STEEL FIBER REINFORCED CONCRETE MADE WITH FIBERS EXTRACTED FROM USED TYRES

BY

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A thesis submitted to

The Schools of Graduate Studies of Addis Ababa University

in partial fulfillment of the requirements for the Degree of

Master of Science in Civil Engineering

(Construction Technology and Management)

NOVEMBER 2009

ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

FACULTY OF TECHNOLOGY

DEPARTMENT OF CIVIL ENGINEERING

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DECLARATION

I the undersigned, declare that this thesis is my original work and has not been presented for a degree in any other university, and that all sources of materials used for the thesis have been duly acknowledged.

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ACKNOWLEDGEMENTS

Acknowledgements to all who have contributed to the completion of this thesis are not an easy task because so many people have participated in one way or another. To list them all will be difficult, but I would like to place in record my deep gratitude and indebtedness to my advisor Prof. Abebe Dinku (Dr. Ing.) for his precious advise, timely response, valuable comments and guidance. I owe my learning of concrete to him.

I wish to express my sincere thanks to Ato Daniel Kifle, Demis Melaku, Abiy Fanta and Liben Bekele from the Construction Material Testing Laboratory of Civil Engineering Department at Addis Ababa University for their devoted assistance from the preparation to testing of the concrete specimens. I also would like to thank Ato Tasew Mekuria and Masresha Wendimu from the Mechanical Engineering Workshop of Addis Ababa University for their technical assistance. My special thanks are also due to Ato Melese and Bisrat for cutting the steel fibers to the required length and for making them available on time.

My sincere gratitude goes to Ato Alemayehu Emiru, Matador Addis Tyre Research and Development Manager, and W/ro Abay Gosaye for sharing their experience with no restriction, for providing the relevant data and for allowing me to carry out the tensile strength of the steel fibers at their laboratory. My special thanks also go to at Yohannes G. Kidan, Messebo Cement Factory Quality Control Manager for providing the quality control certificate.

I gratefully acknowledge Addis Ababa University and ENYI Construction for sponsoring the partial sum of the research expense. I am also thankful to Messay Yohannes and Elias Ahmed for printing all the number of copies required.

Last but not list, my gratefulness is due to all member of my family, friends, colleagues and all my well wishers for their whole hearted cooperation, inspiration and encouragement without which it would have been not only difficult but impossible to complete this work.

Nasir Bedewi

ABSTRACT

Concrete is considered a brittle material, primarily because of its low tensile strength and low tensile strain capacity. The low tensile strength of concrete is due to internal flaws and micro-cracks present in the concrete. The use of randomly distributed, discrete fibers to improve the mechanical properties of the matrix is an age-old and intuitive concept. Recently, worldwide researches have been devoted to the use of steel fibers recovered from used tyres in concrete. The concrete obtained by adding these fibers evidenced a satisfactory improvement of the fragile matrix, mostly in terms of toughness and post cracking behavior. As a consequence steel fibers extracted from used tyres appear to be a potential candidate for steel fiber reinforced concrete.

To this effect this research work was undertaken aiming to investigate the mechanical behavior of concrete reinforced with steel fibers recovered from used tyres and to quantify the benefits obtained by the concept of SFRC over conventional concrete. For this purpose a bead wire having a diameter of 0.89 mm extracted from burnt used tyres was used and three grades of SFRC namely C-25, C-40 and C-60 were produced incorporating three different volumes of fiber i.e. 0.5%, 1.0%, and 1.5%. Furthermore each volume fraction enclosed three different fiber lengths namely 20mm, 40mm and 60mm. For comparison purposes, plain control samples were also considered. The test program included slump test, compressive strength test, impact resistance test, flexural tensile strength and toughness tests including load-deflection curve, determination of first-crack point, and toughness index.

Workability of fresh concrete was largely influenced by the presence of steel fiber; on the other hand it was unlikely to achieve considerable improvements in compressive strength by steel fiber inclusion. Due to the addition of fibers, the flexural tensile strength and the post-crack energy absorption capacity were greatly increased. As far as impact test is concerned both the first crack and ultimate failure strength were enormously improved. The interesting results confirm the promising application of concrete reinforced with steel fibers extracted from used tyres. However, further, research work is still necessary in order to have a more in-depth understanding of the material properties and to evaluate possible practical applications.

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LIST OF ABBREVATIONS

ACI	American Concrete Institute
AR	Alkali Resistant
ASTM	American Standard Testing Method
BS	British Standard
DOE	Department of Environment
ES	Ethiopian Standard
FC	First Crack
FRC	Fiber Reinforced Concrete
GFRC	Glass Fiber Reinforced Concrete
HM	High Modulus
HRWR	High Range Water Reducing Agent
HT	High Tension
ISF	Industrial Steel Fiber
J	Joule
JSCE	Japan Society of Civil Engineers
KJ	Kilo Joule
kN	Kilo Newton
LOI	Loss of Ignition
MPa	Mega Pascal
N/A	Not Available
NFRC	Natural Fiber Reinforced Concrete
PPC	Portland Pozzolana Cement
PPF	Polypropylene Fiber
PRSF	Pyrolysed Recycled Steel Fibers
RCC	Reinforced Cement Concrete
RH	Relative Humidity
RSFRC	Recycled Steel Fiber Reinforced Concrete
SFRC	Steel Fiber Reinforced Concrete
SIFCON	Slurry Infiltrated Fiber Concrete

SNFRC	Synthetic Steel Fiber Reinforced Concrete
SP	Super Plasticizers
SRSF	Shredded Recycled Steel Fiber
SSD	Saturated Surface Dry Condition
VSF	Virgin Steel Fiber
w/c	Water to Cement ratio

CHAPTER ONE

INTRODUCTION

1.1 GENERAL

Cement concrete lends itself to a variety of innovative designs as it can be cast to any desired shape. It also possesses many desirable properties like high compressive strength and stiffness and low thermal and electrical conductivity. However three of its characteristics viz. low tensile strength, limited ductility and little resistance to cracking have limited its use for various applications. Internal micro cracks are inherently present in the concrete and its poor tensile strength is due to the propagation of such micro cracks, eventually leading to brittle fracture of the concrete [1-2].

In the past, attempts have been made to impart improvements in tensile properties of concrete members by way of using conventional reinforced steel bars and also by applying restraining techniques. Although both these methods provide tensile strength to the concrete members, they however do not increase the inherent tensile strength of the concrete itself [2]. Even though the concept of reinforced cement concrete (RCC) has eliminated one of the major weaknesses of concrete (inability to resist tensile forces), it still falls short of many more desirable properties like toughness, ductility, controlling of cracking and energy absorption. This is basically because the reinforcement component in RCC is present in certain pockets of the cross-section of the structural member. In order to achieve all the above mentioned properties it is essential to distribute the reinforcement uniformly throughout the cross-section. Such a way of reinforcing the brittle matrix is possible by adding to the constituents of the concrete mix, short fibers of small diameter that are either metallic or nonmetallic. This new material with improved mechanical properties is called “Fiber reinforced concrete” [1-2]. 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.

The use of fibers in building materials to improve their behavior is an old and intuitive concept. Our ancestors have been adding straw fibers to a mud in wall construction to create a composite with a better performance. In modern times, a wide range of engineering materials (including ceramics, plastics, cement, and gypsum products) incorporate fibers to enhance composite properties. The enhanced properties include tensile strength, compressive strength, elastic modulus, crack resistance, crack control, durability, fatigue life, resistance to impact and abrasion, shrinkage, expansion, thermal characteristics, and fire resistance [3].

Experimental trials and patents involving the use of discontinuous steel reinforcing elements-such as nails, wire segments, and metal chips-to improve the properties of concrete date from 1910. During the early 1960s in the United States, the first major investigation was made to evaluate the potential of steel fibers as a reinforcement for concrete [3]. Since then, a substantial amount of research, development, experimentation, and industrial application of steel fiber reinforced concrete has occurred. However, the application and use of fiber reinforced concrete in Ethiopian context is limited only to text books.

The use of FRC worldwide has been increasing steadily in recent years. As of 2001, over 76 million m^3 of FRC were produced annually, with the principal applications being ground slab (60%), shotcrete (25%), and precast members (5%), and the remainder of the production distributed among a number of other specialty structural forms [4]. But sadly Ethiopia's share in the annual FRC production is nil.

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 [5].

There are numerous fiber types available for commercial and experimental use. 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. Steel fiber is the most often used fiber in fiber reinforced concrete [5].

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. Now a days Steel fibers extracted from used tyres is seen as a potential contestant for steel fiber reinforced concrete.

Waste tires have been a major International waste management problem for a few decades and in some cases have involved serious environmental pollution, particularly when large numbers catch fire. Even if there is no any recorded data of waste tyre for Ethiopian case it is estimated that 450,000 tones of tires are discarded annually in the UK, with over 100,000 worn tires taken off vehicles every day. Of these: 50,000 tones are retreaded, 172,000 tones go to material recovery and 71,000 tones go to energy recovery [6]. Even though tire recycling is very much undermined in Ethiopian case, used tire is a very re-usable material. There are many applications for the re-use, recycling and recovery of used tires: from recovering energy as kiln fuel in the production of cement, to creating recycled rubber sports and playground surfaces, to engineering uses such as fiber reinforced concrete production and landfill engineering. Even if scrap tires are seen more than a waste in developed countries its application in Ethiopia is very much limited to minor uses and no effort has been made to adopt end-use applications of scrap-tire. Lately several investigations and researches have been carried out to determine the current and potential end-use applications for scrap-tire-derived steel and fiber materials in the UK and other European countries.

Recently some researches have been devoted to the use of steel fibers recovered from waste tyres in concrete. The concrete obtained by adding this fiber evidenced a satisfactory improvement of the fragile matrix, mostly in terms of toughness and post cracking behavior. In addition, it was indicated that the mechanical behavior of concrete reinforced with fibers extracted from used tyres is comparable to that of conventional steel fiber reinforced concrete. As a consequence recycled steel fiber reinforced concrete (RSFRC) appears to be a promising candidate for both structural and non-structural applications [24].

To this effect, a research project was undertaken aiming to investigate the mechanical behavior of concrete reinforced with steel fiber recovered from used tyres.

1.2 OBJECTIVE OF THE THESIS

The overall objective of this study is first to develop steel fiber reinforced concrete (SFRC) using steel fibers extracted from used tires and then to characterize the mechanical properties, especially the mechanical properties in the hardened state and quantify the benefits obtained by the concept of SFRC over conventional concrete. Compressive strength, flexural tensile strength, toughness in bending and impact resistance will be measured to determine the mechanical properties of the SFRC mixes in this study.

Furthermore, while conducting the flexural toughness test, the toughness indices will be determined for the different SFRC mixes. In addition, effects of fiber volume, fiber type, concrete strength and fiber length (the aspect ratio) will be studied for the above mentioned mechanical properties of the SFRC mixes.

1.3 RESEARCH SIGNIFICANCE

Results obtained from this study are expected to contribute to the efforts made to characterize the mechanical properties of SFRC and more over to open new concrete application areas in the Ethiopian construction industry.

SFRC can be used on account of the advantage of increased static and dynamic tensile strength, energy absorbing characteristics and better fatigue strength. Also the uniform dispersion of steel fibers throughout the concrete provides isotropic properties not common to conventionally reinforced concrete. Nonetheless, where the additional cost can be justified, SFRC could have an important role to play in modern concrete technology. Therefore the possible application areas for the study are listed as follows:

- It can commonly be used in industrial floors to reduce damage due to abrasion and impact.
- It can be applied in heavy machinery foundations to minimize damage due to vibration and dynamic load.
- It can be used for pavements and for highways and airport runways overlays, to reduce both thickness and cracking.
- It could commonly be used for the fabrication of precast products like pipes, beams, stair case steps, wall panels, roof panels, manhole covers, permanent formworks etc…
- It can also be used for tunnel linings and in concrete repair applications.

It is obvious that all the stake holders in the construction industry will definitely benefit from this study. And it will also encourage tyre factories to think of side business for tyre recycling as the economic benefit is obvious. It will also provide sustainable markets for recycled steel fiber and it will encourage material recovery of large amounts of tires.

1.4 METHODOLOGY

The research started off with problem identification which is done through a brief literature reading. Upon obtaining the identified problem a thorough literature review was conducted to provide an in depth understanding on Steel Fiber Reinforced Concrete, focusing on Mechanical properties of SFRC, fresh properties of SFRC, durability of SFRC, mix design considerations for SFRC, mixing, placing and finishing of SFRC and practical application of SFRC.

Since the research specifically emphasizes on steel fiber reinforced concrete extracted from used tyres, the literature review will provide further understanding on the use of waste tyre products in the construction industry, the different recycling methods of steel fibers from waste tyre and the use of recycled steel fibers for the production of SFRC.

Measurement of properties of SFRC is very important for practice as well as for research efforts. Therefore an overview of currently available and modified test methods used to evaluate the toughness and impact resistance of SFRC will also be provided as a supplement to the literature review. The advantages and shortcomings of these test methods will also be discussed.

Furthermore it is aimed in this research to produce SFRC and then to characterize its properties, especially the mechanical properties in the hardened state. A bead wire having a diameter of 0.89 mm extracted from burnt used tires was used. Concrete specimens having a grade of C-25 from normal strength, C-40 from intermediate strength and C-60 from High strength SFRC will be produced incorporating three different volume fractions which are 0.5%, 1.0% and 1.5%; each volume fraction will include three different fiber lengths namely 20, 40 and 60mm.

Initially, important tests will be conducted on the constituent material to determine the gradation and physical properties of fine and coarse aggregate, chemical composition and other characteristic of cement and properties of steel fibers. After carrying out tests on the fresh concrete the specimens for the testing of mechanical properties in the hardened state will be prepared by pouring the concrete into lubricated moulds. For each mix, three 150mm cubes, two 150x300mm cylinders, and two 100x100x500mm beams will be casted. Cubes will be used for the determination of compressive strength. The cylinder specimens will be cut into 150x63mm discs which will be used to determine the impact resistance. Beam specimens will be used for the determination of flexural tensile strength and flexural toughness.

After carrying out the tests the results obtained will be discussed and analysis will be made. Finally conclusions will be made and recommendations for future studies will be forwarded.

1.6 STRUCTURE OF THE RESEARCH

The thesis is structured into six chapters and each chapter contains a number of sections and further subsections. A general introduction is provided along with the research objective, significance and methodology in the first chapter. In Chapter Two a comprehensive review of fiber reinforced concrete is presented. The different fiber types available along with their properties and current applications are addressed. Furthermore, the aspects of fiber-matrix bond, properties of FRC and factors which affect these properties along with measurement of some of the properties are briefly discussed.

Chapter Three is especially dedicated to steel fiber reinforced concrete. This chapter is structured into two major parts namely fundamentals of steel fiber reinforced concrete and steel fibers extracted from used tyres as reinforcement in SFRC. In the first part; types, properties and manufacturing methods for steel fibers are explained. Effects of steel fiber inclusion on concrete in the hardened and fresh states are overviewed. Durability characteristics of steel fiber reinforced concrete (SFRC) are briefly mentioned. Mix design recommendations, mixing, placing, compaction, and finishing techniques and practical applications of SFRC are also summarized. Since the construction of a tyre and composition is relevant to the recovering of steel fibers, it is discussed in part two of this chapter. A general highlight on applications for used tyres is also provided in this section. Available literatures and finding of some research works relevant with the use of steel fibers extracted from used tyre as concrete reinforcement are also briefly summarized.

Chapter Four deals with the experimental program of the 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 Five. General and specific conclusions are given in chapter Six together with recommendations for further research work. This will be followed by an extensive list of references. The Annexes A to J give the results of the individual tests, other relevant data and representative photos taken during the research work.

Data is presented in three different formats in this thesis. Graphs are used to show trends and to highlight possible relationships. Tables are used to present statistical analysis of the data collected. These two formats appear in the body of the text close to their point of reference as possible, but not necessarily on the same page. Other important data are recorded in the annexes for cross- referencing.

CHAPTER TWO

COMPREHENSIVE REVIEW OF FIBER REINFORCED CONCRETE

2.1 GENERAL

Fiber reinforced concrete (FRC) is concrete made primarily of hydraulic cements, aggregates, and discrete reinforcing fibers. The reinforcement is in the form of short fibers of small diameter distributed throughout the matrix. Fibers suitable for reinforcing concrete have been produced from steel, glass, and organic polymers (synthetic fibers). Naturally occurring asbestos fibers and vegetable fibers, such as sisal and jute, are also used for reinforcement. The concrete matrices may be mortars, normally proportioned mixes, or mixes specifically formulated for a particular application. Generally, the length and diameter of the fibers used for FRC do not exceed 76 mm and 1 mm, respectively [3].

By its very definition reinforcement is supposed to induce an increase in strength in the reinforced material (i.e. the matrix). In order to be effective in concrete matrix, the fibers must have the following properties:

a) Tensile strength significantly higher than that of concrete (two to three orders of magnitude),
b) Bond strength with concrete matrix preferably of same order as or higher than the tensile strength of matrix,
c) The elastic modulus in tension to be significantly higher than that of concrete, and
d) The poison’s ratio and the coefficient of thermal expansion should preferably be of the same order as that of the matrix [1].

Brittle materials are considered to have no significant post-cracking ductility. Fibrous composites have been and are being developed to provide improved mechanical properties to otherwise brittle materials. When subjected to tension, these unreinforced brittle matrices initially deform elastically. The elastic response is followed by microcracking, localized macrocracking, and finally fractures. Introduction of fibers into the concrete results in post-elastic property changes that range from subtle to substantial, depending upon a number of factors, including matrix strength, fiber type, fiber modulus, fiber aspect ratio, fiber strength, fiber surface bonding characteristics, fiber content, fiber orientation, and aggregate size effects. For many practical applications, the matrix first-crack strength is not increased. In these cases, the most significant enhancement from the fibers is the post-cracking composite response. This is most commonly evaluated and controlled through toughness testing [3].

The historical background, the different fiber types available to make FRC along with its applications, the basic difference with the conventional concrete, mechanism of the fiber matrix bond, properties of FRC and factors which affect its properties, measurement of the properties and the economic evaluation will be discussed briefly in the sections to follow.

2.2 HISTORICAL BACKGROUND

Since ancient times, fibers have been used to reinforce brittle materials. Straw was used to reinforce sun-baked bricks, and horsehair was used to reinforce masonry mortar and plaster. A pueblo house built around 1540, believed to be the oldest house in the U.S., is constructed of sun-baked adobe reinforced with straw [3]. In more recent times, large scale commercial use of asbestos fibers in a cement paste matrix began with the invention of the Hatschek process in 1898. Asbestos cement construction products are widely used throughout the world today. However, primarily due to health hazards associated with asbestos fibers, alternate fiber types were introduced throughout the 1960s and 1970s [3].

Experimental trials and patents involving the use of discontinuous steel reinforcing elements - such as nails, wire segments, and metal chips - to improve the properties of concrete date from 1910. During the early 1960s in the United States, the first major investigation was made to evaluate the potential of steel fibers as a reinforcement for concrete. Since then, a substantial amount of research, development, experimentation, and industrial application of steel fiber reinforced concrete has occurred [3].

Use of glass fibers in concrete was first attempted in the former USSR in the late 1950s. It was quickly established that ordinary glass fibers, such as borosilicate E-glass fibers, are attacked and eventually destroyed by the alkali in the cement paste. Considerable development work was directed towards producing a form of alkali-resistant glass fibers containing zirconia. This led to a considerable number of commercialized products [3].

Initial attempts at using synthetic fibers (nylon, polypropylene) were not as successful as those using glass or steel fibers. However, better understanding of the concepts behind fiber reinforcement, new methods of fabrication, and new types of organic fibers have led researchers to conclude that both synthetic and natural fibers can successfully reinforce concrete [3].

Considerable research, development, and applications of FRC are taking place throughout the world. Industry interest and potential business opportunities are evidenced by continued new developments in fiber reinforced construction materials. These new developments are reported in numerous research papers, international symposia, and state-of-the-art reports issued by professional societies.

2.3 FIBER TYPES

Fiber is a small piece of reinforcing material possessing certain characteristic properties. They can be circular or flat. The fiber is often described by a convenient parameter called “aspect ratio”. The aspect ratio of the fiber is the ratio of its length to its diameter. Typical aspect ratio ranges from 30 to 150 [2].

Although every type of fiber has been tried out in cement and concrete, not all of them can be effectively and economically used. Each type of fiber has its characteristic properties and limitations. There are numerous fiber types available for commercial and experimental use. The basic fiber categories are steel, glass, synthetic and natural fiber materials. Specific descriptions of these fiber types along with their physical property and applications are discussed in sections-2.3.1 through 2.3.5 while chapter 3 is specifically dedicated to steel fiber reinforced concrete.

2.3.1 Glass Fibers

Glass fiber is a predominantly used mineral fiber. Glass fibers are silica based glass compounds that contain several metal oxides, which can be tailored to manufacture different types of glasses. Glass fibers are produced in the process in which molten glass is drawn, in the form of filaments, through the bottom of a heated platinum tank or bushing. Most commonly, 204 filaments are drawn simultaneously; after solidification, they are collected into a strand consisting of the 204 filaments. Glass fibers are available both as “chopped strand” and as a continuous roving [1, 5].

Glass fibers have relatively high tensile strength and modulus of elasticity compared to polymeric fibers. Furthermore they are quite economical and hence are the most commonly used fibers for structural applications. In the initial stages borosilicate glass fibers (E-glass) and soda-lime-silica glass fibers (A-glass) were employed to reinforce cement based composites. Since both E-glass and A-glass fibers were found to lose their strength property in the alkaline environment of cement based composites (pH $\geq$ 12.5), the need for alkali resistant fibers resulted in the development of Alkali-resistant glass (AR-glass) fibers. Table 2.1 gives the strength and elastic properties of some selected glass fibers [1].

Using the conventional mixing technique for normal concrete, it is not possible to mix more than about two percent by volume of fibers of length up to 25 mm. One of the most important improvements in the property achieved by glass fiber is the spectacular improvement in impact strength of up to 1500 percent can be registered as compared to other materials, such as plain concrete. With a two percent fiber content (up to 25 mm in length), the flexural strength is almost doubled. The second important improvement is in the resistance in the thermal shock. The ductility also improves along with the increase in strength and modulus of rupture [1].

By far, the single largest application of glass fiber reinforced concrete (GFRC) has been the manufacturing of exterior building facade panels. A growing application for GFRC is building restoration, replacing existing walls and ornate tile facades capitalizing on the light weight and shape versatility of the composite [3]. However, the use of glass fibers in Ethiopia is very much limited to the manufacturing of water tankers.

Table-2.1 Physical Properties of some selected glass fibers [1].

Property	A-Glass	E-Glass	AR-Glass
Specific gravity	2.46	2.54	2.7
Tensile strength, MPa	3030	3450	2480
Modulus of Elasticity, MPa	64,800	71,700	80,000
Strain at break, %	4.7	4.8	3.6

2.3.2 Synthetic Fibers

Synthetic fibers are man-made fibers resulting from research and development in the petrochemical and textile industries. They have become increasingly common in recent years. Synthetic fiber reinforced concrete (SNFRC) utilizes fibers derived from organic polymers which are available in a variety of formulations. The fiber types that have been explored for use in cement based matrices are acrylic, aramid, carbon, nylon, polyester, polyethylene and polypropylene. Even though these fibers have reasonably high tensile strength, the modulus of elasticity of most of them is quite low (except for aramid). Table 2.2 gives a summary of physical properties of various polymeric fibers. Fibers that contain at least 85% by weight of acrylonitrile are classified as acrylic fibers. Nylon was one of the first of the polymer fibers to be included in cement based matrices. However when used in small volumes (< 1% volume fraction of composite) it has been found to reduce the flexural strength of the composite. Compared with other polymeric fibers, aramid fibers have higher tensile strength and modulus of elasticity and hence they can enhance the mechanical properties like tensile and bending strength of the composite. The primary limitation for their use is in concrete is their high cost compared to other fibers. Carbon fibers are the most expensive of all the fibers. This is due to the increased cost of manufacturing process as well as the increased cost of raw materials required for their manufacture [1].

Commercial use of SNFRC currently exists worldwide, primarily in applications of cast-in-place concrete (such as slabs-on-grade, pavements, and tunnel linings) and factory manufactured products (such as cladding panels, siding, shingles, and vaults) [3]. Among the polymeric fibers high performance micro polypropylene fiber also known by its commercial name Fosroc PPF is introduced to Ethiopian construction practice by ABHAM Enterprise. This fiber is primarily used as a crack controlling additive for cementitious materials principally for concrete repairing.

Table-2.2 Selected synthetic fiber types and properties [3].

Fiber Type	Equivalent diameter, [mm x 10^{-3}]	Specific gravity	Tensile strength, [MPa]	Elastic Modulus, [MPa]	Ultimate Elongation, [%]
Acrylic	12.7-104.1	1.16-1.18	269-1000	13,800-19,300	7.5-50
Aramid I	11.9	1.44	2930	62,100	4.4
Carbon, PAN HM	7.6	1.6-1.7	2480-3033	379,900	0.5-0.7
Carbon, PAN HT	8.9	1.6-1.7	3450-4000	230,293	1.0-1.5
Nylon	22.9	1.14	965	5,170	20
Polyester	19.8	1.34-1.39	228-1100	17,238	12-150
Polyethylene	25.4-1,016	0.92-0.96	76-586	5,000	3-80
Polypropylene	-	0.90-0.91	138-690	3,448-4,827	15

2.3.3 Natural Fibers

Since in many parts of the world manmade fibers like steel or polymeric fibers are not available, attempts have been made to incorporate naturally occurring fibers extracted from plants in cement based composites. A unique aspect of these fibers is the low energy needed for their extraction. A major problem in the use of these fibers in cement/concrete matrix is that they disintegrate in the alkaline environment and hence durability of the composite is the matter of concern. Since these fibers are economical, attempts have been made to overcome the problem of durability either by use of admixtures in concrete to reduce its alkalinity or by protecting fibers by some special treatment [1].

