DETERMINATION OF FIBER CONCRETE TOUGHNESS CAPACITY USING TRIANGLE PLATE METHOD

Ibrahim Abdelmoneim Mohammed HAMED

T.C.
BURSA ULUDAĞ UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

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Ibrahim Abdelmoneim Mohammed HAMED
0000-0003-1033-7566

Ass. Prof. Dr. Serkan SAĞIROĞLU
(Supervisor)

MSc THESIS
DEPARTMENT OF CIVIL ENGINEERING

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ÖZET

Yüksek Lisans Tezi

ÜÇGEN PLAKA YÖNTEMİ KULLANILARAK LİFLİ BETONUN TOKLUK KAPASİTESİNİN BELİRLENMESİ

Ibrahim Abdelmoneim Mohammed HAMED

Bursa Uludağ Üniversitesi
Fen Bilimleri Enstitüsü
İnşaat Mühendisliği Anabilim Dalı

Danışman: Dr. Öğr. Üyesi Serkan SAĞIROĞLU

İnşaat teknolojisinin hızlı büyümesi, betonun çatlama sonrası davranışını iyileştirmek için daha etkili malzemelere olan talebi artırmıştır. Betonun mekanik özelliklerini iyileştiren betona lif eklenmesinin etkin katkısı göz önüne alındığında, lif takviyeli betonun çatlama sonrası davranışını belirlemek ve araştırmak için yoğun çalışmalar yapılmıştır. Lifleri betona dahil etmenin temel faydalarından biri, enerji emme kapasitesini arttırmaktır. Bu nedenle betonun enerji emilimini belirlemek için farklı test yöntemleri kullanılmaktadır.

Bu çalışma, fiber takviyeli betonun tokluğunu belirlemek ve karakterize etmek için kullanılan iki farklı test yöntemini karşılaştırmak için yapılmıştır. Beton hacmine göre %0, %0,3, %0,6 ve %0,9 gibi çeşitli lif dozajları eklenmiştir. Tokluk, yöntemin özelliklerine göre 25 mm sapmaya kadar numunelere yük uygulanarak Üçgen Plaka Yöntemi ve EFNARC test yöntemi kullanılarak belirlenir. Buna göre, yük-sehim eğrisi altında kalan alan hesaplanarak belirtilen sehime kadar tokluk belirlenir. İki test yöntemi, emilen enerji ve sonuçların değişkenliği dikkate alınarak karşılaştırılmıştır.

Anahtar Kelimeler: Lifli beton, enerji yutma kapasitesi, üçgen plaka yöntemi, efnarc yöntemi

2021, ix + 67 sayfa.

ABSTRACT

MSc Thesis

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Ibrahim Abdelmoneim Mohammed HAMED

Bursa Uludağ University
Graduate School of Natural and Applied Sciences
Department of Civil Engineering

Supervisor: Ass. Prof. Dr. Serkan SAĞIROĞLU

The rapid growth of construction technology has increased the demand for more effective materials to improve post-cracking behavior of concrete. Considering the effective contribution of adding of fibers to the concrete that enhances the mechanical properties of the concrete, intensive studies have been carried out to determine and investigate post cracking behavior of fiber-reinforced concrete. One of the main benefits of including fibers in the concrete is to enhance the energy absorption capacity. For that reason, different test methods are used to determine the energy absorption of the concrete.

This study is carried out to compare two different test methods which are used to determine and characterize the toughness of the fiber-reinforced concrete. Various dosages of fibers such as 0%, 0.3%, 0.6%, and 0.9% were added by volume of concrete. The toughness is determined using the Triangular Plate Method and EFNARC test method by applying the load on the specimens up to 25 mm in deflection according to the specifications of the method. Accordingly, the toughness is determined up to the specified deflection by calculating the area under the load-deflection curve. The two test methods were compared considering the absorbed energy and the variability of the results.

Key words: Fiber-reinforced concrete, energy absorption capacity, triangular plate method, efnarc method

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CONTENTS

ABBREVIATIONS

Abbreviation	Definition
ACI	American Concrete Institute
ASTM	American Society for Testing Materials
W/C	Water/Cement
TPM	Triangular Plate Method
EAC	Energy Absorption Capacity
COV	Coefficient of Variation
FRC	Fiber Reinforced Concrete
BS	British Standard
EN	European Norms (European Standards)
W	Water
V_f	Volume Fraction (%)

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1. INTRODUCTION

Concrete as a building material has been used since ancient times, since that time concrete using has been developed to meet the rapid growth in construction methods. Due to the rapid growth, one of the main aspects that have been developed in the concrete industry is to improve the concrete post crack behavior due to the brittleness of the concrete. With time the use of fibrous material has been developed to enhance the post crack behavior such as tensile strength, toughness (energy absorption capacities), residual strength and ductility. One of the most important mechanical properties of fiber-reinforced concrete is its energy absorption capacity. This property also called toughness is expressed by the area under the load-deflection curve. Many material properties such as crack resistance, ductility and impact resistance are related to energy absorption capacity.

To determine and characterize the toughness of fiber reinforced concrete, different test methods have been found, with any of these standard test methods. It is difficult to find the accurate characteristics and features of fiber reinforced concrete post crack behavior due to the wide differences between the standards which affected by different factors. In this scope recently a new test method was proposed by (Türker 2015) to characterize the properties of the fiber-reinforced concrete. In this method more determinant factors have been proposed to achieve more accurate results.

1.1 Objectives and Scope

The main aim of this thesis is to make a comparison between the Triangular plate method and the EFNARC test method by determining the energy absorption capacity of the steel fiber-reinforced concrete of different dosages of fiber 0.0%, 0.3%, 0.6% and 0.9% added by volume of the concrete. Then the test setup was done according to the specifications of each test method. Then the energy absorption capacity was calculated for a 25 mm deflection as specified in the standard. In addition, the two test methods were compared taking into account the energy absorption capacities values and the variability results.

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

Chapter 2 contains a background of fiber reinforced concrete and a literature review about the toughness, fiber types, mechanical characteristics of the fiber reinforced concrete, material properties affecting the toughness of fiber reinforced concrete and the test methods used to determine the toughness.

In chapter 3 the experimental process of the tests carried out and the test methods are explained with a detailed demonstration of the material properties and the mixture designs of the concrete specimens.

In chapter 4 the results of the tests and their discussion are presented in detail.

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

2. LITERATURE REVIEW

Fiber-reinforced concrete is a composition that included plain concrete ingredients with fibers as additional material to enhance its structural integrity. A remarkable development in concrete technology was achieved by the imposition of fibers to reinforce the concrete (D.Johnston 2007).

2.1 History of Fiber Reinforced Concrete

Over the last ancients, different materials have been used as fiber reinforcement to enhance some properties of a brittle material that possesses weak tension properties comparing with their compression properties. More than three thousand and five hundred years ago, sun-baked bricks reinforced with straw have been used to build the 57 m high hill of Aqar Quf (near present-day Baghdad) (Bentur and Mindess 2007). In recent times asbestos fibers, cellulose fibers have been used to reinforce cement products for at least 100 and 50 years ago respectively and also with technological development polypropylene, steel, and glass fibers for the past 30 years have been used for the same purpose (Newman and Choo 2003).

2.2 Toughness of Fiber Reinforced Concrete

In the load-displacement curve for fiber reinforcement concrete, the pre-crack response is not expected to be different from conventional concrete. Rather truly the post-peak responses are of primary interest. The inclusion of fibers significantly enhances a few of the mechanical properties of conventional concrete, particularly load-carrying capacity and its energy absorption capacity (toughness). The improved performance of fiber-reinforced concrete compared to its conventional counterpart comes from its improved ability to absorb energy throughout fracture. Whereas an obvious un-reinforced concrete fails during a brittle manner at the diffusiveness of cracking stresses (pre-peak response), the fibers in fiber-reinforced concrete still carry stresses with success on the far side matrix cracking, which helps maintain structural integrity and cohesiveness within the material (post-crack). Furthermore if properly designed, fibers bear disengagement processes and therefore the mechanical and resistance work required for disengagement results in a considerably improved capability of energy absorption. This energy absorption of fiber reinforced concrete is usually referred to as toughness.

2.2.1 Load-Deflection Response of Fiber Reinforced Concrete

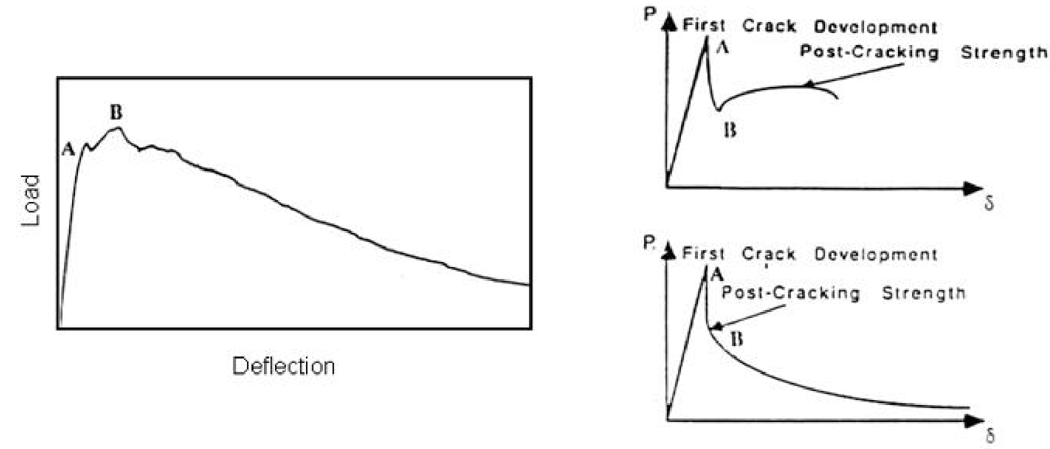
Figure 2.1 illustrate the load – deflection response of a characteristic fiber reinforced concrete beam sample which has been tested under flexure, there are three phases in this diagram.

- Phase one up to point A, a linear response of the matrix can be seen. This range can be named as the elastic response phase of the fiber reinforced concrete. In this part a strengthening mechanism behavior involves a transfer of stresses from the matrix to the fibers. the imposed stresses shared between the matrix and fibers until the first preface of cracks occurred which is named as “First cracking strength” or "Proportional Limit".

- Phase two Between points A and B, a non-linear part of the graph. In this part and after cracking, stresses are continuously transferring from the matrix to the fibers. As the load increases, the fibers tend a little pulling out from the matrix which leads to a non-linear load deflection response until the maximum load capacity, which is named “peak strength” is reached. The strain hardening behavior begins here and continues in the following phases.

- Phase three The part starting from point B, continues until complete failure. A loss in strength is accompanied by increasing deformation. This phase is an important indicative sign that the fibers composite can absorb energy before the failure. This characteristic is referred to as “toughness”.

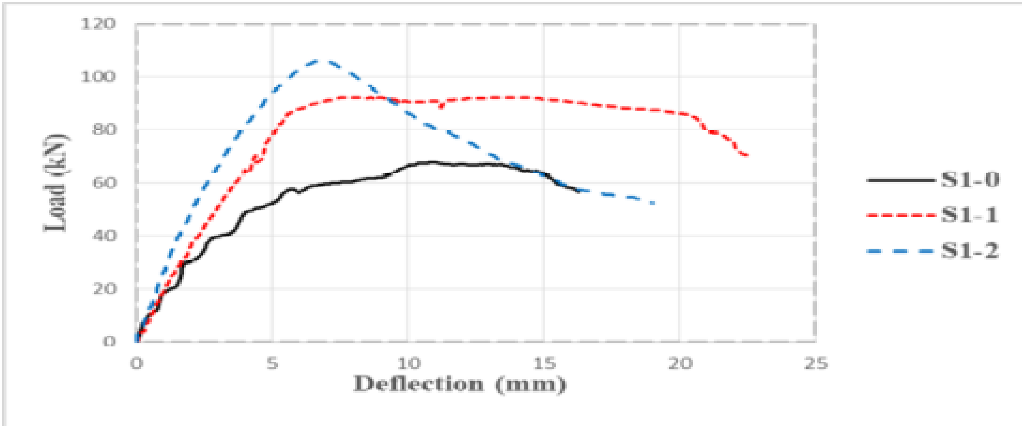
In Figure 2.1a The behavior of the load-deflection curve can be seen only if a sufficient amount of volume fractions of fibers exists. Even after the first crack has occurred, the strain hardening process permits an increase in load that means Load-B is considerably greater than Load-A. For lower volume fractions the ultimate strength intersects with first cracking strength and the load deflection curve starts to decrease unexpectedly as can be seen in Figure2.1b (Fanella and Naaman 1985).



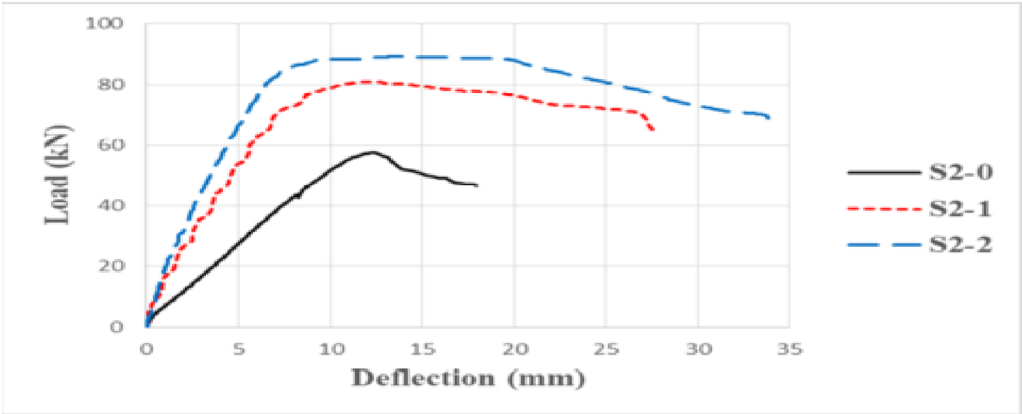
a b

Figure 2.1 Load-deflection curves of FRC beams with low volume fraction.

Comprehensive studies are applied to investigate the impact of the steel and synthetic fibers with their different kinds on the load capacity of slabs (Prisco, Colombo, and Pourzarabi 2019; Baarimah and Mohsin 2017; Bernard 2016; Kahraman 2015). In these studies, different slabs scales ranged between full and custom scales tests were conducted to compare the behavior of centrally loaded SFRC slabs to plain concrete or rebar reinforced concrete slabs. The results of the studies showed that the addition of fibers to the concrete clearly will increase and enhance the load-carrying capacity or capability of the slabs. Figure 2.2a and figure 2.2b illustrate the load-deflection responses from investigations conducted by (Baarimah and Mohsin 2017) the experimental work consisted of two series of slabs series one has 17% more thickness than series two, the fiber content for each series were 0%, 1% and 2% respectively. It is showed that the addition of steel fibers improves the load-bearing capacity of the panels consistently. In terms of ductility performance, the addition of fibers showed an improvement in the ductility, delay cracks propagation and formation. Also showed an extreme development in changing the slab failure pattern from brittleness to a more ductile manner.



(a)



(b)

Figure 2.2 Load deflection curves for SFRC slabs (Baarimah and Mohsin 2017)**.**

There have been several demonstrations recommended to the increased load-bearing capacity of concrete slabs reinforced with steel fiber. The reason behind the enhancement of the slab's load-bearing capability is the post-cracking strength of the fiber-reinforced slabs (Elsaigh and Robberts 2005).

2.2.2 Characterization of Fiber Reinforced Concrete Toughness

Adding an appropriate volume of fiber not only enhances the post crack behavior of the concrete matrix but may also affect pre-cracking behavior. Even though the dominant use of fiber in concrete is to control the cracking of FRC and then to adjust the behavior of the composite after matrix cracking if it is used at high volumes fraction (i.e. >2% by volume), fiber may also develop the pre-crack engineering properties of concrete.

While qualitatively what the fibers do to adjust the post-crack behavior of concrete has a broad agreement. It has been very delicate to get broad agreement on an explicit method to assess this behavior. There are several suspensions related to the method in which this flexural toughness should be used, interpreted or measured. It is well known (Naaman and Reinhardt 1995) that flexural toughness relies altogether upon how it is determined.

Factors that affect the measurement of flexural toughness of FRC contain the following

- Structure of the test
- Loading configuration
- Constant rate of loading
- Loading control type
- The rigidity of the test machine
- Type of displacement measuring tool
- Place of the displacement measuring tool
- Temperature at testing
- Sample size and geometry
- Specimens production methods (molding or sawing)

Since fiber reinforced concrete is the most commonly utilized in flexural usage, the flexural tests are the most commonly static mechanical tests that have been used to characterize FRC. Considerable test methods have been recommended after years and certain have been approved as standards in assorted authorities. According to Mindess, any residual strength or toughness variable used for the specification or quality control of fiber-reinforced concrete should exquisitely fulfill this basis (Bentur and Mindess 2007).

- It should have a physical meaning that is readily understandable
- It should be largely independent of specimen size and geometry
- The"end-point" used in the calculation of toughness parameters should represent the most severe serviceability conditions anticipated for any particular application
- The variability inbuilt in any measurement of concrete properties should be acceptably low
- It should be able to quantify some important aspects of FRC behavior (strength, toughness, crack resistance) and should reflect some characteristics of the load vs deflection curve

Unfortunately none of the test methods that have so far been normalized can meet these standards in a huge part because neither strength nor the form of the load versus deflection curves themselves basic concrete properties (Bentur and Mindess 2007).

