DETERMINATION OF MECHANICAL PROPERTIES OF HYBRID FIBER REINFORCED CONCRETE

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ABSTRACT

DETERMINATION OF MECHANICAL PROPERTIES OF HYBRID FIBER REINFORCED CONCRETE

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Fiber reinforcement is commonly used to provide toughness and ductility to brittle cementitious matrices. Reinforcement of concrete with a single type of fiber may improve the desired properties to a limited level. A composite is termed as hybrid, if two or more types of fibers are rationally combined to produce a composite that derives benefits from each of the individual fibers and exhibits a synergetic response.

This study aims to characterize and quantify the mechanical properties of hybrid fiber reinforced concrete. For this purpose nine mixes, one plain control mix and eight fiber reinforced mixes were prepared. Six of the mixes were reinforced in a hybrid form. Four different types of fibers were used in combination, two of which were macro steel fibers, and the other two were micro fibers. Volume percentage of fiber inclusion was kept constant at 1.5%. In hybrid reinforced mixes volume percentage of macro fibers was 1.0% whereas the remaining fiber inclusion was composed of micro fibers. Slump test was carried out for each mix in the fresh state. 28-day compressive strength, flexural tensile strength, flexural toughness, and impact resistance tests were performed in the hardened state. Various numerical analyses were carried out to quantify the determined mechanical properties and to describe the effects of fiber inclusion on these mechanical properties.

Keywords: Fiber Reinforcement, Hybrid Composite, Toughness, Impact Resistance

ÖZ

HİBRİD LİF TAKVİYELİ BETONUN MEKANİK ÖZELLİKLERİNİN BELİRLENMESİ

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Çimento bağlayıcılı matrislere tokluk ve süneklik sağlamak için lif takviyesi yaygın olarak kullanılmaktadır. Betonun bir tek çeşit lifle takviye edilmesi istenilen özelliği sınırlı bir düzeyde iyileştirebilir. Her ayrı liften fayda sağlayacak ve sinerjik bir tepki gösterecek şekilde iki ya da daha fazla lifin oransal olarak bir arada kullanıldığı kompozit hibrid olarak adlandırılır.

Bu çalışma hibrid lif takviyeli betonun mekanik özelliklerini karakterize etmeyi ve nicel olarak belirlemeyi amaçlamaktadır. Bu nedenle bir tanesi lifsiz kontrol karışımı sekiz tanesi lif takviyeli karışım olmak üzere dokuz karışım hazırlanmıştır. Karışımlardan altı tanesi hibrid şekilde takviye edilmiştir. İki tanesi makro çelik, diğer iki tanesi mikro düzeyde olmak üzere dört farklı tür lif bir arada kullanılmıştır. Lif katkısının hacim yüzdesi %1.5 olarak sabit tutulmuştur. Hibrid takviyeli karışımlarda makro liflerin hacim yüzdesi %1.0 iken kalan lif katkısı mikro liflerden oluşmuştur. Taze durumda kıvamın belirlenmesi amacıyla her karışım için çökme testi yapılmıştır. Sertleşmiş durumda 28 günlük basınç dayanımı, eğilmede çekme dayanımı, eğilmede tokluk, ve darbe dayanımı testleri yapılmıştır. Belirlenen mekanik özelliklerin nicel olarak ifade edilmesi ve lif katkısının bu özelliklere etkisinin tarif edilmesi amacıyla çeşitli sayısal analizler yapılmıştır.

Anahtar Kelimeler: Lif Takviyesi, Hibrid Kompozit, Tokluk, Darbe Dayanımı

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVATIONS

ACI	:	American Concrete Institute
ASTM	:	American Society of Testing Materials
FC	:	First crack
FRC	:	Fiber reinforced concrete
HFRC	:	Hybrid fiber reinforced concrete
JSCE	:	Japan Society of Civil Engineers
PPFRC	:	Polypropylene fiber reinforced concrete
SFRC	:	Steel fiber reinforced concrete
UFS	:	Ultimate Failure Strength

LIST OF SYMBOLS

δ	:	Deflection
δ_u	:	Ultimate deflection
β	:	Material parameter
σ	:	Stress
f_c	:	Compressive strength
f_{flex}	:	Flexural tensile strength
f_{split}	:	Split tensile strength
l	:	Length (of fiber)
d	:	Diameter (of fiber)
P	:	Load
P_u	:	Ultimate Load
V_f	:	Volume percentage of fiber content

CHAPTER 1

INTRODUCTION

1.1 General

The term fiber reinforced concrete (FRC) is defined by ACI Committee 544 as a concrete made of hydraulic cements containing fine or fine and coarse aggregates and discontinuous discrete fibers [1]. Inherently concrete is brittle under tensile loading. Mechanical properties of concrete can be improved by reinforcement with randomly oriented short discrete fibers, which prevent and control initiation, propagation, or coalescence of cracks. FRC can continue to sustain considerable loads even at deflections exceeding fracture deflections of plain concrete. The character and performance of FRC changes depending on matrix properties as well as the fiber material, fiber concentration, fiber geometry, fiber orientation, and fiber distribution.

FRC can be regarded as a composite material with two phases in which concrete represents the matrix phase and the fiber constitutes the inclusion phase. Volume fraction of fiber inclusion is the most commonly used parameter attributed to the properties of FRC. Fiber count, fiber specific surface area, and fiber spacing are other parameters, which may also be used for this purpose. Another convenient numerical parameter describing a fiber is its aspect ratio, defined as the fiber length divided by its equivalent diameter.

It is possible to make several classifications among fiber types. Fibers can be divided into two groups; those with elastic moduli lower than the cement matrix, such as cellulose, nylon, and polypropylene and those with higher elastic moduli such as asbestos, glass, steel, and carbon. Another classification can be made according to the origin of the fiber material such as metallic, polymeric, or natural. Materials and properties of common fibers are listed in Table 1.

Table 1. Typical Properties of Fibers [1]

Type of Fiber	Tensile Strength (MPa)	Young's Modulus (GPa)	Ultimate Elongation %	Specific Gravity
Acrylic	210-420	2.1	25-45	1.1
Asbestos	560-980	84-140	0.6	3.2
Carbon	1800-2600	230-380	0.5	1.9
Glass	1050-3850	70	1.5-3.5	2.5
Nylon	770-840	4.2	16-20	1.1
Polyester	735-875	8.4	11-13	1.4
Polyethylene	700	0.14-0.42	10	0.9
Polypropylene	560-770	3.5	25	0.9
Rayon	420-630	7	10-25	1.5
Rock Wool	490-770	70-119	0.6	2.7
Steel	280-2800	203	0.5-3.5	7.8

There are various applications of FRC. Asbestos fibers have been used in pipes or thin sheet elements for a long time. Glass fibers are also used in thin sheet element production as well as shotcrete applications. Steel fibers have been used in pavements, in shotcrete, and in a variety of other structures. Polypropylene fibers are used to control cracks due to plastic shrinkage [2-4]. New application areas become available as new fiber types and new FRC production techniques are developed.

A composite can be termed as *hybrid*, if two or more types of fibers are rationally combined to produce a composite that derives benefits from each of the individual fibers and exhibits a synergetic response. Concrete is a complex material with several phases all in different orders of magnitude like C-S-H gels in micron scale, sand in millimeter scale, and gravel in centimeter scale. Reinforcement of concrete with a single type of fiber may improve the properties to a limited level. However by using the concept of hybridization with two or more different types of fibers incorporated in a common cement matrix, the hybrid composite can offer more attractive engineering properties because the presence of one fiber enables the more efficient utilization of the potential properties of the other fiber [2].

1.2 Objective and Research Significance

The aim of this study is first to develop hybrid fiber reinforced concrete (HFRC), and then to characterize and quantify the benefits obtained by the concept of hybridization. Compressive strength, flexural tensile strength, impact resistance, and toughness in bending are the measured mechanical properties of the HFRC mixes in this study.

To open new application areas, FRC should be designed so as to perform with adequate strength, sufficient ductility, high durability, and adequate workability. Utilizing the concept of hybridization, a concrete with superior properties can be developed. Ductility and strength of concrete can be improved at lower fiber contents, where fibers are used in combination rather than reinforcement with a single type of fiber. Limiting the high aspect ratio fiber content, without compromising the ductility and the strength of the concrete, problems associated with workability can be eliminated. Durability problems concerning one type of fiber may be offset with the presence of a second type of fiber.

Results obtained from this study are expected to contribute to the efforts made to characterize the mechanical properties of HFRC. With the appropriate interpretation of the obtained results, it can be possible to make various optimization analyses like optimization for a desired mechanical property or optimization for a certain fiber type and content.

1.3 Scope

Chapter 2 is on steel, polypropylene, and hybrid fiber reinforced concrete. Manufacturing methods for steel and polypropylene fibers are explained. Effects of steel and polypropylene fiber inclusion on concrete in the hardened and fresh states are overviewed. Durability characteristics of steel fiber reinforced concrete (SFRC) and polypropylene fiber reinforced concrete (PPFRC) are briefly mentioned. Mix design recommendations, mixing, placing, compaction, and finishing techniques and practical applications of SFRC and PPFRC are summarized. Discussion continues with hybrid fiber reinforced concrete (HFRC). Definitions related to HFRC are given and the chapter concludes with a literature review on HFRC.

In Chapter 3, currently available test methods for measuring toughness and impact resistance of FRC are overviewed. Advantages and shortcomings of these test methods are discussed.

Chapter 4 deals with the experimental program in this study. Properties of materials, mix proportions, mixing, casting, and curing procedures are explained in detail. Procedures applied to perform related tests are explained.

Results and discussions of the tests carried out during this study are covered in Chapter 5. Analyses of the results are also presented in this chapter.

Chapter 6 concludes the discussion; recommendations for future studies are also mentioned in this chapter.

CHAPTER 2

STEEL, POLYPROPYLENE, AND HYBRID FIBER REINFORCED CONCRETE

2.1 Steel Fiber Reinforced Concrete (SFRC)

2.1.1 General

The early theoretical studies, initiated by Romualdi, Batson, and Mandel, in the 1950's and 1960's focused mainly on the characteristics of steel fiber reinforced concrete (SFRC). Only straight steel fibers were used in the beginning. Though remarkable improvements in toughness and ductility were obtained, problems in mixing and workability were encountered. These problems were overcome with the advent of deformed steel fibers and high range water reducers. Today steel is the most commonly used fiber type for concrete reinforcement, with the exception of asbestos fibers [2-4].

Though modest improvements in strength can be obtained, the primary purpose of steel fiber inclusion to concrete is to increase toughness and ductility. Steel fibers are used for crack control, to replace secondary reinforcement, which is also used for this purpose. The increase in toughness can prevent or minimize cracking due to temperature changes, relative humidity etc. Steel fiber inclusion also increases the resistance to dynamic loading.

It is possible to produce steel fibers in many ways. Round fibers are produced by cutting or chopping wires. Flat fibers may be produced either by shearing sheets or flattening wires. Crimped and deformed steel fibers of various shapes are also produced, in which deformations may extend through the length of the fiber or may be limited to the end portions. Some fibers are collated into bundles using water-soluble glue dissolving during the mixing process, in order to ease handling and mixing. Depending on the type of steel and the type of production technique, steel fibers may have tensile strengths of about 280-2800 MPa, and ultimate elongations of about 0.5% to 3.5% [2-4].

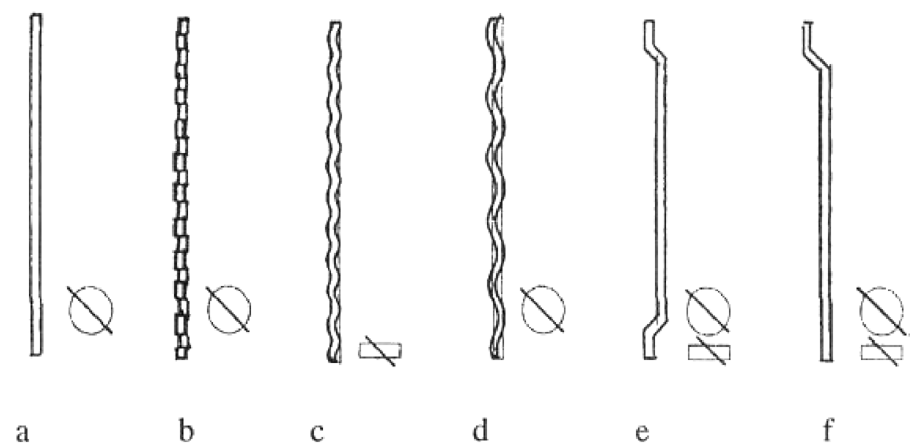

Figure 1. Steel fiber types with different geometric properties (a) straight (b) waved (c) crescent (d) Class C hooked end (e) hooked end (f) single hooked end [5]

2.1.2 Mechanical Properties of SFRC

Compressive Strength: It is unlikely to achieve considerable improvements in compressive strength by steel fiber inclusion. Increases up to 25% can be obtained [2-4]. However reinforcing the concrete with steel fibers provides post-cracking ductility to concrete as can be seen in Figure 2.

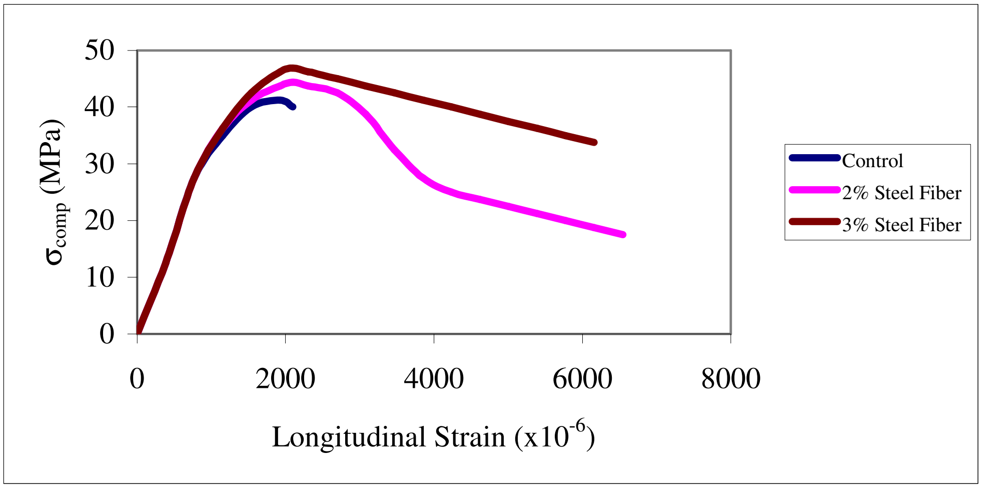

Figure 2. Typical stress-strain curves for SFRC under compression [2]

Tensile Strength: Fiber orientation has a crucial effect on tensile strength of SFRC. Fibers aligned in the direction of loading can increase the direct tensile strength substantially. In cases with more random fiber distributions this effect diminishes, and fiber inclusion does not contribute to the direct tensile strength of concrete. Splitting tensile strength tests for SFRC yield similiar results. Like in compression, steel fiber inclusion to concrete provides post-cracking ductility [2-4].

Flexural Tensile Strength: Steel fibers are more efficient in increasing flexural strength of concrete. The increase in flexural strength is sensitive to the fiber volume and fiber aspect ratio. Fibers with greater aspect ratios lead to higher flexural strengths. Deformed fibers show the same type of increase at lower concentrations because of their improved bond characteristics [2-4].

Toughness and Ductility: The primary purpose of fiber inclusion to concrete is not to increase strength but to provide toughness and ductility. There are various ways of defining and quantifying toughness of SFRC and these will be explained in detail in Chapter 3. Basically flexural toughness can be defined as the area under the complete load-deflection curve. Fibers with better bond characteristics like fibers with a high aspect ratio, or deformed fibers give higher toughness values when compared with other types of steel fibers [2-4].

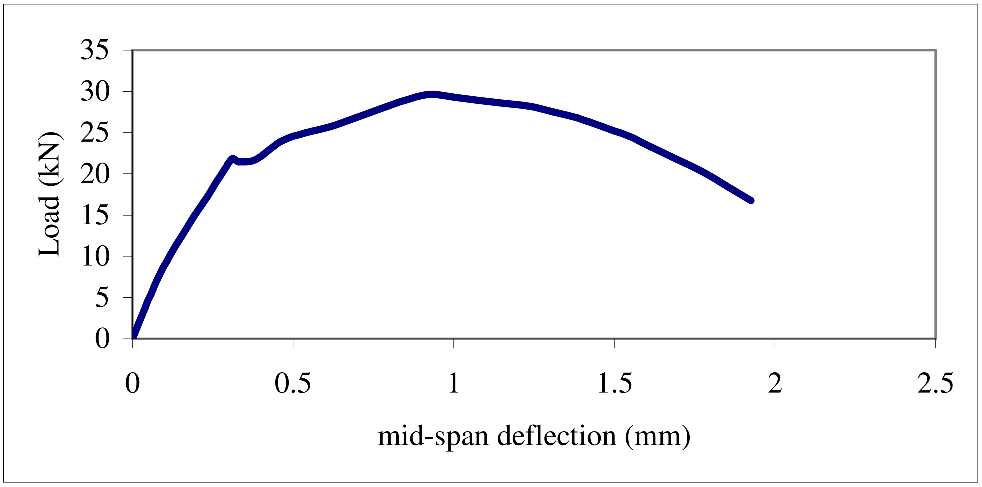

Figure 3 A typical load deflection curve for SFRC under flexural loading [2]

Fatigue Behaviour: Data on fatigue behaviour of SFRC is rare and mixed. Various researchers concluded that steel fiber inclusion does not affect the uniaxial compressive fatigue strength, but improvements in fatigue strength under direct tension can be obtained [2-4]. In general, the fatigue strength increases with increasing steel fiber content.

Creep Behaviour: Steel fiber inclusion does not significantly affect the creep behaviour since the fiber content as a volume percentage is very small when compared with the aggregate content. In addition, since creep does not generally involve micro cracking, steel fiber inclusion is not expected to have a great effect [2-4].

Behaviour under High Strain Rates: Like plain concrete, SFRC is also very strain rate sensitive. Both the compressive and tensile strengths and corresponding ultimate strain values, and therefore fracture energy values are increased as the applied strain rate is increased. Same situation holds true for flexural loading as well. Under impact loading, SFRC exhibits higher strength and fracture energy when compared to static loading [2-4].

2.1.3 Fresh Properties of SFRC

SFRC may be very stiff in fresh state, however may respond very well to vibration. The performance of the hardened concrete is enhanced more, as more fibers with a greater aspect ratio are included in concrete. This is due to the improved fiber-matrix bond. However a high aspect ratio reduces the workability of fresh concrete. When shaken together fibers with aspect ratio greater than 100 tend to interlock in away to form a mat from which it is very difficult to dislodge by vibration alone. As can be seen in Figure 4, aspect ratio has a crucial influence on workability. Movement of fibers may be prevented by coarse aggregates in the matrix, which often are of larger size than the average fiber spacing if the fibers were uniformly distributed. This leads to bunching and greater interaction of fibers between the coarse aggregate particles and the effect becomes more pronounced as the volume and maximum size of the aggregate increase [2-4]. This effect can be observed in Figure 5.

There is limited data on the shrinkage behaviour of SFRC. However steel fibers are reported to reduce the free shrinkage of SFRC by up to 40%. Free shrinkage tests do not reflect the effectiveness of steel fibers in solving the shrinkage origined problems. For restrained shrinkage, steel fibers are reported to reduce the amount of cracks and the crack widths [2-4].

