EFFECT OF TEST METHODS ON THE PERFORMANCE OF FIBER REINFORCED CONCRETE WITH DIFFERENT DOSAGES AND MATRICES

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EFFECT OF TEST METHODS ON THE PERFORMANCE OF FIBER REINFORCED CONCRETE WITH DIFFERENT DOSAGES AND MATRICES

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ABSTRACT

EFFECT OF TEST METHODS ON THE PERFORMANCE OF FIBER REINFORCED CONCRETE WITH DIFFERENT DOSAGES AND MATRICES

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Through the last few decades, the idea of adding fibers in to concrete has been quite improved, considering the significant contribution of fibers to the mechanical properties of concrete such as tensile strength, energy absorption capacity and ductility. As a result of many intensive research Fiber Reinforced Concrete (FRC) has become a high-tech material that ensures great performance yet needs efficient design and application. However, the lack of a universally accepted approach and standardized test method for the performance analyses of FRC is one of the main obstacles in the process of providing the optimum combination between the fiber type, fiber volume and the matrix character of the concrete.

This study investigates the performance of polypropylene fiber reinforced concrete with fiber dosages of 3, 6 and 9 kg/m^3 for two different types of concrete, high performance and pervious concrete, by determining the energy absorption capacities through centrally loaded round and square panel tests. For this scope, three specimens for each concrete type and shape were prepared and tested under displacement control mode to obtain the load deflection curve for each specimen. The energy absorption capacities were then calculated for a displacement up to 25 mm. The two test methods also were compared considering the energy absorption capacities, cracking lengths and variability of test results. Then energy relationship between these two test methods was formulated.

Keywords: High performance polypropylene fiber reinforced concrete (HPFRC), Pervious polypropylene fiber reinforced concrete (PFRC), Round panel test, Square panel pest,

ÖZ

TEST METOTLARININ FARKLI DOZAJ VE MATRİSE SAHİP LİF TAKVİYELİ BETON PERFORMANSINA ETKİSİ

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Liflerin betona eklenmesi fikri özellikle son birkaç on yılda , betonda lif kullanımının betonun çekme mukavemeti, enerji yutma kapasitesi ve sünekliği gibi mekanik özelliklerine önemli katkısı düşünülerek geliştirildi. Yoğun araştırmalar sonucunda Lif Takviyeli Beton (LTB), yüksek performans sağlayan, ancak etkili bir tasarım ve uygulamaya ihtiyaç duyan, yüksek teknoloji ürünü bir malzeme haline geldi. Ancak, LTB'un performans analizleri için evrensel olarak kabul gören bir yaklaşımın ve standart test yönteminin olmaması, fiberin türü, lif hacmi ve betonun matris karakteri arasında etkili bir birleşim sağlamanın önündeki ana engellerden biridir.

Bu çalışmada, iki farklı beton türü (yüksek performanslı ve geçirimli beton) için fiber dozajları 3, 6 ve 9 kg/m^3 olan polipropilen fiber takviyeli betonun merkezi yüklemeli yuvarlak ve kare plaka testleri ile enerji absorpsiyon kapasitelerinin performansı araştırılmaktadır. Bu kapsamda, her beton tipi için üç numune hazırlanmış ve her bir numune yük-yer değiştirme grafiği elde etmek için deplasman kontrol modunda test edilmiştir. Daha sonra enerji absorpsiyon kapasitesi, 25 mm'ye kadar olan yer değiştirmeler için hesaplanmıştır. Ayrıca İki test yöntemi enerji absorpsiyon kapasiteleri, çatlak uzunlukları ve test sonuçlarının değişkenlikleri dikkate alınarak karşılaştırılmıştır. Daha sonra bu iki test yöntemi arasındaki enerji ilişkisi formülize edilmiştir.

Anahtar Kelimeler: Yüksek performanslı polipropilen lif takviyeli beton (YPPLTB), Geçirimli polipropilen lif takviyeli beton (GPLTB), Yuvarlak plaka testi, Kare plaka testi,

To My Daughter

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LIST OF ABBREVIATIONS

ACI	: American Concrete Institute
ASTM	: American Society for Testing and Materials
EFNARC	: The European Federation of Specialist Construction Chemicals and Concrete Systems
EAC	: Energy Absorption Capacity
FRC	: Fiber Reinforced Concrete
LVDT	: Linear Variable Differential Transformer
PP	: Polypropylene
PRVSC	: Pervious Concrete
PFRC	: Pervious Polypropylene Fiber Reinforced Concrete
HPFRC	: High Performance Polypropylene Fiber Reinforced Concrete
SFRC	: Steel Fiber Reinforced Concrete
SNFRC	: Synthetic Fiber Reinforced Concrete
GFRC	: Glass Fiber Reinforced Concrete
NFRC	: Natural Fiber Reinforced Concrete

CHAPTER 1

INTRODUCTION

1.1 General

Conventional concrete has many advantages such as low cost, availability and high compressive strength. However, this concrete is also a very brittle material that has some major flaws such as low tensile strength and strain capacities. To overcome these problems, the idea of adding fiber to the concrete was developed as a result of intensive researches, particularly in the last forty years. When the related publications are examined, it can be seen that fibers have a significant contribution to the mechanical properties of concrete such as tensile strength, impact strength, energy absorption capacity and ductility. At the beginning of the 1960s, studies including steel fiber usage in concrete as reinforcement were performed by Romualdi, Batson and Manuel (ACI Committee 544, 2002). After these studies the term fiber reinforced concrete was first used by the American Concrete Institute for the use of randomly dispersed fibers in concrete (Zollo, 1996).

The main role of fiber in concrete is to control the cracking, to change the post-cracking attitude of the material by transferring the loads through these cracks and to ensure the ductility (Bentur and Mindess, 2007). The increase in toughness and load carrying capacity due to the fiber addition fundamentally depends on the interaction between the fibers and the matrix. In order to demonstrate this relationship between fiber and matrix, studies have focused on the behavior of the different fibers in the composite. To improve the concrete performance many different types of fibers have been used to reinforce the conventional concrete such as steel, glass, polypropylene, carbon and natural fibers. The applications of fiber reinforced concrete have been intensified over the years. Application areas of FRC diversified from many different construction fields. Fibers have been used for many different kinds of construction area such as shotcrete linings, tunnel covering, highway and airport pavements, slabs and some structural sections. Synthetic fiber reinforced concrete is usually used for slab applications. However, according to the recent studies, the application areas of synthetic fiber are growing, especially in tunnel linings and shotcrete applications (Afroughsabet et al., 2017). For this, it is highly necessary to make the performance analyzes of FRC more efficient. However, variation of toughness capacity of FRC is a major problem mainly caused by the heterogeneity of the composite. In addition to the heterogeneity of the material, variability is also affected by the fiber type, fiber dosage and test methods. Many test methods can evaluate the performance of fibers relatively to anchoring and pull out strength. However, the test methods used to measure the energy absorption capacity and load deflection behavior of FRC for structural purposes are insufficient and inconsistent (Bentur and Mindess, 2007). This drawback is a major obstacle on the way of the increasingly widespread use of FRC in structural elements. For this, it is substantial to create and use simple, direct, and consistent test methods to measure the behavior of FRC before it is used in construction field.

1.2. Objectives and Scope

The main aims of this thesis are to examine the performance of synthetic fiber reinforced concrete with fiber dosages of 3, 6 and 9 kg/m^3 for two different types of concrete matrix (one high strength and one very low strength) by determining the energy absorption capacities through centrally loaded round and square panels. As for the very low strength concrete, pervious concrete was selected. For this scope, three specimens for each concrete type, fiber dosage and specimen shape were prepared and tested under displacement control mode to obtain the load deflection curve for each specimen. The energy absorption capacity is then calculated for a displacement up to 25 mm. In addition to this, the two test methods were compared taking into account the energy absorption capacities, cracking lengths and variability results. And then energy relationship between these two test methods was formulated.

This thesis contains five chapters. Chapter 1 presents brief introduction and an overview of FRC with the aims of this thesis.

Chapter 2 contains background knowledge and a literature review about the different types of fiber reinforced concrete, the relation between the composite matrix and the fibers, the characteristics properties of high performance polypropylene fiber reinforced concrete (HPFRC) and pervious polypropylene fiber reinforced concrete (PFRC) and the main characteristics of round panel test and square panel test methods.

In chapter 3, the experimental program and the test methods are explained in addition to the material properties and the mixture designs of the concrete samples.

The results and discussions of the tests applied during this experimental procedure are introduced in chapter 4. The analyses of the results are also explained in this chapter.

Finally, chapter 5 concludes the thesis with significant inferences of the research and gives recommendations for future work related to this topic.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1 History of Fiber Reinforced Concrete

The use of fibers in structural material is not a new approach. The idea of utilizing fibers in order to improve the mechanical performance of the materials is about 5000 years old. Since ancient civilizations, natural fibers like animal hair, straws and herbal fibers have been used in sun-dried clay bricks to improve material toughness performance and cracking resistance (ACI Committee 544, 2002).

In the early 19th century, after Portland cement concrete started to be used extensively for construction, fibers were used to overcome the most important defects of concrete, which were the low ductility and low tensile strength. In the middle of the 19th century, Joseph Lambot added continuous fibers (wires) into the Portland cement concrete (Neville, 2011). After this, a new approach of reinforced concrete has been developed. And for this day, compared to continuous steel reinforcing, the concept of utilizing discontinuous fibers as a part of concrete is still an active research area.

The research about the use of fiber to reinforce concrete was very limited until the 1960’s. At the beginning of the 20th century, asbestos fibers were used in cement composites. However, after asbestos was declared to be a hazardous material, concrete society had to find a new replacement. Starting at 1960’s, natural and man-made engineering fibers such as steel, glass and synthetic fibers started to be used in concrete. After 1960’s, fiber reinforced concrete was one of the most important subject of concrete research field. Today, the studies about fiber reinforced concrete are still being carried on (ACI Committee 544, 2002).

2.2 Fibers

Fibers are raw materials that have length, flexibility, elasticity and durability (Mehta and Monteiro, 2006). They can be obtained from natural sources or manufactured. While naturel fibers are used directly as obtained from their sources (such as animals, plants and minerals), fabricated fibers can be developed and modified to meet specific engineering properties. Fibers are materials that have a large length compared to the cross section. Sometimes, according to the material type and production form, this kind of materials can be named as wires or bristles.

Despite the emergence of fabricated fibers at the end of the 19^{th} century, synthetic fibers are not more than 60 years old. Nevertheless, in this relatively short period of time, fibers have become indispensable for concrete (Ekincioğlu, 2003).

2.2.1 Fiber Types

There are many different types of fibers in terms of properties and uses. These fibers can be classified in various ways, but basically they can be classified as follows (Chawla, 1998):

- Natural Fibers
    - Animal Origin Fibers (Horse hair)
    - Plant Origin Fibers (Wood cellulose, Bamboo, Sisal)

- Artificial Fibers
    - Synthetic (Polymer) Fibers (Polypropylene, polyethylene)
    - Steel Fibers
    - Glass and Ceramic Fibers
    - Carbon
    - Basalt

Table 2.1 shows the mechanical characteristic of some different types of fibers. According to this table steel and glass fibers show higher tensile strength performance compared to polymer fibers.

Table 2.1 Mechanical characteristic of the fibers (Sarzolejo et al., 2013)

Fiber	Diameter(μm)	Density (10^3 kg/m^3)	Young's modulus (kN/mm^2)	Tensile strength (kN/mm^2)	Elongation at break (%)
Steel	5 - 500	7.84	200	0.5-2	0.5 - 3.5
Glass	9.3 - 15.2	2.60	70-80	2.1 - 4.3	2.3 - 3.5
Asbestos	0.02 - 0.04	3.00	180	3.3	2.3 - 3.7
Polypropylene	20 - 200	0.90	5.5 - 7.3	0.5-0.75	8
Nylon	-	1.10	4	0.9	13-15
Polyethylene	-	0.95	0.3	0.0007	10
Carbon	9	1.90	230	2.6	1
Kevlar	10	1.45	65-133	3.6	2.1 - 4.3
Acrylic	18	1.18	14-19.5	0.4 - 1	3

Artificial fibers are produced with various geometrical forms to enhance the bond between the fiber and the concrete matrix. A proper geometrical type of fiber can avoid fiber bundling during mixing operation (Bothma, 2013). The most used steel fiber geometries, for example, can be seen in Figure 2.1

Fibers can be also classified as micro and macro fibers. Micro fibers are designed to increase the early age flexural and tensile strengths of concrete and also to improve the resistance to tensile stresses caused by drying and plastic shrinkage. The dimensions of micro fibers are about 2 to 10 mm in length and 0.1 to 1mm in diameter. On the other hand, macro fibers are usually used to enhance the mechanical performance of the concrete. Generally, macro fibers have lengths between 20-60 mm. They are usually used for stress bridging (link the crack edges) and to contribute to the fracture toughness of hardened concrete (Bothma, 2013).

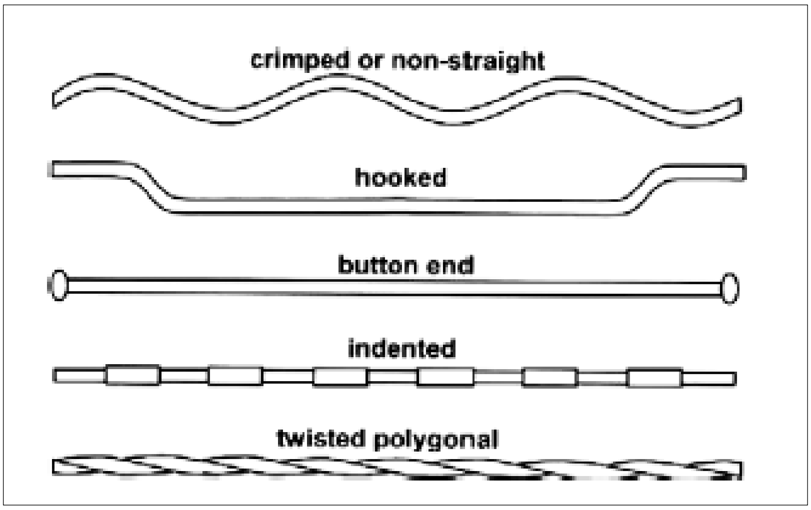


Figure 2.1 Some steel fiber types (Brant, 2008).

Besides their diameter and length another important parameter is the fiber aspect ratio (L/D) which is calculated as fiber length divided by fiber diameter. This ratio varies from 40 to 1000, but is generally less than 300 (Zollo, 1996). The fiber aspect ratio and the amount of fiber added to the mixture greatly affect the workability and mechanical properties. Researches related with fiber aspect ratio have indicated that the addition of fibers reduces the workability of fresh concrete if the aspect ratio is large (Soroushian and Bayasi, 1991).

2.2.2 Natural Fibers

The oldest known natural fibers used to obtain fiber reinforced composites are horse hair and straw. Even nowadays, straw can be seen in the construction of adobe houses. A big advantage of natural fibers is that they are accessible in huge amounts almost everywhere in the world and in a regular sustainable source for every country. Moreover, compared to the other types of fibers, the production of natural fibers can be done even with limited technical ability and energy (ACI Committee 544, 2002).

The main types of natural fibers are sisal, bamboo, wood, coconut, asbestos and plant fibers. These fibers have been used in reinforced concrete for many years (Mabsaut, Hamad and Khatib 2010). Many different studies have investigated the natural fibers in terms of their mechanical properties. Except for some negative consequences about their durability performance, generally promising results were obtained from these studies (ACI Committee 544, 2002). The problems related to durability were mainly caused by the swelling of the fibers because of moisture presence in the reaction area. Recent studies have focused on solving this durability issue (Brant, 2008).

2.2.3 Synthetic Fibers

R&D studies in chemical and textile industries are the main source of synthetic fibers. These fibers are obtained from polymers which are present in various forms. Major types of synthetic fibers are: polypropylene, polyethylene, acrylic, aramid, nylon and carbon (ACI Committee 544, 2002; Portland Cement Association, 1998).

The use of synthetic (polymer) fibers in construction materials has been increasing rapidly all around the world. One of the most preferred synthetic fibers for cementitious composites is polypropylene. The reason of this choice is the low weight and low production cost of polypropylene fibers (Manolis et al., 1995). Straight and crimped forms of fibers are the most preferred shapes for both steel and synthetic fibers especially for macro fibers. On the other hand, for micro fibers generally short straight shape is preferred. According to the strength and modulus of elasticity, the fundamental characteristic of synthetic fibers can change on a large scale (Bentur and Mindess 2007). Some of the characteristic properties can be seen from Table 2.2 for main synthetic fibers.

Table 2.2 Characteristic properties of synthetic fibers (Bentur and Mindess 2007).

Fiber	Diameter(μm)	Specific gravity	Tensile strength (GPa)	Elastic modulus (GPa)	Ultimate elongation
Acrylic	20-350	1.16-1.18	0.2-1	14-19	10-50
Aramid	10-12	1.44	2.3-3.5	63-120	2-4.5
Carbon	8-9	1.6-1.7	2.5-4.0	230-380	0.5-1.5
Nylon	23-400	1.6-1.21	0.75-1	4.1-5.2	16-20
Polyester	10-200	1.14	0.23-1.2	10-18	10-50
Polyethylene	25-1000	1.34-1.39	0.08-0.6	5	3-100
Polyolefin	150-635	0.92-0.96	275	2.7	15
Polypropylene	20-400	0.91	0.45-0.76	3.5-10	15-25
PVA	14-650	0.9-0.95	0.8-1.5	29-36	5-7
Steel	100-1000	7.84	0.5-2.6	210	0.5-3.5
Cement matrix	-	1.5-2.5	0.003-0.007	10-45	0.02

2.2.3.1 Polypropylene Fibers

Polypropylene (PP) is a thermoplastic polymer used in a broad range of applications. PP is obtained by polymerizing monomer units of polypropylene molecules into extended polymer chains with catalyst under low pressure and heat (Brown, Shukla and Natarajan 2002). Simply carbon and hydrogen combine to form the structure of a polypropylene chain as demonstrated in Figure 2.2

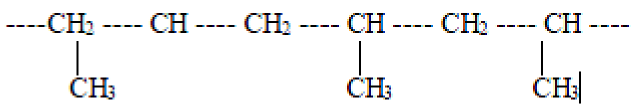


Figure 2.2 Formation of polypropylene (Brown et al., 2002).

As it is shown in Table 2.2, some synthetic fibers have low modulus of elasticity such as PP and Polyethylene and some others have high modulus such as carbon and aramid. In a study about bond relation between cement matrix and fiber, it was stated that to improve the tensile and flexural strength of concrete, fibers with a modulus of elasticity higher than the concrete are needed (Carnovole, 2013). For this, although the bond strength between PP and concrete is insufficient because of the lower modulus elasticity of polypropylene fiber, it is widely used in concrete owing to its multiple advantageous properties (Ludirdja and Young, 1993).

Wang, Backer and Li (1987) have reported that polypropylene fibers can be produced in different shapes and dimensions very easily. This important ability increases the bond strength between the fiber and concrete. It has also a positive impact on the cost of the fiber production. On the other hand, these fibers show sufficient durability performance against corrosion and alkalies. The tendency of the steel fiber to corrode and make damages to the concrete mixers and pumps also leads to an increase in the use of PP fibers. (in ACI Committee 544, 2002; Deng et al., 2016). Polypropylene fibers show poor resistance performance against fire and sun. However, concrete matrix maintains a protective cover, helping to increase resistance performance against fire and other external factors. Moreover, sometimes PP fibers are used especially to improve the fire resistance of concrete when used in tunnel linings (Bentur and Mindess 2007).

2.2.4 Steel Fibers

The first modernist studies about steel fiber usage in concrete as reinforcement were achieved by Romualdi, Batson and Manuel in the beginning of 1960’s (Portland Cement Association, 1998). Steel fibers designed for cementitious composite are defined as structures which are adequately small, short and discrete for homogeneously dispersed in fresh concrete mixture during regular mixture procedure (ACI Committee 544, 2002). In ASTM A 820, steel fibers are classified in four different ways:

- Cold-drawn wire.
- Cut sheet.
- Melt-extracted.
- Other fibers

Generally, steel fibers have diameters varying from 0.25 to 1.00 mm. Moreover, the length of the steel fibers ranges from 5 to 75 mm (Portland Cement Association, 1998). Aspect ratios of steel fibers usually change from 25-100. The bond strength between fiber and concrete is a very important consequence of the aspect ratio of the fibers (ACI Committee 544, 2002). Steel fibers may have tensile strength varying from 300 to 2800 MPa, and can also have ultimate elongations changing from 0.5% to 3.5% (Yurtseven, 2004). ASTM A 820 specified the minimum tensile yield strength of steel fibers as 345 MPa.

2.2.5 Glass Fibers

First researches about the use of glass fiber in concrete were done at the beginning of the 1960s. In these researches, borosilicate glass fibers (E-glass) and soda-lime-silica glass fibers (A-glass) were used (PCA, 1998). However, later studies showed that E-glass and A-glass fibers decrease the strength of concrete very rapidly because of the high alkalinity of the matrix. For this, in terms of durability, using A-glass and E-glass fiber in concrete were found inappropriate. After a series of studies, a new type of glass fiber, alkali resistant fiber (AR-glass fiber), showed better long term performance when compared to other types of glass fibers. Today alkali resistant glass fiber is the most widely used glass fiber type in concrete (ACI Committee 544, 2002).

2.3 Interaction between Fiber and Cement Matrix

The interaction between the matrix and fiber is an essential property that affects the performance of the fiber reinforced cement composites. To understand this interaction, researchers needed to determine the behavior of the fibers within the matrix. The main properties that determine the relation between fiber and matrix can be listed as follows (Shah and Balaguru, 1992):

- Matrix condition: cracked or not,
- Fiber type (Steel, Synthetic, Natural…),
- Geometrical characteristics of the fiber (Micro Fiber, Macro Fiber…),

- Surface properties of the fiber (Twisted, Crimped, Round Surface…)
- The relation between elasticity modulus of the fibers and the matrix,
- Aspect ratio of the fiber,
- Long term performance of the fiber,
- Test method (Beam Tests, Panel Tests…).