2.3 Fibers Type

Fibers are small-length reinforcing elements with specific and classified properties. There are many types of fibers available for commercial use, each with its unique properties and range of use (Newman and Choo 2003).

According to their modulus of elasticity and its origin, there are two ways to classify fibers. Classification of fibers according to their modulus of elasticity can be divided into two parts fibers with a high elastic modulus than the concrete matrix and called (hard intrusion) similarly steel, glass and carbon. The other that has a low elastic modulus is called (soft intrusion) like polypropylene and vegetable. The fibers in category one which has a high modulus of elastic can improve both flexural and impact resistance. The other which has a low modulus of elastic can improve the impact resistance without noticeable contribution on the flexural strength (Chawla 1998).

Depending on their origin fibers can be classified into three basic classes; metallic fibers such as (stainless steel, steel, and carbon steel), mineral fibers such as (asbestos and glass fibers) and organic fiber which in turn is divided into made man fibers a natural (Chawla 1998).

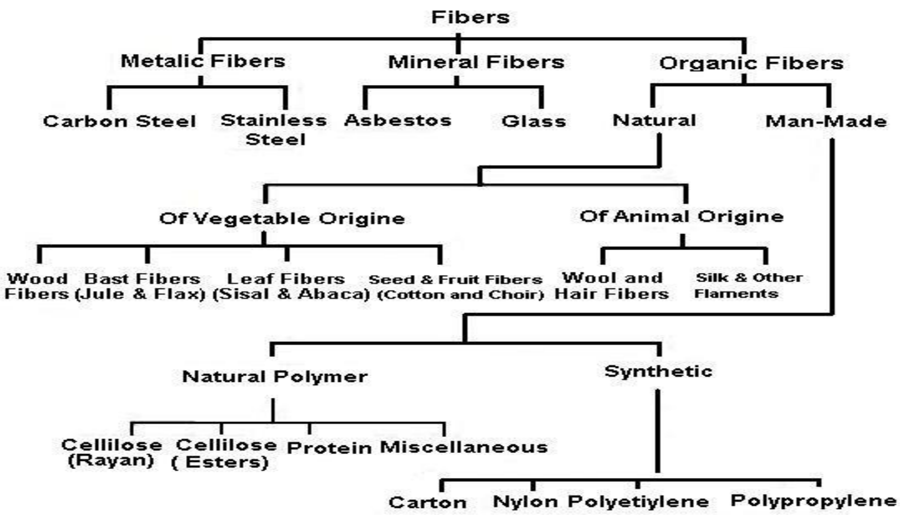


Figure 2.3 Fibers Classification (Chawla 1998)

2.3.1 Steel Fiber

Steel fibers are used to improve the properties of concrete in terms of enhancing load-bearing capacity and toughness. It is used mainly to control cracks and replace the basic reinforcement in tunnel linings, flat slabs and pavement applications while steel fiber is widely used for maintenance purposes. It is also partially used as a replacement for conventional reinforcement. The addition of steel fibers to the conventional concrete can enhance the resistance to fatigue, impact, blast or seismic accident but the strength enhancement is nothing to say for the low volume of fractions. The main feature of using steel fibers in concrete is to enhance the post-crack load-carrying capacity of the concrete matrix after the formation of the first crack (Bentur and Mindess 2007).

Types of steel fibers used in concrete are:

- Smooth cold-drawn wire
- Deformed cold-drawn wire
- Smooth or deformed cut sheet
- Melt-extracted fibers
- Mill-cut or modified cold-drawn wire

The tensile strength values of the steel fibers range between 350-2100 MPa and the elongation between 0.5-35%. The major disadvantage of high strength fibers is that they cause an intense severe spalling around the ends of fibers. Regarding the straight and smooth fibers, they have a weak bond with the matrix. For this reason, a modification has been done in recent years to modify fiber surfaces to increase the bonding strength of the matrix which resulted in the productions of enlarged end fibers, hooked end, crimped and deformed (Bentur and Mindess 2007).

Steel fibers are manufactured by cutting wires having a diameter of about 0.25 to 1.00 mm, flat and straight steel fibers possess a cross-section between 0.15 and 0.64 mm. The dimensional ratio (aspect ratio) of typical steel fibers ranges from 20 to 100 While its length values range from 6.4 to 76 mm (D.Johnston 2007).

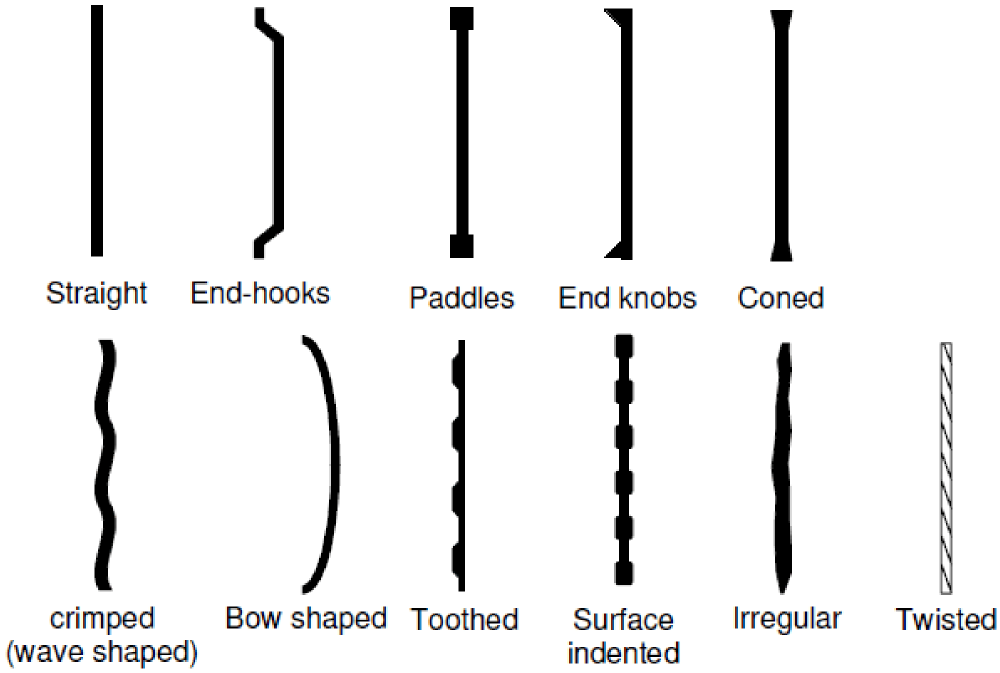


Figure 2.4 Some of standard steel fibers shape (Tameemi and Lequesne 2015)**.**

2.3.2 Synthetic Fibers

Since the middle of the last century, synthetic fibers are used very widely. These materials are made of composite polymers and small molecules where chemicals and petrochemicals are the raw materials for them. To enhance some of the properties of concrete, some synthetic fibers such as acrylic, aramid, carbon, nylon, polyester, polyethylene and polypropylene fibers increasingly have been used. Most of these fibers except Aramid, have a low modulus of elasticity (Bentur ve Mindess 2007). Since the diameters of the polymeric fibers are in the range of micrometers, their very high spect ratios are profitable in fiber reinforced concrete. The disadvantages behind the polymeric fibers low modulus of elasticity are poor bond with concrete matrix and low melting point. The bond to a cement matrix is improved by twisting several fibers together or by manipulating the surface of the fibers. The bonding between the matrix and the fibers is improved by twisting several fibers together or treating the surface of the fibers (Chawla 1998).

Table 2.1 Synthetic fibers properties (Bentur and Mindess 2007)

Fiber type	Diameter (μ*m*)	Specific gravity (g/cm^3)	Tensile strength (GPa)	Elastic modulus (GPa)	Ultimate elongation (%)
Acrylic	20–350	1.16–1.18	0.2–1.0	14–19	10–50
Aramid (Kevlar)	10–12	1.44	2.3–3.5	63–120	2–4.5
Carbon (PAN)	8–9	1.6–1.7	2.5–4.0	230–380	0.5–1.5
Carbon (Pich)	9–18	1.6–1.21	0.5–3.1	30–480	0.5–2.4
Nylon	23–400	1.14	0.75–1.0	4.1–5.2	16–20
polyester	10–200	1.34–1.39	0.23–1.2	10–18	10–50
Polyethylene	25–1000	0.92–0.96	0.08–0.60	5	3–100
Polyolefin	150–635	0.91	275	2.7	15
Polypropylene	20–400	0.9–0.95	0.45–076	3.5–10	15–25
PVA	14–650	1.3	0.8–1.5	29–36	5.7
Steel (for comparison)	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
Note: **The values in the table are for fibres that are commercially available. They may vary considerably from manufacturer to manufacturer.**					

Synthetic fibers can be categorized into microfibers and macro-fibers. Each category has specific characteristics and capabilities, microfiber is preferred to reduce shrinkage in concrete while macro fiber is preferred to control crack (D.Johnston 2007).

The microfibers are generally produced with a diameter of less than 0.1 mm, to have good workability, it must be added in a low volume of fractions. Polypropylene is the most common type of microfiber. On the other hand, the macro fibers are characterized by a length of more than 30 mm and a diameter greater than 0.1 mm. These fibers can be used in a higher volume of fractions. Thus achieving high values of toughness. Macro-fiber can be better to increase performance such as corrosion resistance, better post crack behavior, small cracks and enhanced performance under impact loads compared with traditional reinforced concrete (D.Johnston 2007, Reem Hafiz 2015).

2.4 Mechanical Characteristics of Fiber Reinforced Concrete

It is known that adding fibers to conventional concrete changes some of its mechanical properties. For example, Table 2.2 below demonstrates some of the mechanical properties that are affected by the addition of fiber.

In this research, toughness or energy absorption capacity the main mechanical property was investigated by adding two different types of fiber which have been tested under two various test methods EFNARC and the triangular plate method (EFNARC 1999).

Table 2.2 Performance of fiber reinforced concrete compared to conventional concrete (Bothma J 2013)

Property	Comment
Abrasion resistance	Improvement may be achieved as a result of reduced bleeding.
Compressive strength	Little change.
Electrical resistance	No significant change at fibre dosages generally used.
Fatigue resistance	Improvements even at low dosages.
Flexural strength	Little change in first crack strength at dosage rates commonly used.
Freeze-thaw resistance	Can reduce the deterioration caused by freeze-thaw cycling.
Impact resistance	Major improvements.
Modulus of elasticity	No significant change at fibre dosages generally used.
Restrained shrinkage	Even at low dosages, better distribution of stresses can reduce crack widths.
Shear strength	Improvements even at low dosages can be achieved in combination with reinforcing bars.
Spalling resistance	Being dispersed throughout the matrix, steel fibre reinforcement gives superior protection to exposed areas such as the joint arris.
Thermal shock resistance	As with impact resistance, there are improvements even at low dosage rates, a typical application being foundry floors.
Toughness	Major improvements, even at low dosages.

2.4.1 Compressive Strength

As a result of several types of research related to concrete compressive strength with the fiber presence. It was observed that the addition of fiber has a negligible effect in terms of improving the compressive strength of concrete. The reason for this is due to a high decrease in the value of the compressive strength of the concrete after the first cracking and any stress bridging after that has a little contribution to the concrete compressive strength (Bentur and Mindess 2007).

The effect of adding steel and synthetic fibers of various shapes and sizes to the same concrete matrix was studied by Soutsos et al (2012). Steel fiber has been added 30 kg/m^3 and 50 kg/m^3 by the volume and showed an increase to the compressive strength ranged between 4-5 MPa. On the other hand, the synthetic fibres which have been added 4.5 - 5.3 kg/m^3 showed an increase to the compressive strength ranged between 2-3 MPa.

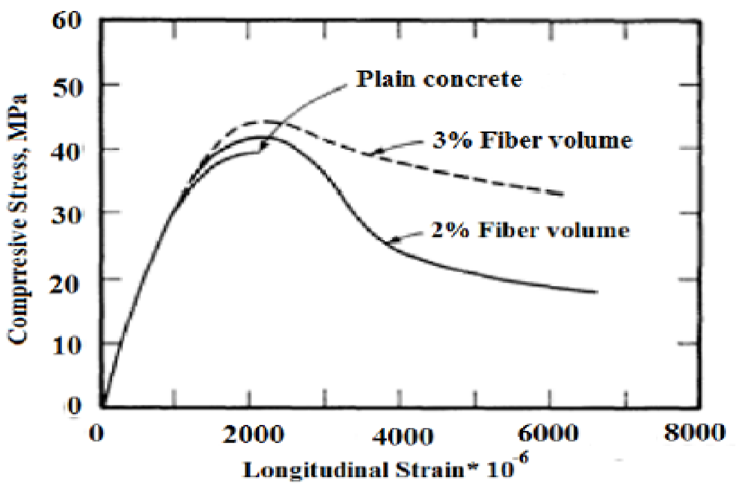


Figure 2.5 Stress-strain curves for steel fiber reinforced concrete under compression (Bentur ve Mindess 2007).

Another study carried out by Modhera, to investigate the effect of the presence of fiber on the mechanical properties of high and normal concrete by adding 1.5%, 3.0%, 4.5%, and 6% by volume. The results conclude that the compressive strength has been slightly increased compared to the conventional concrete but an interesting result has noticed a 10% of concrete compressive strength has decreased for 6% sample (Modhera 2016).

2.4.2 Splitting Tensile Strength

According to Shafigh et al. (2011), addition of steel fiber remarkably increases the splitting tensile strength. In the study, steel fibers have been added with amounts ranged between 0%, 0.25%, 0.5%, 0.75% and 1%. An increase in the splitting tensile from 2.83 to 5.55 MPa. The rate of increase for 0.25%, 0.5%, 0.75% and 1% mixes is 41%, 61%, 94% and 96%, have been achieved respectively, which means even by adding low amounts of fiber an appreciable enhancement can be achieved.

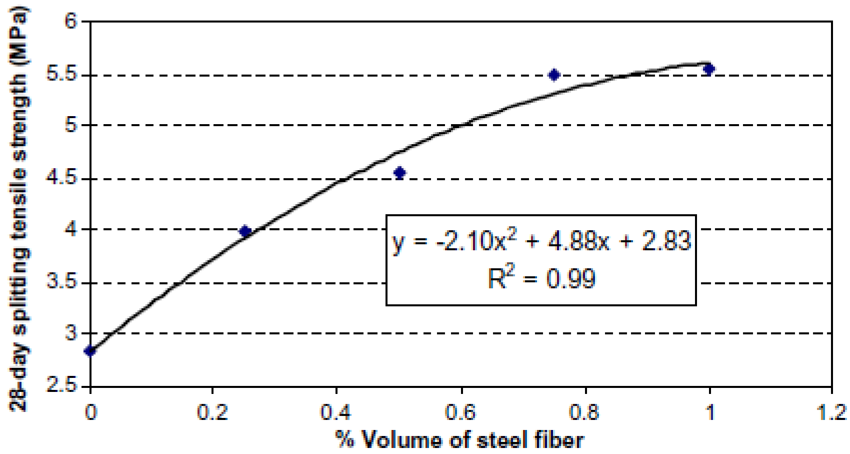


Figure 2.6 Relationship between the volume of steel fiber and splitting tensile strength Shafigh et al. (2011).

Vairagade and Ken carried out an investigation using metallic and synthetic fibers . In the study, 0.5%, 50 mm copper-coated steel fibers and 0.4%, 24 mm cut length fibrillated polypropylene fibers have been added, which conclude that the maximum splitting tensile strength was obtained by steel fibers, on the other hand, the addition of synthetic fibers increases the splitting tensile strength up to 45.61% (Vairagade and Kene 2013).

2.4.3 Modulus of Elasticity

Shafigh et al. (2011) have found in their study, whether steel or synthetic fibers are added to the concrete composite have a slight effect on the modulus of the elasticity. Though, the measured value of modulus of elasticity in this study was equal to 15.5 GPa which approximately about 40% higher than the highest measured values of the studies done before on the normal strength concrete.

2.4.4 Flexural Strength

The influence of adding fibers whether steel or synthetic on the flexural strength of concrete has been studied by Soutsos et al. (2012), by adding steel fibers with different shapes ranged between hooked end, flattened and wavy shapes, with 50 mm and 60mm in length, the dosages were 30, 40, and 50 kg/m^3 respectively. For synthetic fiber 4.6 and 5.3 kg/m^3 were added to the concrete. The incorporation of steel fibers increased the flexural strength by 0.4 to 0.6 MPa, while the synthetic fiber increased the flexural strength by about 0.2 to 0.25 MPa. Figure 2.7 shows the flexural strength of steel and synthetic fibers.