Although historically many fibers have been used to reinforce various building materials, until recently little scientific efforts have been devoted to the use of natural fibers for reinforcement. The use of some of the best known natural fibers such as sisal, coconut, sugarcane bagasse, elephant grass, palm, etc., have mostly been limited to the production of fabrics, ropes, mats, etc. [3]. The physical properties of some of these fibers are presented in Table 2.3. Even though these fibers are sufficiently strong in tension, their modulus of elasticity is quite low.

Table-2.3 Typical properties of Some Naturally Occurring fibers [3].

Fiber type	Coconut	Sisal	Sugarcane Bagasse	Bamboo	Jute	Elephant grass	Wood fiber
Fiber length, (mm)	51-52	N/A	N/A	N/A	7-12	N/A	2.5-5.1
Fiber diameter, (mm)	0.10-0.41	N/A	0.2-0.41	0.05-0.41	0.1-0.2	N/A	0.03-0.08
Specific gravity	1.12-1.15	N/A	1.2-1.3	1.5	1.02-1.04	N/A	1.5
Modulus of elasticity,(MPa)	19-26	13-26	15-19	33-40	26-32	4.9	N/A
Ultimate tensile strength, (MPa)	120-200	276-568	184-290	350-500	250-350	178	700
Elongation at break, (%)	10-25	3-5	N/A	N/A	1.5-1.9	3.6	N/A
Water absorption, (%)	130-180	60-70	70-75	40-45	N/A	N/A	50-75

Concretes reinforced with naturally occurring fibers are generally termed natural fiber reinforced concrete (NFRC). In Africa, sisal fiber reinforced concrete has been used extensively for making roof tiles, corrugated sheets, pipes, silos, and gas and water tanks. Elephant grass fiber reinforced mortar and cement sheets are being used in Zambia for low-cost house construction, while wood and sisal fibers are being used for making cement composite panel lining, eaves, soffits, and for sound and fire insulation [3]. Lately, In Ethiopia sugarcane bagasse is used together with fiberglass in the production of agrostone products. So far the agrostone products are partition boards, decoration reliefs and internal doors.

2.4 FIBER REINFORCED VERSUS CONVENTIONALLY REINFORCED CONCRETE

Unreinforced concrete has a low tensile strength and a low strain capacity at fracture. These shortcomings are traditionally overcome by adding reinforcing bars or prestressing steel. In contrast to reinforcing bars in reinforced concrete which are continuous and carefully placed in the structure to optimize their performance, the fibers are discontinuous and are generally randomly distributed throughout the concrete matrix. As a result, the reinforcing performance of steel fibers is inferior to that of reinforcing rods. In addition, the fibers are likely to be considerably more expensive than conventional steel rods [4, 7].

It must be emphasized that, in general, fiber reinforcement is not a substitute for conventional steel reinforcement. Fibers and steel reinforcement play different roles in concrete: Reinforcing bars are used to increase the load bearing capacity of structural concrete members, while fibers are more effective for crack control. There are many applications in which fibers can be used effectively in conjunction with conventional reinforcement to improve the behavior of structural components, for instance when the concrete is to be subjected to blast or impact loading in seismic applications [4, 7].

2.5 FIBER-MATRIX BOND

For a composite system such as FRC, the mechanical behavior depends not only on the properties of the fibers and the cementitious systems, but also on the bonding between them. For properly designed FRC mixtures, the primary mode of failure is by fiber pullout, since this consumes much more energy than is involved in breaking the fibers and leads to much better utilization of the fibers. For steel fibers, there is a combination of adhesion, friction, and mechanical interlock. For glass fibers, there is chemical reaction between the cement and the glass; in particular, alkali attack tends to weaken the fiber reinforcement, though to a much lesser extent with the alkali resistant glasses. With the organic fibers, the bond is primarily due to mechanical interlock [4, 7].

In contrast to fiber composites in resin and metal matrices where the fibers are aligned and amount to 60 to 80 percent of composite volume, FRC contains much less fibers which are randomly oriented. The tensile cracking strain of cement matrix (less than 1/50) is very much lower than the yield or ultimate strain of steel fibers, as a result, when a fiber reinforced composite is loaded, the matrix will crack long before the fibers can be fractured. Once the matrix is cracked the composite continues to carry increasing tensile stress; the peak stress and strain of the composite are greater than those of the matrix alone and during the inelastic range between first cracking and the peak, multiple cracking of matrix occurs as indicated in Fig. 2.1. Until the initial cracking of the matrix, it is reasonable to assume that both the fibers and the matrix behave elastically and there is no slippage between the fibers and the matrix. After the first cracking of the matrix, the composite will carry increasing loads only if the pullout resistance of fibers at the first crack is greater than the load at first cracking, since in the post-cracking stage, the failure of the composite is generally by fiber-pullout rather than fiber-yielding or fracture. Table 2.4 shows typical pullout strengths for a number of different fibers in various matrices [7].

Table 2.4 Typical fiber-matrix pullout strength [4].

Matrix	Fiber	Pullout strength [MPa]
Cement paste	Asbestos	0.8-3.2
	Glass	6.4-10.0
	Polycrystalline alumina	5.6-13.6
	Steel	6.8-8.3
Mortar	Steel	5.4
Concrete	Steel	3.6 (first crack)
		4.2 (failure)
	Nylon	0.14
	Polypropylene	1.0

In FRC, the fracture is a continuous process and the cracking occurs over a wide range of loading and the de-bonding of fibers over several stages. The bond or the pullout resistances of fibers depend on the average bond strength between the fibers and the matrix, the number of fibers crossing the crack, and the length and diameter of the fibers [4, 7].

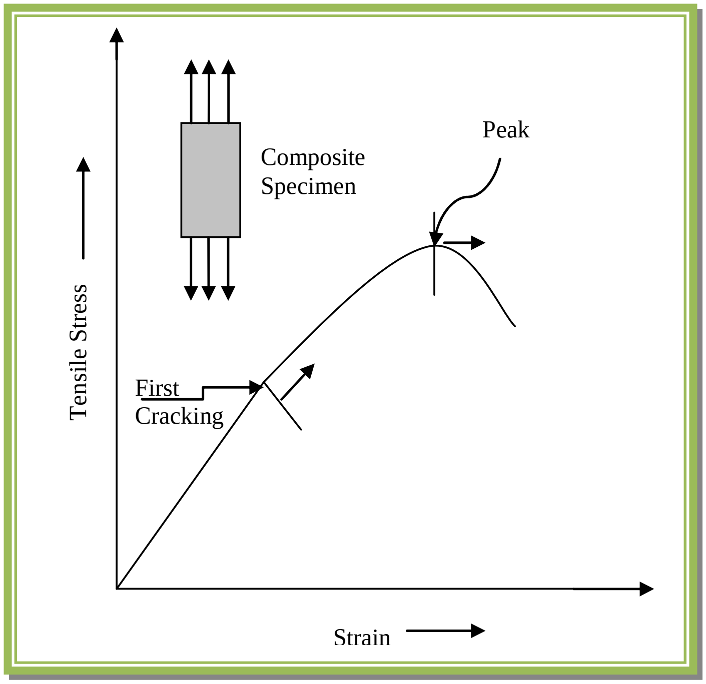


Fig. 2.1 Behavior of Fiber Reinforced Concrete under Tensile Load [7].

2.6 PROPERTIES OF FIBER RENFORCED CONCRETE

2.6.1 Strength

It cannot be emphasized too strongly that, at the fiber volumes used in normal commercial application, *the role of fiber is not to increase strength*, though modest strength increases may occur. If what is desired is a strength increase, it is clearly much easier (and much cheaper) simply to redesign the plain concrete mix, primarily by reducing the w/c ratio.

Similarly, fibers have no significant effects on either the shear strength or the torsional strength of concrete. They also have no particular on the elastic modulus [4].

2.6.2 Toughness

The principal role of the fibers is to bridge across the cracks that develop in concrete as it is loaded (or as it dries). If the fiber has sufficient strength and stiffness, and if they can achieve sufficient bond with the matrix, they will tend to keep the crack widths small and will permit the FRC to withstand significant stresses over a relatively large strain capacity in the post-cracking (or strain softening) stage. Thus, the fibers can provide a considerable amount of post-cracking "ductility." In other words, they increase the toughness of the FRC [4].

2.6.3 Impact Resistance

The impact resistance of plain concrete, which is quite low, can be increased dramatically (by more than an order of magnitude) by the addition of fibers. Steel and carbon fibers are more effective in this regard than synthetic fibers, but all types of fibers increase both the fracture energy and generally the peak loads under impact. Related to impact resistance, it is generally found that fiber additions also improve both the abrasion resistance and the resistance of concrete to cavitation damage [4].

2.6.4 Fatigue

The flexural fatigue strength of plain concrete (out to 2 million cycles of loading) is about 55% of the static strength, for all types of loading. A properly designed FRC, however, will display fatigue strengths of from 65% to 90% of the static load. This improvement is due largely to the effectiveness of the fibers in "tying" the cracks together, and thus inhibiting crack extension during the loading cycles [4].

2.6.5 Creep and Shrinkage

Up to fiber volumes of about 1%, fiber additions have little or no effect on either the creep characteristics or the drying shrinkage of concrete, though they tend to reduce the crack widths significantly during shrinkage. However fibers can be very effective in reducing the plastic shrinkage. Indeed, this is one of the principal uses of polypropylene fibers in modern FRC technology [4].

2.6.6 Durability

Durability is as important as strength in determining the suitability of concrete for any specific application. Generally, durable concrete should be dense and impermeable. It has been found that well made FRCs are slightly less permeable than plain concrete, though the decrease is not large enough to have a significant effect on the overall durability of the concrete.

Synthetic fibers are not subject to corrosion. Steel fibers may, of course, rust. However, it has been found that for good quality FRC, this rusting is confined to the “skin” of the concrete; fibers in the interior of the concrete are protected by the alkaline environment. Thus, even with steel fibers, corrosion leads only to cosmetic effects. If this is a problem in a particular application, stainless steel may be used (though at a considerable increase in cost)

As mentioned earlier under section 2.3.1, ordinary E-glass will be attacked by the alkaline environment, and even FRC made with alkali-resistant glass to show some degradation in properties of over time. Natural organic fibers are likely to suffer from alkaline, bacterial, or fungus degradation and require special treatment if they are to be used widely in FRC [3, 4].

2.7 FACTORS AFFECTING PROPERTIES OF FIBER REINFORCED CONCRETE

Fiber reinforced concrete is the composite material containing fibers in the cement matrix in an orderly manner or randomly distributed manner. Its properties would obviously, depend upon the efficient transfer of stress between matrix and the fibers, which is largely dependent on the type of fiber, fiber geometry, fiber content, orientation and distribution of the fibers, mixing and compaction techniques of concrete, and size and shape of the aggregate. These factors are briefly discussed in the following sections.

2.7.1 Relative Fiber Matrix Stiffness

The modulus of elasticity of matrix in most cases is lower than that of fiber for efficient stress transfer. Low modulus of fibers such as nylons and polypropylene are, therefore, unlikely to give strength improvement, but they help in the absorption of large energy and, therefore, impart greater degree of toughness and resistance to impact. High modulus fibers such as steel, glass and carbon impart strength and stiffness to the composite [2].

Interfacial bond between the matrix and the fibers also determine the effectiveness of stress transfer, from the matrix to the fiber. A good bond is essential for improving tensile strength of the composite. The interfacial bond could be improved by larger area of contact, improving the frictional properties and degree of gripping and by treating the steel fibers with sodium hydroxide or acetone [2].

2.7.2 Volume of Fibers

The strength of the composite largely depends on the quantity of fibers used in it. Fig. 2.2 and 2.3 show the effects of volume on the toughness and strength. It can be seen from Fig. 2.3 that the increase in the volume of fibers, increase approximately linearly, the tensile strength and toughness of the composite. It has been reported that the use of higher percentage of fibers is likely to cause segregation and harshness of concrete and mortar [2].

2.7.3 Aspect Ratio of the Fiber

Another important factor which influences the properties and behavior of the composite is the aspect ratio of the fiber. It has been reported that up to an aspect ratio of 75, increase in the aspect ratio increases the ultimate strength of the concrete linearly. Beyond 75, relative strength and toughness is reduced. Table 2.5 shows the effects of aspect ratio on strength and toughness [2].

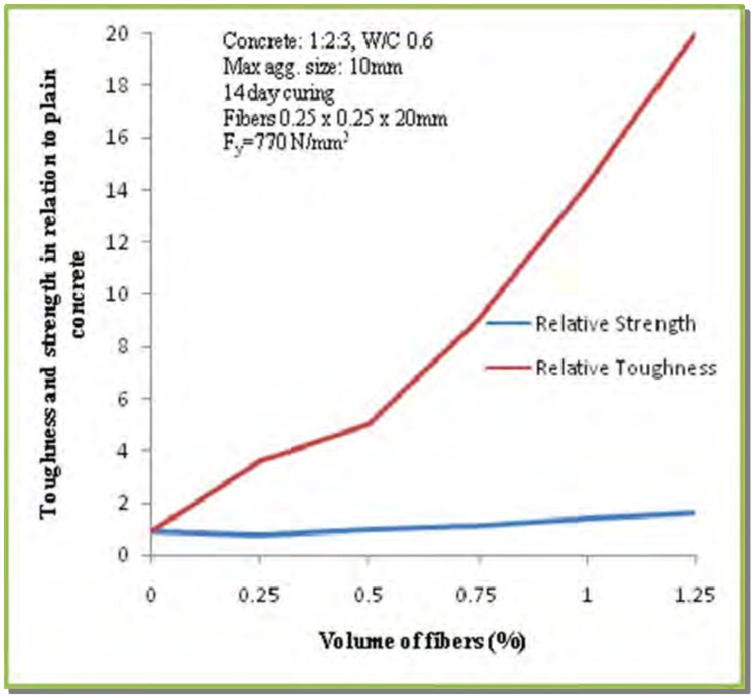


Fig 2.2 Effects of volume of fibers in Flexure [2].

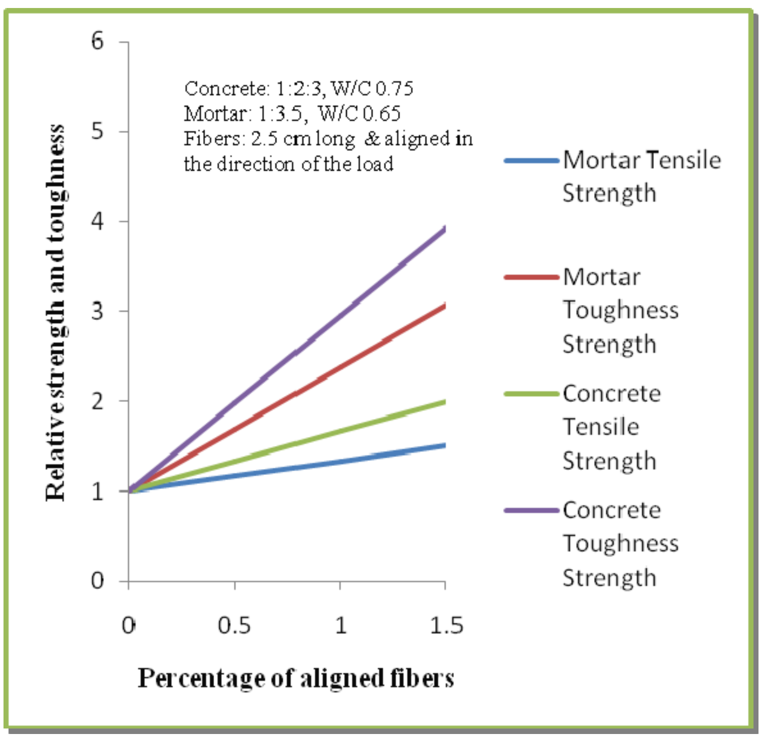


Fig 2.3 Effects of volume of fibers in Tension [2].

Table-2.5 Effects of Aspect Ratio on Strength and Toughness [2]

Type of concrete	Aspect ratio [l/d]	Relative strength [FRC/Plain]	Relative toughness [FRC/Plain]
Plain concrete with Randomly dispersed fibers	0	1.00	1.0
	25	1.50	2.0
	50	1.60	8.0
	75	1.70	10.5
	100	1.50	8.5

2.7.4 Orientation of Fibers

One of the differences between conventional reinforcement and fiber reinforcement is that in conventional, bars are oriented in the direction desired while fibers are randomly oriented. To see the effects of randomness, mortar specimens reinforced with 0.5 percent volume of fibers were tested. In one set specimens, fibers were aligned in the direction of the load, in another along the direction perpendicular to that of the load, and in the third randomly distributed.

It was observed that the fibers aligned in the direction of the applied load offered more tensile strength and toughness than randomly distributed or perpendicular fibers [2].

2.7.5 Workability and Compaction of Concrete

Researches indicate that incorporation of steel fibers decrease the workability considerably. This situation adversely affects the consolidation of fresh mix. Even prolonged external vibration fails to compact the concrete. The fiber volume at which this situation is reached depends on the length and diameter of the fiber.

Another consequence of poor workability is non uniform distribution of the fibers. Generally, the workability and compaction standard of the mix is improved through increased water/cement ratio or by the use of some kind of water reducing admixtures [2].

2.7.6 Size of Coarse Aggregates

Several investigators recommended that the maximum size of the coarse aggregate should be restricted to 10mm, to avoid appreciable reduction in strength of the composite. Fibers also in effect, act as aggregate. Although they have a simple geometry, their influence on the properties of fresh concrete is complex. The inter-particle friction between fibers, and between fibers and aggregates controls the orientation and distribution of the fibers and consequently the properties of the composite. Friction reducing admixtures and admixtures that improve the cohesiveness of the mix can significantly improve the mix workability [2].

2.7.7 Mixing

Mixing of fiber reinforced concrete needs careful conditions to avoid balling of fibers, segregation, and in general the difficulty of mixing the materials uniformly. Increase in the aspect ratio, volume percentage and size and quantity of coarse aggregate intensify the difficulties and balling tendencies. A steel fiber content in excess of 2 percent by volume and an aspect ratio of more than 100 are difficult to mix.

It is important that the fibers are dispersed uniformly throughout the mix. This can be done by the addition of fibers before the water is added. When mixing in a laboratory mixer, introducing the fibers through a wire mesh basket will help even distribution of fibers. For field use, other suitable methods shall be adopted [2].

2.8 MEASURMENT OF PROPERTIES OF FIBER REINFORCED CONCRETE

The use of fiber reinforced concrete (FRC) has passed from experimental small-scale applications to routine factory and field applications involving the placement of many hundreds of thousands of cubic meters annually throughout the world. This has created a need to review existing test methods and develop new methods, where necessary, for determining the properties of FRC [9].

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. Since later in the experimental programs measuring the toughness and the impact resistance is the major task, this section 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 [8-9].

2.8.1 Toughness Measurement for FRC

According to the definition provided by ACI toughness is a measure of the energy absorption capacity of a material and is used to characterize the material's ability to resist fracture when subjected to static strains or to dynamic or impact loads. Toughness 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 addition to being simpler, the flexural test simulates the loading conditions for many practical applications of FRC [5, 9].

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 is highly recommended to be used [5].

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 (see Fig. 2.4). Similar notions were used in the development of the ASTM C 1018 standard. On the other hand another commonly used method was developed by Japan Society of Civil Engineers, which yields absolute toughness. The toughness factor suggested in JSCE SF-4 standard is an indicator of the average flexural strength [24]. All these test methods are based on evaluation of the recorded load versus mid-span deflection curve for a four point bending test [5, 9-11].

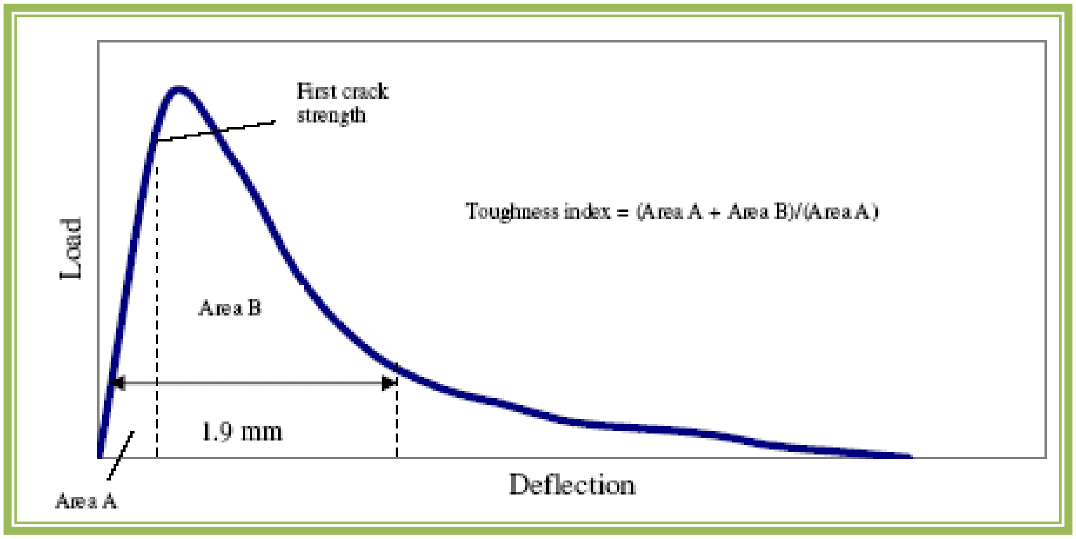


Fig. 2.4 ACI committee 544 toughness index [9].

2.8.1.1 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 an FRC beam, and then to further deflect the beam out to selected multiples of the first crack deflection. As shown in Fig 2.5 toughness indices I_5, I_{10}, I_{20}, I_N etc. are 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 [9-10].

The indices give the relative deviation from the response of a perfectly elastic-plastic material. The indices I_5, I_{10} and I_{20} have a minimum value of 1 (elastic-brittle material behavior) and values of 5, 10, and 20, respectively, for perfectly elastic- plastic behavior (elastic up to first crack, perfectly plastic thereafter).

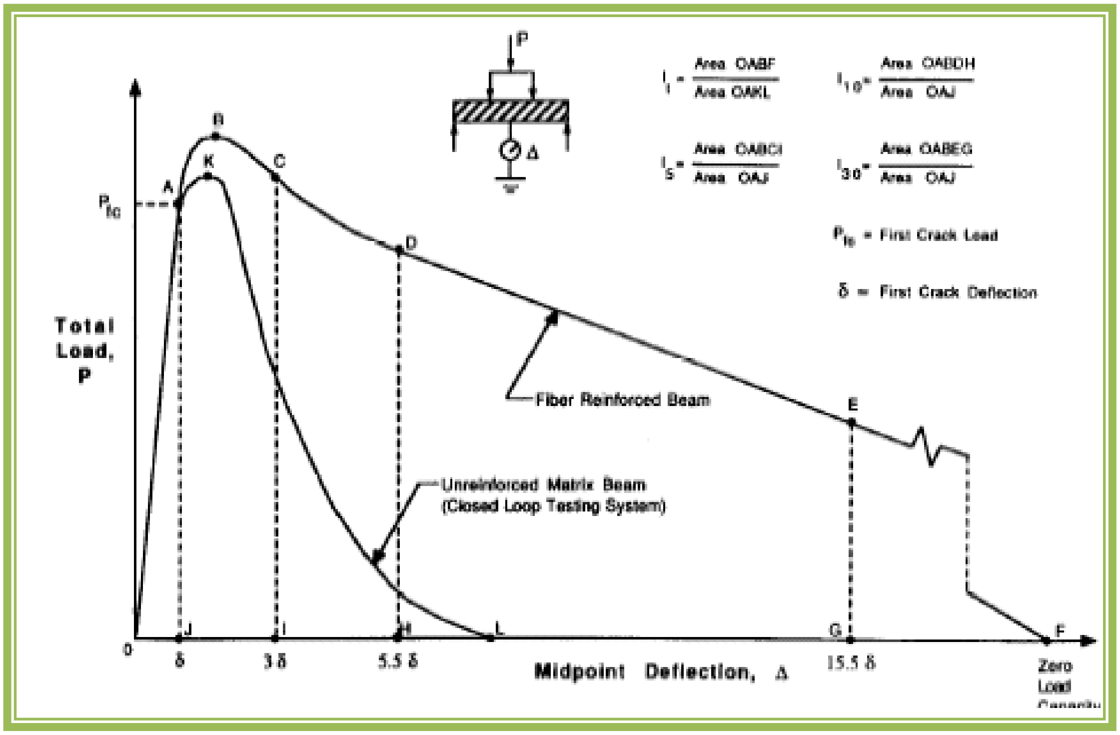


Fig 2.5 Toughness indices from flexural load-defection diagram [9].

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 [5,9,12].

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 [9-10].