2.3.1 Interaction between Fiber and Non-Cracked Matrix

At the beginning of the loading, this kind of interaction is seen in almost all the fiber reinforced concrete. A simple fiber-matrix system with a single fiber is shown in Figure 2.3. During unloaded condition, the stresses in the matrix and the fiber are considered zero as shown in Figure 2.3a.

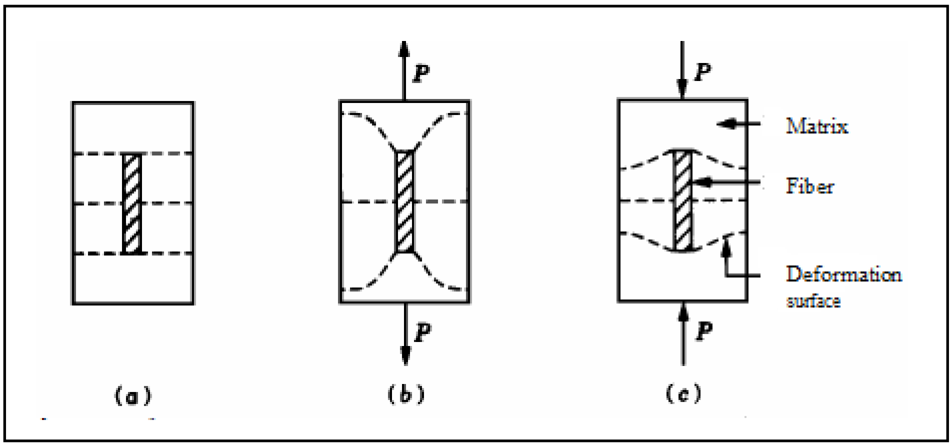


Figure 2.3 Interaction between non-cracked matrix and fiber a) unloaded b) tension forces c) compression forces (Shah and Balaguru, 1992).

Applying tensile and compressive stresses or exposing the concrete to temperature changes creates stresses and deflections. When a load applied on the matrix, some amount of the load affects the surface of the fiber. Due to the different elasticity modulus of the fiber and the matrix, shear stresses are formed along the fiber surface. These shear stresses help to transfer some of the loads to the fibers. If the elasticity modulus of the fiber is larger than the matrix, the deformation of fiber zone will be smaller as shown in Figure 2.3b and Figure 2.3c. Generally, this kind of behavior is obtained with steel and mineral fibers. If the elasticity modulus of the fiber is smaller than the matrix, the deformations at the fiber zone will be bigger. Bigger deformations commonly occur in polymer and natural fibers (Ekincioğlu, 2003; Bentur and Mindess, 2007).

2.3.2 Interaction between Cracked Matrix and Fiber

The matrix will crack when the tensile stress exceeds its tensile strength (Figure 2.4). The most important role of the fibers in concrete appears in the post cracking section. When the matrix cracks, the fibers will begin to transfer the load between both sides of the crack. In other words, the fibers serve as a bridge over the cracks to transmit the loads. If the fibers can transfer a sufficient amount of the load, the crack will not widen. Fibers have different ways to absorb energy and prevent crack widening. These mechanisms can be seen in Figure 2.5.

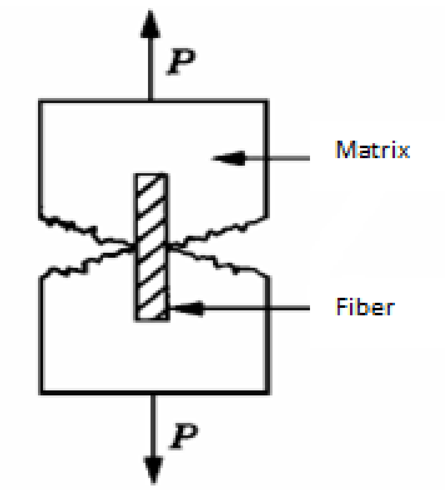


Figure 2.4 Cracked matrix-fiber relations (Shah and Balaguru, 1992).

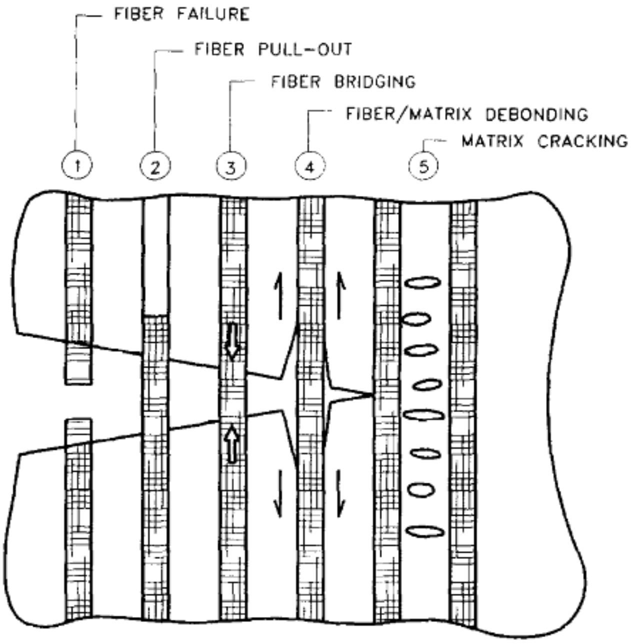


Figure 2.5 Fiber and matrix mechanism (Zollo, 1997).

2.4 Fiber Reinforced Concrete

Fiber reinforced concrete (FRC) is defined as concrete which made of hydraulic cement, aggregate, water and discontinuous discrete fibers. FRC can also have pozzolans, chemical and mineral admixtures that are usually added to concrete. Different kind of fibers such as steel, synthetic, glass and natural fibers can be used in FRC (Mehta and Monteiro, 2006). ACI Committee 544 has classified fiber reinforced concrete into four categories based on the fiber materials. These groups are steel fiber reinforced concrete (SFRC), synthetic fiber reinforced concrete (SNFRC), glass fiber reinforced concrete (GFRC), and natural fiber reinforced concrete (NFRC) (ACI Committee 544, 2002).

The use of fiber reinforced concrete is increasing rapidly year after year. The application areas of FRC vary according to the construction type. SFRC has been used for shotcrete linings, highway and airport pavements, slabs and some structural sections. GFRC generally used for architectural covering panels because of its lightweight and smooth surface structure. SNFRC usually used for slab applications, but according to new studies, its application areas are growing. Unlike the other fiber reinforced concretes, NFRC is used for low volume and low cost applications (ACI Committee 544, 2002).

Plain concrete shows poor tensile strength performance and limited strain capacity, which is the main reason for using reinforcement in concrete. After remarkable studies from Romualdi, Baston and Mandel in the beginning of the 1960's, it was significantly understood that using fiber can improve the tensile ductility of concrete very effectively (Mindess, 2006). In later years, different kinds of fibers have been used to increase concrete's performance. Previous studies have shown that micro cracks in concrete are responsible for low tensile and flexural strength of concrete. Using reinforcing steel and fiber in concrete minimize these weaknesses (Erdoğan, 2005). Other studies have shown that fibers can increase residual tensile strength as a result of fiber link mechanism between the cracks (Buratti, Mazzotti, Savoia, 2010). All of those studies show that tensile and flexural strength of concrete can be increased by adding fibers to the concrete mixture. The fibers can restrain the propagation of micro cracks which will provide a significant contribution to tensile strength of concrete.

The load-deflection behavior of fiber reinforced matrix and plain concrete matrix under applied loads can be seen in figure 2.6. When ultimate flexural strength of plain concrete is exceeded, concrete breaks down at once. On the other hand, FRC can carry substantial amount of loads under larger deflections, and would not suddenly fail after the first crack formation (Mehta and Monteiro, 2006). This will also increase the toughness, which is defined as the ability of the material to absorb energy at the time of deformation. Toughness is demonstrated by the area under the load-deflection curve (Erdoğan, 2005; Soutsos et al., 2012).

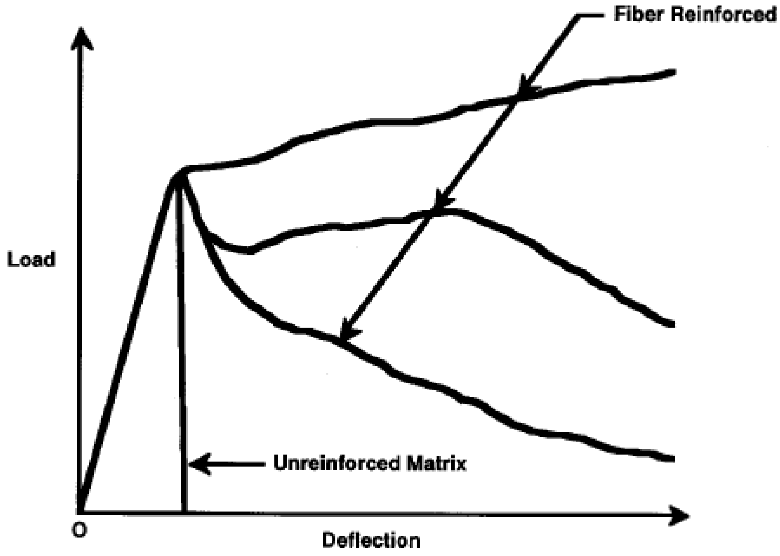


Figure 2.6 Load – deflection relation between unreinforced matrix and fiber reinforced matrix (ACI Committee 544, 2002).

Together with the matrix characteristic, fiber type, fiber volume, fiber shape and fiber distribution, all affect the performance of FRC. Fiber volume is one of the most important factors affecting the performance of FRC. Mainly three types of fiber volume fractions can be seen in FRC. Low volume fiber usage in concrete (< 1 percent), generally used in slabs and pavements to decrease shrinkage cracking. It is also used instead of steel reinforcement to reduce the cost of construction (Mehta and Monteiro, 2006). Moderate fiber volume fraction (between 1 and 2 percent) is usually used in structural applications like linings that need high toughness and energy absorption capacity. In recent years high volume fraction (>2 percent) has begun to be used to get strain-hardening attitude. These kinds of mixtures are generally referred as high performance fiber reinforced concretes (Mehta and Monteiro, 2006).

Fiber geometry and distribution are also important parameters that affect FRC performance. The purpose of producing the fibers in different geometries is to increase the efficiency of the fibers by strengthening the mechanical bond between the matrix and the fiber. Furthermore, the irregularity of the outer faces of the fibers causes strong mechanical link between the fiber and the concrete matrix. Fast solidification also causes this kind of fibers to have a rough surface, which increases the resistance to adhesion and frictional force. In addition to this, the fiber content used in the production should not exceed an optimum value. If the fiber content is high, mixing and placement problems occur and the fibers are agglomerated in the mixture. These fiber balls cause weak spots in the matrix. The use of optimum amount of coarse aggregates, dry mixing of the fibers and the use of fibers with ideal aspect ratio in the mix can provide a homogeneous dispersion of the fibers in the matrix (Afroughsabet et al., 2017; Soroushian and Bayasi, 1991).

2.5 High Performance Fiber Reinforced Concrete

Different types of fiber reinforced cementitious composites, which have great flexibility and self-strengthen before fracturing, are generally named as high performance fiber reinforced concrete. HPFRC was improved to resolve conventional concrete’s weaknesses such as low tensile strength, low flexural strength and long term durability. In addition, adding fibers into cementitious mixture causes decrease in the shrinkage and creep deformation of the concrete. The properties of the materials used in the HPFRC vary according to the availability of the materials in the local facilities and the desired properties (Afroughsabet et al., 2017).

As in conventional concrete, failure of FRC under different types of loading starts by tensile cracking of the matrix where tensile strains exceed tolerable ratios. However, the later fracture mechanism of FRC differs depending on various parameters of the fiber and the matrix. If the concrete fails immediately after matrix cracking, it is because of the deficient fiber usage or insufficient fiber lengths which make the fibers unable to transfer the stresses through the cracks. If the concrete continues to carry further loads at a decreasing ratio after the peak load, this post-cracking behavior is ensured by the pull-out of fibers from the cracked surfaces. In this type of fracture situation FRC shows strain softening (Bentur and Mindess, 2007; Cengiz and Turanli, 2004). HPFRC display strain- hardening behavior after the first crack. The fibers in HPFRC show equal or greater tensile performance than the matrix in the cracking zone, which make the concrete continues to carry the increasing tensile stresses. This strain-hardening behavior depends also on the bond between the matrix and the fibers (Bentur and Mindess, 2007). Figure 2.7 demonstrates the differences between strain softening and strain hardening attitudes mentioned above.

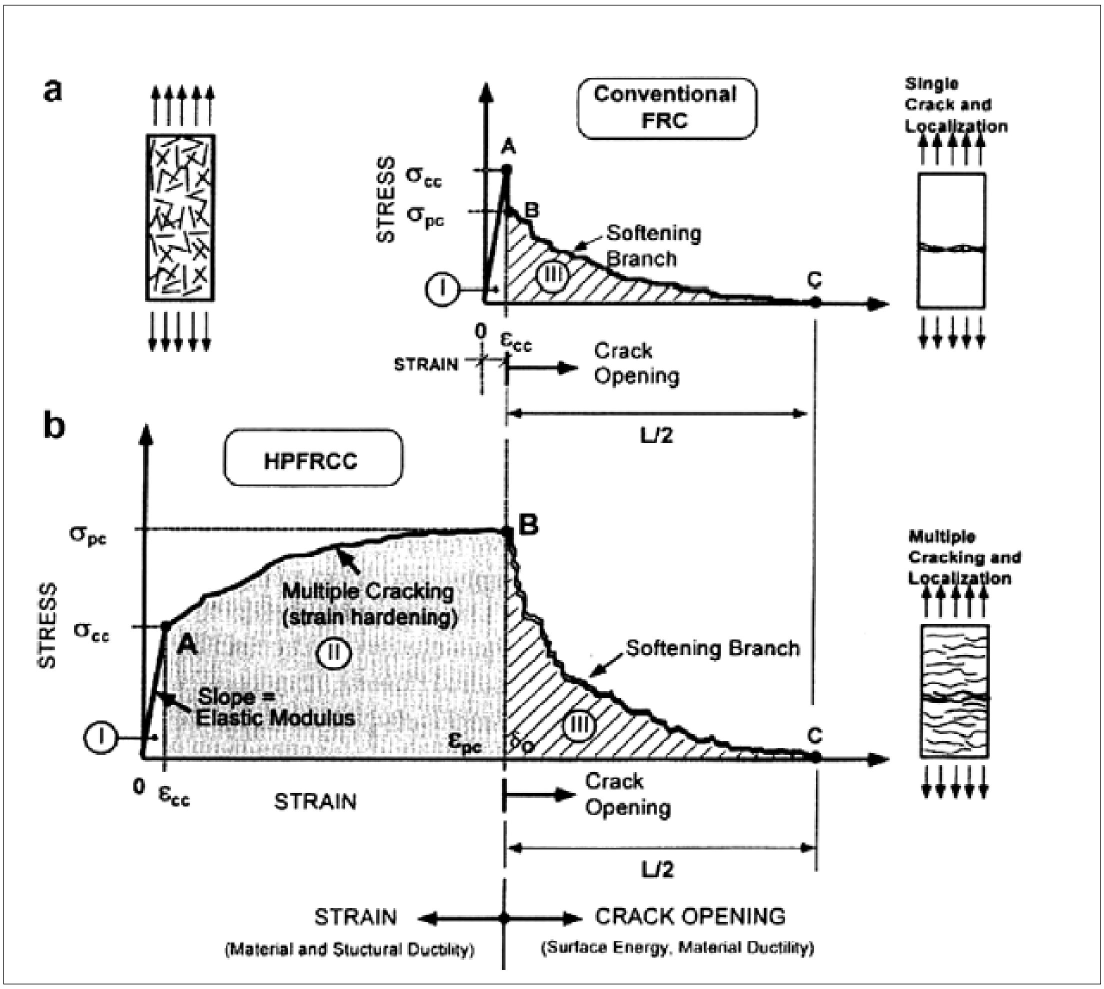


Figure 2.7 Strain hardening and strain softening behavior of HPFRC and FRC (Brandt, 2008)

2.6 Polypropylene Fiber Reinforced Concrete

The studies including the use of small volumes of polypropylene fiber in the mid-60's showed a significant enhancement in the toughness and crack control of the concrete (Zollo, 1996). After this result, significant amount of studies have been conducted on polypropylene fiber reinforced concrete from the end of the 60's to the present day. Along with the result of these studies, polypropylene fibers became an important alternative to improve concrete properties (ACI Committee, 2002). The results generally showed large differences in both plastic and hardened properties of the concrete. These differences largely depend on the fiber volume, fiber geometry, fiber production method and matrix content (PCA, 2008).

2.6.1 Fresh Properties of PFRC

Polypropylene fibers have been used in concrete in many different forms and methods. These fibers can be used as discrete chopped fibers or continuous films. According to the results of some researches made with chopped discrete fibers, the proportion of the fibers used in concrete mixture should be kept low. Litvin (1985) have shown that the use of 51 mm length of chopped polypropylene fiber causes 75 mm slump loss for every 0.1% addition by volume. Moreover, in another study, it has been found that even with the use of high polypropylene content (2.0 percent by volume), a sufficient amount of workability can be achieved by using the suitable amount of plasticizer (Zheng and Feldman, 1995). Nevertheless, concrete mixtures containing polypropylene fibers can be placed utilizing traditional techniques. However, extra care should be taken to ensure that entrapped air is removed from the concrete and the proper density is obtained (PCA, 2008).

2.6.2 Hardened Properties of PFRC

It is generally accepted that the use of polypropylene fiber at different proportions has no significant effect on the compressive strength of the concrete. However, Ramakrishnan and Wu (1989) reported that there might be a decrease in the compressive strength of concretes with high PP fiber content. The main reasons for this are poor workability, higher entrapped air and low unit weight. They also suggested that the optimum mixing ratios should be determined by trial mixes when high PP fiber content is used (ACI Committee 544, 2002). However, the studies have generally shown that low fiber content including 0.1 to 1.0 percent by volume did not cause a decrease in the strength of the concrete (Zheng and Feldman, 1995). Along with the compressive strength values, there is no significant effect of the use of PP fiber in concrete mixtures on the flexural strength of the concrete. As stated in the study of Zollo (1984), a little improvement was observed in the flexural strength of concrete with fiber percentages of 0.7 to 2.6 by volume. Moreover, a slight reduction was obtained in the flexural strength of concrete samples that have a fiber percentage between 0.2 to 0.3 percent by volume (ACI Committee 544, 2002).

Generally, low volume PP fiber content in concrete is used to reduce plastic shrinkage cracking. At the same time, there is no significant effect of the use of PP fiber in small quantities on the strength values of the concrete. According to the test results obtained by Zollo, Ilter, and Bouchacourt (1986), the existence of PP fiber from 0% to 0.3% by volume had little effect on compressive, tensile and flexural strength of test concretes. As shown in Table 2.3, flexural and tensile strength of specimens increased very little with an increase in fiber percentage by volume. However, the compressive strength decreases slightly with an increase in the fiber content (PCA, 2008; Zheng and Feldman, 1995).

Table 2.3 Compressive, tensile and flexural strength Properties of PFRC and plain concrete (PCA, 2008)

Fiber volume content (%)	Compressive strength (MPa)	Splitting tensile strength (MPa)	Flexural strength (MPa)
0	39	2.8	5.9
0.1	36	2.8	6.1
0.2	35	2.8	6.5
0.3	36	3.5	6.2

High fiber volume usage of PP fiber is more important for mechanical properties of concrete especially to improve ductility and toughness performances. Various studies have been carried out about high PP fiber usage in concrete (PCA, 2008). As a result of these researches, it was found out that using high volume of PP fiber in cement composites enhances energy absorption capacity substantially.

In a study conducted by Naaman, Shah, and Throne (1984), concretes reinforced with chopped PP fibers exhibited great post-crack attitude when produced under ideal circumstances like sufficient workability with high fiber content. Moreover, it has been observed that using twisted PP fibers strongly enhanced the bond between the matrix and the fiber (PCA, 2008). The load-deflection graph of that study can be seen in Figure 2.8.

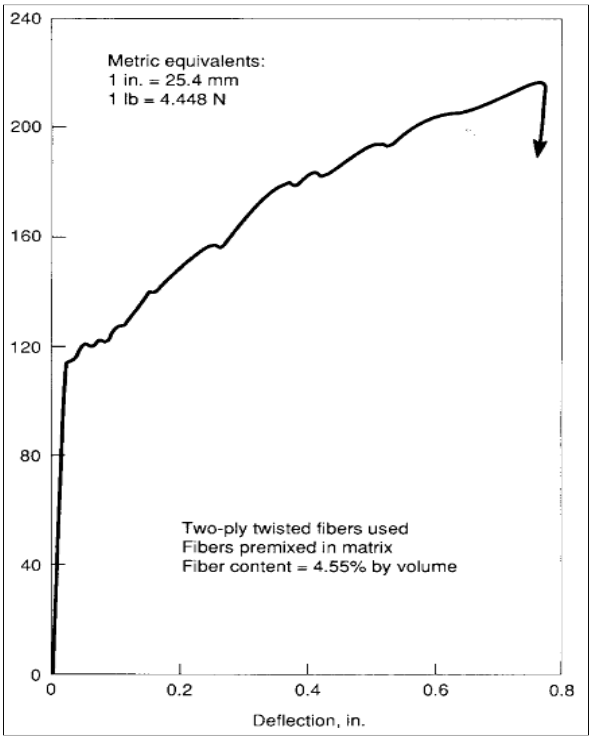


Figure 2.8 Load – deflection graph for concrete containing chopped PP fiber (ACI Committee 544, 2002)

In a similar study, Dave and Ellis determined that chopped PP fiber concretes can carry more loads over the first cracking load. According to the test results, it was seen that the increases in the fiber amount led to a decrease in the initial crack load and an increase in the ultimate strength of concrete (PCA 2008).

