COMPARATIVE EVALUATION OF STEEL MESH, STEEL FIBER AND HIGH PERFORMANCE POLYPROPYLENE FIBER-REINFORCED CONCRETE IN PANEL/BEAM TESTS

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ABSTRACT

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Comparison of concrete mixtures containing steel mesh, steel fiber and polypropylene fibers were evaluated in terms of toughness, flexural strength, compressive strength and split tensile strength. Five types of concrete were prepared with steel mesh, steel fiber and polypropylene fiber with the identical water/cement (w/c) ratio and the identical workability. 10x60x60 cm plates, 8x8x32 cm beams and 10x20 cm cylindrical concrete specimens were prepared. Compressive strength, split-tensile strength and toughness of the concrete specimens were determined at 7, 28 days of age and the results were compared. According to the results obtained from the tests, concrete made with steel mesh showed the best performance in panel tests. Also the results of the beam tests were compared with the plate test to determine the effectiveness of using beam test for toughness instead of plate test. The panel test was observed to be better for determining toughness than the beam test.

Keywords: Steel fiber; Steel mesh; High-performance polypropylene fiber; Toughness; Plate test.

ÖZ

ÇELİK HASIR, ÇELİK FİBER VE YÜKSEK PERFORMANSLI POLİPROPİLEN LİF İLE DONATILI BETONLARIN PANEL/KİRİŞ TESTLERİ İLE KARŞILAŞTIRMALI OLARAK DEĞERLENDİRİLMESİ

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Çelik hasır, çelik fiber ve polipropilen fiber içeren betonların tokluk, eğilmede çekme dayanımı basınç dayanımı ve yarmada çekme dayanımı karşılaştırmaları değerlendirilmiştir. Aynı su/çimento (S/Ç) oranında ve aynı işlenebilirlikte çelik hasırlı, çelik fiberli, polipropilen fiberli 5 çeşit beton hazırlanmıştır. 10x60x60 cm plaka, 8x8x32 cm kiriş ve 10x20 cm silindir beton numuneler hazırlanmıştır. Beton numuneleri 7 ve 28 günlük basınç dayanımı, yarmada çekme dayanımı ve tokluk değerleri belirlenmiş ve sonuçlar birbirleriyle karşılaştırılmıştır. Testlerden elde edilen sonuçlar doğrultusunda, çelik hasırla yapılan beton, plaka deneyleri içinde en iyi performansı vermiştir. Ayrıca tokluk değeri için plaka testi yerine kiriş testi yapmanın etkinliğinin belirlenmesi amacıyla kiriş deneyi sonuçları plaka deneyi sonuçlarıyla karşılaştırılmıştır. Tokluk değerinin belirlenmesi için kiriş testi yerine plaka testi yapmanın daha iyi sonuçlar verdiği gözlemlenmiştir.

Anahtar kelimeler: Çelik fiber; Çelik Hasır; Yüksek performanslı polipropilen lif; Tokluk; Plaka testi.

To my family

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TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

ACI	: American Concrete Institute
ASTM	: American Society for Testing and Materials
FRC	: Fiber Reinforced Concrete
JSCE	: Japan Society of Civil Engineers
PP	: Polypropylene
SCRM	: Self-Compacting Repair Mortars
SF	: Steel Fiber
SFRC	: Steel Fiber Reinforced Concrete
SM	: Steel Mesh

CHAPTER 1

INTRODUCTION

1.1 General

Fiber-reinforced concrete (FRC) is defined as the concrete containing cements, water, aggregate and discrete fibers. It can also contain mineral and/or chemical admixtures for specific uses. Steel fibers are commonly used in FRC applications, also polypropylene, glass and natural fibers can be used as alternative. Adding fibers into concrete mixtures not just increases the tensile and flexural strength but also increases the toughness performance. FRC is a useful material for the applications of seismic strengthening (Mehta and Monteiro, 2006). Fiber-reinforced concrete has been used widely in the world for many applications, including new construction, repairment and rehabilitation of older and deteriorated structures, slope stabilization, retaining walls for large excavations (Morgan and Fekete, 1998).

Steel fibers and polypropylene fibers were added to concrete in the 1970s to achieve strength in tunnel linings. Strength is important for the load distribution between the tunnel lining and the surrounding ground. The tunnel lining carries important load when the soil deforms. The large amount of deformations that exist in the ground can overload a brittle material like plain concrete and this will result with failure.

Generally, steel meshes are used to strengthen the concrete and make the lining ductile. But many soil unstabilization occurs after excavation when the bond of concrete and steel mesh are not improved.

Fiber reinforced concrete has not used mainly for support in weak rock because relation between fiber reinforced concrete lining and the rock mass had not been fully investigated due to safety issues (Jovicic et al, 2009).

It has become more common to use steel fiber reinforcement instead of steel mesh reinforcement in many fields of construction. In steel mesh applications installation of steel mesh can be hard, long lasting, perilous and costly. Also, lining quality can be weak, that is, not have the same "bond between shotcrete and rock, forming weak areas behind the wire due" to inappropriate mesh positions etc. In opposition, fibers eliminate the need for conventional concrete reinforcing steel, welded wire mesh or the chain link mesh, and this alone leads to important improvement of the "ease of shotcrete placement." Also, fibers "impart toughness or energy absorption capability to hardened shotcrete resulting in improved deformability" (Morgan et al, 1995).

Cengiz and Turanlı (2001) investigated properties like "toughness, flexural ductility, energy absorption and load capacity on steel mesh, steel fiber, and polypropylene fiber reinforced shotcrete panels".

1.2 Objective and Scope

The "term fiber-reinforced concrete (FRC) is defined by ACI 116R, Cement and Concrete Terminology, as concrete" that have "dispersed randomly oriented fibers. Over 30 years have passed since" the beginning of the modern time "of research and development on fiber-reinforced concrete. In the early 1960s" papers were published by some researchers "that brought FRC to the attention of academic and industry research scientists around the world." At that time it can be reported that there was an important impact of discovery and excitement that FRC will be helpful for the improvement of materials related with Portland cement concrete. In the next 30 years, many papers have been released on the same topic. Many people have studied academically at all levels to develop FRC. Many seminars and "international conferences still held each year throughout the world" for the improvement of FRC (Zollo, 1996).

The property of "fiber reinforced concrete (FRC) to absorb energy has long been" accepted as the important benefits of the usage of fibers in plain concrete. Proceedings "in the fracture, impact and fatigue performance of FRC are the" important advantages. Many experimental methods have been improved to learn

about the energy absorption capacity of materials in compression, flexure and tension (Gopalaratnam and Gettu, 1994).

Adding fibers helps in changing the brittleness of the material to ductiliness (Ding, 1998).

Beam and slab tests have been used to learn the toughness behavior and the energy absorption of fiber reinforced concrete (Ding and Kusterle, 1999).

Toughness is the energy that is absorbed during “fracture. Ductility and high fracture strains are also important” parameters of fiber “reinforced shotcretes because the main” aim for adding fibers in concrete and shotcrete is to achieve ductility to a brittle material. Also fiber usage increases “the energy absorption and crack resistance of shotcrete” (Morgan et al, 1995).

According to the experiments, the use of steel fibers and polypropylene fibers for concrete can greatly increase the flexural ductility, toughness and load carrying capacity.

For these purposes, five different concrete mixes having different reinforcements in different amounts were produced. They were all cured for 7, 28 days to observe the effects of fibers on toughness, flexural ductility, energy absorption, and load-carrying capacity.

Also split tensile and compressive strength tests were performed on these mixes at the age of 7, 28 days to observe the effects of fiber addition.

CHAPTER 2

LITERATURE REVIEW

2.1 Effects of Using Steel Fiber-Reinforced Concrete for flexural behavior

Trottier and Banthia (1994) carried out experiments about "four deformed fibers with different geometries in steel-fiber reinforced concrete. Three matrices with compressive strengths of 42, 52, and 85 MPa were reinforced with fibers at a rate of 40 kg/m^3. Compressive and flexural strengths were measured along with the elastic moduli." The aim of the experiments was to determine the enhancement of toughness with "the addition of various fibers. Flexural load deflection curves were" studied accompanying "with the ASTM and Japan Society of Civil Engineers (JSCE) standard methods." The "limitations of current techniques for toughness characterization" is searched. A strong impact of fiber geometry and matrix strength on the toughness parameters of fiber-reinforced concrete was observed about the fibers and the matrices investigated. End-deformed fibers were generally, found to perform better to those deformed throughout the length.

The fiber reinforced concrete can absorb energy better than unreinforced concrete during fracture. While a plain matrix failing brittlely when the cracking stresses form, the fibers that have ductility carry stresses beyond matrix cracking. Therefore uniformity is achieved (Nataraja et al, 2000).

The "addition of steel fiber" importantly increases the engineering properties of mortar and "concrete", mainly "strength", flexural toughness and ductility (ACI Committee 544, 1998) (ACI Committee 544, 2002).

If steel fiber reinforced concrete will be designed accurately, fibers bear a fallback process, and then "frictional work needed for" fallback makes an importantly

developed “energy absorption” competence. “This energy absorption is” usually toughness (Nataraja et al, 2000).

Rambo et al, (2014) investigated the “mechanical” behavior “of self consolidating concrete reinforced with hybrid steel” fibers. Straight, “hooked end steel fibers” in “different lengths and diameters were used as reinforcement.” The attained results showed that the fiber crossing upgraded “the behavior of the composites for low strain and displacement levels” enhancing the usability “limit state of the” fracture range.

Ayan et al, (2011) have made investigations affecting compressive strength. They have studied on five parameters “binder type, binder amount, curing type,” age of testing “and steel fiber volume fraction. The direct tensile strength and flexural strength tests have been” carried on with the help of optimum argument degree union. “Twenty seven different concrete mixes having different” quantities “of reinforcements and mineral admixtures were” made.

2.1.1. Effects of Properties of Matrix and Fibers on the Flexural Behavior of Steel Fiber-Reinforced Concrete

Performance “of steel fiber reinforced concrete” is affected “by the properties (geometry and strength) of” fiber, the fiber amounts, the fiber arrangement and “the performance of the matrix” (Kurihara et al, 2000).

According to the study of Nataraja and Dhang (2000) which depends on JSCE “(Japan Society of Civil Engineers) approach; two aspect ratios of fiber and two different concrete strengths” were regarded. “The toughness factor as” rated “by the JSCE approach” was reputated. It was seen that there is a good relation between flexural toughness with the reinforcing ratio and “it can be seen that the flexural toughness and” flexural toughness index “increase as the fiber volume” part “is increased. It also increases as the aspect ratio is increased for a given volume” part. In addition, flexural toughness “increases as the strength of the matrix is” enhanced.

Also Norihiko et al, (2000) studied the properties of characteristics of different steel fiber reinforced concrete measured by tension softening diagrams which “can describe post-cracking behavior of concrete in tension.” At the beginning, the

pertinence of the tension softening diagram to steel fiber reinforced concrete “was investigated. Then the fracture” arguments were assumed as indices for the assesment of properties of different of steel fiber reinforced concrete. The effect “of the tensile strength of the steel” fiber “on the failure behavior of steel fiber reinforced concrete” was tested. The effect of the rupture parameters was investigated through comparison with customary indices.