2.8.1.2 JSCE SF-4 Standard Test Method

In this method the area under the load deflection curve up to a deflection equal to span/150 is calculated and results obtained from this test method yield an absolute toughness value. Determination of first crack point is not a concern in this method as shown in Fig. 2.6. However, the deflection chosen in this test method is often criticized for being much greater than the acceptable serviceability limits [11].

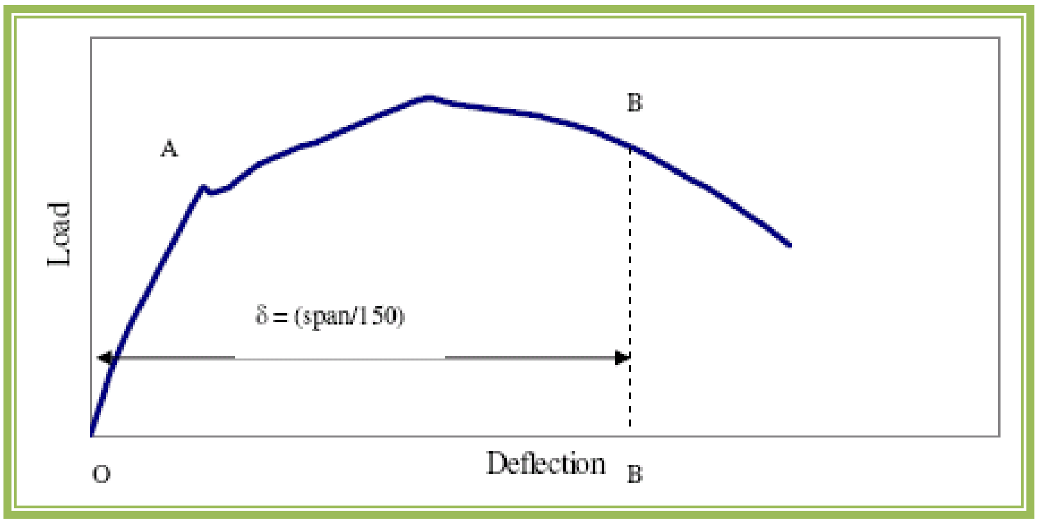


Fig 2.6 Flexural toughness values according to JSCE SF-4 Standard [11].

2.8.2 Impact Resistance Measurement for FRC

Improved impact resistance (dynamic energy absorption as well as strength) is one of the important attributes of FRC. 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 [9,13]:

- repeated drop weight test,
- instrumented impact test, and
- projectile impact test.

Conventionally, the resistance of material is characterized by a measure of one of the following criteria [4,13]:

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

Results from such tests are useful for ascertaining the relative merits of the different mixtures as well as for providing answers to specific practical problems. However, they depend on the specimen geometry, test system compliance, loading configuration, loading rate, and the prescribed failure criterion. Additional information about the behavior of FRC under impact loading can be obtained by performing instrumented and projectile 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 [9]. To this effect only the simplest of the conventional tests i.e. the repeated drop weight test is discussed in the next subsection.

2.8.2.1 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 [9]. Fig 2.7 and 2.8 shows the plan and section view of the test equipment respectively.

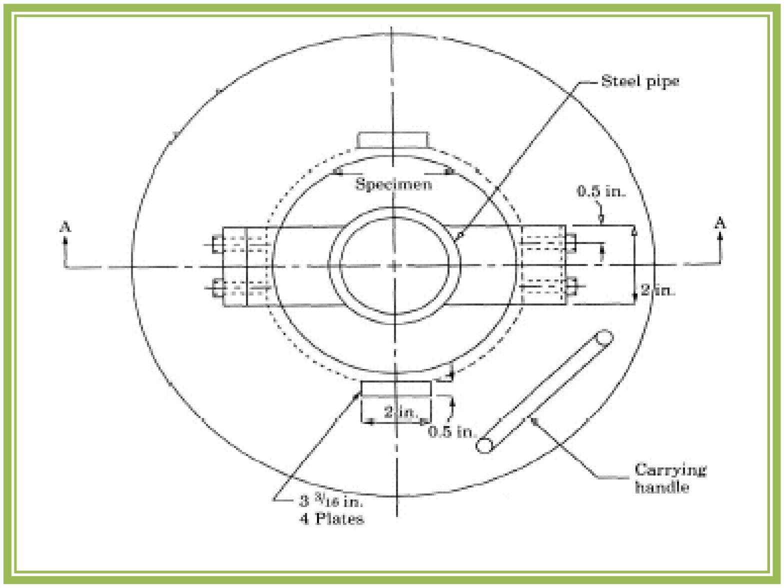


Fig 2.7 Plan view of test equipment for impact strength [9].

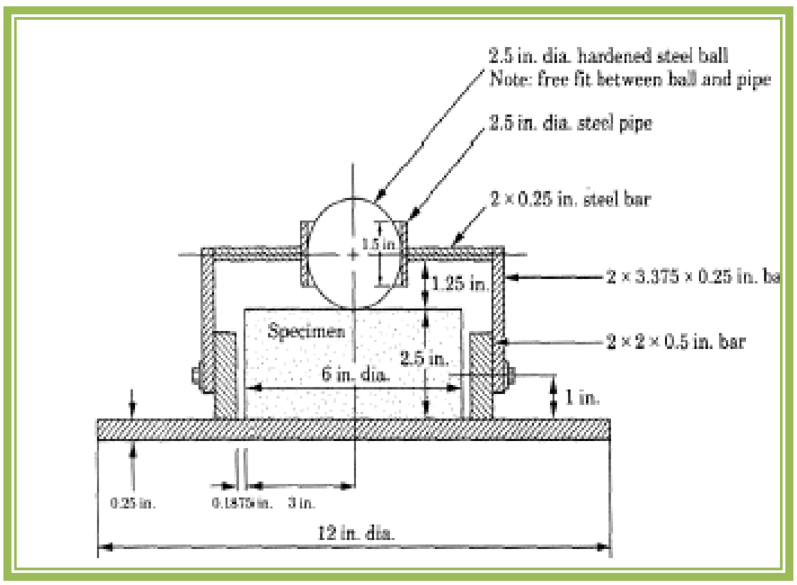


Fig 2.8 Section view of test equipment for impact strength [9].

2.9 ECONOMIC EVALUATION OF FIBER REINFORCED CONCRETE

Traditionally the decision between various alternative solutions to the problems concrete encounter has been made on the basis of initial costs. This approach has some disadvantages in the way that the useful life span for different options and the maintenance cost are not considered. The concept of life cycle costs is found to be better in determining the most cost-effective options because the maintenance cost and useful life span are included [14].

Any new technology should, at the same level of performance, be cheaper than the one it substitutes; otherwise it will stay in the laboratory stage. FRC is not cheaper than the conventional concrete in many applications. Therefore it is very important to select and develop these applications where sufficient economies are guaranteed. Generally the higher initial cost incurred by adding fibers has limited the use of FRC to special applications.

Since the mixing, placing and finishing of FRC can be carried out with conventional equipment with minor refinements in technique and workmanship, the cost of FRC principally depends on the type and amount of fiber volume used together with the admixtures added for enhancement of the workability. An increase in the fiber volume always contributes to the higher initial price. The low energy required for their extraction and the abundantly occurring parent material makes natural fiber the cheapest among the different fiber types. Carbon fibers are the most expensive of all the fibers. This is due to the increased cost of their manufacturing process as well as the increased cost of raw materials required for their manufacture. As a result new technologies are under development to produce low cost carbon fibers.

The extra cost of adding fibers to the concrete mix and other additional cost is usually offset by the savings in maintenance and rehabilitation and the special advantages that could be achieved. It was established by many researchers that initial saving could be made by using FRC in applications such as industrial floor and pavements by reducing the number of joints and thickness of the slab. According to some researches the FRC for pavements is economically viable when compared to the plain concrete. A minimum of 10% to a maximum of 40% saving could be achieved in warehouse and overlay pavements respectively. It was further described that more saving could be perceived if the life cycle performance is considered for the evaluation of different pavement alternatives [14].

In summary, the concept of reinforcing a brittle matrix with discrete fibers is an age old practice. The modern day use of fibers in concrete started in early 1960s. Plain concrete possesses a very low tensile strength, limited ductility and little resistance to cracking. It has been recognized that the addition of small, closely spaced and uniformly dispersed fibers to concrete would act as a crack arrester and would substantially improve its static and dynamic properties. Fibers suitable for reinforcing concrete have been produced from steel, glass, organic polymers and natural fibers. For a composite system such as FRC, the mechanical behavior depends not only on the properties of the fibers and the cementitious systems, but also on the bonding between them.

The addition of fibers significantly improves many of the engineering properties of the concrete, notably impact strength and toughness. Flexural strength, fatigue strength and the ability to resist cracking and spalling are also improved. However, fibers have no significant effect on the compressive, shear and torsional strength, elastic modulus and creep characteristics. The extent of improvement in concrete properties will vary based on the concrete matrix, the type, quantity and orientation of fibers, mixing, compaction and maximum aggregate size. Measurement of properties of FRC is very essential. As some of the properties are matrix dependent, they can be measured using test methods originally developed for conventional concrete. However, tests like toughness and impact strength are different from those of the conventional concrete and should be measured using tests specifically developed for FRC. Regarding the cost the higher initial cost incurred by adding fibers has limited the use of FRC to special applications.

Since steel fiber reinforced concrete made with steel fiber is the main interest of the research objective the next chapter is exclusively dedicated to the fundamental principles of SFRC and also a special attention is given to steel fibers extracted from used tyres.

CHAPTER THREE

STEEL FIBER REINFORCED CONCRETE

3.1 GENERAL

Steel fiber reinforced concrete is a composite material made of hydraulic cements, fine and coarse aggregate, and a dispersion of discontinuous, small steel fibers. It may also contain Pozzolana and admixtures commonly used with conventional concrete [15].

According to ACI Committee 544.3 R Report, fiber length varies from 12.7 to 63.5 mm. The most common fiber diameters are in the range of 0.45 to 1.0 mm. Modern steel fibers have shapes which include round, oval, rectangular, and crescent cross sections, depending on the manufacturing process and raw material used.

The usual amount of steel fibers ranges from 0.25% by volume, i.e., 20 kg/m^3, to 2% by volume, i.e., 157 kg/m^3. The low end of the range applies to lightly loaded ground slabs, some precast applications, and composite steel deck toppings. The upper end of the range is common for security applications (safes, vaults, etc) [15]. Recent investigations have also given rise to highly reinforced SFRC containing up to 20% volume of steel fibers. The recent developments are due to the introduction of new generation of additives such as superplasticizers and microsilicas, which allow the use of high volume of steel fibers and high-strength concrete [16].

The addition of steel fibers significantly improves many of the engineering properties of mortar and concrete. 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 [8,15].

Properties of SFRC in both the freshly mixed and hardened state, including durability, are a consequence of its composite nature. The mechanics of how the fiber reinforcement strengthens concrete or mortar, extending from the elastic pre-crack state to the partially plastic post-cracked state, is a continuing research topic. One approach to the mechanics of SFRC is to consider it as a composite material whose properties can be related to the fiber properties (volume percentage, strength, elastic modulus, and a fiber bonding parameter of the fibers), the concrete properties (strength, volume percentage, and elastic modulus), and the properties of the interface between the fiber and the matrix.

Recently some researches have been devoted to the use of granulated rubber and steel fibers recovered from waste tyres in concrete. In particular, the concrete obtained by adding recycled steel fibers evidenced a satisfactory improvement of the fragile matrix, mostly in terms of toughness and post-cracking behavior. As a consequence steel fiber reinforced concrete made with fibers extracted from used tyres appears a promising candidate for both structural and non structural applications. The mechanical behavior of concrete reinforced with tyre-recycled steel fibers is comparable to that of the conventional steel fiber reinforced concrete. Therefore, it can be presumed that the facts presented about the fundamental principles, the properties of fresh and hardened concrete, mixing placing and finishing methods are also applicable for steel fiber reinforced concrete made with fibers extracted from used tyres.

This chapter is structured into two major parts namely fundamentals of steel fiber reinforced concrete and steel fibers extracted from used tyres as reinforcement in SFRC. The first part briefly discusses on the steel fiber types and property, properties of SFRC both in fresh and hardened state, durability of SFRC, mix design consideration, mixing, placing and finishing of SFRC as well as application of SFRC. In the second part tyre construction and composition, application for used tyres and use of steel fibers recovered from used tyres together with summary of previous relevant researches conducted in this area is presented.

3.2 FUNDAMENTALS OF SFRC

3.2.1 Steel Fiber Types

Steel fibers intended for reinforcing concrete are defined by ACI committee 544.1R as short, discrete lengths of steel having an aspect ratio from about 20 to 100, with any of several cross-sections, and that are sufficiently small to be randomly dispersed in an unhardened concrete mixture using usual mixing procedures [3].

It is possible to produce steel fibers in many ways. Round, straight steel fibers are produced by cutting or chopping wire, typically wire having a diameter between 0.25 to 1.00 mm. Flat, straight steel fibers having typical cross sections ranging from 0.15 to 0.64 mm thickness by 0.25 to 2.03 mm width are produced by shearing sheet or flattening wire (Fig 3.1a). Crimped and deformed steel fibers have been produced with both full-length crimping (Fig. 3.1b), or bent or enlarged at the ends only (Fig. 3.1c, d). Some fibers have been deformed by bending or flattening to increase mechanical bonding. Some fibers have been collated into bundles to facilitate handling and mixing. During mixing, the bundles separate into individual fibers (Fig. 3.1c). Fibers are also produced from cold drawn wire that has been shaved down in order to make steel wool. The remaining wires have a circular segment cross-section and may be crimped to produce deformed fibers. Also available are steel fibers made by a machining process that produces elongated chips. These fibers have a rough, irregular surface and a crescent-shaped cross section (Fig. 3.1e) [3].

Steel fibers are also produced by the melt-extraction process. This method uses a rotating wheel that contacts a molten metal surface, lifts off liquid metal, and rapidly solidifies it into fibers. These fibers have an irregular surface, and crescent shaped cross-section (Fig. 3.1f) [3].

It is possible to make classification of steel fibers either based upon the product or shape of cross-section as provided here under for ASTM and JSCE respectively.

ASTM A 820 provides a classification for four general types of steel fibers based upon the product used in their manufacture:

Type I - Cold-drawn wire.

Type II - Cut sheet.

Type III - Melt-extracted.

Type IV - Other fibers.

The Japanese Society of Civil Engineers (JSCE) has classified steel fibers based on the shape of their cross-section:

Type 1 - Square section.

Type 2 - Circular section.

Type 3 - Crescent section.

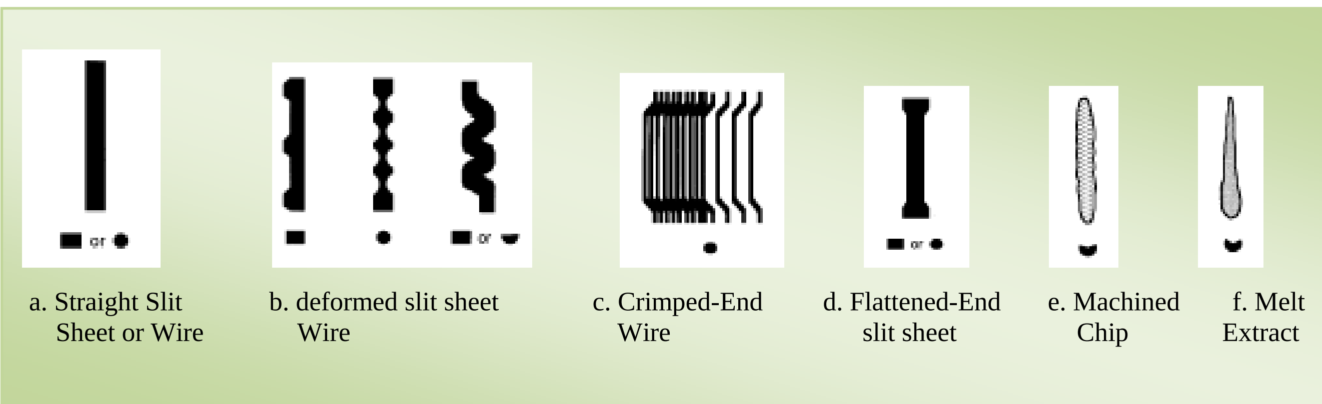


Fig. 3.1 Various steel fiber geometries [3].

3.2.2 Steel Fiber Properties

The composition of steel fibers generally includes carbon steel (or low carbon steel, sometimes with alloying constituents), or stainless steel. Different applications may require different fiber compositions.

The fiber strength, stiffness, and the ability of the fibers to bond with the concrete are important fiber reinforcement properties. Bond is dependent on the aspect ratio of the fiber. Typical aspect ratios range from about 20 to 100, while length dimensions range from 6.4 to 76 mm [17].

Steel fibers have a relatively high strength and modulus of elasticity, they are protected from corrosion by the alkaline environment of the cementitious matrix, and their bond to the matrix can be enhanced by mechanical anchorage or surface roughness. Long term loading does not adversely influence the mechanical properties of steel fibers. In particular environments such as high temperature refractory applications, the use of stainless steel fibers may be required [3].

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% [5,11,12]. ASTM A 820 establishes a minimum tensile strength and bending requirements for steel fibers as well as tolerances for length, diameter (or equivalent diameter), and aspect ratio. The minimum tensile yield strength required by ASTM A 820 is 345 MPa, while the JSCE Specification requirement is 552 MPa.

3.2.3 Properties of Freshly Mixed SFRC

The properties of SFRC in its freshly mixed state are influenced by the aspect ratio of the fiber, fiber geometry, its volume fraction, the matrix proportions, and the fiber-matrix interfacial bond characteristics.

For conventionally placed SFRC applications, adequate workability should be insured to allow placement, consolidation, and finishing with a minimum of effort, while providing uniform fiber distribution and minimum segregation and bleeding. For a given mixture, the degree of consolidation influences the strength and other hardened material properties, as it does for plain concrete.

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 a way to form a mat from which it is very difficult to dislodge by vibration alone. As can be seen in Fig. 3.2, 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 [5,11,12]. This effect can be observed in Fig. 3.3.

There is limited data on the shrinkage behavior of SFRC. However according to some studies steel fibers are reported to reduce the free shrinkage of SFRC by up to 40%. For restrained shrinkage, steel fibers are reported to reduce the amount of cracks and the crack widths [5,11,12].

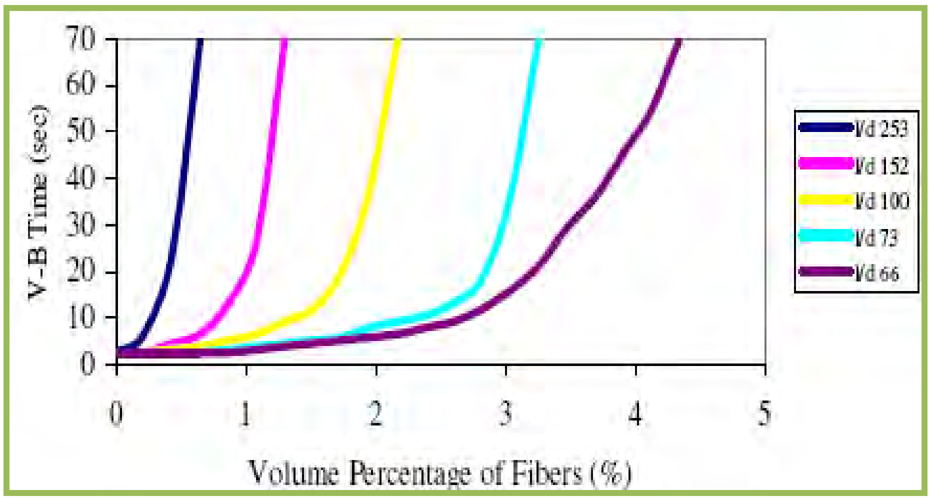


Fig 3.2 Effect of fiber aspect ratio on V-B time of fiber reinforced mortar [12].

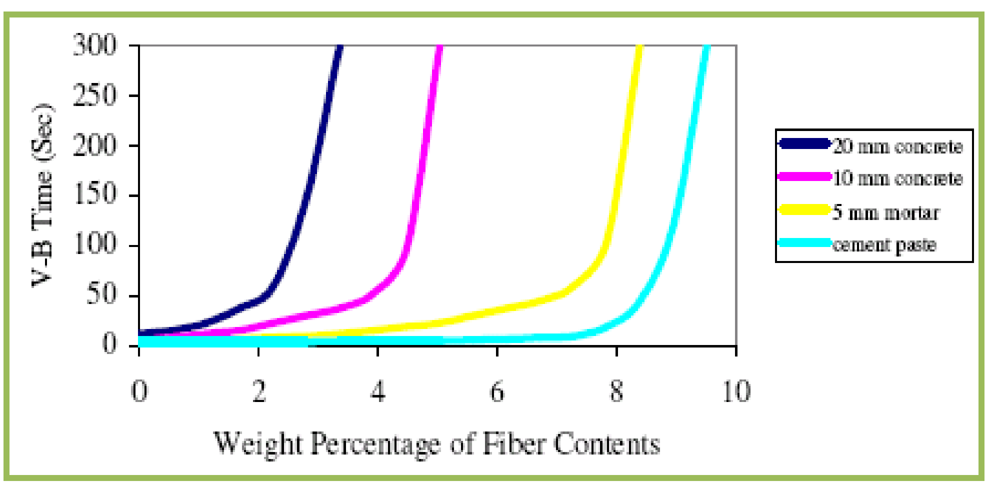


Fig 3.3 V-B times versus fiber content for matrices with different maximum aggregate size [12].

3.2.4 Properties of Hardened SFRC

3.2.4.1 Behavior under Static Loading

Steel fibers improve the ductility of concrete under all modes of loading, but their effectiveness in improving strength varies among compression, tension, shear, torsion, and flexure as discussed here under.

a) Compression

It is unlikely to achieve considerable improvements in compressive strength by steel fiber inclusion. The ultimate strength is only slightly affected by the presence of fibers, with observed increases ranging from 0 to 15 percent and 0 to 23 percent for up to 1.5 and 2 percent by volume of fibers, respectively. However reinforcing the concrete with steel fibers provides post-cracking ductility to concrete as can be seen in Fig. 3.4. In these curves, a substantial increase in the strain at the peak stress can be noted, and the slope of the descending portion is less steep than that of control specimens without fibers [3,8,17].

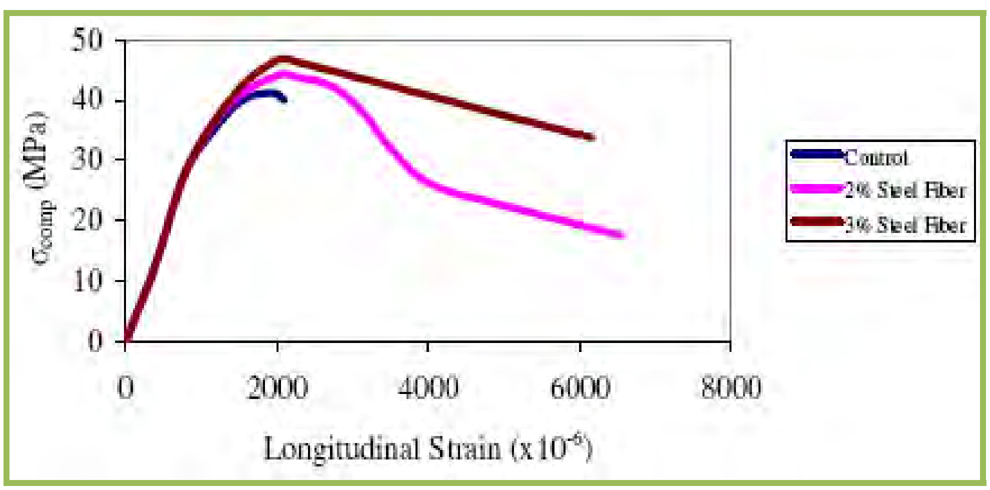


Fig 3.4 Typical stress-strain curves for SFRC under compression [8].

b) Direct Tensions

In direct tension, the improvement in strength is significant, with increases of the order of 30 to 40 percent reported for the addition of 1.5 percent by volume of fibers in mortar or concrete [3]. 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 similar results. Like in compression, steel fiber inclusion to concrete provides post-cracking ductility [5,11,12].

c) Shear and Torsion

Steel fibers generally increase the shear and torsional strength of concrete, although there are little data dealing strictly with the shear and torsional strength of SFRC, as opposed to that of reinforced beams made with a SFRC matrix and conventional reinforcing bars. The increase in strength of SFRC in pure shear has been shown to depend on the shear testing technique and the consequent degree of alignment of the fibers in the shear failure zone. For one percent by volume of fibers, the increases range from negligible to 30 percent [3].

d) Flexure

Increases in the flexural strength of SFRC are substantially greater than in tension or compression because ductile behavior of the SFRC on the tension side of a beam alters the normally elastic distribution of stress and strain over the member depth. A summary of corresponding strength data shows that the flexural strength of SFRC is about 50 to 70 percent more than that of the unreinforced concrete matrix in the normal third-point bending test. Use of higher fiber volume fractions, or center-point loading, or small specimens and long fibers with significant fiber alignment in the longitudinal direction will produce greater percentage increases up to 150 percent [3]. Deformed fibers show the same type of increase at lower concentrations because of their improved bond characteristics [8].

