrix before fiber is pulled-out and the remained groove just after the fiber pull-out.



(a) (b)

Figure 2.5 The structure of fiber in matrix: (a) fiber prior to pull-out and (b) the groove after fiber pull-out [24]



(a) (b)

Figure 2.6 (a) fiber pull-out and (b) fiber rupture [25]

Depending on the physical fiber nature of the matrix interface, different types of deboning mechanism can be observed which can be whether strength or fracture controlled. In a composite, fiber is expected to have different lengths. When crack opening is small, most of the fibers are anticipated to undergo de-bonding which results in an ascending stress-strain relationship (strain hardening). However, when the matrix of a type FRC cracks under uniaxial tension, this behavior might not be possible to be observed because the load has exceeded the maximum bridging stress when the matrix cracks. This will result in a sudden load drop with a large crack opening and descending stress-strain relationship. The strain hardening can only be captured in the case of pseudo strain hardening FRCs. This is possible because in such a compound, the material can continue to carry higher load after the first crack matrix. This stress-strain relationship can be obtained by racking the load-crack opening on one of the multiple cracks in a uniaxial tension test [19] .

The aforementioned mechanisms significantly active even in small amounts down to one fiber. The reason is that, these technics are independent on the spacing between fibers and fiber amount within the matrix and only relies on the fiber/matrix interaction. However, it is the a summation of the total numbers of fibers in the brittle FRC composite that has been shown to be significant.

Primary benefit of FRC arises from the fiber-bridging effect across matrix cracks. As soon as a crack forms or extends in the matrix, the strain in the cracked faces is zero and the crack is irresistible only by transferring stress through the fibers. This is the case if sufficient bonds or fiber anchors are provided, and there is a good chance for a fiber participation, i.e. concentration of the fiber in specific area. It should be attention that the method of placing and mixing will not negatively affect the hardness of a matrix fracture toughness. For instance, if coarse and stiff fiber is employed, the mix design should be modified concerning the size of aggregate used to minimize this effect.

As shown in Figure 2.7, two typical type of tensile stress-strain curves are available depending on fiber/matrix interaction and also fiber content. In cases where fiber volume fraction is very low or the fiber are so well bonded that majority of them break at concrete cracking, the stress-strain behavior of the matrix is similar to curve A. Whereas in presence of higher fiber volume fractions which are mostly pull-out rather than break, the resulting behavior is comparable to curve B. However, depending on the type of fiber used in the composite, the shape of this curve may vary [2].

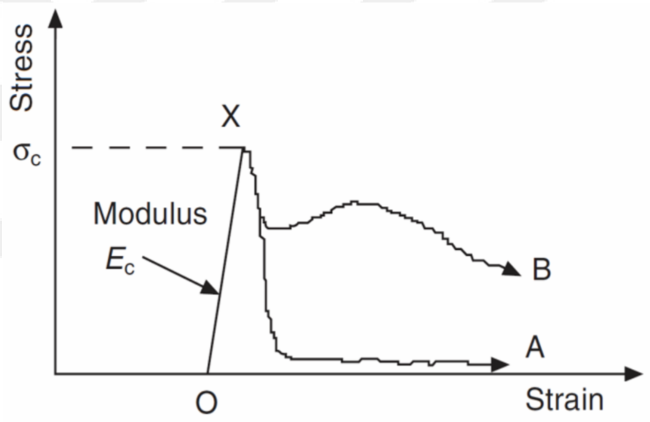


Figure 2.7 Type stress-strain curves for fiber reinforced concrete [2].

Cellulose fibers were used for at least 50 years. Furthermore, steel, glass, carbon and polymeric fibers such as polypropylene, polyethylene, and nylon fibers have been used for the past 3 decades to reinforce cementations materials[2] , [26]. These types of fibers vary considerably in properties, effectiveness and cost. Some common fibers and their typical properties are listed in Table 2.1.

Table 2.1 Typical properties of concrete versus common used fibers in concrete and cementations composites [25 , 2]

Material	Modulus of elasticity [GPa]	Tensile strength [MPa]	Failure strain [%]
Concrete	20-45	1-7	0.1-0.2
Asbestos fiber	164-196	200-3500	2.0-3.0
Cellulose fiber	10-50	300-1000	20
Steel fiber	200	700-2000	0.5-5.0
Glass fiber	70-80	600-4000	2.0-3.6
Carbon fiber	30-390	600-4000	0.5-2.4
Polypropylene fiber	3.5-10	450-760	15-25
PVA fiber	23-40	900-1600	7.0-8.0

Since the early theoretical studies of FRC in the 1960s dealt primarily with the behavior of Steel Fiber Reinforced Concrete (SFRC) it has become the most commonly used fiber in concrete. Although steel fibers are still widely used, however, it is being overtaken by synthetic fibers [26]. One possible reason is that, unlike the steel fiber which is considerably prone to corrosion When located close to the concrete surface, synthetic fibers are generally inert and have noncorrosive nature [27].

Synthetic fibers have become more popular in recent years as secondary reinforcement in cementations materials. This is due to the fact that they can provide effective and relatively inexpensive reinforcement for concrete compared to conventional fibers such as asbestos, steel and glass.

Synthetic fiber types that have been utilized in cementations matrices so far are namely; polyviny1 alcohol (PVA), acrylics (PAN), polyethylene (PE), polypropylene (PP), polyamides (PA), aramid, carbon and polyester (PES). The properties of synthetic fibers may vary broadly, especially in term of modulus of elasticity. This characteristic plays an important role when fibers are used for producing composites [28].

Synthetic fibers can be clear as a flexible, homogeneous, macroscopic body, with high aspect ratio and a small transverse section made of naturally occurring natural particles and synthetic polymers. The chemical, mechanical and physical properties of a synthetic fiber highly depends on the arrangement of the polymer chains in three-dimensional space. By improving the organization of a chain between molecules that can generally be described as high-oriented and crystalline, we are able to enhance the characteristics of this type of fibers. All fibers have a single structural advantage and a common characteristic is the differential orientation of the elemental units with respect to the fiber axis. In the case of synthetic fibers, the preferential orientation is achieved through mechanical drawing process, where the fuse is extended immediately after extrusion, to several times compare to its initial length. Drawing plays two major roles, one of which is directing the structural elements with respect to the fiber axis in order to make these elements in optimal stress-bearing positions and the other is to allow the development of three-dimensional structural regularity. Molecular compounds used to make fibers are similar to those used in plastics, but for fibers, treatment must produce an essentially infinite proportion to the diameter ratio [28].

For to increase the strength of cementations compounds, fiber must have a greater elasticity modulus than the matrix. Since the modulus of elasticity of cementations composite is ranging from nearly 15 to 45 GPa, In this case it is difficult to meet with most synthetic fibers. Therefore, to overcome this challenge, several attempts have been made to develop fiber with so high modulus of elasticity. However, both applied research and theoretical have identified that, even through the use of low modulus fibers, significant improvements can be obtained with respect to crack control, toughness, impact resistance and strain capacity of FRC. In many applications, these improved properties are much more important than a slight increase in tensile strength (flexural) [26].

The low tensile strength of concrete can be improved in some applications by adding small diameter fibers that can be synthetic fibers. Majority of current FRC applications involve the use of fibers with approximately 1% volume fraction. Fibers are commonly considered not to affect the tensile strength of the matrix and only contribute after the initiation of the cracks by bridging the cracks [28].

It is generally accepted that the inclusion of any kind of randomly distributed short fiber at practical fiber volume fractions do not significantly change the first cracking load in hardened concrete [2]. Incorporation of polymeric fibers in concrete are recognized to be most effective in controlling and mitigating susceptibility to plastic shrinkage cracking. In the role of intrinsic reinforcement, these fibers contribute to improving the ductile and damping behavior of the concrete. The main benefit of fiber addition relates to the post-cracking state of hardened concrete. It is worth to clarify the definition of the "strengthening term". If any load, bearing capacity is described as greater than zero as the reinforcement, then all fiber types in any add volume and strengthen the hardened concrete. However, if we consider “strengthening " means carrying a load greater than the load required to crack the concrete, then less than about 0.4 % the volume fraction of the fiber part will not generally enhance the concrete capacity. In fact, two or three times that fiber size needed to increase the load capacity of concrete in uniaxial tension [2].

It has been observed that fibers in concrete enhance resistance to cracking due to external load and improve energy absorption capacity or toughness of conventional concrete [29], [30]. Furthermore, the crack resistance is improved and delayed with increase in fiber content [31], [32]. Fibers can also improve the tensile strength, ductility, impact resistance, dynamic ability and durability of the concrete [33] , [34] .

Previous research has demonstrated that reinforcing concrete with micro fibers does not contribute to the first crack stress as well as the maximum stress and its corresponding strain [35]. Authors of past research studies indicate that fibers assist with increasing concrete’s volumetric strain ability after cracking by bridging cracks and, thereby, changing the post peak behavior of FRC.

Previous field and laboratory research [36] at 0.1 % of synthetic fiber and 0.5 % of steel fiber, reveal that the affection the inclusion of the fiber in the concrete is effectively act in improving the energy absorption and controlling the crack more than improving the load bearing capacity.

2.3 Polyvinyl Alcohol Fiber

PVA is adopted from poly (viny1 acetate) which is readily hydrolyzed by treating an alcoholic solution with aqueous acid or alkali [37], Bringing about the structure appeared in Figure 2.8 PVA containing hydroxyl gatherings (OH) that can shape a hydrogen bond between the molecules resulting in a significant change in the correlation strength between the matrix and the fiber PVA [38].

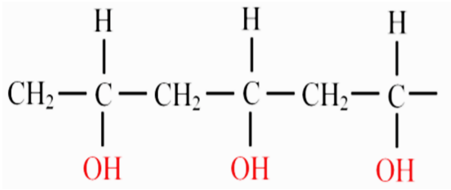


Figure 2.8 PVA fiber structure

PVA is a white powder with specific gravity ranging from 1.2 – 1.3 (1200-1300 kg/m3) [38]. This powder is then formed and extruded into a PVA fiber, which is produced commercially. Table 2 shows the most common types of PVA fiber commercially available in the market. PVA fibers mostly have aspect ratios (Lf/df) of 45 to 250 and different cut length varying from 6 to 30 mm to make fibers suitable for different applications. Depending on fiber geometry (length and diameter), the tensile strength and elastic (Young's) modulus of PVA fiber differ. It varies from 1600 to 800 MPa in the case of tensile strength and 40 to 23 GPa with respect to the elastic modulus with increase in fiber length and diameter. PVA fibers are also available in both resin bundled (oil coated) and virgin (non-coated) type.

Table 2.2 Common types PVA fiber available in the market

Length [mm]	Diameter [mm]	Tensile strength [MPa]	Modulus of elasticity [GPa]	Manufacturer
6	0.024	1600	39	Nycon Corp. - USA
6	0.027	1600	39	Kuraray Co., LTD - Japan
8	0.038	1600	40	Nycon Corp. - USA
8	0.038	1400	30	Nycon Corp. - USA
8	0.04	1600	40	Kuraray Co., LTD - Japan
8	0.04	1300	30	Kuraray Co., LTD - Japan
13	0.1	1200	25	Nycon Corp. - USA
18	0.2	1000	29	Kuraray Co., LTD - Japan
19	0.2	1000	29	Nycon Corp. - USA
30	0.66	900	23	Kuraray Co., LTD - Japan
30	0.66	800	23	Nycon Corp. - USA

PVA fiber has a rough surface. This property mechanical interlocking capability greatly improves the adhesion-related ability of these fibers in the matrix [39]. Generally, the surface structure of a fiber is very active on its performance. The smooth surfaces and highly hydrophobic are often significantly reduced by composite performance [21]. To illustrate the surface roughness differences between fibers, SEM images are captured at the same magnification of PVA fibers versus Polypropylene (PP) fiber, which has a very smooth surface structure, shown in Figure 2.9.

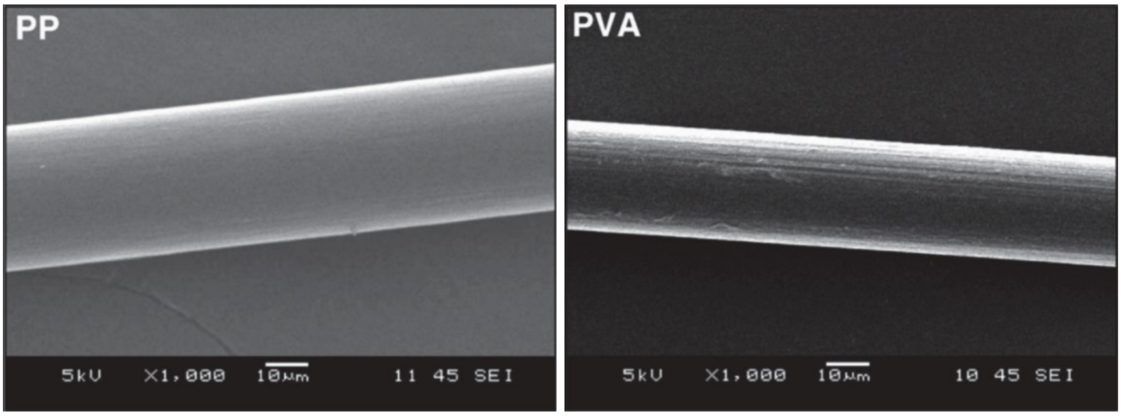


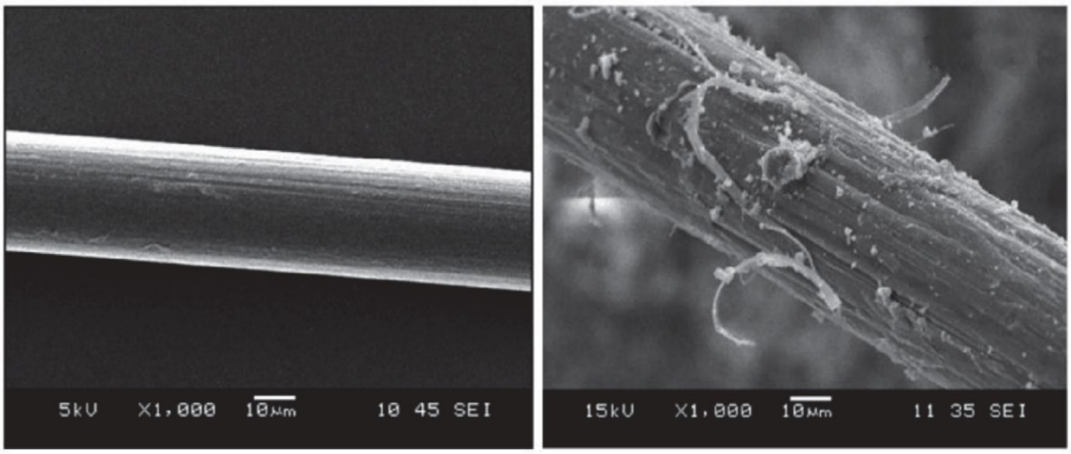
Figure 2.9 Scanning electron microscope (SEM) images of Polypropylene (PP) and PVA fibers [39] .

2.4 Mechanical Properties of PVA-FRC

The pioneering works [40] on synthetic fiber reinforced concrete and cementations composites, emphasized the need to overcome the disadvantages resulting from the weak bonding properties and the low elasticity modulus of synthetic fibers in the matrix. This modulus of elasticity is the main problem that facing the researchers because of the chemical component and the texture characteristics [26].

PVA fiber serves various advantages when utilized as a part of concrete or cementations composites. It has high aspect ratio, relatively high modulus of elasticity, high ultimate tensile strength, good affinity with water and no health risks, excellent chemical compatibility with Portland cement compounds. Since PVA fibers are mostly more solid than the concrete matrix and also provide a good bond with a cement matrix, they generally have a positive effect on bending strength and other mechanical properties of their compounds. The good interfacial bond between matrix and PVA fiber is attributed to non-circular cross-section of the fibers, and hydrogen bonds between the fibers and the cement matrix [28]. However, this very strong chemical bonding of PVA fibers with cementations materials, which is due to the presence of the hydroxyl group in PVA molecular chains, brings up a challenge. This high chemical bonding leads to the tendency of the fibers to rupture and reduces the impact of multiple cracking which results in a reduced strain hardening profiles and tensile strain capacity of the resulting compound [6]. Felekoğlu and colleagues [39] reported that, in a concrete sample containing PVA fibers subjected to flexural loading, after the maximum load, PVA fibers were ruptured, beginning from the bottom of crack plane. By using Scanning Electron Microscope (SEM) images, they have stated that hardly any elongated or slipped fibers were observed on fracture surface of the sample and fibers were mostly ruptured.