2.7 Pervious Concrete

Pervious concrete is a special type of concrete that contains coarse aggregate, a little or no fine aggregate, hydraulic cement, admixtures and water. When compared to conventional concrete, pervious concrete shows a significant amount of water permeability. The void content generally varies from 18% to 35% with a compressive strength of 2.8 MPa to 28 MPa. Depending on the aggregate gradation and the density of the mixture, water permeability rate of pervious concrete will fall into the range of 81 to 730 liters per minute per square meter (ACI Committee 522, 2006; Bonicelli et al., 2016).

Pervious concrete has been used since the middle of the 19th century. However, until the middle of 1920s there were no publications about it. Before the Second World War, pervious concrete was used only as building material in houses, but after the war, the usage area of pervious concrete expanded greatly. By the beginning of the 1950's, pervious concrete has begun to be used in different construction applications in many parts of the world, especially in Europe (ACI Committte 522, 2006).

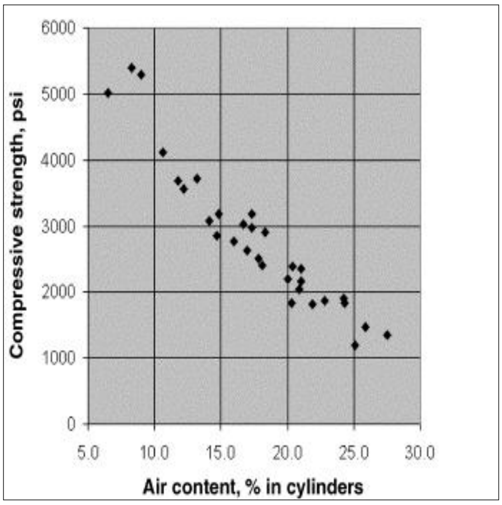
2.7.1 Properties of Pervious Concrete

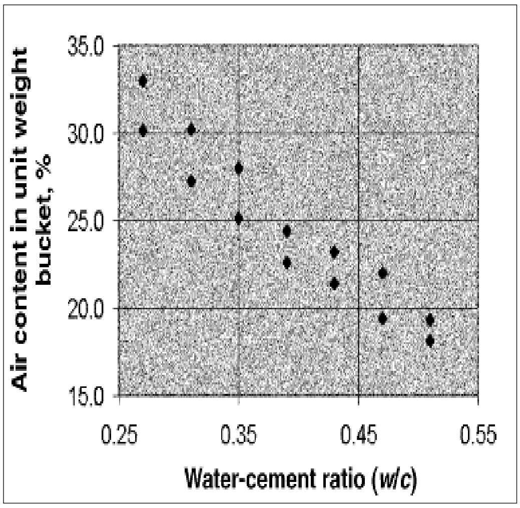
The structure obtained by mixing uniform-sized coarse aggregate, cement, water and admixtures has much more void ratio than conventional concrete. These large voids lead to water migration at a much higher rate than normal concrete. Pervious concrete can also be considered as a special type of porous concrete. Porous concrete can be basically divided into two groups, lightweight aggregate concretes and pervious concrete. Unlike pervious concrete, the porosity of lightweight aggregate concrete is present in the aggregate part of the mixture. Lightweight aggregate concrete can be made by utilizing highly porous aggregates. Because of this void structure, lightweight aggregate concretes have disconnected voids. On the other hand, pervious concrete include interconnected voids, that causes quick water transition through the concrete (ACI Committee 522, 2006; Hesami et al., 2013).

Pervious concrete usually consists of uniform-sized coarse aggregate or aggregates ranging in size from 9.5 mm to 19 mm. In pervious concrete fine aggregate is not used or is only available in very small volume. As a primary binder, portland cement is used. Silica fume, slag and fly ash can be also used. Generally, low water cement ratios (0.30 to 0.40) are suitable for pervious concrete. Since pervious concrete has a low water cement ratio and low workability, it is substantial to provide water-reducing admixtures (Obla, 2010).

Different engineering properties of pervious concrete are mainly related to the water cement ratio, admixture types, mixing conditions and aggregate properties. Although pervious concrete has been used for many years, very few experimental studies have been conducted to state its engineering performance. Meininger (1988) has organized a number of laboratory studies to show the relation between pervious concrete compressive strength and void content as it can be seen in Figure 2.9. (a). Mulligan also has demonstrated a relation between the water/cement ratio and air void content of pervious concrete (Figure 2.9.(b)). The results obtained from the experiments show that high water/cement ratio caused the paste to flow through the aggregates and close the gaps. On the other hand, the low water cement ratio caused settlement problems by causing insufficiency in the connection between the aggregates. The studies have shown that a w/c ratio between 0.26 and 0.45 maintains the ideal cement and aggregate diffusion for pervious concrete (ACI Committee 522, 2006; Mulligan, 2005).

Within the scope of that work, Meininger (1988) also showed the connection between the flexural strength of pervious concrete and air void content. As seen in Figure 2.10, the flexural strength is directly related to the compressive strength, and it is affected by the similar variables (especially air voids) that affects the compressive strength.





(a) Relation between air content and compressive strength

b) Relation between air content and w/c ratio

Figure 2.9 Relationship of w/c ratio, compressive strength and void content in pervious concrete (ACI Committee 522, 2006).

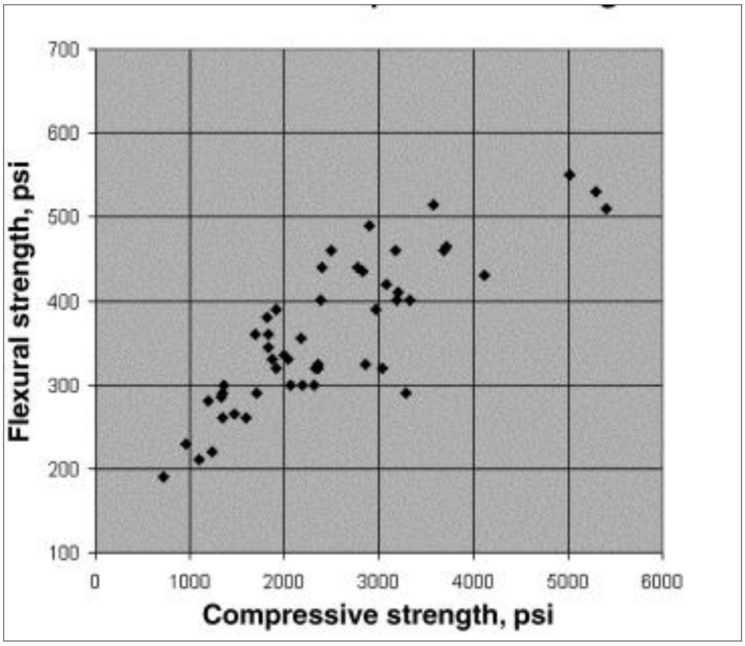


Figure 2.10 Relationship of compressive strength and flexural strength in pervious concrete (ACI Committee 522, 2006).

One of the most important properties of pervious concrete is the ability to let the water pass quickly through the body of concrete. The permeability of pervious concrete varies depending on the aggregate size and the density of the mixture but mainly related to the void content as it can be seen in Figure 2.11. The studies have shown that a minimum of %20 void ratio provides a substantial permeability. An average porosity pervious concrete have a permeability rate of 140 liters per minute per square meters. Since the infiltration rate is directly related to the void ratio, and the compressive strength decreases with increasing void ratio, the most important point in pervious concrete design is to ensure permeability and strength stability (ACI Committee 522, 2006; Obla, 2010).

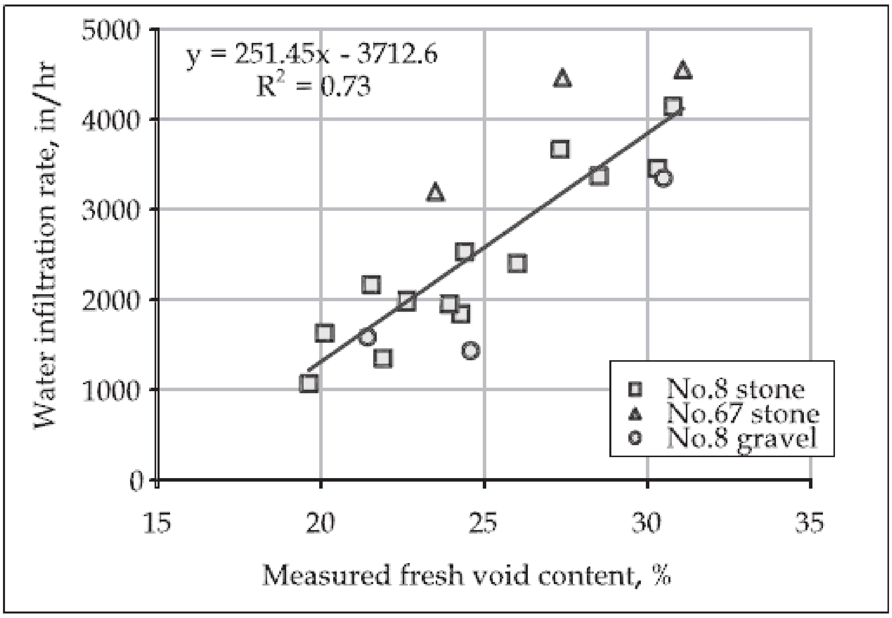


Figure 2.11 Relationship of water infiltration rate and void content in pervious concrete (Obla, 2010).

2.7.2 The Use of Polypropylene Fiber in Pervious Concrete

The increasing use of pervious concrete is also improving its mechanical properties since those properties are considered very poor compared to plain concrete. As the use of fiber in pervious concrete mixtures does not reduce void content and permeability, this use can improve the mechanical properties of the pervious concrete. Yang and Jiang used polymer fibers in pervious concrete mixtures and they observed that the fibers have significantly improved flexural strength properties of pervious concrete. However, a decrease in the hydraulic conductivity (the ease of water to move through pore spaces) was observed (Yang and Jiang, 2003). In another study performed by Rangelov et al., carbon fibers were placed in pervious concrete at three different volume ratios. The aim of that study was to define fresh and hardened property differences between fibers reinforced pervious concrete and plain pervious concrete. The experimental results showed that fiber supplementation improved the workability of the pervious concrete. Moreover, an increase of between 4% and 11% was observed in the 28 day compressive strength. In addition to this, an increase of between %11 and 36% was observed in 7 day tensile strength (Rangelov, Nassiri, Haselbach and Englund, 2016).

2.8 Test Methods of Fiber Reinforced Concrete

For the properties of FRC that are mainly based the on matrix structure such as the compressive strength, those properties can be measured by the same test methods as conventional concretes. However, for the rest of the properties that are based on the interaction between the fibers and the matrix, some different quality test methods are needed, like determining the energy absorption capacity of FRC. The absence of an internationally recognized test method for determining the energy absorption capacity is a big drawback. The variation of energy absorption capacities of FRC, according to the test method used is also a negative factor for construction application of FRC. For this reason, different approaches and test methods are used in many different countries (Minelli and Plizzari 2010; Parmentier et al., 2008).

Energy absorption capacity is generally defined as the region under the load-deflection graph in a beam or panel test. The test method to be used should be able to determine the load-deflection behavior of the specimen. This method should also be as independent as possible from the size and shape of the test sample (ACI Committee 544, 1999). Sticking to these goals, many experimental methods have been developed to define the characteristic of FRC with different fiber types and concrete designs. For FRC, several recommended test methods are based on the flexural load deflection reaction of the composites. In general, these tests can be divided into three categories; three points beam bending test, four points beam bending test and panel tests (Leva and Gregor, 2013). The main experiments used to determine the flexural toughness of FRC are:

ASTM C1609 (previous ASTM C1018): Test method for flexural toughness of FRC using beam sample with third point loading. This experimental technique comprises beam samples with dimensions of 100 x 100 x 350 mm^3 tested with 300 mm span. The test setup can be seen in Figure 2.12. In this test, the first peak and peak loads are detected and the corresponding stresses calculated utilizing the maintained formulas. Although this method has developed over the years, there are some disadvantages related to the type of this practice like extraneous deformations, decision of first crack location and stability problems (ASTM C1609, 2010; Mindess and Banthia 2004).

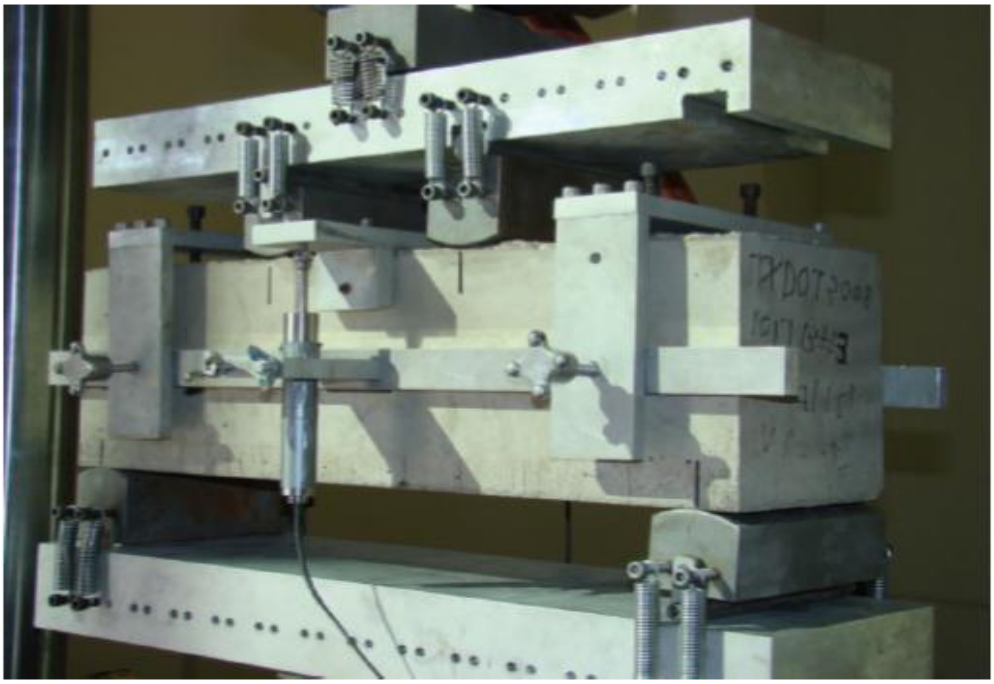


Figure 2.12 Setup for ASTM C1609 test (Chao et al., 2011).

ASTM C1399: Test method for getting the mean residual strength of FRC using beams having dimensions of 100x100x350 mm^3. Third point loading test setup similar to ASTM C1609 is used, but here, a steel plate used to support the specimen beam during the primary loading transfer. For FRC composites with low toughness, a variable situation is usually observed in the load deflection curve after the first major crack has occurred. The steel plate is used in this test as a support to control the cracking in the beams. As a result of this the need for a servo control system is eliminated (ASTM C1399 2010).

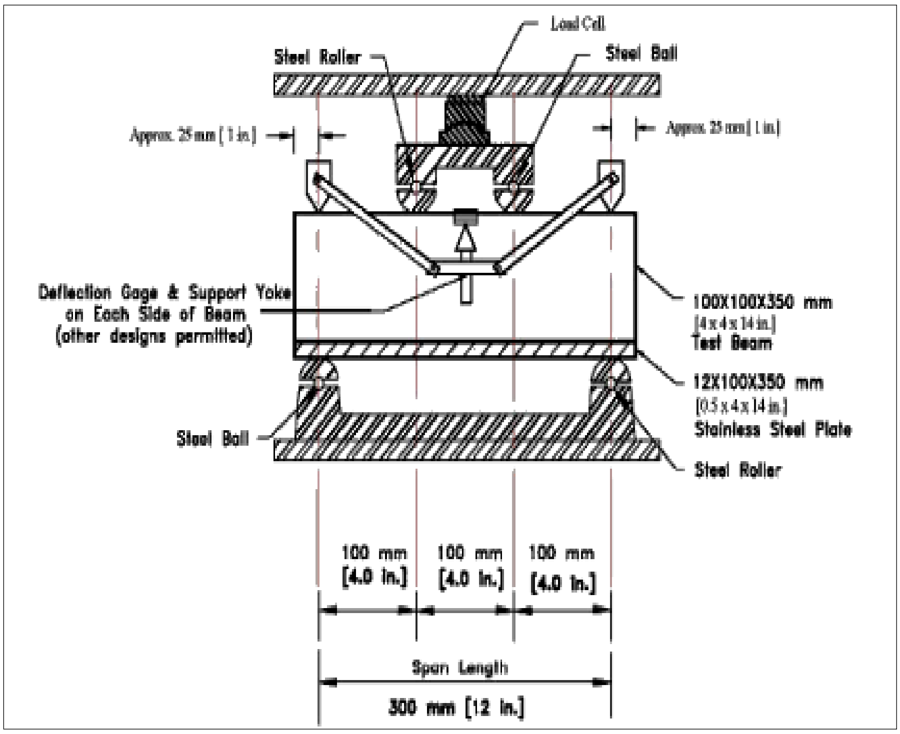


Figure 2.13 Schematic of apparatus ASTM C1399 (2010).

Uniaxial direct tensile test: This test can define strain hardening, strain softening and tensile stress-strain relations which are the fundamental features of the FRC. There is currently no standard for this method due to the difficulty of fixing the apparatus to prevent cracks at gripping points. An example of this test can be seen in the work of Chao et al., were the test samples have bone shape with a total length of 584 mm. The test setup can be seen in figure 2.14. The main advantage of this test method is an absolute axial load performed in tension. But the significant disadvantage is that it maintains just a specific characterization of the FRC behavior, different than the common or large characterization. Moreover, the fracture position and propagation is unstable (Chao et al., 2011).

Figure 2.14 Uniaxial direct tensile testing settings (Chao et al., 2011).

In addition to the beam tests and uniaxial tensile tests, panel tests are also available used for the performance analysis of fiber reinforced concrete. In the next section, the main two of the panel tests, square panel test and round panel test methods will be explained in detail.

2.8.1 ASTM 1550 (Round Panel Test)

This test method, which is relatively new, is generally situated on the study of Bernard (2002). It includes a center point loading on a circular panel that has dimensions of 800 mm in diameter and 75 mm in thickness. The round panel specimen is supported on three arranged pivots. The plan and profile view of round plate test can be seen in Figure 2.15.

The load is applied through a hemispherical steel head and progresses in a specific displacement rate. The applied load and occurred deflection are recorded simultaneously up to a defined central deflection. The energy absorbed from the panel up to that specified central deflection represents the flexural toughness of the FRC specimen. This test is usually used in the field of tunnel and mining construction. Previous works revealed that alteration in cracking load, peak load and energy absorbed up to a specified central deflection in the round panel test are lower than beam tests, with a coefficient of variation between 5% and 15%. The reasons of this decrease in deviation are the more specific crack locations and the increased cracked area that minimizes the impact of irregular fiber distribution. On the other hand, the major drawback of this test method is that the sample is too big and heavy to operate and does not fit into many testing machines (Bentur and Mindess, 2007; ASTM C 1550, 2012).

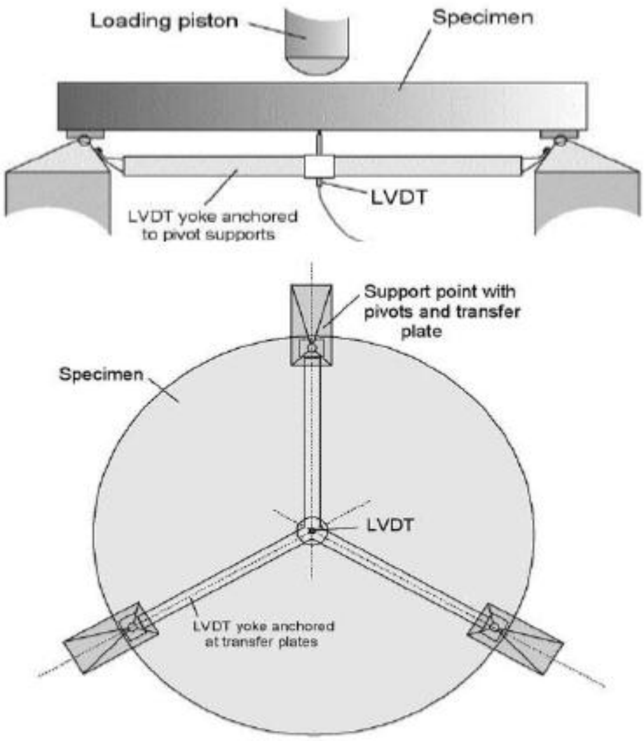


Figure 2.15 Plan and profile view of ASTM 1550 (ASTM C 1550, 2012)

2.8.2 EFNARC Panel Test

The EFNARC panel test is the mostly used test in Europe as an alternative to bending test. This test implements a central load on a 100 × 600 × 600 mm^3 square panel that is simply supported on its four sides by a 500 × 500 mm rigid frame made from 25 mm steel plate. Test setup can be seen in Figure 2.16. Previous studies revealed that the panel test shows well stability and a good structural relation. Crack distribution shows also a stable performance similar to the round panel test.

However, some disadvantages of this test are that the specimen production and transfer can be difficult (EFNARC 1996). Moreover, the most important deficiency of this test method is the difficulty of making a specimen with an ideal flat base. A non-flat specimen will generally deforms unpredictably and shows various peaks in the load capacity. According to these various peaks, the stress is redistributed around the failed plate (Bernard, 2001).