3.2.4.2 Behavior under Impact Loading

In terms of the differences between SFRC and plain concrete under flexural impact loading, it has been found that for normal strength concrete the peak loads for SFRC were about 40 percent higher than those obtained for the plain matrix. For high strength concrete, a similar improvement in the peak load was observed. Steel fibers increased the fracture energy under impact by a factor of about 2.5 for normal strength concrete and by a factor of about 3.5 for high strength concrete. In comparing the behavior of SFRC under impact loading to its behavior under static loading, steel fibers increased the peak loads by a factor of 2 to 3 times for normal strength concrete, and by a factor of about 1.5 for high strength concrete. Steel fibers increased the fracture energies by a factor of about 5 for normal strength concrete and by a factor of about 4 for high strength concrete. Based on tests carried out by repeated drop weight test proposed by ACI Committee 544, for fibrous concrete, the number of blows to failure is typically several hundred compared to 30 to 50 for plain concrete [3,17].

3.2.4.3 Fatigue Behavior

Data on fatigue behavior 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. In general, the fatigue strength increases with increasing steel fiber content [5,11,12].

3.2.4.4 Toughness and Ductility

Early in the development of SFRC, toughness was recognized as the characteristic that most clearly distinguishes SFRC from concrete without steel fibers. The primary purpose of fiber inclusion to concrete is not to increase strength but to provide toughness and ductility. As explained in chapter 2 there are various ways of defining and quantifying toughness of SFRC. 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 [5,11,12].

3.2.4.5 Creep and Shrinkage

Limited test data indicate that steel wire fiber reinforcement at volumes less than 1 percent have no significant effect on the creep and free shrinkage behavior of Portland cement mortar and concrete [3].

3.3.2.6 Modulus of elasticity and poisons ratio

In practice, when the volume percentage of fibers is less than 2 percent, the modulus of elasticity and Poisson’s ratio of SFRC are generally taken as equal to those of a similar non-fibrous concrete or mortar [3].

3.2.5 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, un-cracked 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. To reduce the potential for corrosion at cracks or surface staining, the use of alloyed carbon steel fibers, stainless steel fibers, or galvanized carbon steel fibers are possible alternatives [3,11,12].

All the well-known practices for making durable concrete apply to SFRC. For freezing and thawing resistance, the same air content criteria are used. Exposure tests have generally revealed that for freezing and thawing resistance, SFRC must be air-entrained. Air void characteristics of SFRC and non-fibrous concrete are similar in nature, supporting the above hypothesis [3].

3.2.6 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.

Compared to conventional concrete, some SFRC mixtures are characterized by higher cement content, higher fine aggregate content, and decreasing slump with increasing fiber content. There are various procedures for proportioning of SFRC mixtures proposed by different researches. Typical recommended proportions are shown in Table 3.1. To provide better workability of concrete, amount of paste in the mixture should be increased. This requires 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 enhance the workability of the concrete however it does not necessarily provide the ability to incorporate higher steel fiber content. Regardless of the mix design, in all cases trial mixes should be prepared to ensure workability and strength properties [15].

Table 3.1 Range of proportions for normal weight SFRC [15]

Property	9.5mm Maximum Aggregate size	19mm Maximum Aggregate size	38mm Maximum Aggregate size
Cement (kg/m^3)	355-590	300-535	280-415
w/c ratio	0.35-0.45	0.4-0.5	0.35-0.55
Fine/coarse aggregate (%)	45-60	45-55	40-55
Entrained air (%)	4-7	4-6	4-5
Fiber content (%) by volume Smooth steel Deformed steel	 0.4-1.0 0.8-2.0	 0.3-0.8 0.6-1.6	 0.2-0.7 0.4-1.4

3.2.7 Mixing, Placing and Finishing of SFRC

3.2.7.1 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. It is very important that the fibers be dispersed uniformly throughout the mixture. 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 [8,15].

Primary problem encountered in mixing of SFRC is formation of fiber balls. Most fiber balling occurs somewhere before the fibers get into the mixture. Once the fibers get into a mixture ball-free, they nearly always stay ball-free. This means that if balls form, it is because fibers were added in such a way that they fell on each other and stacked up (in the mixer, on the belt, on the vanes, etc.) This normally happens when the fibers are added too fast at some point in the procedure. The mixer, whatever type, must carry the fibers away into the mixture as fast as they are added. Balls form by hanging up on a rough loading chute at the back of a mixer truck. Fibers should not be allowed to pile up or slide down the vanes of a partially filled drum; this will form balls [15].

Other causes of balling are adding too many fibers to a mixture (more than about 2 percent by volume or even 1 percent of a fiber with a high aspect ratio); adding fibers too fast to a harsh mixture (the mixture is not fluid enough or workable enough and the fibers do not get mixed in fast enough; therefore, they pile up on each other in the mixer); adding fibers first to the mixer (the fibers have nothing to keep them apart, they fall on each other, and form balls); and using equipment with worn out mixing blades. The most common causes of wet fiber balls are over mixing and using a mixture with too much coarse aggregate (more than 55 percent of the total combined aggregate by absolute volume) [15].

3.2.7.2 Placing

In most cases SFRC with a proper water-cement ratio appears relatively stiff and unworkable, compared to conventional concrete. However, use of vibrators or high-range water-reducing admixtures (HRWR) and superplasticizers allows easy placing of such seemingly unworkable concrete. The material tends to “hang together” and resist movement during compaction if an attempt is made to handle it without vibration or an HRWR admixture. Also, at the lower end of fiber quantity, some types of fiber allow easy placing without the methods just mentioned. Generally, however, placing of SFRC with no vibration is discouraged because, without compaction, the concrete will be less dense, may have air voids, and may have less bond with any conventional reinforcement [15].

Water-cement ratios for fibrous mixtures must be carefully controlled. It is very easy to add unnecessary water to the mixture and lose many of the beneficial properties obtained from the addition of fibers. Tests have shown that further addition of water causes an increase in slump without a change in workability under vibration. This water addition reduces the quality of the mixture without improving the placeability and it can give rise to excessive bleeding and segregation [15].

3.2.7.3 Finishing

SFRC can be finished by using conventional methods and equipments; however certain refinements in techniques and workmanship are required. For flat-formed surfaces, normally no special attention is needed. The surface will normally be smooth and will not show fibers when the forms are striped. 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 [15].

3.2.8 Curing and Protection

Curing of steel fiber reinforced concrete and protection from freezing or excessively hot or cold temperatures should be done in the same way as for conventional concrete. One aspect deserves special attention. Since SFRC is often placed in thin sections, as overlays for example, and often has a high cement content, it is particularly vulnerable to plastic shrinkage cracking. This will occur when the rate of surface evaporation is high. In such conditions, placements must be shaded from the sun and sheltered from the wind to prevent this type of damage [15].

3.2.9 PRACTICAL APPLICATIONS OF SFRC

The applications of SFRC will depend on the ingenuity of the designer and builder in taking advantage of the static and dynamic tensile strength, energy absorbing characteristics, toughness, and fatigue endurance of this composite material. The uniform dispersion of fiber throughout the concrete provides isotropic strength properties not common to conventionally reinforced concrete [3].

Steel fiber reinforced concrete has an important role to play in modern concrete technology. SFRC has been used extensively for pavements and for highway and airport runway overlays, to reduce both thickness and cracking. Other applications include different precast elements, stairways, slabs, tunnel linings, vaults and safes, heavy machinery foundation, shotcrete, Slurry Infiltrated Fiber Concrete (SIFCON), 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 the cost of SFRC is higher than the conventional concrete, as a result the use of SFRC is limited to special applications. The wide range of application of SFRC is shown in Fig. 3.5

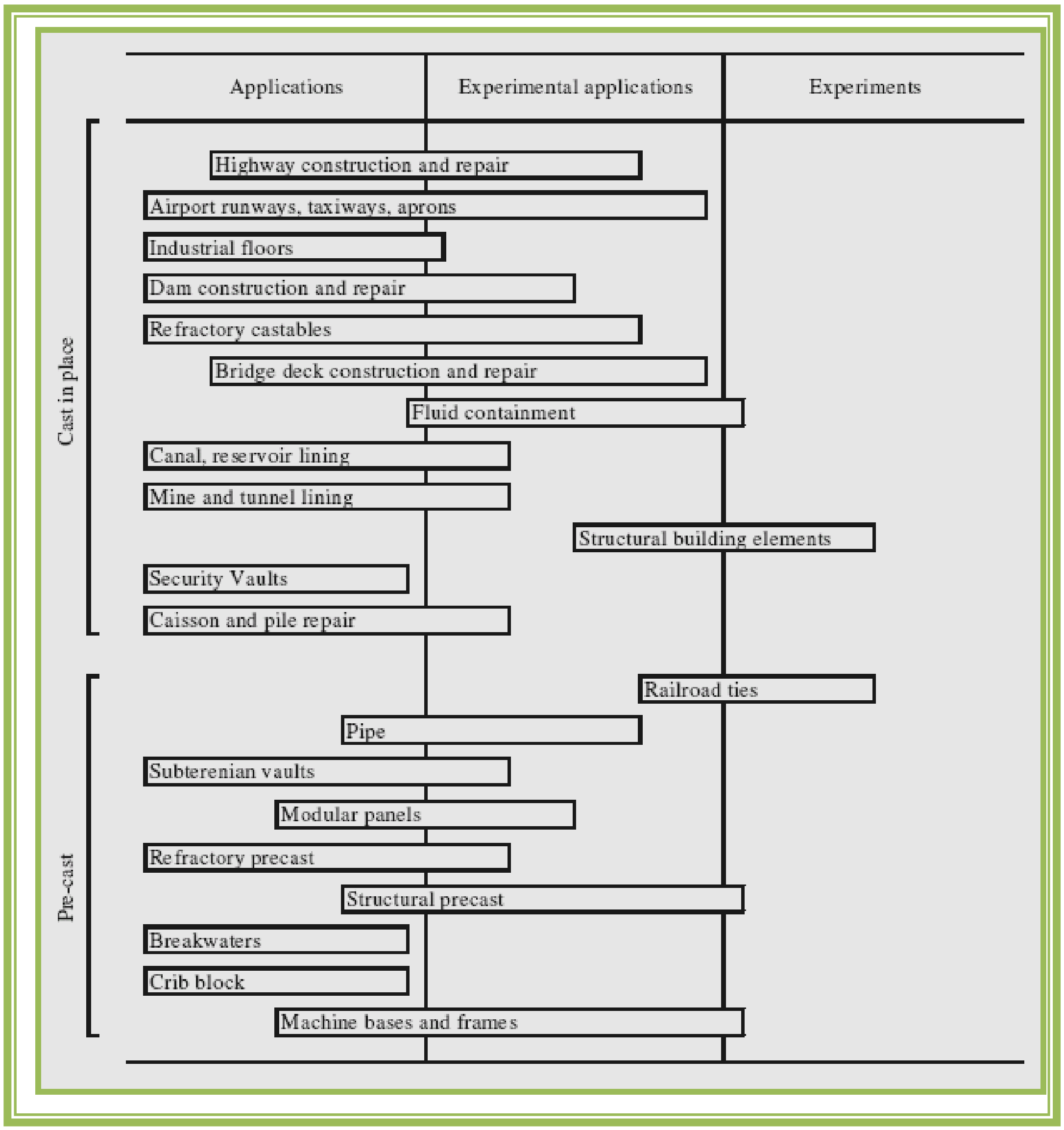


Fig. 3.5 Typical applications of SFRC [8]

3.3 STEEL FIBER EXTRACTED FROM USED TYRES AS REINFORCEMENT IN SFRC

3.3.1 General

The increasing amount of waste tyres worldwide makes the disposition of tyres a relevant problem to be solved. Waste tires have been a major International waste management problem for a few decades and in some cases have involved serious environmental pollution, particularly when large numbers catch fire. According to Matador Addis Tyre Factory market demand prediction, Ethiopia’s annual tyre demand is estimated around 1 million pieces. And it is believed that every three years at least 1 million tyres will be discarded resulting a little over 10,000 tones of waste tyres annually. In UK it is estimated that 450,000 tones of tires are discarded annually, with over 100,000 worn tires taken off vehicles every day. Of these: 50,000 tones are retreaded, 172,000 tones go to material recovery and 71,000 tones go to energy recovery [6]. Research commissioned by WRAP (Waste & Resources Action Program) has revealed that over 100,000 tons of steel and 17,000 tones of fiber could be recovered from scrap tyres generated in the UK each year [18]. Waste arising from used tyres is currently being managed through the implementation of environmental legislation. As a result, tyre recycling has become much more popular since it is one of the most environmentally friendly and economically viable ways of managing waste tyres. Steel fiber reinforced concrete made with fibers extracted from used tyres emerges as a promising candidate for both structural and non structural applications. The mechanical behavior of concrete reinforced with tyre-recycled steel fibers is comparable to that of the conventional steel fiber reinforced concrete. To this effect this second part of the chapter is written to provide an insight about tyre construction and composition, application of used tyres and uses of steel fibers extracted from used tyres.

3.3.2 Tyre Construction and Composition

Tyre is a thermoset material that contains cross linked molecules of sulphur and other chemicals. The general materials of construction of motor vehicle tires include natural rubber, synthetic rubber compounds, steel, polymeric fiber, fabric, and textiles; and fillers. The process of mixing rubber with other chemicals to form this thermoset material commonly is known as vulcanization. This makes postconsumer tyres very stable and nearly impossible to degrade under ambient conditions and has resulted in a growing disposal problem [19].

The materials and percentages used in tyres are primarily a function of the type of vehicle and use, and the design preferences and proprietary formulas of the tire manufacturers. While the composition of tires varies substantially based upon the type of vehicle (for example, commercial truck or passenger car) and severity of use, "typical" compositions are shown in Table 3.2 [19].

Table 3.2 Typical Compositions and Gross Weights of Tyres (source: Rubber Manufacturer Ass.).

Material	**Composition (weight percent)**	
	Passenger	**Truck**
Natural rubber	14	27
Synthetic rubber	27	14
Carbon black	28	28
Steel	14 to 15	14 to 15
Fabric, fillers, accelerators, anti-ozonants, etc.	16 to 17	16 to 17
	Average Weight (kg)	
New tyre	11.34	54.43
Waste tyre	9.07	45.36

The general function of the textile fiber in tyres is to assist in the provision of stable performance of the motor vehicle over the design operating conditions. The steel used in tyres has two distinct uses, as steel belting (such as that underlying the tread near the outer diameter of the tire) in some tyres, and as the circular metal component (bead) that is encased in rubber at the inner diameter of the tyre and assists in sealing the inner diameter against the rim of the vehicle wheel. The steel in the bead and belt wire is coated with copper, bronze, or brass. Among other reasons, steel coatings are used to protect the parent steel from corrosion and to promote adhesion of steel cord to the tread [19].

The construction of a tyre is relevant to the recycling of tyre-derived materials, because a tyre is composed of an integrated mixture of materials using thermal and adhesive processes to forge a high-quality tire product. Recovery of marketable materials from tyres therefore requires overcoming all of the aspects of integration that make a tyre premium consumer product. An illustration of the construction of a typical tire is shown in Fig. 3.6.

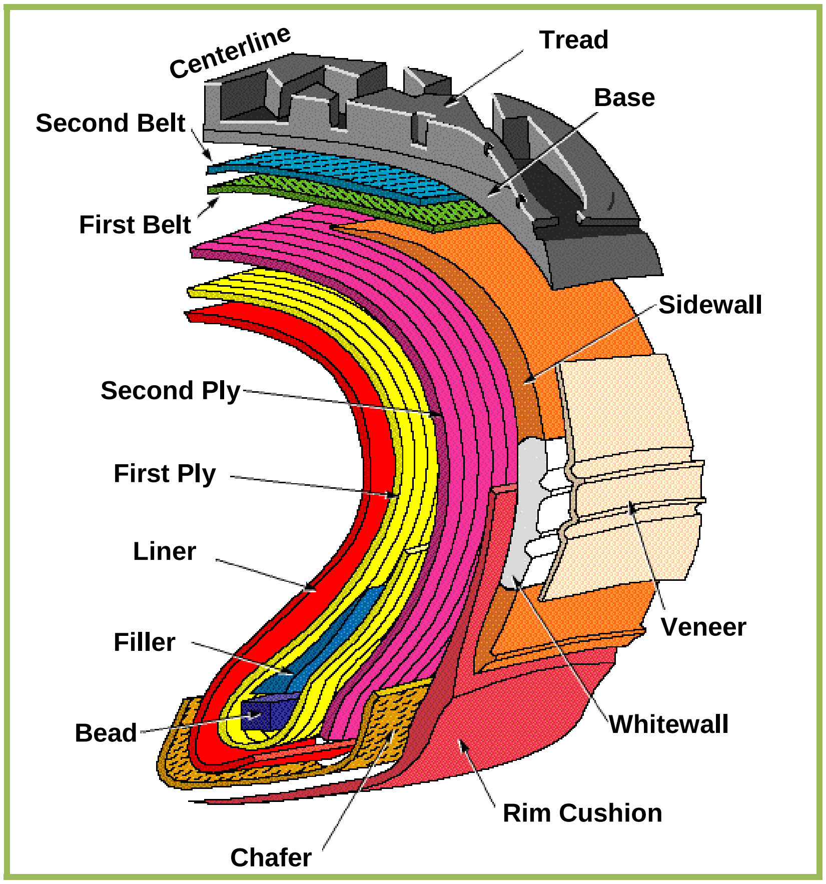


Fig. 3.6 Example of Components of a Typical Radial Tyre (Source: The Cooper Tyre & Rubber Company, 2003)

3.3.3 Application for Used Tyres

Even if there is no any sort of Landfill Directive regarding waste tyres for Ethiopian case, in several developed countries Landfill Directives now prevent whole or shredded tyres being disposed of at landfill sites to protect the environment, and used tyres now have to be disposed of by alternative means [20,21].

To reduce the volume of waste tyres being produced in the first place, manufacturers are being encouraged to expand the life cycle of their products, so that fewer replacements are necessary.

In addition to waste minimization, there are three means to the strategy of finding alternatives to landfill. These are reuse and retread, recycling and reprocessing and recovery of energy. Each of these alternatives is discussed in the following subsections.

3.3.3.1 Reuse and Retread

a) Reuse

There are many other uses for tyres, apart from on vehicles. Scrap tyres are used for various projects including [22]:

- landfill engineering
- motorway embankments
- crash barriers
- various marine applications, such as erosion control, and artificial reefs
- tree guards
- fences
- garden decoration
- silage clamps, and
- boat fenders

However the reuse of tyres in Ethiopia is in its infant stage and limited to very minor uses such as the making of sandal shoes locally known as “berebaso” and tying rope “tefer”, respectively and ‘O’ rings and seals. The steel fibers extracted are mainly used as tying wire.

b) Retread (Remolds)

Retreading involves either replacing only the tread section of a tyre or replacing rubber over the whole outer surface of the tyre, and effectively doubles the life of the tyre. The process involves the removal of the remaining tread and the application and vulcanization of a new tread (the 'camel back') onto the remaining 'carcass'. Retreading uses nearly half the energy that is needed to produce a new. Passenger car tyres can only be retreaded once, whereas truck tyres are designed to be retreaded several times. Tyre retreading is a major industry in most of developed countries [22].

Recently in our country tyre retreading is emerging as a new business. The two business groups which can be considered as a pioneer to this business are Tria and ET Retreading. Big government organizations have also started retreading of their used tyres, worth mentioning are Anbessa City Bus and Ethiopian Roads Authority.

3.3.3.2 Reprocess and Recycle

Tyres can be shredded, granulated or crumbed so the shredded or crumbed rubber can then be used in other applications. The elasticity of a tyre case, which is so important to its efficient use on a vehicle, makes it difficult to separate the steel and textile reinforcement from the rubber. However, there are several methods which can be employed, as discussed below:

a) Crumbing

Crumbing is the process of reducing rubber compounds to a fine granular or powdered form. Crumbing has been made more difficult by the development of the modern steel braced tyres, and by difficulties in securing end markets and price advantages over virgin rubber. Uses of rubber crumb include [22]:

- sports and play surfaces and Rubberized asphalt in road surfacing
- brake linings
- landscaping mulch
- absorbents for wastes
- shoe soles
- carpet backing/underlay
- adhesive
- wire and pipe insulation, and
- conveyor belts and hosing .

b) Cryogenic fragmentation

Cryogenic fragmentation is a method of crumbing in which tyres are shredded and cooled to below minus 80 degrees Celsius. A hammer mill then pounds the chips to separate the components. The resultant rubber granules can be used for athletics tracks, carpet underlay, playground surfaces and rubberized asphalt for road surfaces. However, the energy input required for such low temperatures is relatively high [22].

c) Gasification

Gasification is the process of converting a carbon containing material into a gas which can be used as fuel. Gasification processes can be used on tyres to produce clean gas for power generation and chemical manufacture. However, currently there seems to be little development of commercially operating gasification processes in most countries, though research into its potential is ongoing [22].

d) Pyrolysis

Pyrolysis is an alternative to incineration of tyres which minimizes atmospheric emissions. The tyres are heated without air in an enclosed chamber producing oil and fuel gases and residues of carbon and steel. This means that few emissions are produced, which saves on costs of scrubbing systems. The oil and gas can potentially be used as fuels and the char and oil could also potentially be recovered into marketable materials. The steel could also be sold [22].

e) De-vulcanization

De-vulcanization is the process of breaking down the sulphur cross-links in used tyre rubber and leaving the original polymer chains unbroken so that the resultant de-vulcanized recyclate rubber can be used to produce high quality new rubber products. De-vulcanized rubber can be used to replace part of the virgin material in automotive and cycle tyres, conveyor belts and footwear [22].

3.3.3.3 Energy Recovery

As tyres have a very high calorific value, one of the most successful uses of waste tyres has been as kiln fuel in the production of cement. Old tyres are shredded into small chips and used as an alternative fuel to coal. The benefits of using cement kilns to burn rubber tyres include less use of fossil fuels, fewer emissions of greenhouse gases (especially nitrous oxide) and less waste to dispose of. It is estimated that the UK cement industry currently consumes 5.6 million waste tyres [22,23].

3.3.4 Use of Steel Fibers Recovered From Used Tyres

As previously discussed under section 3.3.3 the most environmentally sound way of recycling waste tyres is to reduce them to their physical and chemical constituents. With this aim, both mechanical and chemical processes, such as tyre shredding, pyrolysis and cryogenic reduction, are currently utilized by the tyre recycling industry. However tyre shredding and pyrolysis process are the most common methods in retrieving steel fibers from used tyres. The shredding process is usually carried out in a variable number of stages, depending on the desired size for the end-products. Steel fibers, rubber pieces and granules obtained from the shredding process are finally separated by an electromagnetic procedure. The pyrolysis process is generally realized in an autoclave where shredded tyres are thermally decomposed; microwave induced pyrolysis process has also been proposed to thermally decompose tyres to their constituents, as reported in [22,25].

Steel fibers recovered by the method of pyrolysis are known as Pyrolysed Recycled Steel Fiber (PRSF) and they are usually clean from rubber and contain carbon black on the surface as shown in Fig 3.7. The tensile property is not affected in most cases and also they are not as such easy to cut. Whereas, Steel fibers extracted by the method of shredding are termed as Shredded Recycled Steel Fiber (SRSF) and they are characterized by the presence of small amounts of rubber and fluff and they also tend to ball up (see Fig 3.8) [26].

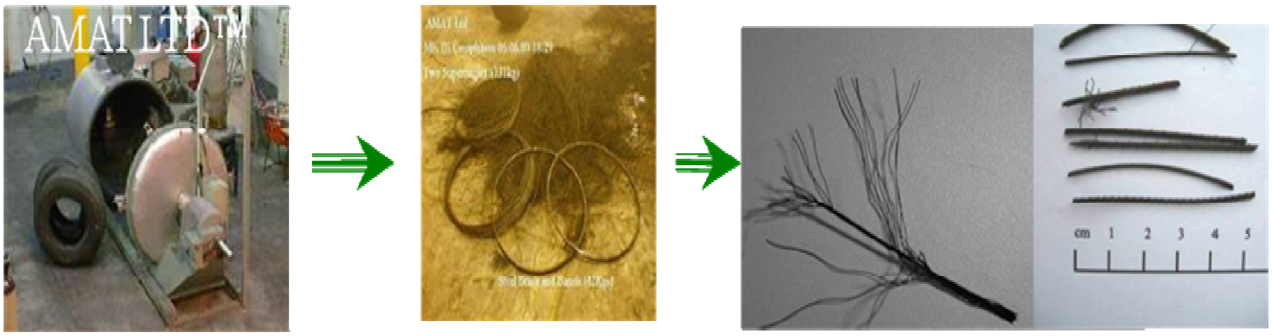


Fig. 3.7 Pyrolysis process and PRSF [26]

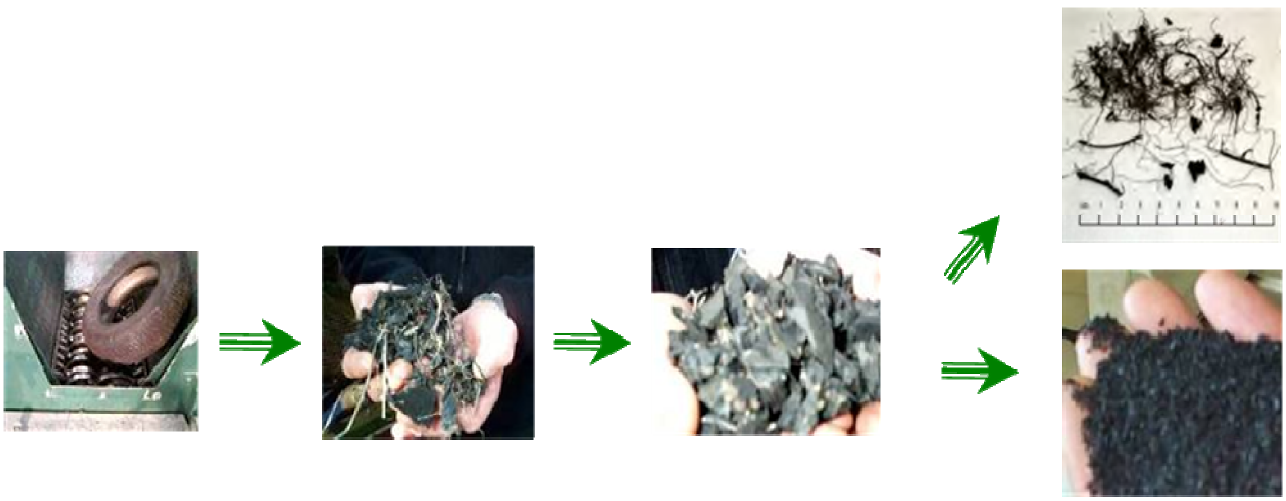


Fig. 3.8 Shredding process and SRSF [26]

In recent years some research efforts proposed the use of rubber particles and steel fibers, obtained from waste tyres in concrete. The available literature on this topic offers promising prospects as briefly summarized below.