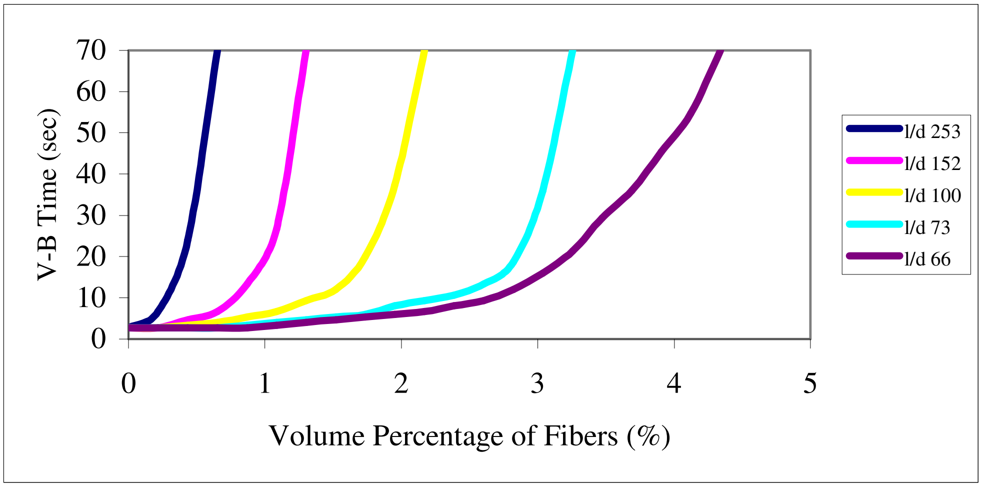

Figure 4. Effect of fiber aspect ratio on V-B time of fiber reinforced mortar [3]

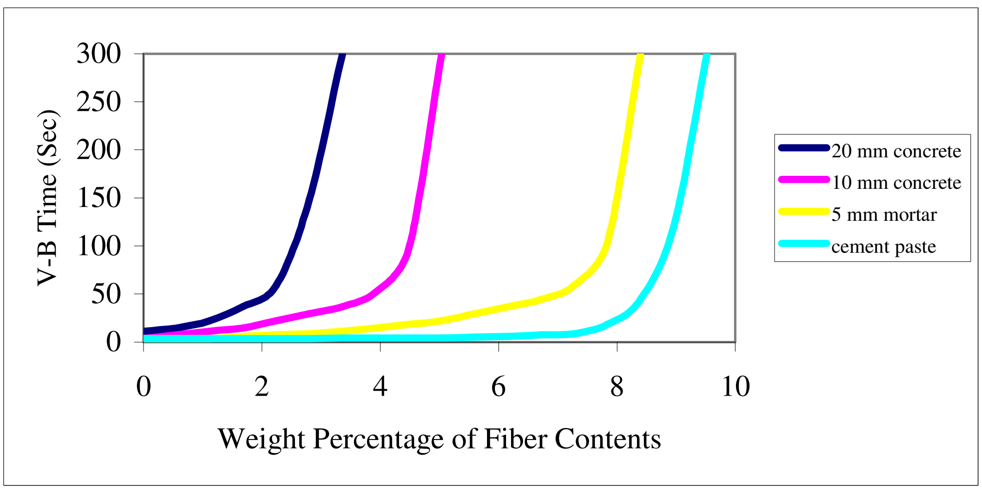

Figure 5. V-B times versus fiber content for matrices with different maximum aggregate size [3]

2.1.4 Durability of SFRC

Durability of SFRC is of equal importance with its mechanical properties. Calcium and other alkaline hydroxides in concrete form a highly alkaline environment with a pH of between 12 and 13. In this environment a thin insoluble oxide film forms on the surface of steel fibers, which provides a passive corrosion protection unless this film is broken. However atmospheric carbon dioxide dissolves in the water in the concrete, and forms a weak carbonic acid, which reduces the pH destroying the protective film on the surface of steel fibers. Because of the loss of protective film on the surface of steel fibers, corrosion may occur if oxygen and water are present. Since the diameter of the fibers are effectively reduced by corrosion, any substantial corrosion of the steel fibers results in considerable decrease in both the strength and the toughness of SFRC. At first glance, steel fibers particularly close to the concrete surface may appear to be susceptible to severe corrosion since the cover is quite small. However various researchers indicated that in practice this is not the case. Even with some corrosion of surface fibers, there was no apparent adverse effect on the structural integrity of concrete and the corrosion did not lead to spalling of concrete surface. Also in submerged SFRC, no durability problems were encountered. In SFRC exposed in the splash zone, corrosion was mainly dependent on the extent of surface cracking. Generally in sound, uncracked components, no adverse effects were observed. Reduction in fiber diameter due to corrosion may result in a change in the mode of failure in both tension and flexure from fiber pull out to fiber fracture making the composite more brittle [2-4].

Steel fibers can increase the freeze-thaw resistance of concrete, provided that fiber matrix bond is sufficiently high; however air entrainment is still necessary to ensure proper freeze-thaw resistance [2-4].

2.1.5 Mix Design Considerations for SFRC

By making certain adjustments to conventional concrete practice, it is possible to produce SFRC. The primary concern is to introduce sufficient amount of uniformly distributed fibers in concrete to achieve improvements in mechanical properties, keeping the concrete workable to permit proper mixing, placing, and finishing.

There are various procedures available for the mix design of SFRC [6]. Typical recommended proportions are shown in Table 2. To provide better workability of concrete, amount of paste in the mixture should be increased. This requires a higher cement content, or moving the ratio of fine aggregates to coarse aggregates upwards. Alternatively pozzolanic admixtures can be used to replace cement. The use of superplasticizers does not provide the ability to incorporate a higher steel fiber content; the cement paste becomes more fluid with the addition of superplasticizers and tends to run out of the fiber clusters as they are about to form. Segregation of fibers occurs approximately at about the same fiber content as for a mix with no superplasticizer addition. Regardless of the mix design, trial mixes should be prepared to ensure workability and strength properties [6].

Table 2. Range of Proportions for Normal Weight SFRC [6]

Property	9.5 mm Maximum Aggregate Size	19mm Maximum Aggregate Size
Cement (kg/m^3)	355-590	300-535
w/c ratio	0.35-0.45	0.40-0.50
Fine/coarse aggregate (%)	45-60	45-55
Entrained Air (%)	4-7	4-6
Fiber Content (%) by volume		
Smooth steel	0.9-1.8	0.8-1.6
Deformed steel	0.4-0.9	0.3-0.8

2.1.6 Mixing, Placing, and Finishing of SFRC

Mixing: Various methods are available for introducing steel fibers to concrete, either with the dry constituents, or to the wet mix. These methods range from charging the aggregate conveyor with fibers sieving directly into the mixer drum, or sieving the fibers and blowing them into the drum. Uniform distribution of fibers throughout the mix is very important. For steel fibers, no special mixing technique is required; however adjustments in the mix proportion, mixing sequence, and rate of addition of constituents may be necessary. Regardless of the employed mixing method, the critical factor in successful addition of steel fibers is that the fibers should reach the mixer individually without clumping and be immediately removed from the point of entry by the mixing action. Besides fiber addition rate should be comparable with the mixing speed. Primary problem encountered in mixing of SFRC is formation of fiber balls. The most common causes of wet fiber balling are over mixing and using a mixture with too much aggregate content, typically more than 55% of the total combined aggregate by absolute volume. Most fiber balling occurs somewhere before the fibers are added to the mixture. This means that, if the fiber balls form, it is because fibers were added in such a way that they fell on each other and stacked up [6].

Placing: Generally SFRC with a proper cement content and water-cement ratio seems to be relatively stiff and unworkable, compared to conventional plain concrete. Water-cement ratios for SFRC mixtures should be carefully controlled, as it is very easy to add unnecessary water to the mixture causing the loss of many benefits obtained by steel fiber inclusion without providing any improvement in workability. SFRC in the fresh state tends to hang together and resist movement during compaction. However SFRC responds well to vibration. Internal vibration should be applied with care to avoid fiber free zones, which is formed by scattering of fibers leaving a zone unreinforced. Pumping SFRC is a common method of placement [6].

Finishing: SFRC can be finished by using conventional methods; however certain refinements in techniques and workmanship are required. For flat-formed surfaces, normally no special attention is needed. If chamfers or rounds have been provided at the edges and in corners, the ends of fibers will not protrude at these points when forms are removed. To provide added compaction and bury surface fibers, open slab surfaces should first be struck off with a vibrating screed. Magnesium floats can be used to establish a surface and close up any tears or open areas, which are caused by the screed. Throughout all finishing operations, care must be taken not to overwork the surface. Overworking may bring excessive fines to the surface [6].

2.1.7 Practical Applications of SFRC

The uses of SFRC are so varied, and making a categorization is difficult. Their range is shown in Figure 6. Applications include stairways, pavements, airport pavements, slabs, tunnel linings, shotcrete, refractory elements, and various types of concrete repair. The application areas of SFRC are expanding through the accumulation of research conducted on this topic, but unfortunately approximately 1% of steel fiber addition to concrete almost doubles the cost, so the use of SFRC is limited to special applications.

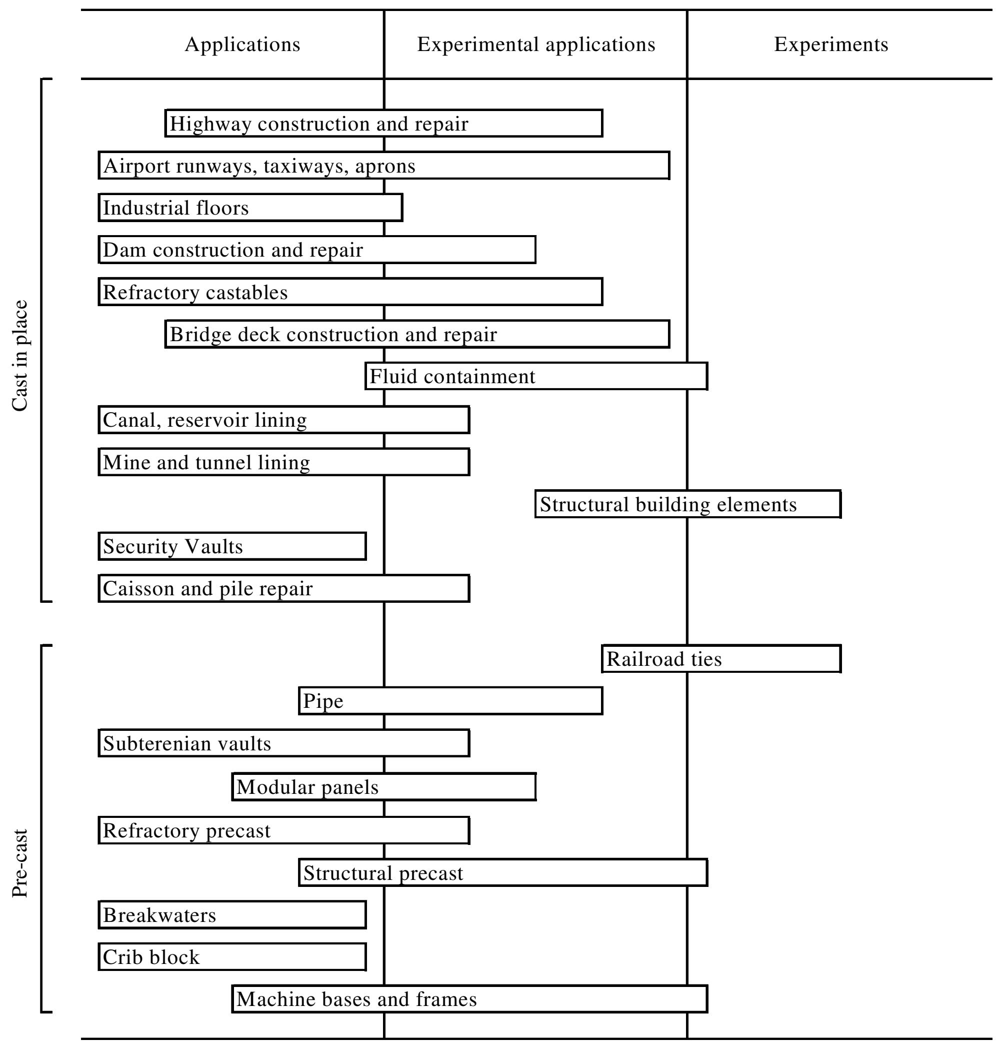

Figure 6. Typical applications of SFRC [7]

2.2 Polypropylene Fiber Reinforced Concrete (PPFRC)

2.2.1 General

Synthetic fibers have attracted more attention for reinforcing cementitious materials in the recent years. In this part emphasis is given on polypropylene fibers, as they were used throughout the experimental program. Polypropylene fibers were suggested as an admixture to concrete in 1965 for construction of blast-resistant buildings for the U.S Corps of Engineers [3]. Results of this research work showed that polypropylene fibers could be practical for reinforcing concrete, since polypropylene is cheap, abundantly available, and possess a consistent quality. Considerable improvements in strain capacity, toughness, impact resistance, and crack control of concrete can be obtained through the use of polypropylene fibers.

Polypropylene fibers are manufactured in various shapes and different properties. The polypropylene fibers are made of high molecular weight isotactic, a type of polymer chain configuration where in all side groups are positioned on the same side of the molecule, polypropylene. The macromolecule has a sterically regular atomic arrangement, thus polypropylene fibers can be produced in a crystalline form, and then processed by stretching to achieve a high degree of orientation, which is necessary to obtain good fiber properties. The polypropylene fibers can be produced in three different geometries, monofilaments, film, or extruded tape. The polypropylene film consists of amorphous material and crystalline micro fibrils. However these films are weak in the lateral direction. Thus using specially designed machines, splits are induced in the longitudinal direction and fibrillation is facilitated. It is used at present as discontinuous fibrillated material for the production of FRC by the mixing method, or as a continuous mat for production of thin sheet elements [2-4]. The modulus of elasticity of both the monofilament and the fibrillated polypropylene is usually about 3.5 GPa, and the tensile strength is about 560 to 770 MPa. The geometry of fibrillated polypropylene is difficult to quantify. It can be described in terms of film thickness and the width of the individual filaments, or alternatively by measuring the specific surface area by adsorption techniques.

Fiber denier, a term commonly used in textile industry, which is the weight in grams of 9000 m. of yarn can also be used for this purpose.

Figure 7. Fibrillated polypropylene fibers [8]

Figure 8. Dispersed polypropylene fibers in fresh concrete [8]

2.2.2 Mechanical Properties of PPFRC

Conventionally polypropylene fibers are used in concrete at relatively low contents, 0.1 to 0.3% by volume, as a secondary reinforcement to control and reduce the plastic shrinkage cracking of concrete. Polypropylene is hydrophobic due to its chemical structure, which leads to reduced bonding with the cement, and negatively affecting its dispersion in the matrix. In addition polypropylene has a relatively higher Poisson ratio. Under tensile loading, the cross section of polypropylene fibers reduce rapidly, and fiber surface is debonded from the matrix. On the other hand, dynamic modulus of elasticity of polypropylene is much higher when compared with static values. As a result, under dynamic loading PPFRC can perform with success [2-4].

Compressive and Tensile Strength: The compressive strength and tensile strength of concrete reinforced with polypropylene fibers are not significantly affected, if the fiber inclusion is limited at very low volume percentages. However at higher fiber contents strength is adversely affected. This is practically because a considerable part of the matrix is replaced with a weaker material. In addition, insufficient compaction due to reduced slump may be the reason of the decline in strength values. Polypropylene fibers may increase flexural tensile strength, due to their ability to enhance the load bearing capacity in the post crack zone, but this increase is not that significant [2-4].

Toughness and Ductility: Polypropylene fibers enhance the energy absorption capacity rather than static strength values. The effect of polypropylene fiber inclusion on toughness of concrete can be observed in Figure 8. Toughness enhancement induced by polypropylene fiber inclusion increases as the fiber content increases [2-4].

Impact Behaviour: Dynamic modulus of elasticity of polypropylene fibers is higher when compared with static values. Thus PPFRC can perform with success under dynamic loading conditions. Impact resistance of PPFRC is of great interest. According to Hannant, polypropylene fibers can absorb as much energy as some steel fibers for the same fiber content when tested using a modified Charpy machine [3]. An argument in describing such a behaviour may be the effect of relatively softer polypropylene fibers on the propagation of shock waves in concrete.

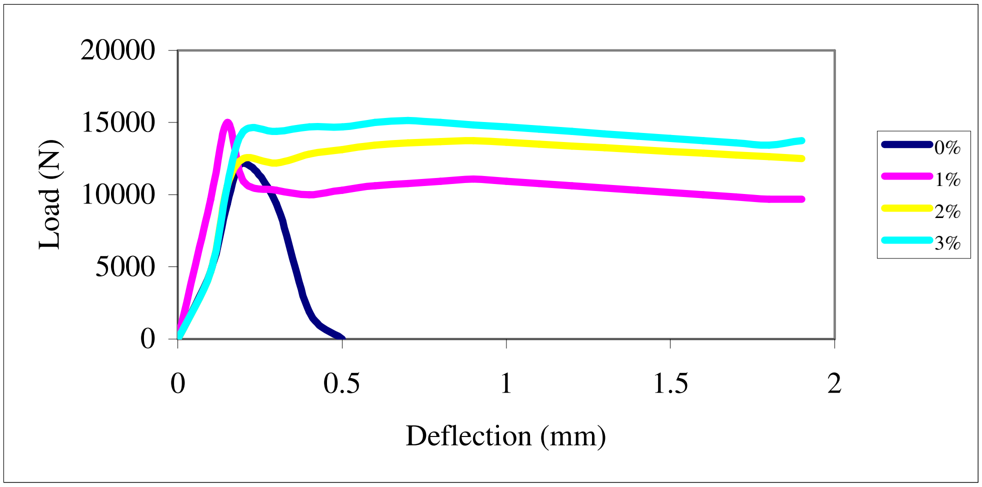

Figure 9. Effect of the content of rectangular polypropylene fibers on the load-deflection curve under flexural loading [2]

2.2.2 Fresh Properties of PPFRC

Fibrillated fibers in concrete tend to separate into individual fibers during the mixing process. The dispersion of such individual fibers has a crucial effect on the workability of concrete. Consistency is reduced with increasing fiber contents, and this reduction is even greater with longer fibers. Effect of the content and length of fibrillated polypropylene fibers on the consistency of the concrete can be seen in Figure 10. Reduction in consistency may not be an indication of reduction in workability. Under dynamic conditions, PPFRC can still show sufficient workability and can be compacted without excessive vibration [2-4].

Although modulus of elasticity of polypropylene fibers is lower than that of concrete in the hardened state, it is higher in the plastic state of concrete. Thus polypropylene fibers can be effective in improving the cracking characteristics of the fresh concrete. Free shrinkage and restrained shrinkage tests conducted in laboratory conditions show that addition of polypropylene fibers reduce cracking and crack widths and this effect is more pronounced with increasing fiber contents. However there is a lack of field-originated data on this topic [2-4].

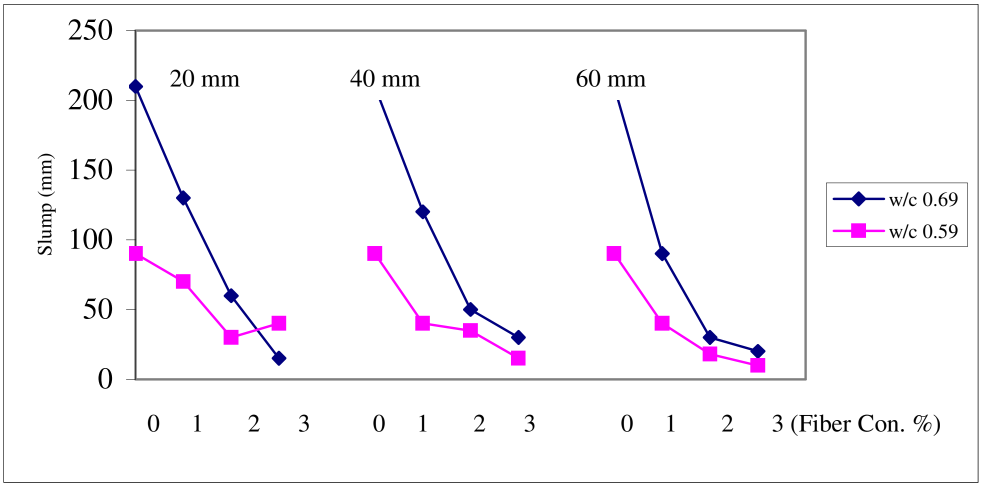

Figure 10. Effect of the content and length of rectangular polypropylene fibers on the slump of concrete [2]

2.2.4 Durability of PPFRC

Generally it is assumed there are no durability problems associated with the use of polypropylene fibers, as they are highly alkali resistant. However some problems may arise due to oxidation or softening at elevated temperatures. Polypropylene melts at about 165 ^{o}C , thus PPFRC can withstand elevated temperatures only for a short period of time. Since primary purpose of polypropylene fiber inclusion to concrete is to inhibit cracks during the early handling stage, durability associated problems are hardly encountered [2-4].

2.2.5 Mix Design Considerations for PPFRC

Mix design for PPFRC should take into account the properties of polypropylene fiber that best suits the aggregate, the required workability, and the equipment to be used in making the product. For thin sheet products, more flexible polypropylene fibers should be accommodated as stiffer ones may protrude after demolding, whereas use of stiffer polypropylene fibers would be more beneficial in applications where toughness is of concern [2-4].

2.2.6 Practical Applications of PPFRC

Polypropylene fibers are frequently used at small contents, and the main objective in polypropylene fiber inclusion is to provide a secondary reinforcement in order to control cracking due to effects like temperature and moisture changes. In most of these applications fiber content is below the critical fiber volume, and fibers are mixed with the concrete using conventional equipment. Polypropylene fibers are mainly used in shotcreting, in blast-resistant structures, and in piling operations [2-4].

2.3 Hybrid Fiber Reinforced Concrete (HFRC)

2.3.1 General

A composite can be termed as hybrid, if two or more types of fibers are rationally combined in a common matrix to produce a composite that derives benefits from each of the individual fibers and exhibits a synergetic response. According to Benthur and Mindess the advantages of hybrid fiber systems can be listed as follows [2];

1- To provide a system in which one type of fiber, which is stronger and stiffer, improves the first crack stress and the ultimate strength, and the second type of fiber, which is more flexible, and ductile leads to improved toughness and strain in the post-cracking zone.

2- To provide a hybrid reinforcement in which one type of fiber is smaller, so that it bridges the micro cracks of which growth can be controlled. This leads to a higher tensile strength of the composite. The second type of fiber is larger, so that it arrests the propagating macro cracks and can substantially improve the toughness of the composite.

3- To provide a hybrid reinforcement, in which the durability of fiber types is different. The presence of the durable fiber can increase the strength and/or toughness relation after age while the other type is to guarantee the short-term performance during transportation and installation of the composite elements.