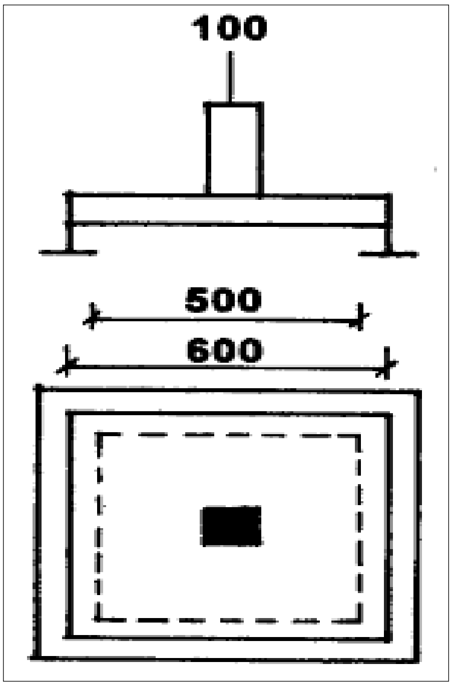


Figure 2.16 Set up for square panel test (EFNARC, 1996).

2.9 Recent Studies on the Comparison of Different Test Methods.

Paegle et al. (2016) have compared the potential of testing methods to evaluate the tensile and flexural behavior of FRC with using various beam and panel test methods. They used uni-axial tension tests, flexural beam tests and flexural panel tests. According to the test results, the authors underlined that tensile tests ensure more straightforward examination than others. However this test is difficult to apply in ordinary laboratory conditions. They also indicated that the four point bending test more realistically represents the material behavior particularly when the sample geometry is slenderer. In this study the round panel test showed no considerable decrease in variability of test results compared to three and four point bending test.

Myren and Bjontegaard (2010) have studied a comparative study of round and square panels on a continuous simple support. They stated that bedding material of plaster is not practical for the square panel test. They also indicated that the obtained energy absorption capacities should be corrected for panel thicknesses which is directly effect the specimen flexure performance. The coefficient of variation values obtained in this study were 7.6% for the square panel test and 12.4% for the round panel test.

Minelli and Plizzari (2010) have investigated the effect of different test methods for FRC performance analysis. Tests are applied both of panel and beam specimens. The study has shown that high variability mainly present in beam tests is caused by the small specimen size and fracture area. The researchers also concluded that lower variability can be obtained from larger fracture areas involved in test methods.

In a study by Öztürk (2018), high dosage polypropylene FRC and normal dosage polypropylene FRC were prepared and tested by round panel test and square panel test. The test results show less variability due to high fiber dosage. In addition to this, a relationship was founded between the two test methods in terms of Energy absorption capacity.

CHAPTER 3

EXPERIMENTAL STUDY

3.1 Experimental Program

This section gives a comprehensive description of the experimental procedures and the materials used in this work. The main purpose of this experimental study is to evaluate the energy absorption capacity of high performance polypropylene fiber reinforced concrete and pervious polypropylene reinforced concrete with round panel and square panel tests.

Within the scope of this experimental study, eight different concrete mixtures were designed and prepared. The first mix was prepared as high performance concrete for comparison purposes. The second, third and fourth mixes were high performance polypropylene fiber reinforced concrete (HPFRC) with different fiber ratios (3kg/m^3, 6kg/m^3, 9kg/m^3). The fifth mix was plain pervious concrete for control purposes. The sixth, seventh and eighth mixes were pervious polypropylene fiber reinforced concrete (PFRC) with the same fiber proportions as HPFRC.

In the following section of this chapter, the material properties, the mixture designs, sample preparations and test methods will all be specified. All the experimental studies were performed in the Materials of Construction Laboratory at Civil Engineering Department of Middle East Technical University.

3.2 Materials Properties

3.2.1 Cement

CEM I 42, 5 R type portland cement was obtained from Baştaş Cement Company in Ankara and used in the preparation of all the mixes during this experimental study.

The chemical, physical and mechanical properties of the cement are shown in Table 3.1.

Table 3.1 Technical specification of the cement

PC CEM I 42.5 R*	
Chemical Properties (%)	
CaO	63.26
SiO_2	19.15
Al_2O_3	5.16
Fe_2O_3	3.56
MgO	1.28
SO_3	2.77
K_2O	0.37
Na_2O	0.30
Cl	0.0238
Loss on ignition	3.83
Insoluble Residue	0.91
Physical and Mechanical Properties	
Specific Gravity (g/cm^3)	3.11
Blaine Fineness (cm^2/g)	3700
Initial Setting (min)	120
Final Setting (min)	170
Compressing Strength (MPa) 2 days	26
Compressing Strength (MPa) 7 days	43.5
Compressing Strength (MPa) 28 days	57.5

* As provided by the quality-control department of Baştaş Çimento, Ankara.

3.2.2 Silica Fume

The silica fume used in this study was obtained from Antalya Ferrochrome Plants. The silica fume was used to enhance the strength in HPFRC mixtures.

3.2.3 Fly Ash

F type fly ash obtained from Sugözü thermal power plant was used as an additional binder material. The aim of this use is to enhance the workability, the durability and the strength of the mixtures.

3.2.4 Aggregates

Crushed limestone aggregates with three different size ranges (one fine and two coarse aggregates) were used in this study. The sieve analysis and physical properties of the aggregates are shown in Figure 3.1 and Table 3.2 respectively.

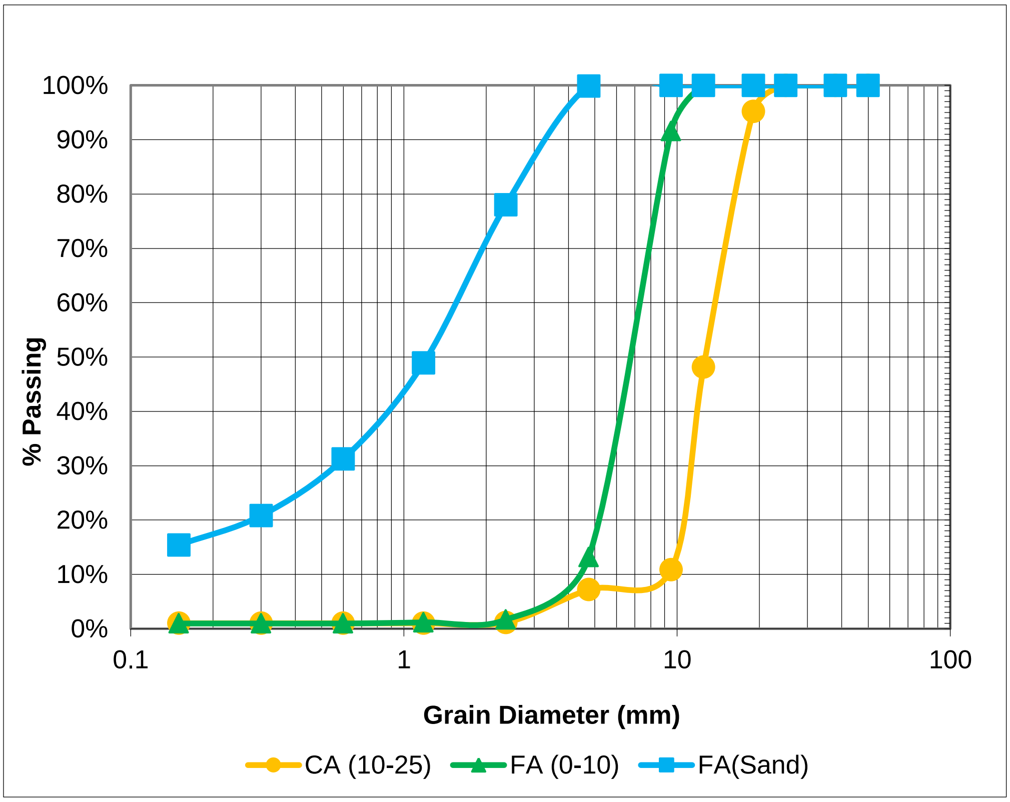


Figure 3.1 Sieve analyses of aggregates

Table 3.2 Physical properties of aggregates

	Fine Aggregate	Coarse Aggregate 1	Coarse Aggregate2
Dry Specific Gravity	2.58	2.67	2.64
SSD Specific Gravity	2.63	2.69	2.66
Apparent Specific Gravity	2.71	2.71	2.7
Water Absorption %	1.94	0.83	0.86

3.2.5 Chemical Admixtures

In all the mixtures, to provide adequate workability, MasterGlenium 51 polycarboxylate high range water reducer was used.

3.2.6 Fibers

One type of polypropylene fiber named as Barchip48 was used in all the mixtures with different quantities (3kg/m^3, 6kg/m^3, 9kg/m^3). The volume percentage of fibers was 0.32%, 0.65% and 0.98% respectively. The properties of the fibers as obtained from the manufacturer are presented in Table 3.3. Polypropylene fiber that used in experiment can be seen in Figure 3.2.

Table 3.3 Material properties of polypropylene fiber

Material	BarChip48
Base Resin	Modified Olefin
Length	48 mm
Tensile Strength	640 MPa
Surface Texture	Continuously Embossed
No. Fibers per kg	59,500
Specific Gravity	0.90 - 0.92
Young’s Modulus	10 GPa
Melting Point	159°C - 179°C
Ignition Point	> 450°C

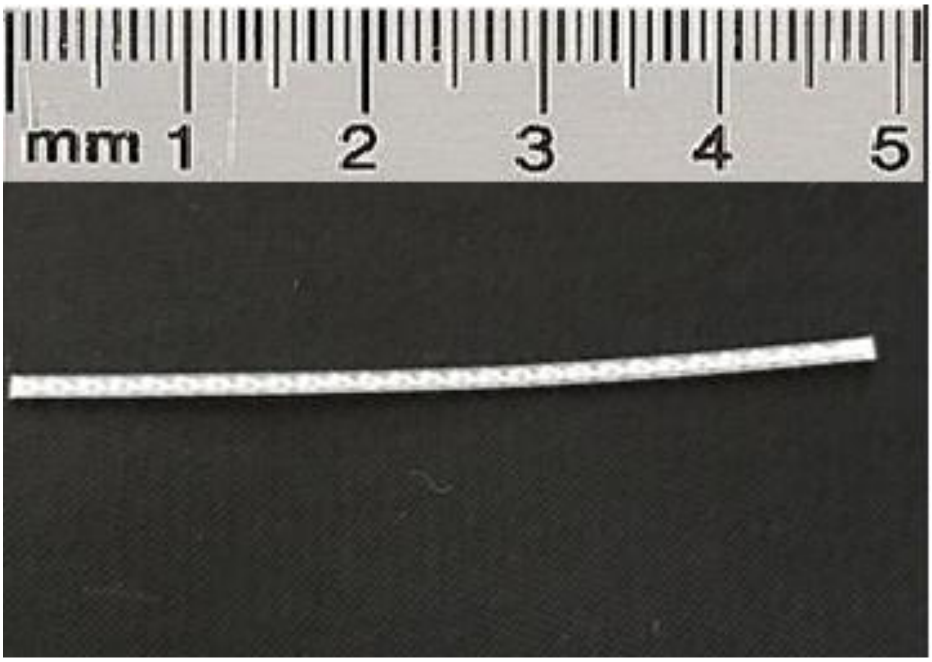


Figure 3.2 Polypropylene fiber used in fiber reinforced mixes

3.3 Mix Design

In this study, two different concrete types and eight different mixtures were produced. For high performance concrete, cement dosage was kept constant at 400 kg/m^3. Moreover, for all high performance concrete mixes, the same amount of silica fume and fly ash were used. The water/binder ratio was between 0.30 – 0.34 for high performance mixes in order to obtain a similar consistency. On the other hand, for pervious concrete, cement dosage was kept constant at 150 kg/m^3 and the water/binder ratio for pervious concrete mixes was between 0.29 – 0.32. Mixtures proportion details are listed in Table 3.4 and Table 3.5. It was taken into consediration that samples had similar workability values in w/c ratios within a certain range when the mixing water was added.

Table 3.4 High performance fiber reinforced concrete mixture proportions

	HPC CONTROL	HPFRC 3	HPFRC 6	HPFRC 9
Cement (kg/m^3)	400	400	400	400
Silica fume (kg/m3)	30	30	30	30
Fly ash (kg/m3)	100	100	100	100
Water (kg/m3)	163	160	175	179
Admixture(SP) (kg/m3)	5.3	5.3	5.3	5.3
Polypropylene fiber (kg/m3)	0	3	6	9
Fine aggregate (kg/m3)	821	817	812	808
Coarse aggregate 1 (kg/m3)	424	423	420	418
Coarse aggregate 2 (kg/m3)	424	423	420	418
Total weight (kg/m3)	2367	2361	2368	2367
Air content (%)	2.2	2.8	1.7	1.6
Water/Binder ratio	0.31	0.30	0.33	0.34

Table 3.5 Pervious fiber reinforced concrete mixture proportions

	PRVSC CONTROL	PFRC 3	PFRC 6	PFRC 9
Cement (kg/m^3)	150	150	150	150
Fly ash (kg/m3)	100	100	100	100
Water (kg/m3)	72	69	78	80
Admixture(SP) (kg/m3)	2.5	2.5	2.5	2.5
Polypropylene fiber (kg/m3)	0	3	6	9
Fine aggregate (kg/m3)	150	149	149	148
Coarse aggregate 1 (kg/m3)	1013	1008	1001	995
Coarse aggregate 2 (kg/m3)	389	387	385	383
Total weight (kg/m3)	1877	1869	1872	1868
Air content (%)	25.8	26.4	25.8	26.0
Water/Binder ratio	0.29	0.28	0.31	0.32

A rotary drum mixer was used to prepare the specimens. The mixer used in this study can be seen in the Figure 3.3

Figure 3.3 Rotary drum mixers

The mixing steps for all mixtures are listed below:

- The aggregates were added to the mixture and mixed for about one minute before 20% of the water added to them and mixed for another one minute.
- Cement and fly ash were added and mixed for another one minute.
- After that, the fibers were slowly added to the mixture while the mixer is rotating, to ensure a good fiber distribution.
- When silica fume was used it was mixed with 60 percent of the mixture water
- The water–silica fume mix previously was mixed with the superplasticizer and the whole was slowly added to mixer along with the remaining of the water.
- The mixture was mixed for a further 10 minutes to obtain a well homogenous mix.

After the mixing operation was done, the concrete was placed into the molds with the help of a concrete vibrator. From each mix, three cylinders with a diameter of 100 mm and a height of 200 mm, three 600x600x100 mm^3 square plates and three round plates with a diameter of 600 mm and a thickness of 75 mm were cast. The cylinders were used for the determination of the compressive strength. The plates were used for determination of the energy absorption capacity. HPFRC samples were removed from molds after 24 hours, while PFRC samples were removed from the molds after 48 hours due to the low early strength. Molds used in experiment can be seen in Figure 3.4.

Figure 3.4 Round and square panel molds

3.4 Tests on Fresh Concrete

3.4.1 Slump Test

The workability of the fresh mixtures was measured by the slump test in accordance with ASTM C143 (ACI Committee 544, 1999). It was observed during the tests that the workability of all the mixtures was suitable for the concrete placement. The slump test results were close to each other and one example can be seen in the Figure 3.5. The values obtained from the slump tests are shown in Table 3.6.

Figure 3.5 Slump test

3.4.2 Density

The fresh density values of mixtures were determined according to ASTM C 138. The results of the test were included in Table 3.6.

Table 3.6 Slump and density characteristic of fresh concrete mixtures

Mixes	Slump (cm)	Unit Weight (kg/m^3)
HPC Control	20	2429
HPFRC 3kg	20	2394
HPFRC 6kg	20	2358
HPFRC 9kg	20	2376
PRVSC Control	21	2020
PFRC 3kg	21	2014
PFRC 6kg	22	1961
PFRC 9kg	22	2005

3.5 Tests on Hardened Concrete

3.5.1 Compressive Strength Test

The compressive strength tests of the cylinder specimens with a diameter of 100 mm and a height of 200 mm were performed at the age of 28 days in accordance with ASTM C39. Before the test, samples removed from molds and the top and bottom of the cylindrical specimens were cut and capped with a sulphur compound. After that, the specimens were placed and loaded at a constant loading rate of 6.8 kN/s, by using a universal testing machine.

3.5.2 Infiltration Rate Test

An experimental and calculation method similar to the ASTM 1701 test was applied on the samples to measure the infiltration rate of the pervious concrete. The center of the pervious concrete was marked by a circle with 300 mm in diameter. As seen in Figure 3.6, the water was poured in this circle, taking care to the constant speed and quantity. The amount of water used in this time interval was noted when the flow rate of the downstream is maximum. The water mass that falls in this area for a certain time gives us an appreciation of the permeability of the samples. As a result of this test, an average infiltration rate of 110 liters per minute per square meter was observed (ASTM 1701, 2009).

Figure 3.6 Test for infiltration rate of pervious concrete

3.5.3 Square Panel Test

The square panel test (EN 14488-5), also called EFNARC panel test, was performed to determine the energy absorption capacities of hardened concrete mixtures from the load-deformation curve. The square plates were supported on a steel frame using a gypsum mixture as bedding material to ensure a full contact between the specimen and the frame at the beginning of the test. The dimensions of the square plates were 600×600×100 mm^3, while the frame has an inner opening dimension of 500×500 mm^2. The load was applied on the center of the plate through a steel plate with an area of 100 ×100 mm^2. The load was applied using displacement control mode with a speed rate of 1mm/minute. The test setup for the square plate test can be seen in Figure 3.7. The machine used for the tests was an MTS brand universal testing machine with a 250 kN capacity. This machine has a servo hydraulic pump that allows performing a precise displacement control tests. The test data were collected by the device itself with a sample rate of 100 Hz.

Figure 3.7 Set-up for square panel tests

Before each test, the sample was removed from the curing environment for size and weight measurements. After the middle point of the sample was marked, the panel was moved to the testing area. The square panel was placed on the test machine and then the test was started. The rate of deformation at the center was 1.0 mm/min, so the test was finished by itself when the midpoint deflection reaches 30 mm. After the test was done, the panel was lifted and the bottom surface of the panel was photographed as seen in Figure 3.8. The load–deformation graph along with the energy-deformation graph were obtained for each plate (EFNARC, 1996).

Figure 3.8 Representative pictures of cracked square panels

3.5.4 Round Panel Test

The round panel test was performed in accordance with the ASTM 1550, for the same application aim as the square plate test. The test includes the determination of flexural toughness of fiber reinforced concrete expressed as energy absorption in the post cracking period (ASTM C1550, 2012).

A total 24 round panels were casted during the experimental work. 12 of them were HPFRC and the other 12 were PFRC. As indicated in the ASTM 1550, steel round molds were prepared for the test. However, because of the limited opening distance of the test machine used in this study, the diameter of the round panels used in this study was reduced to 600 mm and the thickness to 75 mm. During the tests, the panels were supported by three hinged pivots symmetrically arranged at 120º, and the load was applied on the center of plate through a semispherical head with a diameter of 100 mm. The loading was performed using displacement control mode with a rate of 1 mm/minute. The test setup of the round plate test can be seen in Figure 3.9.

Figure 3.9 Set-up for round panel tests

Before each test, the specimen was removed from the curing environment for size and weight measurements. After the middle point of the sample was marked, the panel was moved to the testing area. The panel was carefully positioned to sit on the three support points and the center mark was aligned according to the center of the spherical head before the test was started. The test was performed until a total midpoint deflection of 30 mm was reached. The central displacements of the panels were measured by an LVDT for the first 5 mm (the stroke of the LVDT), then form the displacement of the machine head. When the test was finished, the plate was lifted out and the bottom surface of the panel was photographed as seen in the figure 3.10.

Figure 3.10 Representative pictures of cracked round panels

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Compressive Strength Tests

In this section, the 28-days compressive strengths of all the tested mixtures are presented in Figure 4.1 and Table 4.1. Except for the mixtures that contain 9 kg of fibers, the compressive strength results for each concrete type were close to each other. The decrease in the compressive strength values for HPFRC 9 and PFRC 9 is because of the compaction of those concrete mixtures becomes a lot harder, hence more voids are presented in the system . It has been observed that the addition of fibers to the mixtures significantly increased the variability of compressive strength tests. That increase may be due to the heterogeneous nature of the fiber containing mixtures as well as the difficulties in achieving proper compaction.

Table 4.1 28-day compressive strength values

Mixes	f_{comp} 28 Days (MPa)		Average	Δf/Mean
	1	2	(MPa)	
HPC Control	69.4	70.3	69.9	1.3
HPFRC 3kg	71.5	67.9	69.7	5.2
HPFRC 6kg	73.8	69.8	71.8	5.6
HPFRC 9kg	42.3	60.3	51.3	35.1
PRVSC Control	8.4	7.3	7.9	14.0
PFRC 3kg	11.0	9.4	10.2	15.7
PFRC 6kg	6.2	7.6	6.9	20.3
PFRC 9kg	6.5	5.4	6.0	18.5

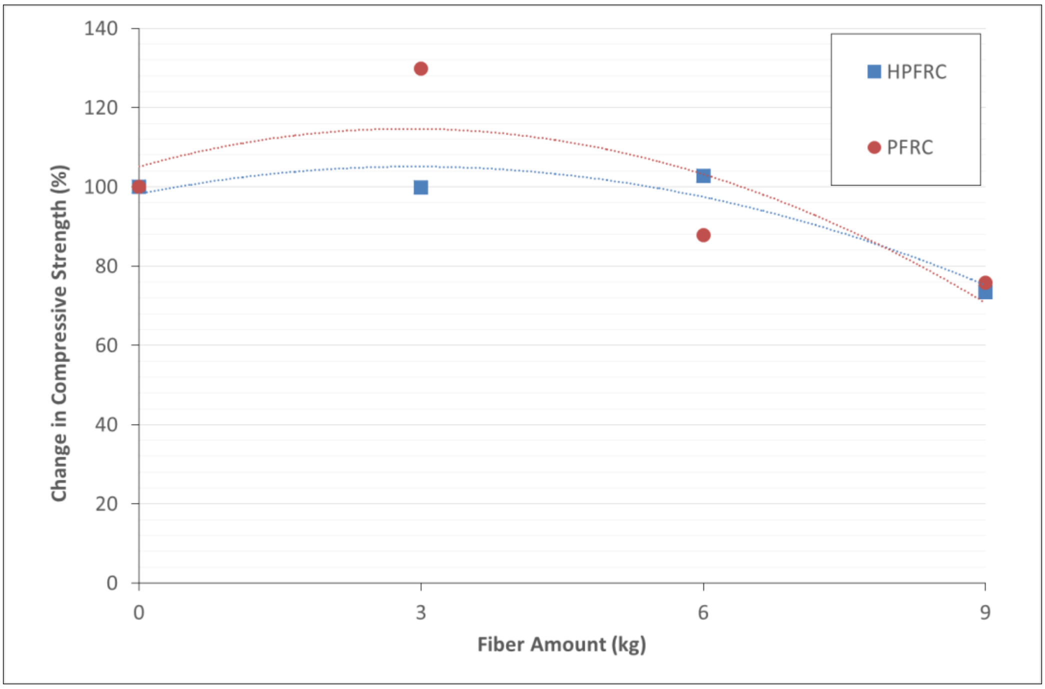


Figure 4.1 Change in compressive strength of all mixes

4.2 Square Panel Tests

4.2.1 Square Panel Test for HPFRC

The load displacement graphs of the square panel tests for HPFRC are shown in Figures 4.2 – 4.6. Each figure contains the test results of three panels for each mixture and the average of these test results. In addition to that, the photos of the crack pattern and panel thickness at the bottom of the each plate are included in these figures as well. Moreover, the first peak load, the ultimate load and the energy absorption capacity for a deflection of 25 mm are all shown in Table 4.2.