Figure 2.10 shows the surface of PVA fiber after failure. As seen, PVA fibers severely delaminate at the previous embedded ending after the extraction. This is due to the strong interfacial bond between matrix and PVA fiber. Since failure always occurs at the weakest point through which the load is transferred between the matrix and the fiber, in which case the failure is converted to the fiber at the proximity of the interface, the strength of the matrix fiber bond is greater than the fiber shear strength [41]. For this reason, the PVA fibers usually rupture without elongation (they maintain the primary diameters) or the fiber surface gets too damaged if the slip occurs rarely [39].



(a) (b)

Figure 2.10 microscope viewing (SEM) images of PVA fibers surface; (a) original fiber (b) after failure [39].

Reducing the “chemical bond between PVA fiber and matrix enhances the complementary energy [42] by minimizing premature fiber breaking during the fiber/matrix interface deboning process, prior to fiber slippage. Decreasing the interfacial frictional bond strength within a certain limit at the beginning of fiber slippage process can also facilitate fiber pull-out which results in even further energy absorption [6]. In order to reduce the frictional bond, an oiling agent may be applied to the surface of PVA fibers. An oiling agent makes PVA fibers more hydrophobic and allow them to slip-out more easily and minimize the rupture in composite [6]. This way, fiber slipping from the matrix and slip hardening response during fiber pull-out might be obtained. This increase in displacement capacity results in a formation of a higher area under the load–displacement curve and enhances the composite toughness[39], [43], [6].

ECC is a mortar-based composite reinforced with specially selected short random fibers invented in the early 1990's. ECC is a class of ultra-ductile fiber reinforced cementations composites. Unlike conventional concrete, ECC has a strain capacity in the range of 3 - 7 %, which is hundred times more than that of concrete. In terms of matrix component, it is very similar to normal concrete, except it does not include coarse aggregate [44].

PVA-ECC shows a strain hardening behavior with average strain at peak stress of approximately 5 - 6 % [43]. A successful strain-hardening performance in PVA-ECC has been reported using PVA fibers of 12.7 mm length and 0.048 mm diameter [45]. PVA fiber is likely to rupture rather than being pulled out in a cementations matrix, as a result of the strong chemical bonding with cement due to the presence of the hydroxyl group in their molecular chains [46]. Therefore, the surface of the PVA fibers is coated with the proprietary hydrophobic lubrication factor of 1.2% of the mass. This treatment helps with increasing the interfacial properties between fiber and matrix for ECC strain-hardening performance [47].

In a previous study [47] on PVA-ECC, it has been reported that the compressive strength of ECC is improved by adding PVA fibers to the mix. In addition, an acceptable freeze–thaw resistance (according to ASTM C666, Procedure A) has also been recorded.

According to isotropic mechanical properties of PVA-ECC which results in a ductile material with high energy absorption capacity (toughness) and tensile strength and high flexural leading to a significant impact on structural response, Li [11] states that PVA-ECC has the potential to be used in applications such as joints seismic retrofits, structures subjected to dynamic and impact loads (e.g. bridge, decks pavements) and concrete covers for durability.

Betterman and colleagues [48] studied tensile properties of PVA fiber reinforced mortar. In their investigation, specimens reinforced with varying volume fractions (V_f

= 1 %, 2 % and 4 %) of different-sized (L_f = 4, 7 and 12 mm) fibers were tested in direct tension. The diameter of fibers varied (d_f = 0.012, 0.024 and 0.041 mm) so that each fiber length had an approximate aspect ratio of 300. Experimental results indicate that the first peak stress increases with an increase in the fiber size fraction as well as a decrease in fiber diameter to the fixed ratio of the fiber aspect ratio. On the other hand, the toughness increases with an increase in fiber volume fraction as well as an increase in fiber diameter.

PVA fiber has also been used in self-compacting micro-concrete composite. In a study carried out by Felekoğlu et al. [39], 1 % by volume of 8 mm length PVA fibers with diameter of 0.030 mm (aspect ratio = 267) were added to a micro concrete composite containing; Portland cement, fly ash and limestone powder as micro-aggregate. Results conclude that the flexural strength and toughness of micro concrete significantly improves by incorporation of PVA fibers. The rate of improvement in flexural strength is in the range of 100 %.

PVA has also been used in high performance lightweight concrete. Arisoy and Wu [49] investigated the effect of adding 1.5 % volume fraction of PVA fiber (L_f = 15 mm, d_f = 0.037, E_f = 40 GPa) on a lightweight concrete matrix containing; Portland cement, fly ash, silica fume, lightweight aggregates, regular sand, air entraining agents and super plasticizer. Results of the experiments showed that lightweight concrete exhibits higher flexural strength, ductility and also strain hardening behavior by adding 1.5 % volume fraction of PVA fiber.

Limited research has also been carried out to date to investigate the effect of adding PVA fiber to a concrete matrix. Researchers [50] have reported that the use of PVA fibers in concrete affect the fresh properties of concrete demonstrating a decrease in the workability of the mix. Comparing 6mm length PVA fiber in two different diameters, 16 and 40 μm, Bangi and Horiguchi observed that the air content remained constant at 1.7 % for both mixes whereas slump decreased significantly from 209 to 49 mm with an increase in fiber diameter [50]. Fibers with smaller diameter showed 115 % higher compressive strength than other fiber sizes and both PVA concrete mixes demonstrated lower air content (AC) and compressive strength compared to control concrete. These results are also supported by Li and Yang [51], [52].

Furthermore, from previous experimental research carried out on PVA reinforced mortar fibers comprising 30 % styrene butadiene and latex polymer [53], , it was reported that compressive strength and indirect tensile strength increased from 35 MPa to 45 MPa and 4.0 MPa to 4.6 MPa for mixtures which Contains fiber volume fraction of 2 %, 3 %, 4 %", respectively.

In a recently completed research [54], using 6 mm length PVA fiber in a concrete matrix with a mix proportion, it has been reported that although the concrete compressive strength was not considerably affected by adding PVA fiber, the crack resistance and flexural properties of concrete and, to some degree, its toughness increased.

In an investigation Ong et al, [27] on PVA-FRC slabs subjected to low velocity projectile impact, it has been concluded that slabs reinforced with 12 mm length PVA fibers of three different fiber volume fraction (0.5 %, 1 % and 2 %) exhibited higher fracture energy values compared to the conventional concrete. A comparison of failure pattern of PVA-FRC slabs showed that as the fiber content increased, the number of cracks and the size of the failure zone decreased. It was also observed that fibers have been failed due to pull-out at the fracture zone.

In a study carried out by Bangi and Horiguchi [50], it was generally observed that addition of synthetic fibers reduced the workability of concrete which may have been caused by intertwining of the fibers during mixing which results in a lower slump. Furthermore, a reduction in compressive strength and an increase in tensile strength have been recorded. It is also noticeable that with the same fiber length (6 mm), PVA fibers of greater diameter (0.040 mm) reduce the concrete workability and compressive strength more than that of smaller diameter (0.016 mm) fibers.

An investigation Sun et al, [55] on shrinkage and water permeation of concrete (matrix ingredients; PC, silica fume, river sand, crushed debase stone with continuous grading of 5 – 15 mm and W/C = 0.32) containing different types of fibers, including PVA fiber of 8 mm length, 0.015 mm diameter with tensile strength of 1200 MPa and Young's modulus of 26-28 GPa, showed that a hybrid of PVA and steel fiber significantly reduce the shrinkage of concrete. It was also observed that when the volume fraction of fiber was kept constant, the effect of fiber on drying shrinkage depended on the elastic modulus of fiber besides its size and volume fraction. Fibers with higher elastic modulus in a relatively high volume fraction (1.5 %) are the most effective to reduce the concrete shrinkage strains.

It is reported by Flores-Johnson and Li [56] that the compressive strength, tensile strength and integrity of foamed concrete was considerably increased by reinforcing matrix with 3 % volume fraction of 8 mm length PVA fibers (d_f = 0.04 mm, tensile strength = 1600 MPa, E_f = 40 GPa). It is notable that foam concrete is an ideal core material for composite sandwich structures. This material is a type of cellular solid composed of cement mortar matrix and air-void of minimum 20 % in volume, which is manufactured by incorporating air-voids into the cement matrix using preformed foam.

In a study Corinaldesi and Moriconi [57] performed on self-compacting concrete (SCC) reinforced with PVA fibers (L_f = 12 mm, d_f = 0.2, tensile strength = 1000 MPa, E_f = 30 GPa), has revealed that compressive strength at 28 days of SCC increases by adding PVA fiber to the mix. On the other hand, results show that the flexural strength of the concrete decreased with inclusion of PVA fibers. It has also been reported that the modulus of elasticity of concrete seems not to be noticeably affected by fiber additions, although a very small reduction is observed for PVA-SCC. In the case of concrete drying shrinkage, PVA-SCC showed higher drying shrinkage values compared to the reference concrete at the first 3 weeks of age, however, after 21 days of age the reverse is true. PVA-SCC showed 25 % lower drying shrinkage at 180 days of age.

2.5 Structural Properties of FRC Beams

The main weaknesses of concrete as a structural material are the low tensile strength and Brittleness. The addition of fiber may greatly enhance the mechanical properties of concrete such as the carrying load bearing capacity of the residual carrier (toughness) and ductility [58].

It is worth mentioning that the ductility has advantages but the most important feature of the dominant safety in the structure because it provide an indication on the resistance of the structural element to with keeping the maximum strength. Ductility, commonly used to delay the local failure of structures that are not fixed by allowing the redistribution of stresses from one critical division to other [59].

Adding fiber to the conventional concrete materials, is enhanced the behavior beyond the peak load due to its post peaking reinforcing that can called as a toughness. From the structural view, the fibrous concrete toughness initiation of the small multi-cracks that lead to increase the durability. The importance of the mentioned properties can be develop at the service level. Furthermore, using FRC, it may be possible to reduce (or even completely remove) shear enhancement [60].

Reinforced concrete is exposed to cracks that begin with tensile stress when exposed to bending load. The concentration of the post stress in the intersection with the reinforcement lead to deformation of the bars in plastic manner. Adding the PVA fiber to the concrete mixture, the reinforcement bar may reach the yield due to bridging and restraint the cracks, which lead to increase the load resistance. Moreover, fiber can also behave as miner reinforcement in the inelastic zone of the beams and participate in transforming the applied load in the cracks that lead to magnifying the ductility of the tensile action. Literature provides some specific information and research results on the calculation of FRC reinforced beams. The best testing methodology for assessing the materials properties is the toughness in the flexural test of the cracks initiate after peak load. the code of practice adopted two method to determine the flexural capacity, these are one point and two points flexural test [61].

On the utilizations of different types of fibers in concrete to measure the structural behavior, findings are summarized in the following paragraphs.

The influence of steel, glass and polypropylene fiber have been reported in an earlier investigation [62] to improve the post peak behavior of concrete. By increasing fiber content, ductility and toughness (energy absorption) are also increased.

It has been noted that, use of steel fiber in concrete can be very useful for improving the mechanical behavior of the mix. These fibers have been investigated extensively over the past few decades.

For instance, Craig [63] studied that adding 2 % fiber by volume of the mix is very useful for improving the behavior of reinforced concrete beams. This study shows that by adding the amount of fiber mentioned in the mixture, the increase in ductility, strength and ultimately the special compressive strength and stiffness can be observed.

Soroushian and Bayasi [35] Investigation that the use of steel fibers in the mix can effectively improve the toughness and impact strength. Investigating the use of fiber in FRC, it is reported that using steel fiber in concrete can enhance the bond between the concrete paste and steel reinforcement [64].

In a study Meda et al. [60] Which were carried out on full-scale reinforced beams with steel fibers subjected to a 4-point bending test, it has been shown that the fiber can be adjusted to lay the collapse of RC beams and transform the failure from concrete crushing to steel rupture and higher ductility is observed for FRC beams. Moreover, fiber greatly enhances the behavior of FRC beams in service conditions by increasing the cracked-stage stiffness and as a result limiting the deformations and crack openings.

Bentur and Mindess [65] also report that the addition of steel fibers to traditional RC beams improves the strength (ultimate load),ductility and rigidity under static loading. Moreover, the addition of fibers is associated with a decrease in the width of the cracks and an increase in the quantity. In addition, the length of the cracks were much greater in traditionally reinforced concrete, which has almost extended to the top of the beam; however, the cracks in the fiber concrete did not usually extend beyond half the depth of the beam. The addition of fibers to traditionally reinforced concrete changes the cracking pattern on loading; the number of cracks increases and their width and length decreases. These observations are also supported by Purkiss and Blagojević [66].

Rinaldi and colleagues [67] have investigated the effect of adding 1 % volume fraction of steel fibers (L_f = 30 mm, d_f = 0.6 mm) to a concrete beam (f_c = 25 MPa) reinforced with steel bars (f_{sy} = 460 MPa, f_{su} = 550 MPa) with geometry as depicted in Figure 2.11. The obtained results are agreed that adding fiber to the RC beams improves the ductility by 166 %.

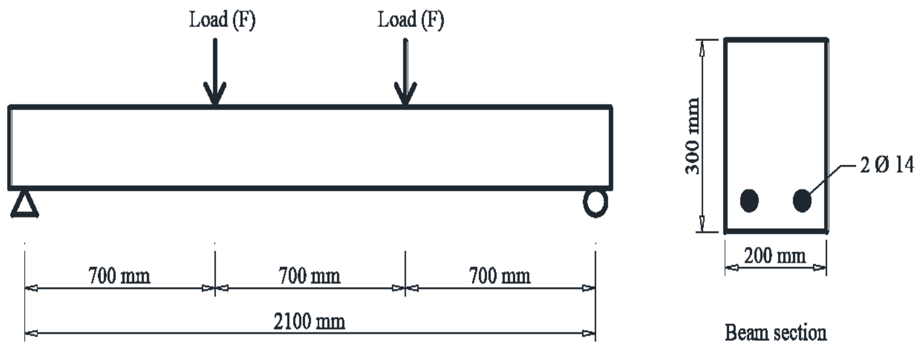


Figure 2.11 Schematic beam and reinforced section geometry [67].

Swamy and Al-Ta'an [68]"studied the influence of fibers on the deformational behavior and ultimate strength in flexure of reinforced concrete beams with 20 mm maximum size of aggregates and containing steel bar reinforcement with specified minimum yield strengths of 460 and 617 N/mm2, respectively. Their experimental work consisted of flexural test (3-point bending test over a span of 2250 mm) on 130 × 203 × 2500 mm RC beams with steel ratio ranging from 0.99 % to 1.78 % containing 0.5 % and 1 % steel fibers (L_f= 50 mm, d_f= 0.5 mm). Test results indicated that FRC beams demonstrated much higher inelastic deformations and ductility at failure. The ultimate strength of the beams only showed a slight improvement whereas the post cracking behavior has improved noticeably. As fibers arrest advancing cracks, the post cracking stiffness at all stage of loading up to failure increases; therefore, narrower crack widths and substantially less deformation can be observed.

A study Soliman and Osman [69] conducted on glass fiber reinforced RC beams under 4-point bending test, indicated that the failure mode of test samples become more ductile by the means of discrete glass fibers. Furthermore, an increase in the crack numbers and decrease in their width were also reported.

The addition of synthetic fibers to RC beams has rarely been investigated previously. Mindess and colleagues [70] reported that the addition of polypropylene fibers to RC beams had only a small influence on toughness in static loading, whereas it exerts a much bigger influence on ductility during impact.

In a study Shimizu et al. [71] on ECC beam reinforced with conventional steel bars and PVA fibers it has been observed that maximum strength of concrete beam increases by addition of fiber to the mix. Crack numbers were also increased and crack widths decreased – multiple cracking.