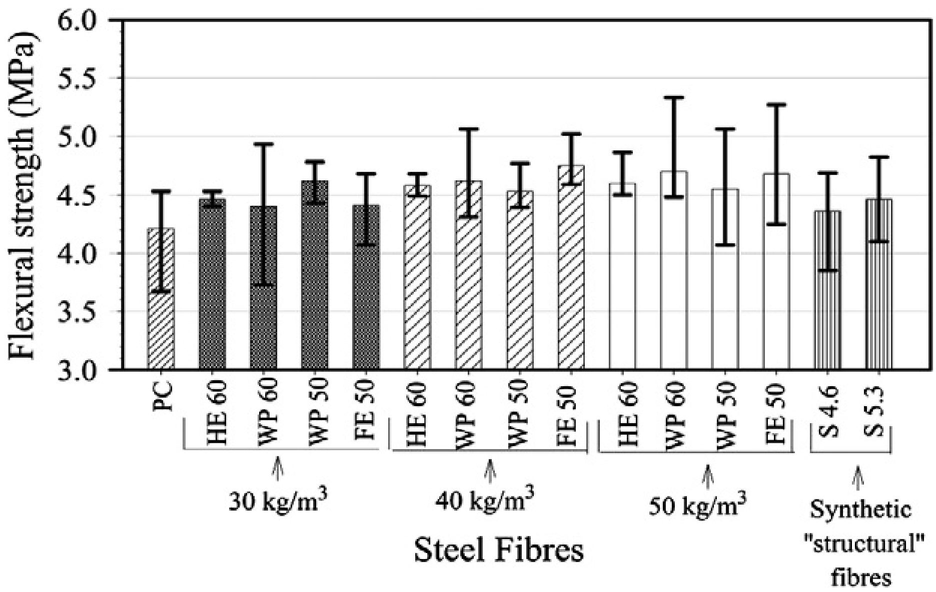


Figure2.7 Flexural strengths of steel and synthetic fiber

Through some previous studies, at a lower dosage of fibers, it was found that no significant improvement in the flexural strength of concrete which recommended to use a higher dosage of fibers to attain a significant improvement in the flexural strength Jose et al. (2015).

2.4.5 Impact Resistance

To investigate the effect of fibers on the impact resistance. A study carried out by (Abhinav and Rao 2016) hooked end steel fiber was added randomly with 0.5%, 1.0% and 1.5% by volume of concrete. Based on the results of the study the steel fibers added a considerable improvement to the impact resistance. Furthermore high fiber dosages led to an increase in the impact resistance, which achieved for %1.5 fiber volume.

In another study, various fiber types with different properties have been used to investigate the impact resistance of concrete. The study obtained hooked end steel fibers were most effective in enhancing impact resistance followed by flattened and twin cone fibers. The inclusion of synthetic fibers to the concrete increased the Impact resistance, crimped synthetic fibers were more effective compared to the straight ones. Furthermore replacing a small part of steel fibers with synthetic fibers to form what is called a hybrid fiber reinforced concrete showed better impact resistance (Yoo and Banthia 2019).

2.5 Material Properties Affecting Toughness of FRC

2.5.1 Fiber Type and Length

In terms of toughness or energy absorption capacity, a lot of studies have been carried out to investigate the effect of fiber type and length on concrete.

Soutsos et al. (2012) studied the effect of the inclusion of synthetic and steel fibers to concrete with different shapes wavy, hooked end and flatten with 50 and 60 mm in length. It concluded that the hooked end with 60mm in length absorbed more energy compared to other types. On the other hand, the energy absorbed by the synthetic fibers was lower than the steel ones.

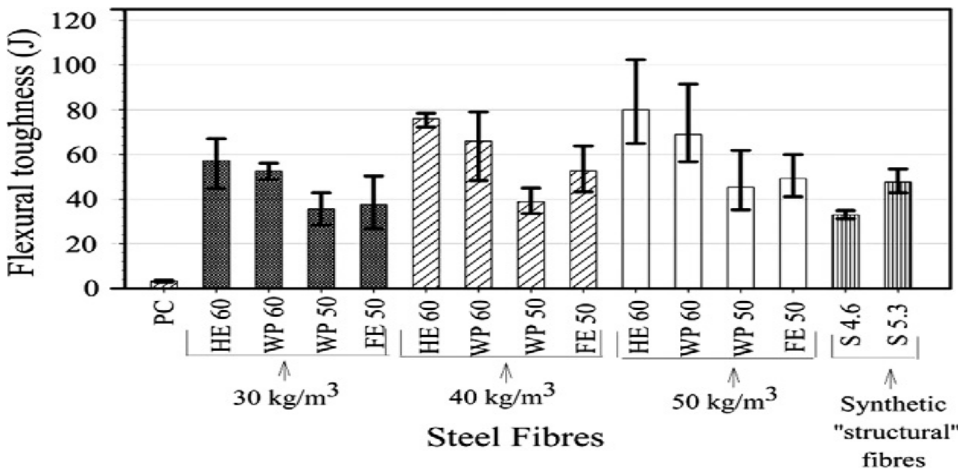


Figure2.8 Flexural toughness of synthetic and steel fibers Soutsos et al. 2012

Due to the diversity of steel fibers shapes and surface texture, tested steel fibers showed higher performance than synthetic in terms of energy absorption capacity. Also it has been found increasing fibers dosages are accompanied by an increase in energy absorption capacity. Mercan (2019) found that the increase in fiber length has led to an increase in toughness. Back to the study, 30 and 60 mm have used and it found that the toughness value is three times higher than the short one. The length of the fibers greatly affects the concrete. Whether it is synthetic or steel, the mixing properties of fresh concrete will change due to the length. More spaces will be generated by the longer fibers, while the synthetic tends to bend around the aggregate (Juhász and Kis 2017).

It is known that synthetic fibers have a lower modulus of elasticity than steel fibers. Accordingly, it is found that the synthetic fibers control the member response near the maximum load. Furthermore, synthetic fibers play an important role in control permeability and corrosion comparing with steel fibers (Bentur and Mindess 2007).

2.5.2 Fiber Aspect Ratio, Orientation and Dispersion

Aspect ratio is the ratio of length to the diameter of the fiber (Bentur and Mindess 2007). The aspect ratio is related to the critical length of the fiber which is defined as the lowest length of the fiber that allows the improvement of adequate stress to cause the fiber to fail at its midpoint. he critical fiber length could be as much as 50 times the diameter of the fiber (Neela 2010).

Al-ghamdy et al. (1992) In their study of the flexural toughness of fiber reinforced concrete. Found that a higher value of toughness has been achieved from fibers with (l/d=100) than those that have (l/d=63). Yoo showed that a high energy absorption capacity achieved from the fibers with a high value of aspect ratios (Yoo et al. 2017).

Determination of orientation and dispersions of the fibers in the concrete is a complex and difficult process. However, studies that carried out the effect of orientation and dispersion of fibers, demonstrate that In the case that the fibers are in the same direction as the load provides high toughness and strength compared with randomly distributed fibers (Öztürk 2018). Microstructure studies found that short fibers spread better than long fibers, resulting in an increase in toughness accompanied by high performance.

In a study on fiber reinforced extruded cement composites carried out by Akkaya et al. (2001), two lengths of fibers 2 mm and 6 mm with an identical volume have been used to investigate the post-peak behavior. The result of the study concludes that short fibers exhibited multiple cracking with an improved post-peak property. Nevertheless, the 6 mm one didn't exhibit the same. Enhanced toughness and effective crack bridging can be achieved if the dispersion of the fiber is better in the first crack.

2.5.3 Matrix Strength

Concrete matrix strength significantly depends on the water-cement ratio w/c. Through flexural toughness tests like the third point test and panel tests. It has been observed changing in w/c ratio leads to change in first crack stress and ultimate strength of fiber-reinforced concrete with a small noticeable effect on the load-deflection curve concrete. Thus, the absolute toughness value can be changed noticeably, but a slight influence on the relative toughness could be noticed (Chen 1995).

(Hetemoğlu 2018, Öztürk 2018) Found a sudden fall in the value of the post-peak load of high-strength matrices. High strength concrete matrix, after the first crack there was usually an abrupt and sharp fall in the load-carrying capacity.

2.5.4 Other Material Factors

Many variables affect the mechanical properties of fiber-reinforced concrete, including the size of aggregate, the age of the concrete, the amount of cement, the degree of humidity, the amount of fiber in the concrete and so on. In fiber reinforced concrete, fibers are separated by aggregates, which are typically larger than the typical fiber spacing if the fiber is uniformly distributed. This ends up in an accumulation of fibers and increasing interactions with aggregate. The effect becomes explicit when the size of the aggregate increases (Chen 1995).

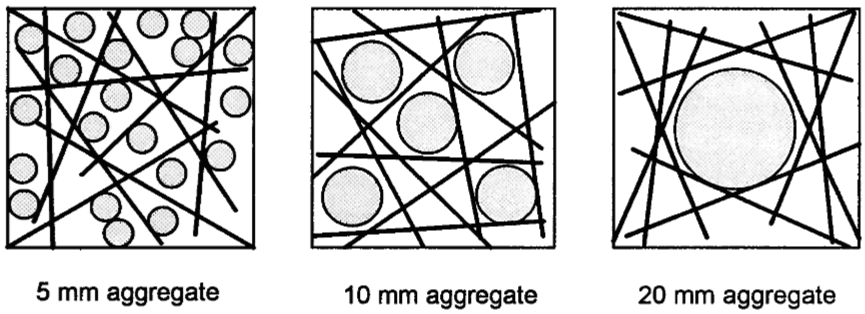


Figure 2.9 Effect of aggregate size on fiber distribution (Chen 1995).

Seleem et al. (2020) Studied the effect of maximum aggregate size on the mechanical performance of plain and fiber reinforced concrete by using four various sizes of aggregates 10, 20, 25, 40 mm and the steel fibers with 35 mm in length and an aspect ratio of 43.75. The results indicate that the maximum size of aggregate influenced the mechanical properties significantly. Nevertheless, in terms of energy absorption capacity, the increase in size is accompanied by a decrease caused by the length of the fiber. Previous studies showed that the length of fiber should be 2-4 times the maximum aggregate size (Bentur and Mindess 2007).

With an increase in aggregate size, the absorbed energy decreases, while for normal strength concrete, the absorbed energy increases by increasing the size of aggregate. It can be said that the length of fiber depends on the maximum size of aggregate (Kozul and Darwin 1997).

2.6 Test Methods For Determining Flexural Toughness of FRC Panels

In terms of determining the concrete flexural behavior, there are many test methods used for beams and panels. Some of these test methods are listed below:

- ASTM C1018: Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)
- ASTM C 293: Standard Test Method for Flexural Strength of Concrete (UsingSimple Beam With Center-Point Loading)
- ASTM C1550: Standard Test Method for Flexural Toughness of Fiber ReinforcedConcrete (Using Centrally Loaded Round Panel)
- BS EN 14488-5: Testing sprayed concrete. Determination of energy absorption capacity of fiber reinforced slab specimens
- EFNARC Square Panel Test Method
- BS EN 14651: Test method for metallic fiber concrete. Measuring the flexural tensile strength (limit of proportionality (LOP), residual)

The flexural behavior and the energy absorption capacity were usually determined using beam samples. However, many drawbacks were encountered in sorting relative behaviors. In the panel tests, characteristic values and low variability have been obtained. Furthermore, related to the field performance panel tests were more prototypical.

2.6.1 Centrally Loaded Square Panel Method

The EFNARC square panel test is the most widely used (Bernard 2016) which measures the energy absorption capacity of plates by calculating the area under the load-deflection curve between 0 and 25 mm deflection. The test is designed to create a more realistic model for biaxial bending applications that may occur in the structural applications.

A 100 × 600 × 600 mm^3 square plate has to be loaded centrally and supported by a continuous frame that supports the plate from the four edges, with an internal clear span of 500 mm. The center point of contact is a rigid smooth block has an area of 100 × 100 mm^2 (BS-EN 2006) the test setup is shown below in Figure 2.10.

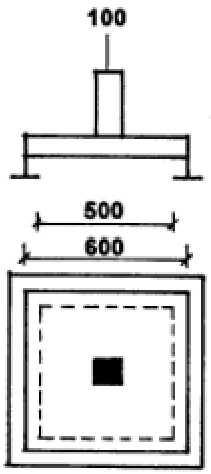


Figure 2.10 Set-up for plate test (BS-EN 2006)

EFNARC has specified a (1 ± 0,1) mm/min as a constant loading rate at the center of the slab until the deflection reaches 30 mm (BS-EN 2006).

Previous studies revealed some disadvantages of this test method as the difficulty of specimen production, transfer and the most important ability is the difficulty of making an ideal flat base for the specimen. The non-flat specimen will deform unpredictably and shows various peaks in load-bearing capacity (Bernard 2016).

2.6.2 ASTM 1550 (Round Panel Test)

The round panel test or ASTM C1550 has been used to determine the flexural toughness of the fiber-reinforced concrete expressed in terms of energy absorption capacity and was calculated by subjected a central load point on a round panel that has dimensions of 800 mm in diameter and 75 mm in thickness. While the specimen was supported on three symmetrically arranged pivots. A high sensitivity LVDT has to be replaced at the mid of the sample to measure the deflection (ASTM 2012).

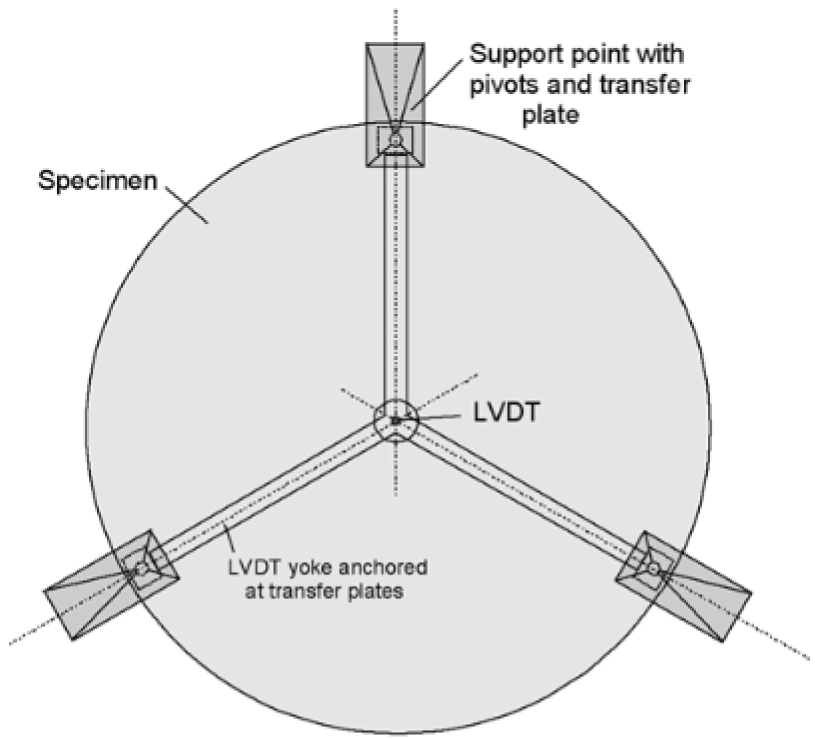


Figure 2.11 Plan view of suggested method of deflection measurement (ASTM 2012).

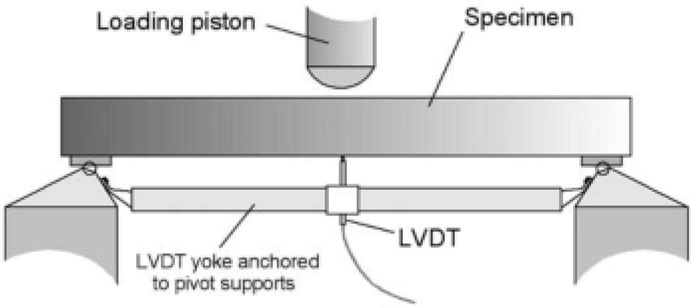


Figure 2.12 Side profile view of ASTM 1550(ASTM 2012)

ASTM has recommended a displacement rate of 4.0 mm/min, while the loading should be up to 40 mm deflection (ASTM 2012). Previous studies showed that the changes in cracking load, maximum load and absorbed energy up to specific central deflection in the round plate tests are lower than beam test with a coefficient of variation ranged between 5% and %15. The reason for this decrease is due to the specific location of the cracks and the increase in its area which decrease the impact of fiber's distribution. On the other hand, the main disadvantage of this test method is that the sample is too large and very heavy to operate and doesn't fit with many test machines (Bentur and Mindess 2007).

2.7 Previous Studies Carried out Using Different Test Methods

A comparative study was carried out at middle east university by Ozturk. The main aim of the study is to compare the behavior of high doses of concrete synthetic fibers under different tests methods. For high doses of synthetic fibers a 12, 18 and 24 kg/m^3 were added to the concrete. On the other hand a 3, 6 and 9 kg/m^3 were added to the concrete as considered a low volume content. EFNARC plate test and ASTM plate test both have been used to compare the behavior of the synthetic fibers.

As a result of the study, some differences have been obtained such as the crack pattern in the EFNARC test was remaining unpredictable due to the undetermined support conditions. But in the ASTM test were predictable due to the determined support conditions. It was noticed a high energy absorption capacity resulted in EFNARC test compared with ASTM. The most distinguished property was friction, where it can be negligible in ASTM standard due to the support condition but in EFNARC it can not be said to be friction-free (Öztürk 2018).