In the present approach the strengthening and toughening mechanisms for cement-based composites are viewed on two different scales. To strengthen the matrix, the specific fiber spacing must be decreased in order to reduce the allowable flaw size. This may be achieved through the use of short discrete fibers. These fibers can provide bridging of micro cracks before they reach the critical flaw size. To provide the toughening component, fibers of high ultimate strain capacity are required so that they can bridge the macro cracks in the matrix.

The concept of hybridization was developed in conjunction with asbestos replacement, where it was difficult to produce synthetic fibers that would provide simultaneously a reinforcing effect and the filtering and solid retention characteristics, which are needed in the Hatschek process. The combination of different types of fibers to optimize the performance in the hardened state, with respect to strength and toughness, has been studied by various researchers, using asbestos, carbon, and steel to achieve strength, and polypropylene and polyethylene to improve toughness [2].

2.3.2 Literature Review

In their work "Development of Hybrid Polypropylene-Steel Fiber Reinforced Concrete" Qian and Stroeven measured the compressive strength, split tensile strength, and modulus of rupture of different mixes incorporating various volume fractions of steel and polypropylene fibers [9].

A common concrete matrix was used in all mixes, with a water cement ratio of 0.40 and cement content of 400 kg/m^3. Properties of the fibers are shown in Table 3. Volume fractions of fibers and obtained test results are presented in Tables 4 and 5 respectively.

Table 3. Types and Properties of Fibers Used [9]

Fiber Type	Designation	l (mm)	d (mm)
Monofilament PP	PP	12	0.018
Hooked Steel	SF1	40	0.300
Hooked Steel	SF2	30	0.300
High-Strength Steel	SF3	6	0.1

Table 4. Fiber Contents [9]

Mix No:	Fiber Content (%)				
	PP	SF1	SF2	SF3	Total
1	0.15	0.00	0.00	0.00	0.15
2	0.15	0.20	0.20	0.20	0.75
3	0.15	0.40	0.40	0.40	1.35
4	0.30	0.00	0.20	0.40	0.90
5	0.30	0.20	0.40	0.00	0.90
6	0.30	0.40	0.00	0.20	0.90
7	0.00	0.00	0.40	0.20	0.60
8	0.00	0.20	0.00	0.40	0.60
9	0.00	0.40	0.20	0.00	0.60

Table 5. Obtained Test Results [9]

Mix No:	f_{comp} 1 day (MPa)	f_{comp} 28 days (MPa)	MOR (MPa)	f_{split} (MPa)
1	43.60	71.20	8.76	5.28
2	44.50	73.60	9.53	6.20
3	47.40	82.80	12.66	8.01
4	48.60	73.00	9.37	6.06
5	36.10	67.90	8.49	6.34
6	43.00	72.20	9.98	6.16
7	34.40	5880	8.47	4.93
8	46.60	72.80	9.12	5.43
9	41.00	61.40	9.04	5.86

Results of this study indicate that due to their crack bridging capacity, even low modulus fibers may increase the strength of the matrix. However an excess of fibers leads to additional defects during the production stage, because optimum packing stage of particles and fibers can not be achieved. Thus strength may be reduced. Steel fibers of various sizes contributed to different mechanical properties. Incorporation of relatively smaller fibers had a considerable effect on the compressive strength, but the splitting tensile strength was not affected significantly. A larger type fiber gave rise to opposite results.

In their work "Mechanical Properties of. Hybrid Fiber Reinforced Concrete at Low Fiber Volume Fraction", Yao, Li, and Wu studied the effects of combined use of carbon, steel, and polypropylene fibers at relatively low volume fractions on the mechanical properties of concrete [10]. Compressive strength, splitting tensile strength, and flexural tensile strength tests were conducted on various mixes. Flexural toughness was also measured in accordance with ASTM C 1018.

A common concrete matrix was used in all mixes. Properties of the fibers are presented in Table 6, fiber contents of mixes and obtained test results are presented in Table 7.

Table 6. Types and properties of fibers used [10]

Fiber Type	Length (mm)	Diameter (mm)	Density (g/cm^3)	Elongation At Break %	Young's Modulus (GPa)	Tensile Strength (MPa)
Carbon	5	7	1.60	240	1.4	2500
Steel	30	500	7.80	200	3.2	1500
Polypropylene (PP)	15	100	0.90	8	8.1	800

Various conclusions can be drawn from this study. Carbon fibers proved to be very effective in increasing the compressive, splitting tensile, and flexural tensile strengths. All fibers contributed to the toughness up to a certain extent. Steel-carbon hybrid reinforcement gave the optimum results. Steel-carbon hybrid composite demonstrated an almost elastic-plastic behaviour.

Table 7. Fiber Contents as Volume Percentage and Obtained Test Results [10]

	Fiber Volume Fraction (%)			f_{comp}	f_{split}	MOR	Toughness Index		
Mix No:	Carbon	Steel	PP	(MPa)	(MPa)	(MPa)	I_5	I_{10}	I_{30}
1	0.0	0.0	0.0	44.3	4.36	5.5	3.16	5.89	9.78
2	0.5	0.0	0.0	50.7	5.21	6.0	4.08	7.48	14.82
3	0.0	0.5	0.0	47.8	4.80	6.9	4.15	7.90	22.80
4	0.0	0.0	0.5	44.5	4.14	5.7	4.04	6.26	16.76
5	0.2	0.3	0.0	58.2	5.95	7.4	4.23	8.14	29.32
6	0.2	0.0	0.3	57.8	5.72	7.3	3.89	6.20	15.90
7	0.0	0.2	0.3	45.3	4.46	5.8	3.40	6.31	18.44

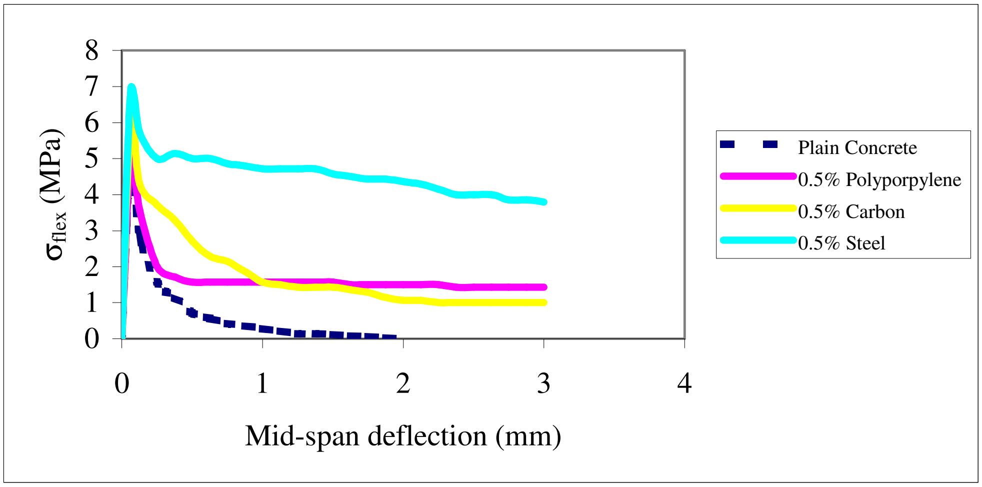

Figure 11. Flexural stress-deflection curves for simple FRC beams [10]

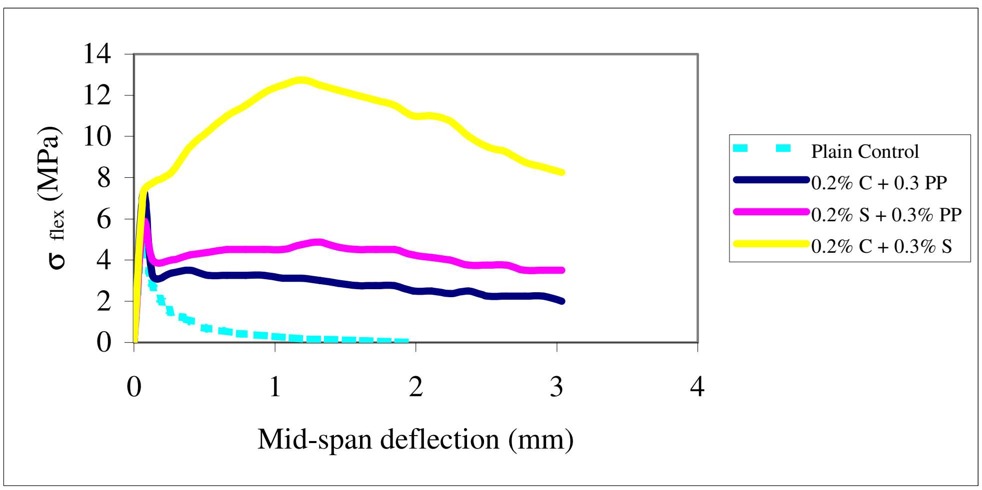

Figure 12. Flexural stress-deflection curves for HFRC beams [10]

In their study "Impact Resistance of Fiber Reinforced Concrete at Subnormal Temperatures" Banthia, Yan, and Sakai investigated the temperature and strain-rate sensitivity of FRC under impact loading [11]. A pitch based carbon fiber 3mm in length and 18µm in diameter, and a steel fiber 3mm in length and 25x5µm in cross section were used as micro fiber, whereas a crimped steel fiber 25mm in length and 2mm in width with a crescent cross section was used as macro fiber. Table 8 shows the fiber contents of the five mortar and four concrete mixes in this study.

From each of the mixes, six beam specimens were cast and impact resistance tests were conducted on these beam specimens. Impact resistance test machine used in this study was an instrumented drop-weight type with a 10 kg hammer, which can be dropped from heights of up to 1.45m. Hammer can fall freely on the beam specimen. The contact end of the hammer is instrumented with a bolt-type load cell, which can read the contact load-time pulse between the hammer and the specimen. For measurement of specimen displacements a laser based, non-contact, linear photoelectric sensor was used. Results obtained from this study are presented in Table 9.

Table 8. Investigated Composites [11]

Designation	Matrix	Micro Fiber Fiber Content (%)		Macro Fiber Fiber Content (%)
		Carbon	Steel	Steel
M	Mortar	0	0	0
C	Concrete	0	0	0
MC1	Mortar	1	0	0
MC2	Mortar	2	0	0
MS1	Mortar	0	1	0
MS2	Mortar	0	2	0
CF0.5	Concrete	0	0	1
CF1C1 (hybrid)	Concrete	1	0	1
CF1S1 (hybrid)	Concrete	0	1	1

Table 9. Impact Resistance of Various Composites [11]

Designation	Drop Height (m)	Fracture Energy (J)	
		Normal Temperature	Low Temperature
M	0.3	0.18	0.21
	0.6	0.22	0.24
C	0.3	0.27	0.25
	0.6	0.28	0.25
MC1	0.3	0.29	0.26
	0.6	0.30	0.28
MC2	0.3	0.32	0.29
	0.6	0.33	0.32
MS1	0.3	0.36	0.33
	0.6	0.37	0.35
MS2	0.3	0.38	0.38
	0.6	0.42	0.39
CF0.5	0.3	0.45	0.40
	0.6	0.47	0.43
CF1	0.3	0.49	0.45
	0.6	0.52	0.48
CF1C1	0.3	0.56	0.49
	0.6	0.63	0.51
CF1S1	0.3	0.70	0.58
	0.6	0.87	0.66

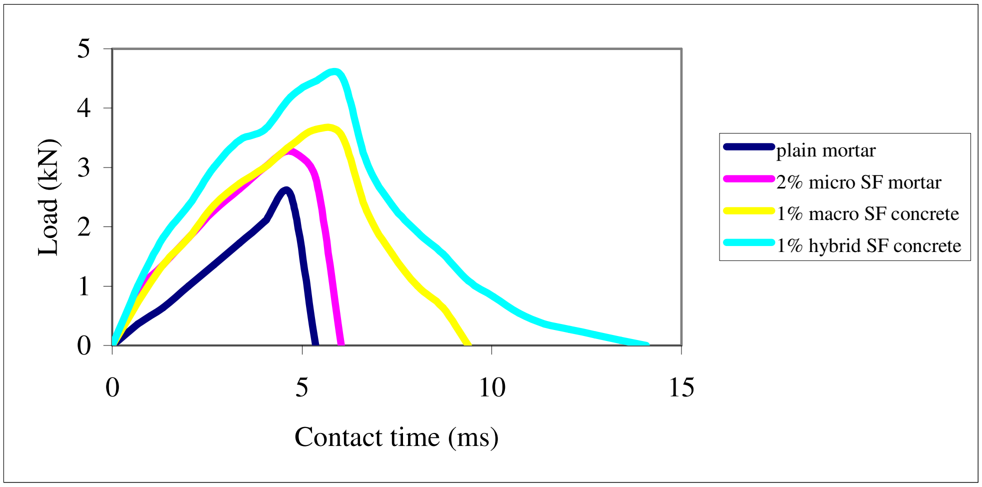

Figure 13. Recorded contact load-time pulses for plain and fiber reinforced concrete beams [11]

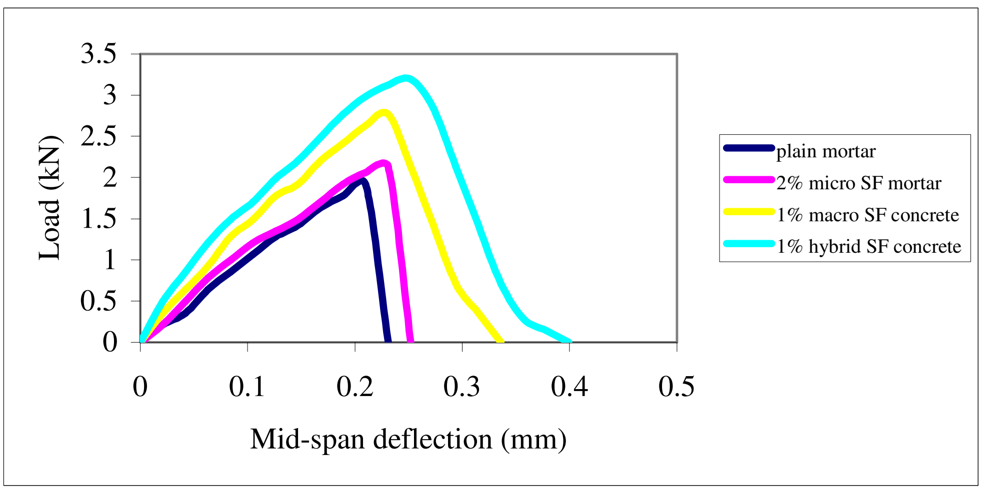

Figure 14. Typical load-deflection curves for plain and fiber reinforced specimens [11]

Following conclusions can be drawn from this study. Lower elastic modulus of the pitch-based carbon fiber, its brittle structure, and poor bonding capability may be the reason of unfavorable performance of carbon fiber reinforced composites. Macro steel fibers prove to be efficient under impact loading due to their capacity to span large crack openings. Micro fiber reinforcement provided an increased strength, however this generally results in a more brittle behaviour in the post crack zone. The synergy observed between macro and micro fibers may be attributed to the improved bond-slip characteristics between the macro fibers and the surrounding matrix, which is already reinforced with micro fibers.

CHAPTER 3

TEST METHODS FOR MEASURING TOUGHNESS AND IMPACT RESISTANCE OF FIBER REINFORCED CONCRETE

3.1 General

Measurement of properties of FRC is very important for practice as well as for research efforts. Some of these properties are largely matrix dependent and can be measured using methods originally developed for conventional concrete. On the other hand some properties of FRC, like crack control and impact resistance, are quite different from those of conventional concrete and the effects of fiber inclusion are observed primarily on these properties. Thus test methods specifically developed for FRC should be used to evaluate these properties. Some of these test methods are well established and are in the form of standard tests while some are still in development. This chapter gives an overview of the common test methods used to evaluate the toughness and impact resistance of FRC, however detailed information on testing procedures is not provided as it can be found in the references cited.

3.2 Toughness Measurement for FRC

Toughness of FRC can be termed as the energy absorption capacity, which is conventionally characterized by the area under the load-deflection curve. Although toughness tests can be carried out under different loading conditions like tensile, compressive, and torsional loading, most of the toughness measurements are performed on beams in flexure using four point bending arrangement.

In order to obtain the complete load-deflection curves, the testing system must be equipped with strain or deflection measurement gauges. Obtaining a reliable curve in the post crack zone is very important, thus a closed loop servo controlled rigid testing machine should be used [2].

Various attempts have been made to quantify load-deflection curves in terms of a parameter, which would be useful for comparison between different fibers and fiber contents. An advantageous approach for quantification of load-deflection curves is using a unitless value termed as the toughness index. The practical application of this approach began with the introduction of ACI 544 toughness index, which is defined as the ratio of the amount of energy required to deflect a FRC beam by a prescribed amount to the energy required to bring the beam to the point of first crack. Similiar notions were used in the development of the ASTM C 1018 standard [12-13]. Independent toughness indices were proposed by Barr and Liu, and Barr and Hasso [14]. These test methods give relative toughness values. On the other hand another commonly used method was developed by Japan Society of Civil Engineers, which yields absolute toughness [15]. The toughness factor suggested in JSCE SF-4 standard is an indicator of the average flexural strength. All these test methods are based on evaluation of the recorded load versus mid-span deflection curve for a four point bending test.

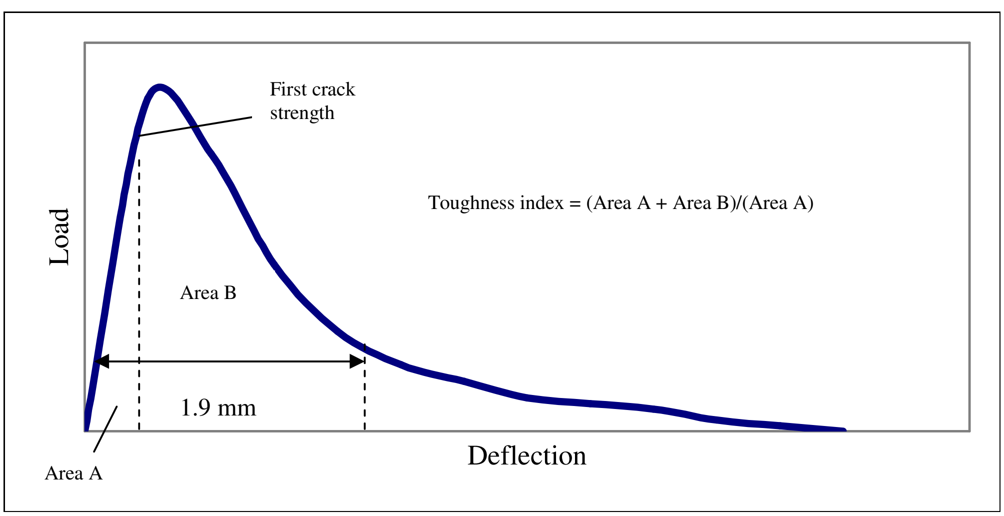

Figure 15. ACI Committee 544 toughness index [12]

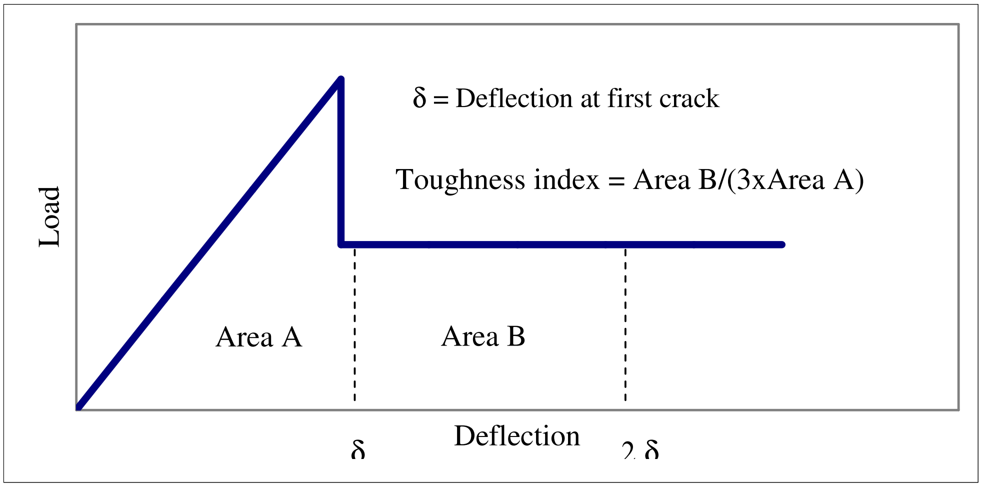

Figure 16. B/3A toughness index proposed by Barr and Hasso [14]

3.2.1 ASTM C 1018 Standard Test Method

The ASTM C 1018 standard test method is based on determining the amount of energy required first to deflect and crack a FRC beam, and then to further deflect the beam out to selected multiples of the first crack deflection [13]. Toughness indices I_5, I_{10}, I_{20}, I_N etc. are then calculated by taking the ratios of the energy absorbed to a certain multiple of first crack deflection and the energy consumed up to the occurrence of the first crack.

The indices give the relative deviation from the response of a perfectly elastic-plastic material. For such material the indices would be equal to the indices themselves.