In another study Li and Xu [72] the bending behavior of RC beams with composite sections of conventional concrete on top and PVA-ECC at the bottom was investigated. Beams had a 80×120 mm rectangular cross section, 2000 mm span and longitudinal reinforcement ratio of 1.18 %. The PVA fiber used was 12 mm in length and 0.039 mm in diameter with a tensile strength and modulus of elasticity of 1620 MPa and 42.8 GPa, respectively. The results of 4-point bending test showed that compared with the reference concrete beams (full section made of conventional concrete), introduction of PVA-ECC layer at the bottom of the beam significantly improved the load bearing capacity and ductility as well as controlling the beam deformations.

2.6 Concluding Remarks

According to previous studies on FRC, it can be concluded that fiber reinforcement is an efficient way of improving the strength, ductility, and toughness of brittle materials. To achieve the best FRC function, the fibers is supposed to have a relatively higher tensile strength (at least 200 % - 300 %), higher modulus of elasticity and significantly higher elongation in the tension compared to that of plain concrete and additionally, having proper bond properties with a cement matrix.

PVA fiber was observed to have significant effect on improving the ductility and toughness of engineered cementations composite (ECC) and it has great potential to be used in concrete as an intrinsic reinforcement due to its unique characteristics such as high tensile strength, high modulus of elasticity and proper bond with cement matrix. Most of previous theoretical and experimental studies on FRC beams are limited to steel fiber reinforced RC beams. The result of those studies show that addition of fibers to the mix contributes efficient to preserve the structural stability and integrity as well as improving ductile behavior of a concrete beam [61, 68].

CHAPTER 3

PVA FIBER CONCRETE MATERIAL TEST

3.1 Generals

This chapter presents a preparation of the specimens for casting and curing process. Also, the Characteristics of materials used in this study are described in this chapter together with specifying their mix proportions. The experimental work was conducted at the Structural and Materials Laboratories at the University of Gaziantep.

3.2 Mix Design and Materials Properties

According to earlier researches and studies, fibers are more active with a mixture with fine aggregate, therefore; the plan was introducing a mixture with 63 % of fine aggregate and 37 % of the total mix percentage as shown in the Table 3.1.

Table 3.1 Concrete mixture amount per cubic meter

mix code	V_f[†] (%)	C kg	G kg	S kg	S.fm kg	HWR kg	W Lt
N	-	465	680	1170	35	6.6	216
PVA0.5	0.5						
PVA1.0	1.0						
PVA1.5	1.5						

[†] V_f is the fibre volume fraction
C; Cement, **G**; Gravel, **S**; Sand, **S.fm**; Silica fume, **HWR**; High water reducer, **W**; Water

Cement: The type of cement used in this study was cem II / A-LL 42.5 R. It is obtained from Limak Gaziantep cement factory.

Fine aggregate: A graded river sand brought from local source. The size of particles are ranging from 0.075 mm to 4.75 mm was used. The sieve analysis of the used fine aggregate as shown in Table 3.2 and Figure 3.1.

Coarse aggregate: A crashed stone with a gap graded of crashed stone are used. The maximum size of the particles was 9.5 mm. As seen in Table 3.3, it is shown that there are a gap between particles of 4.75 mm and 9.5 mm, this means that even the coarse aggregate has higher fine aggregate.

Table 3.2 Grading of fine (river sand) aggregate.

Sieve opening (mm	Retained weight (gm.)	Passing %
12.5	0	100
9.5	0	100
4.75	104.7	93
2	554	63
1.18	816.5	45
0.6	1048.7	29
0.3	1255.4	16
0.15	1407.4	5
0.075	1431	4

Table 3.3 Grading of coarse (crashed stone) aggregate.

Sieve opening (mm)	Retained weight (gm.)	Passing %
12.5	0	100
9.5	186.6	89
4.75	1690.8	5
2	1749.7	2
1.18	1754.9	1
0.6	1758.5	1
0.3	1763.8	1
0.15	1770	0
0.075	1770	0

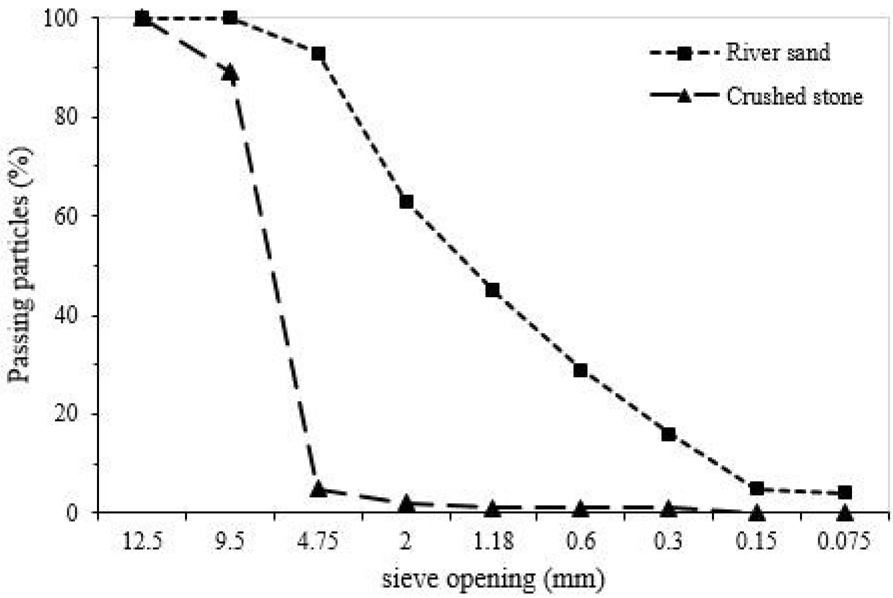


Figure 3.1 Sieve analysis

Polyvinyl alcohol fiber: PVA is designed for use in cement mortar or concrete to increase the internal quality, reduce maintenance cost and prolong service life of concrete and cement mortar. PVA fiber can reduce the formation of shrinkage cracking in concrete and cement mortar before to the curing process and increase their toughness. PVA fiber is produced from polyvinyl alcohol as the main raw material which undergoes the process of dissolving, placing heat, spinning, baling and cutting to form high strength, high modulus fiber. These high-strength fibers, high-modulus PVA can be dispersed quickly and easily in concrete mix and mortar after being added to the core material. The fiber can form a randomly guided support system in concrete, which can thus effectively control the formation and development of non-structural cracking such as drying cracking and plastic shrinkage cracking, effectively reducing the separation of aggregates and forming cracking settlements. The PVA fiber sourced from China as shown in Figure 3.2 are used in this study. Table 3.4 shows characteristics of PVA fibers as provided by the manufacturer.

Table 3.4 PVA fibers characteristics

Density kg/m^3	Length mm	Diameter mm	Aspect ratio mm/mm	Tensile strength MPa	Elastic modulus (GPa)
1260	12	0.015	800	1600	34

Figure 3.2 Polyvinyl alcohol fiber (PVA)

Silica fume: Micro silica (silica fume) is an intensely dense densities or mixture, consisting mainly of mainly unclear SiO2 particles that meet the ASTM C-1240 models. Silica is used in construction, construction chemicals and heat-resistant industries. Table 3.5 shows the technical specifications.

Table 3.5 Technical Specifications of silica fume

Amorphous SiO2	min% 90 (real %93,1)
H20 (humidity)	max%0,3 (real %0,19)
LOI	(L.O.I max%3,5) (real % 1,81)
Density	0,25-0,35 kg/dm³(U)
Retained 45micron	max %2.5 (real %0,58)
BET	min. 15-28 m2/gr (real 23,36 m2/gr)

Steel reinforcement :The beams are reinforced on tension zone by two, three and four ϕ 8 mm flexural reinforced bars, and two more bars on compression part, ten stirrups of ϕ 6.3 are included as shear reinforcement, the yielding strength of the ϕ 8 mm and the ϕ 6.3 mm bars were 503 and 558 MPa respectively. Figure 3.3 shows the reinforcing details of the beams used in test.

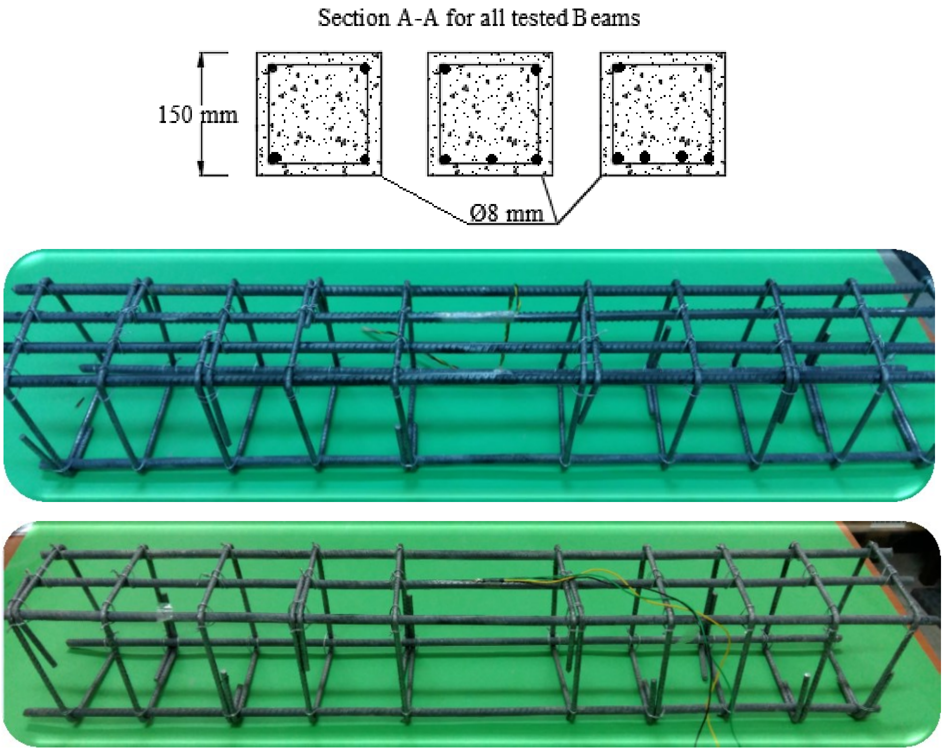


Figure 3.3 reinforcement details

3.3 Mixing of concrete

As a first step, the dry materials (sand, gravel, cement and silica fume) was mixed in vertical rotations mixer that has four paddles for blending the materials as shown Figure 3.4. The dried materials were mixed for almost five minutes to get homogeneous mixture before adding water. The water is added slowly to the mixture also in slow rotations for almost five minutes, then super plasticizer is added and rotate the mixer on the maximum speed before adding the steel fiber, which is added slowly soon after adding the PVA fiber the mixture will be ready for casting. The mold was oiled well to prevent the concrete attaching the mold and make it easy to extract the sample.

Figure 3.4 Mixing of materials

When the mix is ready it was moved to the mold for casting the beam by using vibrator in this operation, exterior vibration for the beams. Also a standard cylinder, 100 mm in diameter and 200 mm long was casted, exterior vibration for the cylinder containing PVA fiber however: the cylinder containing normal concrete was casted as three layers, each layer flattened with a rod carefully. The vibration process continued until the air bubble escaped from the surface of the specimen. These mentioned cylinders are used to determine the compressive strengthfc', and the tensile strength fct, casting three cylinders to get an accurate test reading.

After pouring the concrete in the mold, surface of the concrete was leveled and smoothed using a trowel. It can easily be noticed that the concrete mix without steel fiber is so ease when it comes to finishing using trowel and a lot more workable than the mix containing PVA fiber.

3.4 Curing process

When 24 hours is past, the mold was opened and the sample was taken to a water tank with heater to begin the curing process with an average temperature of 25°C and it remains there for 28 days as summarized in figure 3.5.

Figure 3.5 Curing tank.

3.5 Slump test

The Slump test is an experimental method that measures the viability of fresh concrete. More specifically, it measures the consistency and variations in uniformity of the concrete in a specific batch. The apparatus used for this test is a hollow frustum of a cone with specifications shown in Figure 3.6.

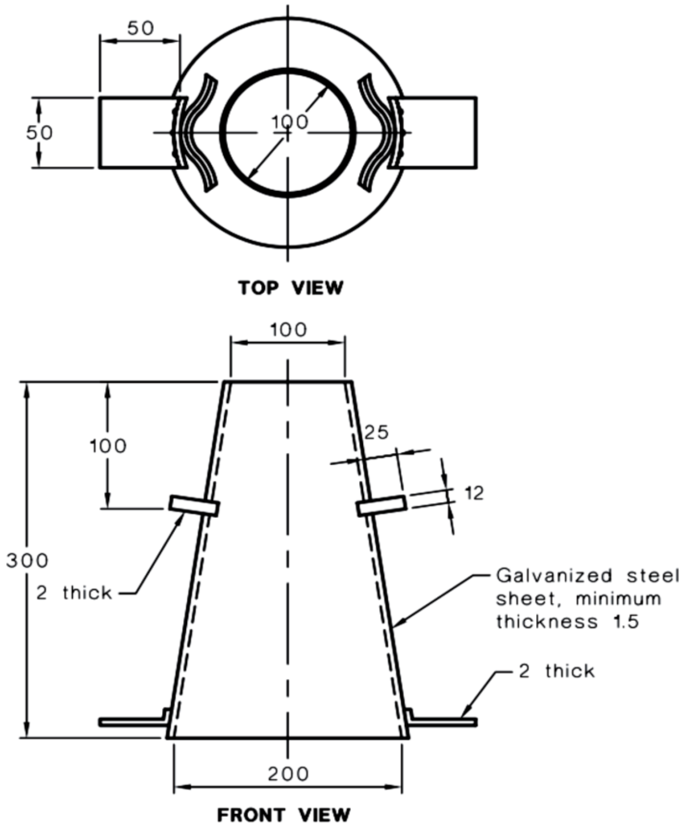


Figure 3.6 Type mold for slump test

The slumped concrete may take one of the three forms; true slump, shear slump and collapse slump as shown in Figure 3.7 if concrete is slumping equally all rounds, called real slump, which is of use in the tests. If instead of true slump, half of the cone slides down a jet inclined, and it is said that the shear slump has occurred. In this case, the test should be repeated and if the shear slump continues, this indicates a lack of cohesion in the mix. It may undergo segregation and bleeding and thus is not desirable. A collapse slump generally means that the mix is too wet or there is a high workability level, for which the slump test is not appropriate. The concrete slump values may vary in the range between zero (no slump-very low workability) to collapse.

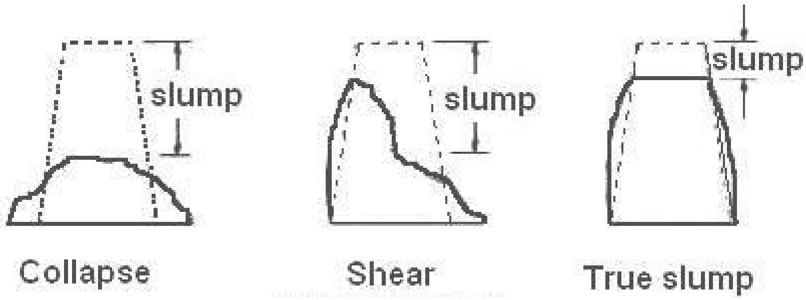


Figure 3.7 Different profiles of concrete slump

The slump test result of the work were as shown in Table 3.6 which shows that there is a direct relation between the slump result and the increasing percentage of PVA fiber. In addition, it shows that there is an inverse relation between the workability and the percentage of PVA fiber. As shown Figure 3.8.

Figure 3.8 Slump test

Table 3.6 Slump test results.

Specimen	Slump test result (mm)
N	87
PVA0.5	63
PVA 1.0	61
PVA1.5	59

3.6 Mechanical Properties of PVA Fiber Concrete

As mentioned in experimental work in order to overcome the errors, average of three cylinders of 100 × 200 mm are tested for both compressive strength (f'_c) , tensile strength (f_{sp}) and modulus of elasticity (MOE) , Table 3.7 summarizes the test results of the specimens at the test moment.