From the test results, it is clearly seen that even though the addition of the fibers did not significantly improve the first peak or the ultimate load, it has hugely enhanced the EAC of the mixtures.

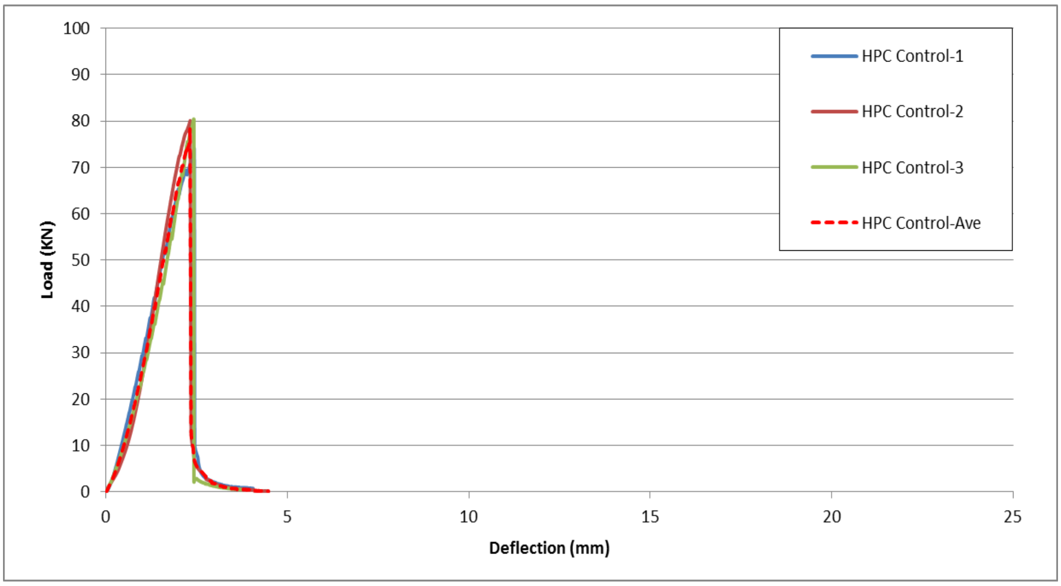


Figure 4.2 Load deflection curves of HPC Control samples with square panel test for 28 days.

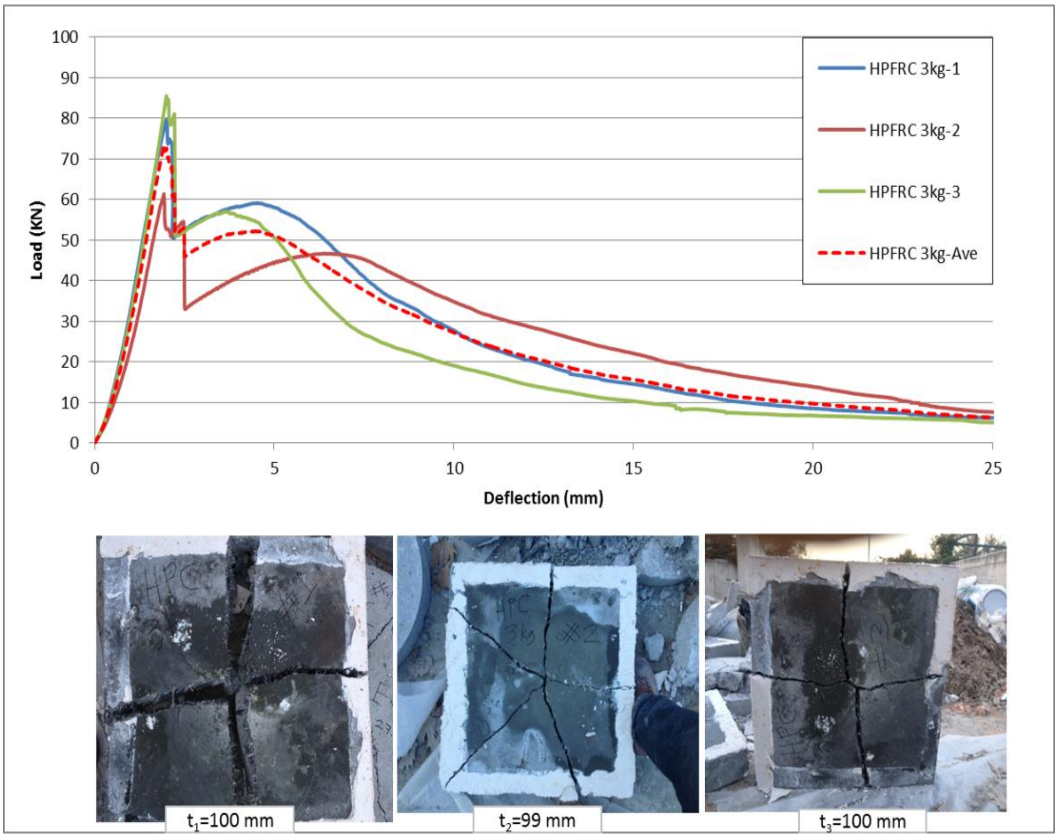


Figure 4.3 Load deflection curves and crack formations of HPFRC 3 kg samples with square panel test for 28 days.

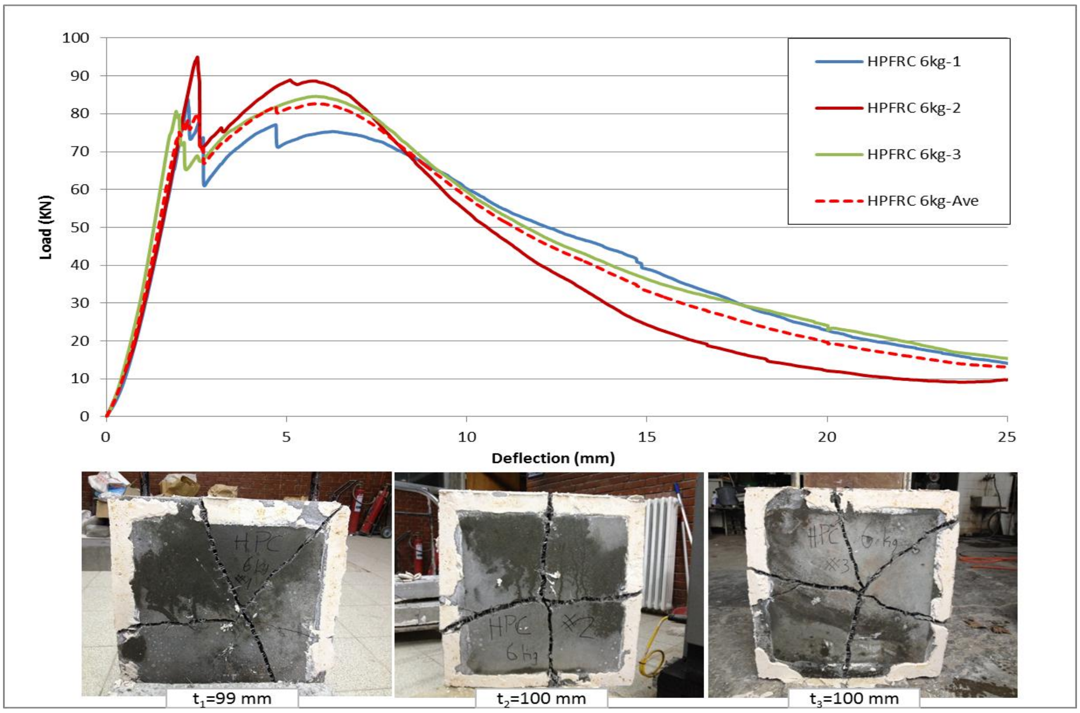


Figure 4.4 Load deflection curves and crack formations of HPFRC 6 kg samples with square panel test for 28 days.

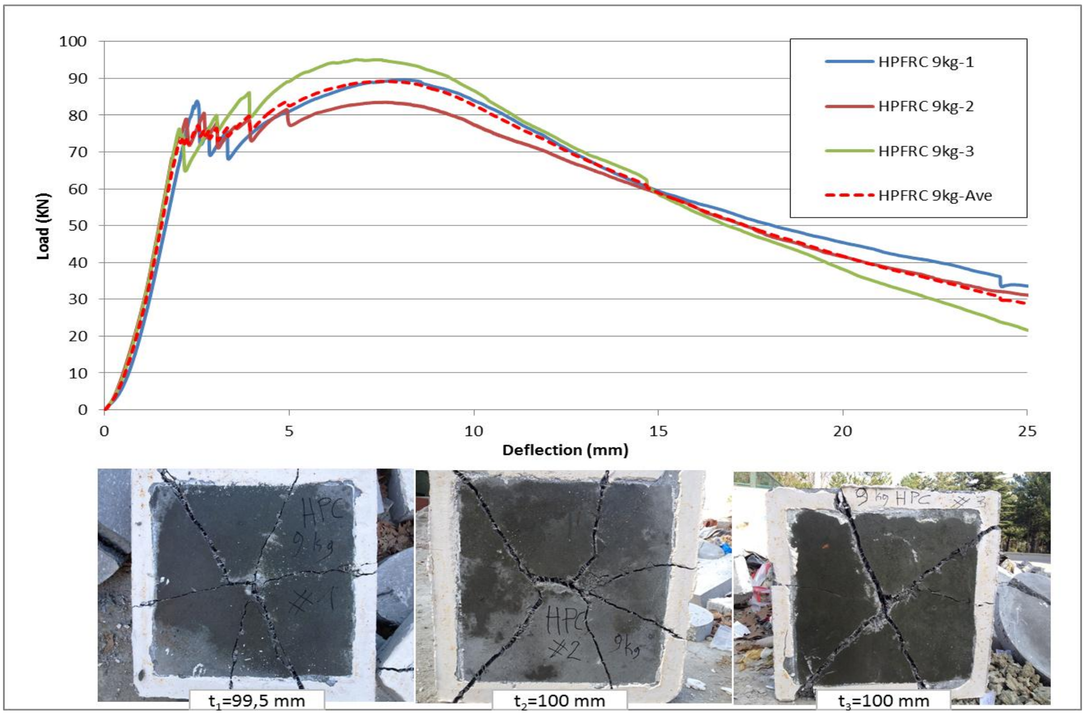


Figure 4.5 Load deflection curves and crack formations of HPFRC 9 kg samples with square panel test for 28 days.

The average load displacement curves for HPFRC mixtures are plotted in Figure 4.6. As seen in that figure, fiber inclusion significatly improved the post-cracking behaviour. as the amount of fibers increased the improvement was quite enormous. The ultimate strength even exceeded the cracking strength.

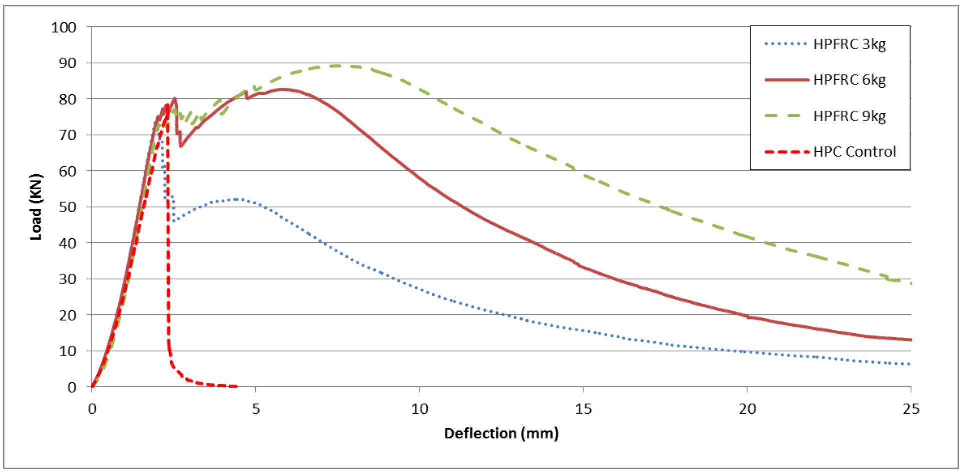


Figure 4.6 Comparison of load deflection curves of HPFRC mixes with square panel test for 28 days.

When the area under the load deflection curves of HPFRC are calculated as the EAC of mixtures, the following energy-deflection curves Figure 4.7 will be obtained.

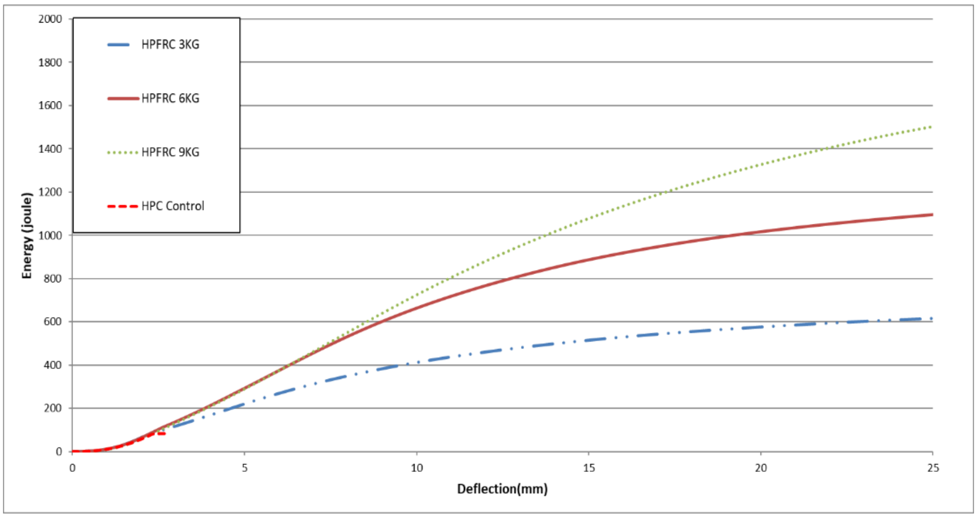


Figure 4.7 Comparison of energy deflection curves of HPFRC mixes with square panel test for 28 days.

4.2.2 Square Panel Test for PFRC

The load displacement graphs of the square panel tests for PFRC are shown in Figures 4.8 – 4.12. In addition to that, the photos of the crack pattern and panel thickness at the bottom of the each plate are included in these figures as well. As seen from the graphs, the variation of the PFRC samples is quite much. That significant difference in variation may be due to inhomogeneity and fiber distribution problems as well as panel thicknesses.

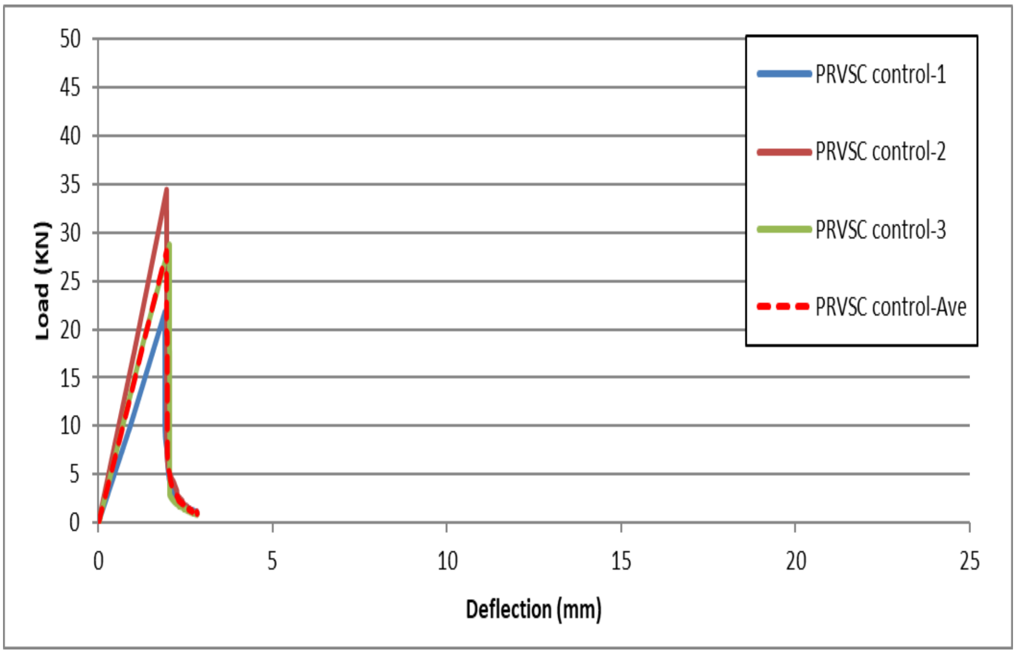


Figure 4.8 Load deflection curves of PRVSC Control samples with square panel test for 28 days.

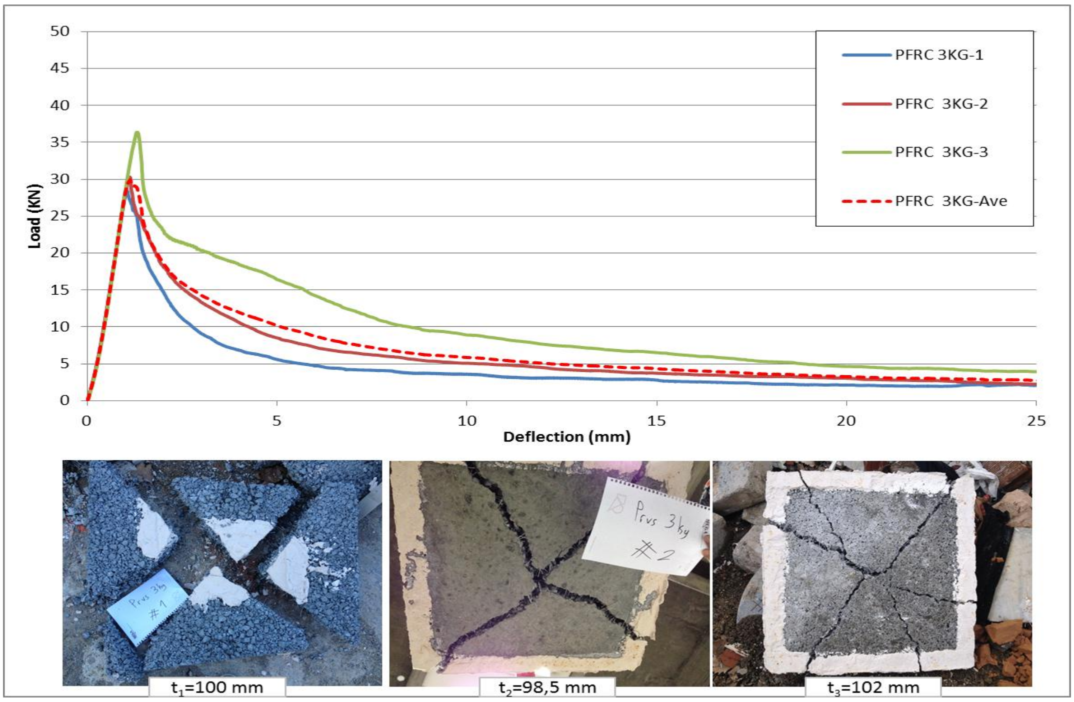


Figure 4.9 Load deflection curves and crack formations of PFRC 3kg samples with square panel test for 28 days.

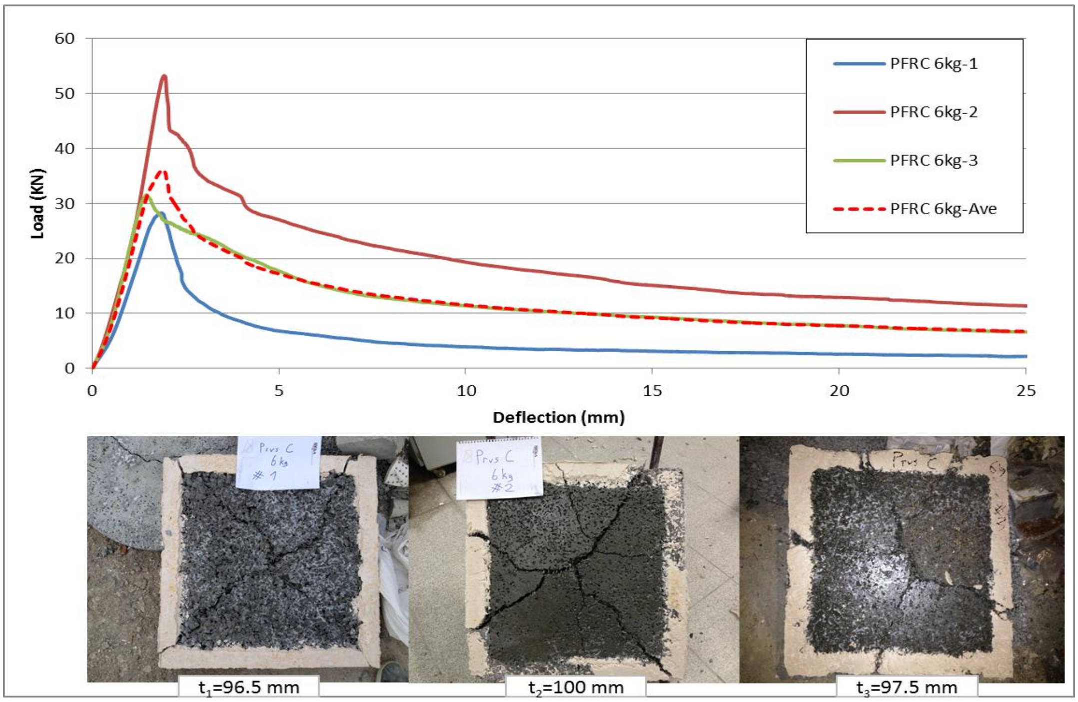


Figure 4.10 Load deflection curves and crack formations of PFRC 6kg samples with square panel test for 28 days.