Some studies analyzed the possibility of using rubber recovered from waste tyres in concrete in order to increase some specific properties, such as acoustic and thermal isolation and impact resistance. The partial replacement of ordinary coarse aggregate with rubber chips produced a concrete with a higher capacity of energy absorption and low weight, but reduced its mechanical properties [24]; as a consequence its potential use includes non-structural applications, as building facades and crash barriers.

The steel component separated from rubber can be used as fibers in concrete. As well known, the presence of steel fibers in concrete improves in different ways the performances of this material, including post-cracking behavior and impact resistance.

Recent research, carried out at the University of Sheffield, demonstrated that steel fibers recovered from waste tyres (RSF) can be successfully used to prepare fiber-reinforced concrete (FRC). In addition, it was indicated that the mechanical behavior of concrete reinforced with tyre-recycled steel fibers (RSFRC) is comparable to that of conventional steel fiber reinforced concrete (SFRC). Therefore, it can be presumed that the design models developed to evaluate the flexural resistance of conventional SFRC are also applicable for RSFRC [25].

In their work “Stress-strain characteristic of SFRC using recycled fibers”, H Tlemat, K. Pilakoutus and K. Neocleous studied the workability, compressive and flexural strength of concrete reinforced with RSF, industrial steel fibers (ISF) and pyrolysed RSF (PRSF). They also proposed a new tensile stress–strain model to predict the flexural resistance of concrete reinforced with conventional and recycled steel fibers.

Results of this study indicate that increasing the fibers ratio reduces the workability as measured by the slump test. For the compressive strength, if date of testing is taken into account, no major differences are noted. As shown in Fig 3.9 for SRSF the flexural behavior of the prisms improves as the fiber fraction increases. A comparison between PRSF and virgin steel fiber (VSF) is shown in Fig 3.9-3.11. The virgin fibers appear to give a higher strength and energy absorption capacity. Figure 3.11 shows the behavior of the prism reinforced with 6% ISF-1 and ISF-2 fibers is similar to that of VSF and PRSF [25].

In their research project “Use of steel fibers recovered from waste tyres as reinforcement in concrete: Pull-out behavior, compressive and flexural strength” Aiello M.A. et al., investigated the mechanical behavior of concrete reinforced with RSF (recycled steel fibers) recovered from waste tyres by a mechanical process. In order to evaluate the concrete-fibers bond characteristic and to determine the critical fiber length, pull out tests were carried out. Furthermore compressive strength of concrete was evaluated for different volume ratios of added RSF and flexural tests were performed to analyze the post-cracking behavior of RSFRC. For comparison purpose, samples reinforced with industrial steel fiber (ISF) were also considered [24].

From this research project satisfactory results were obtained regarding the bond between recycled steel fibers and concrete; on the other hand compressive strength of concrete seems unaffected by the presence of fibers despite their irregular geometric properties. Finally, flexural tests furnished in some cases results comparable to those obtained when using ISF as concerns the post-cracking behavior [24].

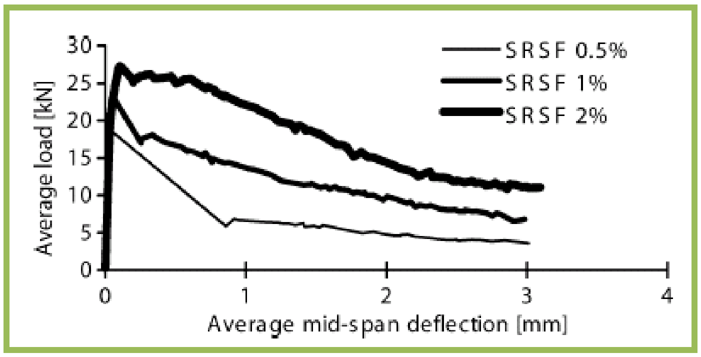


Fig. 3.9 Flexural behavior of SFRS prisms with different % of fibers [25].

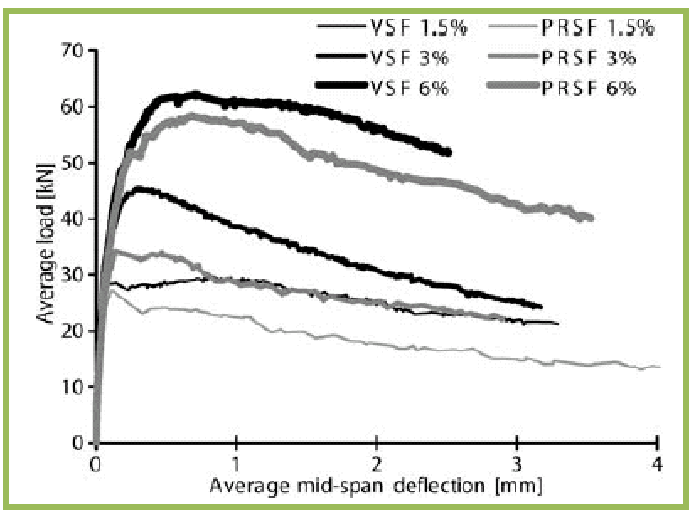


Fig. 3.10 Effects of PRSF and VSF fiber ratios on flexural resistance [25].

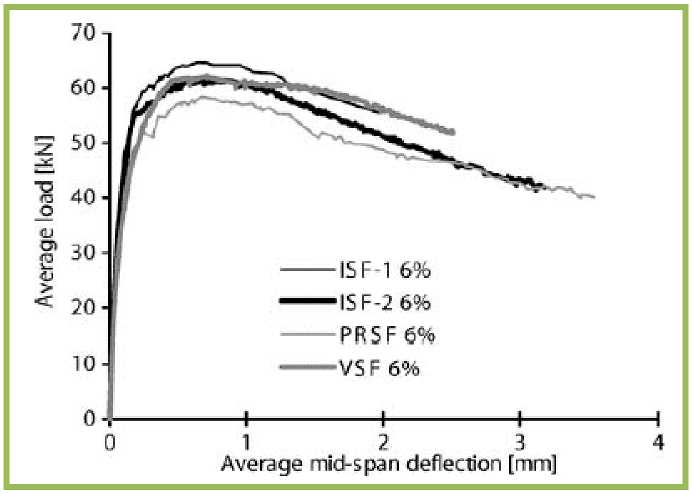


Fig. 3.11 Flexural behavior of prisms containing 6% ISF, PRSF, and VSF [25].

In summary, the addition of steel fibers significantly improves many of the engineering properties of concrete. Though modest improvements in strength can be obtained, the primary purpose of steel fiber inclusion to concrete is to increase toughness and ductility. Steel fiber inclusion also increases the resistance to dynamic loading. Properties of SFRC in both the freshly mixed and hardened state, including durability, are a consequence of its composite nature. Today steel is the most commonly used fiber type for concrete reinforcement. SFRC has a wide range of application ranging from industrial floors to airport runways, from cast in place application to precast elements, from vaults and safes to heavy machinery foundation.

Tyre recycling has become much more popular since it is one of the most environmentally friendly and economically viable ways of managing waste tyres. The steel fibers recovered from used tyres can be used as fibers in concrete. Concrete obtained by adding recycled fibers evidenced a satisfactory improvement of the fragile matrix mostly in terms of toughness and post cracking behavior. The promising results obtained by the pioneer research efforts performed on the topic, suggest the need for further experimental and theoretical studies, finally aiming to get reliable design information for possible structural and non-structural applications related to the use of RSF in concrete. With this context a research was undertaken to investigate the fresh and hardened properties of SFRC made with fibers extracted from used tyres. The experimental study adopted in this research is presented in the chapter to follow.

CHAPTER FOUR

EXPERIMENTAL STUDY

4.1 EXPERIMENTAL PROGRAM

The main target of this study is to produce SFRC made with fibers recovered from used tyres and then to characterize its properties, especially the mechanical properties in the hardened state. A bead wire having a diameter of 0.89 mm extracted from burnt used tires was used. Three grades of SFRC namely C-25 from Normal strength, C-40 from Intermediate strength and C-60 from High strength were produced incorporating three different volume fractions which are 0.5%, 1.0%, and 1.5%. Each volume fraction enclosed three different fiber lengths namely 20mm, 40mm and 60mm. Also each grade of concrete comprised one set of plain concrete, which were used as control mix.

As already discussed in the other chapters, the main factors controlling the mechanical performance of the obtained composite materials are the properties of the fibers and the matrix, as well as the bond between them. For this reason investigation of the properties of the constituent material and preliminary characterization of recovered steel fibers was made to obtain the necessary data about their geometric and mechanical properties. The performances of unreinforced concrete were evaluated in order to better appreciate the improvement gained by the addition of fibers. Thereafter, the slump test and fresh density in the fresh state, as well as compressive strength, flexural tensile strength, flexural toughness and impact resistance in the hardened state were evaluated for each mix, varying the volume fraction and length of the fibers.

4.2 MATERIALS

4.2.1 Cement

The cement used in all mixes was the locally manufactured Messebo PPC which was produced in accordance with EN 196 and BS 1370. Chemical composition, physical, mechanical and other characteristic of the cement, as provided by the manufacturer, are presented in Table 4.1 whereas the full data is attached in Annex A.

Table 4.1 Chemical, Physical and Mechanical Properties of the Cement [Source: Messebo Cement Factory, August 2009].

Chemical properties		**(%)**
SiO_2		29.14
Al_2O_3		5.91
CaO		6.76
MgO		55.86
SO_3		1.52
Sulfur content		2.46
Chloride content		0.01
Loss on Ignition (LOI)		2.31
Percentage of Pozzolana		25
Physical and Mechanical Properties		
Specific gravity (g/cm^3)		-
Specific Surface Area (cm^2/g)		2970
Initial Setting time (min)		155
Final Setting time (min)		195
Soundness (mm)		1.25
Compressive strength (N/mm^2)	2 day	13.8
	28 day	36.6
Heat of Hydration (Kj/Kg)	3 day	153
	28 day	258

4.2.2 Aggregates

The fine aggregate (river sand) used for this research work was brought from Meki located 120 km East of Addis Ababa as reported by the suppliers. The silt content of the original sample was found to be 11% which is well higher than the allowable limit. As a result it was washed and dried in the sun and kept in the laboratory. Thereafter, it was blended to meet the gradation requirements of the Ethiopian standard.

The coarse aggregate used for the preparation of the specimens was crushed basaltic stone with a maximum size of 19mm. It was brought from Blue Nile Construction crusher site, located at Akaki which is about 25 km East of Addis Ababa. The aggregate was initially screened using a 19mm sieve. And then it was washed and dried and kept in the laboratory. Sieve analysis results and other characteristics of the aggregates are presented in Table 4.2 and Annex B.

Table 4.2 Sieve analysis and physical characteristics of the aggregates.

I. Sieve Analysis		
Sieve Size	% Passing	
	Coarse Aggregate	Fine Aggregate
19mm	100	
12.5mm	51.47	
9.5mm	21.89	
4.75mm	1.76	98.2
2.36mm		95.4
1.18mm		84.4
600µm		41.8
300µm		12
150µm		2
Fineness Modulus	2.25	2.66
II. Physical properties		
Silt Content (%) Not Washed	-	11
Washed	-	1.2
Moisture Content (%)	1.37	2.04
Absorption Capacity (%)	4.38	1.72
Bulk Specific Gravity	2.79	2.41
Bulk Specific Gravity (SSD Condition)	2.84	2.51
Apparent Specific Gravity	2.93	2.69
Crushing Value (%)	17.83	-
Los Angeles Abrasion (%)	14.9	-

4.2.3 Water

As the time-honored rule of the thumb for water quality is, “If you can drink it, you can make concrete with it”, potable water supplied by the municipality was used for all concrete mixes.

4.2.4 Chemical Admixtures

To obtain sufficient consistency in the steel fiber reinforced concrete mixes high performance superplasticizing admixture with the commercial name Conplast SP 430 was used in all mixes. Conplast SP430 is a chloride free, superplasticising admixture based on selected sulphonated naphthalene polymers. It is supplied as a brown solution which instantly disperses in water. Conplast SP430 conforms with BSEN 934-2, BS 5075 Part 3 and with ASTM C494 as Type A and Type F, depending on dosage used. Conplast SP 430 has several advantages; some advantages among many worth mentioning are [27]:

- major increases in strength at early ages without increased cement contents are of particular benefit.
- makes possible major reductions in water/cement ratio which allow the production of high strength concrete without excessive cement contents, and
- increased workability levels are maintained for longer than with ordinary sulphonated melamine admixtures.

Based on the product manual for high workability concrete the normal dosage range is from 0.70 to 2.00 liters/100 kg of cementitious material. In this research work 1% of admixture per cementitious material (i.e. 1.0 liter/100 kg) was used in all mixes. The chemical and physical properties of the superplasticizer used are provided in Table 4.3 and Annex C.

Table 4.3 Properties of the Superplasticizer [27].

Appearance	Brown liquid
Main Component	Sulphonated naphthalene
Specific Gravity	1.18
Water Soluble Chloride	Nil
Alkali Content (Na_2O equivalent/liter of admixture)	55g

4.2.5 Steel Fiber

Since the diameter and tensile strength of steel fibers in a tyre vary from one factory product to another, the tyres used for the extraction of the steel fibers are all from the same source (Matador Addis Tyre Factory products). The steel fibers were purchased from suppliers who primarily used the tyres for heating sheet metals to produce different house hold utensils. The steel fiber used in this research was obtained by burning of waste tyres (pyrolysis process). The steel fibers were undamaged, since the tyres were burnt at a relatively low temperature. They are clean from rubber and contain carbon black on the surface as shown in Fig 4.1.

Basically three types of steel fiber diameters are recovered depending on the type of cord used in the tyres which are steel cords twisted together into a core strand of 0.72 and 0.77 mm as well as a bead wire with a diameter of 0.89 mm. Among these only the later was used in this research in order to have a consistent diameter. The fibers were prepared by cutting the bead wire into a length of 20, 40 and 60 mm with aspect ratio of 23, 45 and 67, respectivey as shown in Fig. 4.2-4.3.

Fig. 4.1 Steel fibers (Bead wire) extracted from burnt tyres.

Fig. 4.2 Cutting the steel fibers to the required length.

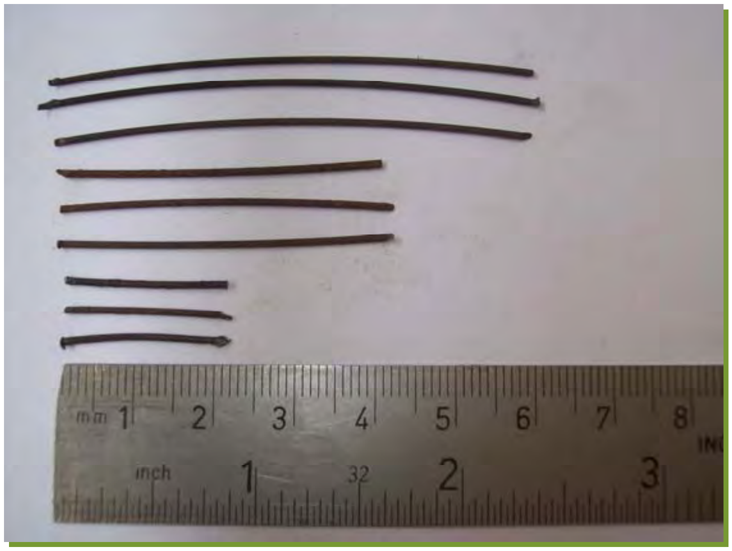


Fig. 4.3 The three lengths of steel fibers used in the mix.

Mechanical properties of steel fibers were evaluated by tensile tests on 10 randomly chosen samples. The test was performed both on the recovered and the virgin steel fiber for comparison purpose and also to examine the effect of burning on the tensile strength. The tensile test was carried out by Testometric machine (M350-5KN) in Matador Addis Tyre Laboratory (see Fig. 4.4). Table 6.4 reports the values of breaking load, tensile strength and elongation at break of both recovered steel fiber (RSF) and virgin steel fiber (VSF). The specification for the original bead wire is attached in Annex D.

Fig. 4.4 Testometric Machine for tensile strength of steel fiber.

An average tensile strength of 970.2 and 1892.6 MPa were found for the RSF and VSF respectively. The tensile strength of the RSF has decreased nearly by half (by 48.7 %) from that of VSF. The lower value is mainly due to the burning process. The test results obtained for the RSF is highly variable compared to the VSF, as the tyres were burnt under uncontrolled temperature. However, the obtained results are in good agreement with experimental results reported by Tlemat and et al. (2005), where an average value of 1250 MPa was found for the RSF used. They also meet the tensile requirement specified in ASTM A820 stated as "*The average tensile strength shall not be less than 345 MPa and the tensile strength of any one of the ten test specimens shall not be less than 310 MPa*."

Moreover, from the results reported in Table 4.4 and 4.5, it is possible to deduce that, as far as tensile strength concerned, RSF are comparable to industrial steel fibers (ISF). Depending on the type of steel, production processes and shape, ISF may present tensile strength in the range of 300-2000 MPa. For a comparison purpose the geometry and tensile strength of some ISF along with RSF and VSF are summarized in Table 4.5. The specifications for some selected industrial fibers are provided in Annex E.

Table 4.4 Tensile strength, breaking load and elongation at break of RSF and VSF.

Sample No.	Breaking Load (N)		Tensile Strength (MPa)		Elongation at Break (%)	
	RSF	**VSF**	**RSF**	**VSF**	**RSF**	**VSF**
1	424.6	1156.1	682.5	1858.3	5.4	12.2
2	574.9	1148.5	924.1	1846.1	6.8	13.0
3	476.1	1146.9	765.2	1843.6	4.4	9.9
4	571.9	1146.9	919.3	1842.3	4.9	9.7
5	432.0	1154.5	694.5	1855.8	7.2	10.9
6	443.4	1134.2	712.8	1823.1	3.8	8.9
7	642.8	1261.6	1033.3	2027.9	4.6	9.4
8	1021.1	1252.9	1641.3	2013.9	6.3	12.2
9	862.7	1241.8	1386.7	1996.1	6.5	10.5
10	585.9	1131.6	941.8	1819.0	11.4	10.9
Min.	424.6	1131.6	682.5	1819.0	3.8	8.9
Mean	**603.5**	**1177.4**	**970.2**	**1892.6**	**6.1**	**10.8**
Max	1021.1	1261.6	1641.3	2027.9	11.4	13.0
S.D.	196.79	52.25	316.3	84.07	2.17	1.35

Table 4.5 Summary of geometry and tensile strength of VSF, RSF and ISF.

Fiber Type	Length (mm)	Diameter (mm)	Tensile strength (MPa)
RSF	20/40/60	0.89	970.2
VSF	20/40/60	0.89	1892.6
XOREX	25/35/50/63	1.0	828
MATRIX-CS 1.0	25	0.33-0.6	414-825
NOVOCON XR	38/50	1.14	966-1242

4.3 MIX PROPORTIONS

The Department of Environment (DOE) mix design method was adopted to proportion the mixes [29]. Three different grades of concrete were designed to give a slump value of 10-30 mm and a 28-day compressive strength of 25, 40 and 60 MPa with a water-cement ratio of 0.53, 0.42 and 0.33 respectively. Besides the control mix for each grade of concrete 9 additional mixes with three fiber volume fractions namely 0.5%, 1.0% and 1.5% incorporating three different fiber lengths which are 20mm, 40mm and 60mm were produced. Altogether a total of 30 mixes were investigated to study the effect of concrete strength, fiber volume and fiber length over the mechanical properties of SFRC in the hardened state. Moreover Concrete mixes with characteristic strength of 25, 40 and 60 are categorized under a group referred as Mix Series I, II and III, respectively. The DOE mix design data sheet for all mix series is attached in Annex F.

Proportions of these three mix series along with the volume of percentage of fiber contents and the length of fiber are presented in Table 4.6**.** The mixes are designated in such a way that the first, second and third letters and subscripts describe the mix series, volume proportion of the fiber and the length of the fiber, respectively. For instance, a concrete mix designated by $C_1V_{0.5}L_6$ is considered as a concrete from mix series I (with characteristic strength of 25 MPa) and incorporates 0.5% of fiber volume with a length of 6 cm.

Table 4.6 Mix proportions for the three mix series.

Mix Designation	Cement Quantity (kg/m^3)	W/C Ratio	Water (liter)	Fine Agg. (kg/m^3)	Coarse Agg. (kg/m^3)	Steel fiber (kg/m^3)	Admix. (lit/m^3)
Mix Series I (C-25)							
Control-1	340	0.53	180	670	1270	0	3.4
$C_1V_{0.5}L_2$ $C_1V_{0.5}L_4$ $C_1V_{0.5}L_6$	340	0.53	180	670	1270	39.3	3.4
$C_1V_{1.0}L_2$ $C_1V_{1.0}L_4$ $C_1V_{1.0}L_6$	340	0.53	180	670	1270	78.6	3.4
$C_1V_{1.5}L_2$ $C_1V_{1.5}L_4$ $C_1V_{1.5}L_6$	340	0.53	180	670	1270	117.9	3.4
Mix Series II (C-40)							
Control-2	430	0.42	180	575	1250	0	4.3
$C_2V_{0.5}L_2$ $C_2V_{0.5}L_4$ $C_2V_{0.5}L_6$	430	0.42	180	575	1250	39.3	4.3
$C_2V_{1.0}L_2$ $C_2V_{1.0}L_4$ $C_2V_{1.0}L_6$	430	0.42	180	575	1250	78.6	4.3
$C_2V_{1.5}L_2$ $C_2V_{1.5}L_4$ $C_2V_{1.5}L_6$	430	0.42	180	575	1250	117.9	4.3
Mix Series III (C-60)							
Control-3	550	0.33	180	500	1193	0	5.5
$C_3V_{0.5}L_2$ $C_3V_{0.5}L_4$ $C_3V_{0.5}L_6$	550	0.33	180	500	1193	39.3	5.5
$C_3V_{1.0}L_2$ $C_3V_{1.0}L_4$ $C_3V_{1.0}L_6$	550	0.33	180	500	1193	78.6	5.5
$C_3V_{1.5}L_2$ $C_3V_{1.5}L_4$ $C_3V_{1.5}L_6$	550	0.33	180	500	1193	117.9	5.5

4.4 SPECIMENS PREPARATION

Initially a certain amount of water for adjustment obtained from the mix design was added to the measured aggregates and left for a short while to bring the aggregates to the Saturated Surface Dry condition (SSD). The fine aggregate, coarse aggregate and cement were dry mixed for about a minute. The fibers were added during the dry mix as a rainfall very carefully in order to avoid balling effect. This was then followed by the addition of two third of the total mixing water. After two minutes of mixing, remaining mixing water together with superplasticizer was added. Mixing was ceased after four minutes for all mixes.

The specimens for the testing of mechanical properties in the hardened state were casted in two layers using appropriate moulds, wet inside with a release agent and, thus placed on a vibration table. The vibrating procedure was executed in order to obtain a more homogeneous distribution of fibers. For each mix, nine 150 mm cubes, two 150x300 mm cylinders, and two 100x100x500 mm beams were casted. Cubes were used for the determination of 7th, 28th and 56th-day compressive strength. Cylinder specimens were cut into 150x63.5mm discs which were used in the impact resistance tests. Beam specimens were used for the determination of flexural tensile strength and flexural toughness.

The moulds were left to cure for 24 h. Once hardened, the specimens were carefully demolded and placed in a curing room for 7, 28 and 56 days for compressive strength tests and 28 days for flexure and impact tests at approximately 95±5% RH and 22±2°C.

4.5 TESTING PROCEDURE

4.5.1 Testing of Fresh Concrete

Slump test in accordance with the Ethiopian 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

Compressive strength tests were carried out by an oil-pressure machine with a nominal capacity of 3000 KN. Dimension and weight of each specimen were accurately measured before testing. The 7, 28 and 56-days compressive strength of each mix were determined in accordance with the Ethiopian standard. The load was applied at a constant rate of 0.442 MPa/s and the compressive strength was measured to the nearest two digits after a decimal. Average of the test results of three specimens belonging to a mix was accepted as a compressive strength of that mix for the testing day. Specimens were tested so that the direction of loading was 90° with the direction of casting.