Table 3.7 Concrete material properties

Mix	PVA V_f (%)	f'_c (MPa)	$\frac{f'_{c\ fiber}}{f'_{c\ normal}}$	f_{sp} (MPa)	$\frac{f_{sp\ fiber}}{f_{sp\ normal}}$	$f_{sp}/\sqrt{f'_c}$	E_C (GPa)
N	0.0	30.00	1.00	6.56	1.00	1.20	25.32
PVA0.5	0.5	39.23	1.30	6.74	1.03	1.08	30.53
PVA1.0	1.0	42.86	1.42	6.60	1.02	1.01	35.43
PVA1.5	1.5	43.38	1.44	6.56	1.00	1.00	37.21

3.6.1 Compressive Strength

The compressive strength test is the most common of all tests on concrete hardness. This is partially because it is an easy test to perform. Moreover, many of desirable properties of concrete are qualitatively related to its compressive strength. However, the main reason for compressive test popularity is the intrinsic importance of the compressive strength in concrete structural design [73]. In Standard, method of testing concrete, only cylindrical specimens which are prepared in accordance with (ASTM C39, 1997) [74] are accepted to be tested to determine the concrete compressive strength. Therefore, all compressive tests are performed on cylindrical specimens of 100 mm diameter with 200 mm length following (ASTM C39, 1997) [74] procedural requirements. Prior to the test, concrete samples were properly capped complying with the latter mentioned standard. For each concrete type, compressive strength test is performed at 28 days of age and for each age, 3 cylindrical samples were tested. The compressive strength of the specimens is calculated by dividing the maximum force applied to the specimen by the cross sectional area. This area is calculated from the average of the two measured diameters. As shown in Figure 3.9.

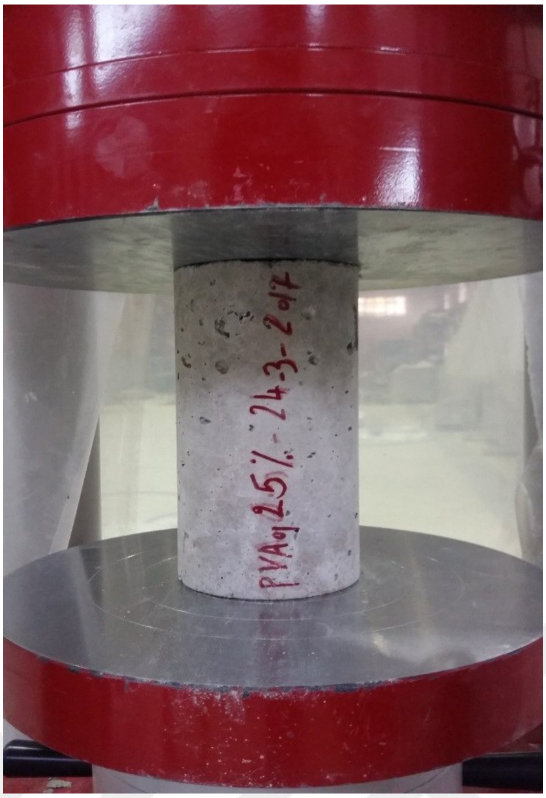
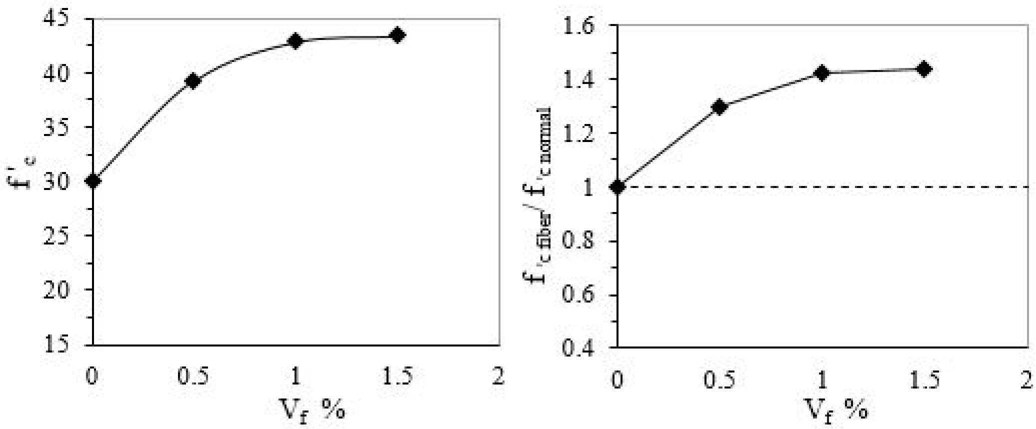


Figure 3.9 Cylinder compressive test**.**

Table 3.7 summarizes the test result, and include the compression between the f ′c of fibrous concrete with that of plain concrete.



(a) (b)

Figure 3.10 (a) effect of PVA on compressive strength of concrete (b) normalized compressive strength of concrete

It is clear from Figure 3.10 that the f 'c is significantly affected by the inclusion of PVA fiber. Where adding 0.5, 1.0, and 1.5 % of PVA increases the compressive strength by 31, 43, and 44 % respectively, compared with normal concrete. As also previously stated by Li [77], the compressive strength may rise with increasing fiber volume fraction. Improved strength can be an indication of an increase in resistance to microcrack sliding and extension, while strength degradation can be due to an increase in pore or microcrack density. Pores may be connected to insufficient compaction and can be related to additional microcrack-touching fibers, (unopened) cracks and fiber, weak fiber / matrix bonding, or poor adhesion between filaments within fiber bundles [77].

When the results are investigated, it can be noted that FRCs with fiber additions have higher compressive strength compared to the control. Furthermore, the optimum fiber volume fraction was found to be 1.5 %.

3.6.2 Indirect Tensile Strength

The indirect tensile test ('Brazil' or splitting test) is a simple and indirect way of determining the tensile strength of concrete, which gives more consistent results than other tension tests. The measured strength in the split test is believed to be close to the direct tensile strength of the concrete and approximately 5 to 12 per cent higher [73].

In this study, the indirect tensile test is conducted in accordance with (ASTM C496, 2004) [75] on cylindrical specimens of 100 mm diameter by 200 mm length. The concrete cylinder is placed, with its axis horizontal, between the plates of testing machine as shown in Figure 3.11 and Figure 3.12 is loaded until the failure takes place by indirect tension in the form of splitting along the vertical diameter. For each concrete type, indirect tensile test is performed at 28 days of age and for each age, 3 cylindrical samples are tested. The indirect tensile strength of the specimen can be estimate using below equation;

$$f_{Ct,\,SP} = \frac{2P}{\pi L D}$$

Where $f_{ct.sp}$ is the indirect tensile strength in MPa, P is the peak-applied load in kN, L is the sample length in mm, and D is the diameter in mm.

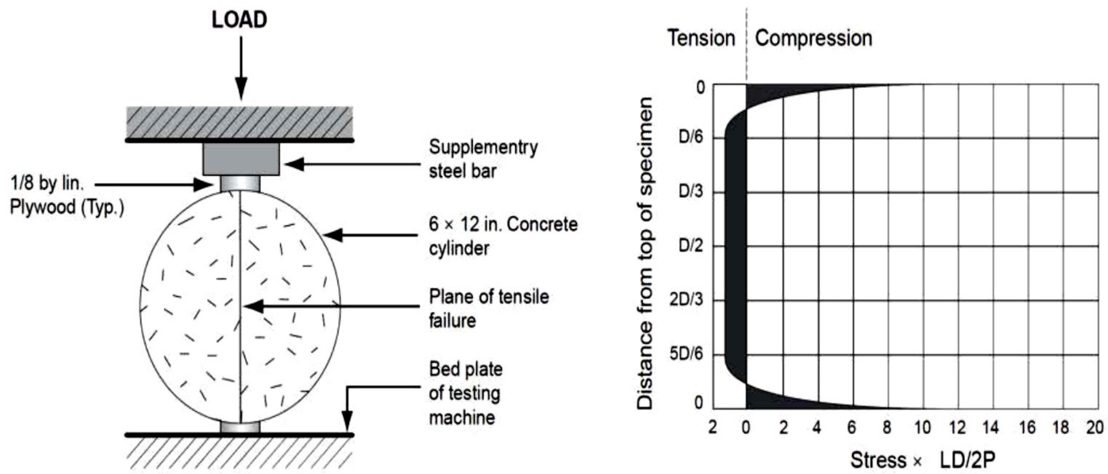
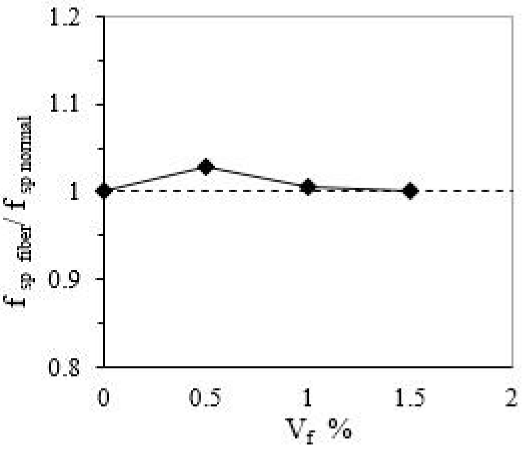


Figure 3.11 Splitting tensile test; (left) typical arrangement of the test (right) stress distribution across the loaded diameter of a cylinder compressed between two plates.

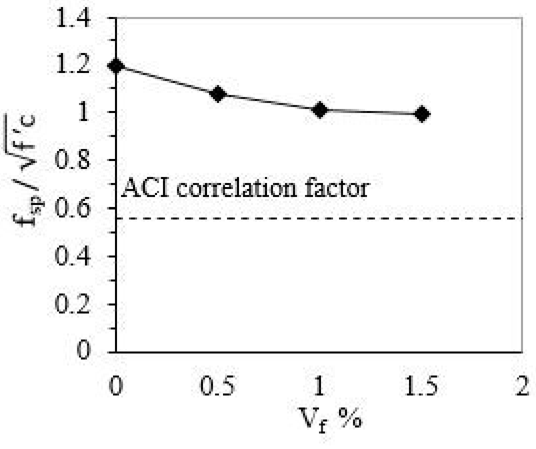
Figure 3.12 Brazilian indirect tensile test.

The result of the control specimen and those reinforced by 0.5%, 1% and 1.5 % fiber volume fractions that obtained from Brazilian test (well known as splitting test) are presented in Table 3.8.

Figure 3.13a shows the normalized indirect tensile strength of FRCs with respect to the control concrete. The results in Table 3.7 can be inferred that the tensile strength of the fiber-reinforced concrete is almost equal because the fiber enhances the post-crack properties by compressing the pressure through the crack so the results show that fibers does not always enhance the tensile strength.



(a)



(b)

Figure 3.13 (a) effective PVA on splitting tensile strength of concrete (b) correlation of splitting strength to square root compressive strength in PVA reinforced concrete

ACI318-14 [7] defined the relation between the f_{sp} and the f'_c in terms of square root as $f_{sp} = 0.56\sqrt{f'_c}$, this correlation is valid for plain concrete. Figure 3.13b depicted the relation between f_{sp} and f'_c that governs the FRC used in the current work. It is clear that for normal concrete, the correlation factor ($f_{sp}/\sqrt{f'_c}$) is higher than 0.56 (adopted by ACI318) by approximately 100 %, this is attributed to the good stress distribution due to proper distribution of the matrix particles. For PVA reinforced concrete, the correlation factors are reduced due to high sensitivity of the compressive strength with the inclusion of the PVA.

3.6.3 Modulus of Elasticity Test

The static modulus of elasticity of concrete as seen in Figure 3.14 according to (ASTM C469, 2002) [76]. The test method provides a stress-strain curve for a hardened concrete at whatever age and curing conditions may be designated. The slope of this curve, which represents the chord modulus, is given by the slope of a line drawn from the point representing the longitudinal strain of 50 micro strains to the point that corresponds to 40 % of the ultimate load. The cylinders specimens were grinding top surface to be smooth and level. The average value of three cylinders was calculated at each result.

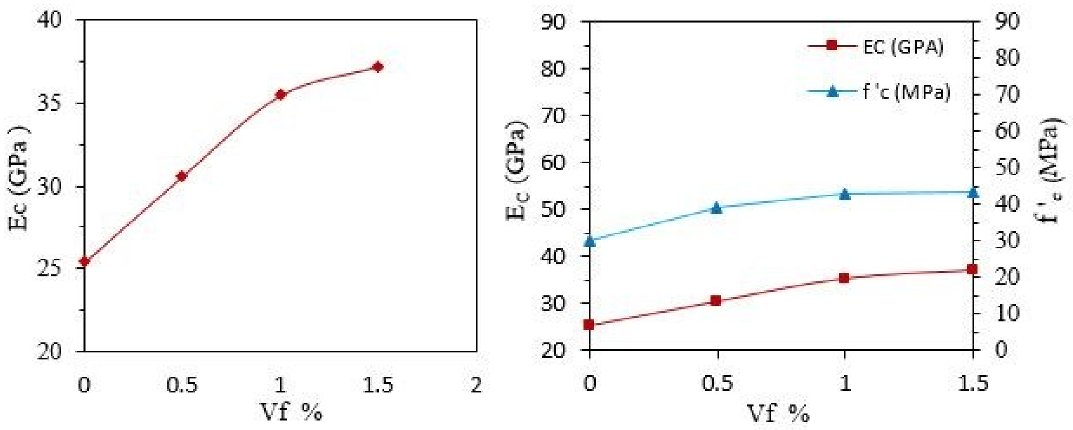
The modulus of elasticity is calculated by following:

$$E_c = \frac{(S_2 - S_1)}{(\varepsilon_2 - 0.00005)} \tag{4.1}$$

where Ec is the concrete modulus of elasticity in MPa, S_2 is the load test (as shown above), divided by the cross-sectional area of the sample in MPa, S_1 is the applied load at a strain of 50×10^{-6} divided by the cross-sectional area of the sample in MPa and ε_2 is the corresponding strain of deformation at test load, (strain = deformation divided by the gauge length) in 10^{-6} m/m.

Figure 3.14 Modulus of elasticity test.

Modulus of elasticity of FRCs and control at 28 days are compared in Table 3.7 and Figure 3.15a from the results, it can be seen that the modulus of elasticity of concrete mixtures increases with the increase of the ratio of PVA.



(a) (b)

Figure 3.15 (a) Effective PVA on modulus of elasticity of concrete (b) Relationship between compressive strength and concrete modulus of elasticity.

Previous investigations on conventional concrete [77] ; [78] ; [79] show that the concrete modulus of elasticity has a relationship with the compressive strength as seen in Figure 3.15b It has been stated that the concrete modulus of elasticity has a direct relationship with compressive strength

CHAPTER 4

STRUCTURAL BEHAVIOR OF FRC BEAMS

4.1 General

Although creating a perfect engineered construction material is of great achievement, it should also be applied to structures to reap the benefits from the structural point of view. Accordingly, the structural properties of RC beams incorporating PVA fiber as intrinsic reinforcement are investigated. As mentioned earlier, twelve RC beams constructed for three PVA volume fractions (V_f %) (0.5, 1.0, and 1.5 %). It is compared with control beam and three tensile reinforcement ratio are used (0.5 %, 0.75 %, 1.0 %). The results of tested twelve beams are presented in Table 4.1 and Figure 4.1 are tested for 4-point flexure.