The “properties of steel fiber reinforced concrete” were measured by the fracture energy the “flexural toughness” and the similar flexural strength. The result was the effect of the properties of added fibers “on the performance of steel fiber reinforced concrete” was high “when the matrix strength was high. For the” assessment “of the properties of steel fiber reinforced concrete with different matrix strength, the shape of the tension softening diagram” was superior to flexural strength. Also, if steel fiber reinforced concrete is made “with high strength matrix, the toughness” developed by adding steel fibers “was dependent on the properties of the” fibers. Finally the flexural toughness is directly relied “on the specimen size and the” similar flexural strength inclined “to depend on the size. But there was” not important affect of the “specimen size on the fracture energy. Therefore, the fracture energy was more” appropriate guide than the flexural toughness and the similar flexural strength for the appraisal “of the properties of steel fiber reinforced concrete” (Kurihara et al, 2000).

Also it “is known that steel fibers” decrease “the deflection of reinforced strength concrete beams” (Kormeling et al, 1980).

Qian and Indubhushan (1999) studied the traits “of high strength steel fiber reinforced concrete beams in bending.” The experiments were made on “ten high strength reinforced concrete beams and steel fiber reinforced high strength concrete beams, with steel fiber content of 1% by volume. The enlarged ends of mild carbon steel fibers with three dimensions were selected.” The study “shows that the flexural rigidity before” yielding “and the displacement at 80% ultimate load in the descending curve” developed “and crack number and length at comparable loads is” diminshed after adding steel fibers. The descending part of the load displacement curve “of the concrete beams without steel fibers is” sharper “than with steel fibers,

which shows the addition of steel fibers makes the high strength concrete beams more ductile."

For "steel fiber-reinforced concrete with" practical "fiber volume fractions," the major post-peak energy dissipation mechanism is the pullout of fibers across a crack. With undeformed, smooth fibers, post–peak energy dissipation or toughness is mainly a function of fiber-matrix adhesional bond, whereas for the highly stressed deformed fibers, properties of the bulk matrix are significant. High-performance matrices tend to be brittle, "and the addition of" pozzolanic admixtures, particularly "silica fume, increases the" brittleness. An increased matrix brittleness can cause crushing and splitting of the matrix and in turn, decrease the ability of fibers to transmit stresses during pullout thus reducing the overall toughness (Ashish and Nemkumar, 1998).

Also the effect of "high reactivity metakaolin and silica fume on the flexural toughness of high performance steel fiber-reinforced concrete" was studied by Ashish and Nemkumar (1998). The influence of two pozzolanic materials-"high reactivity metakaolin (HRM) and silica fume on the toughness" characteristics "of high performance fiber-reinforced concrete" was examined. The results showed that HRM was peculiarly impressive in recovering "the post-peak energy absorption capacity of concrete with" fiber and different from "silica fume" that any significant "post-peak brittleness was" seen to occur.

Alani and Beckett (2013) investigated the mechanical properties of 6x6x0.15 m synthetic fiber reinforced ground supported slab.

2.1.2 Effects of Fabrication Techniques and Environmental State on the Flexural Behavior of Steel Fiber-Reinforced Concrete

"Steam curing is" advised "in concrete that" has "mineral additives, such as silica fume and slag, to" ameliorate "strength and durability. Fly ash can be" a significant constituent "to be added to the fibrous concrete mixtures. The addition of fly ash to the fiber concrete mixture" enhances the capacity "of paste content and thus facilitates the accommodation of the fibers, minimizing" the fiber rapproachment. Also, fly ash increases "workability and pumpability of fiber reinforced concrete.

Results show that" mechanical properties "of fiber reinforced concrete are positively affected by the curing" system, "matrix" combination "and fiber size, fiber content, fiber spacing and arrangement, fiber direction, testing direction and" supplement "of fly ash" (Toutanji and Bayansi, 1997).

Toutanji and Bayansi (1997) also studied "the effects of curing" conditions "and that of testing direction relative to" molding "direction on the mechanical properties of fiber reinforced concrete." On their study, "specimens were cured in three different environmental" states; "steam, moisture and air." According to the results steam curing did not increase the "flexural strength of steel fibrous concrete but" decreased "the flexural toughness." Also "air curing" showed adverse "effects on all" positions "of the test results as compared to steam and moisture curing." It is reported that the "flexural behavior of steel fiber reinforced concrete" was impressed positively "by testing direction. When testing direction" was "perpendicular to casting direction, specimens" exhibited step-down "in flexural strength and toughness" when compared to the state of "testing and casting directions" parallelism. The impression "of testing direction relative to casting direction on flexural strength and toughness" enhanced "with increasing workability of fibrous mixture, which" increased "fiber settlement during placement."

Chen et al, (1994) had determined the first-cracking "strength and flexural toughness of steel- fiber-reinforced concrete specimens with different dimensions using the procedures" drafted in ASTM C 1018 and JSCE-SF4 and they calculated "the ASTM toughness indices and JSCE toughness parameters." The results showed that variation in specimen size did not only affect "the stress and deflection at first crack, and the ultimate strength, but" variation in specimen size affect the toughness arguments. Toughness arguments "decreased in an increase in the span-to-depth ratio of the specimens. All toughness parameters were affected by the width of the specimen, when depth and span were the" same; the "toughness increased with an increase in width."

Pigeon and Cantin (1998) had determined the "mechanical properties of steel" fiber-"reinforced concrete at low temperatures" using "the standard ASTM" C 1018 flexure experiment. The experiments were done at, 20ºC, -10ºC, and -30ºC. Also the

type of cement, “the water binder ratio, the type of” fiber, “the fiber” ratio were investigated in this study. According to the results the toughness of steel fiber reinforced concrete “under flexural loading” enhances “with a decrease in temperature. This increase” seems to be affiliated “to the increase in strength of the matrix at low temperatures, which increases the energy required for fiber pull-out. The toughness increase was” seen “for normal and high performance” concrete, and for same “types of fibers” at equal “dosages.” Therefore, effect of fiber geometry was found to be relatively small.

Leung et al, (2005) compared “properties of wet-mixed reinforced shotcrete and fiber reinforced concrete” including “compressive strength, flexural behavior, permeability and shrinkage behavior.” Five different mixes were prepared for the study. The results show that the manufacturing “process (i.e.shotcreting vs. casting) can” importantly “affect compressive strength and permeability but has little effect on” shrinking.

2.1.3 Comparison of the Test Methods to Investigate the Flexural Toughness of Steel Fiber-Reinforced Concrete

Many “methods have been” offered to determine “the fracture toughness of cement-based materials” (Trottier and Banthia, 1994); “for example, ASTM” C 1018 (four-point loading), “RILEM 50-FMC Draft Recommendation (three-point bending with notched beam), Japan Institution of Standard (four-point bending), Canadian post-crack” strength etc. The most “widely used standard test methods are the ASTM C 1018 standard test method and the Japan Society of Civil” Engineers “(JSCE) standard SF-4 method.”

The “ASTM” 1018 “standard method” depends on determining the quantity of “energy required first to” distract “and crack a fiber-reinforced concrete beam loaded at” its third points, and to further distract “the beam out to” selected multiplies “of the first-crack deflection”.

“Toughness” indices “I_5, I_{10}, I_{20}, I_{30}” etc. are computed by getting the ratios of the “energy absorbed to a” specific “multiple of first-crack deflection and the energy” wasted “up to the occurrence of first crack.” For example, “standard” toughness

indices “I_5, $I_{10,}$ I_{30}” are “defined for” a “deflection” up to “3 δ, 5.5 δ and 15.5 δ, where δ is the deflection at” the “first crack”.

“Expressed in general terms.

I_N = Energy absorbed up to a certain multiple of first-crack deflection/Energy absorbed up to the first crack.

The subscript N in these marks are based on the elasto-plastic analogy such that, for a perfectly elasto-plastic material, the index I_N would have a value equal to N” (Cengiz, 2001).

Banthia and Trottier , (1994) have “many concerns with the ASTM C 1018 and JSCE test methods”.

2.1.3.1 Concerns about the ASTM C 1018 Method

2.1.3.1.1 Measuring true specimen deflections

A true “measurement of deflection” is significant to get the toughness of fiber reinforced concrete. For the specimen under a cross load, the main origin of mistake is the establishment “of the specimen supports themselves, the measured displacement of the load points” does not include the true translation due to the reaction “of the beam material to the applied stress but also those” existing from accommodation “and the downward movement of the beam as a” solid “body. If not properly considered, the settlement in the supports can lead to” a “big overestimation of the first crack energy and hence to erroneous” marks. The computation of “toughness” marks needs a true “assessment of the first-crack energy,” which includes “the denominator in the definition of the” different marks. Also, the recognition of “first-crack deflection is not” complicated, due to the considerable “non-linearity of load-deflection curves even prior to” get “the peak load” (Cengiz, 2001).

2.1.3.1.2 Instability after peak load

“The point peak load occurrence however is also the point of instability for the loading machine, which, if not” solid “enough, will” endure unexpected “unloading

and release large amount of energy. This sudden" dismissal "of energy has major effects on the load-deflection curves immediately following the peak-load. The problem" related "with instability can be" solved "by using a closed-loop servo controlled test system. The commercial laboratories unfortunately, do not" usually "use this kind of" advanced machine (Cengiz, 2001).

2.1.3.2 JSCE Standard SF-4 Test Method

"In this technique, the area under the load-deflection" scheme "up to a deflection of span/150 is" attained. It may be acclaimed that flexural toughness "has the unit of stress such that its value" points, "in a way, the post-matrix cracking" remaining "strength of the material when loaded to a deflection of span⁄150. The chosen deflection of span⁄150 for its" computation "is purely" random "and is not" depended on usability circumstances (Cengiz, 2001).

2.1.3.2.1 Concerns with the JSCE SF-4 Test Method

"Identifying the" right "occurrence" position "of the first crack, which is" vital "and one of the" important "problems with the ASTM method, is not a concern with the JSCE method." Different from "the ASTM method the instability in the load-deflection" scheme "after the first crack is not of" significant "concern in the JSCE method, since the end point deflection of span⁄150 is too far out in the curve to be affected by the instability in the" original part. "However, there are other limitations and" relations. Firstly, "FTs are specimen geometry-dependent, which makes" precise "correlation with the field performance of" fiber reinforced concrete more difficult. Also the "end point chosen on the curve at a deflection of span⁄150 is often criticized for being" more than the agreeable "deflection/serviceability limits. The behavior immediately following the first crack, which may be" significant in same "applications, is not" pointed in FT. At last, the technique may be criticized for lack of distinguishment the "pre-peak and post-peak behaviors by adopting the" blurred "approach of using the" whole "area under the curve to calculate FTs" (Cengiz, 2001).

2.1.3.3. Comparison of Beam Tests with Slab Test.

According to explanations, the tests mentioned above can be generalized as beam tests. In fact, there have been mainly two tests, beam and slab tests, “to investigate toughness” behavior “and energy absorption” capacity “of steel” fiber “reinforced concrete.” Although in slab-like concrete structure “effective prestressing for crack control purposes will be very difficult, especially in the two principal directions, because of the following reasons, the panel test was” considered “as better for examining the material properties than the beam test.

1. A beam is statically determinate system and will be subjected to bending in the longitudinal length direction only.
2. A plate is statically indeterminate system and will be subjected to bending in two directions. A statically indeterminate system allows stress redistribution in another direction after the first peak-load.
3. A slab is considered to represent more realistically the two-directional bending of thin” concrete “shell structures in” tunneling “and mining than the beam.” Also, the slab support on the four edges simulates the continuity of the concrete lining.
4. “Steel fiber-reinforced concrete” and high performance “polypropylene fiber-reinforced concrete” can be compared very easily with a mesh-reinforced concrete, to be tested in the same way (Cengiz, 2001).