Flexural tensile strength and energy absorption up to failure under flexural loading tests were carried out in Addis Ababa University Civil Engineering Department Material Testing Laboratory, which was equipped with a UTM testing machine with the capability of performing deformation controlled loading. Two point loading was used to determine the flexural tensile strength. 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. Furthermore location of first crack point and energy absorption up to specified deflections were determined according to ASTM C 1018 as discussed in Chapter 2. Specimens were tested so that the direction of loading was 90° 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 2. For this purpose standard Marshall hammer apparatus located in the Highway Laboratory was used and the test equipment were prepared in Addis Ababa University Mechanical Engineering Department workshop. In this test four specimens were used because the adopted test method is known to yield highly variable results. Average of the test results of four 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 FIVE

RESULTS AND DISCUSSION

5.1 TEST RESULTS OF FRESH CONCRETE PROPERTIES

5.1.1 Slump Test

The workability of freshly mixed concrete is a measure of its ability to be mixed, handled, transported, and, most importantly, placed and consolidated with a minimal loss of homogeneity and minimal entrapped air. Among the several tests available the slump test is a common, convenient and inexpensive test. Predicting the workability of SFRC is difficult because of the large number of parameters involved. Two factors which influence significantly the characteristics of SFRC in its fresh state are the aggregate content, and fiber geometry and volume fraction. The influence of aspect ratio and volume fraction of fiber on the properties of fresh concrete is investigated in this research work.

All the control mixes (plain concretes) were designed to give a slump value of 10-30 mm. And it was proved to be so for the trial mixes without adding the superplasticizer. Without the presence of the superplasticizer the SFRC appeared to be relatively stiff, unworkable and the materials tend to “hang together” and resist movement compared to the control mixes. It was almost impossible to work with fibers having higher aspect ratio and volume fraction. As a result 1% of SP 430 superplasticizer per cementitious material was added to all mixes in order to improve the workability.

To evaluate the effect of aspect ratio and volume fraction of fibers on workability a slump test were performed on the fresh concrete for each mix and the results are reported in Table 5.1. As shown in this table, slump values of concretes vary between 0 and 91 mm. It can be noted that the presence of the steel fibers strongly affected the workability of the fresh concrete. The slump value in particular mixtures with the highest concentrations of fibers (1.5%) and aspect ratio (67) in all three grade of concrete is found to be zero. The test results, as expected, in all mix series indicated that as the fiber length and the volume of fraction increases the workability tend to decreases significantly especially for fiber length of 40 and 60 mm. While compacting the sample in the cone using the steel tamping rod for the slump test the fibers tend to act as reinforcement and resist the compaction. Those concrete made with 20 mm fiber length due to its lower aspect ratio (23) relatively has shown a better workability comparable with the control plain mix. For an illustration purpose the slump values for the three mix series reported in Table 5.1 are further organized as a line graph in Fig. 5.1-5.3.

Aspect ratio and volume of fiber have a crucial influence on workability. The results obtained in this research regarding the effect of this two parameters on workability is in a good conformity with those stated in the literature review under section 2.7.5, 3.2.3 and 3.3.4, where increasing the fibers ratio and the volume fraction reduced the workability of fresh concrete as measured by the slump test.

Despite lowest slump value obtained, almost all mixes were workable, had even distribution of fibers without balling effect and responded well to mechanical vibration and could be placed and compacted without much effort. As a result of this it can be concluded that slump test provides little indication of either the workability or the ease with which SFRC can be compacted. Since this test is inadequate and cannot distinguish the effects of fiber inclusion on the consistency of SFRC, as suggested by ACI code to obtain a more reliable measures of workability inverted slump cone test or Vebe test should be used.

Table 5.1 Results of slump values.

Mix Series I			Mix Series II			Mix Series III		
Concrete Grade	**Mix Design.**	**Slump Value (mm)**	**Concrete Grade**	**Mix Design.**	**Slump Value (mm)**	**Concrete Grade**	**Mix Design.**	**Slump Value (mm)**
C-25	Control-1	79	C-40	Control-2	91	C-60	Control-3	80
	$C_1V_{0.5}L_2$	64		$C_2V_{0.5}L_2$	74		$C_3V_{0.5}L_2$	76
	$C_1V_{0.5}L_4$	38		$C_2V_{0.5}L_4$	55		$C_3V_{0.5}L_4$	65
	$C_1V_{0.5}L_6$	31		$C_2V_{0.5}L_6$	43		$C_3V_{0.5}L_6$	30
	$C_1V_{1.0}L_2$	56		$C_2V_{1.0}L_2$	58		$C_3V_{1.0}L_2$	65
	$C_1V_{1.0}L_4$	11		$C_2V_{1.0}L_4$	19		$C_3V_{1.0}L_4$	27
	$C_1V_{1.0}L_6$	5		$C_2V_{1.0}L_6$	5		$C_3V_{1.0}L_6$	0
	$C_1V_{1.5}L_2$	47		$C_2V_{1.5}L_2$	54		$C_3V_{1.5}L_2$	56
	$C_1V_{1.5}L_4$	6		$C_2V_{1.5}L_4$	8		$C_3V_{1.5}L_4$	12
	$C_1V_{1.5}L_6$	0		$C_2V_{1.5}L_6$	0		$C_3V_{1.5}L_6$	0

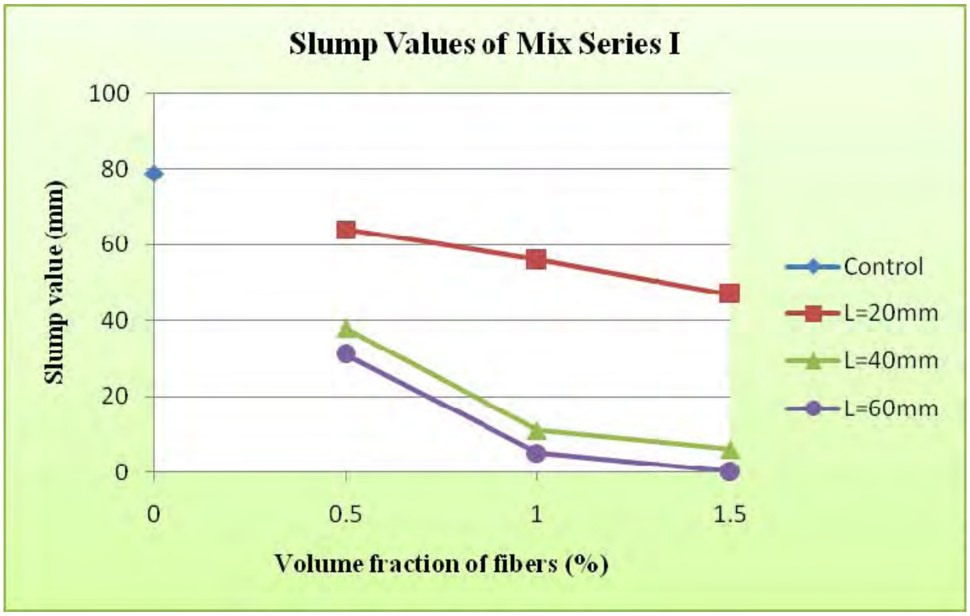


Fig. 5.1 Comparison of slump values of Mix Series I.

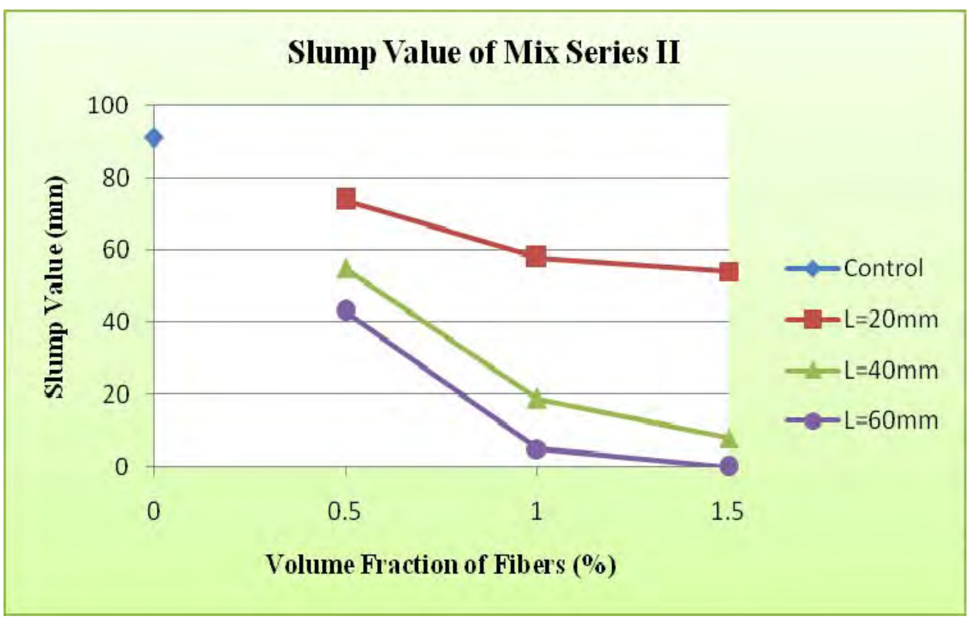


Fig. 5.2 Comparison of slump values of Mix Series II.

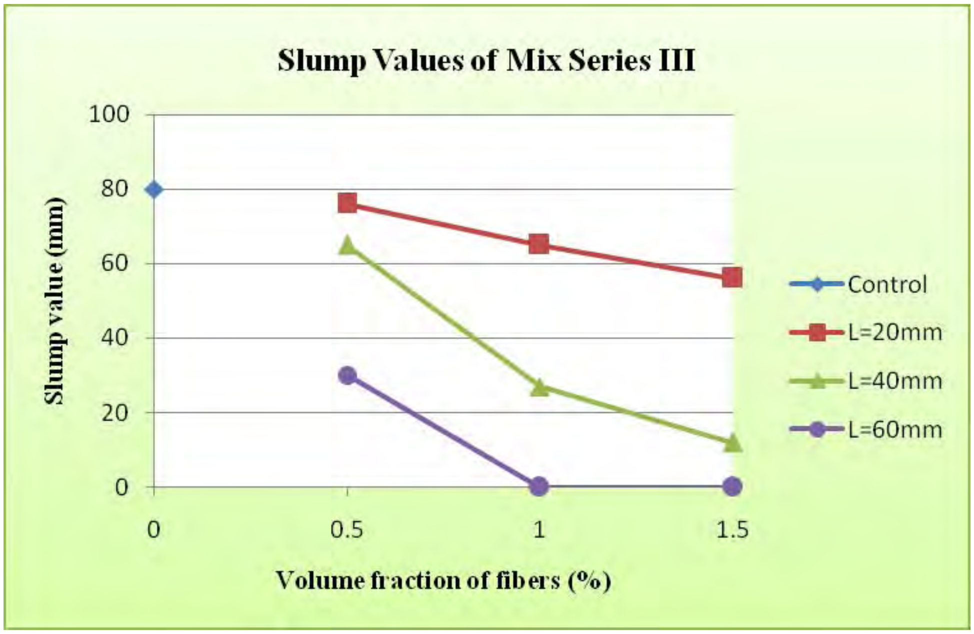


Fig. 5.3 Comparison of slump values of Mix Series III.

5.2 TEST RESULTS OF HARDENED CONCRETE PROPERTIES

5.2.1 Compressive Strength

The 7, 28 and 56 days compressive strengths were determined as explained in Chapter 4. Table 5.2 shows the 28 day compressive strength as the mean of three specimens tested on the same day along with the standard deviation of the specimens and the relative strength gain or loss to that of the control mix. The 7, 28 and 56-days compressive strength results and all raw data are attached in Annex G.

Since different constituents are used in the different mixes, a direct comparison between groups is not easy to make. Therefore, the comparison is only made among each mix series as follow.

As reported in Table 5.2, the 28^{th} day mean compressive strength for the plain control mix in Mix Series I is found to be 28.05 MPa. In this mix series addition of steel fibers of different length and volume ranging from 0.5% to 1.5% has resulted mean compressive strength values varying from 27.72 MPa to 31.37 MPa with a maximum relative strength loss and gain of 1.17% and 11.77% respectively. A decrease in compressive strength was noticed in mix $C_1V_{0.5}L_2$,

$C_1V_{1.0}L_2$ and $C_1V_{1.0}L_6$ with a relative compressive strength loss of 0.28, 0.4 and 1.17, respectively, whereas in the rest of the mixes a very slight increase was observed. The lowest strength value in this Mix Series was exhibited in mix $C_1V_{1.0}L_6$, while the highest strength was seen in mix $C_1V_{1.5}L_4$. In this mix series except to fiber length 60mm an increase in fiber volume has increased the compressive strength slightly; however, a direct relationship with an increase of fiber length and compressive strength was not witnessed (see Table 5.2 and Fig.5.4).

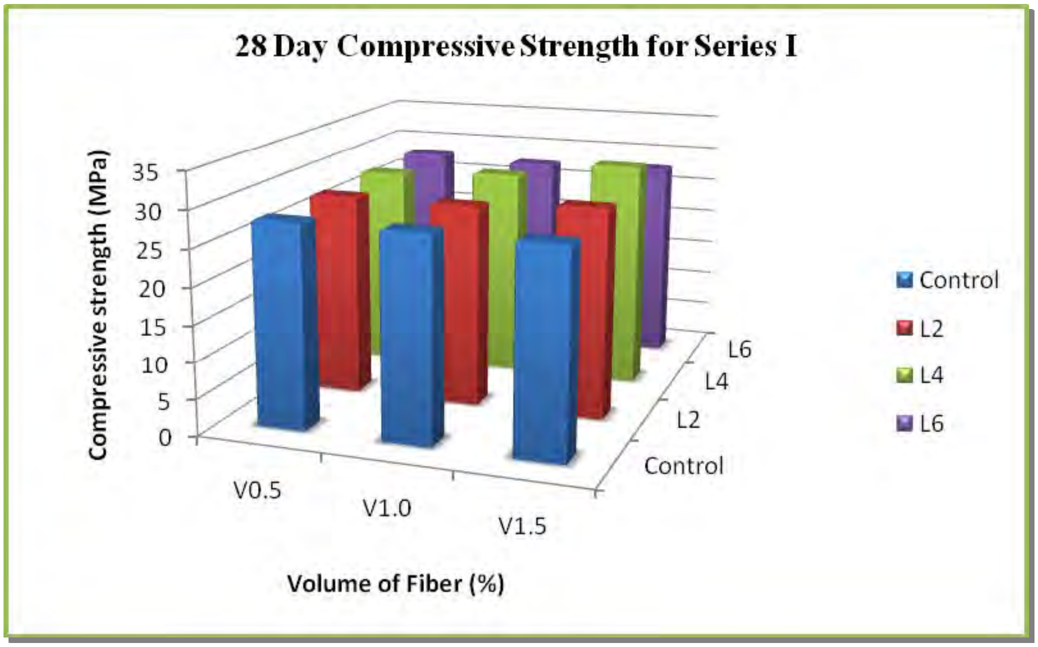


Fig. 5.4 Comparison of 28 day compressive strength for Mix Series I.

In Mix Series II the mean compressive strength of the control plain mix is 41.03 MPa. Compressive strength values ranging from 40.92 MPa to 43.94 with a maximum relative strength loss and gain of 0.29% and 7.07% respectively was obtained by inclusion of fibers of different length and volume. In this mix series a decrease in compressive strength was noticed only in mix $C_2V_{0.5}L_2$ with a relative loss of 0.29% which is very insignificant. In the rest of all mixes a slight increase ranging from 0.06% up to 7.07% was registered. The highest compressive strength value was observed in mix $C_2V_{1.5}L_4$. Except to fiber length 60 mm a slight increase of compressive strength was registered with an increase in the volume of fiber; however, similar to that of Mix Series I a direct relationship with an increase of fiber length and compressive strength was not witnessed (see Table 5.2 and Fig.5.5).

Table 5.2 Mean 28 day compressive strength results.

Mix Series I				**Mix Series II**				**Mix Series III**			
Mix Designation	Mean 28 day f_{comp} (MPa)	Standard Deviation	Relative Strength Gain (%)	Mix Designation	Mean 28 day f_{comp} (MPa)	Standard Deviation	Relative Strength Gain (%)	Mix Designation	Mean 28 day f_{comp} (MPa)	Standard Deviation	Relative Strength Gain (%)
Control-1	28.05	0.65		Control-2	41.03	0.67		Control-3	58.40	1.39	
$C_1V_{0.5}L_2$	27.97	0.33	-0.28	$C_2V_{0.5}L_2$	40.92	0.12	-0.29	$C_3V_{0.5}L_2$	58.98	1.21	1.00
$C_1V_{0.5}L_4$	28.20	0.58	0.54	$C_2V_{0.5}L_4$	41.51	0.99	1.17	$C_3V_{0.5}L_4$	60.45	0.77	3.51
$C_1V_{0.5}L_6$	28.23	0.61	0.66	$C_2V_{0.5}L_6$	41.58	0.59	1.33	$C_3V_{0.5}L_6$	56.25	0.51	-3.68
$C_1V_{1.0}L_2$	27.94	0.79	-0.4	$C_2V_{1.0}L_2$	41.32	0.84	0.69	$C_3V_{1.0}L_2$	60.56	2.20	3.7
$C_1V_{1.0}L_4$	29.09	1.38	3.71	$C_2V_{1.0}L_4$	43.66	0.86	6.39	$C_3V_{1.0}L_4$	60.52	1.45	3.63
$C_1V_{1.0}L_6$	27.72	0.42	-1.17	$C_2V_{1.0}L_6$	41.06	0.46	0.06	$C_3V_{1.0}L_6$	59.50	0.61	1.88
$C_1V_{1.5}L_2$	28.95	0.49	3.20	$C_2V_{1.5}L_2$	41.78	0.50	1.82	$C_3V_{1.5}L_2$	62.41	0.73	6.87
$C_1V_{1.5}L_4$	31.35	0.32	11.77	$C_2V_{1.5}L_4$	43.94	1.38	7.07	$C_3V_{1.5}L_4$	59.17	0.45	1.31
$C_1V_{1.5}L_6$	28.07	1.25	0.08	$C_2V_{1.5}L_6$	41.97	0.48	2.27	$C_3V_{1.5}L_6$	61.02	0.60	4.48

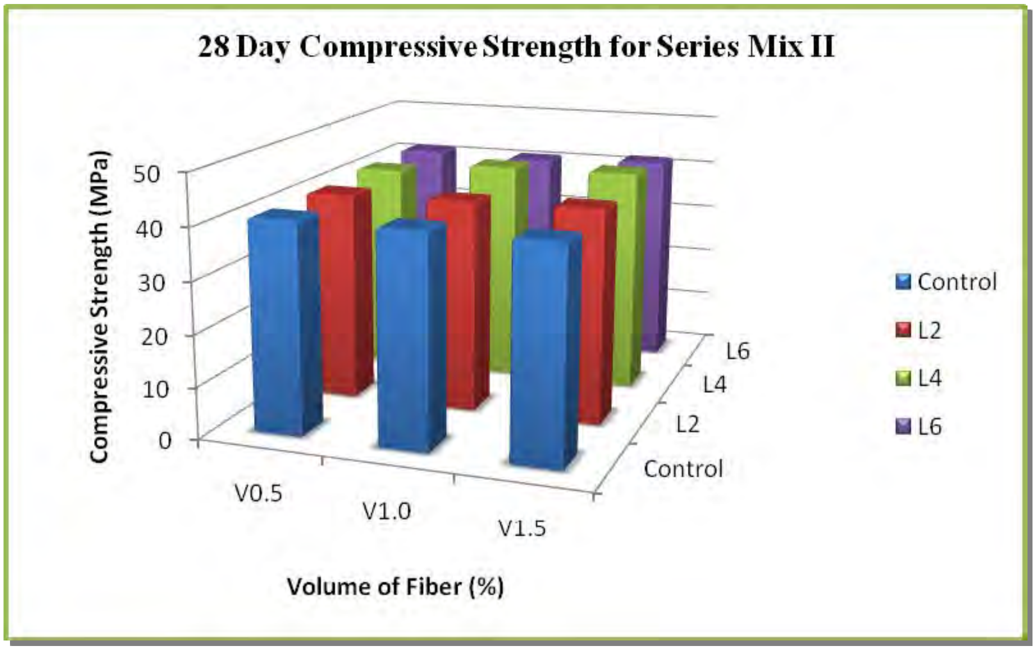


Fig. 5.5 Comparison of 28 day compressive strength for Mix Series II.

The mean compressive strength of the plain control mix in mix series III which was primarily designed for characteristic strength of 60 MPa at 28 day was found to be 58.40 MPa (2.7% lower than the characteristic strength). This is mainly due to the slower rate of early strength development of the type of cement used (Messebo PPC). However, the 56 day mean compressive strength value is turn out to be 66.47 MPa with a relative strength gain of 10.78% to that of the characteristic strength (see Annex). In this mix series mean compressive strength values ranging from 56.25 MPa to 62.41 with a maximum relative strength loss and gain of 3.68% and 6.87%, respectively were observed by inclusion of fibers. Only mix $C_3V_{0.5}L_6$ has shown a decrease in compressive strength with a relative strength loss of 3.68%. A slight increase in compressive strength ranging from 1.0% to 6.87% to that of the control mix was recorded in the rest of the mixes. In Mix Series III it was not possible to witness any sort of direct relationship either with an increase in aspect ratio or an increase in volume of fiber and compressive strength (see Table 5.2 and Fig.5.6).

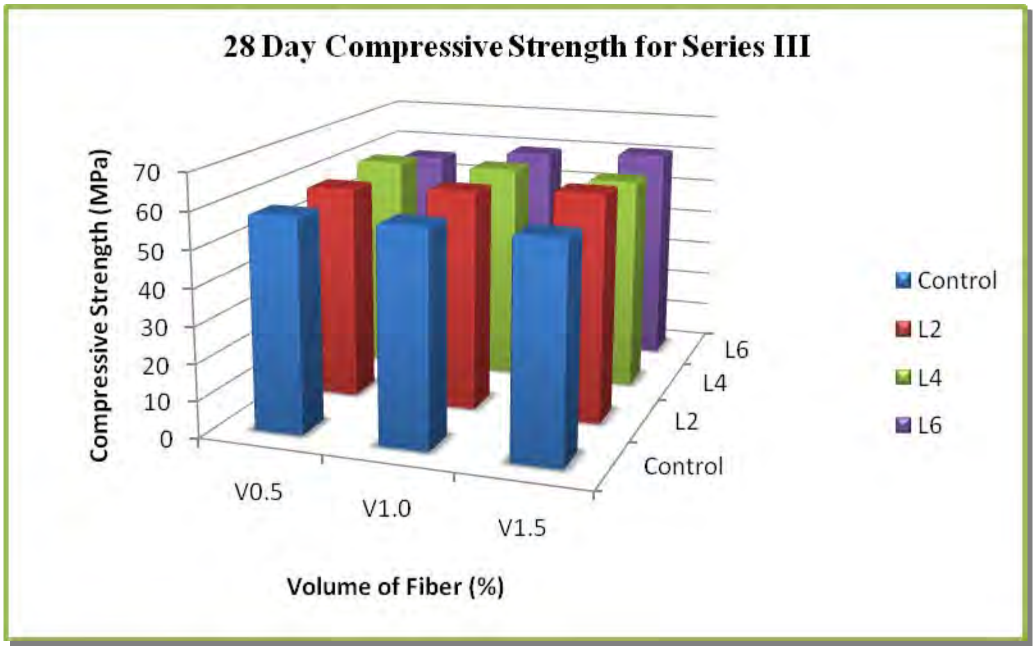


Fig. 5.6 Comparison of 28 day compressive strength for Mix Series III.

Generally, among the 30 mixes a slight decrease in compressive strength was observed only in 5 of the mixes. However, for the rest of the mixes fiber inclusion of all lengths and volume fraction has increased the compressive strength. But this increase was not that significant in neither of the mixes. The observed decline of compressive strength for some of the specimens can be always attributed to different factors Viz. moisture in aggregates, curing efficiency and temperature, and degree of compaction.

Rather than increasing the compressive strength the inclusion of fibers in concrete is very much advantageous in delaying the materials failure and increasing the strain at the peak in the stress-strain curves for steel fiber reinforced concrete in compression. This occurrence is also confirmed by the examination of the specimens after testing. For the plain concrete specimens a sudden ejection of materials was observed at the collapse, while for SFRC a more ductile collapse was observed.

The results obtained in this research work regarding the compressive strength are very much in harmony with the experimental results reported in the literature review. In fact, values illustrated in Table 5.2 confirm the experimental results reported in the literature (Tlemat H. et al. and

Aiello M.A. et al.), where compressive strength of concrete seems unaffected by the presence of steel fibers despite their geometry and volume fraction. In addition, comparing these results with those reported in section 2.6.1, 3.2.4.1a and 3.3.4 the slight increase in compressive strength with respect to unreinforced concrete is confirmed and the relative strength gains are also in a range reported in section 3.2.4.a stated "*It is unlikely to achieve considerable improvements in compressive strength by steel fiber inclusion. The ultimate strength is only slightly affected by the presence of fibers, with observed increases ranging from 0 to 15 percent and 0 to 23 percent for up to 1.5 and 2 percent by volume of fibers, respectively*".