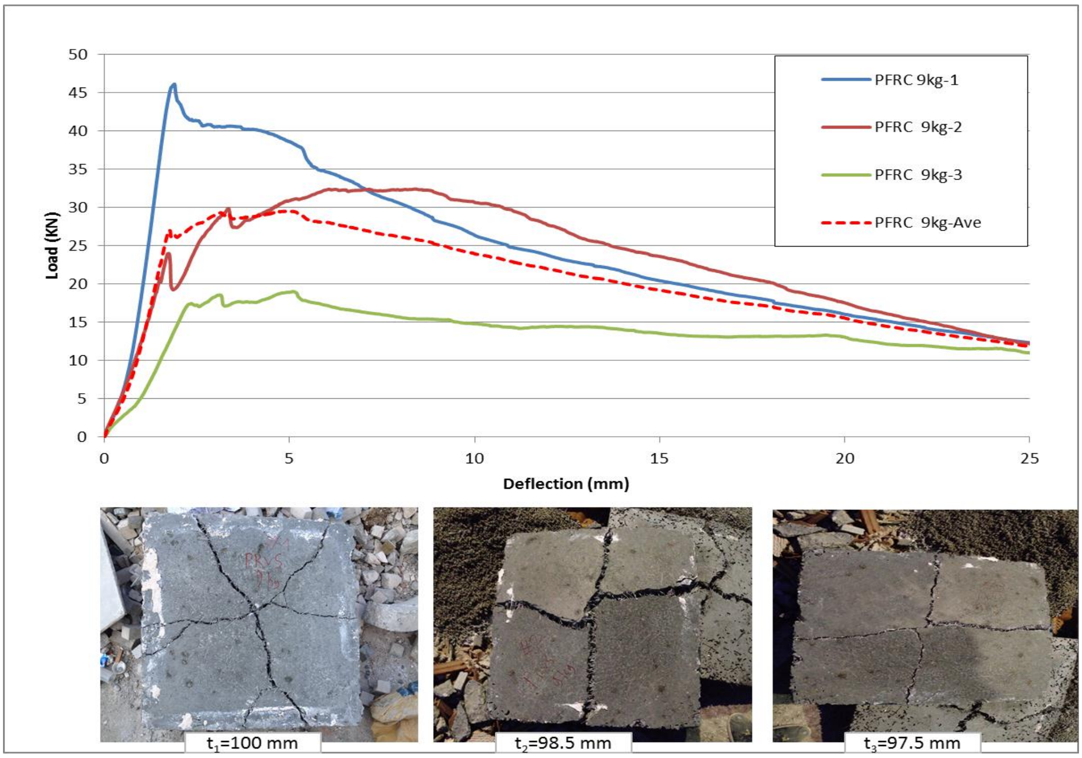


Figure 4.11 Load deflection curves and crack formations of PFRC 9kg samples with square panel test for 28 days.

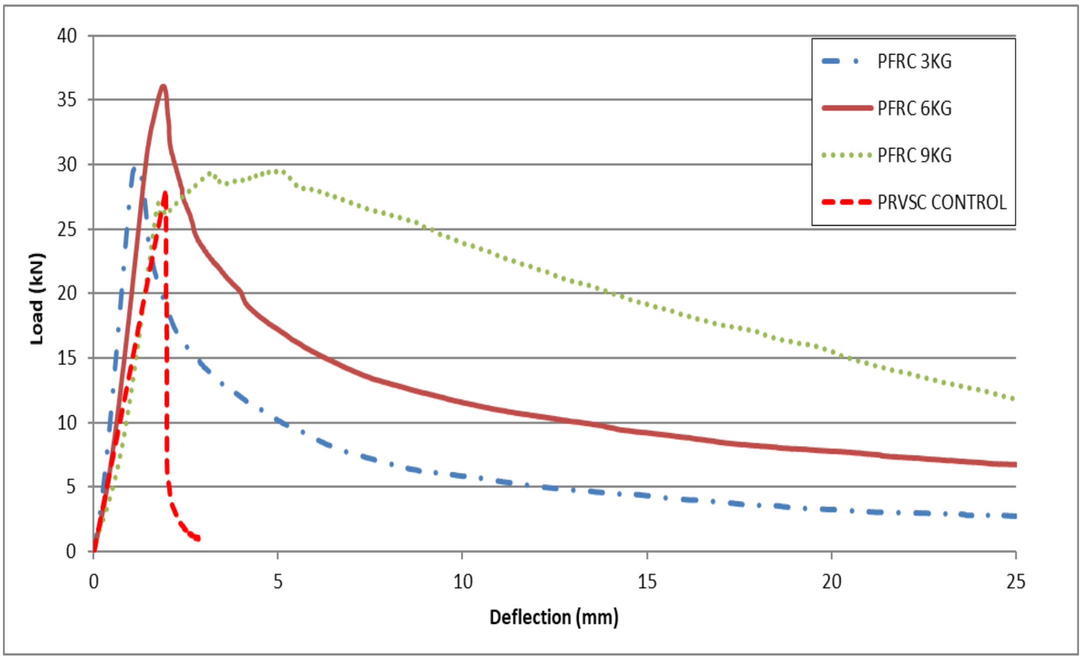


Figure 4.12 Comparison of load deflection curves of PFRC mixes with square panel test for 28 days.

When the area under the load deflection curves of PFRC are calculated as the energy absorption capacity of mixtures, the following energy-deflection curve Figure 4.13 will be obtained.

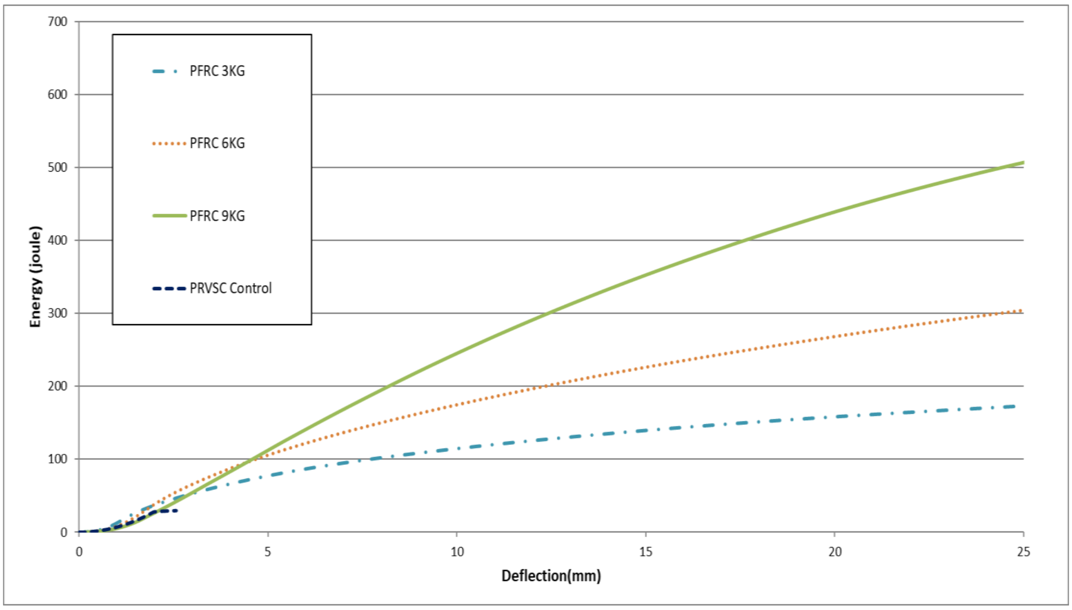


Figure 4.13 Comparison of energy deflection curves of PFRC mixes with square panel test for 28 days.

Table 4.2 The first-peak load (kN), ultimate load (kN) and energy absorption (J) of the square panels.

Types of concrete	Average first peak load (kN)	Average ultimate load (kN)	Average energy at 25 mm deflection (J)	Cov (%)
HPC Control	78.1	78.1	85.5*	4.5
HPFRC 3kg	75.5	75.5	616.1	12.3
HPFRC 6kg	86.3	87.8	1095.8	7.2
HPFRC 9kg	80.9	89.4	1503.0	2.3
PRVSC Control	28.3	28.3	29.5**	21.5
PFRC 3kg	31.6	31.6	173.0	37.1
PFRC 6kg	37.7	37.7	304.2	57.7
PFRC 9kg	29.1	32.4	506.7	25.9

* Energy at 2.75 mm deflection

** Energy at 2.5 mm deflection

As shown in Figures 4.6, 4.12 and Table 4.2 After the first crack, a decrease in the load carrying capacity occurs. However, when fibers are used in the mixtures, the specimens were able to continue carrying some amount of the load after the first crack. With the increase in the fiber dosage, the decrease in the load carrying capacity after the first crack becomes smaller. When the addition of the fibers exceeds an optimum value, no decrease in the load carrying capacity will occur after the first crack, and the specimen can reach an ultimate load higher than the first peak load. Moreover, in HPFRC 9 and PFRC 9 specimens, strain hardening was observed after the first peak load or the first crack, which can be related to the good bond and the dense distribution of the fibers.

With the addition of different amounts of fibers, the specimens might show the same behavior for all the different dosages at the beginning. However, after a specific deformation for each dosage, the amount of fibers available in the matrix will not be enough to continue on improving the performance. For example, HPFRC 6 and HPFRC 9 show similar load carrying capacities and energy absorptions up to 8 mm displacement. From 8 mm to 25 mm displacement, HPFRC 9 shows a better performance. All of these mean that the optimum fiber amount can be found based on the required deformation and energy absorption. After 12 mm displacement, the PFRC 9 exhibited better load carrying capacity than HPFRC 3 although its matrix has significant disadvantages. Their energy absorption capacity up to the deflection of 25 mm is close to each other despite the huge differences in their matrix structures. This indicates that the load transfer is substantially absorbed by the fibers after particular displacement.

All mixtures except PFRC 3 and PFRC 6 achieved energy absorption capacity Class A (500J) at a deflection of 25 mm that is defined for EFNARC square panel test.. HPFRC 9 and HPFRC 6 achieved Class C (1000J) at a deflection of 14 and 19 mm respectively.

4.3 Round Panel Tests

4.3.1 Round Panel Test for HPFRC

The load displacement graphs for the round panel tests for HPFRC are shown in Figure 4.14 – 4.18. Each figure contains the test results of three panels for each mixture and the average of these test results. In addition to that, the photos of the crack pattern and panel thikcness at the bottom of the each plate are included in these figures as well. Moreover, the first peak load, the ultimate load and the energy absorption capacity for a deflection of 25 mm are all shown in Table 4.3.

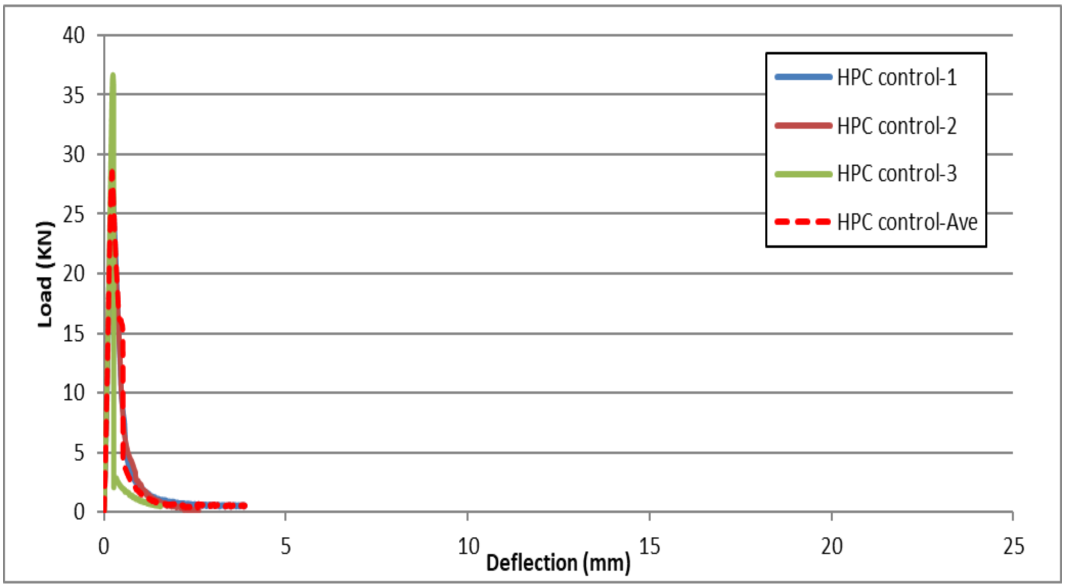


Figure 4.14 Load deflection curves of HPC control samples with round panel test for 28 days.

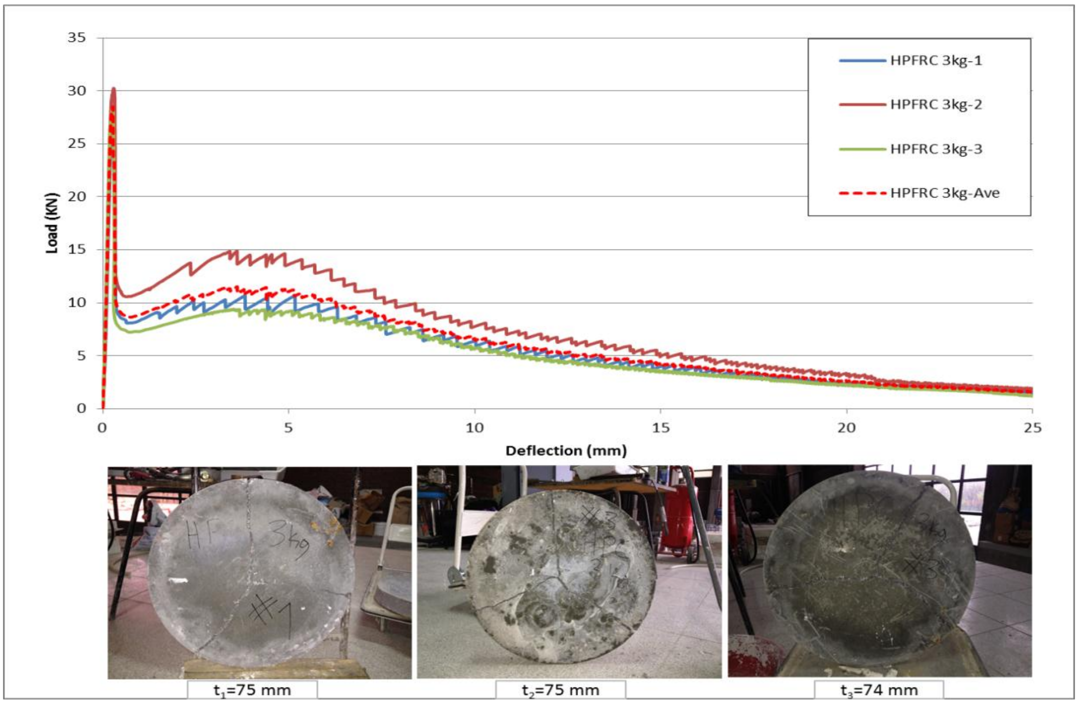


Figure 4.15 Load deflection curves and crack formations of HPFRC 3 kg samples with round panel test for 28 days.

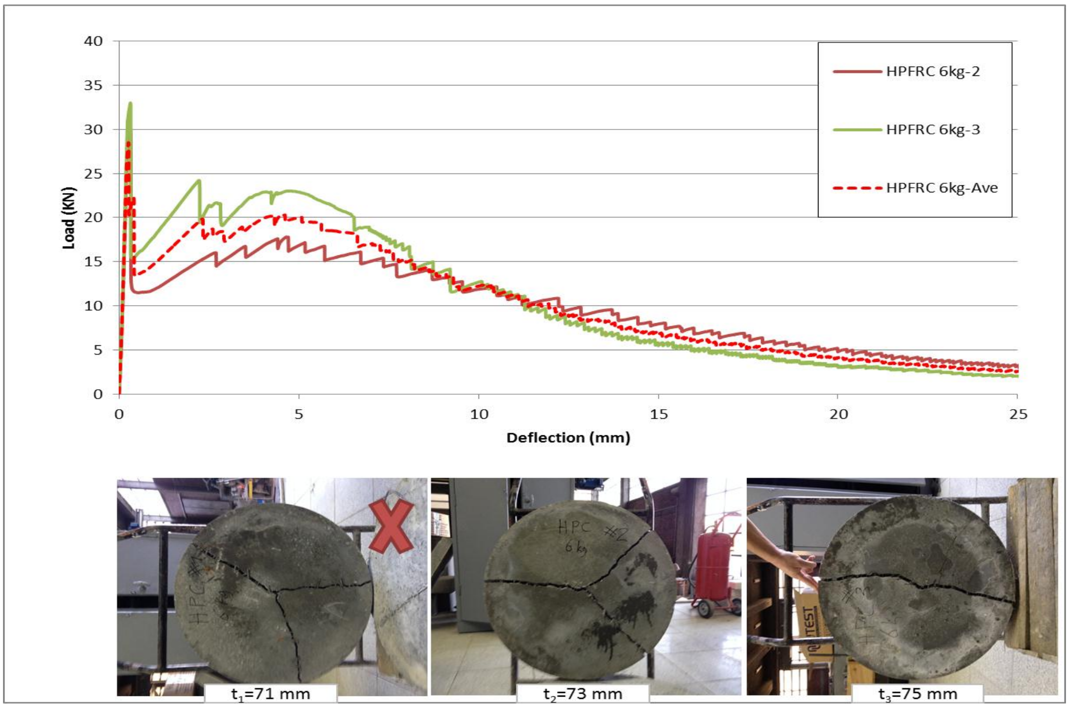


Figure 4.16 Load deflection curves and crack formations of HPFRC 6 kg samples with round panel test for 28 days.

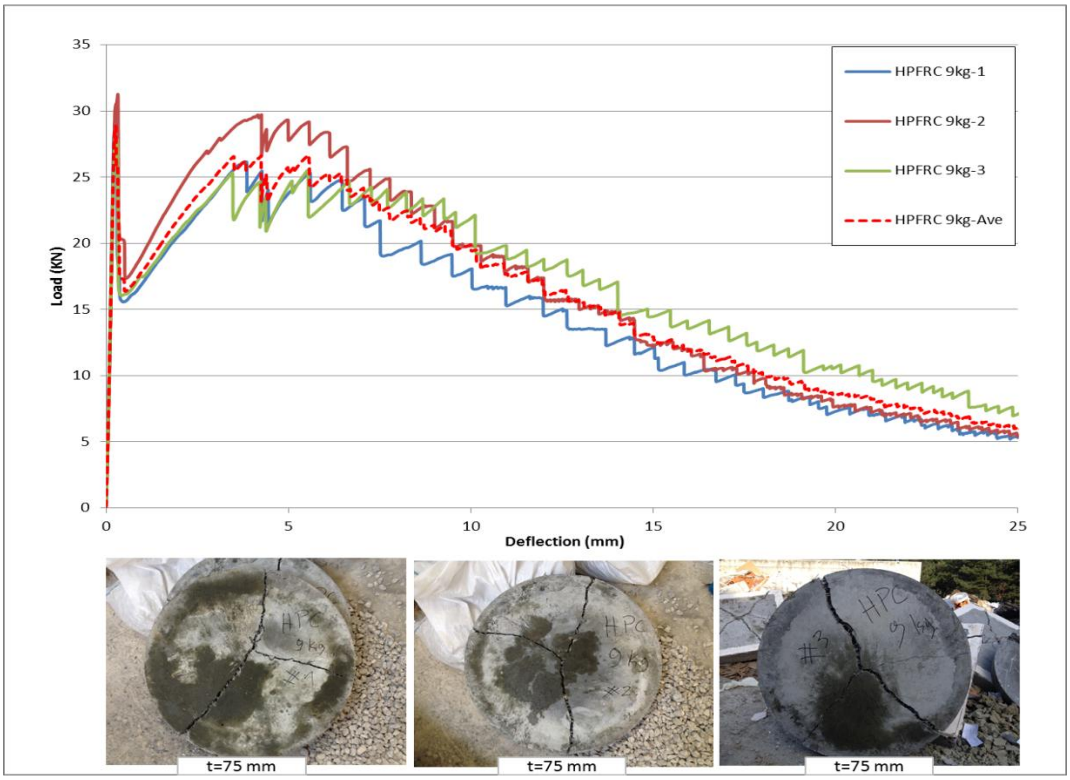


Figure 4.17 Load deflection curves and crack formations of HPFRC 9 kg samples with round panel test for 28 days.