2.2 Properties of Steel Fiber Reinforced Concrete under Compression

Okuyucu et al, (2011) carried out a comprehensive study “in order to investigate” some characteristics “of fiber-reinforced” semi-lightweight “concrete for seismic strengthening” purposes “of reinforced concrete framed structures. Semi-lightweight concrete containing unexpanded perlite, both as” lightweight “aggregate and as a supplementary cementing material,” was reinforced by polypropylene and steel fibers, separately. “Compressive strength split tensile strength and modulus of elasticity” measurements were carried out on cylinder specimens. Steel-mesh reinforced semi-lightweight concrete plates were also tested as reference specimens

for the toughness test and the results were compared. Cylinder test results indicated a huge increase in “28-day compressive strength in the case of” unexpanded perlite powder replacement, while providing lower “tensile strength and modulus of elasticity.” Toughness test results showed the superiority of polypropylene fiber-reinforced semi-lightweight concrete for seismic strengthening purposes in the case of fiber utilization.

The “mechanical properties of concrete can be” developed “by the addition of steel” fibers. “Toughness of steel” fiber “reinforced concrete can be measured by different test methods, such as the beam test and the panel test.” Although “most methods give an indication of the flexural energy, the compressive test” should be considered to see the “behavior of steel fiber reinforced concrete for underground construction especially at an early age, because in many cases steel fiber reinforced concrete in tunnels is mainly subjected to compression.”

“Many researchers hold the view that steel” fibers “do not have” an important effect “on the compressive behavior of concrete due to small volume of” fibers “in concrete mix” especially at the age of 28 days (Ding and Kusterle, 2000).

Ding and Kusterle (2000) also investigated the “compressive stress relationship of steel fiber reinforced concrete at early age.” Experimental studies were done “on laboratory” concrete “as well as on dry mix” shotcrete “at a tunnel site. The measurements were” done “at about 9 h and continued up to 81 h” on 20x20x20 cm cube specimens. “This study demonstrated that the use of” fiber “reinforcement in concrete can greatly” increase “the compressive ductility, toughness and energy absorption at early ages.”

Nataraja et al, (1999) also carried out studies about “stress-strain curves for steel fiber reinforced concrete under compression. In this experimental” study, “an attempt has been made to generate the complete stress-strain curve experimentally for steel-fiber reinforced concrete for compressive strength ranging from 30 to 50 MPa. Round crimped” fibers “with three volume fractions of 0.5%, 0.75% and 1.0% (39, 59 and 78 kg/m^3) and for two aspect ratios of 55 and 82 are considered.” The effect of fiber utilization in “concrete on some of the major parameters namely peak stress,

strain at peak stress, the toughness of concrete and the nature of the stress-strain curve is studied." It was concluded that utilization of "crimped steel"-fibers "to concrete" enhances "the toughness considerably." The enhancement "in toughness is directly proportional to the reinforcing index." Enhancement "in toughness is higher for lower grade of concrete compared to higher grade of concrete. A marginal increase in compressive strength, strain at peak stress is also observed. This increase is directly proportional to the reinforcing index."

2.3. Impact and Abrasion Resistance of Steel Fiber-Reinforced Concrete

Steel "fiber reinforced concrete" in many civil engineering structures must have adequate resistance to impact and heavily applied loads. It is currently used to provide massive armors against the impact of projectiles in sentry boxes, arms and powder depots, and other defense buildings (Cengiz, 2001).

Nataraja et al, (1999) reported the "variation in impact resistance of steel fiber reinforced concrete and plain concrete as determined from a drop weight test. The observed coefficients of variation are about 57 and 46% for the first-crack resistance and the ultimate resistance in the state of fiber concrete and the corresponding values for plain concrete are 54 and 51%, respectively. The goodness-of fit test showed poor fitness of the impact-resistance test results in the study to normal distribution at 95% level of confidence for both fiber-reinforced and plain concrete. But, the percentage increase in the number of blows from first crack to failure for both fiber-reinforced concrete and as well as plain concrete fit to normal distribution as indicated by the goodness-of fit test. The coefficient of variation in percentage increase in the number of blows beyond first crack for fiber-reinforced concrete and plain concrete is 51.9 and 43.1%, respectively. Minimum numbers of tests are required to reliably measure the properties of the material can be suggested based on the observed levels of variation."

Luo et al, (2000) studied the "characteristics of high-performance steel-fiber reinforced concrete subjected to high velocity impact. Targets made of high-performance steel fiber-reinforced concrete which was produced by fluidized mortar, steel fibers and casting process of mortar infiltrating and vibrating, were subjected to

high velocity affect of projectile and compared with those targets made of reinforced high strength concrete." According to the "results when impacted by projectiles at high speed, the reinforced high strength concrete targets exhibited smash failure, while high-performance steel fiber-reinforced concrete targets remained intact with several radial cracks in the front faces penetrated by projectiles and some minor cracks in the side faces. The projectiles were embedded in or rebounded from high-performance steel fiber-reinforced concrete targets".

Soil saving dam, breakwater and pavement that are located in severe wearing condition are usually subjected to rapid deterioration of structure. Ultra-high strength concrete exceeding 200 MPa with or without steel fiber has a possibility of becoming high abrasion resistance concrete (Cengiz, 2001).

Lok and Xiao (1999) studied the behavior of "steel-fiber reinforced concrete panels exposed to air blast loading. Scaled explosive tests have been conducted to investigate the response of steel-fiber reinforced concrete model structural elements. The structural elements were (a) rectangular panels, simply supported on two opposing shorter edges, (b) square panels, simply supported on all edges, and (c) fully fixed panels, in the form of an open box. Seven air blast tests were done. For each test, six panels were exposed simultaneously to air blast overpressure generated from the detonation of bare high explosives; charge weights ranged from 8 kg to 40 kg. The panels were fabricated with different types of steel fiber, fiber concentration and conventional wire mesh reinforcement".

According to the "results, as a construction material" steel fiber reinforced concrete can make a significant "contribution to the integrity and resistance of blast"-resistance structures. A "single-degree of freedom" model, "which incorporates an" elastoplastic structural "resistance function" for "the dynamic analysis, is used to" predict "the response" of the panels. The "deformed" configuration of the panels was computed "at constant load steps and the results were employed to" evaluate "the parameters of an equivalent dynamic model".

"Self-compacting repair mortars (SCRM), as new technology products, are especially preferred for the rehabilitation and repair of reinforced concrete structures. The self-

compactability of repair mortars may bring" significant "advantages at narrow mould systems. However, due to the high powder content and absence of coarse aggregate, plain SCRMs are susceptible to surface abrasion, especially in case of repair of surfaces under high rates of abrasion (floors, slabs). Steel fiber reinforcement can be an excellent solution for the abrasion resistance problem of SCRMs. However, the optimum amount of fiber reinforcement to sustain self-compactability should be predetermined. The optimum superplasticizer dosage and the maximum possible amount of fiber addition, which maintain the self-compactability and stability, were determined for mortars incorporating steel fibers in" this study. Also, "the mechanical performance and abrasion resistance of SCRMs prepared by using these fibers were determined. It was concluded that steel fibers can have rheological and mechanical synergistic effects, and that optimised fiber-superplasticizer dosage combinations can better improve the wear resistance while" attaining "adequate flow properties for FR-SCRM" (Felekoğlu et al, 2006).

2.4. Fatigue Behavior of Steel Fiber-Reinforced Concrete

Most engineering components are subjected to cyclical stresses in use to alternating stress that recur indefinitely. This variation is either attributable to changes in the load, or else to changes in the position of the component in relation to the load. Steel-fiber reinforced concrete structures are also subjected to these cycling loads in their fatigue life.

Yin and Thomas (1995) investigated the "fatigue behavior of steel-fiber reinforced concrete in uniaxial and biaxial compression" by comparing that of plain concrete. "Seventy-two steel reinforced concrete specimens, with 1%" by "volume 25 mm long fibers, were tested under compression fatigue loading. The S-N curves were" attained "under four stress ratios of 0 (uniaxial), 0.2, 0.5, and 1.0, resulting in a series of fatigue stress envelopes for fiber concrete." Deformations in all three directions were measured. The S-N curves, strength envelopes, failure modes, and cyclic deformations of fiber concrete "were compared to those of plain concrete. According to the results the addition of fibers does not enhance "the endurance limit but" it is useful "above the endurance limit in the low-cycle region." Also, "adding fibers"

increases “concrete’s ductility and changes failure modes from splitting type to faulting type”.

Zhang et al, (2000) studied the “crack bridging in steel fiber reinforced concrete materials under deformation-controlled uniaxial fatigue tension. Two types of” steel fibers, straight “steel fiber and hooked end steel fiber, were used separately in” the experiment. “A total of six series of fatigue tensile tests with constant amplitude between maximum and minimum” cracking “openings were conducted.” According “to the results, the bridging stress decreases with the number of load cycles and this phenomenon is” called “bridging degradation. The general behavior of the bridging degradation with the number of cycles in” steel-fiber reinforced concrete “is represented by a fast dropping stage (reduction in bridging stress within the first 10-15 cycles) with a decelerated degradation rate, followed by a stable stage with an almost constant degradation rate for straight” steel-fiber reinforced concrete, “or by several periods with a decelerated rate in each period for hooked” steel-fiber reinforced concrete. “Although fiber deformation, such as in hooked end fiber, can improve the monotonic crack bridging significantly, faster bridging degradation is found in hooked steel-fiber reinforced concrete” than in “straight steel-fiber reinforced concrete with the same maximum crack width (>0.1 mm) and minimum load condition”.

“The influence of steel fibers on the fatigue resistance of concrete in direct compression, based on experiments, and an assessment of it through neural network modeling have been presented. Straight and hooked fibers were incorporated in the concrete together. The volume fraction was 1% for straight fibers, and both 1 and 2% for hooked fibers. The applied stress levels ranged from 0.55 to 0.95 of the (static) compressive strength. The number of cycles was up to 1,000,000. The neural network was based on a feed forward back-propagation algorithm. Steel fibers increased the fatigue strength, distinctly, at all stress levels. Hooked fibers enhanced the fatigue strength more than the straight ones; the larger the fiber content, the greater was the enhancement of fatigue strength. Strains measured just before failure showed that fiber reinforced concrete could undergo larger strains before failure than plain concrete. Based on strains measured throughout the fatigue cycling, stages of

dilation and failure have been apparent. The adopted neural network modeled both the *S-N* (strength–number of cycles) and strain-*N* behaviors extremely well. It was considered possible to extrapolate the *S-N* behavior beyond 1,000,000 cycles in order to estimate the fatigue strength in the super-high cycle ranges of 107 and more" (Rafeeq et al, 2000).

2.5 Properties of Steel Fiber-Reinforced Concrete Beams under Shear

"When principal tensile stresses within the shear region of a reinforced concrete beam exceed the tensile strength of concrete, diagonal cracks develop in the beam, eventually causing failure. The brittle nature of concrete causes the collapse to occur shortly after the formation of the first crack. The addition of steel" fibers helps "in converting the brittle" properties "to a ductile one. The principal role of" fibers "is resisting the formation and growth of cracks by providing pinching forces at crack tips. In addition," an "improvement in tensile strength" is seen and fiber "reinforced concrete has higher ultimate strain than plain concrete" (Cengiz, 2001).