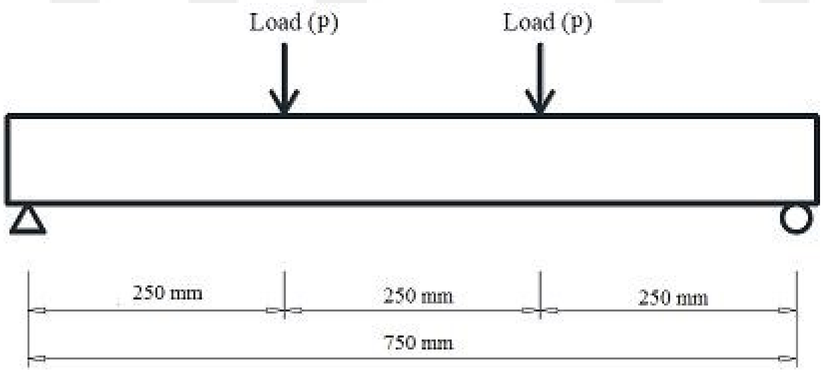


Figure 4.1 Tested for 4-point flexure

Table 4.1 Numerical values for the parameters of the flexural behaviour

				Crack		Ultimate	
Group No.	ρ %	Beam No.	PVA %	P_{cr} (kN)	δ_{cr} (mm)	P_u (kN)	δ_u (mm)
A	0.50	A-0.0	0.0	11.6	1.8	70.54	15.3
		A-0.5	0.5	22.6	1.6	73.22	15.6
		A-1.0	1.0	25.8	2.0	73.80	17.0
		A-1.5	1.5	27.8	2.4	77.06	15.3
B	0.75	B-0.0	0.0	12.6	1.1	90.75	10.1
		B-0.5	0.5	23.0	1.4	96.62	12.0
		B-1.0	1.0	24.7	1.9	97.99	13.5
		B-1.5	1.5	25.6	2.1	99.95	14.5
C	1.00	C-0.0	0.0	13.3	1.6	109.9	7.40
		C-0.5	0.5	22.2	1.7	116.2	11.8
		C-1.0	1.0	25.2	2.1	120.4	12.2
		C-1.5	1.5	26.3	1.8	126.4	15.0

The experimental program can be described as follows: the main parameters are the effect of PVA volume fraction (V_f %), and the tensile reinforcement ratio (ρ). The experimental program consists of casting and testing of twelve beams, including three control beams of normal concrete that were marked three groups. Each group contains one beam of plain concrete and three beams of different percentages of PVA fiber beam.

4.2 Description of Beam

Twelve reinforced concrete beams as grouped in Figure 4.2 were tested under the applied point load transfer into two points load on the beam point loading system. For all beams, the cross section are 150 mm wide and 150 mm in depth. The overall length was 850 mm with clear span 750 mm. The beams were designed to have extra strength in shear to ensure flexural failure even after strengthening; therefore, ten stirrups of ϕ 6.3 are included as shear reinforcement as shown in Figure 4.2.

The main variables that have been considered in this study are the amount of tensile steel (ρ) for concrete beam and PVA fiber percentage.

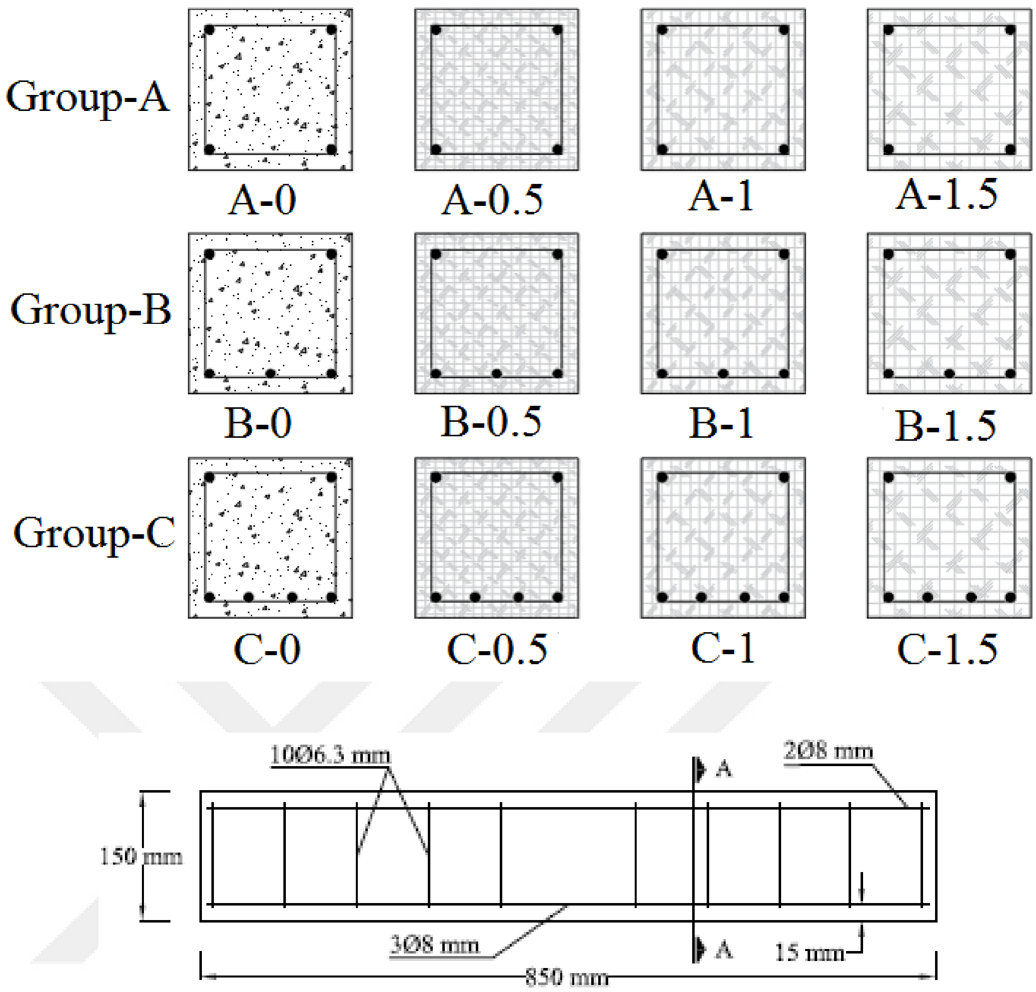


Figure 4.2 beam geometry

The mold clear dimensions in the X-Y-Z direction were 150 × 150 × 850 mm, the base is smooth 20 mm thickness, coated plywood and the sides consisted of the same-coated plywood, which was connected to the base by screws to close and open it easily. As shown in Figure 4.3.

Figure 4.3 Casting mold

4.3 Specimen test setup

Figure 4.4 shows the beams' test configuration, in order to prevent the friction induce from axial forces and freely rotation, two stiff rollers represent the load and supports. The distance between the loading point and the support (a) is 250 mm, so that the shear arm (a/d) is 1.85. The load applied until the failure, in displacement control rate of 0.4 mm/min. In addition to the jack displacement measurement, one more LVDT is attached to the beam at mid-span from bottom side. Two dial gages were used to measure the edge lifting and the deflection at the quarter distance of the beam (125 mm from the support).

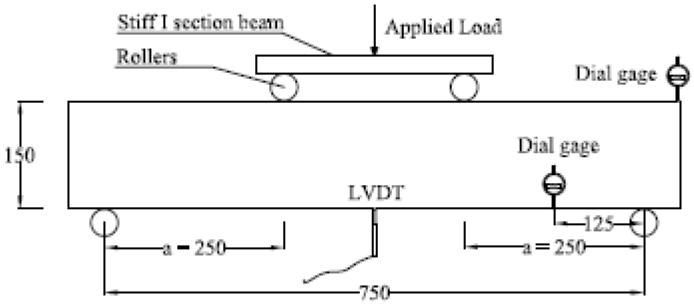


Figure 4.4 Beams test setup and location of the LVDT and the dial gages

A testing machine (Instron 5590R) with maximum capacity of 250 kN was used as shown in Figure 4.5 and Table 4.2 the details of the testing machine and specimen.

Table 4.2 Details of the testing machine

INSTRON	Cϵ Assembled in USA
Model No	5985
System ID / SN	5985L2125
Configuration	E1-F1-G1
Capactity	250 Kn (56250 lb)
Wight	882 kg (1949 lb)
Date of Manufacture	July - 2011
Voltage	220 Volts
Frequency	47 – 63 Hz
Maximum Power	3500 VA
Circuit Breaker	20 AMP
Short Circuit Current	

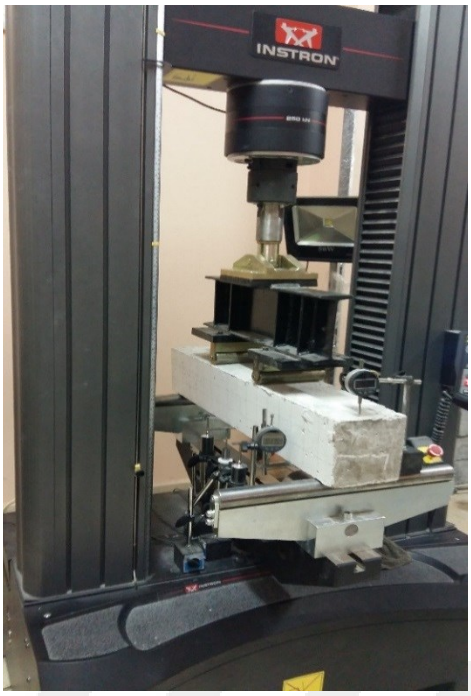


Figure 4.5 Testing machine.

When the test is finished, the sample was removed from the test machine and the crack lines were marked with red marker as shown in Figure 4.6 then the sample was photographed and placed a side and another sample is placed on the test machine.

Figure 4.6 Sample of marking the tested beam.

4.4 Load-deflection Responses of Beam

The load deflection data are recorded from the machine load cell and LVDT amounted at the bottom center of the beam. It is well known that the typical load-deflection relationship (p-δ) of a regular reinforced concrete beam may essentially compose of three types of behavior: pre-cracking stage, post-cracking stage, and post-yielding stage. The load-deflection response of each beam is shown in Figure 4.7 to 4.9.

It was noted that once the beam extreme tension fiber reached its tensile strength, there was a significant deviation of the curve from the original slope, implying a relative reduction in the flexural rigidity of the beam beyond the working load level. This is representing the pre-cracking stage, where the deflection increases almost linearly with the loading. The strains in steel and concrete are expected to be relatively small and both materials are in the elastic portion of their respective responses.

From Figure 4.7 to 4.9 there were nonlinear extraneous displacements because it is often associated to such a test. Up to the first initiation crack, the displacement is proportional to the applied load linearly; the first cracks are hardly and carefully located on the curve. After the first crack take place, the slope of the curve was slightly changed, but looks to be in linear increasing rate, the increasing rate continues up to yield point. After yielding of the reinforcement, the curves are increasing in nonlinear manner up to the maximum resistance load, the test is continuing until the beam is collapsed.

As soon as the strain in the tensile steel reached yield level, the beam was considered to have failed structurally. The test samples continued to drift rapidly until the secondary compression failure developed, resulting in crushing the total concrete in the maximum moment zone, followed by a large-scale cracking afterwards and a large widening of the stable cracks.

The (p- δ) curves of all the tested beams of reinforcement ratio from 0.5 % to 1 %, with various PVA contents are shown in Table 4.1 It shows that the addition of PVA has a significant effect on the cracking load that induced first crack, which may be defined as the crack that occurs at the initial change of slope of the (p- δ) curves. However, on the other hand, it is clearly shown that the PVA concrete beams are stiffer in the initial loading stages (elastic) before the significant change of slopes.

For the ranges bounded by the point of the first crack and ultimate load, specimens made with PVA concrete exhibited less deformation and larger load-carrying capacity from that of conventional concrete, as seen in the Table 4.1 This is due to the ability of PVA concrete in arresting crack growth and crack widening. Figure 4.8 also shows that the effect of PVA in increasing the ultimate strength is less significant than its effect in reducing the vertical deformation. The main reason for such behavior is due to the influence of PVA addition to the reinforced concrete beam, which does not lie in improving the strength but rather in control of cracking and deformation.

Generally, the first crack resistance load is increased with increasing the fiber percentages, although, the first crack resistance loads is take place before the participation of the exterior fibre, but the effectiveness of the interior fibre on the microcrack is play important role in whole resistance. For group A (beams with ρ = 0.5 %), the first crack resistance loads for A-0.5, A-1.0 and A-1.5 increases by 95, 122, and 139 % respectively. Almost same increasing percentages shows in both group B and C, where increment percentages of P_{cr} for B-0.5, B-1.0 and B-1.5 were 82, 96 and 100 %, in the same manner the increment percentages of P_{cr} for C-0.5, C-1.0 and C-1.5 were 66, 89 and 97 %. In turns, this will affect the first crack deflection as shows in Table 4.1 where the central deflection is increases with increasing the V_f % as shown in Figure 4.10.

Figures 4.7 to 4.9 shows that the ultimate deformation is not affective by the reinforcement ratio, this is not surprisingly, because the beams are failing before the yielding of the reinforcement.

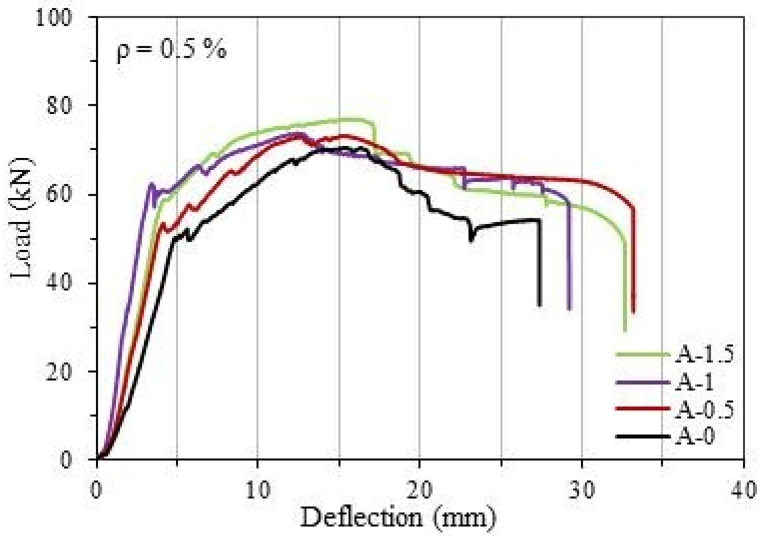


Figure 4.7 Load-deflection curves for Group A tested beams (ρ = 0.5 %)

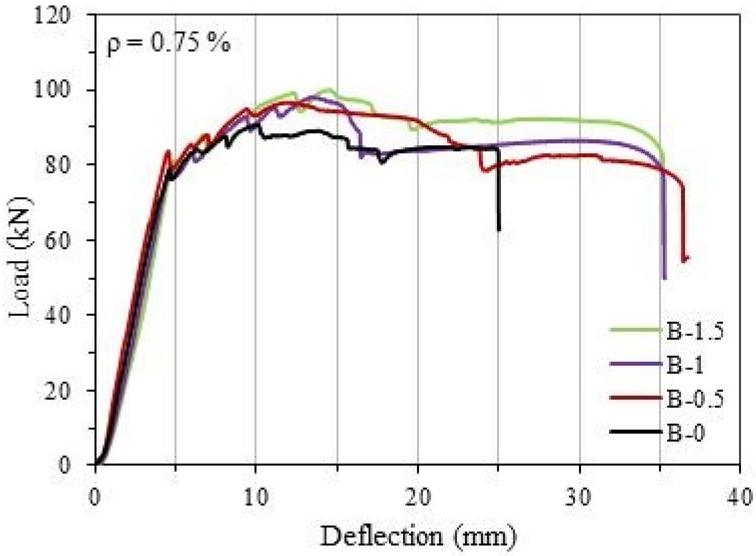


Figure 4.8 Load-deflection curves for Group B tested beams ($\rho = 0.75\ \%$)

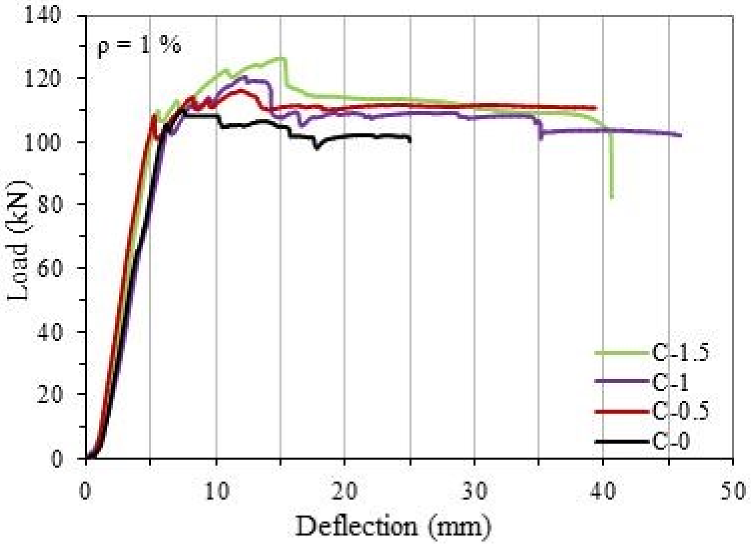


Figure 4.9 Load-deflection curves for Group C tested beams ($\rho = 1.0\ \%$)