All in all it cannot be emphasized too strongly that, the role of fiber is not to increase strength, though modest strength increases may occur. If what is desired is a strength increase, it is clearly much easier (and much cheaper) simply to redesign the plain concrete mix, primarily by reducing the w/c ratio and by changing the cement type.

5.2.2 Flexural Strength

5.2.2.1 Flexural Tensile Strength

Basically there are two commonly adopted forms of the flexure test; the two point loading or center point loading (also known as four point and three point loading respectively). The former is generally preferred for many materials, but the latter is often used where greater testing simplicity is required. In this research work the flexural tensile strength of all mixes was determined as clarified in Chapter 2 using a two point loading. This method is preferred over center point loading for the different advantages it possesses [28]. In this test the concrete beam to be tested is supported at its ends and loaded at its interior location by gradually increasing load to failure. The failure load (loading value at which the concrete cracks heavily) is then recorded and used to determine the tensile at which the member failed, i.e. its tensile strength.

The mean flexural tensile strength for all mix series are presented in Table 5.3 along with the standard deviation of the samples and the relative flexural strength gain to that of the control mix. Apparently fiber inclusion of all lengths and volume fractions resulted in substantial increase in flexural tensile strength values as discussed below.

Table 5.3 Mean 28 day flexural tensile strength results.

Mix Series I				Mix Series II				Mix Series III			
Mix Designation	Mean 28 day $f_{flex.\ tens.}$ (MPa)	Standard Deviation	Relative $f_{flex.\ tens.}$ Gain (%)	Mix Designation	Mean 28 day $f_{flex.\ tens.}$ (MPa)	Standard Deviation	Relative $f_{flex.\ tens.}$ Gain (%)	Mix Designation	Mean 28 day $f_{flex.\ tens.}$ (MPa)	Standard Deviation	Relative $f_{flex.\ tens.}$ Gain (%)
Control-1	6.18	0.42		Control-2	7.72	0.25		Control-3	8.73	0.13	
$C_1V_{0.5}L_2$	6.84	0.42	10.68	$C_2V_{0.5}L_2$	8.34	0.42	5.30	$C_3V_{0.5}L_2$	8.85	0.13	1.37
$C_1V_{0.5}L_4$	6.96	0.25	12.62	$C_2V_{0.5}L_4$	8.64	0.59	9.09	$C_3V_{0.5}L_4$	9.09	0.21	4.12
$C_1V_{0.5}L_6$	8.19	1.57	32.52	$C_2V_{0.5}L_6$	9.24	0.76	16.67	$C_3V_{0.5}L_6$	9.21	0.81	5.50
$C_1V_{1.0}L_2$	7.17	0.13	16.02	$C_2V_{1.0}L_2$	8.46	0.17	6.82	$C_3V_{1.0}L_2$	9.30	0.17	6.53
$C_1V_{1.0}L_4$	7.89	0.38	27.67	$C_2V_{1.0}L_4$	9.6	0.76	21.21	$C_3V_{1.0}L_4$	12.0	1.01	37.46
$C_1V_{1.0}L_6$	10.08	1.61	63.11	$C_2V_{1.0}L_6$	12.57	1.99	58.71	$C_3V_{1.0}L_6$	12.84	0.34	47.08
$C_1V_{1.5}L_2$	8.07	0.72	30.58	$C_2V_{1.5}L_2$	8.7	0.17	9.85	$C_3V_{1.5}L_2$	11.37	0.21	30.24
$C_1V_{1.5}L_4$	8.64	0.42	39.81	$C_2V_{1.5}L_4$	9.6	0.76	21.21	$C_3V_{1.5}L_4$	13.53	3.18	54.98
$C_1V_{1.5}L_6$	13.71	0.72	121.84	$C_2V_{1.5}L_6$	14.79	0.04	86.79	$C_3V_{1.5}L_6$	16.14	2.63	84.88

As reported in Table 5.3 the flexural tensile strength of the control plain mix in Mix Series I is found to be 6.18 MPa. Flexural tensile strength values ranging from 6.84 MPa to 13.71 MPa with a relative flexural tensile strength gain of 10.68 % to 121.84% was obtained by inclusion of fibers of different length and volume. In this mix series for all three different fiber volumes highest flexural tensile strength was observed in those specimens incorporating fiber length of 60 mm, namely $C_1V_{0.5}L_6$, $C_1V_{1.0}L_6$ and $C_1V_{1.5}L_6$ with a relative flexural tensile strength gain of 32.52, 63.11 and 121.84%, respectively. Also it was possible to note that an addition of 1.5% volume of fiber length 60 mm has increased the tensile strength by more than two fold. Also in this series an increase in flexural tensile strength was observed when both the fiber length and volume of fibers increase as shown in Fig. 5.7.

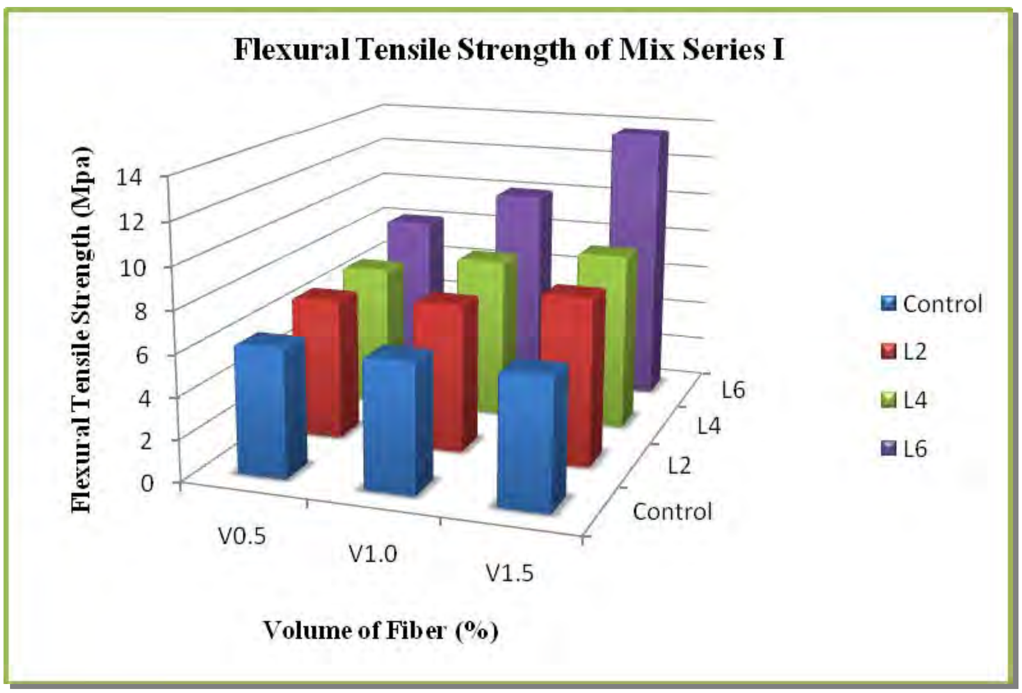


Fig. 5.7 Comparison of flexural tensile strength for Mix Series I

In Mix Series II the flexural tensile strength of the control mix is 8.34 MPa and tensile strength values ranging from 8.64 to 14.79 MPa with a relative flexural tensile strength gain of 9.09 to 86.79% was registered by adding fibers of different volume and length to the concrete. Also in this mix series an increase in length and volume of fibers has increased the flexural tensile strength similar to that of the first mix series. In order to show effects of fiber length and fiber volume on flexural tensile strength test results presented in Table 5.3 is organized in the form of bar charts and are shown in Fig. 5.8.

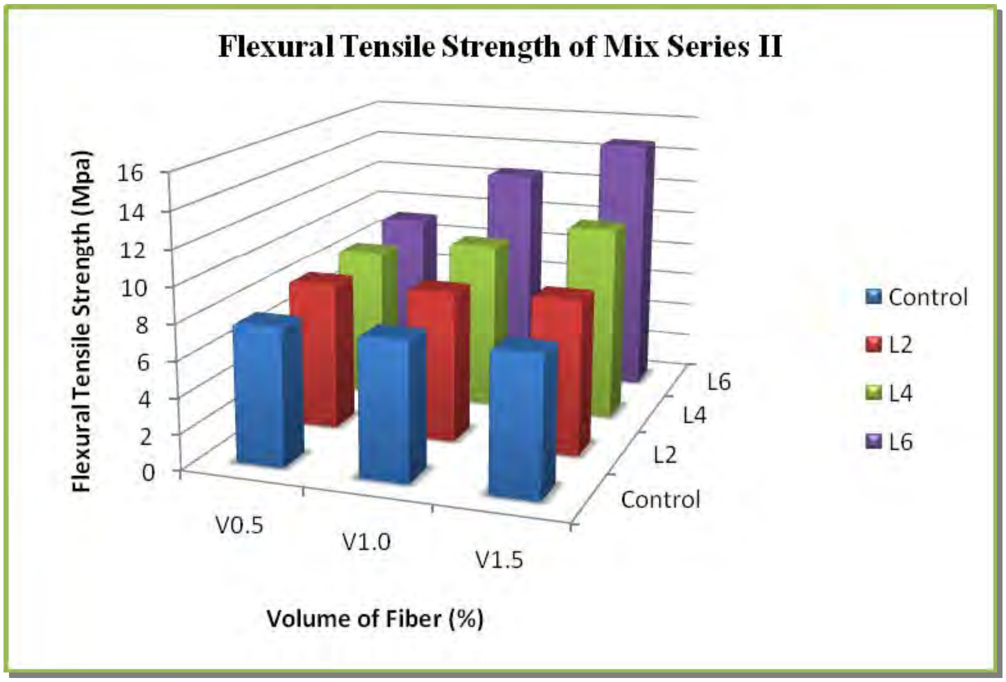


Fig. 5.8 Comparison of flexural tensile strength for Mix Series II

The flexural tensile strength of the control mix in Mix Series III is 8.73 MPa. The minimum and maximum flexural tensile strength values registered in this series by adding of fibers into the concrete are observed in mix $C_3V_{0.5}L_2$ and $C_3V_{1.5}L_6$ and the values obtained are 8.85 and 16.14 MPa with a relative flexural tensile strength gain of 1.37 and 84.88% respectively. Similar to the other mix series the flexural tensile strength has significantly improved with increasing fiber length and volume of fiber (see Table 5.3 and Fig. 5.9).

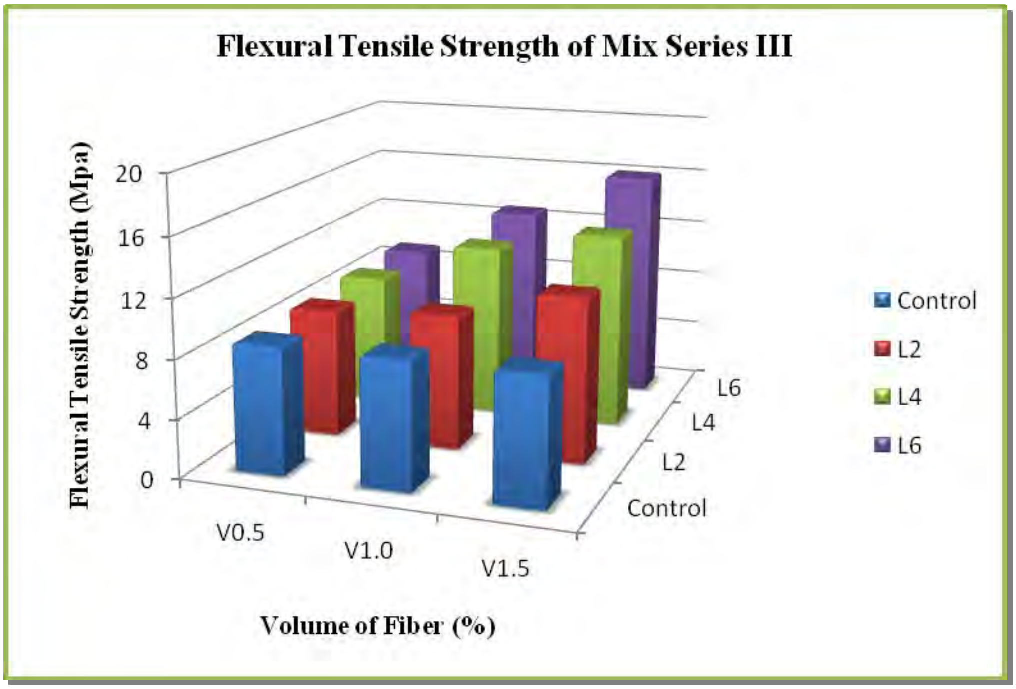


Fig. 5.9 Comparison of flexural tensile strength for Mix Series III

The test results indicated that as the concrete grade increases the flexural tensile strength also tends to increase. For example for fiber length of 60 mm and 1.5% fiber volume in Mix series I, II and III namely $C_1V_{1.5}L_6$, $C_2V_{1.5}L_6$ and $C_3V_{1.5}L_6$ the flexural tensile strength values are 13.71, 14.79 and 16.14 MPa with a relative flexural tensile strength gain of 121.84, 86.79 and 84.88%, respectively to that of the plain control mix belonging to each mix series. A better relative flexural tensile strength was observed in Mix Series I compared to the other mix series.

From the test results it can be noted that lowest values of tensile strength were obtained in those mixes incorporating smaller length and volume of fibers, whereas, highest values were recorded for those mixes with higher aspect ratio and volume of fibers. This can be explained by the fact that failure in flexure for steel fiber reinforced concrete is mainly due to fiber pull out as a result when the fiber length and volume increases the peak flexural strength required to bring the samples to failure will definitely increase resulting higher flexural tensile strength.

Generally a similar pattern was exhibited in all mix series with regard to increment in flexural tensile strength when both the fiber length and volume of fibers increased. Even for the same proportion of fiber volume an increase in flexural tensile strength was attained due to an increase of aspect ratio. Compared to the other fiber lengths the relative flexural strength gain by 20mm fiber length is not as such appreciable. This is because of its lower length the strength required to pull out the fiber from the concrete matrix will certainly be lower than the other fiber lengths. As can be seen in Table 5.4 and Fig. 5.5-5.7 utilization of 1.5% fiber volume and 60mm fiber length is more efficient on flexural tensile strength.

From the test results it is possible to observe that addition of steel fibers appreciably improved the flexural tensile strength of concrete compared to the compressive strength. Increases in the flexural strength of SFRC are substantially greater than compression because ductile behavior of the SFRC on the tension side of a beam alters the normally elastic distribution of stress and strain over the member depth.

The flexural strength values obtained in this research work are in good agreement with the literature review provided under section 3.3.4 (Tlemat H. et al. and Aiello M.A. et al.) where addition of steel fibers extracted from used tyre significantly improved the flexural strength and an increase in aspect ratio and fiber volume resulted an improvement in the flexural strength as well the results obtained are comparable to concretes reinforced with industrial fibers. The relative flexural strength gain recorded in this research work ranging from 1.37 up to 121.84% are also within a range specified for SFRC under section 3.2.4.1d where it was stated that the flexural strength of SFRC is about 50 to 70 percent more than that of the unreinforced concrete matrix in the normal third-point bending test and use of higher fiber volume fractions, or center-point loading, or small specimens and long fibers with significant fiber alignment in the longitudinal direction will produce greater percentage increases up to 150 percent.

5.2.2.2 Flexural Toughness

Energy absorptions up to failure under flexural loading for all mixes were calculated as explicated in Chapter 2 and 4. Area under the load deflection curve was designated as the energy absorption up to failure and it was calculated using the trapezoidal rule. Mean of the test results of two beam specimens belonging to a mix were accepted as flexural toughness of that mix.

Since determination of first crack point is not a concern and stability problems encountered right after the first crack do not affect the obtained results significantly in JSCE Standard method, this method was preferred over ASTM C 1018 method to determine the flexural toughness. In this method the area under the load deflection curve up to a deflection of span/150 (2mm in this case) is obtained and the calculated values together with the relative energy absorption gain for all mix series are presented in Table 5.4. The Averaged load deflection curves from which the energy absorption values are calculated are shown in Fig. 5.12, 5.14 and 5.16.

As reported in the literature review part, the main effect of the steel fibers is to prevent and control the crack propagation; as a consequence the flexural behavior is characterized by a residual strength in the post cracking stage with a significant improvement of the material toughness. As expected and shown in Fig. 5.10, the failure in flexure for all SFRC specimens was due to fiber pull out. In the experiment it was observed that all control plain beams broke suddenly in two halves, and as shown in Fig. 5.12, 5.14 and 5.16 the load versus deflection curve of the control mixes made a closed loop instantly after the first crack was observed. This clearly shows the typical brittleness of plain concrete, which makes this material unsuitable for a reliable structural use without tensile reinforcement. Apparently steel fiber inclusion prevented sudden and brittle failure. Fiber inclusion of all length and volume of fraction greatly enhanced the flexural toughness up to failure compared with the plain control mixes.

Fig. 5.10 A beam sample failed in flexure by fiber pull out

Table 5.4 Calculated mean energy absorption.

Mix Series I			Mix Series II			Mix Series III		
Mix Designation	Energy Absorption (Joule)	Relative Energy Gain (%)	Mix Designation	Energy Absorption (Joule)	Relative Energy Gain (%)	Mix Designation	Energy Absorption (Joule)	Relative Energy Gain (%)
Control-1	4.77		Control-2	3.65		Control-3	9.77	
$C_1V_{0.5}L_2$	8.48	77.78	$C_2V_{0.5}L_2$	7.88	115.89	$C_3V_{0.5}L_2$	11.44	17.09
$C_1V_{0.5}L_4$	8.78	84.07	$C_2V_{0.5}L_4$	12.98	255.62	$C_3V_{0.5}L_4$	12.12	24.05
$C_1V_{0.5}L_6$	14.4	201.89	$C_2V_{0.5}L_6$	16.38	348.77	$C_3V_{0.5}L_6$	16.17	65.51
$C_1V_{1.0}L_2$	9.26	94.13	$C_2V_{1.0}L_2$	11.52	215.62	$C_3V_{1.0}L_2$	16.91	73.08
$C_1V_{1.0}L_4$	16.34	242.56	$C_2V_{1.0}L_4$	21.89	499.73	$C_3V_{1.0}L_4$	26.68	173.08
$C_1V_{1.0}L_6$	20.85	337.11	$C_2V_{1.0}L_6$	29.41	705.75	$C_3V_{1.0}L_6$	29.71	204.09
$C_1V_{1.5}L_2$	13.84	190.15	$C_2V_{1.5}L_2$	15.74	331.23	$C_3V_{1.5}L_2$	18.39	88.23
$C_1V_{1.5}L_4$	19.6	310.90	$C_2V_{1.5}L_4$	21.51	489.32	$C_3V_{1.5}L_4$	28.8	194.78
$C_1V_{1.5}L_6$	34.6	625.37	$C_2V_{1.5}L_6$	36.51	900.27	$C_3V_{1.5}L_6$	35.48	263.15

From Table 5.4 it can be noted that flexural energy absorption of the plain control mix in Mix Series I is 4.77 Joule. However, fiber inclusion has resulted energy absorption with a maximum and minimum value of 8.48 and 34.6 Joule with a relative energy absorption gain of 77.78 and 625.37%, respectively. These minimum and maximum values were recorded for mix $C_1V_{0.5}L_2$ and $C_1V_{1.5}L_6$ correspondingly. As can be seen from Table 5.4, addition of 0.5, 1.0 and 1.5% of 60mm fiber length, namely in mix $C_1V_{0.5}L_6$, $C_1V_{1.0}L_6$ and $C_1V_{1.5}L_6$ has increased the energy absorption by more than 3, 4 and 7 folds respectively. Also the effect of fiber length on energy on energy absorption was obvious, for example addition of only 0.5% fiber volume of 20, 40 and 60mm length has resulted energy absorption values of 8.48, 8.78 and 14.4 Joule with a relative energy absorption gain of 77.78, 84.07 and 201.89%, respectively. In this mix series it was also possible to notice that an increase in both fiber length and volume has tremendously improved the energy absorption of the concrete matrix (see Table 5.4 and Fig. 5.11). The load versus deflection curves of Mix Series I belonging to each fiber volume percentage from which the values of energy absorptions calculated are shown in Fig 5.12.

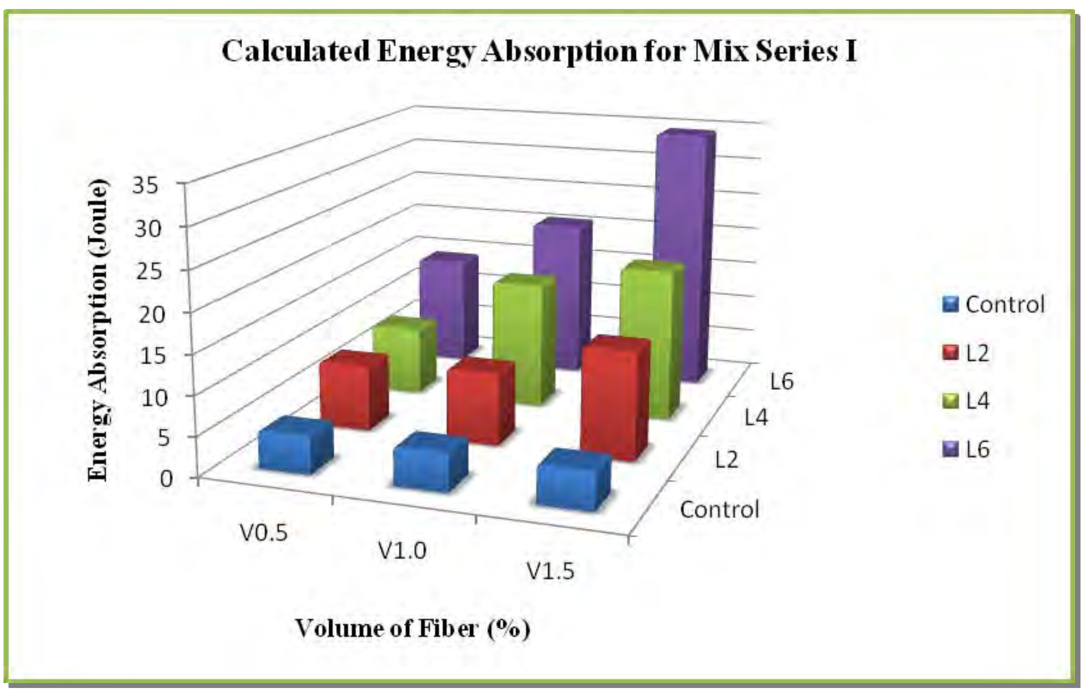
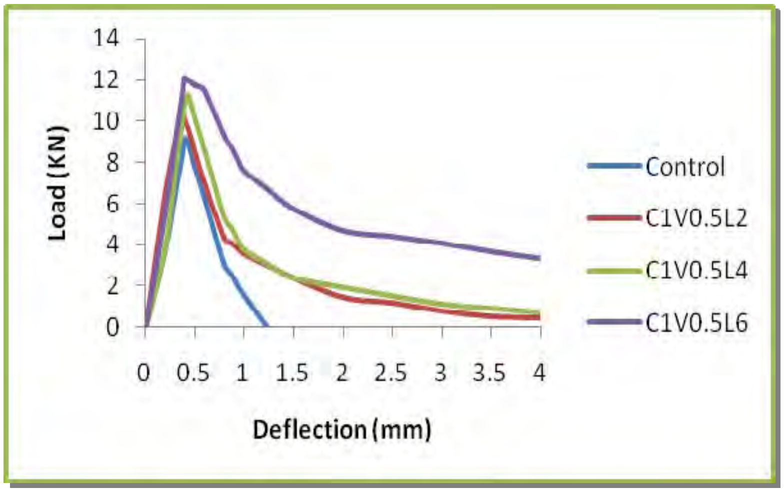
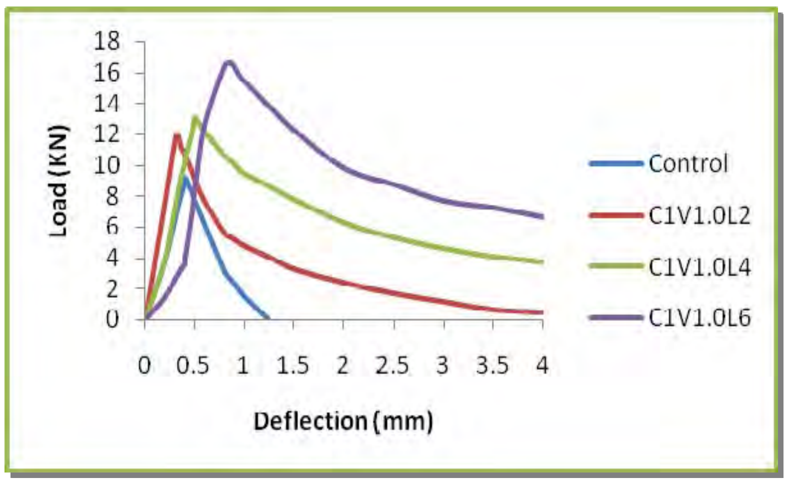


Fig. 5.11 Comparison of calculated mean energy absorption for Mix Series I



b)



c)

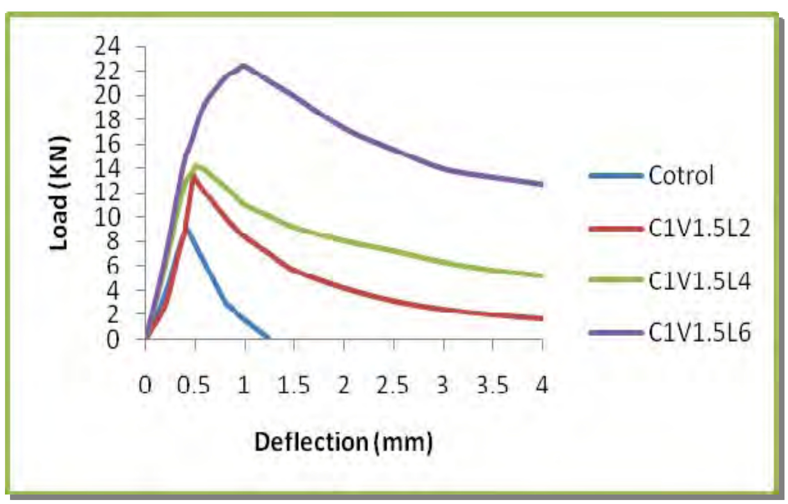


Fig. 5.12 Load versus deflection curves of Mix Series I; a) $V_{f\,=\,0.5}$ b) $V_{f\,=\,1.0}$ c) $V_{f\,=\,1.5}$

In Mix Series II the energy absorption of the control mix is 3.65 Joule, surprisingly lower than the control mix in Mix Series I. But addition of fibers has significantly improved the energy absorption ranging from 7.88 to 36.51 Joule with a relative energy absorption gain of 115.89 to 900.27%. In this Mix Series addition of 0.5, 1.0 and 1.5% by volume of 60 mm fiber length in mix $C_2V_{0.5}L_6$, $C_2V_{1.0}L_6$ and $C_2V_{1.5}L_6$ have improved the energy absorption by more than 4, 8 and 10 folds respectively which is higher than Mix Series I. Similar to that of Mix Series I the effect of fiber length in energy absorption is also very much pronounced, for instance addition of 0.5% of 20, 40 and 60 mm in length of fibers in mix $C_1V_{0.5}L_2$, $C_1V_{0.5}L_4$ and $C_1V_{0.5}L_6$ have shown a relative energy absorption gain of 115.89, 255.62 and 348.77% respectively to that of the control plain mix (see Table 5.4 and Fig. 5.13). The load versus deflection curves belonging to this mix series are provided in Fig. 5.14.