Another similar study has been carried out to investigate the performance of low volume of synthetic fibers with two different types of the concrete matrix. 3, 6 and 9 kg/m^3 have been added to one high strength matrix and the other low strength matrix by determining the absorption energy of each matrix using two different test methods round panel test (ASTM) and square panel test (EFNARC). Based on the results of the study the coefficient of variation for the square panel was lower than the round panel test for both matrices high performance and low performance (pervious concrete). The values of (COV) were 6.6% and 9.3% for high-performance square and round panels matrices respectively. While for low-performance concrete the (COV) were 36% and 45% for square and round panel test respectively. The reason behind the difference in the coefficient of variation was mainly due to the decrease in the diameter of the round panels from 800 mm to 600 mm to be suitable for the machine dimensions. More further the results also obtained the crack predictability as remain unpredictable for the square test and predictable for the round panel test, this due to the determining conditions of the supports in the round panel test.

One of the most distinguished properties for the square panel test was the frictional force that araised to the edges of the specimen due to the continuity of the supports. Nevertheless, for the round panel test pin supports have been used. The friction between the supports and specimen was too little to be considered. For that reason, the round panel test can consider as a frictionless test method. In the square panel test, in the first 5 mm of the deflection the contribution of fibers was very small, but it was increased highly with fiber ratios at later deflection ranges. The final and corrected energy absorptions capacities for the square panels were 2.17 times larger than the round panels (Hetemoğlu 2018).

Another study has done by the Norwegian Public Roads Administration Directorate of Public Roads to determine the absorption energy of fiber-reinforced concrete panels. The main aim was to study the effect of friction on the absorption capacity using two different test methods, the Norwegian test method and the EFNARC panel test.

A total of 16 square and round panels have been divided into two groups. Every group contains eight panels. Both groups have been tested for standard conditions and no friction conditions. In terms of energy absorption capacity, the test results showed the coefficient of variation was 7.8% for round panels(Norwegian test method) and 11.7% for the square panels(EFNARC test method). The results showed that between zero and 25 mm 35% of the overall absorbed energy uptake is due to friction and the remaining 65% is due to fiber action in the concrete plate.

The results showed that between zero and 25 mm 35% of the overall absorbed energy uptake is due to friction and the remaining 65% is due to fiber action in the concrete plate. 4-5 cracks have been obtained from the standard condition while on the other hand, just 4 cracks have been obtained from the no friction condition(Bjøntegaard 2009).

2.8 Triangular Plate Method

The triangular plate method was proposed by (Türker 2015) to determine the biaxial flexural tensile strength of the cement-based material. It is worth mentioning that despite its being a new test, many studies have been done using the triangular plate method ranged between numerical and experimental studies.

In this test, specimens are prepared in the form of triangular panels. The load is applied to the triangular's center of gravity and supported by three pivots (steel sphere) placed at a distant one-third of the median side of the triangular. In this way, the supports are kept away from the sample's edges and the edges are prevented from the formation of fractures. The ease of sample preparations, simplicity of test procedure and relatively better tolerance of sample surface smoothness is the most advantages of the triangular plate method. Furthermore, since the contact between the supports and the sample surface is less compared to the other methods, it can be considered as a frictionless test method or in another way the friction is neglectable.

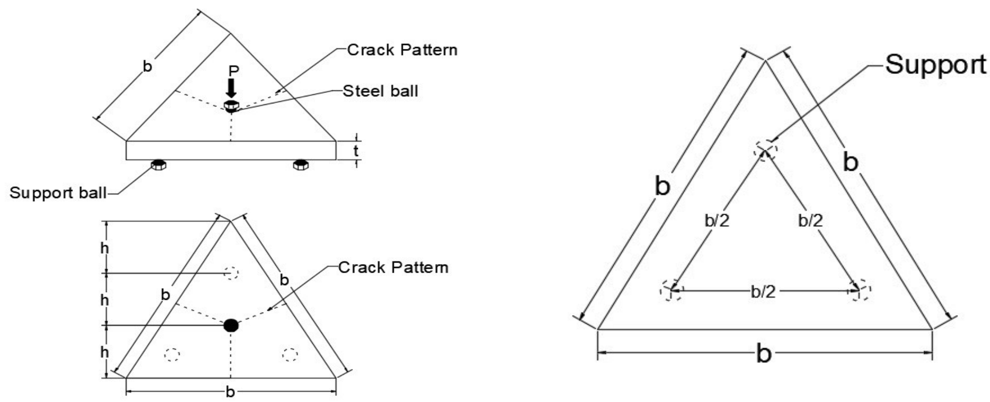


Figure 2.13 Geometry of the triangular plate specimen and support layout.

The failure mechanism for the triangular plate method is determined by using the yield line theory which is widely used in the design of the reinforced concrete slabs and similar elements. For slabs or any structure, there may be more than one failure mechanism satisfying the kinematic conditions. However, only one of these possible mechanisms is the one that gives the smallest failure load. Following the YLM lower limit theorem, it investigates the state of the yield line which determines the minimum collapse load value. Figure 2.14 illustrates the accepted failure mechanism for ultimate load capacity.

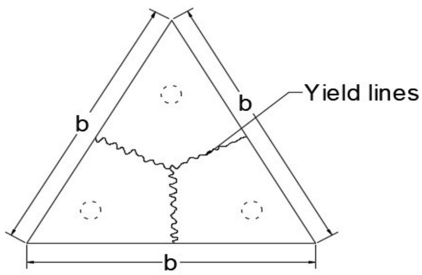


Figure 2.14. The accepted failure mechanism for ultimate load capacity.

In the study carried out by (Türker 2015) a limited number of mortar specimens with different compressive strengths and classes were done. As a result of the study, a new formula was proposed for calculating the tensile strength of the mortars by using the yield line theory. The results obtained from the study were compatible with the proposed formula.

A comprehensive study was carried out by (Mirkheel 2018) to investigate the effect of specimen geometry using the triangular plate method. Two different proportions of water-cement ratios and different sizes were prepared using steel fiber and without steel fibers. For this purpose, three classes of mortar with a water-cement ratio of 0.42 and 0.62 without steel fiber and the water-cement ratio of 0.42 with steel fibers were designed. Seven different dimensions have been used in the study. Two water-cement ratios 0.62 and 0.42 a total of 63 triangle plates have done.

The study concludes that the triangular plate method can be used as an alternative method for testing the cement-based materials with the absence and presence of the steel fibers since it noticed that the size effect was observed in the samples produced from all the mixture.

3. MATERIAL AND METHOD

3.1 Experimental Program

In the scope of this study, fiber reinforced concrete specimens were prepared with different dosages of steel fibers were tested using the Triangular Plate Method and EFNARC Square Panel Test Method to determine the energy absorption capacity(Toughness).

The specimens were divided into four sets according to the doses of fiber, while all sets were reinforced with steel fibers except the last set remained without fiber for comparison purposes, different fibers ratios were used (0.3%, 0.6%, and 0.9% by volume of concrete respectively). Since no large amount of fibers were used in the study a normal strength matrix type was chosen, the same concrete matrix was used in all experiment sets.

Mixture designs, specimen preparations and testing methods will all be specified later in this chapter. All experimental studies were carried out in the laboratory of Bursa Uludag University.

3.2 Materials Properties

3.2.1 Cement

CEM I 42, 5 R type portland cement was obtained from Bursa Cimento Company in Bursa and used in the production of all the concrete mixes during this study. The chemical and physical properties of the cement used were provided by the manufacturer are shown in Tables 3.1 and 3.2.

Table 3.1 Chemical Properties of Cement

Oxide (%)	Cement
SiO_2	18.8
Al_2O_3	5.71
Fe_2O_3	3.09
CaO	62.70
MgO	1.16
SO_3	2.39
Na_2O+0,658 K_2O	0.92
Cl^-	0.01
Insoluble residue	0.32
Loss of ignition	3.20
Free Cao	1.26

Table 3.2 Physical Properties of Cement

Physical Properties		CEM I 42.5R
Density (gr/cm^3)		3.15
Mechanical properties		
Compressive Strength (MPa)	1-day 2-day 7-days 28-days	14.7 26.80 49.80 58.5
Soundness		≤ 10mm
Specific Surface (Blaine, cm^2/gr)		3530
Residue on Sieve 0.045 mm (%)		7.60

3.2.2 Aggregate

The aggregate used in the mixtures was supplied from Bursa Beton Company. Two different types of aggregate 0-5 mm fine and 5-12 mm coarse crushed limestone. The proportions of fine and coarse aggregates were divided equally at 50% each to obtain the best particle size distribution that can be used in the mixture.

3.2.3 Chemical Additive

To ensure the required workability a Superplasticizer concrete admixture was added to the mix. The additive used was supplied from AYDOS construction chemicals company. Some properties of the chemical additive used by the manufacturer are given in table 3.3

Table 3.3 Technical Properties of Superplasticizer

Technical Properties (Aydosper NBA71)	
Chemical Content	Modified naphthalene sulfonate based
Appearance – Color	Brown liquid
Density	1.19 ± 0.02 kg/l
pH Value	7.0 ± 1
Chloride Content (Cl)	< % 0.1
Alkali Content	< % 5
Freezing Point	-6 ºC

3.2.4 Steel Fibers

BEKAERT Company supplied the fiber used in this study. The fiber has an aspect ratio (65/35) with a hooked end. Some of the fiber properties as specified by the manufacturer are listed below in Table 3.4.

Table 3.4 The physical properties of fibers

Characteristic	Material Property
Commercial Name	Dramix 3D
Base material	Steel
Shape / Surface texture	Curved 3 times in both end
Length (mm)	35
Diameter (mm)	0.55
Aspect ratio	65
Number of fibers per kg	14531
Tensile strength (MPa)	1.345
Young's Modulus (GPa)	210

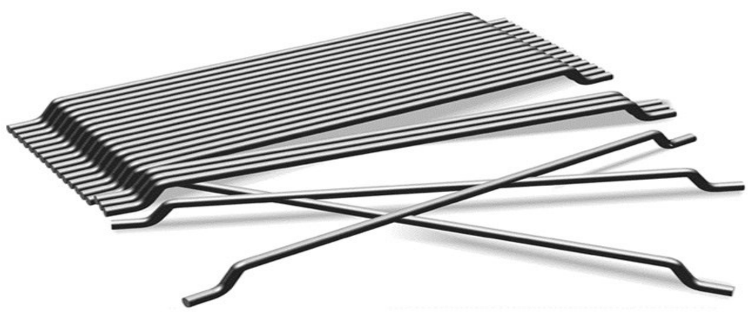


Figure 3.1. Steel fiber used

3.2.5 Water

In concrete production, the water coming from the potable water distribution network has been used.

3.2.6 Concrete mix

In this study, one concrete mixture was produced for all samples. The details of the materials used in the production of the mixture are mentioned earlier in this chapter. Normal concrete strength was produced for all sets of this study. The concrete mix proportions are listed below in Table 3.5.

Table 3.5 Proportions of the mix used

w/c	**0.46**
Cement(kg)	485
Water (kg)	225
Coarse aggregate (kg)	800
Fine aggregate (kg)	800
Super plasticizer(kg)	7.5

3.3 Test Equipment

3.3.1 Molds

The molds in this study were made by using plywood plates for both square panels and triangular panels, the plywood panels have been cut into three dimensions according to the two test methods specifications. For EFNARC plates the standard dimensions are 600×600×100 mm^3. For the triangular panel's dimensions were 500×500×50 mm^3 and 800×800×80 mm^3.

Figure3.2 Square panels molds.

Figure 3.3 Triangular panels mold -800 mm.

Figure 3.4 Triangular panels mold -500mm.

3.3.2 Mixer

An electric mixer with a capacity of 120 lt has been used to mix the concrete homogeneously.

Figure 3.5 Concrete mixer

3.3.3 Loading Frame

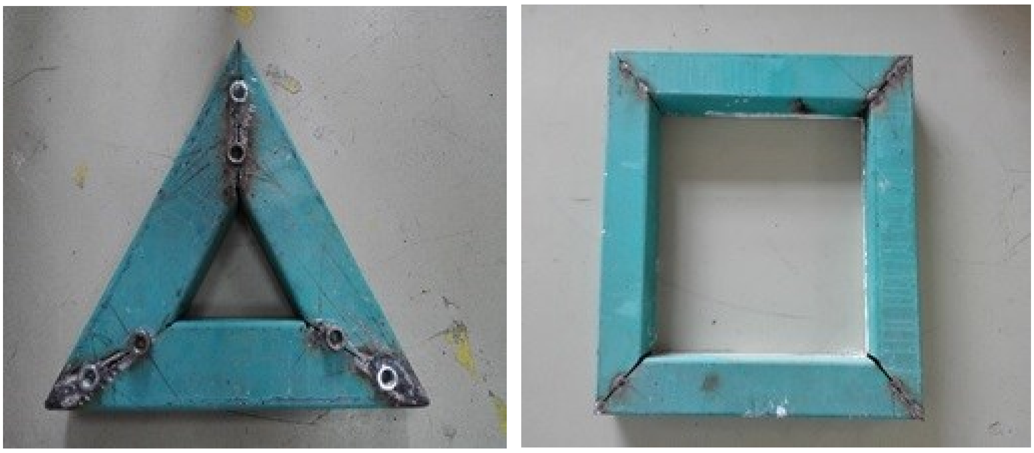
The steel frame shown in Figure (3.6) below was used in the loading application process. The main aim of this frame is to perform multiple loading systems. In this test, the loading was carried out using an automatic hydraulic piston connected at the end with a load cell with a carrying capacity of 200 kN. A displacement transducer was placed at the bottom of the sample to measure the vertical displacement. Since data cannot be collected directly from the piston, a data logger was used to collect recordings from the load cell and displacement transducer.

Figure 3.6 Demonstration of the loading system and the hydraulic piston used

The piston comes with multiple loading rates. Within the scope of this study, the EFNARC test has defined a fixed rate of 1.0 mm/min and this rate has been applied to all samples square panels and triangular panels to make an accurate comparison with high sensitivity.

A three-point support base was used for triangular panel samples and the load was applied over a 30 mm diameter half-spherical head. A displacement transducer was placed at the center of the specimen base to measure the deflection.

On the other hand, for square panel specimens a square steel frame with an internal distance of 500 mm was used as specified in the EFNARC standard. A square steel frame was used to make the four edges stand on simple support and the load was applied over a square plate that has dimensions 100×100 mm^2 according to the standard, as in the triangular panel test also a displacement transducer placed at the center of the specimen base to measure the deflection.



a) Triangular panel base b) Square panel base

Figure 3.7 Base panels of the two test specimens

a) Displacement transducer b) Data logger

Figure 3.8 Displacement transducer and data logger used

3.4 Experimental Procedure

3.4.1 Mixing Process

- At first, the aggregates were added to the mixer, and the mixer was turned on for approximately 2-3 minutes to obtain a homogeneous mixture.
- Water was added gradually with the addition of fiber to obtain a homogeneous aggregate and prevent the formation of agglomeration and balling.
- During fiber addition, the fibers were added slowly to ensure that spread perfectly.
- In the end, cement was added to the mixture while the mixer continued to operate for an appropriate period to obtain the ideal mixture.
- When it was confirmed that the mixture was ready, the concrete was placed in the molds and kept in the molds for 24 hours.
- From each mix, 3 to 4 cubes were taken to measure the compressive strength.
- After 24 hours, the samples were removed from the molds, all samples were kept under the same curing conditions.

Figure 3.9 Concrete samples in plywood mold**.**

3.4.2 Testing Process

After 28 days, the samples were ready for the test. For triangular panels, the displacement transducer has been placed in the center point of the panel's base where it measured the deflection up to 30 mm, during this time the data was collecting by the data logger.

It was different and very difficult for the square samples, because the weight of the samples was too large, which made it very difficult to place them on the support, also a layer of gypsum was used as a bedding material between the sample and the support to ensure full surface contact as specified by the EFNARC standard.

The loading process was carried out for both tests until the deflection reached 30 mm. However, the calculation and the evaluation of data have been performed up to 25mm as specified in EFNARC.

Figure 3.10 The two types of test Square panel & Triangular panel test

3.4.3 Evaluation of Data

From the load-deflection curve shown in Fig 3.11 the energy absorption capacity or the toughness has been calculated as the area under the curve. The graph represents the measured data collected by the data logger. The trapezoidal rule has been used for all calculations to determine the toughness or the energy absorption capacity.

The trapezoidal rule is a numerical method to be used to approximate the integral or the area under a curve. Using the trapezoidal rule to approximate the area under a curve first involves dividing the area into a number of strips of equal width. Then, approximating the area of each strip by the area of the trapezium formed when a chord replaces the upper end. The sum of these approximations gives the final numerical result of the area under the curve.

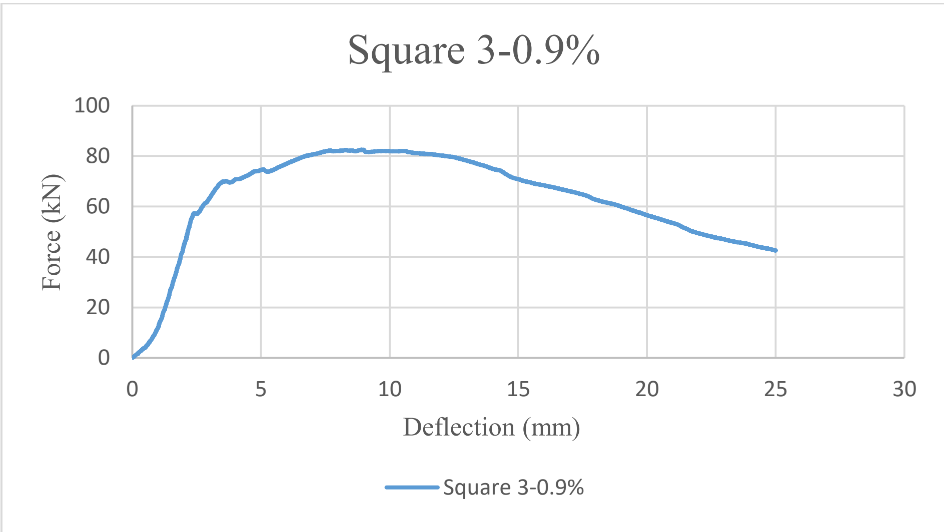


Figure 3.11 Typical load-deflection curve for the square plate.