Tan and Paramasivam (1994) studied "punching shear strength of steel fiber reinforced concrete slabs. Each of 14 square slabs was simply supported along four edges and loaded to failure under a concentrated load over a square area at the center." According to the results, "the load-deflection curve of slabs" exhibit "four distinct regions that may be characterized by first cracking, steel yielding, and ultimate load. Within the scope of the test program, an increase in the values of" steel fibers, slab thickness, size of loading-bearing plate "was found to lead to an increase in both the punching shear strength and the ductility of the slab. The ultimate punching shear strength of the slabs was compared with the predictions of equations available in the literature and code equations for reinforced concrete".

Ding et al, (2011) "carried out" experiments "on a series of simply supported rectangular beams, using steel fiber reinforcement with and without stirrups and subjected to four point symmetrically placed vertical loads". The investigation showed "that the shear strength increases by increasing the" fiber "content, the addition of steel" fibers "in an adequate" ratio "can change the failure" made "from a

brittle shear collapse into a ductile flexural mechanism." According to the results the "stirrups can be partially replaced by steel" fibers.

Campione and Mangiavillano (2008) studied the "flexural behavior of plain and fibrous reinforced concrete beams under monotonic and cyclic actions. Twelve beams were reinforced with top and bottom longitudinal deformed steel bars and transverse steel stirrups." The results showed that "the addition of fibers" increased "the bearing capacity of the beams and" ductility behavior, also reduced the "cover spalling process in the presence of high cover" thickness.

Chunxiang and Patakuni (1999) carried out investigations about "ten high-strength reinforced concrete beams and steel fiber-reinforced high strength concrete beams, with steel fiber content of 1% by volume. The enlarged ends of mild carbon steel fibers with three different dimensions were selected." According to the study "the flexural rigidity before yield stage and the displacement at 80% ultimate load in the descending curve are improved, and crack number and length at comparable loads is reduced after the addition of steel fibers. The descending part of the load-displacement curve of the concrete beams without steel fibers is much steeper than that with steel fibers, which shows that the" inclusion "of steel fibers makes the high strength concrete beams more ductile".

2.6 Durability Properties of Steel Fiber-Reinforced Concrete

The corrosion resistance "of steel fiber reinforced concrete" is "governed by the same factors that influence the corrosion resistance of conventionally reinforced concrete. As long as the matrix" retains its inherent "alkalinity and remains" uncracked, "deterioration of steel fiber reinforced concrete is not likely" to occur. It has been found that good quality steel fiber reinforced concrete, when exposed to conditions conducive to reduced alkalinity, such as atmospheric pollution, deicing chemicals or a marine environment, will only carbonate to a depth of millimeters over a period of many years (Cengiz, 2001).

Jovicic et al, (2009) studied whether fiber "reinforced shotcrete can be" used "successfully as the only material for the primary tunnel lining in" harsh "geological

conditions.” According to the results fiber “reinforced shotcrete for the primary lining in a” 410 m “long section of the tunnel” can be used succesfully.

Fuente et al, (2011) studied on the “innovations related to precast concrete panels to be used in reinforced earth retaining wall systems. These innovations” include “the anchor system of the panel, the set up of the pull out test to assess the effectiveness of the anchors and the use of” fibers “as reinforcement”.

2.7 Comparison of Steel Fiber-Reinforced Concrete with Steel Mesh Reinforced Concrete

It has become “common to replace steel reinforcement with steel”-fiber “reinforced concrete” especially “in underground constructions. It is of great importance to compare the” behavior of steel-fiber “reinforced concrete and conventional steel-reinforced concrete. In cases of shotcrete at the tunnel face, it is important to get a fast stabilizing effect. To avoid damage to the shotcrete caused by blasting or drilling for bolts, it is also” significant to get “high early strength. Compared to the actual strength, the tunnel shell is loaded to the highest degree during the first advance rounds after spraying, and therefore most failures occur at early ages” (Cengiz, 2001).

Although the fiber “influence on concrete at later ages is well known, at present, there are few research results comparing the properties of steel” fiber “reinforced concrete with various” fiber “contents and steel- reinforced concrete, especially at ages of 10 h to 2 days.” Ding and Kusterle (2000) studied steel-fiber “reinforced concrete and steel mesh reinforced concrete at early ages in panel tests. To evaluate the development of punching shear and flexural ductility for panels, experimental investigations were” performed “on laboratory concrete in accordance with EFNARC (1996). The measurements were taken at the earliest age of the specimen possible, about 10 h and continued up to 48 h”.

2.8 Usage of Steel Fiber with Polypropylene Fiber in Concrete

Steel fibers “have a considerably larger length and higher Young’s modulus as compared to the” polypropylene fiber. “This leads to an improved potential for crack control. But volumetric density is high, and steel is conductive in electric and”

magnetic “fields.” Therefore, steel fiber “content has to be reduced to below certain level in structures such as tunnels.” Optimization of mechanical “and conductivity properties can be” attained by uniting different kinds, “types, and sizes of fibers” (Qian and Stroeven, 1999).

Qian and Stroeven (1999) has also investigated the “optimization of” fiber size, fiber “content, and fly ash content in hybrid polypropylene-steel” fiber “concrete with low” fiber “content based on general mechanical properties.” According to “the results a certain content of fine particles such as fly ash is necessary to disperse” fibers. “The different sizes of steel” fibers “contributed to different mechanical properties at least to a different degree.” Addition of small fiber type had an important “influence on the compressive strength but the splitting tensile strength was” affected “slightly. A large” fiber “type gave rise to opposite mechanical effects, which were fortified by optimization of the aspect ratio. There is synergy effect in the hybrid” fibers system.

Qian and Stroeven (1999) also made investigations on “fracture properties of concrete reinforced with steel-polypropylene hybrid fibers”.

CHAPTER 3

EXPERIMENTAL STUDY

3.1 Experimental Program

Five concrete mixes having different reinforcements were produced to be used in the tests for the aim of determining the performances like toughness, flexural ductility, energy absorption and load carrying capacities of steel mesh and fiber reinforced concrete. Reinforcement types and amounts of these different concrete mixes can be seen in Table 3.1.

The first mix was steel mesh reinforced concrete. The second mix was steel fiber-reinforced concrete. The third, fourth and fifth mixes were polypropylene fiber-reinforced concrete.

Cement, aggregates were mixed in concrete mixing machine. Also the fibers were introduced into the mixture during mixing. Finally the mixes were put into 60x60x10 cm, 32x8x8 cm and 10x20 cm cylindrical forms.

Beside the tests conducted on cement, cement paste, mortar, and aggregates to be able to determine physical and chemical properties, tests were performed to find out the effect of different reinforcements on compressive strength, energy absorption capacity, ductility and toughness of hardened concrete mixes.

Table 3.1 Concrete Mixes Produced for the Experimental Study

Mix.No.	Designation	Reinforcement Types and Amounts for 1 m^3 Concrete
I	SM	Steel Mesh (Ø10- Ø6x150x150 mm) Diameter: 10 mm, 6 mm and interval 150 mm
II	SF	Steel Fiber; 25 kg/m^3
III	PP-1	Polypropylene Fiber Type-1; 6 kg/m^3
IV	PP-2	Polypropylene Fiber Type-2; 6 kg/m^3
V	PP-3	Polypropylene Fiber Type-3; 6 kg/m^3

All of the tests were done according to ASTM Standard Specifications and experimental works were conducted in the Materials of Construction Laboratory at M.E.T.U.

Tables 3.2.a, 3.2.b and 3.2.c show the relevant standards followed for performing the tests on cement, cement paste, cement mortar, aggregates and hardened concrete.

Table 3.2.a Tests Performed on Cement, Paste and Mortar

Tests	Relevant Standards
For Cement:	
Chemical Analysis	ASTM C 114, C 150
Density	ASTM C 188
Fineness	ASTM C 204
For Cement Paste:	
Normal Consistency	ASTM C 187
Time of Setting	ASTM C 191, C 150
Fineness	ASTM C 204
For Cement Mortar:	
Compressive Strength	ASTM C 109, C 150

Table 3.2.b Tests Performed on Aggregates

Tests	Relevant Standards
Specific Gravity and Absorption	ASTM C 127, C 128
Sieve Analysis	ASTM C 136

Table 3.2.c Tests Performed on Concrete

Tests	Relevant Standards
For Fresh Concrete:	
Slump	ASTM C 143
Unit Weight	ASTM C 138
Air Content	ASTM C 231
For Hardened Concrete:	
Compressive Strength, Flexural Strength	ASTM C 31, C 39, C 78
Split Tension Test, Beam Test	ASTM C 1399, C 496
Specific Gravity, Absorption	ASTM C 642-90
Permeable Void	

3.2 Materials Used

3.2.1 Portland Cement

A typical Turkish Portland cement, CEM I 42.5 R, was used (This type of cement corresponds to ASTM Type I cement) for the preparation of paste, mortar and concrete.

The chemical and physical properties of this cement are shown in Tables 3.3 and 3.4, respectively.

Table 3.3 Chemical Composition of Portland Cement

Oxides	(%)	ASTM C150 Limits
SiO_2	19.83	-
CaO	61.88	-
MgO	1.79	Max 6.0 %
SO_3	3.66	Max 4.0 %
Cl	0.01	-
Na_2O	0.39	-
K_2O	1.05	-
LOI	2.26	Max 3.0 %
IR	2.70	Max 5.0 %

Table 3.4 Physical Properties of Portland Cement

Property		ASTM C150 Limits
Specific Gravity	3.11	-
Specific Surface Area (cm^2/g)	3464	min 2800
Time of Setting (min)		
Initial	166	min 45
Final	217	max 375
Compressive Strength (MPa)		
3 days	27.1	min 12.4
7 days	36.8	min 19.3
28 days	51.2	-

3.2.2. Aggregates in Concrete

A natural river sand having a particle size (0-9.5 mm) was used as aggregates. Sieve analysis of the aggregates in concrete is shown in Table 3.5

Table 3.5 Sieve Analysis of Aggregates in Concrete

Sieve No		Cumulative Percent Passing
3/8	(9.5 mm)	100
No. 4	(4.75 mm)	84
No. 8	(2.36 mm)	54
No. 16	(1.18 mm)	34
No. 30	(600 μm)	23
No. 50	(300 μm)	16
No. 100	(150 μm)	10

Figure 3.1 displays the gradation curve of the aggregate representing all the size groups and the gradation curve meets the gradations specified in ACI 506.

Table 3.6 gives the results of the specific gravity and absorption tests conducted on aggregates.

Table 3.6 Specific Gravity and Absorption of Aggregates in Concrete

Specific Gravity	
Aggregate (Dry)	2.63
Aggregate (SSD)	2.66
Absorption (%)	
Aggregate	1.2

3.2.3. Mixing Water and Admixtures

Normal, drinkable tap water that was assumed to be free from oil, organic matter and alkalis, was used as mixing water.

3.2.4. Reinforcements

Steel mesh was used made of ø10 steel bars in horizontal, ø6 steel bars in vertical for the plate tests. For the beam tests 28 cm ø10 steel in horizontal and two pieces of 3 cm ø6 steel in vertical that were cut from the steel mesh welded from the edges were used. Tensile strength of the ø10 steel is 628 MPa and tensile strength of the ø6 steel is 728 MPa. Their specific gravity is 7.9, elastic modulus is 200 GPa and tensile strain is 10.7%.