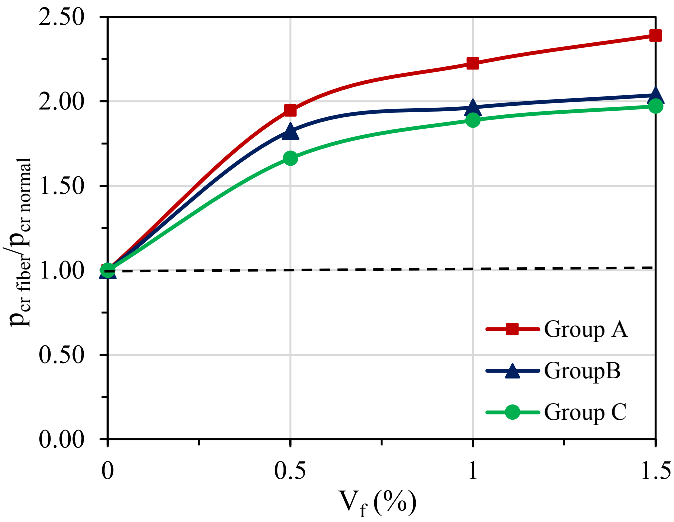
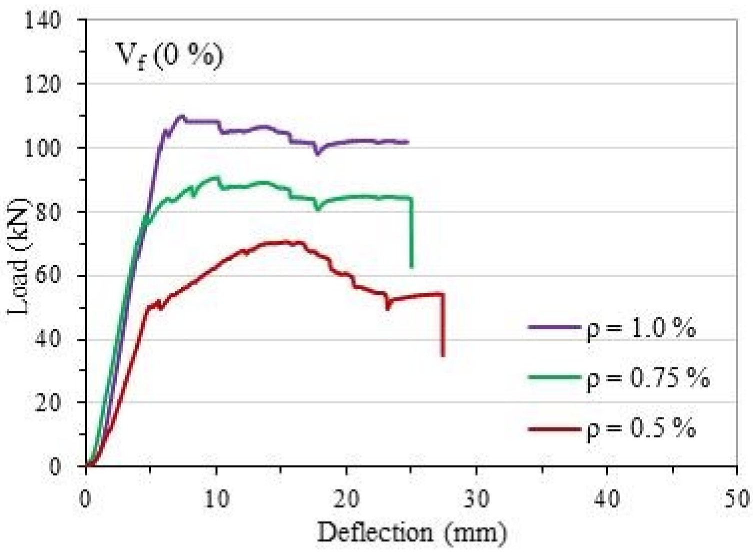


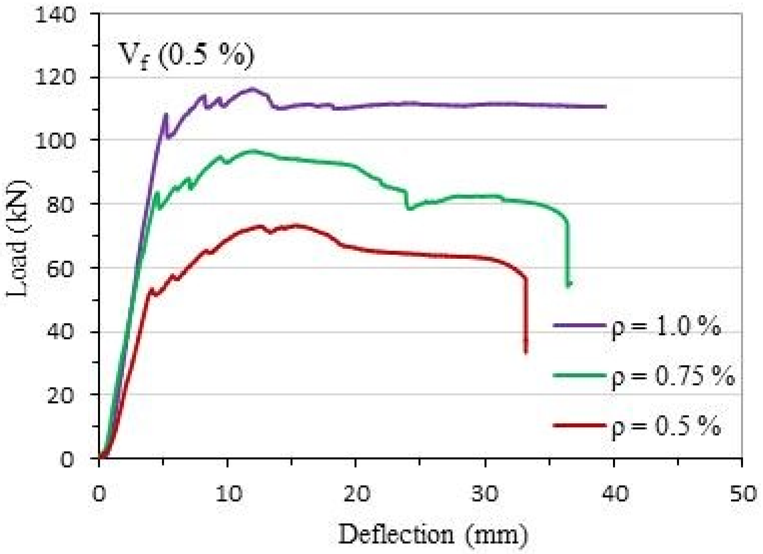
Figure 4.10 The normalized the first crack resistance loads strength

Figure 4.11 shows the effect of reinforcement ratio, which is investigated as second parameter. Comparing the beams with same PVA content but different amount of ρ, the beam with the higher steel content has a stiffer response in terms of (p- δ) behavior and a higher yielding load. This trend is primarily due to the larger effective moment of inertia due to larger amount of tensile reinforcement.

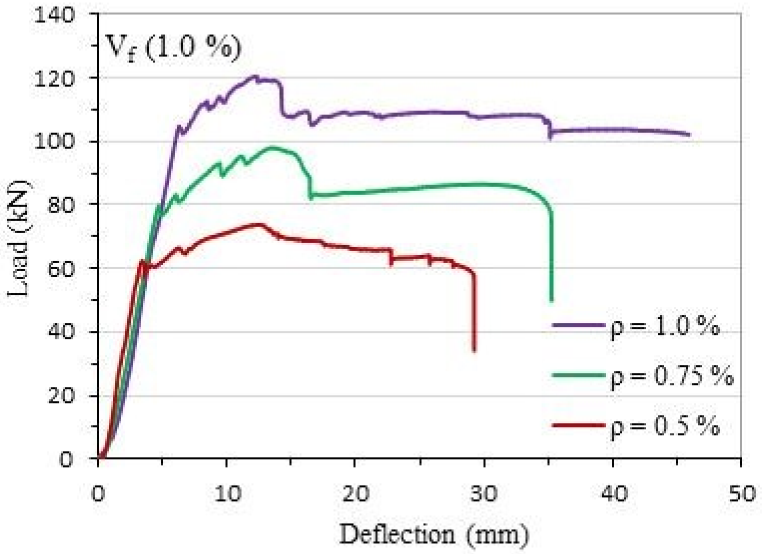
In the post-yielding stage due to the yielding of the tensile steel, all the (p- δ) curves experience some change in slope. At a sectional level, the depth of the neutral axis is reduced significantly, thereby increasing the deflection immediately after yielding. Each beam exhibited different post-yielding load-deformation response, depending upon the amount of tensile steel reinforcement.



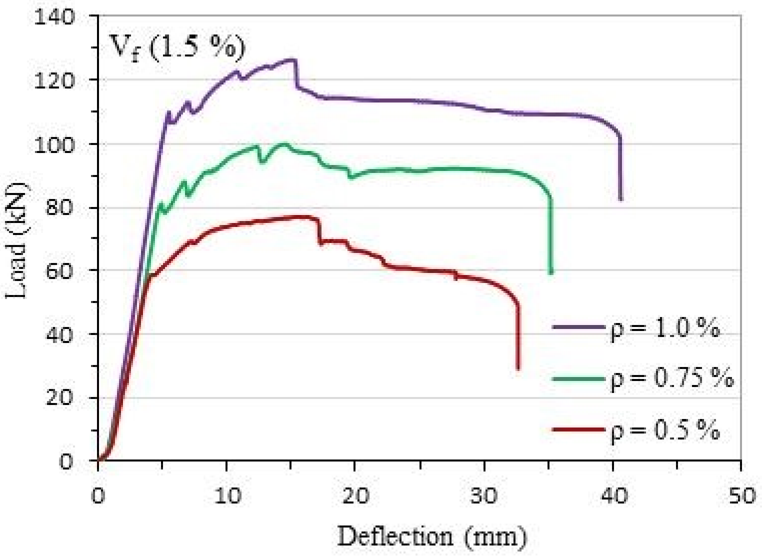
(a) V_f = 0.0 %



(b) $V_f = 0.5$ %



(c) $V_f = 1.0$ %



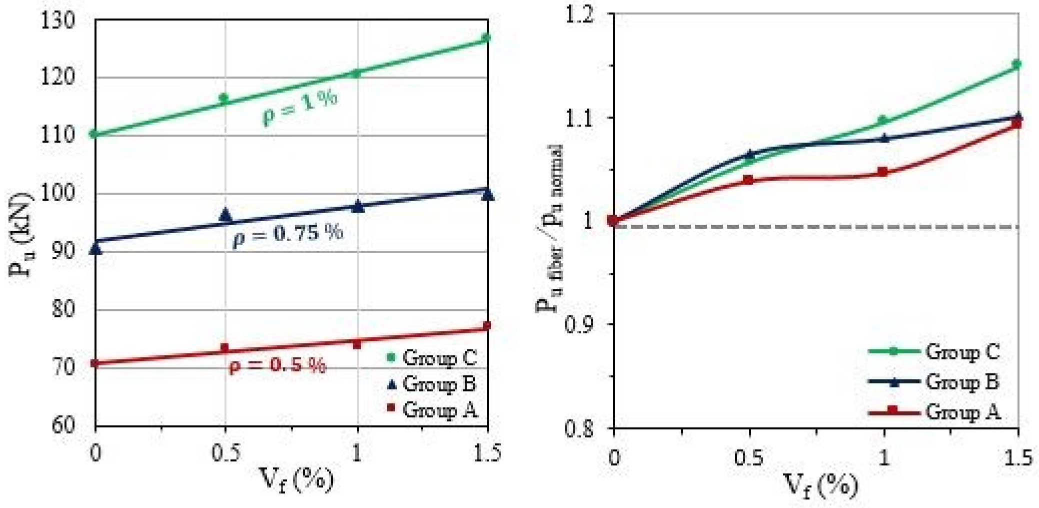
(d) $V_f = 1.5$ %

Figure 4.11 (a, b, c and d) Effect of reinforcement ratio (ρ) on Load-deflection

From the results of the beams of first parameter (Figure 4.7- 4.9) and beams of second parameter (Figure 4.11), it can be seen that the increasing reinforcement ratio with same fibre volume fraction has decrease the corresponded deflection, interns minimize the total deformation at the post-yielding stage.

4.5 Ultimate Beam Strength

Table 4.1 summarized the result of four points test, the cracked and ultimate beam strength are listed with its corresponding displacement. For all reinforcement ratios, it shows that addition of fibres are significantly enhance the resistant of the beams. Where inclusion 0.5 % of fiber by volume are improved the ultimate strength (P_u) by 4 % compared to the control beam. Whereas, adding 1.5 % fiber by volume was less improvement percentage (5 %), moreover, duplicating the fiber content was duplicating the improvement percentage (10 %) as shown in Figure 4.12 and 4.13.



(a) (b)

Figure 4.12 (a) The effect of PVA fiber dosages on the ultimate beam strength (b) normalized the ultimate beam strength

Increasing the reinforcement ratio from 0.5 % to 0.75 % shows more activity of the fiber than the previous group (Group A). Where the ultimate load resistance of the beams of the Group B were 6 %, 8 % and 10 % for beams with fibre 0.5 %, 1 % and 1.5 % respectively, compared to the beam of normal concrete, as shown in Figure 4.12 and 4.13.

More increasing in reinforcement ratio for group C shows significantly increasing in the effectiveness of the fiber. Where the beams with 1.0 % and 1.5 % shows 10 to 14 % improvement in beam ultimate load.

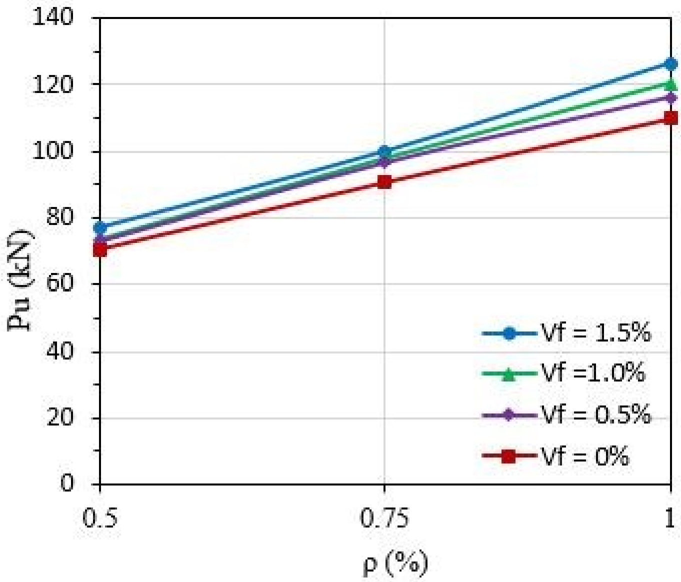


Figure 4.13 Effect of reinforcement ratio (ρ) on the ultimate beam strength

The interested finding, were increasing the reinforcement ratio were increasing the effectiveness of the fiber. This lead to conclusion that the effect of fiber is affected by the behavior of beam of normal concrete, i.e. increasing the brittleness of the beam was increase the effect of fiber. This is not surprisingly, where the activity of fiber is start after initiation of the local cracks, these cracks shows early in beams with high reinforcement ratio. In next section, equations controlling the ultimate load were empirically driven.

4.5.1 Interaction between fiber and reinforcement ratio

As mentioned in the previous section, it shows that the reinforcement ratio are significantly affect the improvement percentages of the fiber.

Referring to Figure 4.14, its shows that the improvement of the ultimate resistance load are linearly with in increasing the volume fraction, and govern by the following equation,

$$y = k\, x + c \qquad (4.\ 1)$$

Where y refer to the ultimate load, k is the reciprocal of the line slope $\frac{\Delta Pu}{\Delta V_f}$, x is the fibre volume fraction, and c is the intersection of the curve with y-axis in turns refer to the ultimate resistance load of the control beam. The controlled equation can be obtained from the tredline of the data with high R^2 as follows,

$$Pu_{(P = 1.0\%)} = 10.7V_f + 110 \quad (4.2a)$$

$$Pu_{(P=0.75\%)} = 5.8V_f + 92 \quad (4.2b)$$

$$Pu_{(P=0.5\%)} = 4V_f + 71 \quad (4.2c)$$

In order to include the effect of both reinforcement ratio and the fiber, k in equation 5.2a, b, and c are related to the volume fraction as shown in Figure 4.12a. The obtained flowing equation are substituted in equation 4.1 yields equation 4.4.

$$K = 13.4V_f - 3.2 \quad (4.\ 3)$$

$$P_{uf} = [(13.4 \times V_{f\text{-}3.2}) \times V_f] + Pu_{Normal} \quad (4.\ 4)$$

For normal concrete ($V_f = 0$) equation 5.4 yields

$$P_{u,\ (Vf=0)} = P_{u\ NORMAL} \quad (4.\ 5)$$

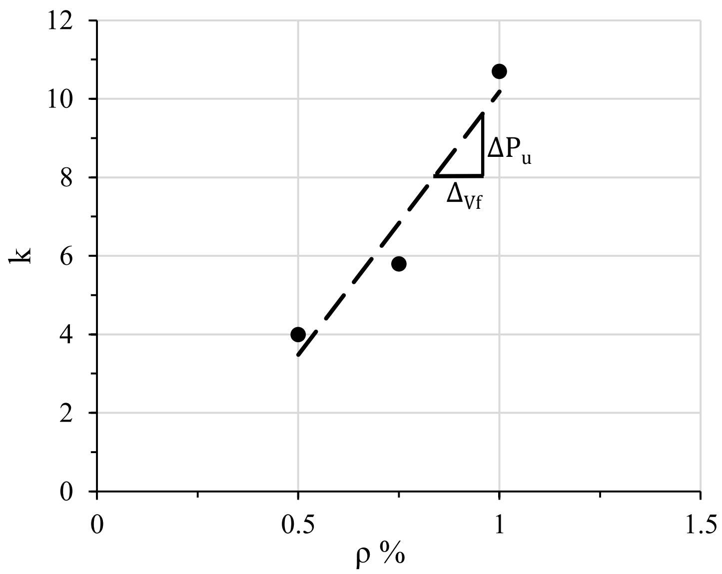


Figure 4.14 Interaction between fiber and reinforcement ratio

4.6 Ductility of PVA-FRC Beams

Ductility is a term used in seismic design to demonstrate the ability of the structure to withstand periodic amplitude deformities in an inflexible range without reducing strength reduction [7]. The ductility factor (μ) known, as the proportional of the ultimate deformation (δ_u) to the yield deformation (δ_y). This can be used as a predictor for the non-elastic deformation of seismic analysis and design. The ductility index is communally defined as the many parameters such as deformities, curvature, rotation and namely displacement [7].