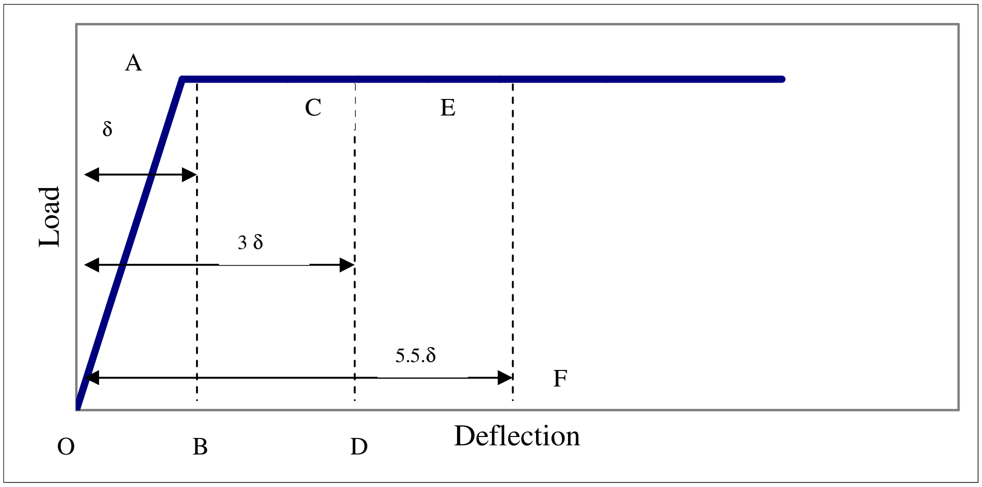

Figure 17. Elastic-brittle and elastic-plastic load-deflection curves according to ASTM C 1018 Standard [13]

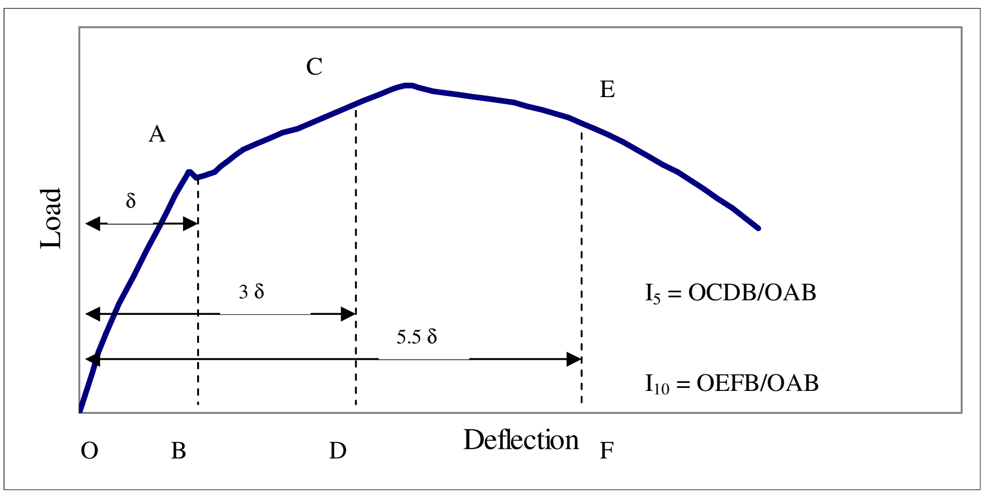

Figure 18. Flexural toughness values according to ASTM C 1018 Standard [13]

Although ASTM C 1018 is a widely accepted standard test method, there are some problems related to the application of this method like effect of extraneous deformations, decision of location of the first crack point, and stability problems [2,4,14].

Evaluating the toughness indices without excluding the extraneous deformations like support settlements, leads to erroneous results. This is due to the fact that all indices are dependent on the first crack deflection. In order to measure correct deflections some modifications are necessary. The use of so called yoke, which is a frame attached to the beam allowing direct measurement of the net central deflection of the beam, or the use of a top mounted deflection measurement system are possible solutions to this problem [2,4,14].

In ASTM C 1018 the first crack point is defined as the point at which the curvature first increases sharply and then slope of the curve exhibits a definite change. This is a subjective definition and often the load-deflection curves lack a distinct point as mentioned in the definition due to micro cracking and subsequent multiple cracks before the peak load is reached. There is a need for an objective definition of first crack so that determination of first crack point is not affected by whom the test is performed and evaluated [2,4,14].

If the machine is not sufficiently stiff, the elastic energy stored in the system is released after the peak load and this causes a sudden jump in the curve. Most of these stability problems are reduced if a closed loop system is used. Unfortunately most of the laboratories lack such sophisticated instruments [2,4,14].

3.2.2 JSCE SF-4 Standard Test Method

In this method the area under the load deflection curve up to a deflection of (span/150) is obtained and results obtained from this test method yield an absolute toughness value. A flexural toughness factor is calculated which has a unit of stress. This factor can be considered as the post crack residual strength of the material when loaded to a deflection of (span/150) [14-15].

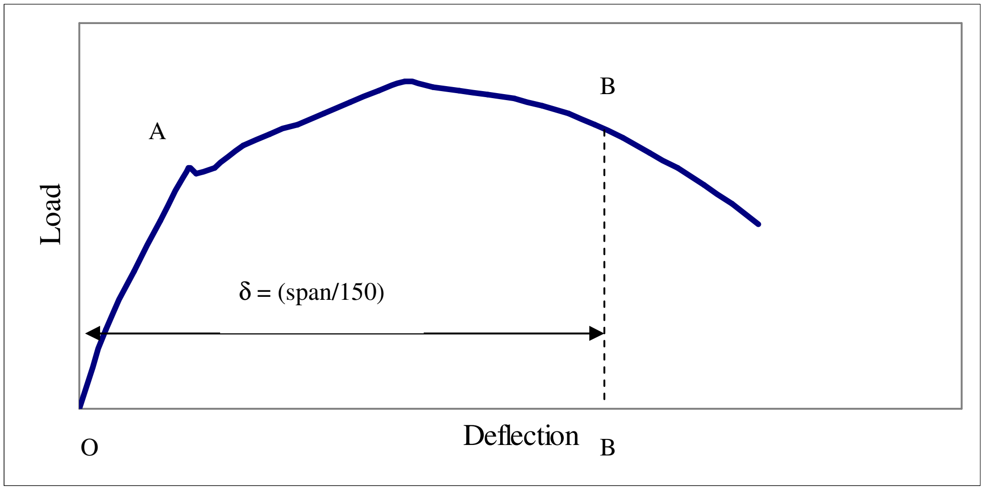

Figure 19. Flexural toughness values according to JSCE SF-4 Standard [15]

Determination of first crack point is not a concern in this test method. In addition stability problems encountered right after the first crack do not affect the obtained results significantly as beams are deflected too far out from the first crack point. However results of this test method are highly dependent on specimen size and geometry. The (span/150) deflection chosen in this test method is often criticized for being much greater than acceptable serviceability limits. This test method does not distinguish between the pre and post crack behaviour, which may be very important in some applications [14-15].

3.3 Impact Resistance Measurement for FRC

FRC can perform very well under dynamic loading. Thus FRC is a suitable material for applications where dynamic loading conditions such as impact loading are present. Impact resistance of FRC can be measured by using a number of different test methods, which can be broadly listed as follows [4]:

- Repeated drop weight test
- Instrumented impact test
- Projectile impact test

The resistance of the material is measured using one of the following criteria [4]:

- The number of blows in a repeated impact test to achieve a specified distress level
- Energy needed to fracture the specimen
- The size of damage, measured using crater size, perforation, or scab

Results obtained from these test methods can be used to compare different material compositions or to design a structural system that should withstand certain kinds of impact loading.

3.3.1 Repeated Drop Weight Test

This is the simplest test for evaluating impact resistance proposed by ACI Committee 544. This test method does not yield quantitative results; rather the test is designed to obtain the relative performance of plain concrete and FRC containing different types and amounts of fibers. A disc 150 mm in diameter, 64 mm in thickness is subjected to repeated blows by dropping a 4.54 kg hammer from a height of 460 mm. The load is transferred from the hammer to the specimen through a steel ball 64 mm in diameter. The number of blows to cause the first visible crack on the surface of the specimen is recorded as the first crack strength. Loading is continued until the specimen failure that is the specimen opens up so that it touches three of the four positioning lugs. Number of blows to cause the failure of the specimen is recorded as the ultimate strength. Although this test method is very simple and useful for comparison purposes, it yields highly variable results and has poor reproducibility [12].

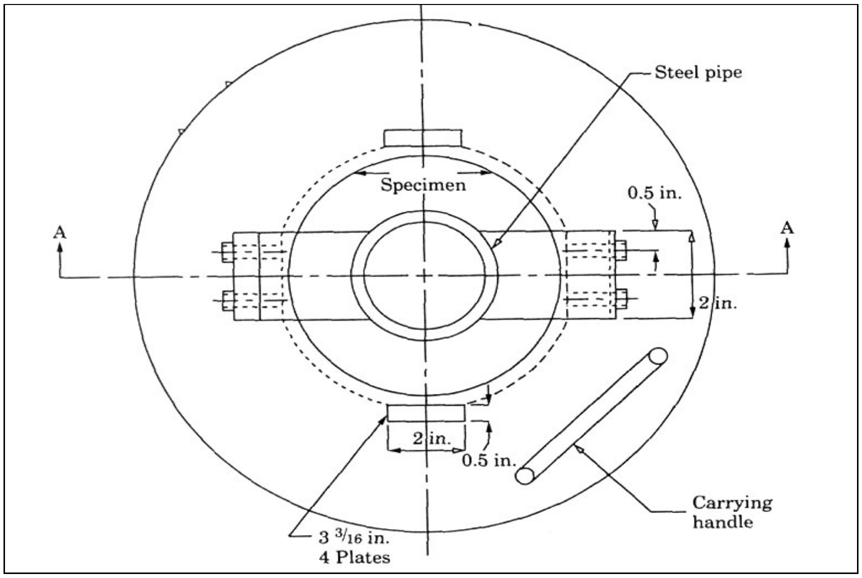

Figure 20. Plan view of test equipment for measuring impact strength with repeated drop weights. Section A-A is shown in Figure 21 [4]

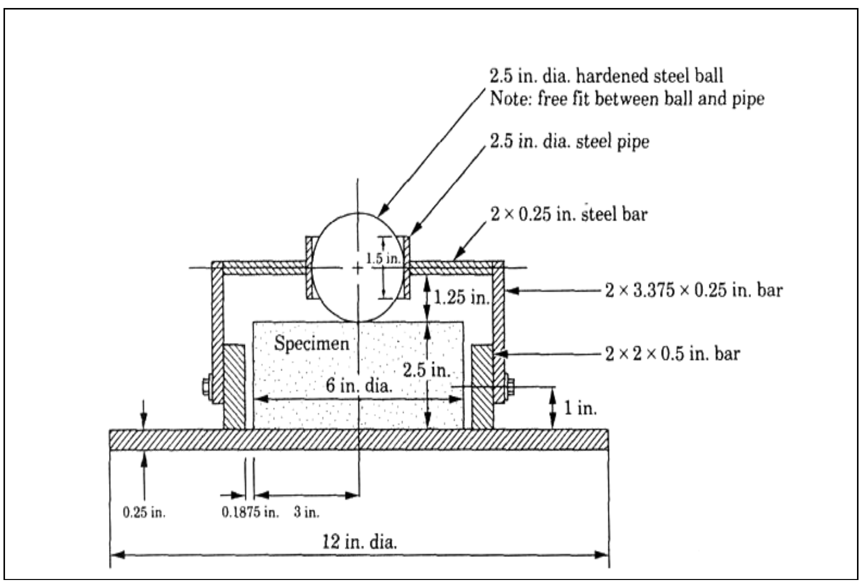

Figure 21. Section through test equipment for measuring impact strength shown in Figure 20 [4]

3.3.2 Instrumented Impact Test Methods

Additional information about the behaviour of FRC under impact loading can be obtained by performing instrumented impact tests. In this manner load-deflection histories and magnitude of the ultimate strength can be determined. However these test methods require the use of highly sophisticated measuring devices, which are rarely available.

Generally two types of systems are employed. In the instrumented drop weight system a heavy weight, which is attached to an instrumented tup, is dropped to cause the impact. The weight and the height of the fall provide for the adjustment needed in terms of energy capacity and impact velocity. In the Charpy system the pendulum weight and the height of the lift are used to obtain the required energy and impact velocity. Conventional setups can only be used to test small specimens because of the limitation on the maximum energy that can be attained in these machines.

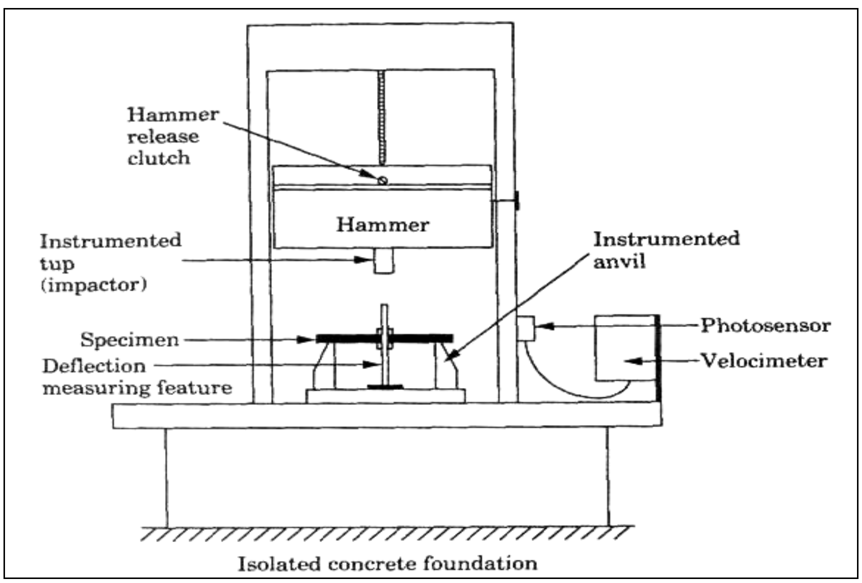

Figure 22. Block diagram of the general layout of the instrumented drop weight system [4]

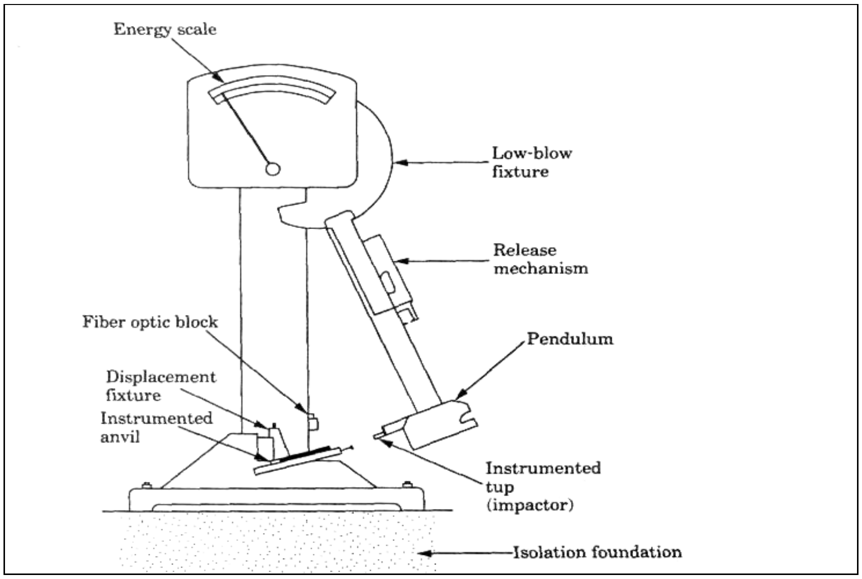

Figure 23. Block diagram of the general layout of the modified instrumented Charpy system [4].

3.3.3 High Velocity Projectile Impact Testing

Concrete structures can be subjected to impact of high velocity projectiles due to tornado-born missiles, explosion fragments etc. Quantification of the effects of fiber inclusion to concrete on resistance to high velocity impact is a very complex task. There are no standards developed for this purpose and most of the research conducted on this topic focuses on obtaining empirical relationships. Penetration depth, crater diameter, amount of spalling, and scabbing depth are measured after the impact of the projectile.

Hopkinson's split bar technique can be considered in this category. It consists of two elastic bars between which the specimen is placed. An incident stress pulse is generated in the first elastic bar and the pulse transmitted through the specimen is measured in the second elastic bar. This technique can be used for uniaxial compressive or tensile loading.

CHAPTER 4

EXPERIMENTAL STUDY

4.1 Experimental Program

Aim of this study was to produce HFRC and then to characterize its properties, especially the mechanical properties in the hardened state. Four different types of fibers were used in combination, two of which were macro steel fibers, and the other two were micro fibers. For this purpose nine mixes, one plain control mix and eight fiber reinforced mixes were prepared. In six of the fiber-reinforced mixes, a hybrid form of reinforcement was used. A common concrete matrix with a w/c of 0.50 was used in all mixes.

The volume percentage of fibers was kept constant at 1.5%; this value was chosen after a careful examination of available literature considering the capability of compaction equipment in the laboratory. Macro steel fibers constituted two thirds of the total fiber content whereas the remaining part was composed of micro fibers in hybrid fiber reinforced mixes.

Slump test was performed for each mix in the fresh state. Compressive strength, flexural tensile strength, flexural toughness, and impact resistance tests were carried out for each mix in the hardened state.

4.2 Materials

12 mm maximum size crushed limestone and 5 mm maximum size crushed sand from the same local source were used as coarse and fine aggregate respectively. Sieve analysis results and other characteristics of the aggregate are presented in Table 10.

The cement used in all mixes was normal Portland cement, which corresponds to PÇ 42.5 in accordance with TS 19. Chemical composition, and other characteristics of the cement, as provided by the manufacturer, are presented in Table 11.

Four different types of fibers were used in combination, keeping the total volume percentage of fibers at 1.5%. Steel fibers Dramix RC 80/60 and Dramix ZP 305 were used as macro fibers. Steel fiber OL 6/16 and polypropylene fiber Duomix 20 were used as micro fibers. Properties of the fibers are presented in Table 12.

To obtain sufficient consistency in fiber reinforced mixes a novel polycarboxylic type superplasticizer with the commercial name Smart Flow was used in all mixes. The chemical and physical properties of the superplasticizer used are given Table 13.

Table 10. Properties of The Aggregate

	Passing (%)	
Sieve (mm)	Coarse	Fine
19.1	100.0%	100.0%
12.7	100.0%	100.0%
9.5	82.3%	100.0%
4.76	17.6%	97.9%
2.38		70.2%
1.19		48.1%
0.59		33.4%
0.297		23.5%
0.149		17.0%
Dry S.G	2.63	2.50
S.S.D S.G	2.66	2.57
Apparent S.G	2.69	2.70
Absorption	0.8%	2.9%

Table 11. Chemical, Physical, and Mechanical Properties of The Cement

Chemical Properties	(%)
Insoluble Residue	0.38
SiO_2	18.85
Al_2O_3	5.58
Fe_2O_3	2.5
CaO	63.27
Free CaO	0.88
MgO	2.82
SO_3	2.93
Loss on ignition	2.44
Physical and mechanical properties	
Specific Gravity (g/cm^3)	3.11
Fineness (Blaine) (cm^2/g)	3020
Initial setting time (min)	188
Final setting time (min)	240
Comp. Strength (MPa), 1 day	18.7
7 days	29.5
28 days	42.4

Table 12. Properties of Fibers (As Provided by The Manufacturer)

Fiber Name	Designation	Density (kg/m^3)	Length (mm)	Diameter (mm)	Min f_t * (MPa)	Geometry
Dramix RC 80/60	R	7850	60	0.75	1050	Hooked
Dramix ZP 305	Z	7850	30	0.55	1100	Hooked
OL 6/16	L	7170	6	0.16	2000	Straight
Duomix 20	D	910	20	0.016	400	Fibrillated

* Minimum tensile strength of the wire

Table 13. Properties of The Superplasticizer

Specific gravity	pH	Solid contents (%)	Quantity, % (cement weight)	Main component
1.08	5-7	40	0.5-2.5	Polycarboxylic

4.3 Mix Proportions

A common concrete matrix was used in all mixes. This common matrix was designed to give a slump value of about 15 cm and a 28-day compressive strength of about 35 MPa, and it proved to be so. Proportions of this mix are presented in Table 14. Volume percentages of fiber contents for each mix are presented in Table 15.

Table 14. Mix Proportions for The Plain Mix

Constituent	Amount (kg/m^3)
Water	210
Cement	422
Aggregate	1603
Fine	784
Coarse	819
Superplasticizer	4.22

Table 15. Fiber Contents for Each Mix as Volume Percentage

		Volume Percentage of Fiber Contents (%)			
Mix No	Designation	R	Z	L	D
1	Control	0.0	0.0	0.0	0.0
2	R1.5	1.5	0.0	0.0	0.0
3	R1.0L0.5	1.0	0.0	0.5	0.0
4	R1.0L0.3D0.2	1.0	0.0	0.3	0.2
5	R1.0D0.5	1.0	0.0	0.0	0.5
6	Z1.5	0.0	1.5	0.0	0.0
7	Z1.0L0.5	0.0	1.0	0.5	0.0
8	Z1.0L0.3D0.2	0.0	1.0	0.3	0.2
9	Z1.0D0.5	0.0	1.0	0.0	0.5

4.4 Mixing, Casting, Curing

The fine aggregate, coarse aggregate and fibers were dry mixed for about 30 seconds. This was followed by the addition of cement and one thirds of total mixing water. After two minutes of mixing, remaining mixing water together with superplasticizer was added. Mixing was ceased after five minutes for all mixes.