Figure 3.1 Steel mesh and steel bar used in the plate/beam experiments

In fiber reinforced concrete, four types of commercially available fibers were investigated as reinforcement in this research.

- The first one was called SF (Steel fiber) having hooked ends, length of 35 mm, diameter of 0.55 mm and aspect ratio of 64. They were cold drawn fibers. Tensile strength of the steel fiber is 1100 MPa, its specific gravity is 7.9, elastic modulus is 200 GPa and tensile strain is 2% (Figure 3.2).
- The second one was called PP-1 (Polypropylene fiber) having round ends ragged surface that has length of 58 mm, diameter of 0.9 mm and aspect ratio of 64. Tensile strength of the steel fiber is 600 MPa, its specific gravity is 0.92, elastic modulus is 10 GPa and tensile strain is 15% (Figure 3.2).
- The third one was called PP-2 (Polypropylene fiber) having rectangular ends that has length of 54 mm, end lengths of 1.1-0.2 mm and aspect ratio of 49. Tensile strength of the steel fiber is 640 MPa its specific gravity is 0.9, elastic modulus is 9 GPa and tensile strain is 15% (Figure 3.2).
- The fourth one was called PP-3 (Polypropylene fiber) having square ends ragged surface that has length of 40 mm, end lengths of 0.55 mm and aspect ratio of 36. Tensile strength of the steel fiber is 500 MPa, its specific gravity is 0.9, elastic modulus is 7.1 GPa and tensile strain is 15% (Figure 3.2).

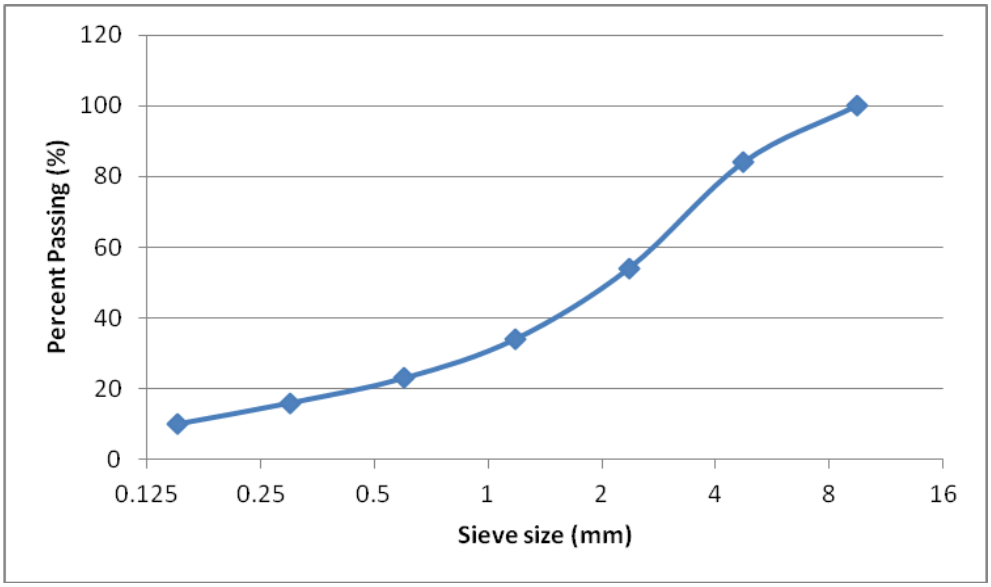
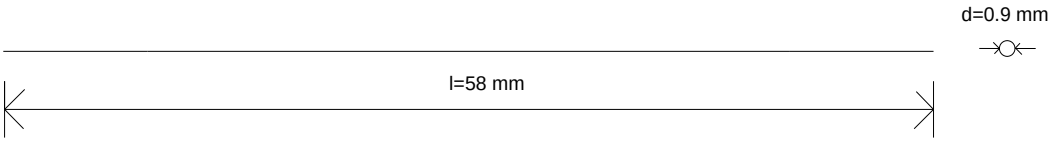


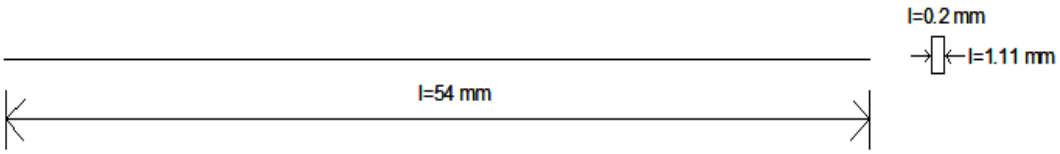
Figure 3.2 Sieve analyses of the aggregate that used.

a) SF type l/d =64

b) PP-1 type l/d =64



c) PP-2 type l/d =49



d) PP-3 type l/d =36

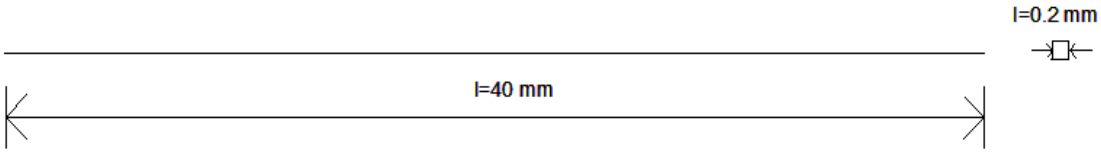


Figure 3.3 Fiber types used in the experiments

In addition, in the design of steel mesh-reinforced concrete panels the mesh (diameter 10-6 mm, intervals 150 mm) was placed centrally.

3.3 Concrete Mixtures

The procedure given by the American Concrete Institute, ACI 211, was followed to calculate the mix design proportions.

Concrete mix proportions used in this experimental study are given in Table 3.7, Table 3.8 and Table 3.9.

Table.3.7 Concrete Mix Proportions (for the first mix)

	Concrete
Cement (kg/m^3)	420
Water (kg/m^3)	251
Aggregate (kg/m^3)	1611
Total Weight(kg/m^3)	2282

Table.3.8 Concrete Mix Proportions (for the second mix)

	Concrete
Cement (kg/m^3)	420
Water (kg/m^3)	251
Aggregate (kg/m^3)	1611
Steel fiber (kg/m^3)	25
Total Weight (kg/m^3)	2307

Table.3.9 Concrete Mix Proportions (for the third, fourth, fifth mix)

	Concrete
Cement (kg/m^3)	420
Water (kg/m^3)	251
Aggregate (kg/m^3)	1611
Polypropylene fiber (kg/m^3)	6
Total Weight (kg/m^3)	2288

Table 3.10 gives a summary of the information given in Table 3.9 and the unit weights of concrete mixes were determined experimentally. The slumps of concrete mixes were adjusted to 12 mm also the water/cement ratio of concrete mixes was 0.6.

Table.3.10 Characteristics of Fresh Concrete

Mixes	Slump (cm)	Air content (%)	Unit weight(kg/m³)
Steel Mesh	12	2.0	2265
Steel Fiber	11	3.0	2270
PP Fiber-1	11	3.3	2265
PP Fiber-2	12	4.0	2230
PP Fiber-3	12	4.0	2245

3.4 Tests on Fresh Concrete

Slump, unit weight and air content were the types of tests performed on concrete.

3.4.1 Slump Test

While concrete mixes were being prepared, a strict slump control was made for batches, and slumps of concrete mixes were adjusted to exact values given in Table 3.10 values.

3.4.2 Unit weight of Fresh Concrete

Unit weight tests of concrete mixes were performed according to ASTM C 138. The results were given in Table 3.10.

3.4.3 Determination of Air Content

Air contents of concrete mixes were determined by Pressure Method according to ASTM C 231 and the results were given in Table 3.10.

3.5 Tests on Hardened Concrete

Compressive strength tests and plate tests were conducted on concrete specimens.

3.5.1 Compressive Strength Tests

Compressive strength tests of plain or fiber reinforced concrete specimens at the ages of 7, 28 days were performed according to ASTM C 39. Cylindrical cores of 10 cm in diameter and 20 cm in height were used for the tests. The results are tabulated and discussed in Chapter 4.

3.5.2 Plate Tests

The plate tests were performed to investigate the toughness, ductility, load carrying and energy absorption capacities of concrete mixes. The results are tabulated, graphed and discussed in Chapter 4.

Firstly, the plates having dimensions of 600x600x100 mm were prepared according to the specification. Then, the specimens were allowed to be cured and stored in water for 7, 28 days immediately before testing.

As can be seen from Figure 3.3, the prepared test panels for each mix were supported on its four edges by a rigid metallic frame and center point load applied by using 40 t Universal Testing machine through a contact surface of 100x100 mm. The rough side of the panel was on the bottom during the test, i.e. the load was applied to the spraying direction. The rate of deformation at the mid point was nearly 1.5 mm per minute. Tests continued until a deflection of 25 mm was achieved at the center point of the slab.

After that, the load-deformation curves were drawn for all mixes having four plates each and comparative load-deflection curves were obtained as average results of the tests.

Then, the energy-deflection curves “were found by integrating the area under these curves giving the absorbed energy” amount “as a function of the” plate “deflection” (Roux and Rivallain) (EFNARC, 1996).

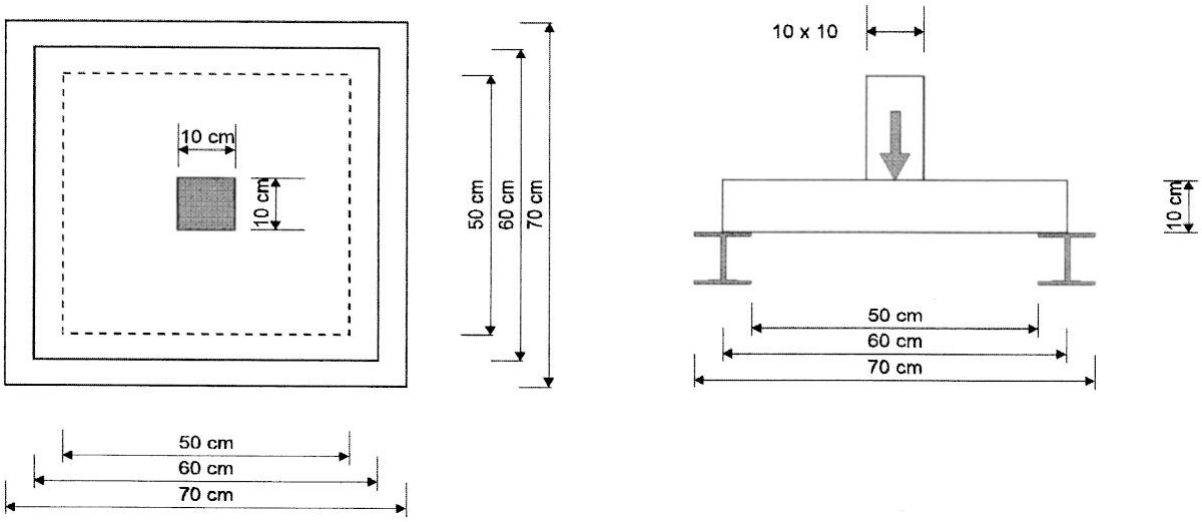


Figure 3.4 Set-Up for Plate Test

Comparative load-deflection curves of the panels, the "average results for the first-peak load, the maximum load and the energy absorption in” joule for concrete plates are presented in Chapter 4.