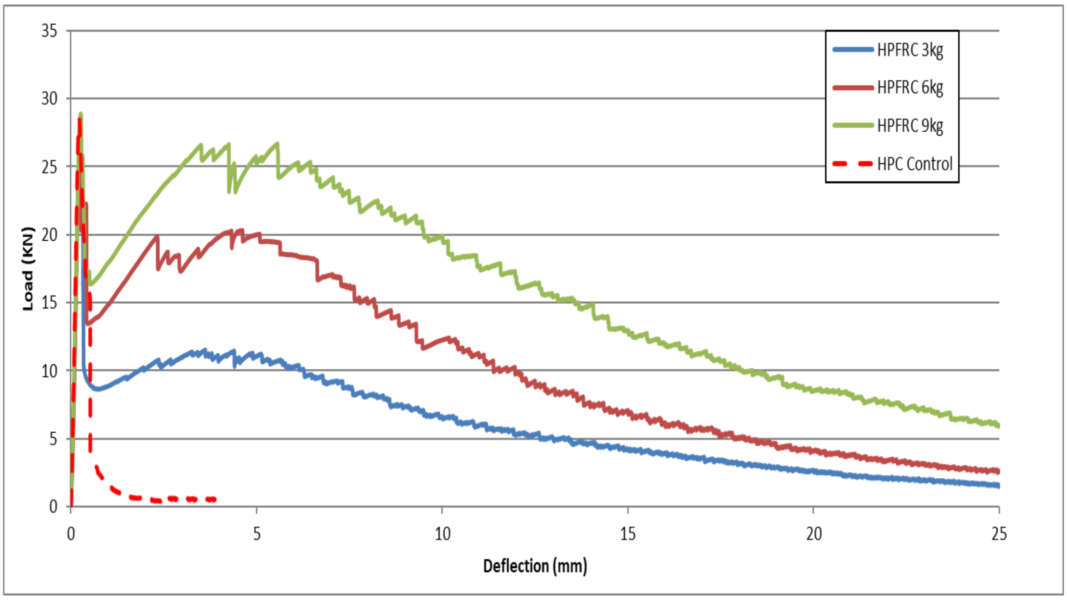


Figure 4.18 Comparison of load deflection curves of HPFRC mixes with round panel test for 28 days.

The average load displacement curves for HPFRC mixtures are plotted in Figure 4.18. As seen in that figure, similar to the square panel test, fiber inclusion significatly improved the post-cracking behaviour. However, up to the 5 mm displacement HPFRC 9 showed a better performance than HPFRC 6 Unlike the square panel test.

When the area under the load deflection curves of HPFRC are calculated as the energy absorption capacity of mixtures, the following energy-deflection curve Figure 4.19 will be obtained.

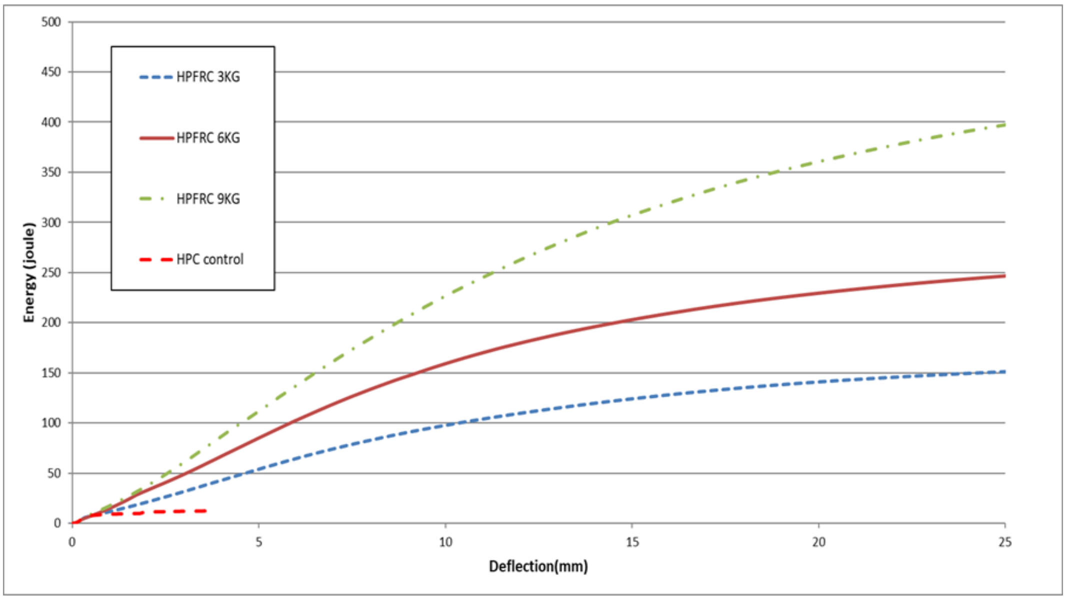


Figure 4.19 Comparison of energy deflection curves of HPFRC mixes with round panel test for 28 days.

4.3.2 Round Panel Test for PFRC

The load displacement graphs for the round panel tests for PFRC are shown in Figure 4.20 – 4.24. The deflection under the load were measured from both piston and LVDT. Due to the non- uniform surfaces of the pervious concrete, displacement measurements obtained from the piston were used instead of LVDT in the graphs.

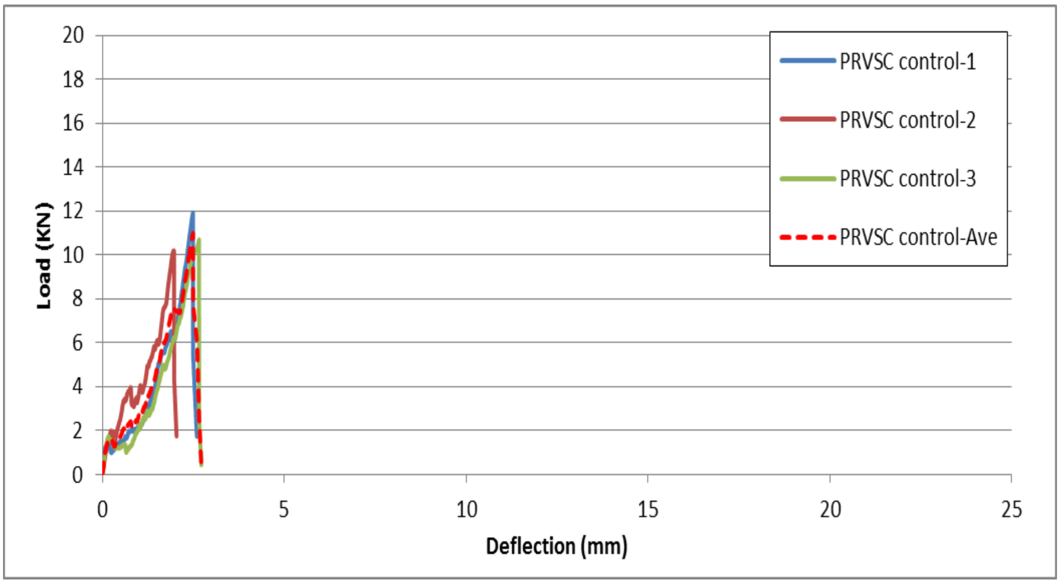


Figure 4.20 Load deflection curves of PRVSC Control samples with round panel test for 28 days.

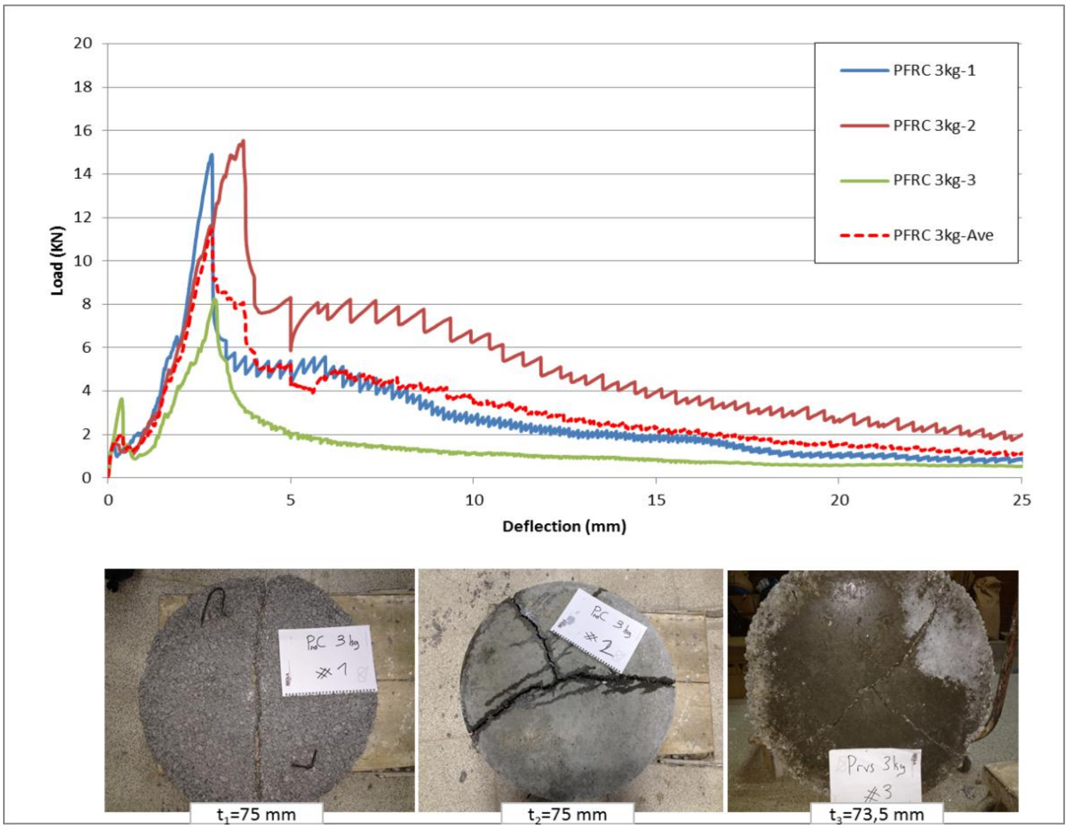


Figure 4.21 Load deflection curves and crack formations of PFRC 3kg samples with round panel test for 28 days.

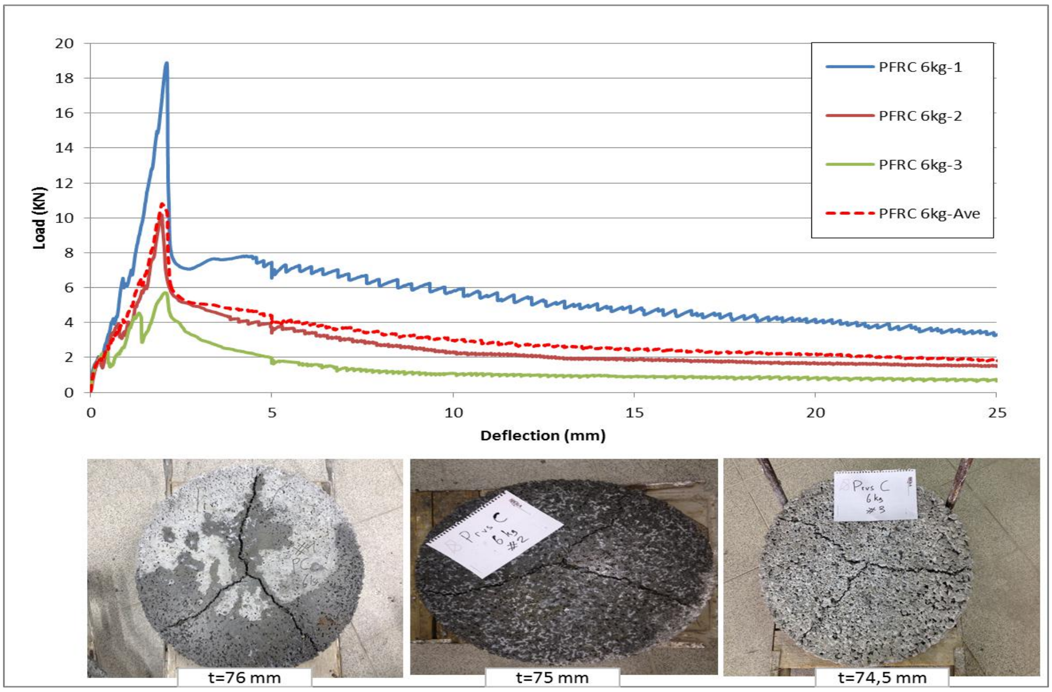


Figure 4.22 Load deflection curves and crack formations of PFRC 6kg samples with round panel test for 28 days.

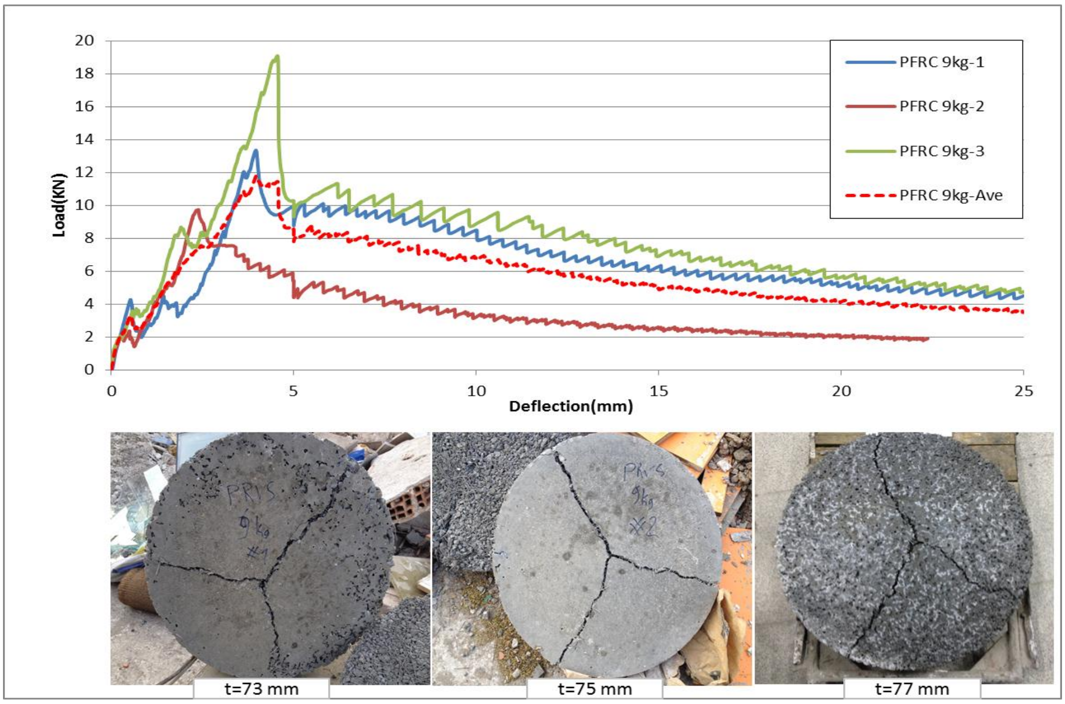


Figure 4.23 Load deflection curves and crack formations of PFRC 9kg samples with round panel test for 28 days.

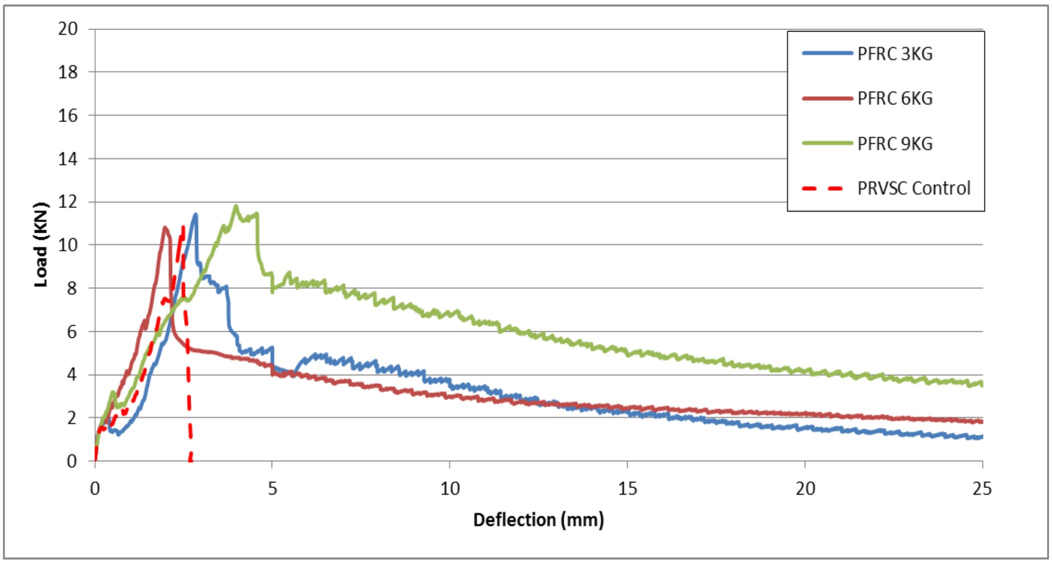


Figure 4.24 Comparison of load deflection curves of PFRC mixes with round panel test for 28 days.

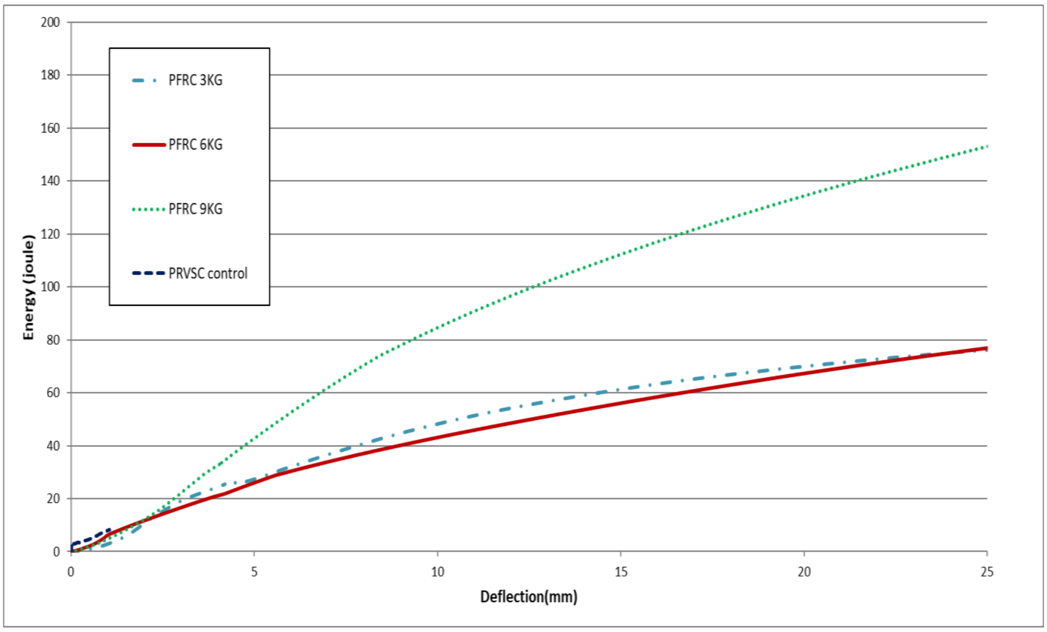


Figure 4.25 Comparison of energy deflection curves of PFRC mixes with round panel test for 28 days.

Table 4.3 The first-peak load (kN), ultimate load (kN) and energy absorption (J) of round panels.

Types of concrete	Average first peak load (kN)	Average ultimate load (kN)	Average energy at 25 mm deflection (J)	Cov (%)
HPC Control	28.5	28.5	12.4*	5.5
HPFRC 3kg	28.8	28.8	151.1	20
HPFRC 6kg	29.0	29.0	247.1	4.1
HPFRC 9kg	29.5	29.5	397.2	7.6
PRVSC Control	10.7	10.7	9.3**	12.6
PFRC 3kg	12.8	12.8	76.5	58.3
PFRC 6kg	11.5	11.5	76.5	65.7
PFRC 9kg	14.0	14.0	148.5	44.2

***** Energy at 3.5 mm deflection

****** Energy at 2.1 mm deflection

As shown in Figures 4.18, 4.24 and Table 4.3, the ultimate load and energy absorption capacity of the HPFRC 9 and HPFRC 6 mixtures are considerably larger than the rest of the mixtures. Moreover, in HPFRC 9 and HPFRC 6 specimens, strain hardening was observed after the first crack, which can be related to the good bond and the dense distribution of the fibers.

The PFRC 9 and HPFRC 3 show similar load carrying and energy absorption capacity. Their energy absorption capacity up to the deflection of 25 mm is close to each other despite their huge differences between matrix structures. This indicates that the load transfer is substantially absorbed by the fibers after particular displacement.

Although they have the same matrix design and compressive strength, the PFRC3 and PFRC 6 mixtures exhibited low performance energy absorption capacity compared to PFRC 9. Also, like the square panel test, the round panel tests of PFRC 3 and PFRC 6 exhibited almost the same load carrying capacity and toughness performance. The energy absorption capacity of PFRC 9 is 2 times greater than PFRC 6 and PFRC 3 at 25 mm deflection.

In addition to this, the energy absorption capacity of HPFRC 9 is 1.5 times greater than HPFRC 6 at 25 mm deflection. For the same deflection point HPFRC 6 is also 1.5 times greater than HPFRC 3.

Only HPFRC 3 and HPFRC 6 achieved the minimum energy absorption capacity level (195 J) at a deflection of 20 mm that is defined by ASTM 1550 round panel test. However, it should be noted that the round plate specimens used in this work have smaller size compared to the one specified in the standard.