4. RESULTS AND DISCUSSION

In the scope of this thesis, different dosages of steel fibers have been used to compare two different test methods, the EFNARC Square plate test method, and the Triangular plate test method to determine the energy absorption capacity or toughness. The load-deflection curves of all tested samples are shown in this chapter. Moreover, the correlation between the EFNARC panel test and the Triangular panel test is determined.

4.1 Fresh Concrete Tests

Slump test results are shown in Table 4.1.

Table 4.1 Slump test results

Mix label	Slump (cm)	Density (kg/m^3)
Control	20	2342
SFRC-0.3%	16	2406
SFRC-0.6%	11	2426
SFRC-0.9%	7.5	2446

4.2 Compressive Strength

Compressive strength results are given separately in the subsection for each set. It is noteworthy that the difference in compressive strength values is due to the samples being produced from different batches since the volume of some specimens was greater than the capacity of the mixer, such as the square panel case.

In the study, cube samples of 10x10x10 cm dimensions were produced for each mixture (non-fibrous and fibrous).

4.3 Square Panels Results

In the following subsection of this chapter, a detailed demonstration of the test results of the square panels, the load-deflection diagrams, thickness measurements, energy absorption capacities and the crack patterns all are represented in this part. The thickness effects are slightly noticeable in the peak loads obtained in this study. While the differences in thickness weren't that so large, they were almost very close.

For each volume of fraction, three specimens were done to achieve more accurate results of the test. All specimens were tested under the same conditions.

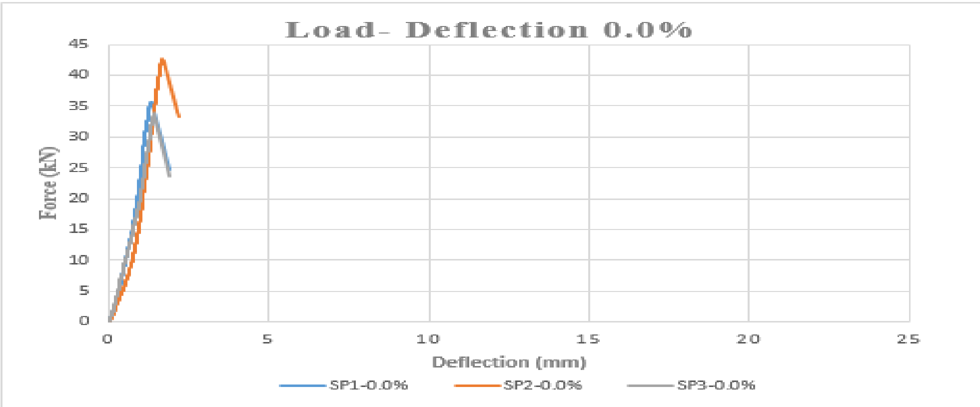


Figure 4.1 Load-deflection garph of control Square panel-(0.0%)

Table 4.2. Properties of the square panel- control

Specimen label	Thickness (cm)	Compressive Strength (MPa)
SP1-0.0%	10.15	52.35
SP2-0.0%	10.2	47.14
SP3-0.0%	10.2	44.84

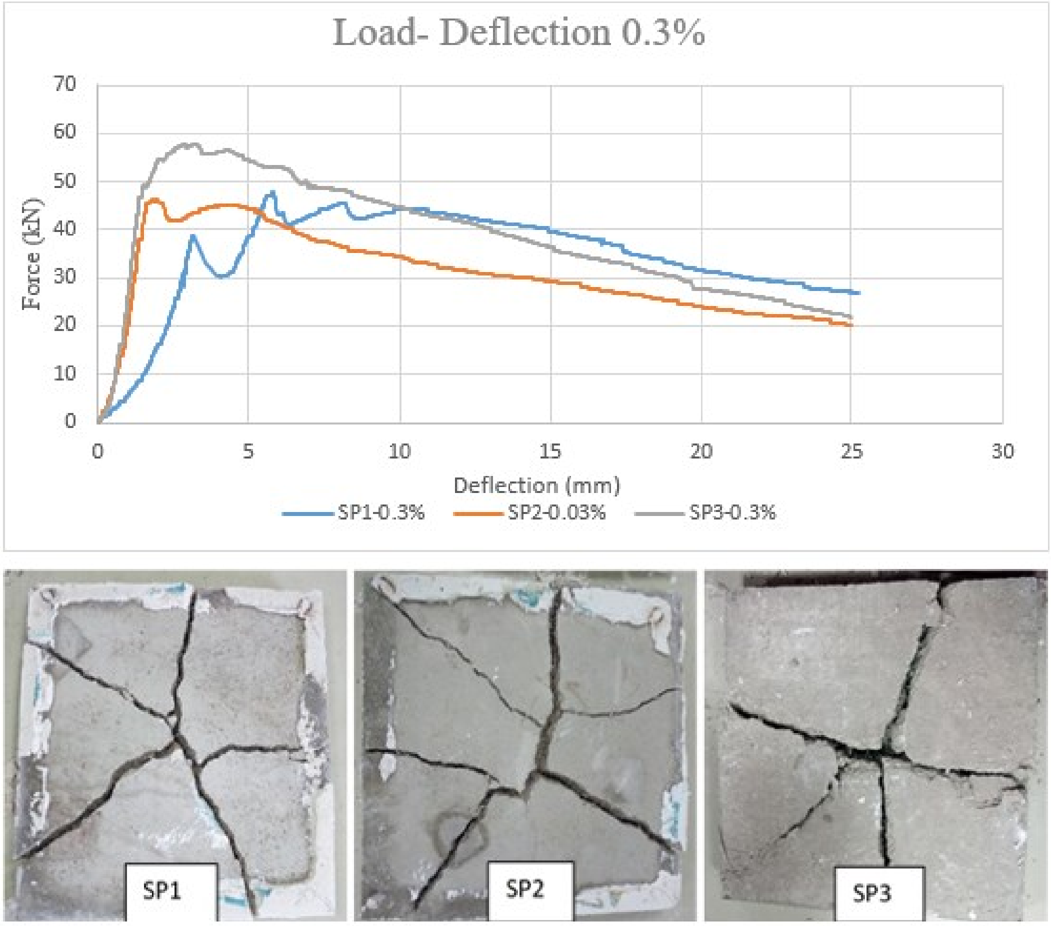


Figure 4.2 Load-deflection and crack pattern graph of Square panel-(0.3%)

Table 4.3 Properties of Square Panel- (0.3%)

Specimen label	Thickness (cm)	Compressive Strength (MPa)
SP1-0.3%	9.58	52.52
SP2-0.3%	10.19	46.52
SP3-0.3%	10.11	50.23

For the square plates with 0.3% fibers in volume contents, a noticeable decrease has obtained after the first crack in the load-carrying capacity followed by a strain hardening. Sample three behaved slightly differently from the other samples after the first crack, where the decrease in the load-carrying capacity was not obvious, and this might be due to the bedding material being not sufficiently rigid. In sample one, the difference in rigidity become from the low thickness and the non-uniformity of the loading surface.

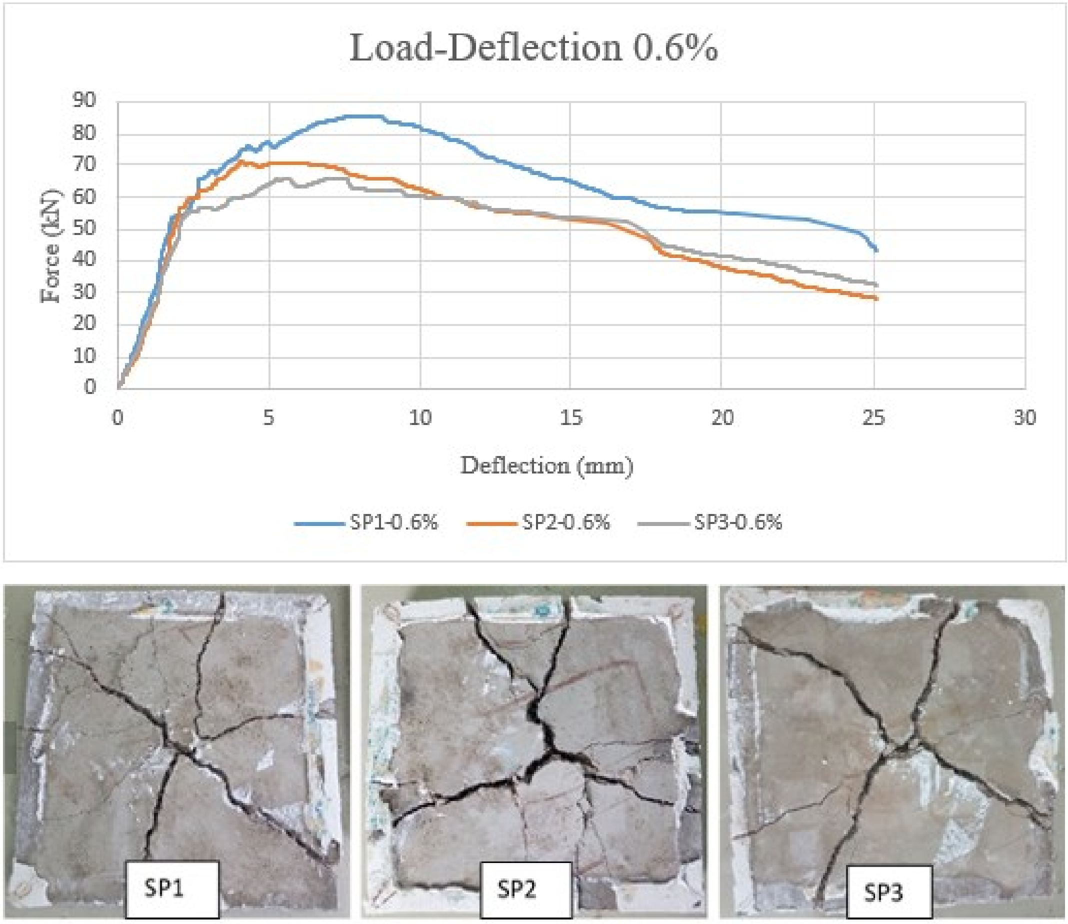


Figure 4.3 Load-deflection and crack pattern graph of Square panel-(0.6%)

Table 4.4 Properties of Square Panel- (0.6%)

Specimen label	Thickness (cm)	Compressive Strength (MPa)
SP1-0.6%	10.11	56.12
SP2-0.6%	10.09	49.37
SP3-0.6%	10.08	40.16

For 0.6% square panels, there is no difference in the elastic zone. For the post crack behavior, sample one absorbed more energy compared to the others, the reason behind

that return to the thickness was slightly larger. Moreover, sample one has the largest compressive strength which proves that the energy absorption capacity is a function of both the matrix strength and the volume of fibers as mentioned in the literature review.

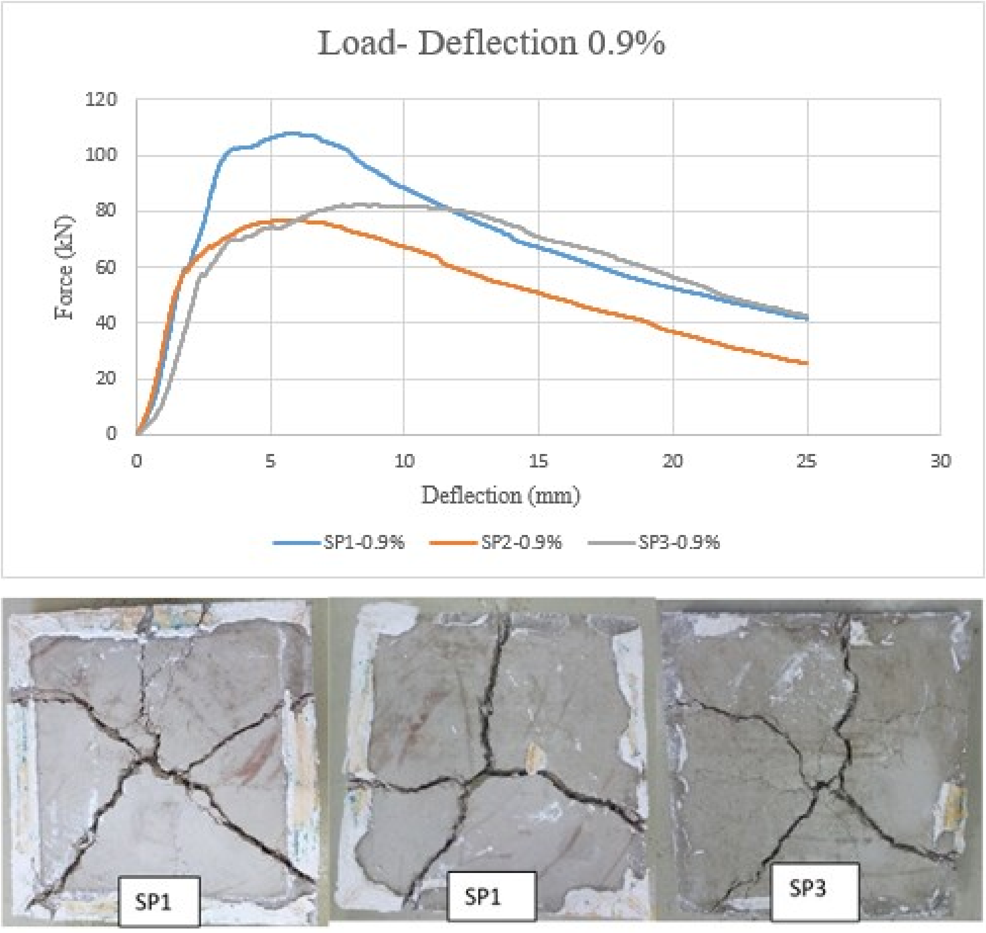


Figure 4.4 Load-deflection and crack pattern graph of Square panel-(0.9%)

Table 4.5 Properties of Square Panel- (0.9%)

Specimen label	Thickness (cm)	Compressive Strength (MPa)
SP1-0.3%	10.17	47.29
SP2-0.3%	10.05	47.63
SP3-0.3%	10.03	50.06

For 0.9% samples, sample one absorbed the highest energy and achieved the highest peak load. The sample has the highest thickness, dense distribution, and good bond.

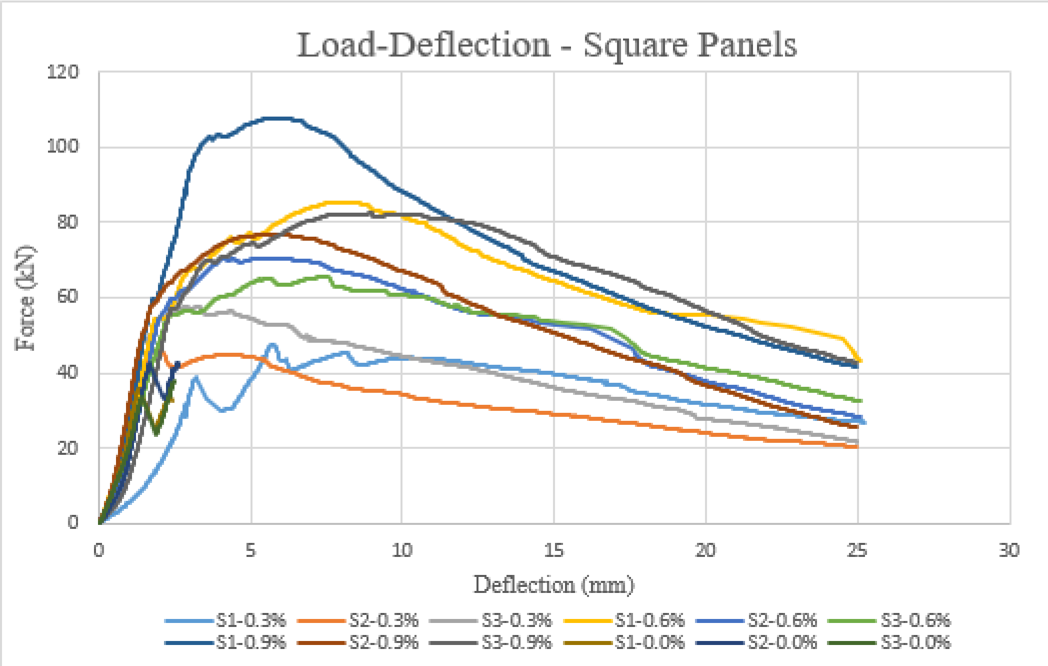


Figure 4.5 Load-deflection curves of square panels.