“The criterion for the evaluation of the material toughness of panel test is the energy absorption" classes (Table 4.5) (Ding and Kusterle, 1999). “For tunnel repair jobs, the SNCF specifies energy absorption of 500 J till a deflection of 25 mm” (Roux.J, Rivallain).

CHAPTER 4

TEST RESULTS AND DISCUSSIONS

In this chapter, results of the tests performed on reinforced hardened concrete will be given and these results will be discussed extensively.

4.1 Comparison of the plates according to their performances

It can be seen from Figures 4.1 and 4.2 that the first peak and ultimate loads of steel mesh are more than the other mixes. All mixes having decrease in load-carrying capacities show unstable zone after the peak load. On the other hand, up to 25 mm deflection, the area under the load deflection curve of the steel mesh is much higher than other mixes causing steel mesh having also higher energy absorption capacity.

PP-2 showed more ductile behavior and has better load carrying capacity up to 25 mm deflection than other panels except steel mesh.

Steel fiber, PP-1 and PP-3 come subsequently with respect to absorption capacity after steel mesh and PP-2.

Steel fiber and PP-2 show a small decrease in load carrying capacity between the deflections of 1 mm and 2 mm after their peak load, but then they preserve their load carrying capacities representing the stable and ductile behavior. At the end up to 25 mm deflection, the area under the load-deflection curve of PP-2 is higher than steel fiber causing PP-2 having also higher energy absorption capacity. PP-3 shows the least energy absorption capacity.

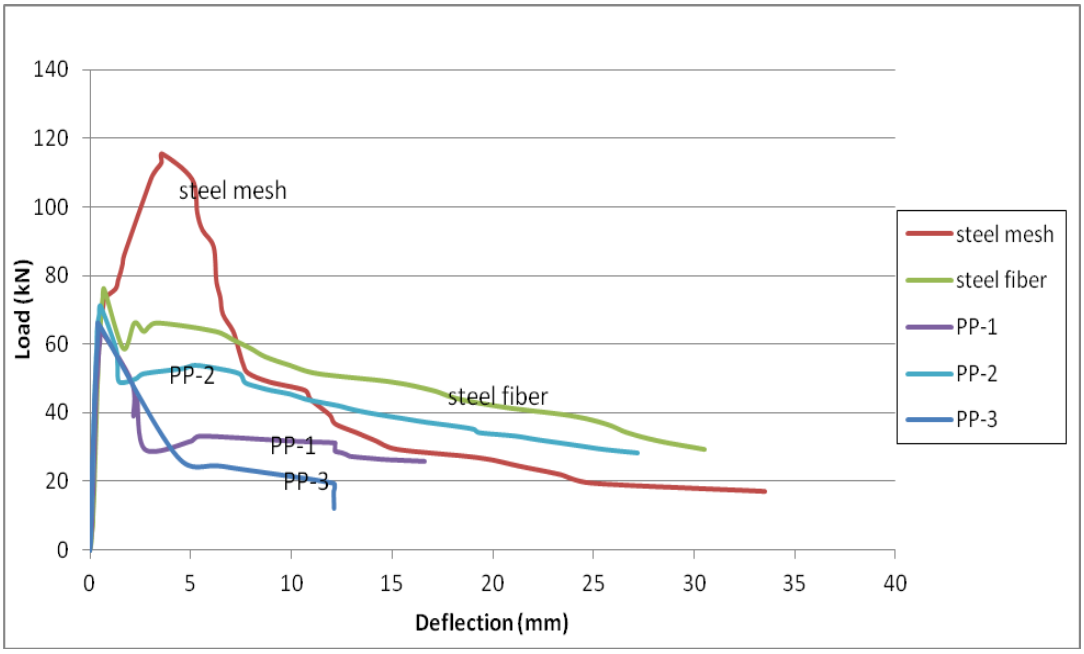


Figure 4.1 Comparison of Load-Deformation Graphs of the plate mixes for 7 days.

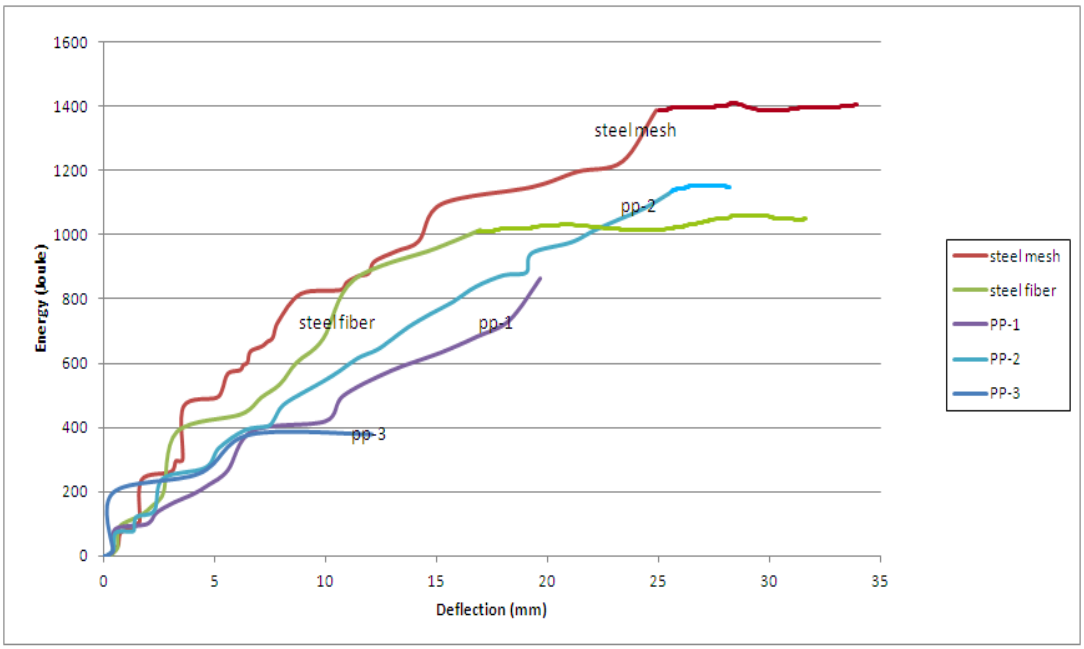


Figure 4.2 Comparison of Energy-Deformation Graphs of the plate mixes for 7 days.

It can be seen from Figures 4.3 and 4.4 that the 7 day values increased approximately from 10% to 30%. First peak and ultimate load of steel mesh are more than the other mixes. On the other hand, up to 25 mm deflection, the area under the load deflection curve of steel mesh is much higher than the other mixes causing steel mesh having also higher energy absorption capacity. Also it can be seen from Figure 4.3 and 4.4 that the first peak and ultimate load of steel mesh are the maximum. After the first cracking load, the load carrying capacities of all panels with fibers drop up to a deflection of 2.5 mm and then, the load capacity of steel fiber panel continues to decrease and PP panels remains stable or show little decrease till the last deflection. But steel mesh indicating different behavior increases its load-carrying capacity and reaches its ultimate value at the deflection of 3.5 mm and it shows much better load carrying and energy absorption capacity than others although its load capacity decreases after it's ultimate load. Also, its energy absorption up to the deflection of 25 mm is nearly 1.5 times of steel fiber, PP-1, PP-2 and 3 times that of PP-3.

PP-2 again show more ductile behavior and has better load carrying and energy absorption capacity up to 25 mm deflection than other panels except steel mesh.

Steel fiber, PP-1 and PP-3 come subsequently with respect to absorption capacity after steel mesh and PP-2.

Steel fiber and PP-2 have similar load carrying capacities between the deflections of 15 mm and 25 mm.

Steel fiber, PP-2 and PP-1 show a decrease in load carrying capacity between the deflections of 1 mm and 3 mm after their peak load but then they preserve their load carrying capacities representing the stable and ductile behavior. At the end up to 25 mm deflection, the area under the load-deflection curve of PP-2 is higher than steel fiber and PP-1 having also higher energy absorption capacity. PP-3 shows the least energy absorption capacity.

On the other hand, as can be seen from Figures 4.1-4.4 for PP-2 and steel fiber panels, increase in fiber content decreased the first cracking and ultimate load capacities of them causing not so much increase in toughness and energy absorption capacities. Values show variation upon the unequal dispersion of the fibers.

The main reason of steel mesh panels “having higher energy absorption capacity than the other panels is that the bond and the friction stresses between the steel mesh and the concrete matrix are greater” and the steel mesh has enough bond length that provides better yielding and plastic deformation of it also increasing of the load carrying and energy absorption capacity (Cengiz, 2001). In addition, the diameters of steel mesh are 10 and 6 mm.

According to results, it can be said that using steel fibers which is hooked and having high aspect ratio or PP fibers in concrete is considerably more advantageous than using steel mesh in performance point of view especially for tunnel applications where there are also many difficulties in application of steel mesh (Cengiz, 2001).

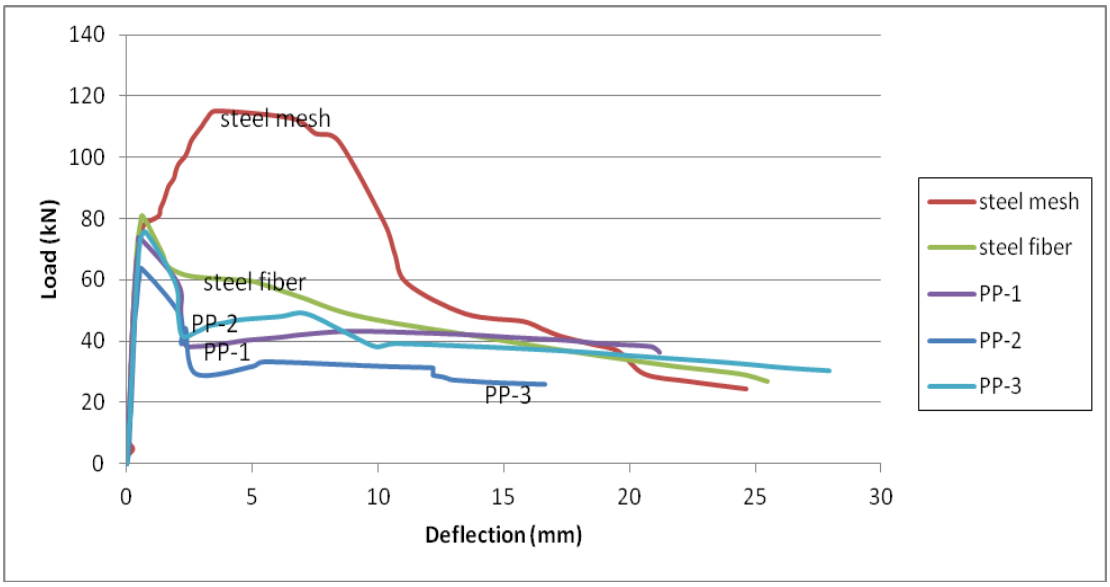


Figure 4.3 Comparison of Load- Deformation Graphs of the plate mixes for 28 days.