Specimens for the testing of mechanical properties in the hardened state were prepared by pouring the concrete into lubricated molds. For each mix, three 150 mm cubes, two 150x300 mm cylinders, and two 150x150x500 mm beams were cast. Cubes were used for the determination of compressive strength. Cylinder specimens were sawn into 150x60 mm discs which were used in the impact resistance tests. Beam specimens were used for the determination of flexural tensile strength and flexural toughness.

The specimens were demolded after one day and then placed in the curing room with 90 ± 5% relative humidity and 20 ± 1 ^{o}C temperature until testing day.

4.5 Testing Procedure

4.5.1 Testing of Fresh Concrete

Slump test in accordance with TS 2871 standard was performed for each mix in the fresh state. Mixes with fiber reinforcement gave slump test results varying from zero to a few centimeters, however it was observed that all fiber reinforced mixes responded well to mechanical vibration and could be placed and compacted without much effort.

4.5.2 Testing of Hardened Concrete

28-day compressive strength of each mix was determined in accordance with TS 3114 ISO 4012 standard. Average of the test results of three specimens belonging to a mix was accepted as the 28-day compressive strength of that mix. Specimens were tested so that the direction of loading was 90^{o} with the direction of casting.

Flexural tensile strength and energy absorption up to failure under flexural loading tests were carried out in the Turkish Cement Manufacturers Association's laboratory, which was equipped with a testing machine with the capability of performing deformation controlled loading. However due to a malfunction of the testing machine which could not be fixed, tests were carried out in a load controlled manner. Thus, post crack portions of the load deflection curves could not be obtained. A single point load was applied at the mid span of the specimens and the deflections were measured from the bottom of the specimens using a mechanical dial gauge with an accuracy of 0.0001". For each load increment corresponding deflection was read and recorded. Area under the load deflection curve was designated as the energy absorption up to failure and it was calculated using the trapezoidal rule. Average of the test results of two beam specimens belonging to a mix were accepted as the flexural tensile strength and flexural toughness of that mix. Specimens were tested so that the direction of loading was 90^o with the direction of casting.

Impact resistance was determined in accordance with the repeated drop weight method suggested by ACI Committee 544 as explained in Chapter 3 of this text. For this purpose standard Marshall hammer apparatus located in the Transportation Laboratory was modified. In this test eight specimens were used because adopted test method is known to yield highly variable results. Average of the test results of eight specimens belonging to a mix were accepted as first crack strength and ultimate failure strength of that mix. Specimens were tested so that the direction of loading coincided with the direction of casting.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Slump Test

Results of the slump tests are presented in Table 16. Test results show that methods employing dynamic consolidation should be used to determine the consistency of FRC. Slump test is inadequate for this purpose and can not distinguish the effects of fiber inclusion and fiber hybridization on the consistency of FRC.

Table 16. Obtained Slump Values

Mix Designation	Slump (cm)
Control	16
R1.5	1
R1.0L0.5	1
R1.0L0.3D0.2	1
R1.0D0.5	0
Z1.5	1
Z1.0L0.5	2
Z1.0L0.3D0.2	1
Z1.0D0.5	0

5.2. Compressive Strength Test

28 day compressive strength of each mix was determined as explained in Chapter 4. Obtained test results are presented in Table 17. Fiber inclusions of all types increased the compressive strength, but this increase was not significant in neither of the mixes. Highest 28-day compressive strength was obtained in composite Z1.0L0.5, whereas

lowest value was obtained in composite R1.0D0.5. In all composites micro steel fiber OL 6/16 increased compressive strength values, on the contrary micro polypropylene fiber Duomix 20 caused a decrease in compressive strength. OL 6/16 fibers are high strength micro steel fibers and they can contribute to the strengthening component of hybrid fiber reinforcement successfully. On the other hand Duomix 20 is weaker than matrix itself and the decrease in compressive strength values of composites with Duomix 20 content was an expected result. Effects of OL 6/16 and Duomix 20 contents on 28-day compressive strength values can be seen in Figure 24 and Figure 25.

Table 17. 28 Day Compressive Strength Values

Mix Designation	f_{comp} 28 Days (MPa) 1	2	3	Average (MPa)	St. Dev.
Control	36.80	37.50	37.32	37.21	0.36
R1.5	40.46	40.46	38.80	39.91	0.96
R1.0L0.5	42.73	43.08	42.73	42.85	0.20
R1.0L0.3D0.2	42.73	41.42	42.90	42.35	0.81
R1.0D0.5	36.28	37.67	38.37	37.44	1.06
Z1.5	40.64	40.98	42.03	41.22	0.72
Z1.0L0.5	45.52	45.26	45.34	45.37	0.13
Z1.0L0.3D0.2	41.94	41.16	41.42	41.51	0.40
Z1.0D0.5	37.50	37.84	37.50	37.61	0.20

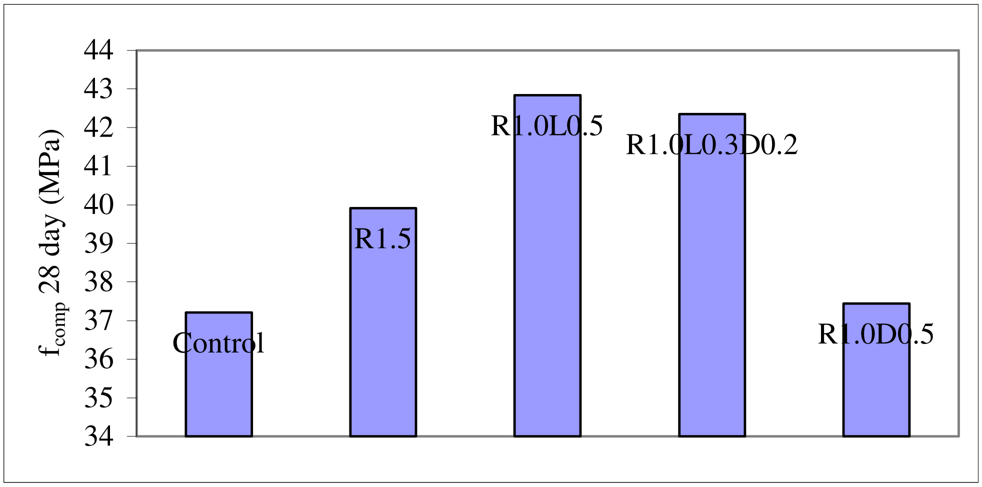

Figure 24. Comparison of 28-day compressive strength values of composites with RC 80/60 macro steel fiber

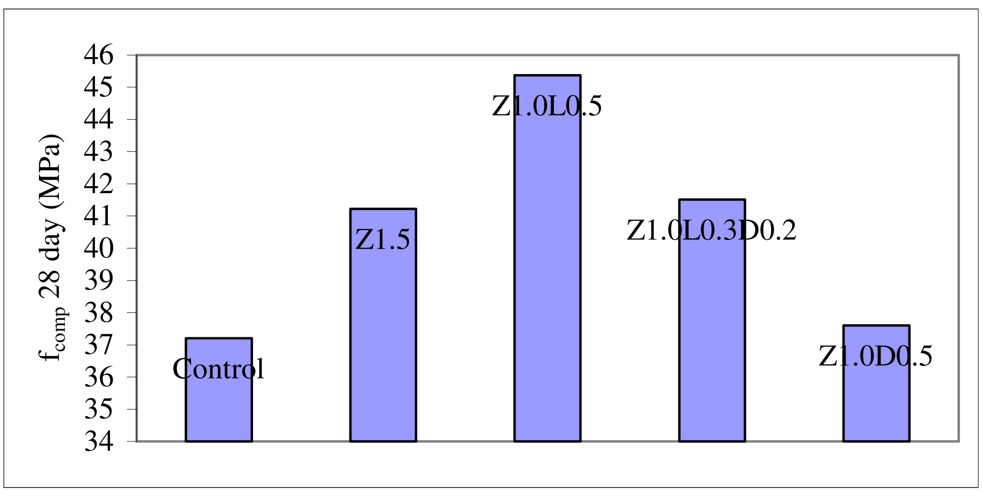

Figure 25. Comparison of 28-day compressive strength values of composites with ZP305 macro steel fiber

5.3 Flexural Tensile Strength Test

Flexural tensile strength of all mixes was determined as explained in Chapter 4. Obtained test results are presented in Table 18. Apparently fiber inclusion of all types resulted in considerable increases in flexural tensile strength values. Highest flexural tensile strength was obtained in composite the R1.0L0.5 and the lowest value was obtained in the composite Z1.0L0.3D0.2, although this value is 33% higher than that obtained from the control mix. Macro steel fiber RC 80/60, which has a higher aspect ratio, was more effective in increasing the flexural tensile strength when compared with macro steel fiber ZP 305. Combination of macro steel fibers with micro steel fiber OL 6/16 gave higher flexural tensile strength values than the composites reinforced simply with macro steel fibers. However similiar synergy was not observed between OL 6/16 and micro polypropylene fiber Duomix 20. Combination of OL 6/16 and Duomix 20 gave the lowest flexural tensile strength values among hybrid fiber reinforced composites.

Table 18. Flexural Tensile Strength Values

Mix Designation	f_{flex} (MPa) 1	2	Average (MPa)	St. Dev.
Control	5.0	4.6	4.8	0.28
R1.5	8.6	9.0	8.8	0.28
R1.0L0.5	10.4	11.6	11.0	0.85
R1.0L0.3D0.2	7.8	7.0	7.4	0.57
R1.0D0.5	7.4	8.2	7.8	0.57
Z1.5	7.2	6.0	6.6	0.85
Z1.0L0.5	7.2	8.0	7.6	0.57
Z1.0L0.3D0.2	6.0	6.8	6.4	0.57
Z1.0D0.5	6.6	7.0	6.8	0.28

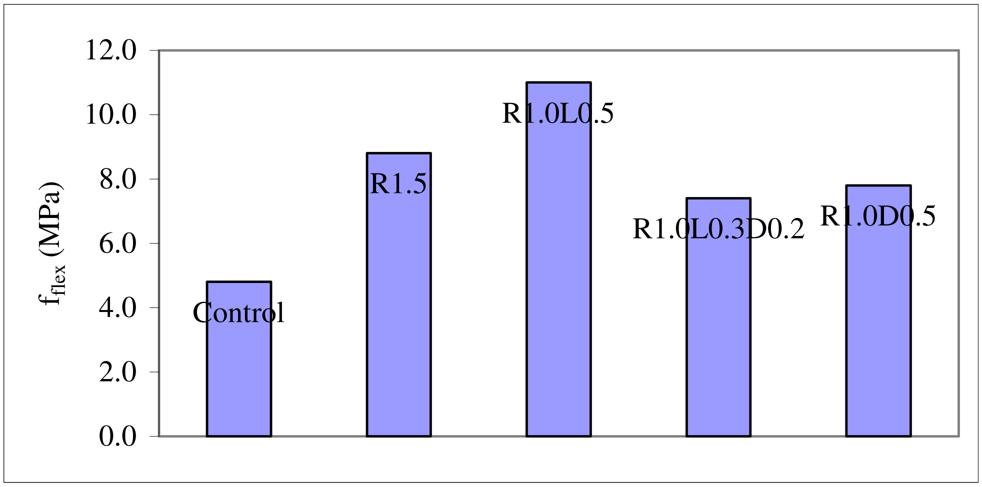

Figure 26. Comparison of flexural tensile strength values of composites with RC 80/60 macro steel fiber

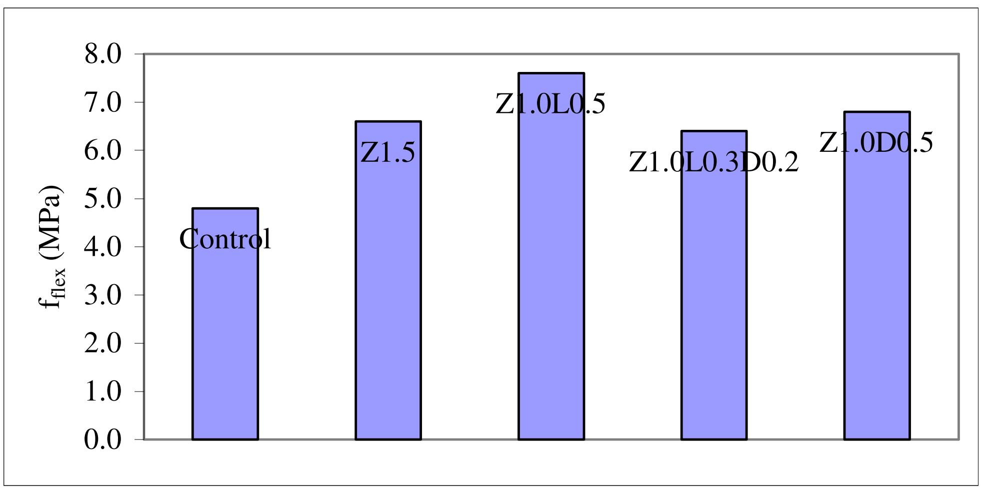

Figure 27. Comparison of flexural tensile strength values of composites with ZP 305 macro steel fiber

5.4 Energy Absorption up to Failure under Flexural Loading

Energy absorptions up to failure under flexural loading for all mixes were calculated as explained in Chapter 4. Calculated values are presented in Table 19. Load deflection curves can be seen in Figure 30 and Figure 31. Due to experimental problems related with the testing machine, post-crack portion of the load deflection curves could not be obtained. However softening effect of fiber inclusion, occurrence of a distinct point at which load deflection curve looses its linearity indicating a reduction of the stiffness of the composite and formation of plastic deformations, can be seen in load deflection curves. ASTM C 1018 standard suggests that concavity in the initial portion of the load deflection curve is an indication of erroneous deformation measurement due to support settlement or rocking of specimen on its supports. ASTM C 1018 standard suggests the initial concave part to be discarded and replaced by the extension of linear portion of the load deflection curve. Load deflection curves after correcting the experimentally obtained data for composites R1.0L0.5, R1.0L0.3D0.3, Z1.0L0.5, Z1.0L0.3D0.2, and Z1.0D0.5 can be seen in Figure 32 and Figure 33. Energy absorptions were calculated over the corrected load deflection data. Apparently fiber inclusion prevented sudden and brittle failure Fiber inclusion of all types greatly enhanced energy absorption up to failure when compared with the plain control mix. Macro steel fiber RC 80/60 proved to be effective in increasing the energy absorption. RC 80/60 has a high aspect ratio and can successfully bridge the macro cracks pulling out of these fibers requires more energy. Composite R1.5 had the highest energy absorption, in addition a slightly lower value was obtained in composite R1.0L0.5. High strength micro steel fiber OL 6/16 is manufactured from high strength steel wires and has relatively smaller dimensions. Thus OL 6/16 can successfully delay the formation of micro cracks and prevent their propagation up to a certain extent. As a result during pulling out macro steel fibers from a matrix already reinforced with OL 6/16, more energy is consumed. Hybridization of RC 80/60 and micro polypropylene fiber Duomix 20 resulted in a decline in calculated energy absorption values. On the other hand, as can be seen in Figure 34, Duomix 20 provides ductility due to its high ultimate elongation capacity. For a certain energy absorption level, Duomix 20 inclusion shifted the failure deflection upwards for composites with RC 80/60. Due to its lower aspect ratio, macro steel fiber ZP 305 was not as effective as RC 80/60 in enhancing energy absorption. Combination of ZP 305 with OL 6/16 resulted in a considerable increase in energy absorption when a comparison is made among composites with ZP 305. However hybridization of ZP 305 with Duomix 20 adversely affected both energy absorption and ductility. A synergetic response was not observed between these two fibers.

Table 19. Calculated Energy Absorptions up to Failure

Mix Designation	Energy Absorption (Joule)
Control	3.86
R1.5	51.99
R1.0L0.5	51.63
R1.0L0.3D0.2	39.67
R1.0D0.5	44.78
Z1.5	29.97
Z1.0L0.5	39.67
Z1.0L0.3D0.2	30.89
Z1.0D0.5	18.01

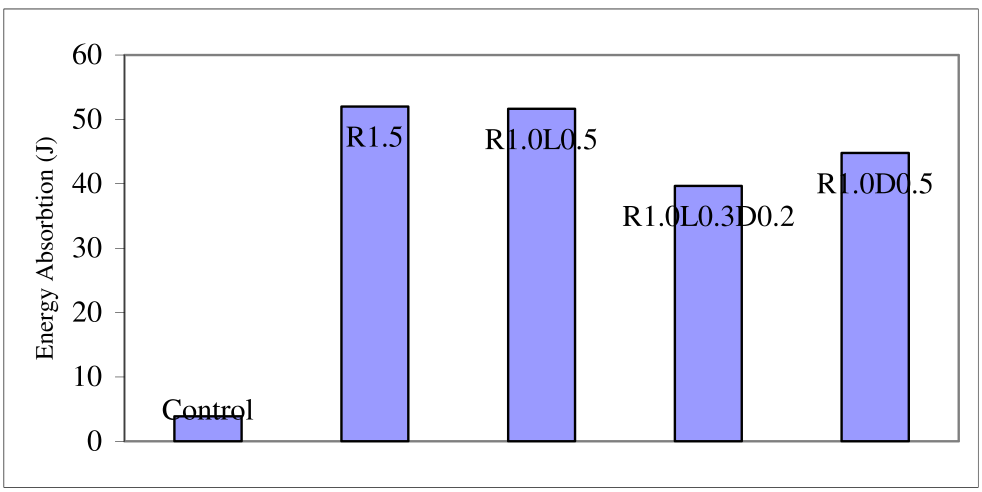

Figure 28. Comparison of calculated energy absorption values up to failure for composites with RC 80/60 macro steel fiber

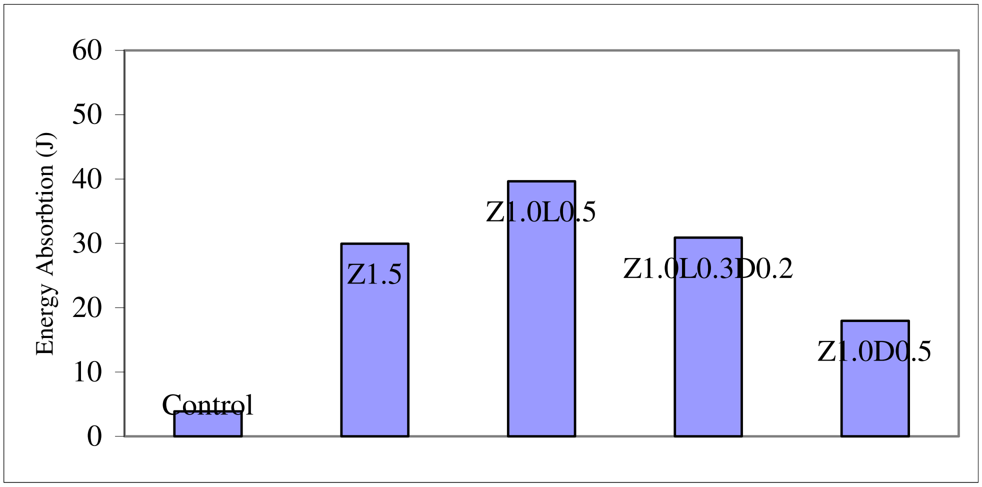

Figure 29. Comparison of calculated energy absorption values up to failure for composites with ZP 305 macro steel fiber