Figure 4.8 illustrates the behavior of the square panels altogether. Significantly, the increase in fiber volume greatly improves the load-carrying capacity. After the first crack, the specimens were able to carry some amount of loads. Increasing the volume of fiber significantly increase the load-carrying capacity. When the addition of fibers exceeds the optimum value, the samples can achieve higher load values than the first crack load and there will be no place for any decrease in the load-carrying capacity after the first crack. The same behavior for different dosages might be seen such as SP1-0.6% has the same behavior of SP3-0.9%. Returning to the specimen's detail a slight difference in thickness has been observed but the strength of matrix was higher in SP1-0.6% this leads actually to say that to force all fibers to works effectively a strong concrete matrix should use.

4.4 Triangular Panels Results

4.4.1 Triangular Panels – 50 cm

In this subsection, the load-deflection diagrams for TPM-50 are shown. In addition to that the crack pattern, thickness of samples and compressive strength are also included for each volume of a fraction.

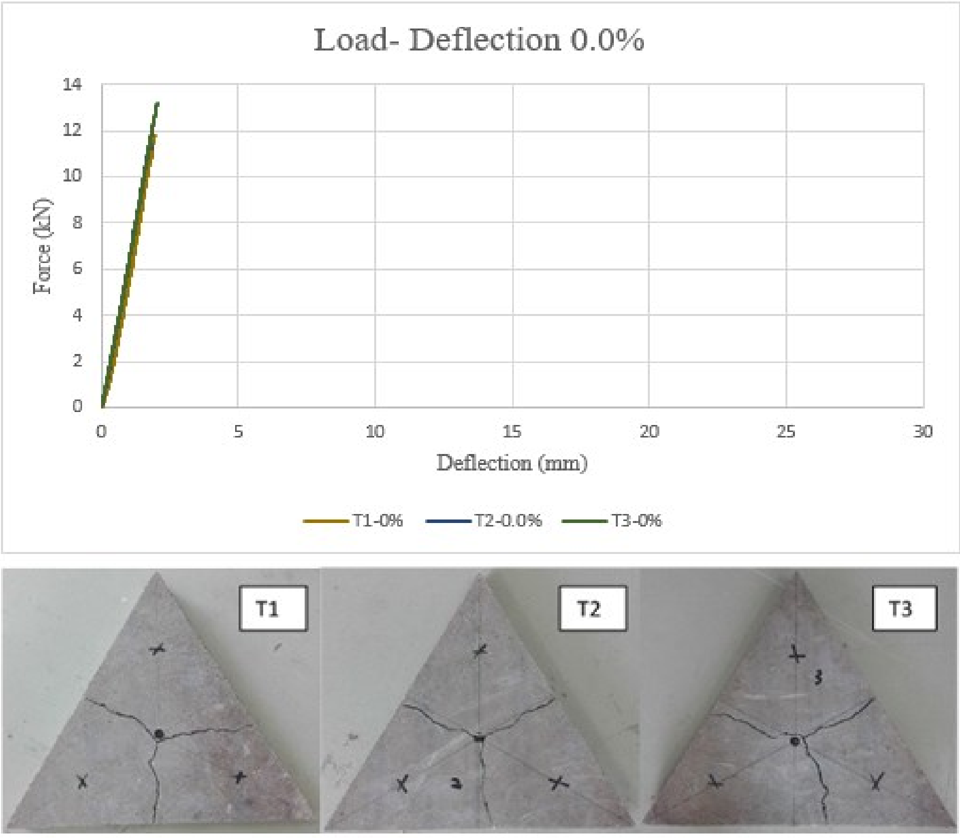
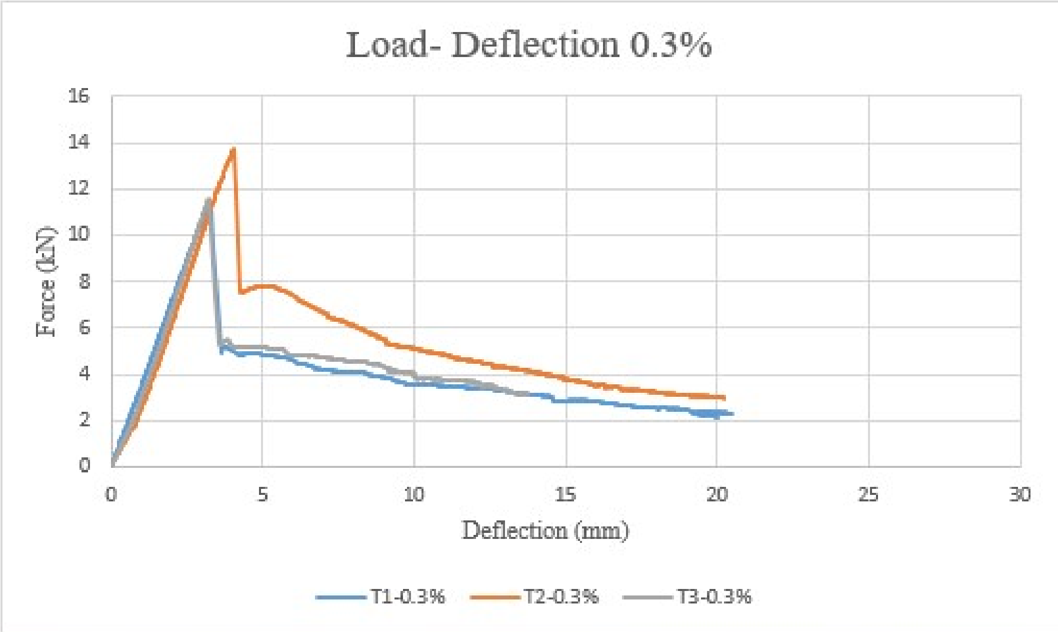


Figure 4.6 Load-deflection and crack pattern graph of Triangular panel 50-(0.0%).

Table 4.6 Properties of Triangular Panel 50- (0.0%)

Specimen label	Thickness (cm)	Compressive Strength (MPa)
T1-0.0%	5.1	48.35
T2-0.0%	5.04	48.35
T3-0.0%	5.1	48.35



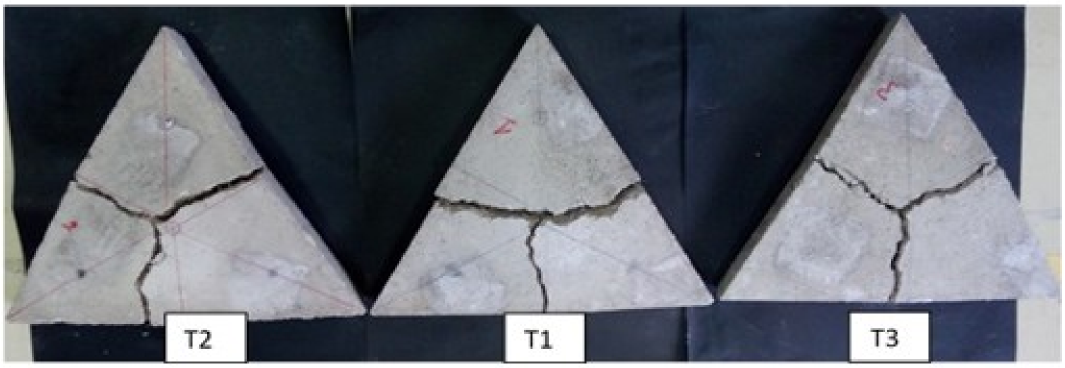


Figure 4.7 Load-deflection graph of Triangular panel 50-(0.3%)

Table 4.7 Properties of Triangular Panel 50- (0.3%)

Specimen label	Thickness (cm)	Compressive Strength (MPa)
T1-0.3%	5.15	52.21
T2-0.3%	5.28	52.21
T3-0.3%	5.2	52.21

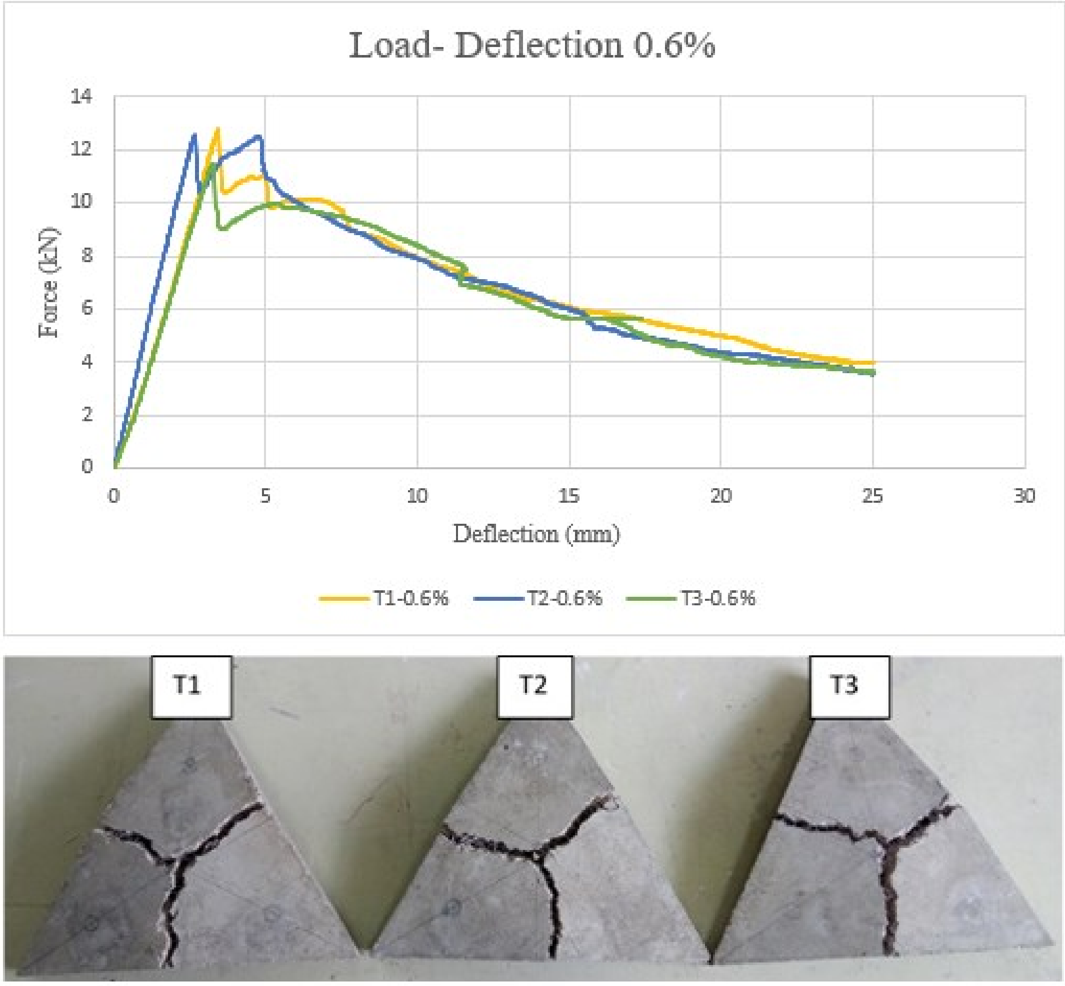


Figure 4.8 Load-deflection and crack pattern graph of Triangular panel 50-(0.6%)

Table 4.8 Properties of Triangular Panel 50- (0.6%)

Specimen label	Thickness (cm)	Compressive Strength (MPa)
T1-0.6%	5.05	52.21
T2-0.6%	5.14	52.21
T3-0.6%	5.16	52.21

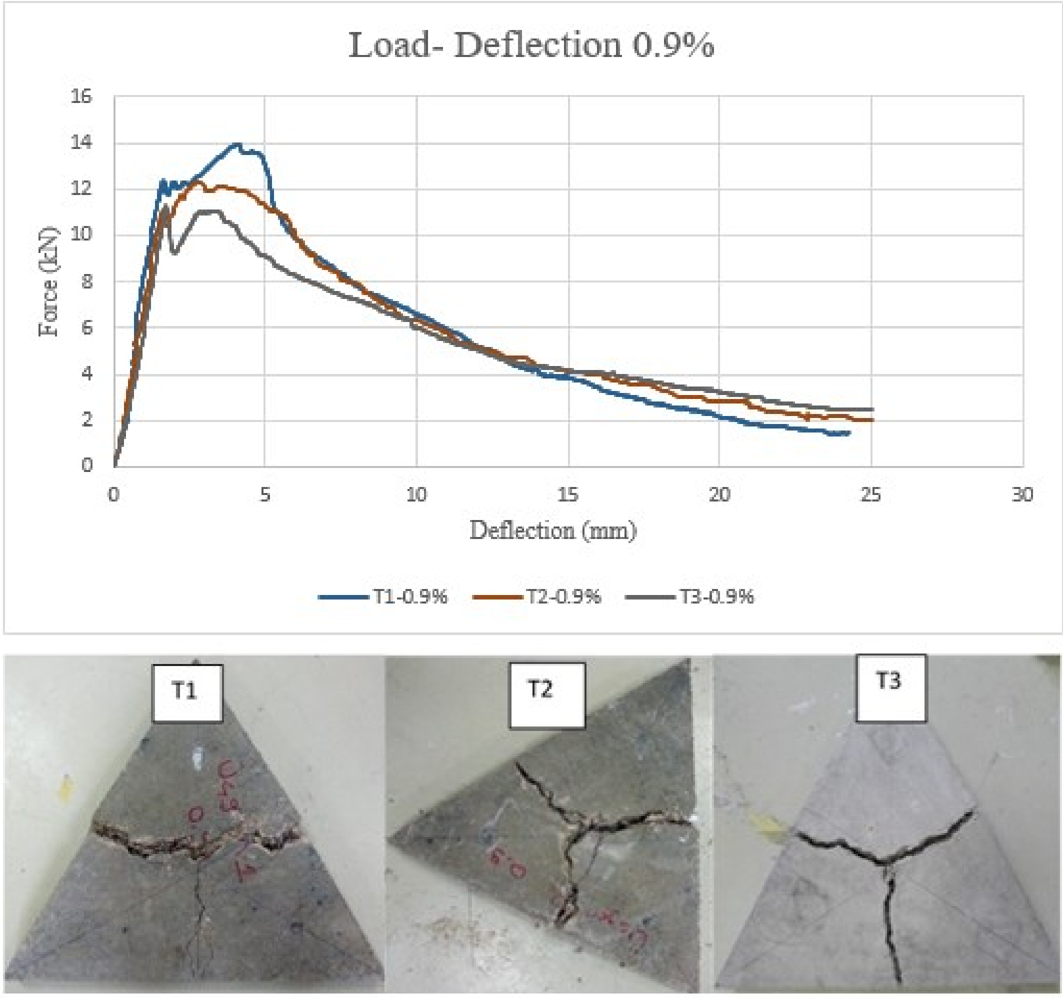


Figure 4.9 Load-deflection and crack pattern graph of Triangular panel 50-(0.9%)

Table 4.9 Properties of Triangular Panel 50- (0.9%)

Specimen label	Thickness (cm)	Compressive Strength (MPa)
T1-0.9%	5.11	47.88
T2-0.9%	5.17	47.88
T3-0.9%	5.09	47.88

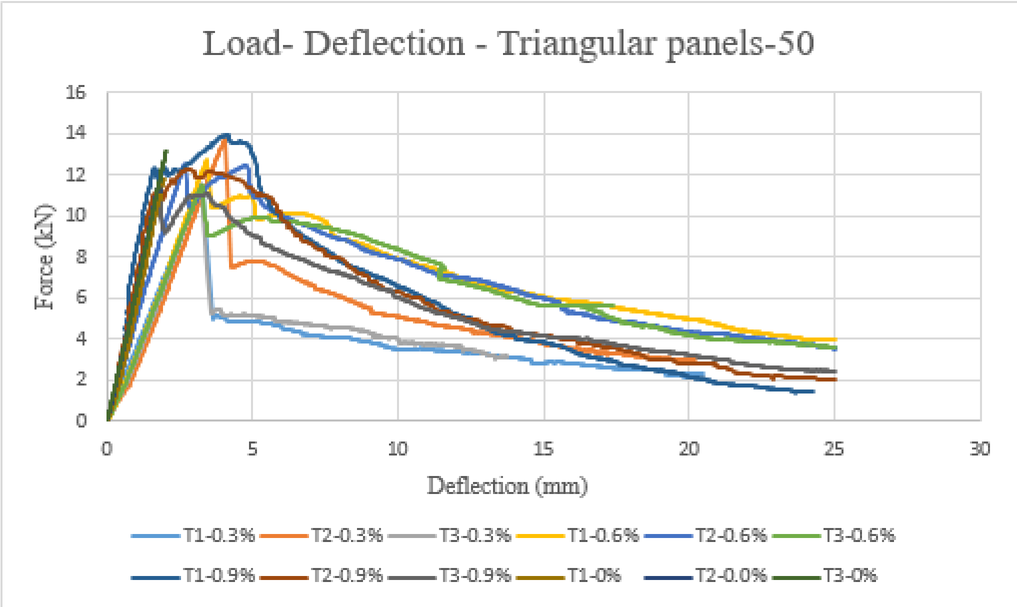


Figure 4.10 Load deflection curves of TPM-50.

As noticed in the square panel test, the inclusion of fiber-enhanced the load-carrying capacity and the peak loads were very close to each fiber dosages. The post crack behavior was quite different. For 0.3% volume of fiber, no strain hardening has been observed after the first crack and the diagrams show brittle behavior.