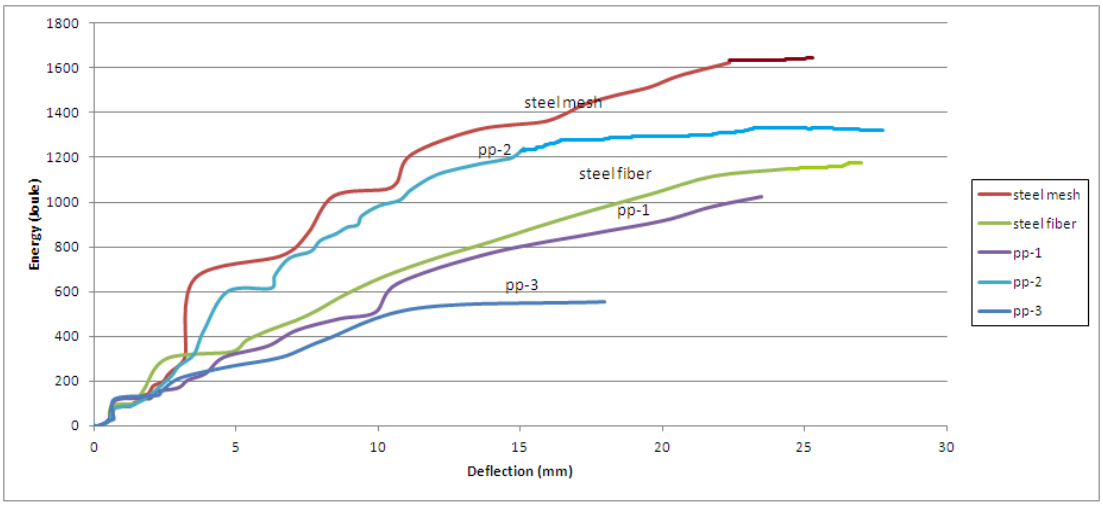


Figure 4.4 Comparison of Energy- Deformation Graphs of the mixes for 28 days.

Values vary upon the unequal dispersion of the fibers during mixing and placing.

4.2. Effect of Fiber Geometry on the Performances.

The geometrical properties of the fibers play significant role on the performance of the panels. For this reason the influence of fiber geometry was discussed in this study.

According to results it could be said that using PP fibers with rough surface contributed significantly to the increase in bond between the fiber and the matrix. Also using steel fibers with hooked ends contributed significantly to the increase in bond between the fiber and the matrix because of the anchored hooked ends of the fibers to transmit the maximum amount of force and prevented any splitting force from being exerted on the concrete.

4.3. Effect of Aspect Ratio (l/d) of Fibers on the Performances.

It can be seen from Figures 4.1- 4.4 that although the aspect ratio of PP-2 is not higher than steel fiber and PP-1, it showed higher amount of absorption capacity.

4.4. Effect of Fiber Addition on Compressive and Split Tensile Strength of Concrete Mixes.

In this section the compressive and split tensile strengths of mixes will be compared to evaluate the effect of fiber addition.

The compressive and split tensile strength results can be seen in Table 4.1. From this table, it can be said that the compressive and split tensile strengths were little influenced by addition of fiber for concrete mixes.

Therefore it can be concluded that for concrete mixes compressive and split tensile strength is mainly controlled by concrete mix design.

Table.4.1 Compressive and Split Tensile Strength of Concrete Mixes

Mixes	7 day Compression Strength (MPa)	28 day Compression Strength (MPa)	7 day Split T. Strength (MPa)	28 day Split T. Strength (MPa)
Steel Mesh	30.2	37.5	2.9	3.2
Steel Fiber	30.3	35.0	3.3	3.4
PP Fiber-1	27.5	34.8	3.0	3.2
PP Fiber-2	28.2	38.0	2.7	3.8
PP Fiber-3	26.8	29.9	2.4	2.7

10x20 (dxh) cylindrical core compressive and split tension strengths at 7, 28 days in MPa.

4.5. Comparison of the beams according to their performances

It can be seen from Figures 4.5 and 4.6 that the first peak and ultimate loads of steel mesh are more than the other mixes. All mixes having decrease in load-carrying capacities show unstable zone after the peak load. On the other hand, up to 25 mm deflection, the area under the load deflection curve of PP-1 is much higher than other mixes causing PP-1 having also higher energy absorption capacity.

Steel mesh showed more ductile behavior and has better load carrying capacity up to 25 mm deflection than other panels except PP-1.

PP-2, steel fiber and PP-3 come subsequently with respect to absorption capacity after steel mesh and PP-1.

Steel fiber and PP-1 show a small decrease in load carrying capacity between the deflections of 1 mm and 5 mm after their peak load, but then they preserve their load carrying capacities representing the stable and ductile behavior. At the end up to 25 mm deflection, the area under the load-deflection curve of PP-1 is higher than steel mesh causing PP-1 having also higher energy absorption capacity. PP-3 shows the least energy absorption capacity.

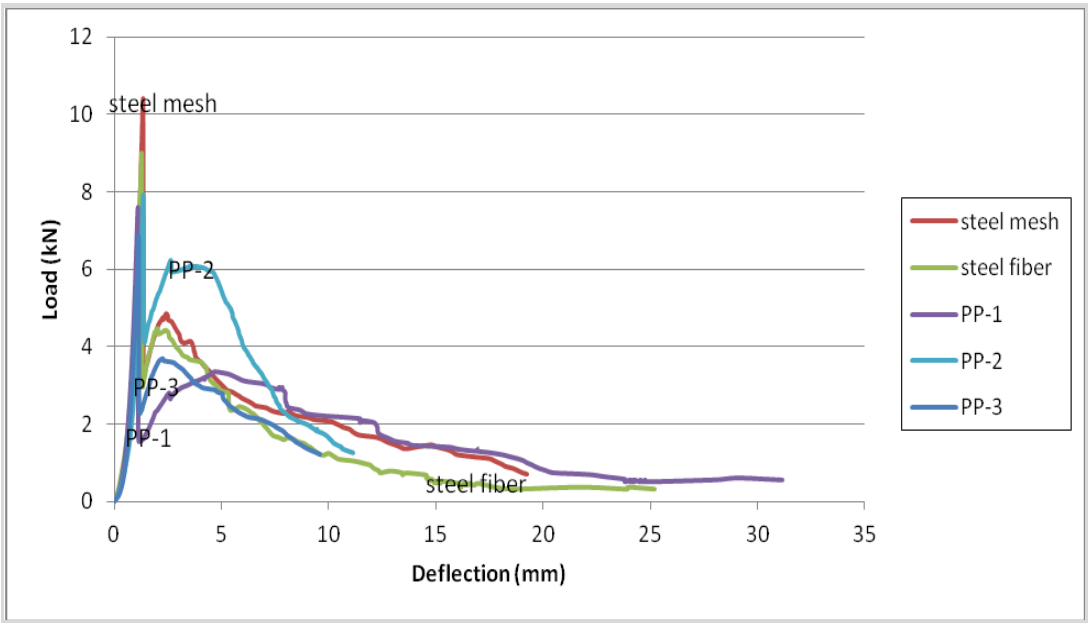


Figure 4.5 Comparison of Load- Deformation Graphs of the beam mixes for 7 days.

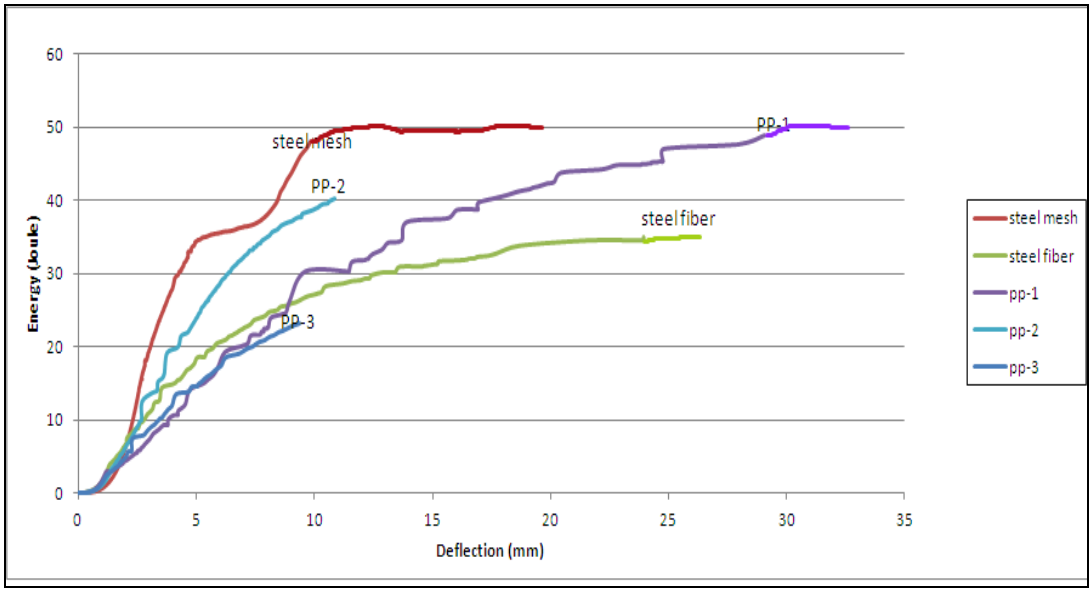


Figure 4.6 Comparison of Energy-Deformation Graphs of the beam mixes for 7 days.

It can be seen from Figures 4.7 and 4.8 that the 7 day values increased approximately from 10% to 30%. First peak and ultimate load of steel mesh are more than the other mixes. On the other hand, up to 25 mm deflection, the area under the load deflection curve of PP-1 is much higher than the other mixes causing PP-1 having also higher energy absorption capacity.

Steel mesh show more ductile behavior and has better load carrying and energy absorption capacity up to 25 mm deflection than other panels except PP-1.

PP-2, PP-3 and steel fiber come subsequently with respect to absorption capacity after steel mesh and PP-1.

Steel fiber, PP-1 and PP-2 have similar load carrying capacities between the deflections of 13 mm and 19 mm.

Steel fiber, PP-1, PP-2 and PP-3 show a decrease in load carrying capacity between the deflections of 1 mm and 2 mm after their peak load but then they preserve their load carrying capacities representing the stable and ductile behavior. At the end up to 25 mm deflection, the area under the load-deflection curve of PP-2 is higher than

steel fiber and PP-1 having also higher energy absorption capacity. PP-3 shows the least energy absorption capacity.

On the other hand, as can be seen from Figures 4.5-4.8 for PP-1 and steel fiber panels, increase in fiber content decreased the first cracking and ultimate load capacities of them causing not so much increase in toughness and energy absorption capacities. Values vary upon the unequal dispersion of the fibers.