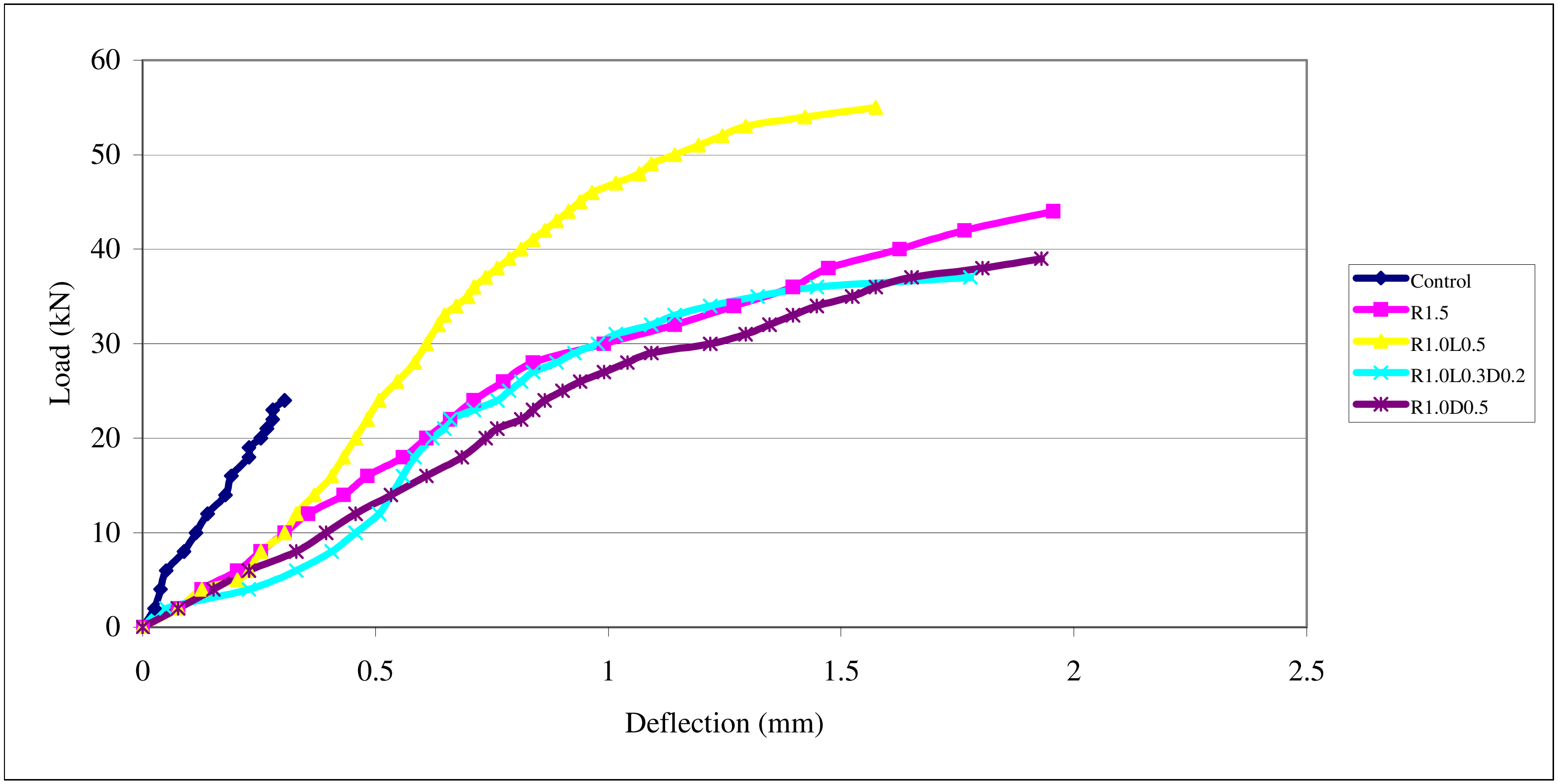

Figure 30. Load deflection curves for composites with macro steel fiber RC 80/60 under flexural loading

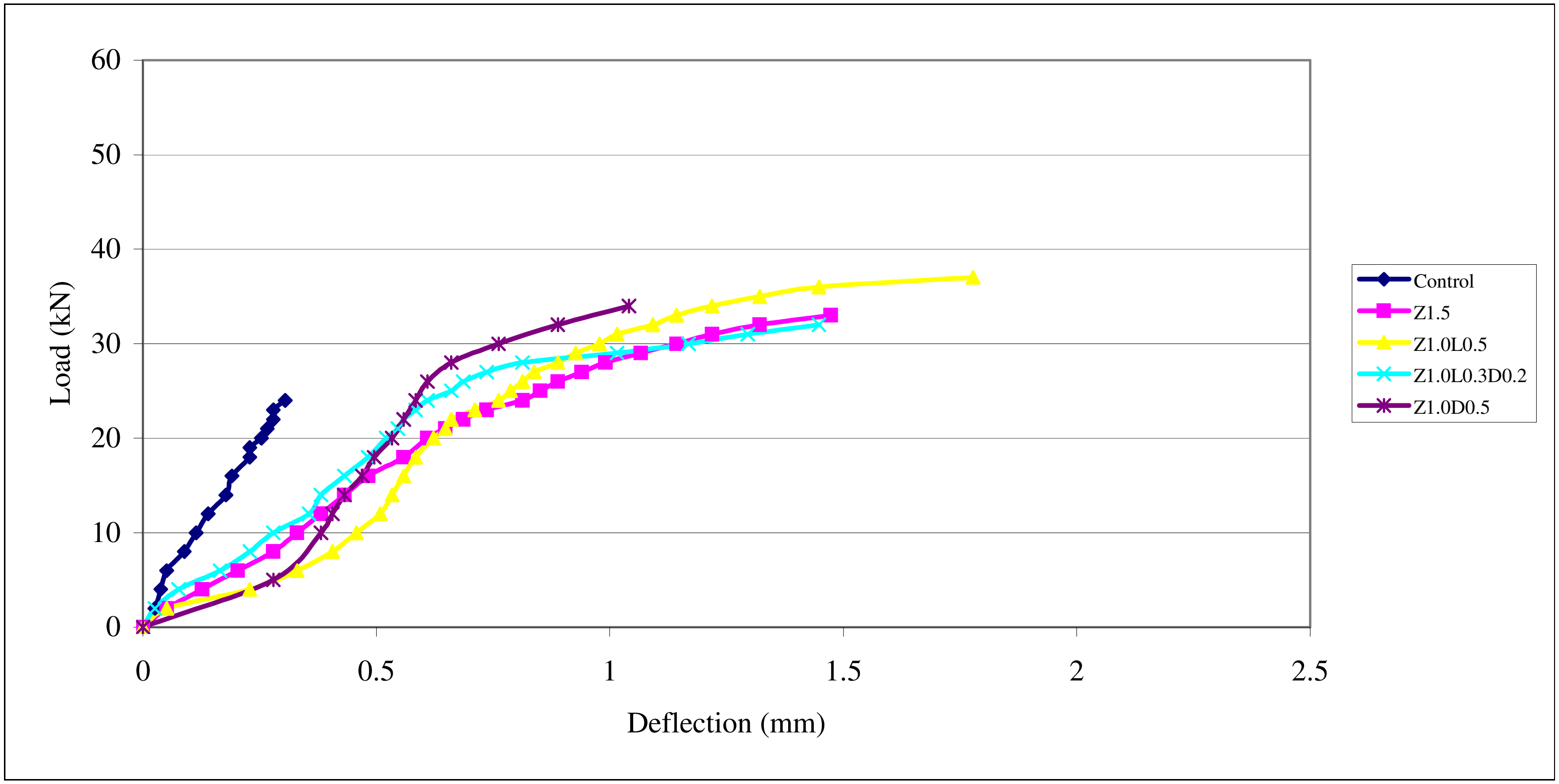

Figure 31. Load deflection curves for composites with macro steel fiber ZP 305 under flexural loading

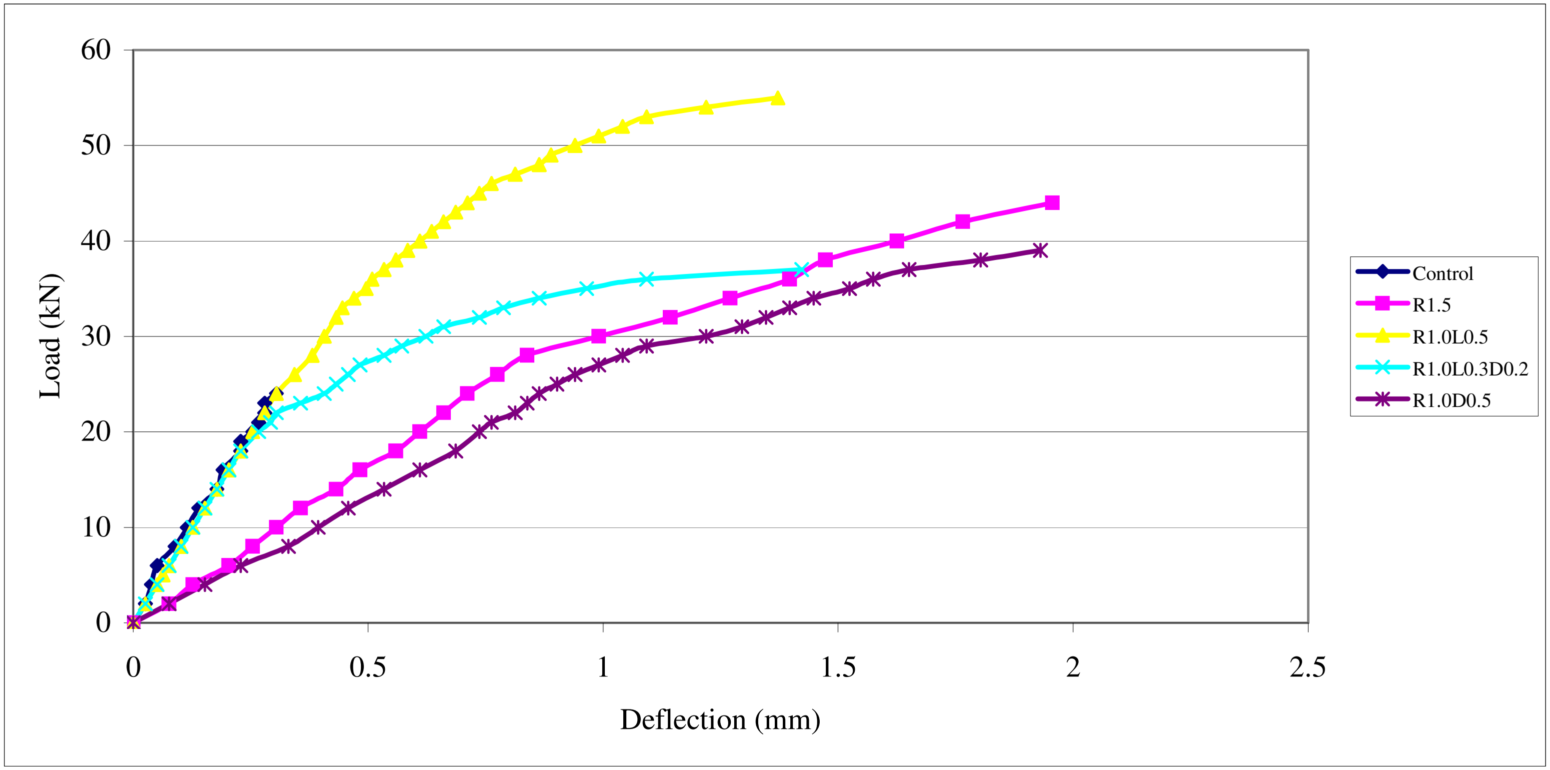

Figure 32. Corrected load deflection curves for composites with macro steel fiber RC 80/60

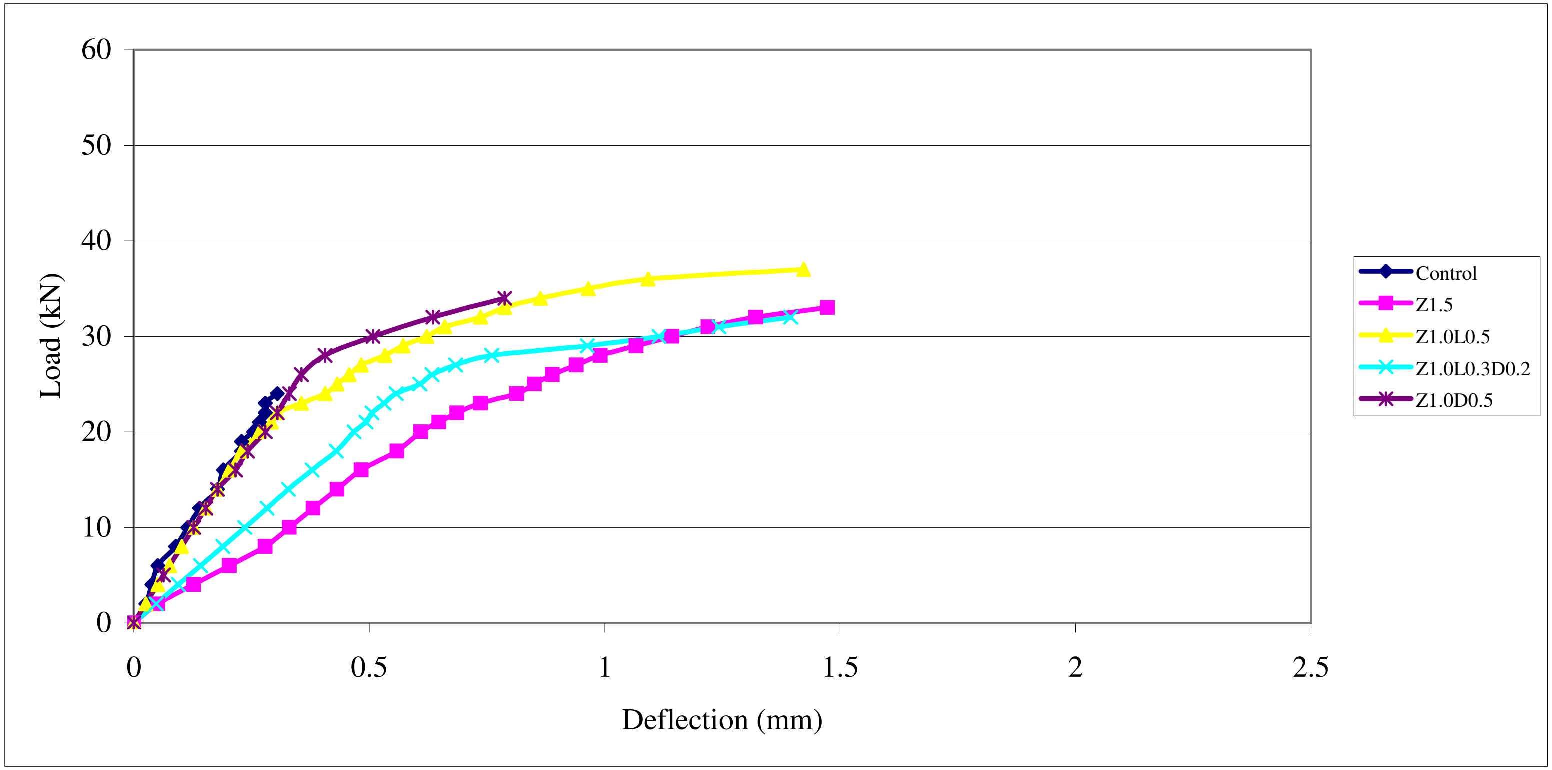

Figure 33. Corrected load deflection curves for composites with macro steel fiber ZP 305

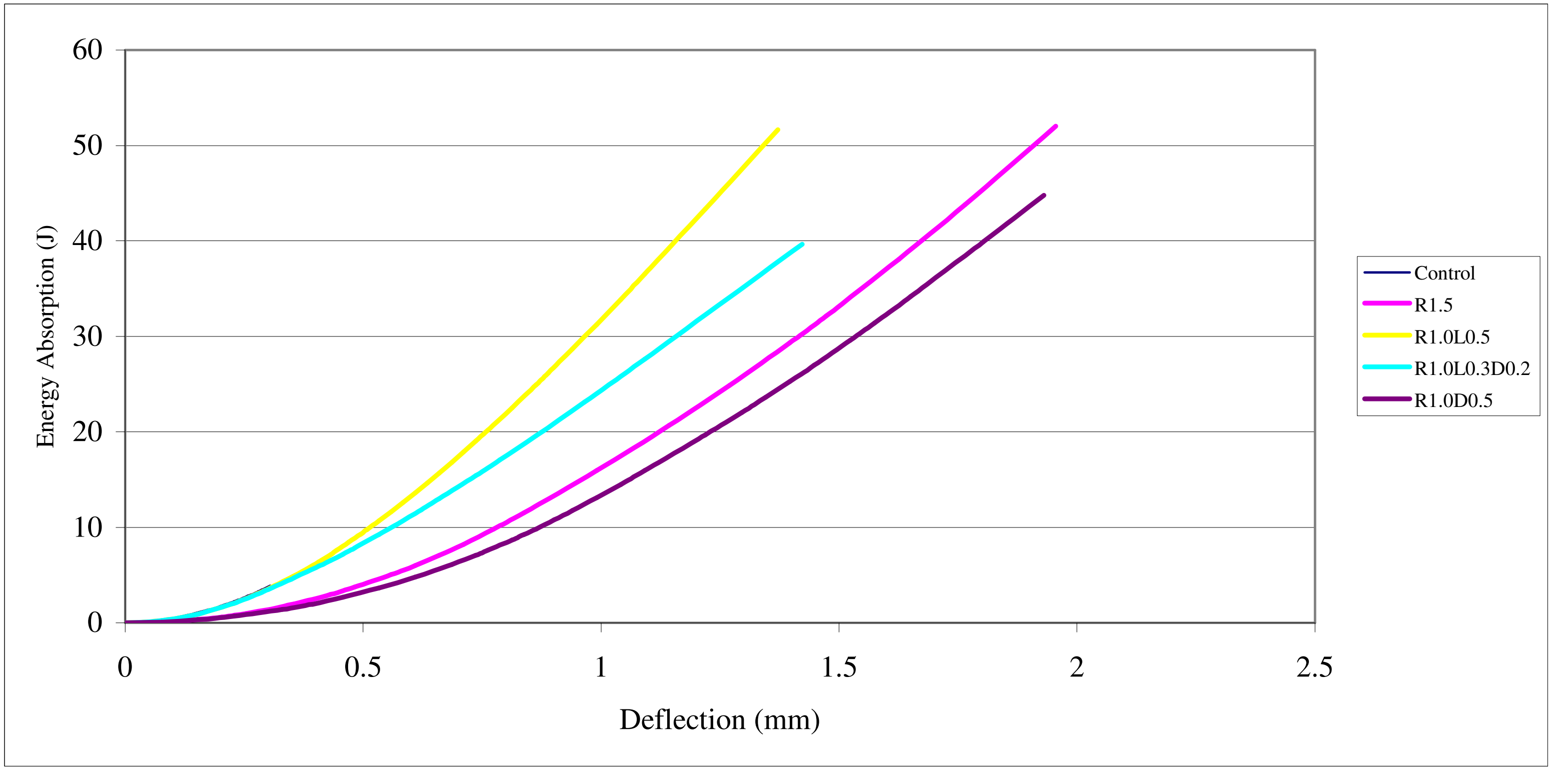

Figure 34. Energy Absorption vs. deflection for composites with macro steel fiber RC 80/60

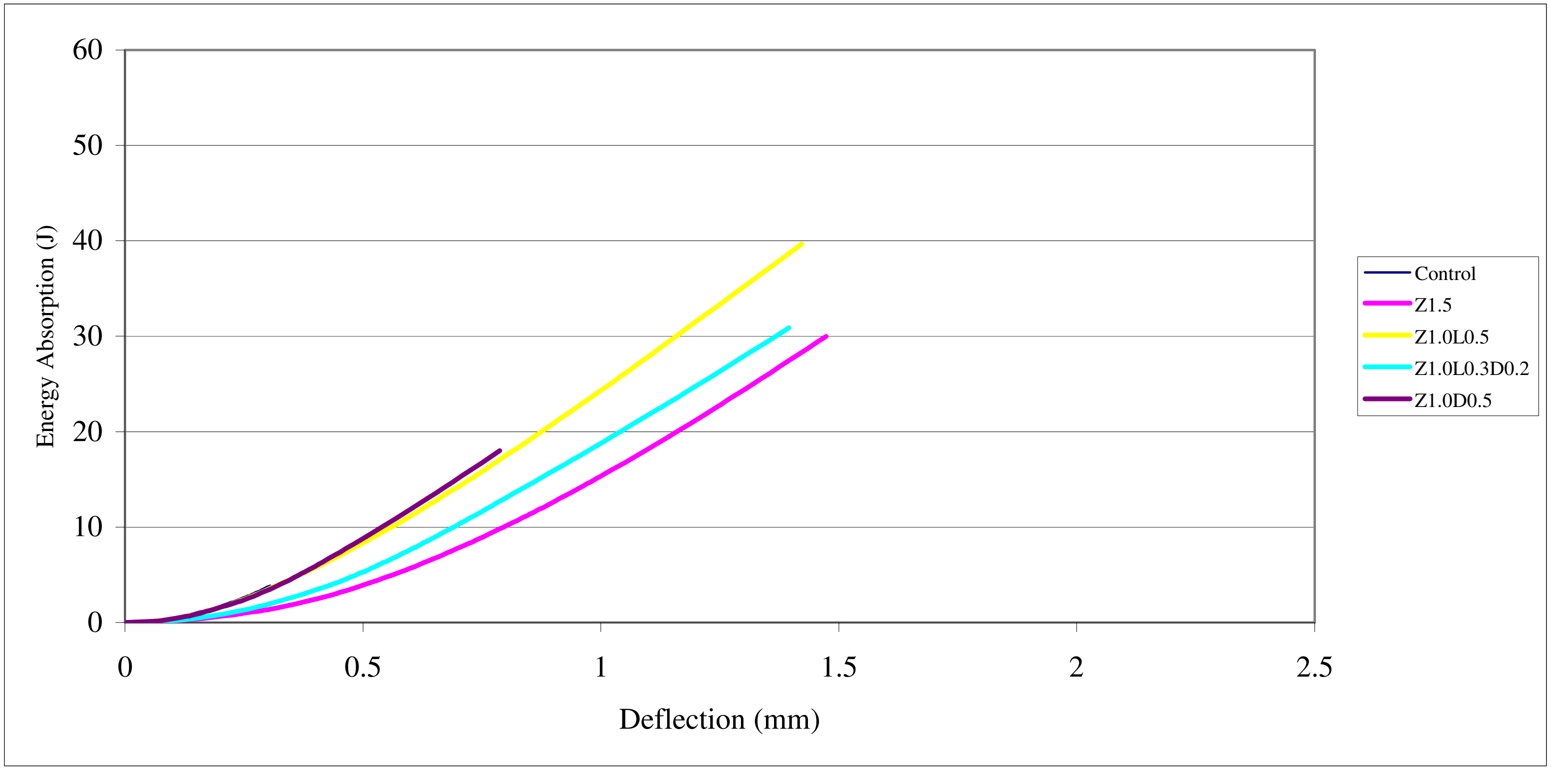

Figure 35. Energy Absorption vs. deflection for composites with macro steel fiber

5.4 Impact Resistance Test

Impact resistance was determined as explained in Chapter 4. Obtained test results are presented in Table 20. Main effect of fiber inclusion was on ultimate failure strength (UFS); first crack strength (FCS) was not significantly affected with fiber inclusion. In composites with macro steel fiber RC 80/60 UFS was increased at least 9 times when compared with the plain control mix. Addition of 0.5% of micro steel fiber OL 6/16 resulted in a 16% decrease in UFS relative to the composite simply reinforced with RC 80/60. However this decrease was compensated with 0.2% replacement of OL 6/16 with micro polypropylene fiber Duomix 20; highest UFS was obtained in this composite. Duomix 20 proved to be effective under dynamic loading and a synergetic response was observed between RC 80/60 and Duomix 20 as well as OL 6/16 and Duomix 20. Due to its lower aspect ratio macro steel fiber ZP 305 did not enhance UFS as much as RC 80/60, though UFS was at least three times increased in composites with macro steel fiber ZP 305. Highest UFS was achieved in composite Z1.5. Hybridization of ZP 305 with micro OL 6/16 and Duomix 20 resulted in decreased UFS values.