Typically the displacement ductility factor (μ) is determined at a time of non-flexible dynamic date analysis, may vary between 1 and elastic response structures up to 7 for ductile structures. Nevertheless, it is typically ranging from 3 to 6 [7]. The displacement ductility factor can be estimate using Equation 5.6 below and Figure 4.15.

$$\mu = \frac{\delta u}{\delta y} \qquad (4.6)$$

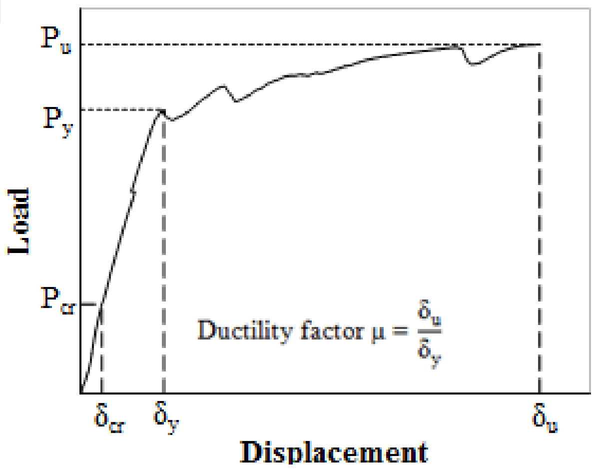


Figure 4.15 Definition of the ductility factor (μ) of the beams

Where δ_u is the ultimate deformation is that the deformation corresponding to the maximum resistance load and δ_y is the yield deformation. The yield deformation definition can cause a significantly confusing. This is because the relationship between the applied load and the central displacement may have many defined yield points. This may occur due to different angle of view. For example, due to materials nonlinearity, there are different levels of applied test load that required forming a plastic hinges in many places along the member, moreover, different flexural stages that need to make the reinforcement bars at along the member thickness to reach yield [7].

Figure 4.16 depicted the different available definitions proposed by different researchers that introduced the first yield point. Figure 4.16a, illustrated the corresponding displacement to the yielding point. Moreover, Figure 4.16b, is determine the displacement corresponding to the elastic-plastic that reach the same ultimate load and stiffens. However, in Figure 4.16c the yield point is determine from the intersection of the horizontal line tangent to the peak load with that second line that separate two equal area. The yield point in the Figure 4.16d can be find from the same above intersection but with secant at 75 % of the maximum load [7].,

This latter definition (Figure 4.16d), takes the hardness of the secant as described before, considering the decay in hardening induced from cracking that occurs close to the ends where the elastic range take place. The aforementioned description can be considered as a real representation of the deflection corresponding to the reinforcement yielding [7].

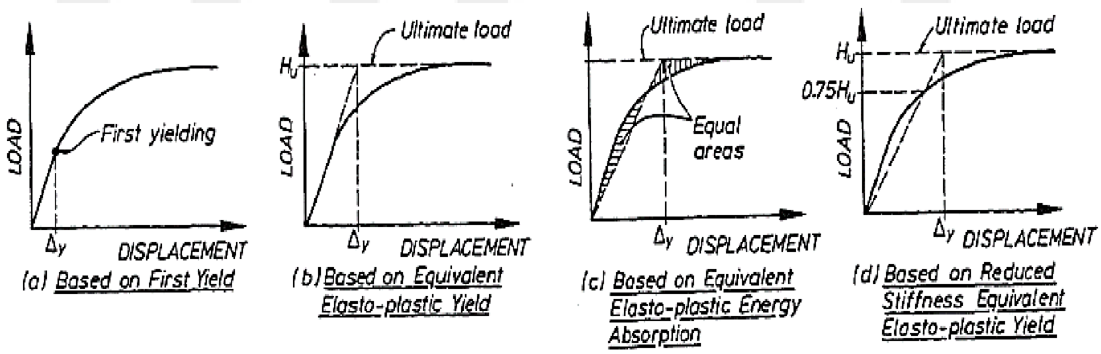


Figure 4.16 Yield displacement definition according to [7].

On the other hand, the deflection at ultimate can be defined in different approach, as shown in Figure 4.17. These potential proposed approaches are introduced by Park [7]. The displacement corresponding to the specific value for the concrete compressive strain Figure 4.17a. Determine the required ultimate displacement that the point corresponding to the ultimate load. While, the ultimate displacement in Figure 4.17b is that the displacement point that displacement corresponding to the load producing from intersection of the horizontal line of the peak load, with that tangent of the cure at elastic zone. Displacement after peak when the load capacity was reduced to a small reduction of Figure 4.17c, displacement at fractional or longitudinal steel fractions or longitudinal pressure strengthening buckles Figure 4.17d. The definition of ultimate displacement will be the standard shown in Figure 4.17b [7].

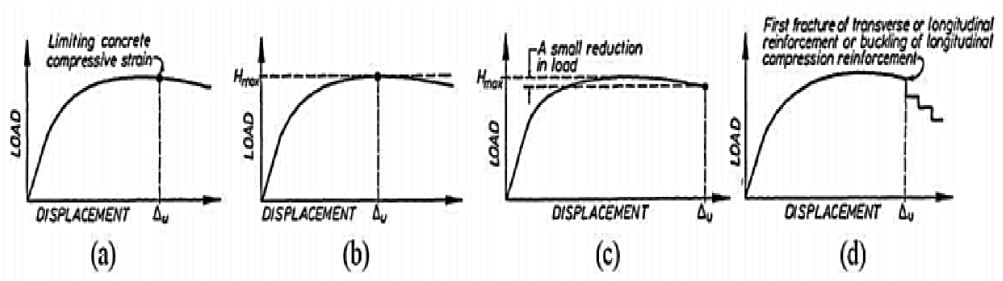


Figure 4.17 Ultimate displacement definition according to [7].

Mathematically the ductility index is the ratio of the displacement at the yield point (δ_y) to the ultimate displacement (δ_u) as in Equation 4.6 and Figure 4.15.

In accordance with the above mentioned, ductility factor of all twelve concrete beams was calculated as shown in Figure 4.18 to Figure 4.20.

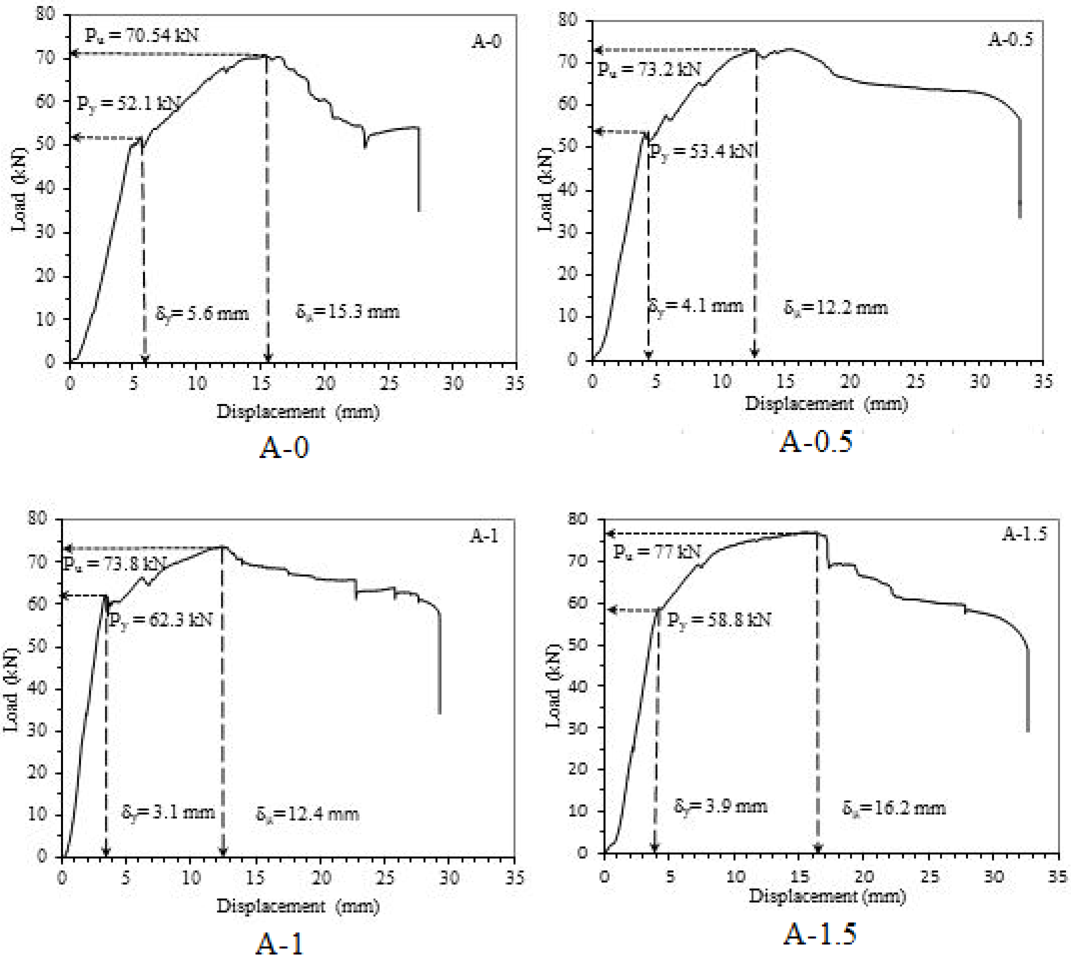


Figure 4.18 Equivalent yield displacement and ultimate displacement for (Group A)

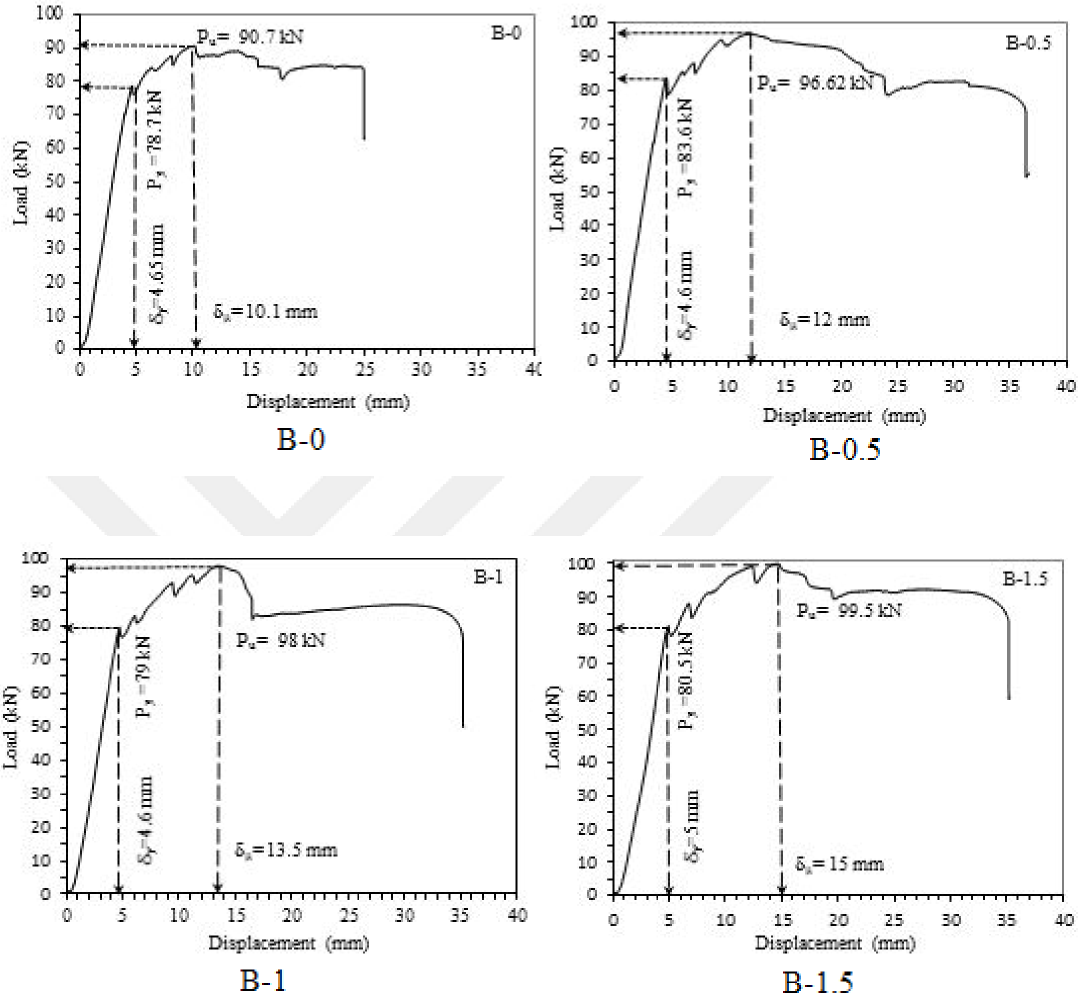


Figure 4.19 Equivalent yield displacement and ultimate displacement for (Group B)

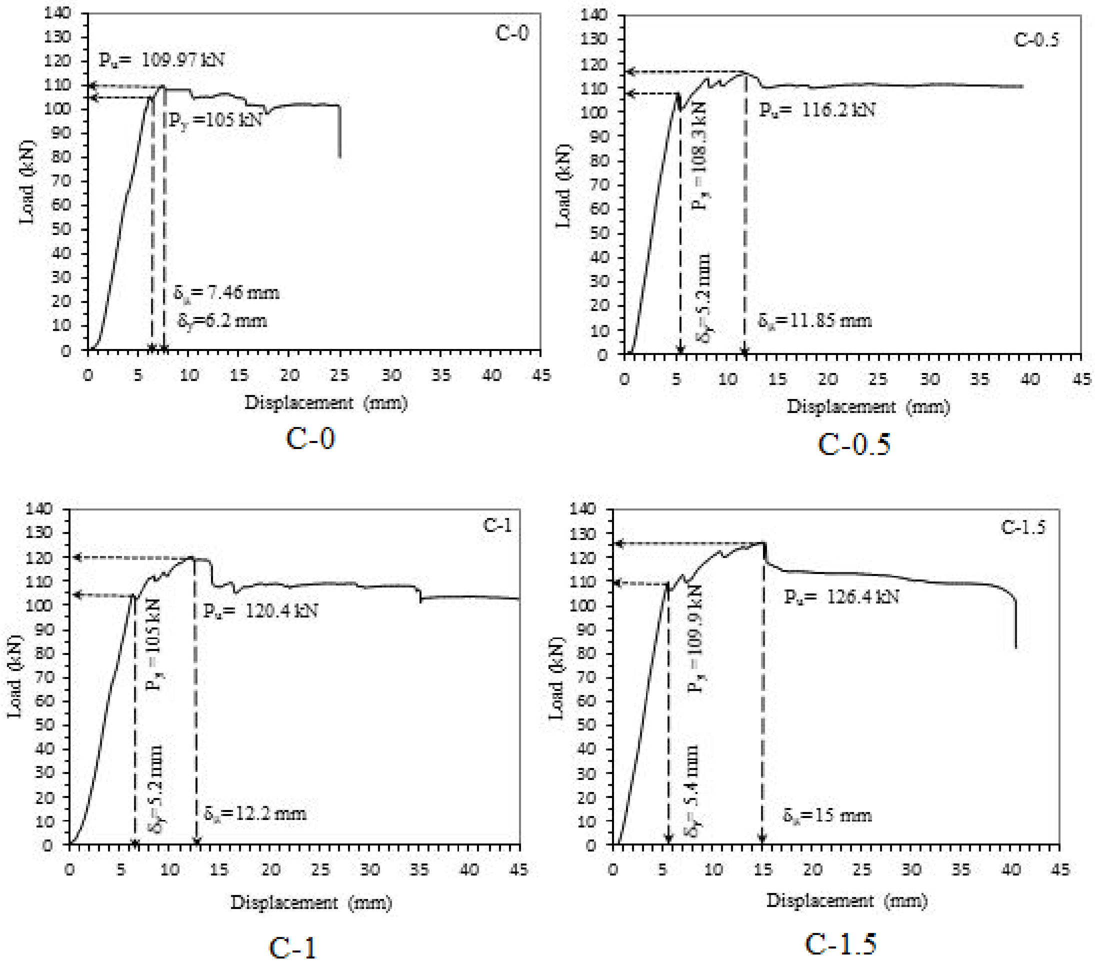


Figure 4.20 Equivalent yield displacement and ultimate displacement for (Group C)

Table 4.3 Ductility factor of FRC beams

Group No.	Beam No.	PVA %	P_y (kN)	δ_y (mm)	P_u (kN)	δ_u (mm)	μ	$\frac{\mu_{fiber}}{\mu_{normal}}$
A	A-0	0	52.1	5.6	70.54	15.3	2.7	1
	A-0.5	0.5	53.4	4.1	73.22	12.4	2.97	1.1
	A-1	1	62.3	3.1	73.80	15.6	4	1.48
	A-1.5	1.5	58.5	3.9	77.06	15.3	4.15	1.53
B	B-0	0	78.7	4.65	90.75	10.1	2.17	1
	B-0.5	0.5	83.6	4.6	96.62	12.0	2.6	1.19
	B-1	1	79	4.6	97.99	13.5	2.93	1.35
	B-1.5	1.5	80	5	99.95	14.5	3	1.38
C	C-0	0	105	6.2	109.9	7.4	1.2	1
	C-0.5	0.5	108.3	5.2	116.2	11.8	2.27	1.89
	C-1	1	105	5.2	120.4	12.2	2.34	1.97
	C-1.5	1.5	109.9	5.4	126.4	15.0	2.77	2.3

Table 4.3 and Figure 4.21 are summarized the test result, and include the comparison between the ductility factor (μ) of fibrous concrete with that of plain concrete. It shows that all fiber types are significantly enhanced the ductility factor (μ). The enhancement are ranging between 10 to 130 %, this is depend on the reinforcement ratio (ρ) and fiber volume fractions (V_f%).