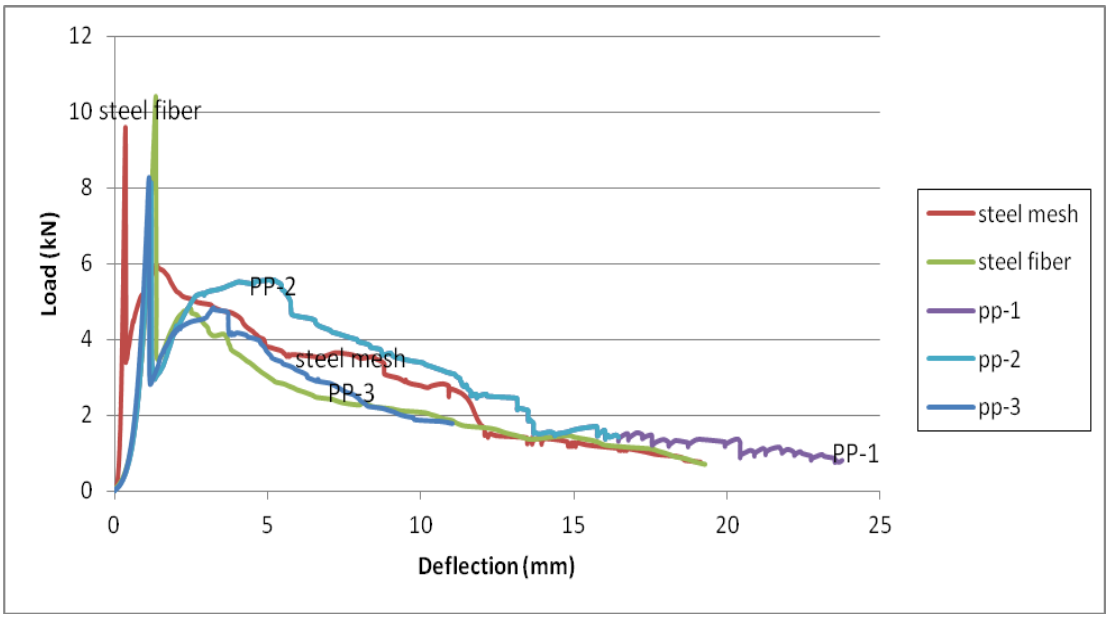


Figure 4.7 Comparison of Load-Deformation Graphs of the beam mixes for 28 days.

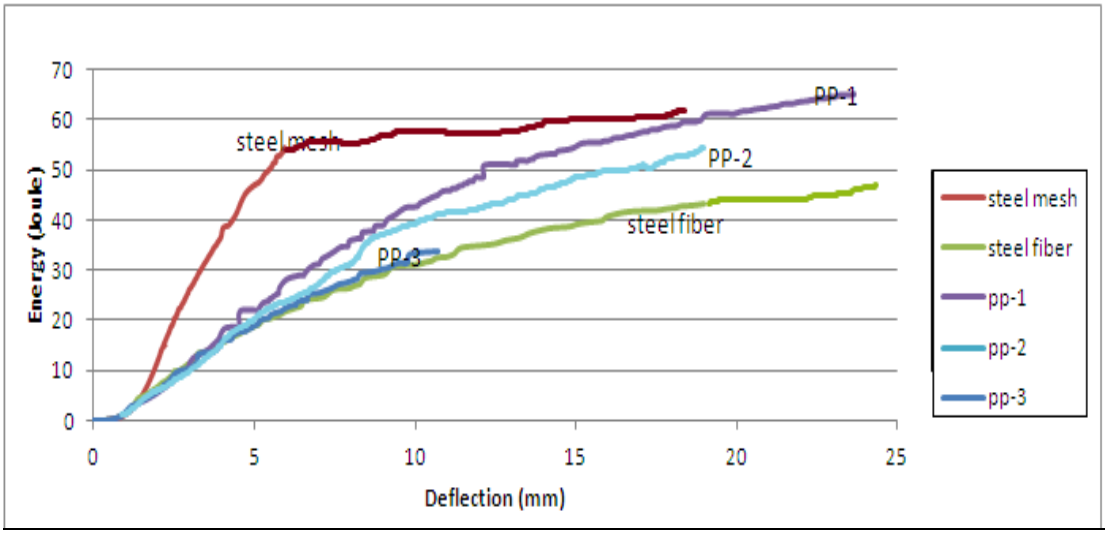


Figure 4.8 Comparison of Energy-Deformation Graphs of the beam mixes for 28 days.

The load deflection graph illustrated in Figure 4.1 and 4.3 is “typical for a panel test and it differs from the beam test” (Ding, 1998) because the beam is only subjected in one direction but the plate is moving in two directions.

4.6. Failure Mechanisms of Panels.

There are differences between steel mesh panels and fiber reinforced panels from performance point of view as mentioned before. It was seen that in this study that there were also differences between failure mechanisms of the mixes.

Figures 4.9-4.13 show the failure patterns of the panels. It seems that steel mesh panels failed in punching shear modes and showed flexural failure modes due to the hardened concrete having tensile strength. Friction stresses and the bond between steel mesh and concrete matrix increased the punching shear capacity by a little amount although not having shear reinforcement.

Figure 4.9 Failure pattern of steel mesh panel.

Figure 4.10 Failure pattern of steel fiber panel.

These studies show that using fibers prevented cracks by punching shear as it is seen in figures 4.10-4.13 fibers failed mainly in flexural modes with punching shear. The underside of the panels developed a series of cracks radiating outward to the edges from the centrally loaded area upon loading and the failure occurred by the damage from the radial cracks. Fibers worked partly as shear reinforcement by enhancing the shear capacity also enhancing the ductility in great amount.

Figure 4.11 Failure pattern of PP-1 panel.

Figure 4.12 Failure pattern of PP-2 panel.

Figure 4.13 Failure pattern of PP-3 panel.

4.7 Comparison of Panel Test Results According to Toughness Classes.

In this section panel test results for all concrete mixes which was presented in graphical form in previous sections were tabulated and discussed according to energy absorption classes.

The average results for the first-peak load, the maximum load and the energy absorption in joule for a deflection until 25 mm for concrete plates can be seen in Table 4.2.

It can be seen in Table 4.2 that steel mesh plate has the maximum first peak load and its ultimate load is also the highest one.On the other hand, PP-3 has the lowest first peak-load and its ultimate load is also the lowest one. In addition PP-3 has the lowest energy absorption capacity up to deflection of 25 mm.

“The criterion for the evaluation of the material toughness of panel test is the energy absorption” classes (Table 4.4) (Ding and Kusterle, 1999).

Also by comparing Figures from 4.1 to 4.4 with Table 4.4 the results of achieving of energy absorption classes according to related deflections can be obtained and it can be seen in Table.4.3.

Table 4.2 Comparison of the Average Values of First Peak Load (kN), Ultimate Load (kN), and Energy Absorption for Concrete Plates (28 days)

Mixes	First Peak Load (kN)	Ultimate Load (kN)	Energy Absorption (Joule)
Steel Mesh	80	115	1589.4
Steel Fiber	82	82	1149.5
PP Fiber-1	74	74	1016.3
PP Fiber-2	76	76	1242.3
PP Fiber-3	64	64	553

Table 4.3 Energy Absorption Classes with respect to Deflections for Concrete Mixes (28 days)

Mixes	Deflection (mm) achieved class (a)	Deflection (mm) achieved class (b)	Deflection (mm) achieved class (c)
Steel Mesh	5.1	7	10.2
Steel Fiber	8.5	13	21
PP Fiber-1	11.5	17	22
PP Fiber-2	10.6	16.5	24
PP Fiber-3	19	-	-

Table 4.4 Energy Absorption Requirements according to EFNARC (1996).

Toughness Class	Energy Absorption for Deflection up to 25 mm in Joule
a	500
b	700
c	1000

It can be seen from Table 4.3 that steel mesh panel firstly achieved the energy absorption class of (a), (b) and also (c). On the contrary, PP-3 panels lastly achieved the energy classes. In general, it can be said that panels including steel fibers that had hooked end and high aspect ratio showed good performance.

Apart from these polypropylene fibers showed good performance except PP-3.

CHAPTER 5

CONCLUSION& RECOMMENDATIONS

The experimental investigations were performed on steel mesh (SM), steel fiber (SF), polypropylene fiber (PP)-reinforced concrete mixes to observe their performance characteristics such as toughness, flexural ductility, energy absorption and load carrying capacities, compressive behavior etc.

As a result of this study, the following conclusions can be written.

1. All types of fibers have the ability to increase mechanical properties of brittle concrete.

Fiber addition improved toughness, flexural ductility, punching shear, energy absorption capacity and load carrying capacity of concrete significantly.

2. The increase in fiber content did not enhance the load carrying and energy absorption capacities for all types of panels. Although the amount of fibers that used in SF is higher than PP-2, PP-2 showed better load carrying and energy absorption capacity. According to these results mechanical properties of the fibers have more effect on strength than the amount of fiber used.

3. The size, shape and geometry of the fibers are very important for fiber reinforced concrete from performance point of view. Among the four types of fibers, PP-2 and SF showed the best results from the mechanical point of view. It can be said that using steel fibers with hooked ends in concrete contribute significantly to the increase in bond between the fiber and the matrix because of the anchored hooked ends of the fibers which make it available to use all parts of the fiber to transmit the maximum amount of force. Also PP fibers that has smooth surface, disperse uniformly in the concrete and showed best results with respect to flexural strength, toughness, ductility, and load carrying capacity.

4. According to the results, it can be said that compressive strength of the mixes were little influenced by fiber addition for all concrete mixes. Compressive strength is mainly controlled by the concrete mix design and the compressive strength of the concrete depends on the compressive strength of the matrix.

5. According to the performances of the mixes, it can be said that using steel fiber or PP fiber can be more advantageous than using steel mesh in concrete for the applications. Although steel mesh has many difficulties in application it showed the best results with respect to toughness, flexural strength, ductility and the load carrying capacity. Therefore the material to be used has to be selected according to the importance degree of strength or easiness in application. Also it must be stated that steel mesh gave the best results in laboratory conditions. In the field fibers can give better results than steel mesh. Lining quality of steel mesh is poor and there is no uniform bond between concrete and rock in the field. Irregular mesh positions and low qualified shadow areas behind the wire can lower the toughness of steel mesh.

6. This investigation showed that using fibers in concrete prevented cracks by punching shear and the fiber usage greatly improved the punching shear capacity with ductility according to the working of fibers which are distributed mainly two or three dimensionally as shear reinforcement. Panels with fiber failed mainly in flexural modes with some punching shear, panels with steel mesh failed mainly in punching shear modes and showed also flexural failure behaviors.

7. Polypropylene fibers can be as effective as steel fibers.

8. This investigation showed that the panel test works better for determining toughness than the beam test. The results of the beam tests were compared with the plate test to determine the effectiveness of using beam tests for toughness instead of plate test. The results of the beam tests did not show parallelism with the results of the plate tests.

The main purpose to apply panel tests and beam tests is to evaluate the performances of reinforced concrete mixes such as toughness, ductility, energy absorption and load capacity, compressive strengths and split tension strengths etc. According to the results obtained from the study the following recommendations are made for further investigations.

1- In this experimental study, the experimental investigations were performed on steel mesh, steel fiber and high performance polypropylene fiber-reinforced concrete panels and beams for 7, 28 days. Further studies should be performed on the specimens at very early age. By this way, the evaluation of the performances can be made for early strength developments.

2- The energy absorption capacity and flexural toughness of the specimens were obtained in this study by integrating the area under load-deflection curve of them. Additional tests can be performed to investigate the compressive behavior of the same materials by using stress-strain relationships. By this way, compressive toughness of the mixes can be obtained.

3- Further studies should cover different types of reinforcements other than steel mesh, steel fiber and polypropylene fiber to get the best efficiency from concrete. For example coconuts and glass particles can be used to investigate toughness behavior.

4- Concrete panels reinforced with steel mesh, steel fiber, polypropylene fiber were tested in this research to investigate the effects of using them. Additional tests can be made for hybrid steel-polypropylene fiber reinforced concrete containing hooked steel fibers having high aspect ratio to improve the performance.

5. Polypropylene fibers can be used in water structures with respect to corrosion. Also it can be disadvantageous to use polypropylene fibers in the case of fire.

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