Table 20. Impact Resistance Test Results

Mix	First Crack		Ultimate Failure	
Designation	Average	St. Dev.	Average	St. Dev.
Control	44	19	48	20
R1.5	53	24	512	102
R1.0L0.5	51	21	429	131
R1.0L0.3D0.2	60	24	522	116
R1.0D0.5	61	14	499	123
Z1.5	60	28	238	107
Z1.0L0.5	69	24	182	60
Z1.0L0.3D0.2	61	14	139	45
Z1.0D0.5	55	20	151	37

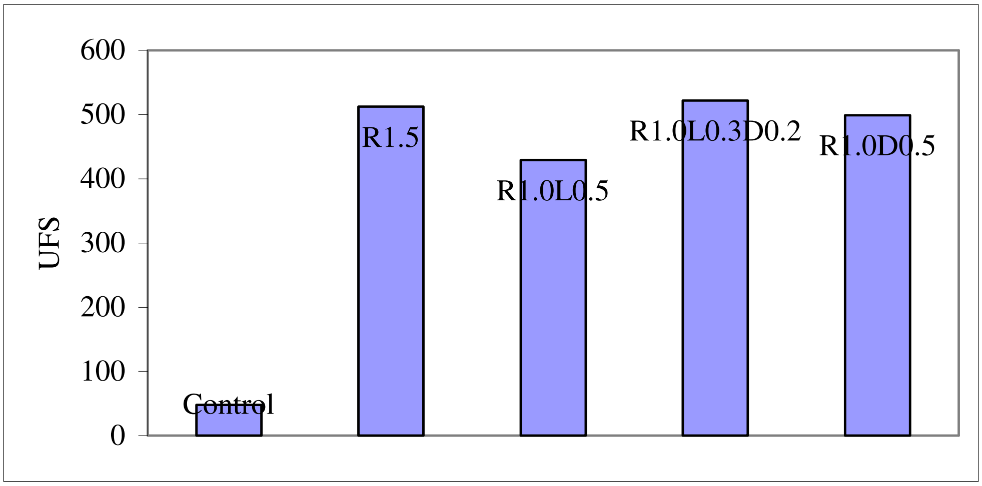

Figure 36. Comparison of ultimate failure strength values of composites with macro steel fiber RC 80/60

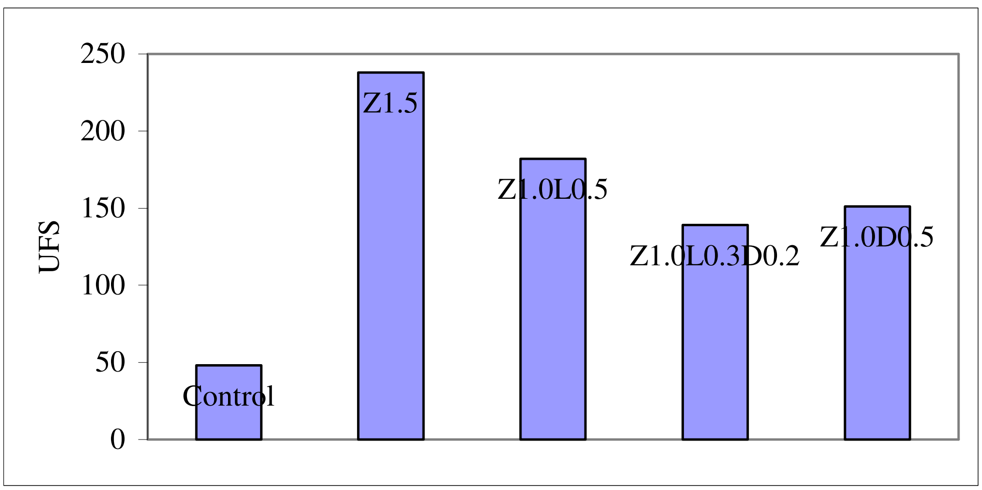

Figure 37. Comparison of ultimate failure strength values of composites with macro steel fiber ZP 305

5.5 Analysis of Results

5.5.1 Curve Fitting for Experimental Load Deflection Data

In order to obtain a continuous load-deflection curve the following fitting function is proposed.

$$P = P_u \times \left[\frac{\beta \times \left(\frac{\delta}{\delta_u} \right)}{\beta - 1 + \left(\frac{\delta}{\delta_u} \right)^{\beta}} \right] \quad [16]$$

where β is material parameter, P_u is the ultimate flexural load, δ_u is the corresponding ultimate deflection. To describe a load-deflection curve with this fitting function it is necessary to know P_u, δ_u, and β. After performing a non-linear least squares regression analysis on experimentally obtained load deflection data, β values have been determined as follows.

Table 21. Determined β Values

Mix Designation	β
Control	33.450
R1.5	3.398
R1.0L0.5	2.033
R1.0L0.3D0.2	1.452
R1.0D0.5	4.028
Z1.5	3.329
Z1.0L0.5	1.452
Z1.0L0.3D0.2	1.885
Z1.0D0.5	2.143

Generated load-deflection curves using these β values together with P_u and δ_u, which are already known, are presented in Figure 38 and Figure 39. Extrapolated portion of the load deflection curves are shown in dashed lines. As can be seen in Figure 38 and Figure 39, proposed function is suitable to describe the experimentally obtained load deflection data. When extrapolation is carried out, typical load deflection curves common for FRC are obtained, as a consequence this function could be suitable to estimate the post crack portion.

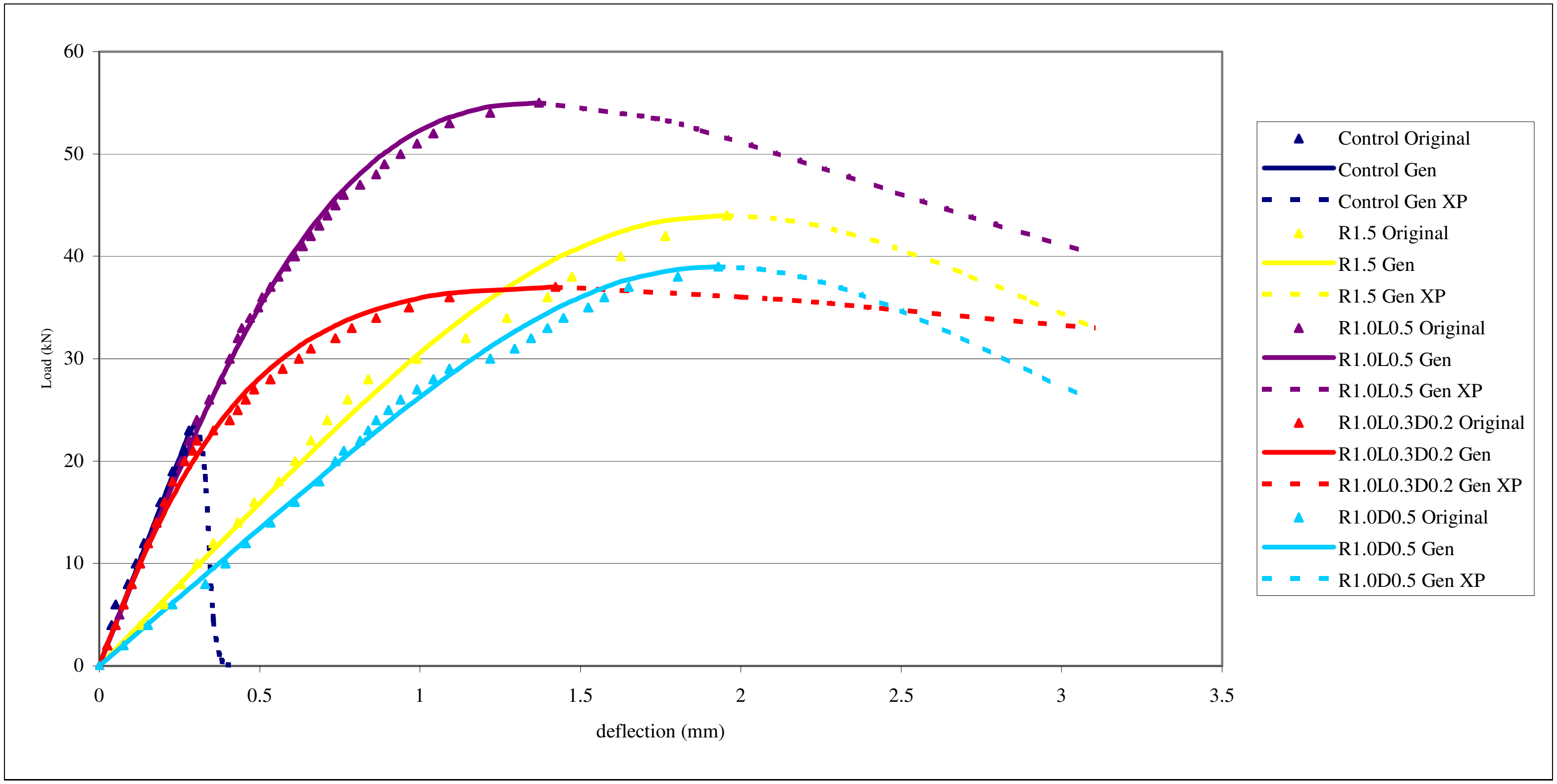

Figure 38. Generated load-deflection curves for composites with macro steel fiber RC 80/60.

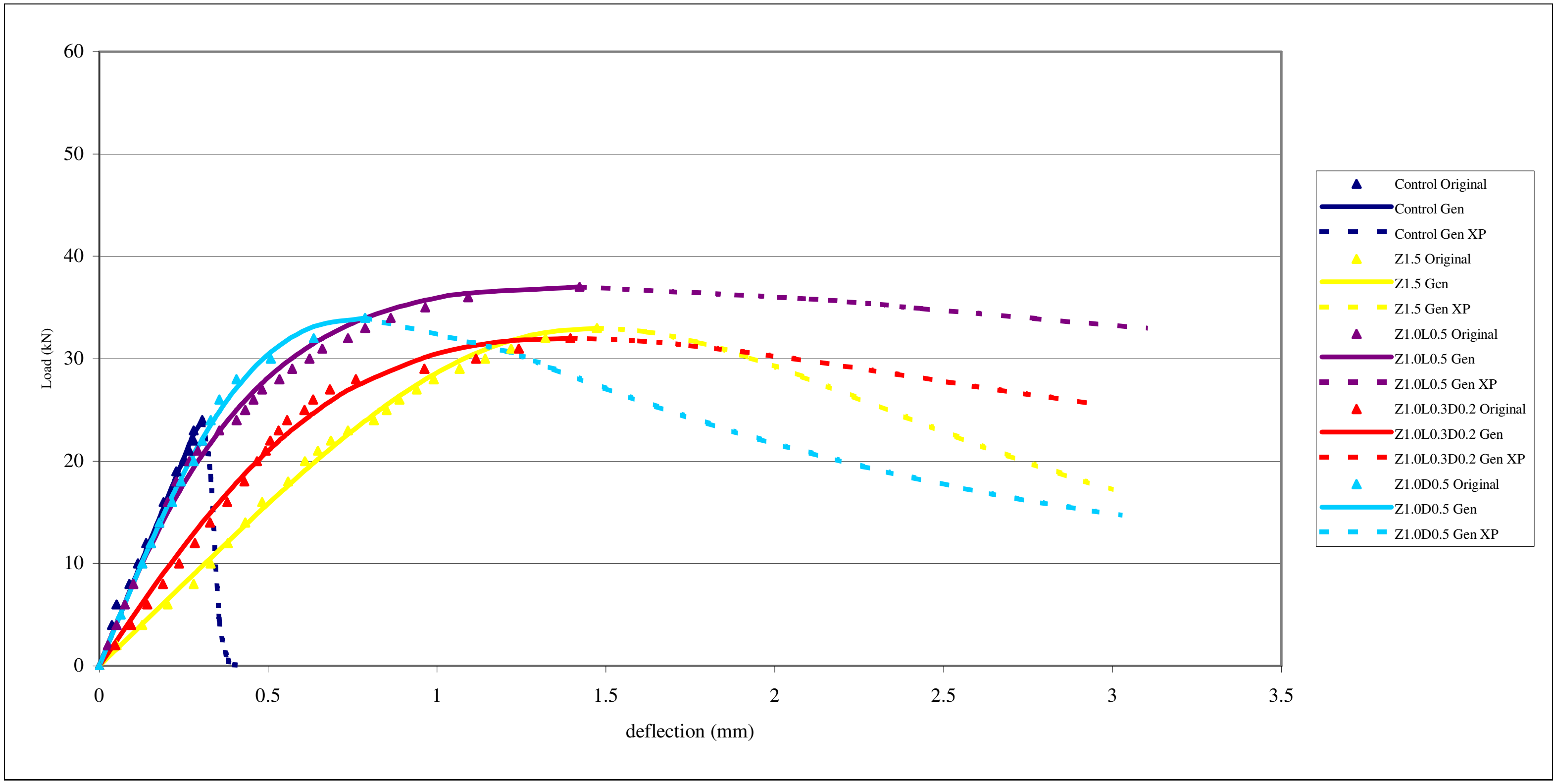

Figure 39. Generated load-deflection curves for composites with macro steel fiber RC 80/60.

5.5.2 Location of First Crack Point

First crack point may be termed as the point at which load deflection curve deviates from linearity considerably. Due to the subjective definition, location of first crack point may vary according to whom the test is performed and evaluated.

In order to locate the first crack point, three different approaches were adopted in this experimental study. Plain control mix was assumed to fail upon the formation of first crack in the first and second approaches. In the first approach experimentally obtained load deflection curves were visually examined and the first point where a deviation from linearity occurred according to the judgment of the author was assumed to be the first crack point. In the second approach, first crack in a fiber reinforced mix was assumed to occur at the same stress level for plain control mix. Deflection corresponding to the ultimate flexural load of plain control mix for each fiber reinforced mix was read from experimentally obtained load deflection curves and recorded as first crack deflection.

In the third approach fitting function proposed to describe the experimentally obtained load deflection data was used. By derivating this function with respect to deflection (δ), slope of the tangent line at any point on the function can be obtained.

$$\frac{dP}{d\delta} = \frac{P_u}{\delta_u} \times \left[\frac{\beta}{\beta - 1 + \left(\frac{\delta}{\delta_u}\right)^{\beta}} - \frac{\beta^2}{\left(\beta - 1 + \left(\frac{\delta}{\delta_u}\right)^{\beta}\right)^2} \times \left(\frac{\delta}{\delta_u}\right)^{\beta} \right]$$

First crack point can be located using the following criteria; slope of regression line up to 25% of experimentally obtained ultimate deflection is calculated over generated data. This value is compared with slopes calculated at 0.01mm intervals. Point at which a deviation of 10% from the slope of regression line occurs is assumed to be the first crack point. First crack deflections obtained from these approaches are presented in Table 22. Loads at first crack point are presented in Table 23.

Table 22. First Crack Deflections

Mix Designation	δ_{FC} (mm) Approach 1	2	3	Average	St. Dev.
Control	0.30	0.30	0.29	0.30	0.008
R1.5	0.84	0.71	0.85	0.80	0.077
R1.0L0.5	0.41	0.30	0.33	0.35	0.053
R1.0L0.3D0.2	0.30	0.41	0.24	0.32	0.084
R1.0D0.5	1.09	0.86	0.98	0.98	0.114
Z1.5	0.74	0.81	0.63	0.73	0.092
Z1.0L0.5	0.29	0.41	0.24	0.31	0.085
Z1.0L0.3D0.2	0.63	0.56	0.31	0.50	0.169
Z1.0D0.5	0.41	0.33	0.21	0.32	0.099

Table 23. Flexural Loads at First Crack Point

Mix Designation	P_{FC} (kN) Approach 1	2	3	Average	St. Dev.
Control	24	24	23.40	23.80	0.346
R1.5	28	24	26.44	26.15	2.016
R1.0L0.5	30	24	24.72	26.24	3.276
R1.0L0.3D0.2	22	24	17.16	21.05	3.517
R1.0D0.5	29	24	25.78	26.26	2.534
Z1.5	23	24	19.67	22.22	2.267
Z1.0L0.5	21	24	17.18	20.73	3.416
Z1.0L0.3D0.2	26	24	14.20	21.40	6.315
Z1.0D0.5	28	24	16.17	22.72	6.019

Adopted approaches yielded varying results. In a broad view, for composites with macro steel fiber RC 80/60, micro steel fiber OL 6/16 increased first crack load whereas micro polypropylene fiber Duomix 20 increased first crack deflection. For composites with macro steel fiber ZP 305, neither OL 6/16 nor Duomix 20 significantly affected first crack deflection, nevertheless Duomix 20 caused a slight increase in first crack load.

Overall average of the first crack loads is 23.40 kN, which is very close to the ultimate failure load of plain control mix. This result can be accepted as validation of second approach in which first crack in fiber reinforced mixes was assumed to occur at the same stress level for plain control mix, thus first crack deflections obtained from second approach were used.

5.5.3 Estimation of Energy Absorptions up to Specified Deflections

Energy absorptions up to δ_{FC}, 3 δ_{FC}, and 5.5 δ_{FC}, as suggested in ASTM C 1018, were estimated by integrating the fitting function up to specified deflections mentioned above. Toughness indices I_5 and I_{10} were also calculated. Obtained results are presented in Table 24.

Table 24. Energy Absorptions up to Selected Multiples of First Crack Deflection and Toughness Indices

Mix Designation	Energy Absorption (J)			Toughness Index	
	$\delta = \delta_{FC}$	$\delta = 3\ \delta_{FC}$	$\delta = 5.5\ \delta_{FC}$	I_5	I_{10}
Control	3.65	4.67	4.67	1.3	1.3
R1.5	8.00	61.05	121.33	7.6	15.2
R1.0L0.5	3.48	26.81	67.29	7.7	19.4
R1.0L0.3D0.2	5.84	33.12	70.53	5.7	12.1
R1.0D0.5	9.99	69.55	111.75	7.0	11.2
Z1.5	10.28	58.38	87.15	5.7	8.5
Z1.0L0.5	5.84	33.12	70.53	5.7	12.1
Z1.0L0.3D0.2	6.96	40.50	80.22	5.8	11.5
Z1.0D0.5	4.14	25.06	48.41	6.0	11.7

For an ideally elastic-plastic material toughness index value would be equal to the index itself. However depending on amount, type, and orientation of fibers as well as type and rate of loading, calculated toughness indices may exceed the index values.

Energy absorptions up to a deflection of 3 mm, as suggested in JSCE SF-4 Method, were also calculated. Obtained results are presented in Table 25. Estimations show that combination of micro steel fiber OL 6/16 with macro steel fibers is effective in enhancing energy absorption.

Table 25. Energy Absorption up to a Deflection of 3 mm

Mix Designation	Energy Absorption (J) $\delta = \delta_{FC}$	δ = 3 mm	$E_{3mm}/E_{\delta FC}$
Control	3.65	4.67	1.28
R1.5	8.00	95.52	11.95
R1.0L0.5	3.48	117.38	33.77
R1.0L0.3D0.2	5.84	82.84	14.18
R1.0D0.5	9.99	82.37	8.25
Z1.5	10.28	69.98	6.81
Z1.0L0.5	5.84	82.84	14.18
Z1.0L0.3D0.2	6.96	76.40	10.98
Z1.0D0.5	4.14	37.09	8.95

5.5.4 Relationship between Energy Absorption and Ultimate Failure Strength

Flexural toughness tests are relatively hard to carry out and calculation of toughness values and other toughness related parameters is a time consuming process. Thus it would be useful to relate energy absorption under flexural loading to ultimate failure strength suggested in repeated drop weight impact resistance test, as this test is relatively simpler. After performing least squares linear regression analysis, following relationships were derived.