In group A, addition of 0.5 % of PVA with 0.5 % reinforcement ratio (ρ) to the concrete, it improved the ductility factor (μ) about 10 % compared to the plain concrete, while addition 1% of fiber, μ are increased 48 %. Increasing the fiber volume fraction to 1.5 % has increased μ to about 53 %.

Increasing the reinforcement ratio (ρ) from 0.5 % to 0.75 %, for group B, shows less improvement than the previous group (Group A). Where addition of 0.5, 1.0 and 1.5 % for beam B-0.5, B-1.0 and B-1.5 the ductility factor (μ) are increased by 19, 35 and 38 %, respectively, which are less than those obtained from previous group except beam B-0.5, where it increased by 90 % when compared with group A.

Increasing the reinforcement ratio in group C, shows more activity of the fiber than the two previous groups .Where inclusion 0.5 % fiber, ductility factor (μ) was, increased 89 % compared to plain concrete, this is means that increase the (ρ) from 0.5 % to 1.0 % led to an increased the ductility factor (μ) by 790 %. While increase the (ρ) from 0.75 % to 1 % are increased the ductility factor (μ) by 368%. Moreover, increasing the fiber percentage to 1 % are increased the ductility factor (μ) by 97 %, i.e. 102% and 177 % compared with two previous group (Group A and B), increasing the fiber to 1.5 %, shows more improvement than the previous two percentages, where the ductility factor (μ) increased 130% compared to plain concrete, i.e. 145 % and 242 % compared with two previous group (Group A and Group B). This is not surprisingly, because, fiber play important role in balling the fibers, and in turns decreases the effect of bonding and bridging of the cracks.

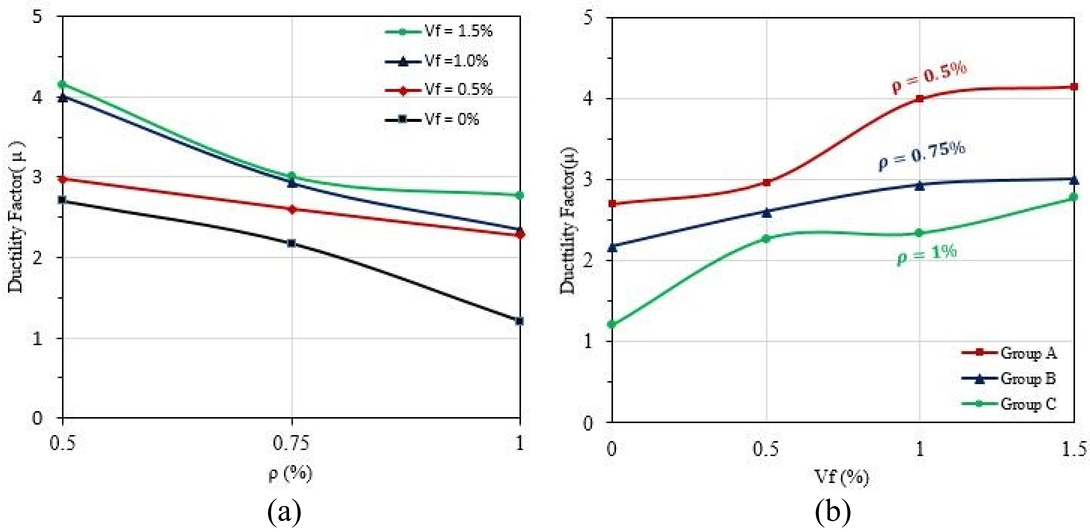


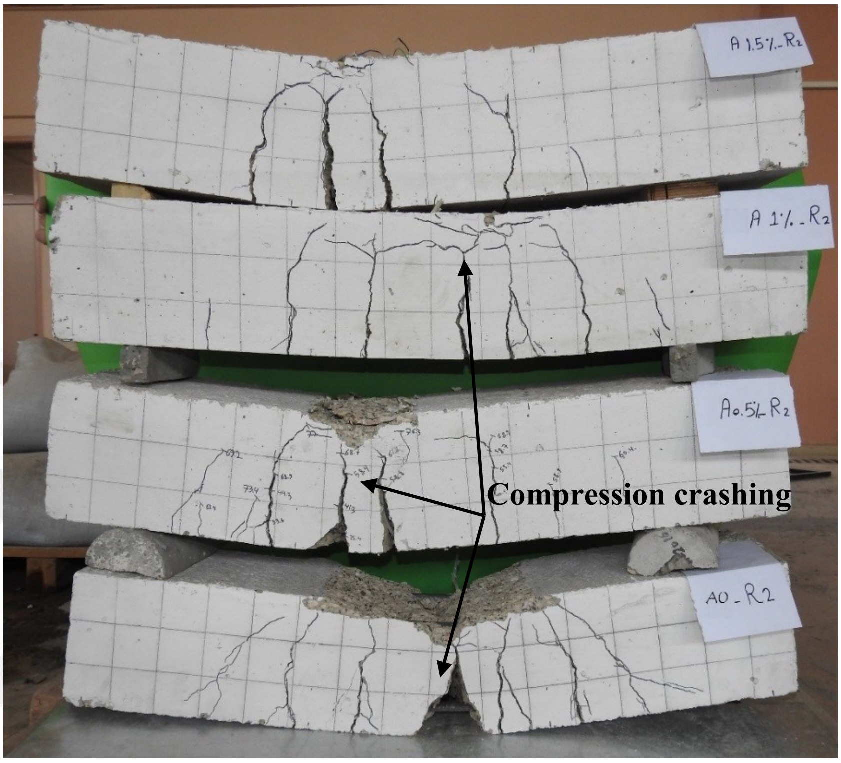
Figure 4.21 (a) Effect of PVA fiber dosages on the ductility (b) Effect of reinforcement ratio (ρ) on the ductility

The interesting finding, were increasing the reinforcement ratio were increasing the effectiveness of the fiber. This lead to the conclusion that the effect of fiber is affected by the behavior of beam of normal concrete, i.e. increasing the brittleness of the beam was increase the effect of fiber. This is not surprisingly, where the activity of fiber is start after initiation of the local cracks, these cracks show early in beams with high reinforcement ratio.

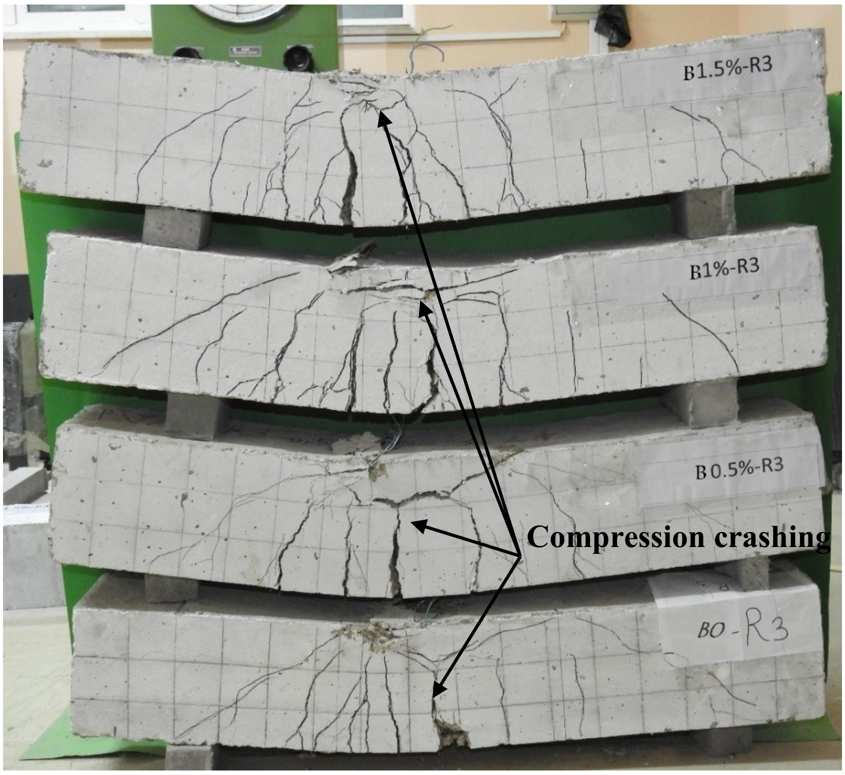
4.7 Failure Patterns

As mentioned in section 4.6, adding PVA fiber are increasing the ductility of the beams, in turn the cracks number are increased. Generally, all beams with a fiber show higher number of cracks compared with the normal beams. This is due to bridging effect that expected from fiber activity after postcracking. This clearly can be seen in beams A-1.5, B-1.5 and C-1.5, where the number of cracks is more than those in remaining beams.

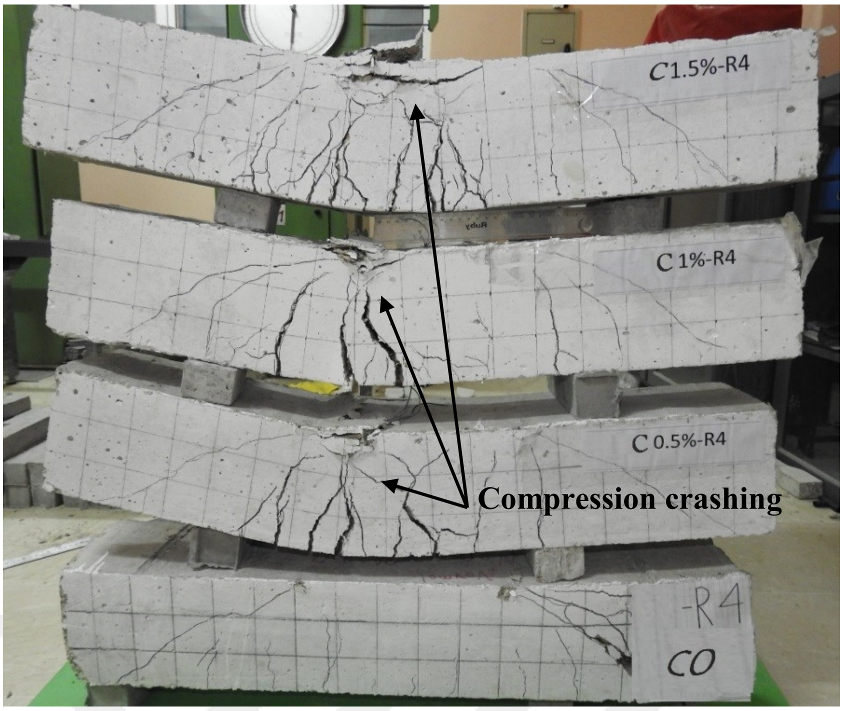
The camera is programmed to take a photo every 5 minutes. From the taken photos, the load required to initiation first crack at the compression zone (the area between the applied load rollers) is listed in Table 4.4. It shows that the inclusion of PVA is not just improving the maximum load resistance, but also increasing the load required to initiate the cracks at the compression zone (top edge of the beam). Furthermore, the inclusion of 0.5, 1.0 and 1.5 % of PVA increased the flexural crack number that increases the curvature of the beam, which leads to reducing the stress on compression zones. The shear cracks at the beam of normal concrete are extended from the support up to the load points, whereas inclusion the fibers decrease the shear effect, this can be recognized from the uncompleted shear cracks at the beams of PVA-FRC Figure 4.22.



Group (A)



Group (B)



Group (C)

Figure 4.22 (A, B and C) Groups Crack patterns of the tested beams

Table 4.4 Initiation and shape of the first crack at compression zone

Group	Specimen	Load to initiate a first compression crack (kN)	Crack distance from upper fiber (mm)	Shape of crack
A	A-0	66	48	V-shape
	A-0.5	68.6	42	V-shape
	A-1.0	70.9	30	Horizontal
	A-1.5	71	-	-
B	B-0	87.3	50	V-shape
	B-0.5	87.54	45	Trapezoidal
	B-1.0	89.2	21	Horizontal
	B-1.5	94.4	15	Very small
C	C-0	105.3	-	-
	C-0.5	110.9	20	Horizontal
	C-1.0	115.3	20	V-shape
	C-1.5	123.7	10	Horizontal

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

A systematic and comprehensive investigation has been undertaken on the effect of PVA fiber addition on mechanical and structural properties of conventional concrete. Concrete mixes containing three tensile reinforcement ratio are used (0.5 %, 0.75 %, 1.0 %) in different fiber volume fractions ranging from 0.5 % - 1.5 % were prepared and tested. These beams have been tested for 4-point monotonic in flexure, to assess their structural properties. The outcomes of the current research on PVA-FRC are presented under the following:

a) Compressive strength is increased significantly by about 44 %, when 1.5 % PVA is used, whereas the tensile strength is not affected.
b) The concrete elasticity of concrete increases with the increase in fiber content and the optimum volume fraction goes 1.5 % with an improvement of about 47% compared to normal concrete.
c) Using of PVA fibers in concrete made from high fine aggregate percentages are increases the load required to initiate the first crack, and improved the beam ultimate strength up to 10 %. In the same manner, compression resistance is increased with increasing the fiber content.
d) Fibres transferred the brittle type failure to the flexural failure by discontinuing the shear cracks.
e) By increasing the post-cracking, the ductility of the beams is increased significantly up to 130 %.
f) The results shown that the reinforcement ratio significantly affects the improvement percentages of the fiber.

g) All beams with a fiber show higher number of cracks compared with the normal beams. Moreover the compression cracks failure also varying in its shape and distance from the upper fiber.

h) The first crack resistance load is increased with increasing the fiber percentages, although, the first crack resistance loads are taken place before the participation of the exterior fiber, but the effectiveness of the interior fiber on the microcrack is playing an important role in whole resistance. The inclusion of PVA increases the first crack resistance load up to 139 %.

5.2 Recommendations for Future Works

A number of future research works beyond the scope of this study are suggested below;

a) In order to utilize the maximum achievable capacity of FRC composites, the fiber matrix interaction is of great significance. Hence, a supplementary study investigating the effect of coated PVA fibers of higher diameters and longer length.
b) An investigation on the mechanical and structural properties of PVA fiber reinforced self-compacting concrete (PVA-FRSCC) is warranted.
c) A long-term study into the creep performance of PVA-FRC structural elements.
d) An investigation on fire exposed properties of PVA-FRC, including; the effect of PVA fibers on compressive strength at high temperatures (roughly 500 °C to 700 °C) and also the effects of PVA fibers on the residual strength (ambient strength after fire exposure).

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