For 0.6% the post crack behavior was more ductile, after the first crack an abrupt decrease in the load-carrying capacity has occurred followed by a strain hardening while the peak load didn't exceed the first crack load.

For 0.9% the post crack behavior was the most ductile. After the first crack, a slight decrease in the load-carrying capacity occurred for two samples while no decrease has observed for the third sample. The ultimate load exceeds the first crack load in sample one while for the other two samples was very close.

It can be seen the post crack behavior for the triangular plate for all samples was very close.

4.4.2. Triangular Panels – 80 cm

In this subsection, the load-deflection diagrams for TPM-50 are shown. In addition to that the crack pattern, thickness of samples and compressive strength are also included for each volume of a fraction.

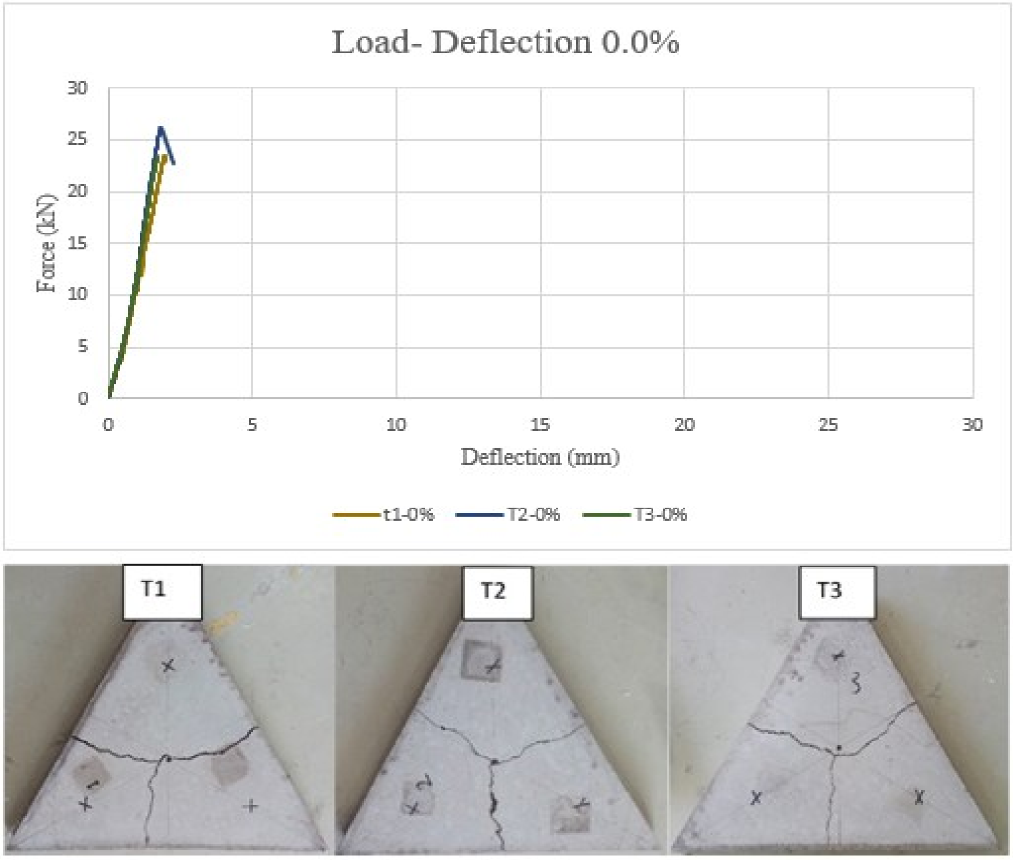


Figure 4.11 Load-deflection and crack pattern graph of Triangular panel 80-(0%)

Table 4.10 Properties of Triangular Panel 80- (0.0%)

Specimen label	Thickness (cm)	Compressive Strength (MPa)
T1-0.0%	8.16	40.74
T2-0.0%	8.16	48.89
T3-0.0%	8.04	50.69

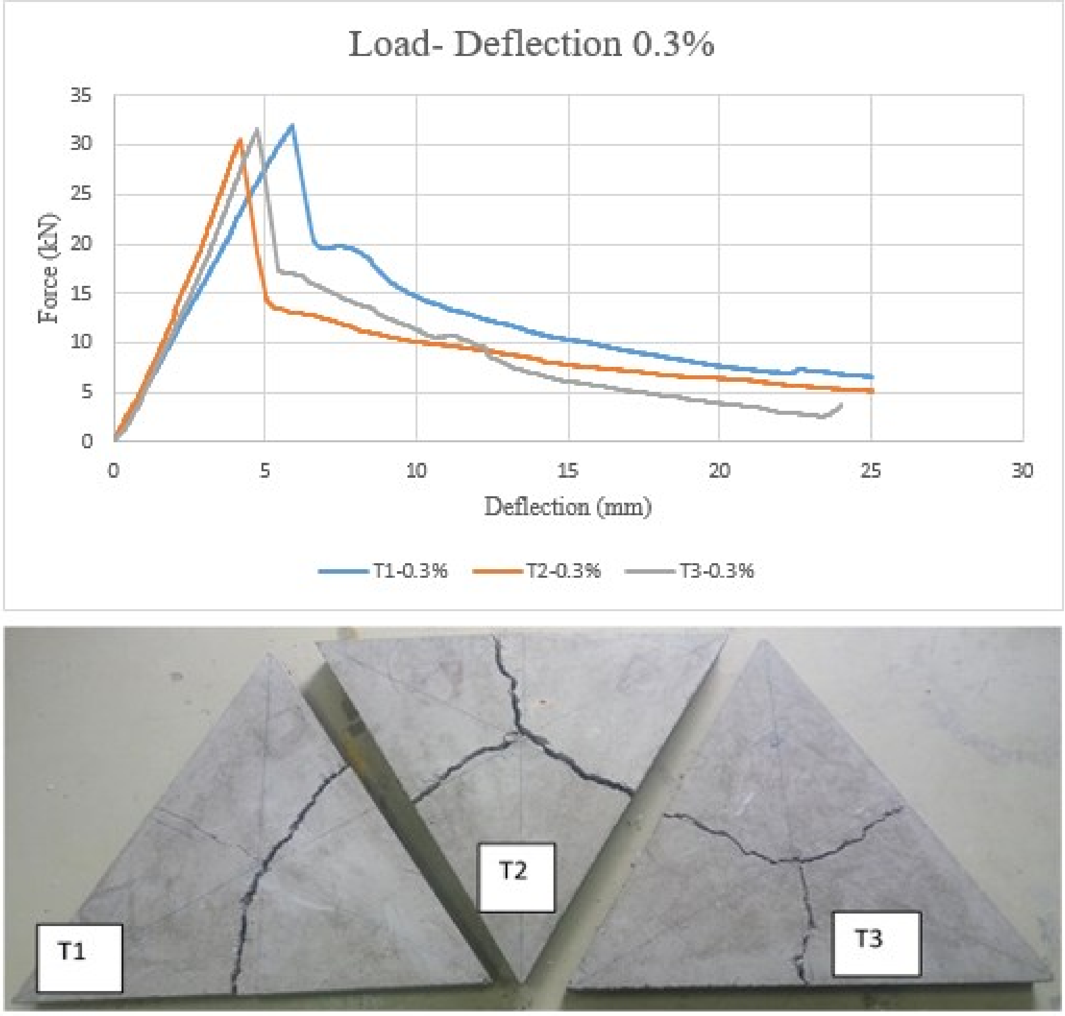


Figure 4.12 Load-deflection and crack pattern graph of Triangular panel 80-(0.3%)

Table 4.11 Properties of Triangular Panel 80- (0.3%)

Specimen label	Thickness (cm)	Compressive Strength (MPa)
T1-0.0%	8.28	49.71
T2-0.0%	8.09	48.28
T3-0.0%	8.07	52.19

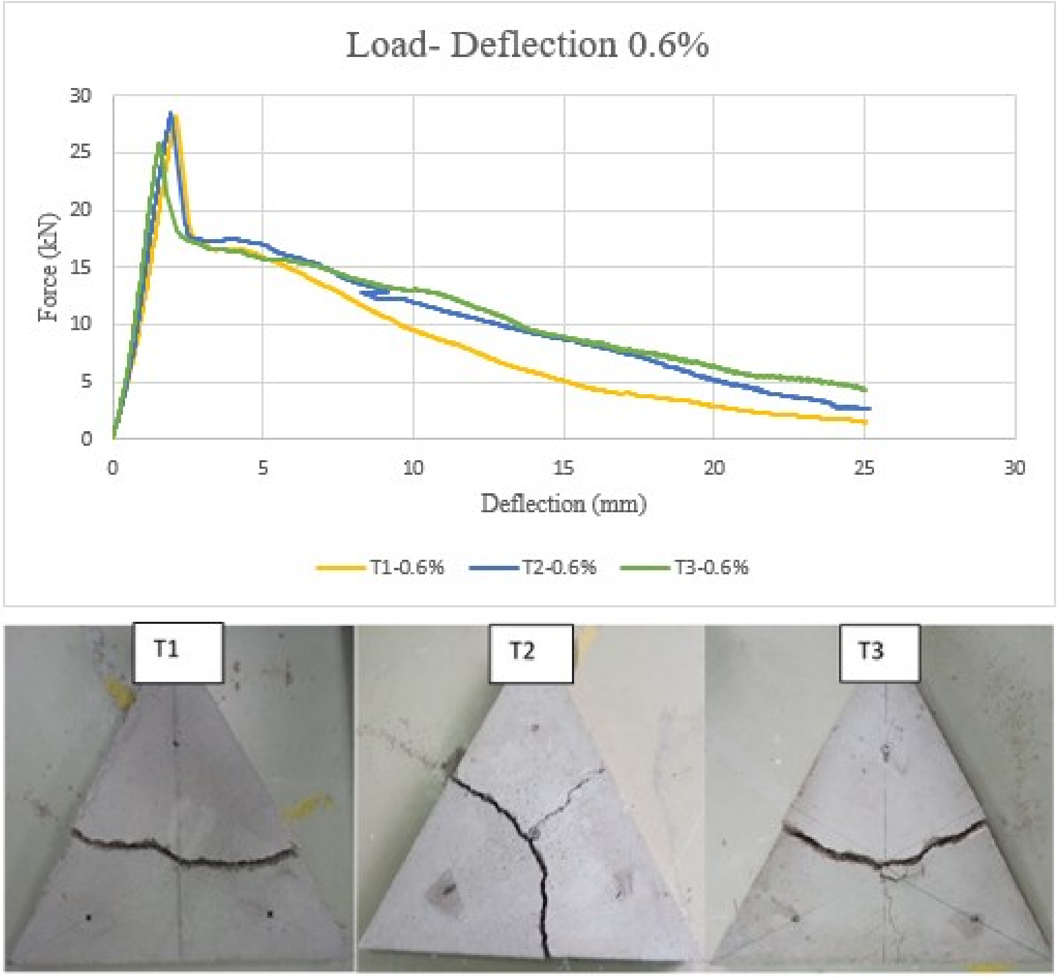


Figure 4.13 Load-deflection and crack pattern graph of Triangular panel 80-(0.6%)

Table 4.12 Properties of Triangular Panel 80- (0.6%)

Specimen label	Thickness (cm)	Compressive Strength (MPa)
T1-0.0%	8.07	44.40
T2-0.0%	8.0	48.08
T3-0.0%	7.92	42.40

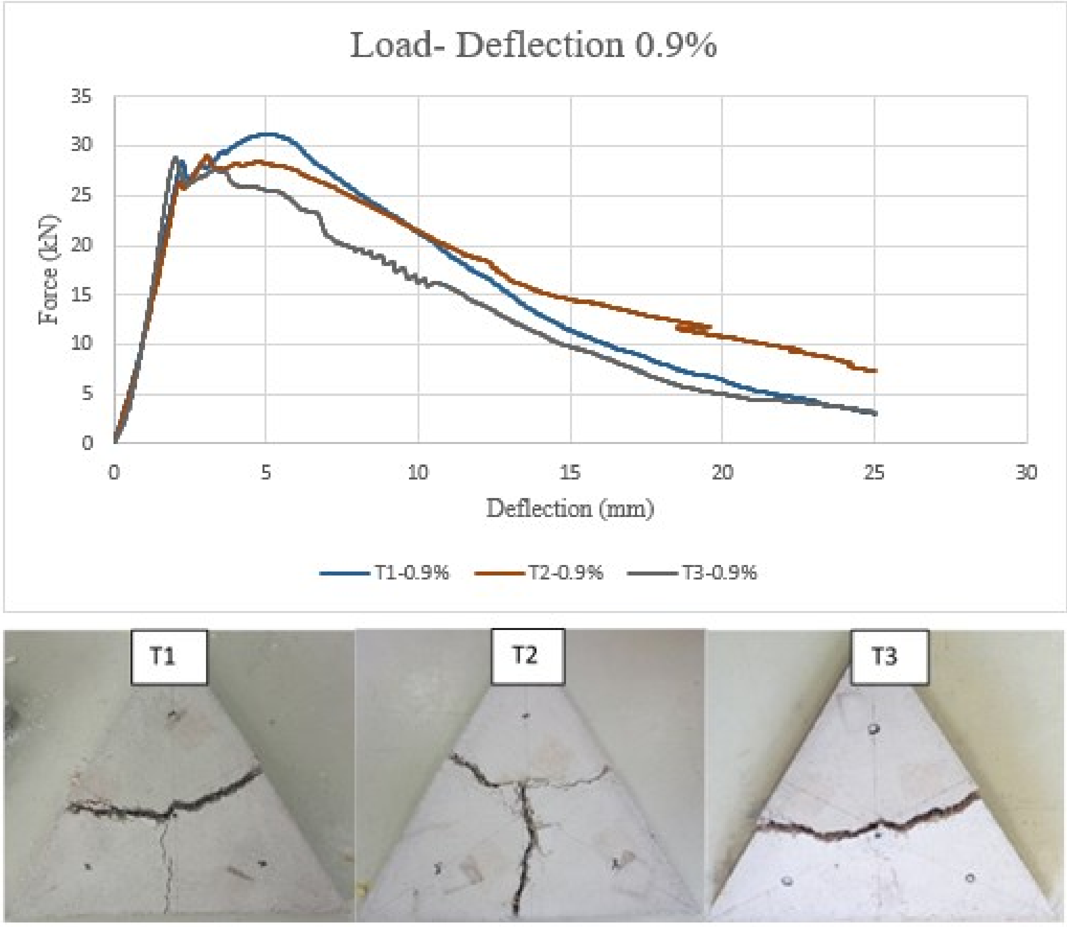


Figure 4.14 Load-deflection and crack pattern graph of Triangular panel 80-(0.9%)

Table 4.13 Properties of Triangular Panel 80- (0.9%)

Specimen label	Thickness (cm)	Compressive Strength (MPa)
T1-0.0%	8.22	41.29
T2-0.0%	8.32	41.09
T3-0.0%	8.08	43.03

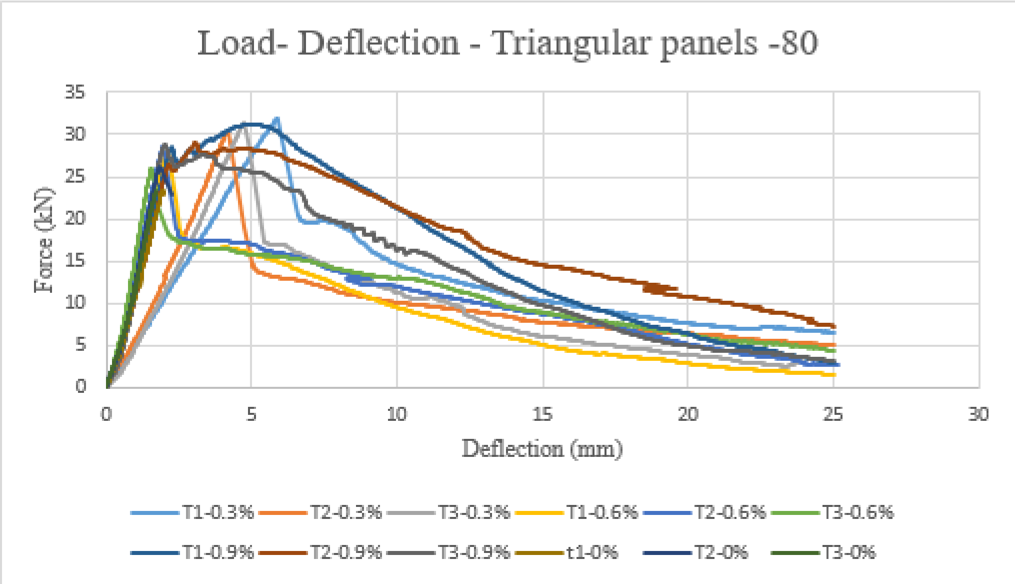


Figure 4.15 Load deflection curves of TPM-80.

The inclusion of fiber improves the post crack behavior, as noticed in both square panels and the triangular plate.

For 0.3% triangular plates, the diagrams showed a brittle behavior where no strain hardening has observed. The elastic region showed different rigidity that affected the peak loads and post crack behavior and the reason behind that return to the slight movement occurred by the system which was solved later.