Composites with macro steel fiber RC 80/60

$E_{Failure}$ = 1.504 + 0.093 UFS **(R^2 = 0.86)**

$E_{3\delta FC}$ = -1.932 + 0.102 UFS **(R^2 = 0.60)**

$E_{5.5\delta FC}$ = -6.335 + 0.203 UFS **(R^2 = 0.78)**

E_{3mm} = 2.205 + 0.185 UFS **(R^2 = 0.76)**

Composites with macro steel fiber ZP 305

$E_{Failure}$ = 1.002 + 0.164 UFS **(R^2 = 0.54)**

$E_{3\delta FC}$ = -7.293 + 0.263 UFS **(R^2 = 0.84)**

$E_{5.5\delta FC}$ = -5.888 + 0.423 UFS **(R^2 = 0.77)**

E_{3mm} = -1.596 + 0.368 UFS **(R^2 = 0.61)**

Plots of the obtained relationships together with the 95% F distribution confidence intervals are presented in the following figures. Though data obtained from control mix was used in regression analysis, data point corresponding to the control mix is not shown in neither of the figures as it is too distinct from remaining data points.

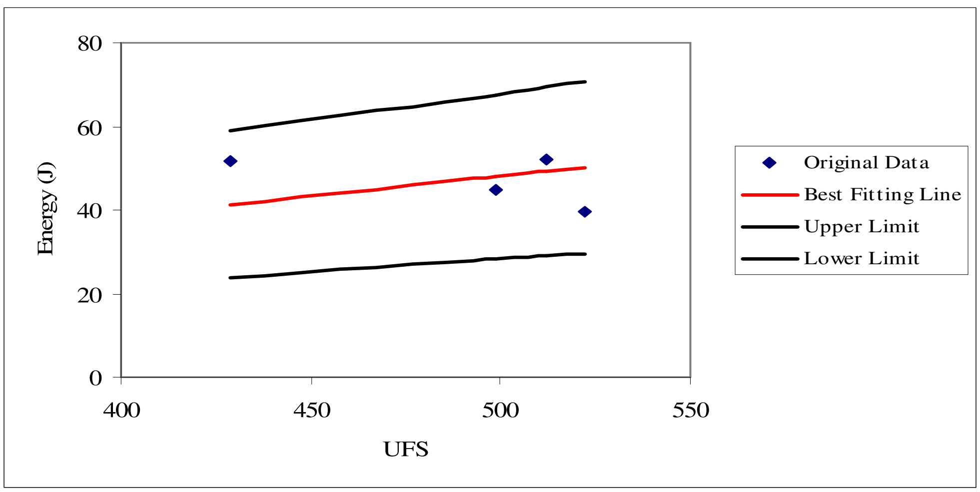

Figure 40 Energy absorption up to failure vs. UFS for composites with macro steel fiber RC 80/60

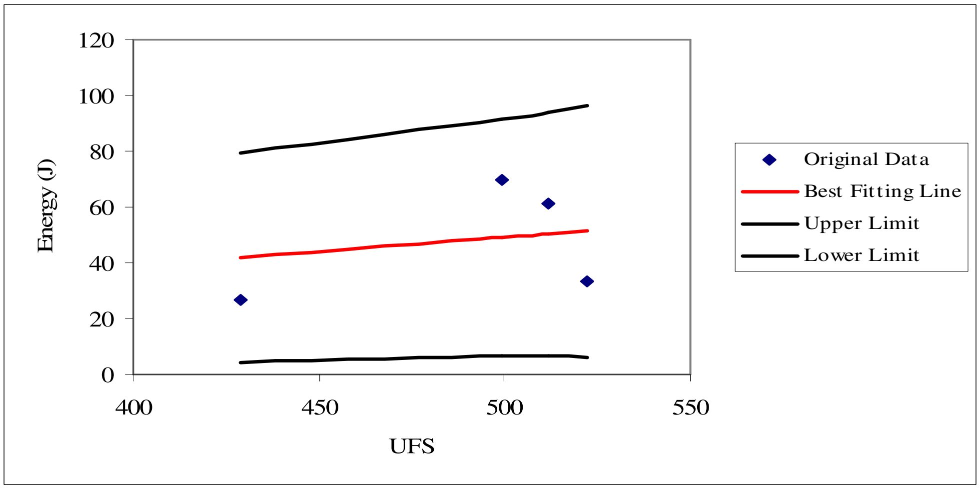

Figure 41. Energy absorption up to δ=3 δ_{FC} vs. UFS for composites with macro steel fiber RC 80/60

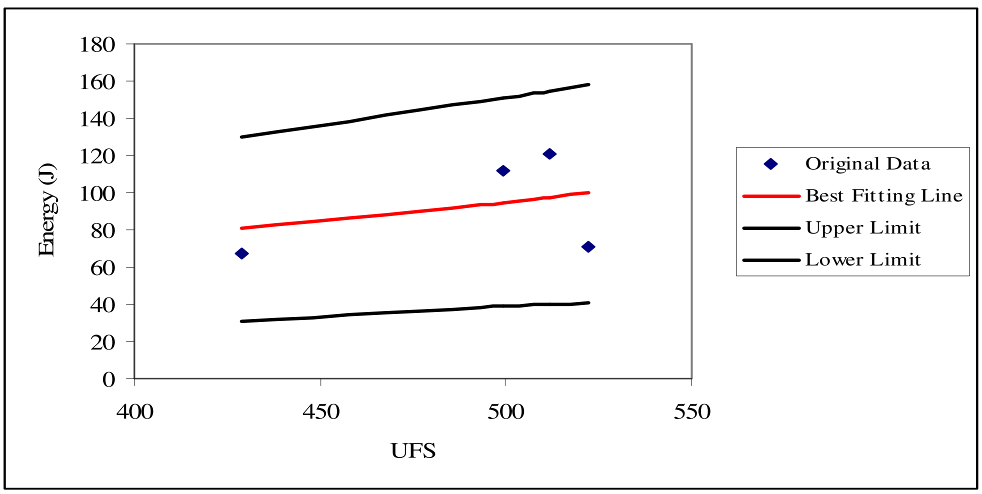

Figure 42. Energy absorption up to δ=5.5 δ_{FC} vs. UFS for composites with macro steel fiber RC 80/60

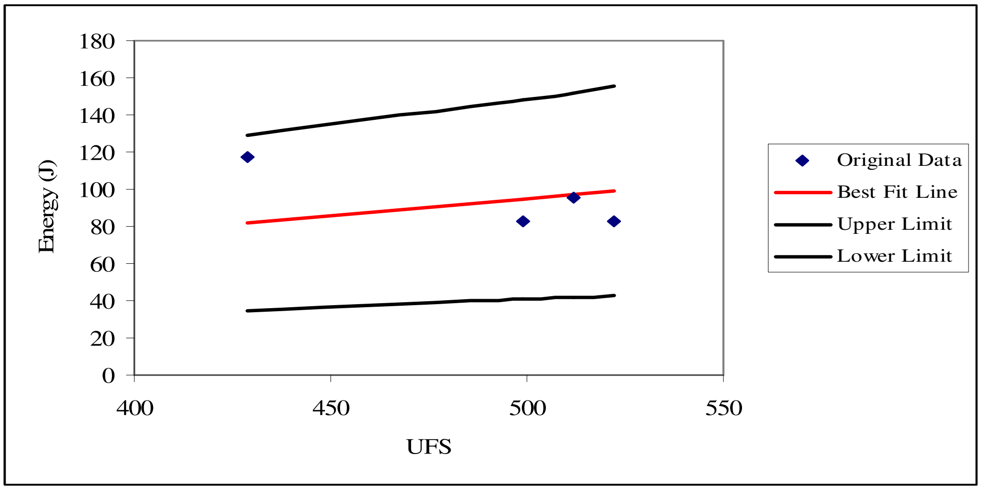

Figure 43. Energy absorption up to δ=3 mm vs. UFS for composites with macro steel fiber RC 80/60

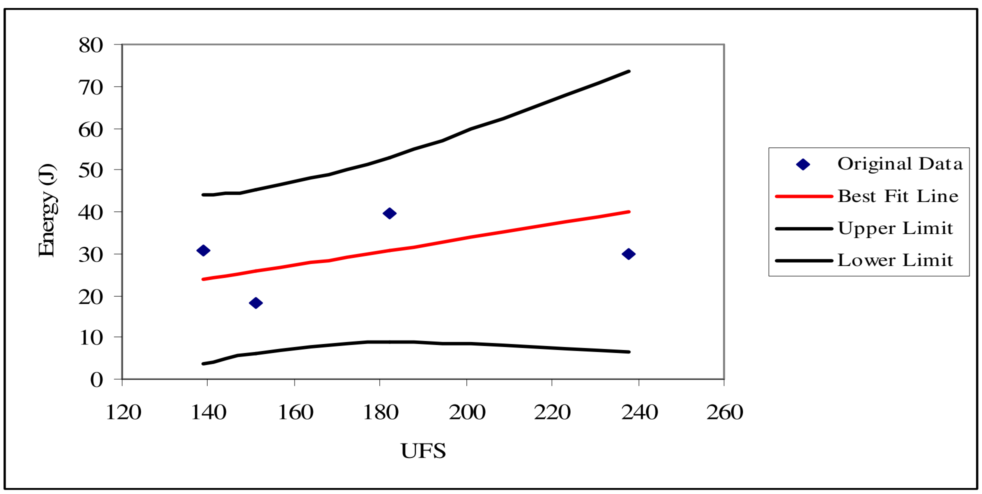

Figure 44. Energy absorption up to failure vs. UFS for composites with macro steel fiber ZP 305

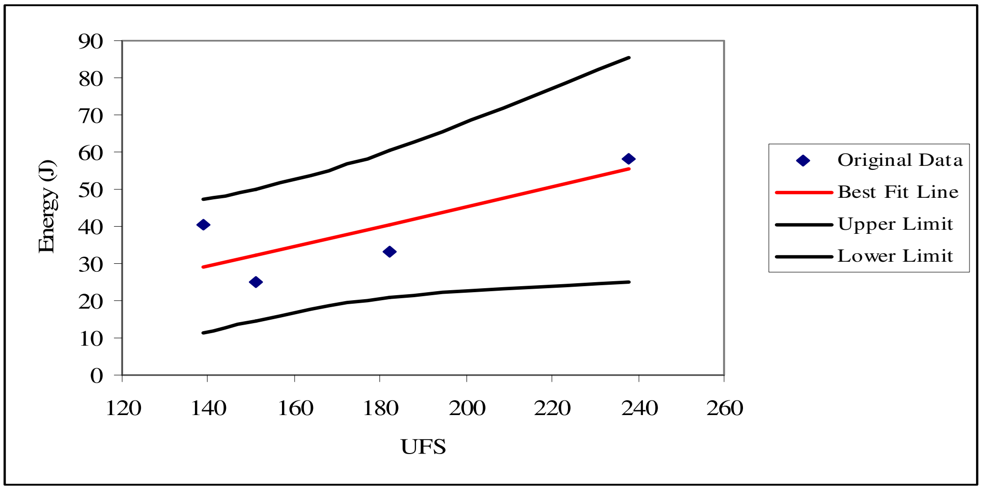

Figure 45. Energy absorption up to δ=3 δ_{FC} vs. UFS for composites with macro steel fiber ZP 305

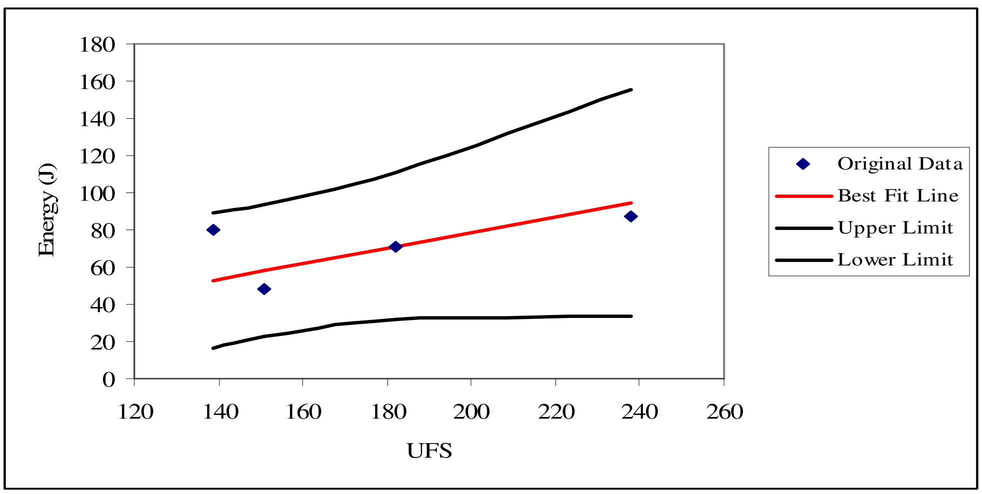

Figure 46. Energy absorption up to δ=3 δ_{FC} vs. UFS for composites with macro steel fiber ZP 305

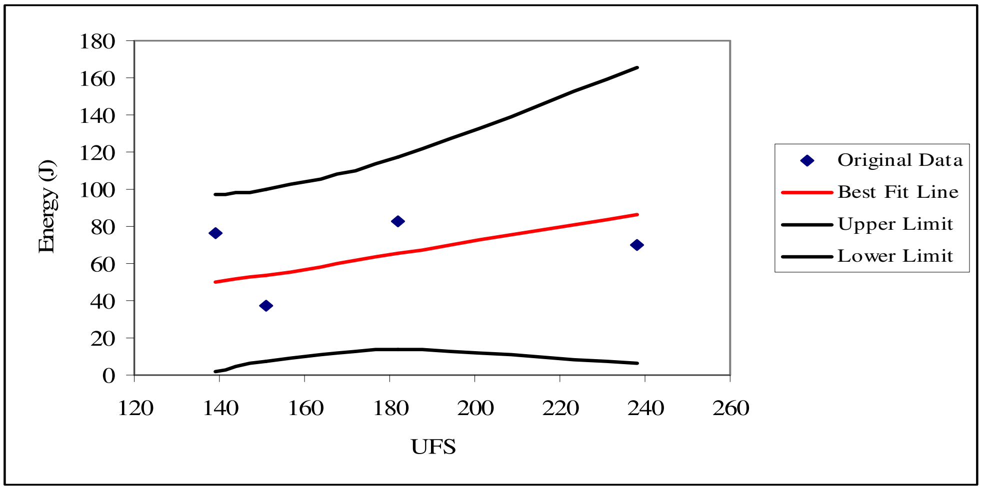

Figure 47. Energy absorption up to δ=3 mm vs. UFS for composites with macro steel fiber ZP 305

Although reasonable correlation coefficients were obtained, these results should be verified using toughness values calculated over full load deflection curves under high strain rates.

5.5.5 Multivariate Linear Regression Analysis on Mechanical Properties

($V_f l/d$), termed as fiber reinforcement ratio, is volume fraction times the aspect ratio of fiber. Using this parameter for the different fibers involved in this experimental program multiple linear regression analysis was performed and the following relationships were derived. MathCAD 11 Enterprise Edition was used for the multivariate linear regression analysis.

Composites with macro steel fiber RC 80/60

f_{comp} $= 37.21 + 2.25\ (V_f l/d)_R + 23.88\ (V_f l/d)_L - 0.18\ (V_f l/d)_D$

(R^2 = 0.93)

f_{flex} $= 4.8 + 3.33\ (V_f l/d)_R + 13.91\ (V_f l/d)_L\ -.0.05(V_f l/d)_D$

(R^2 = 0.82)

$E_{Failure}$ $= 3.86 + 40.11\ (V_f l/d)_R + 63.99\ (V_f l/d)_L + 1.02(V_f l/d)_D$

(R^2 = 0.97)

UFS $= 48 + 386.54\ (V_f l/d)_R + 517.79\ (V_f l/d)_L + 25.40\ (V_f l/d)_D$

(R^2 = 0.98)

Composites with macro steel fiber ZP 305

f_{comp} $= 37.21 + 4.86\ (V_f l/d)_Z + 27.58\ (V_f l/d)_L - 0.40\ (V_f l/d)_D$

(R^2 = 0.98)

f_{flex} $= 4.8 + 182.00\ (V_f l/d)_Z + 6.66\ (V_f l/d)_L + 0.09(V_f l/d)_D$

(R^2 = 0.87)

$E_{Failure}$ $= 3.86 + 31.65\ (V_f l/d)_Z + 97.61\ (V_f l/d)_L - 0.53\ (V_f l/d)_D$

(R^2 = 0.98)

UFS $= 48 + 230.31\ (V_f l/d)_Z - 25.38\ (V_f l/d)_L - 5.01\ (V_f l/d)_D$

(R^2 = 0.96)

Derived relationships have high correlation and tend to represent the raw data successfully. Observed trends are well emphasized on the derived relationships.

CHAPTER 6

CONCLUSIONS

After investigation of obtained results of this study, following conclusions are derived.

1. Slump test is not adequate to assess the consistency of FRC. Methods employing dynamic consolidation should be used in order to attain a clearer view of the effects of fiber inclusion and fiber hybridization on consistency.

2. Fiber inclusion of all types increased compressive strength, although this increase was not that significant and could have been obtained with simpler and more economical methods like reducing water-cement ratio. High strength micro steel fiber OL 6/16 proved to be efficient in strengthening the matrix. This result can be attributed to the high strength and relatively smaller dimensions of OL 6/16.

3. Flexural tensile strength was increased considerably with fiber reinforcement. Macro steel fiber RC 80/60, which has a higher aspect ratio than the other macro steel fiber ZP 305, was more effective in increasing flexural tensile strength. Combination of macro steel fibers with micro steel fiber OL 6/16 yielded the best results. Inclusion of micro polypropylene fiber Duomix caused a slight decrease in flexural tensile strength for composites with RC 80/60, whereas a slight increase was obtained in combination of ZP 305 with Duomix 20. However a synergetic response was not observed between OL 6/16 and Duomix 20 in neither of the mixes.

4. Energy absorption under flexural loading was greatly enhanced with fiber reinforcement. Macro steel fiber RC 80/60 was more efficient in enhancing energy absorption when compared with ZP 305. Combination of macro steel fibers with micro steel fiber OL 6/16 yielded the best flexural toughness

5. results. As mentioned previously OL 6/16 can successfully strengthen the matrix and pulling out of macro fibers from a matrix already reinforced with OL 6/16 requires more energy. In composites with RC 80/60 micro polypropylene fiber Duomix 20 also contributed to energy absorption with a lesser extent, but primary effect of Duomix 20 was providing ductility. In composites with RC 80/60, for a certain energy absorption value composites with Duomix 20 failed at greater deflections. However combination of ZP 305 with Duomix 20 had an adverse effect on energy absorption. A synergetic response in neither energy absorption nor ductility was observed between these fibers.

6. First crack strength under repeated drop weight impact test was not significantly affected with fiber reinforcement, but ultimate failure strength (UFS) was greatly enhanced. Macro steel fiber RC 80/60 was more efficient in increasing UFS when compared with ZP 305. Micro polypropylene fiber Duomix 20 performed well under dynamic loading and a synergetic response was observed between RC 80/60 and Duomix 20 as well as OL 6/16 and Duomix 20. In composites with ZP 305, highest UFS was obtained in composite simply reinforced with ZP 305 and combination with OL 6/16 and Duomix 20 resulted in declined UFS values.

7. Three different approaches were adopted to locate the first crack point, however varying results were obtained. In a broad view, micro steel fiber OL 6/16 increased load at first crack whereas micro polypropylene fiber Duomix 20 increased first crack deflection for composites with macro steel fiber RC 80/60. For composites with macro steel fiber ZP 305, neither OL 6/16 nor Duomix 20 significantly affected first crack deflection, nevertheless Duomix 20 caused a slight increase in first crack load.

8. Fitting function, general form of the serpentine curve, was found to be suitable to describe the experimentally obtained load deflection data, though estimations based upon the data generated from the fitting function should be verified with results obtained from full load deflection curves.

9. Fiber reinforcement ratio ($V_f l/d$) proved to be a suitable parameter in describing the mechanical properties of HFRC. Sufficiently high correlation coefficients were obtained through the use of this parameter. A relation between UFS and energy absorption under flexural loading, which could be used for practical applications, was sought and such relations were derived. Although reasonable correlation coefficients were obtained, obtained results should be verified using toughness values obtained from full load deflection curves under high strain rates.

Following remarks and recommendations can be made for studies in purpose of future excellence.

1. Flexural toughness should be determined using a testing machine with the capability of making deflection controlled loading. Primary effects of fiber inclusion and fiber hybridization are expected to occur in the post-crack zone and in order to obtain the post-crack portion of the load deflection curves such a setup is required.

2. Direct or indirect fiber pull out tests should be carried out in order to attain a clearer view on the behaviour of pulling out of a macro fiber from a matrix already reinforced with micro fibers. If such tests are performed, a relation between pull out stresses and flexural tensile strength or flexural toughness can be sought.

3. For repeated drop weight impact resistance tests, drop weight or drop height should be adjusted for convenience as the setup suggested by ACI results in very high drop numbers which make the test difficult to carry out and leads to highly variable results.

4. Objective procedures to locate the first crack point under flexural loading should be developed, so that results do not vary by whom the test is performed or evaluated.

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