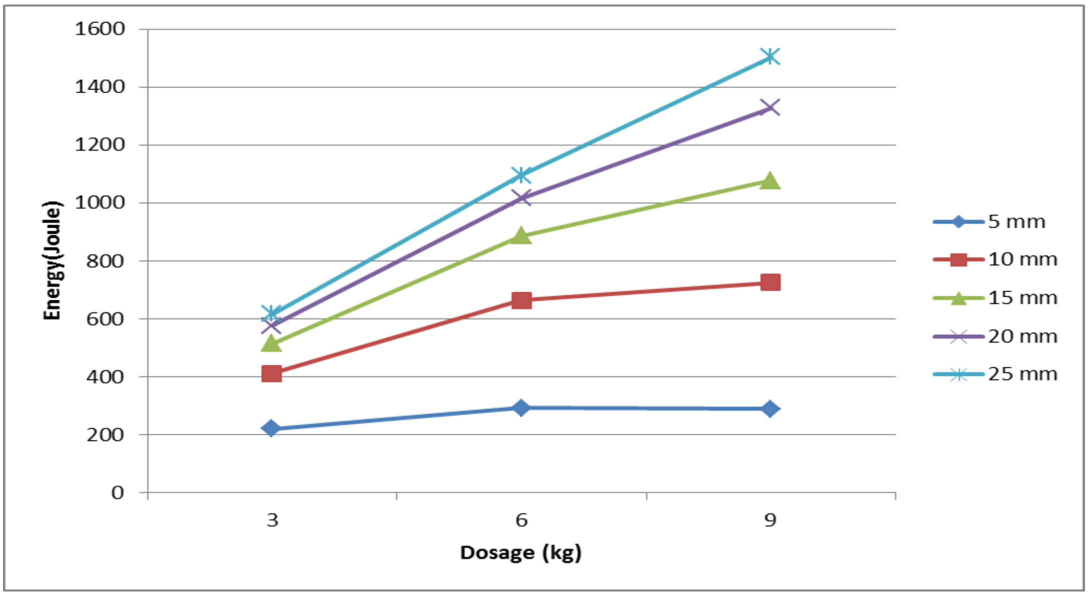
4.4 Energy Absorption Capacity at Specified Deflections

For HPFRC and PFRC specimens, which are subjected to square panel test, at 5 mm deflection the matrix performance is dominant and the fiber effect is negligible. This is mainly because of the fact that PP fibers start to work after the size of the cracks exceeds a specific limit that make the fibers completely stretched and ready to transfer the load. The energy absorption capacity increases proportionally with the increase in the fiber dosage in the deflection range between 10 mm to 25 mm.

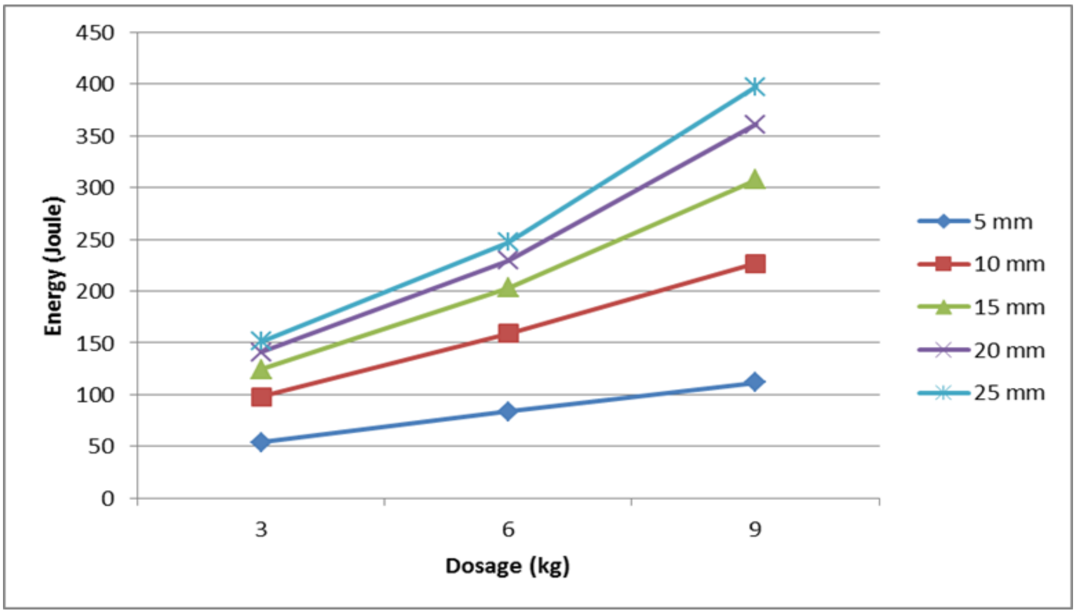
Square panel test is an indeterminate test and after the cracking there is a redistribution of the stresses. Both the supports and the fibers take part in this redistribution.

In the round panel tests, it was observed that the fibers have more contribution to the energy absorption capacity for the deflections up to 5 mm. Unlike the square panel test, the use of fibers in PFRC mixtures did not improve the energy absorption capacity until the dosage value was raised to 9 kg/m^3.

Round panel test is a determinate test therefore after the cracking the redistribution of the stresses will be only covered by the fibers.

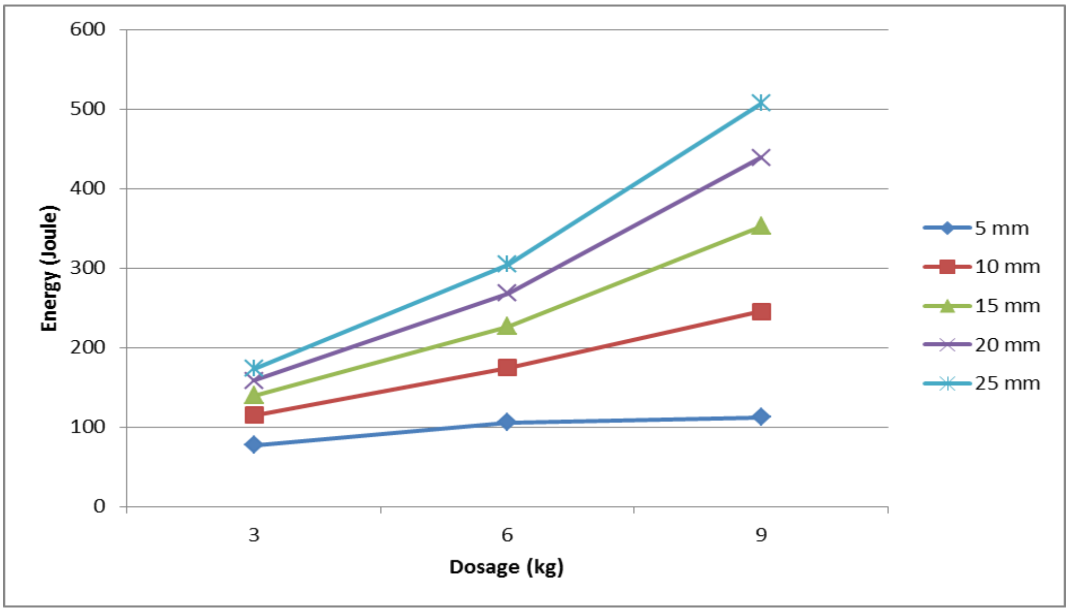


a) Square panel test

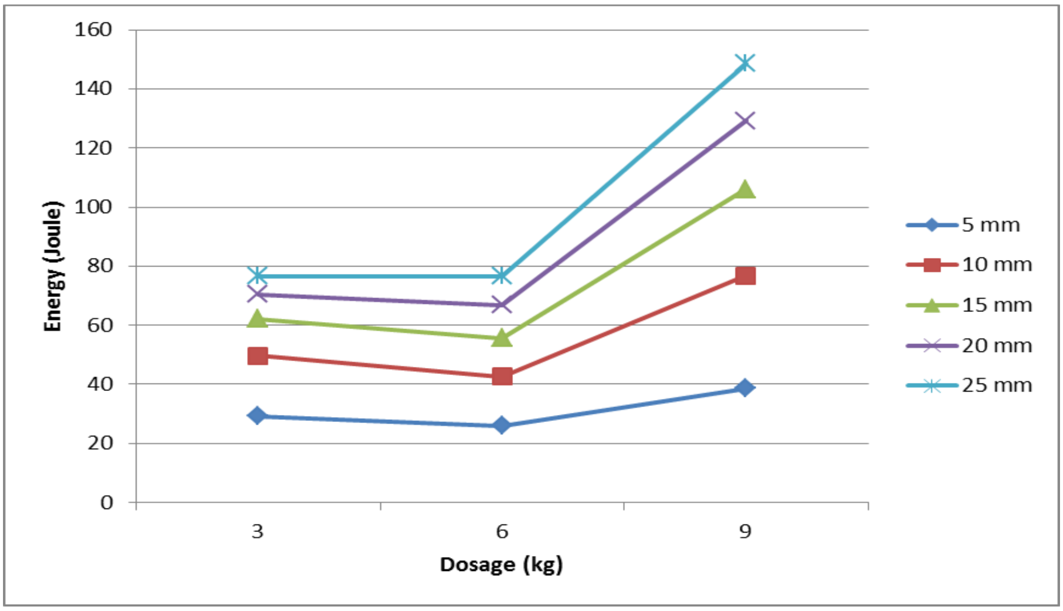


b) Round panel test

Figure 4.26 Energy absorption capacities of HPFRC mixes at specified deflections



a) Square panel test



b) Round panel test

Figure 4.27 Energy absorption capacities of PFRC mixes at specified deflections

4.5 Comparison of Center Point Deflection Methods

Measuring deflection using LVDT generally provides better sensitivity than measurement from the piston. LVDT was used for round panel specimens during the experiments, while the piston measurement was used for square panel specimens. For pervious round panel specimens the deflection under the load were measured from both piston and LVDT. Due to the non- uniform surfaces of the pervious concrete, displacement measurements obtained from the piston were used instead of LVDT in the graphs.

When the load displacement graphs obtained by both measurement methods of the same sample are examined, it can be seen that the initial slopes vary little but the energy absorption values are almost the same. The reason for the change in slope is simply the change in deflection measurement. Comparison of the load – deflection curves obtained from one round panel specimen of HPFRC 9 can be seen in the Figure 4.28. When displacements are measured from the piston, the differences between the surface roughness of the concrete and the settlement of the plaster are taken into account. For this reason, these deviations are relatively high compared to deviations measured from LVDT.

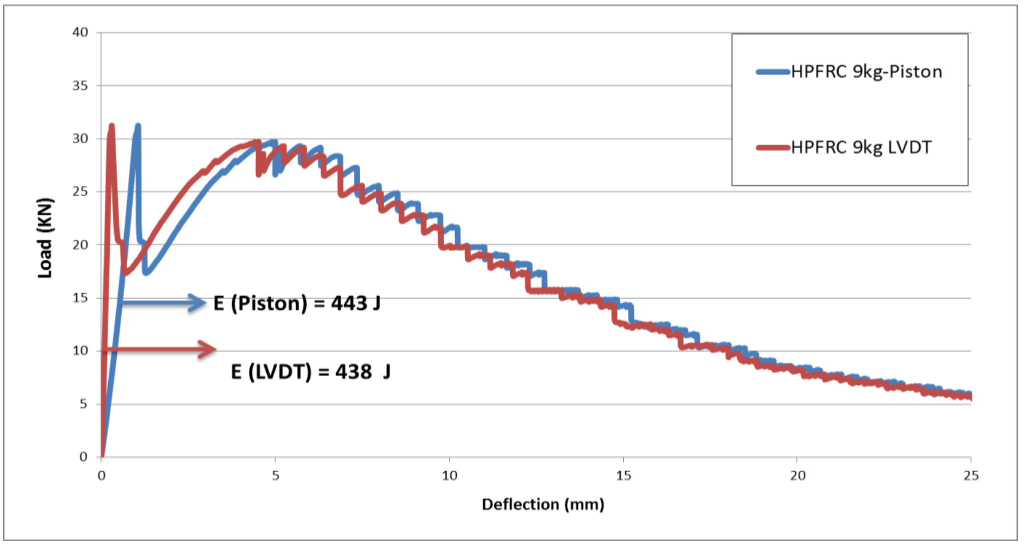


Figure 4.28 Load-deflection curves obtained from piston and LVDT

4.6 Relation of Round Panel Test and Square Panel Test

The coefficient of variation, as an indicator of the test-result scatter, was calculated and listed in Table 4.4. The coefficient of variation value of PFRC was considerably larger than the coefficient of variation value of HPFRC. For high performance panels, The average coefficient of variation (COV) of the energy absorption test results was 6.6% for square panels and 9.3% for round panels. Additionaly For pervious concrete panels, The average coefficient of variation (COV) of the results was 36% for square panels and 45% for round panels. While some of previous studies have shown that the round panel test has low variability against other test methods, the high variability obtained here may be related to the smaller panel size. For a similar work done by Paegle et al. in 2016, also showed no significant reduction in variability of test results by using round panel test instead of beam test (Paegle et al., 2016).

Table 4.4 Variation of the energy capacity results vs. dosage for panel tests

	Round panel test	Square panel test
Types of Concrete	COV (%)	COV (%)
HPC control	5.5	4.5
HPFRC 3	20	12.3
HPFRC 6	4.1	7.2
HPFRC 9	7.6	2.3
PRVSC control	12.6	21.5
PFRC 3	58.3	37.1
PFRC 6	65.7	57.7
PFRC 9	44.2	25.9

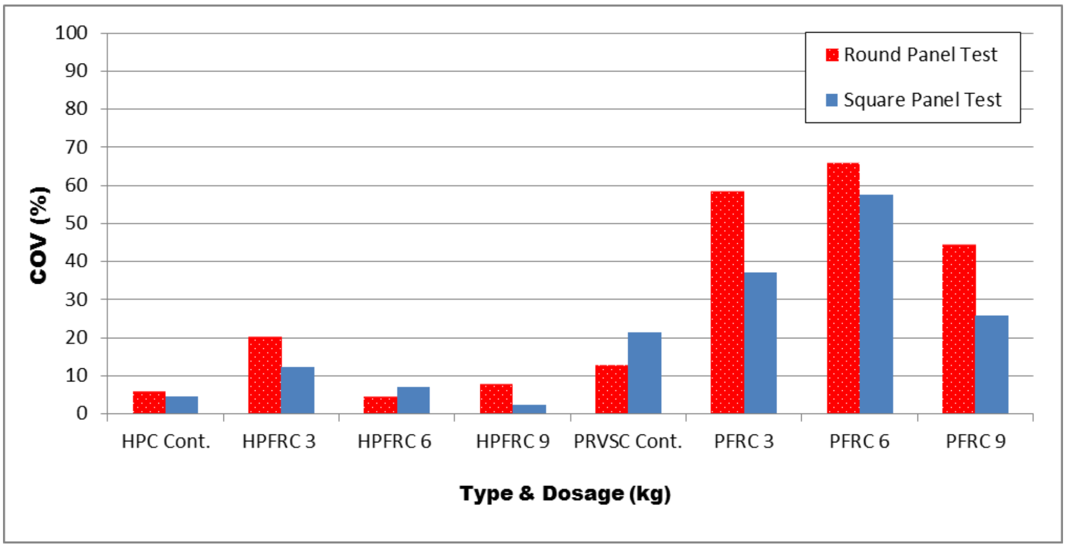


Figure 4.29 Variation of the EAC results vs. dosage for panel tests

The correlation between the two test methods helps to improve the reliability of the results of the test samples while it helps, at the same time, getting the test results for both methods by testing only one specimen type. This might significantly reduce the number of the tests required for research and quality control. Considering the test results of the square and round plates of HPFRC and PFRC mixtures, the energy absorption capacity values were divided by panel volumes to make the necessary dimensions adjustments. In addition to the HPFRC and PFRC mixtures, the EAC values obtained from the panel specimens prepared in the same laboratory and in the same dimensions by Öztürk (2018) are shown below. The mixtures used in that study are normal performance fiber reinforced concrete and high-dosage fiber reinforced concrete. Round and square panel test methods were applied to both mixtures and EAC values were also corrected by dividing into panel volumes. According to the that results, EAC of the square plates is about 2,17 times bigger than the one obtained from the round plate test method. Figure 4.30 exhibits the correlation between round panel test and square panel test.

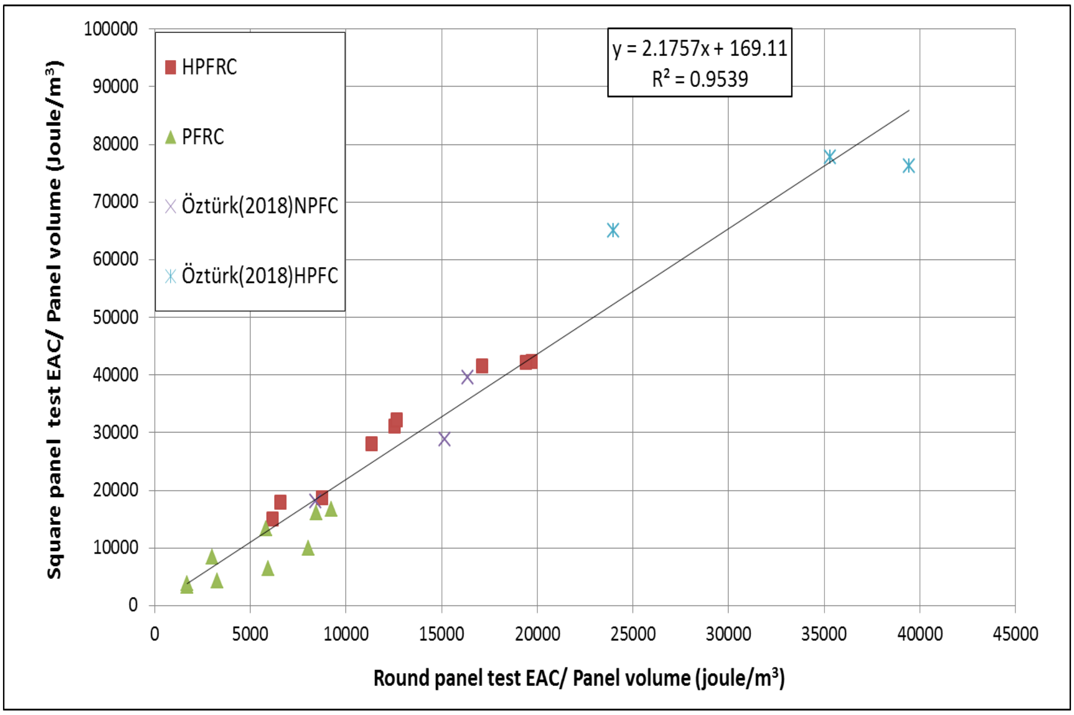


Figure 4.30 Correlation between round panel test and square panel test

CHAPTER 5

CONCLUSIONS & RECOMMENDATIONS

Square panel tests (EFNARC panel test) and round panel tests (ASTM 1550) were conducted on high performance polypropylene fiber reinforced concrete (HPFRC) and pervious polypropylene fiber reinforced concrete (PFRC). Considering these test methods, the performance properties of the mixtures, such as energy absorption capacities (toughness), load carrying capacities and compressive strengths, were examined including a comparison of the two different test methods. The load-displacement graphs and the energy absorption capacity for each mixture and specimen type were obtained.

The following conclusions can be drawn based on the test results obtained in this study:

1. Although the slump test results did not show any remarkable difference with the addition of fibers, using a fiber amount of 9 kg/m^3 reduced the compactability of the concrete, which lowered the compressive strength for both strong and weak matrices.

2. Based on the results, it can be clearly seen that the fiber addition increased energy absorption capacity and load carrying capacity for both strong and weak matrices substantially after fracture.

3. Considering the very low strength of the pervious concrete, it has been seen that the EAC of pervious concrete can be increased by a very serious amount through the addition of fiber.

4. The addition of synthetic fibers in amounts up to 9 kg/m^3 to high performance concrete and pervious concrete did not improve the ultimate flexural load of these mixtures. Considering that the used fibers have high tensile strength compared to the concrete matrix, these results can mean that with the used mix designs it was not possible to make the fibers act efficiently when the matrix starts to fail.

5. The addition of fibers had increased the energy absorption capacity for both high performance concrete and pervious concrete. The amount of the increase was related to the dosage of the fibers.

6. From the results, it can be said that the energy absorption capacity is a function of both the matrix strength and the amount of fibers. The more the fibers that actively act at early deformations in a strong matrix the higher the performance will be.

7. For high performance panels, the average coefficient of variation (COV) of the energy absorption test results was 6.6% for square panels and 9.3% for round panels. Additionaly for pervious concrete panels, the average coefficient of variation (COV) of the results was 36% for square panels and 45% for round panels. While some of previous studies have shown that the round panel test has low variability against other test methods, the high variability obtained here may be related to the smaller panel size.

8. Crack patterns were predictable in round panel test method because of determinate support conditions which always give the same cracking patterns, may imply that the test results for the round panel should be more consistent. The cracks in the round panel test will always occur in the coordinates, regardless of the fiber distribution, but in square panel test methods crack patterns were not predictable.

9. Along with the deformations of the square panels under load, frictional forces arise along the edges of the square panel specimens due to the support conditions. However, in round panel specimens, a pin-supported base was used, and friction between the support hinges and the sample was very little. For this reason, it can be said that the round panel is a frictionless process unlike the square panel test.

10. In square panel tests, the contribution of the fibers in the first 5 mm range of deflection was very small, but it was highly increased with the fiber ratio increment at the later displacement ranges. This was valid for both types of matrices, the strong (HPFRC) and the weak (PFRC). However, in round panel test, using more fiber has always increased the energy absorption capacity at all the displacement ranges.

11. Based on the test results, there is a good correlation for the energy absorption capacity obtained by the two test methods, the square and round panel tests. The energy absorption capacity corrected by panel volumes of the square panel test is about 2.17 times bigger than the one of the round panel test. Considering that conducting the round panel test is much easier than the square panel test, in the term of preparing the test specimen, this relation might save the extra work needed for the square panel test especially for trial and R&D mixtures.

In the light of the information obtained from this study, there is a major potential of the use of synthetic fiber reinforced concrete in structural elements with simple and consistent test methods. Considering this potential, further research topics can be suggested as the following:

1. Steel fiber reinforced concrete can be tested to investigate further effects of different matrices on the structure.

2. Higher fiber dosages should be tested in order to increase not only the energy absorption capacity but also the strength of the concrete. .

3. Further studies examination of different types of fibers with various matrices will help to establish stronger correlation between round panel and the square panel tests.

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