For 0.6% the behavior in the elastic region was more similar in terms of stiffness but T1 and T2 achieved high peak load than T3, while this return to the thickness values. In the post crack region, no strain hardening has been observed.

For 0.9% the elastic region behavior also was close in terms of stiffness and peak loads. In the post crack region, the effect of the fiber dosages has been observed clearly since a strain hardening and the ultimate loads exceed the first crack loads. It is important to mention that samples behaved so close after the first crack in terms of load-carrying capacity.

4.5 Inspection of Interaction Between Cracked Matrix And Fiber

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. Figures 4.16, 4.17, and 4.18 show the interaction mechanisms between the fibers and the concrete matrix obtained in this study.

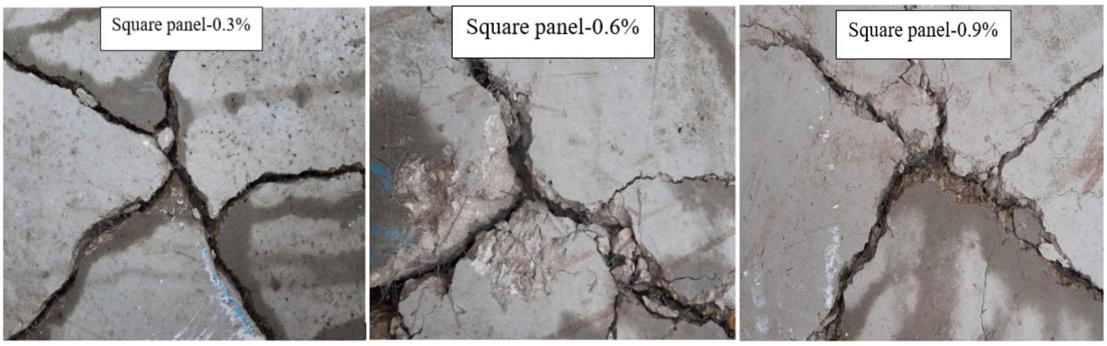


Figure 4.16 Close-up of Square panels

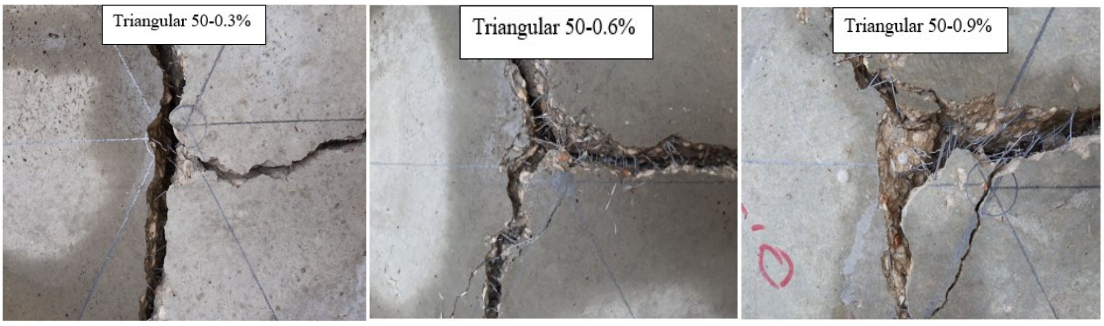


Figure 4.17 Close-up of Triangular 50

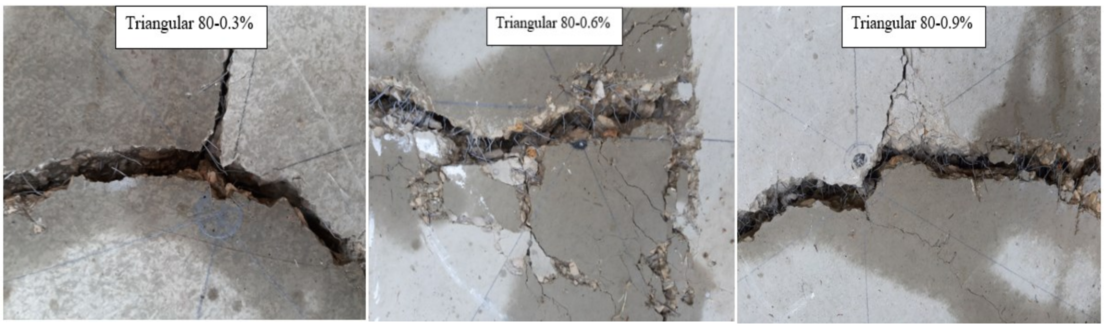


Figure 4.18 Close-up of Triangular 80

4.6 Effect of The Bedding Material In EFNARC Test Method

In Figure (4.2), SP3 behaved quite differently from SP1 and SP2, resulting in a high peak load leading to a high toughness value compared to the other samples. The reason behind this behavior was that the bedding material was not hard enough.

4.7 Triangular Plate Method vs Square Plate Method

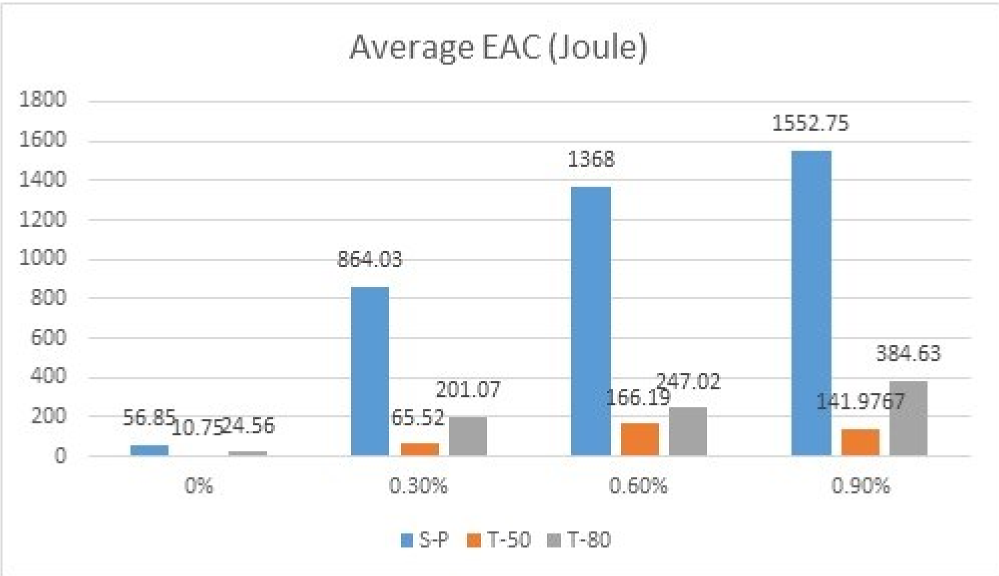


Figure 4.19 Average EAC for Square and Triangular panels.

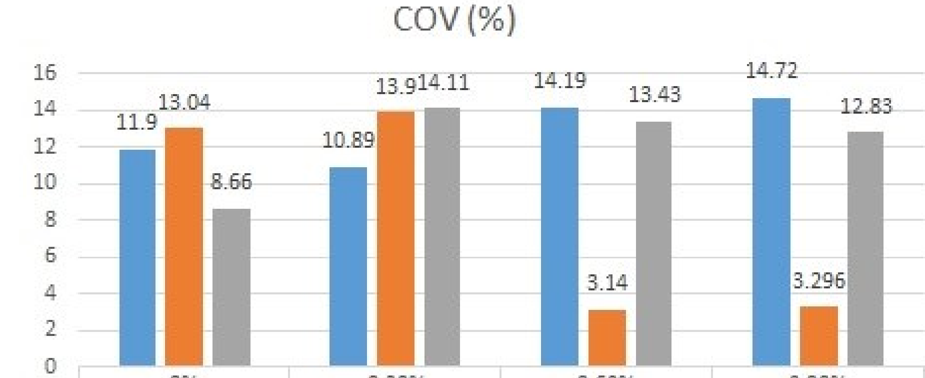
In Figure 4.19 the average values of the energy absorption capacities of the square and triangular panels have shown. For the square panels according to the EFNARC toughness classifications, square panels with 0.3% achieved class B (E700J) and the other dosages achieved class C (1000J). On the other hand, the triangular panels obtained the minimum energy absorption capacity.

The square panel test is known as the indeterminate test, the addition of fiber increased the toughness significantly and different classes of toughness have been achieved. The indeterminacy of the test has been obtained clearly since the stresses are distributed between the support and fibers while in the triangular plate method the specimen carried all the applied stresses. In addition, as mentioned earlier in the literature review that the square panels even achieved 3 to 4 times EAC as other tests.

The energy absorption capacity for the square panel test is affected by the most distinguished property related to the EFNARC test which is friction. Since the toughness is calculated as the area under the load-deflection curve, the maximum toughness achieved by the square panel achieved high loads due to the friction. This means in the post crack phase, the friction does not just only work to resist the opening of the crack but also increases the flexural strength in the pre-crack phase due to restraining the radial sliding at the support. In the triangular panel test, the friction between the supports and the sample was very small which can be neglectable.

For the triangular plate method, the toughness values obtained from the test were small compared to the square test, as demonstrated above more than one factor contribute to the post crack behavior. The main aim of these tests is to determine the toughness where the fibers play the main role. In the square panel test, even using a low volume of fiber there was a tendency of strain-hardening behavior. On the other hand, the triangular plate showed brittleness behavior for a low volume of fibers and more ductile for a high volume of fibers which describes the pure action of fibers.

The addition of fibers increased the toughness of panels. Nevertheless, the triangular panels with 50 cm in dimensions showed a lower toughness value for panels with 0.9% fiber volume. The reason behind this might be the panel geometry since triangular panels with 80 cm in dimensions behaved more accurately and the effect of increasing fibers resulted in an ascending value of toughness.



	0%	0.30%	0.60%	0.90%
S-P	11.9	10.89	14.19	14.72
T-50	13.04	13.9	3.14	3.296
T-80	8.66	14.11	13.43	12.83

Figure 4.20 Coefficient of variation for square and triangular panels

Figure 4.20 illustrates the coefficient of variation for each test type and each dose. Then the average coefficient of variation was calculated for each test. The average coefficient of variation of energy absorption capacity was 12.92% for the square panel test, 8.34% for the 50 cm triangular plate and 12.25% for the triangular panels with 80cm dimensions. The values of the coefficient variation for the square and large triangular panels were so close. Previous studies showed a high to an equal coefficient of variation of the square panel against other tests but for most studies the square panels have had a high coefficient of variation.

The energy relationship between the square panels and the triangular panels are given below in Figure 4.21 and 4.22.

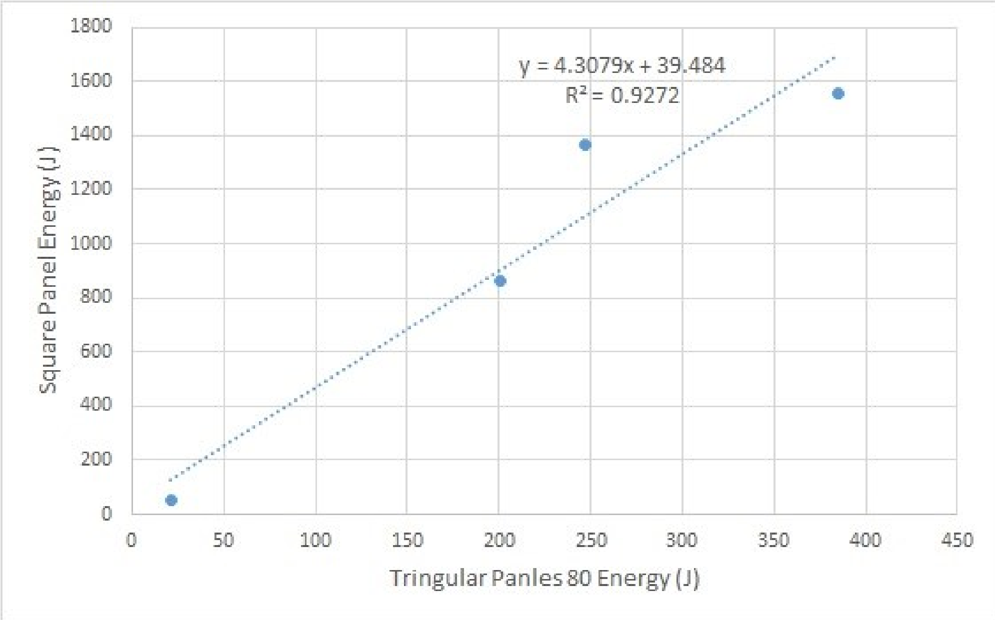


Figure 4.21 The energy relationship obtained from Square panels and Triangular panels -80

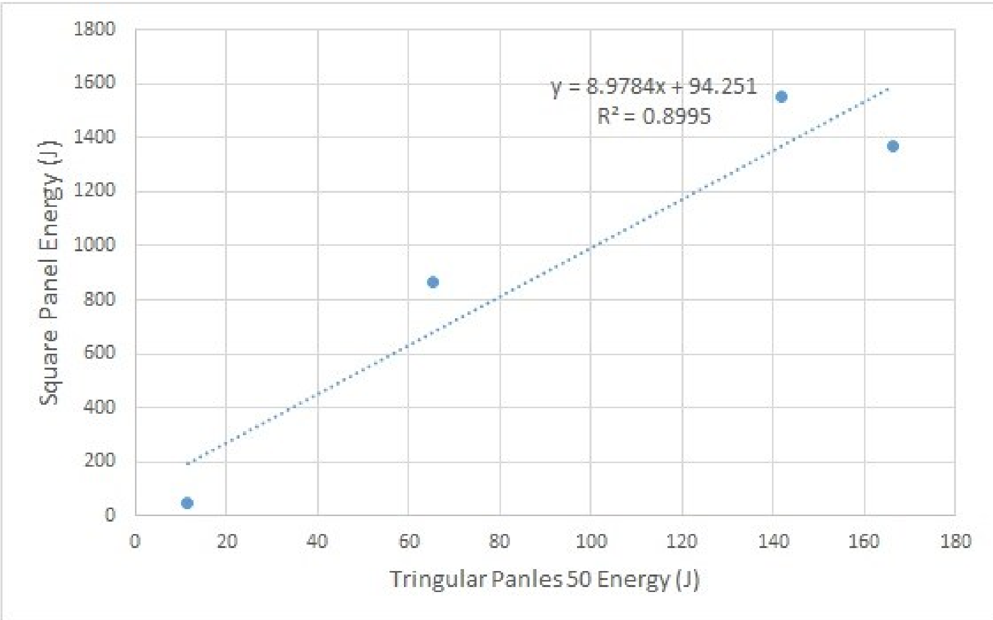


Figure 4.22 The energy relationship obtained from Square panels and Triangular panels -50

5. CONCLUSION

Square panel test (EFNARC test) and the Triangular plate test have been conducted on normal performance concrete to determine the energy absorption of fiber reinforced concrete. As a result of this experimental study, the following conclusions can be drawn based on the gained results.

- Increasing the volume of fibers in the concrete matrix significantly reduced the workability of the concrete.

- Based on the results of this study, the inclusion of fibers in the concrete improved the post crack behavior and increased the toughness of concrete.

- In the square panel test, the friction effect was remarkable due to the support condition. In the triangular plate method, the friction was very little, since pin supported base was used in this method. For this reason, the triangular plate method can be considered a frictionless test method, unlike the square panel test.

- In the square panel test, using a low amount of fibers led to ductile behavior. In the triangular panel test, the use of a low amount of fibers leads to brittle behavior that changes to ductile behavior with increasing the volume of fibers, which indicates the ability of the triangular plate test to exhibit the pure action of fibers, unlike the EFNARC test.

- Based on the results, the crack patterns for the EFNARC test were unpredictable unlike the triangular plate test where the crack patterns were predictable and obtained according to the yield line theory.

- Due to the friction and the supports conditions, the toughness obtained from the square panels was higher than the triangular panels; approximately, it was 4.04 times the triangular panels.

- Triangular panel Test is a determinate test method. Square Panel Test is an indeterminate test. Triangular panel Test, because of its statically determinate property exhibits better biaxial flexural capacity of fiber reinforced concrete. The difference in the measured toughness between the two tests is because of the static determinacy perspective.

- The average coefficient of variation for the square panel test was 12.92%. For the triangular panels with 80 cm the average coefficient of variation was 12.25% and 8.34% for the triangular panels with 50 cm.

- Based on the gained results of the study, the applicability and setup of the Triangular plate method were easier than the EFNARC test. From the perspective of the results, it can be said more accurate and trusted.

In light of the conclusions reached from this study, for additional research studies, it can be suggested

- For a more accurate comparison, the triangular plate test can be compared with a similar test method from the perspective of static determinacy.

- Various concrete matrices can be used, as various types and doses of fibers can be used.

- Large geometric dimensions are recommended to obtain the optimal geometry. In addition, the test can be performed to 40 mm or more to determine the optimal deflection.

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RESUME

Name Surname	: Ibrahim Abdelmoneim Mohammed HAMED
Place and Date of Birth	: Saudi Arabia –1992
Foreign Languages	: Arabic- English-Turkish
Education Status	
High School	: Almawhib High School
Bachelors	: University of Science and Technology

Work Experience :

Teaching Assistant- University of Science and Technology- 06.2015 to 06.2017

Contact (e-mail) : ibrahimwm7@gmail.com