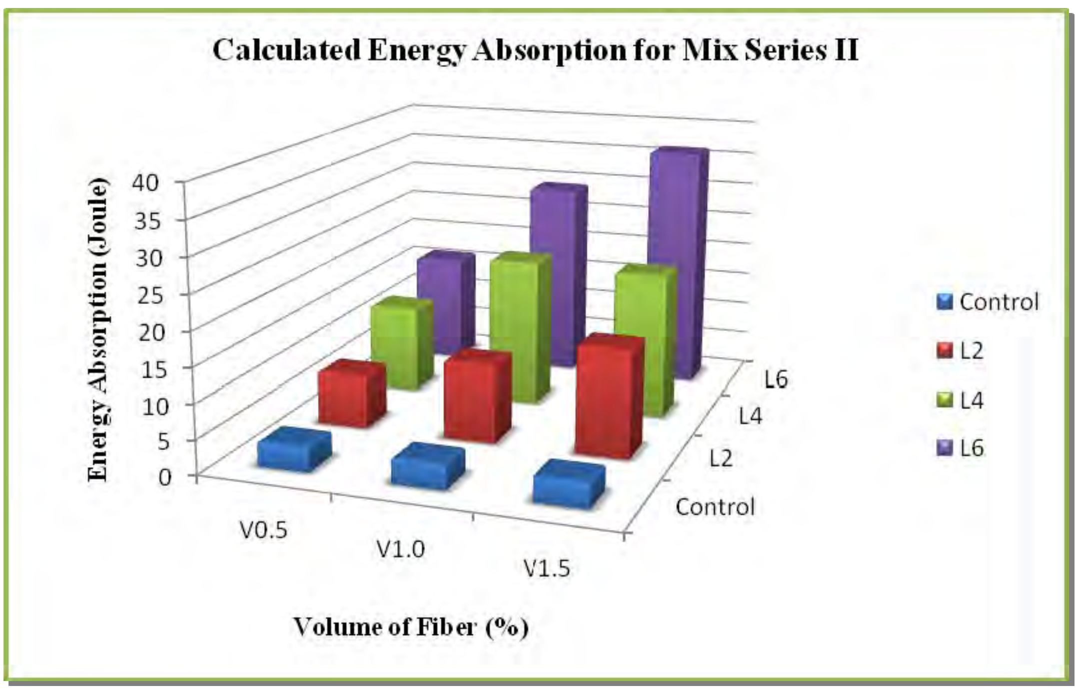


Fig. 5.13 Comparison of calculated mean energy absorption for Mix Series II

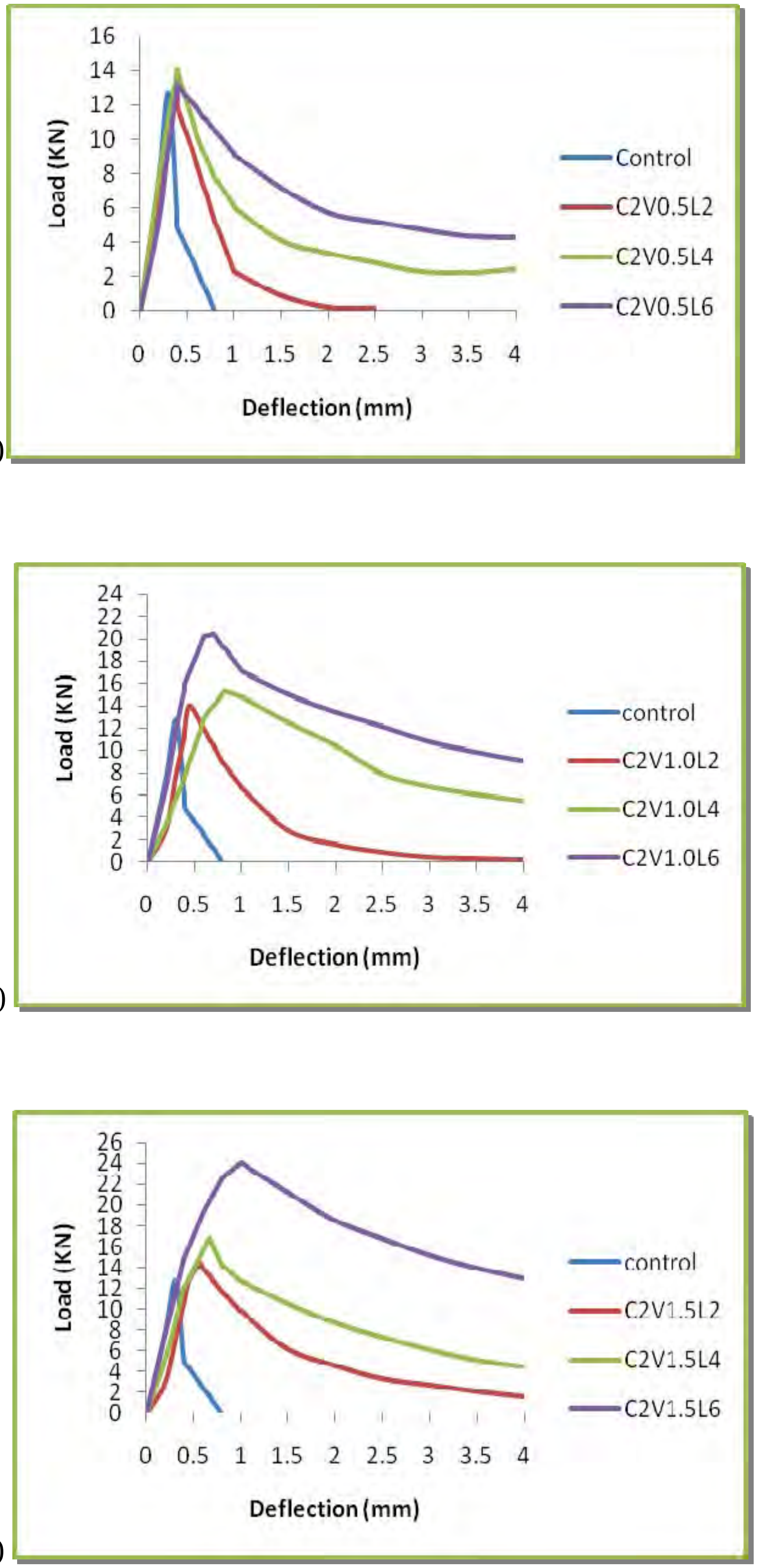
a)
b)
c)


Fig. 5.14 Load versus deflection curves of Mix Series II; a) $V_{f = 0.5}$ b) $V_{f = 1.0}$ c) $V_{f = 1.5}$

Compared to the other mix series higher energy absorption for the control mix is observed in Mix Series III, which is 9.77 Joule. A minimum and maximum energy absorption value of 11.44 and 35.48 Joule with a relative energy absorption gain of 17.09 and 263.15% was obtained by adding fibers of different length and volume to the concrete mix. These minimum and maximum values are exhibited in mix $C_3V_{0.5}L_2$ and $C_3V_{1.5}L_6$. The relative energy absorption gains in this Mix Series are lower than the other two mix series. The energy absorption obtained by adding 0.5, 1.0 and 1.5% of 60 mm length fiber is found to be 16.17, 29.71 and 35.48 Joule while the energy absorption for the same volume fraction and fiber length in Mix Series I and II are 14.4, 20.85 and 34.6; and 16.38, 29.41 and 36.51 respectively. This can be a good evidence that in SFRC higher concrete grades does not necessarily secure higher energy absorption even if the higher peak flexural strength can be achieved. Similar to the other mix series an increase in fiber length and volume has increased the energy absorption of the concrete (see Table 5.4 and Fig. 5.15). The load versus deflection curves of Mix Series III belonging to each fiber volume percentage from which the values of energy absorptions calculated are shown in Fig 5.16.

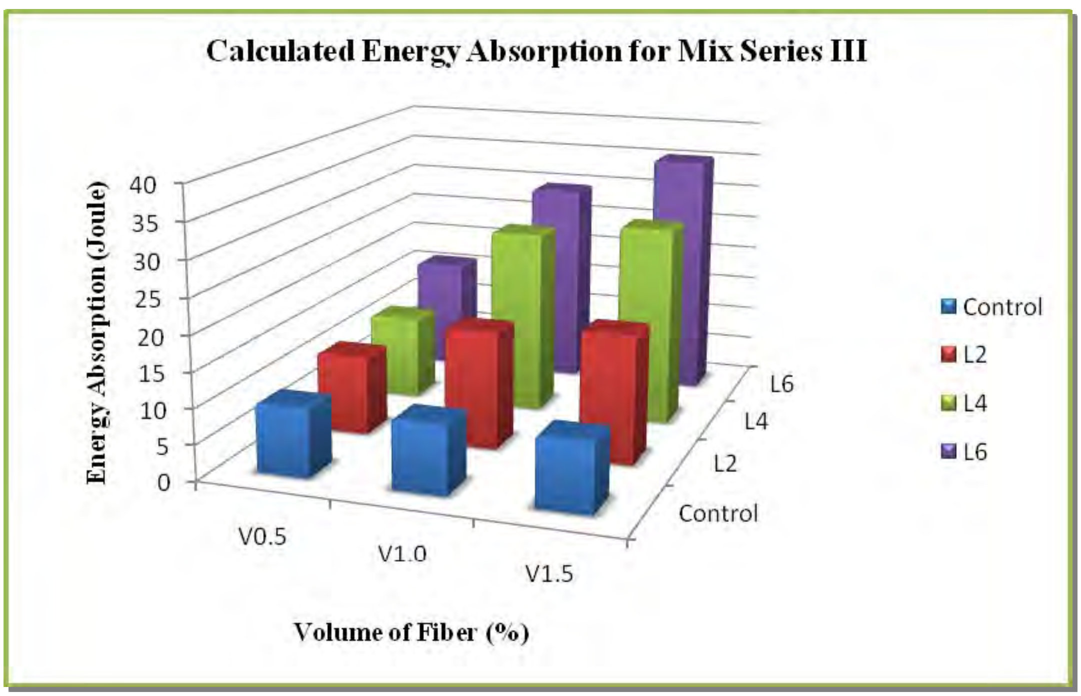
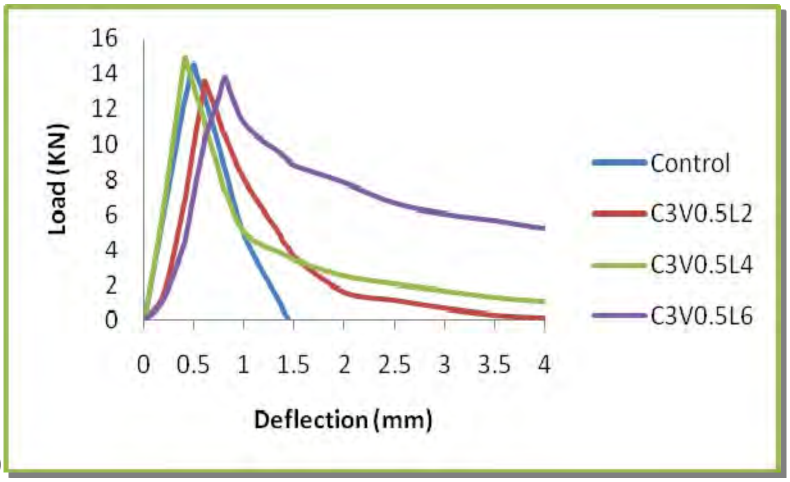
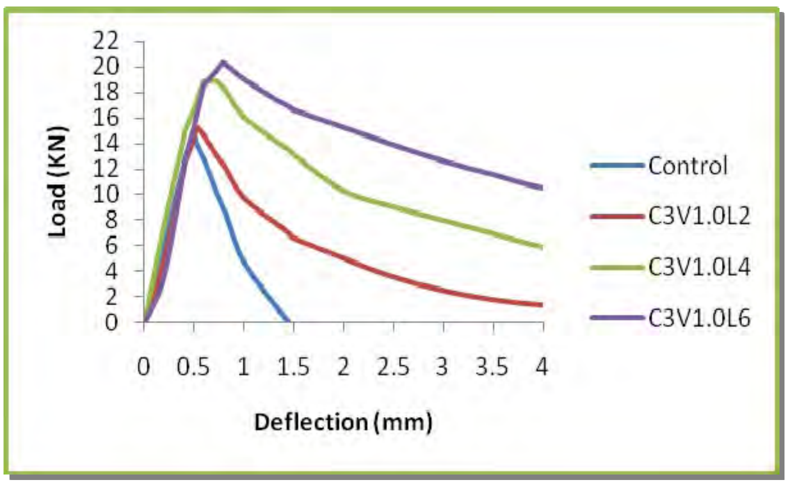


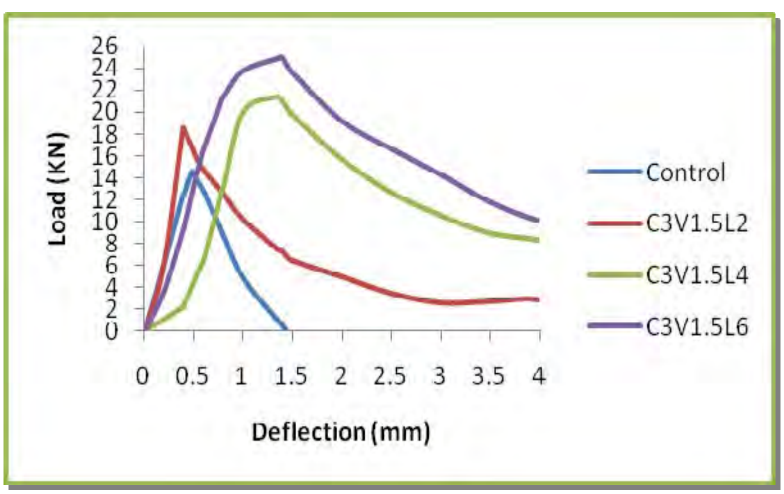
Fig. 5.15 Comparison of calculated mean energy absorption for Mix Series III



a)



b)



c)

Fig. 5.16 Load versus deflection curves of Mix Series III; a) $V_{f=0.5}$ b) $V_{f=1.0}$ c) $V_{f=1.5}$

From the test results of the three mix series it can be noted that higher energy absorption was exhibited in those beams reinforced with larger aspect ratio and volume of fibers. Highest energy absorption was acquired in Mix $C_1V_{1.5}L_6$, $C_2V_{1.5}L_6$ and $C_3V_{1.5}L_6$ with a relative energy absorption gain of 625.37, 900.27 and 263.15% in mix series I, II and III respectively. From this it can be deduced that utilization of 1.5% fiber volume and 60mm fiber length is more efficient on flexural toughness. Addition of steel fibers extracted from used tyre significantly improve the flexural toughness of concrete compared to the other two mechanical property already discussed which are compressive strength and flexural tensile strength.

As explained in the literature review under section 3.2.4.4 early in the development of SFRC, toughness was recognized as the characteristic that most clearly distinguishes SFRC from concrete without steel fibers. The primary purpose of fiber inclusion to concrete is not to increase strength but to provide toughness and ductility. Even if any value was not provided in the literature review to what extent addition of steel fiber increase the flexural toughness, the test results obtained in this research work support the aforementioned statement. Similar to the research conducted by Tlemat H. et al. and Aiello M.A. et al., in this research work the flexural behavior of the prisms improves as the fiber fraction increases.

The effect of fiber length, volume of fiber, and concrete strength on the load versus deflection curves from which the flexural toughness of SFRC determined is further discussed as follow:

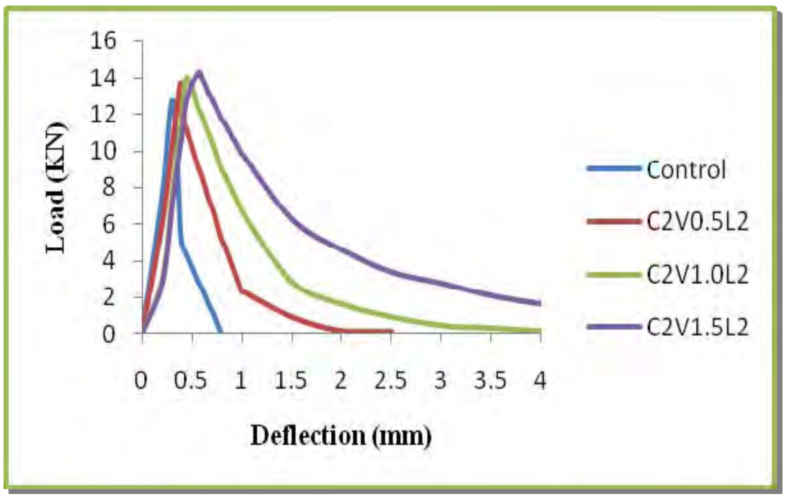
i) Effects of Fiber Length

As discussed previously fiber length (aspect ratio) is one of the important factors which influence the properties and the behavior of SFRC. An overall comparison between the examined fiber lengths, as shown in Fig 5.10, 5.12 and 5.14, reveals that an increase in fiber length for each fiber volume results a considerable increase in the peak flexural load. Among the examined specimens those with 60mm fiber length exhibit a stable post peak load-deflection response in all mix series.

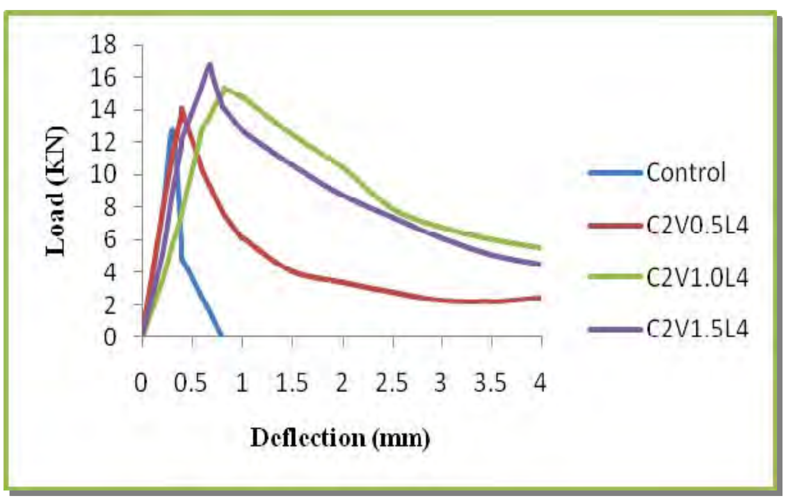
ii) Effects of Fiber Volume

The flexural strength of SFRC largely depends on the quantity of fibers used in it. Fig. 5.15 shows the effects of fiber volume on the flexural toughness for Mix Series II. From this figure it can be seen that the increase in the volume of fibers increase the peak load and the residual strength after cracking. This also applies to all the other mix series. These effects are especially very much pronounced for 60 mm fiber length.

a)



b)



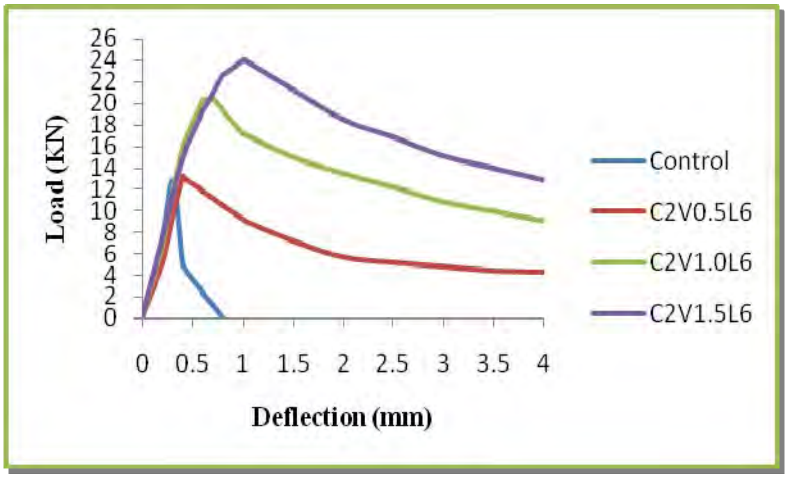
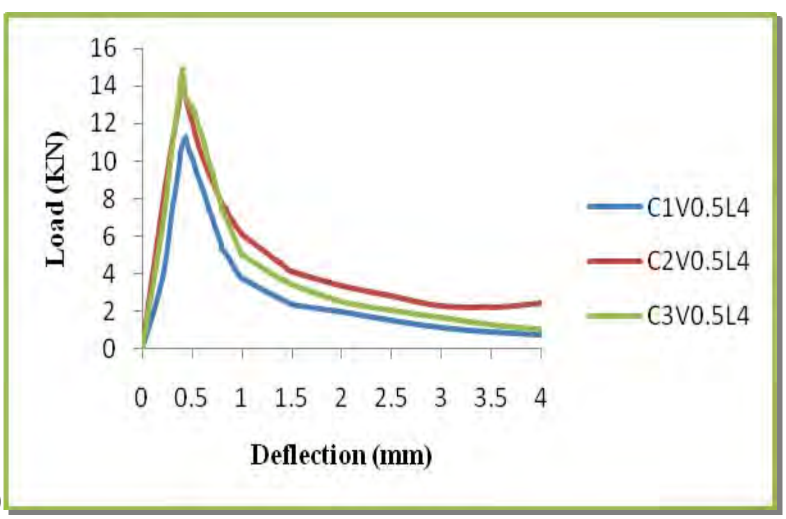
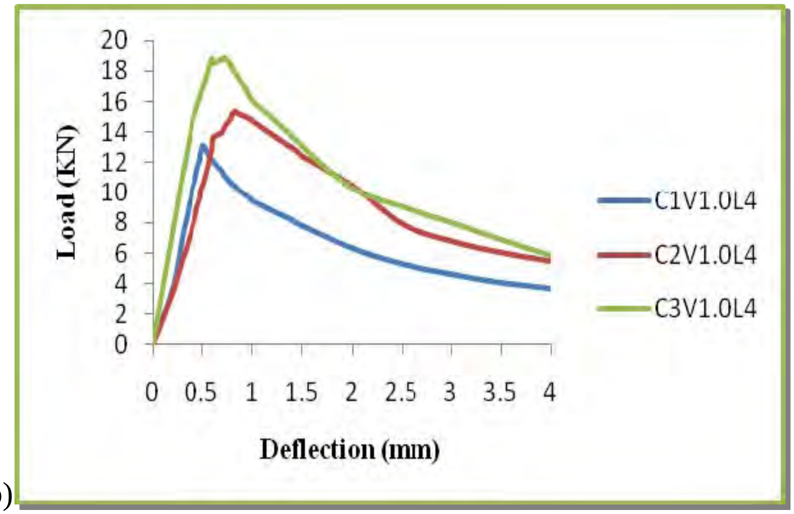
c) 

Fig. 5.17 Load versus deflection curves of Mix Series II; a) L_{20mm} b) L_{40mm} c) L_{60mm}

iii) Effects of Concrete Strength

In order to show the effects of concrete strength on flexural toughness and for an illustration purpose a fiber length of 40 mm is selected as it is the average length of the three lengths used in this experiment. By keeping the fiber length and volume constant the load versus deflection curve for different concrete grades is shown in Fig. 16. From this figure it can be noted that high strength concrete results in a much higher peak load for all fiber volume percentages, but not necessarily ductility. This statement also holds true for the other fiber lengths.

a) 

b) 

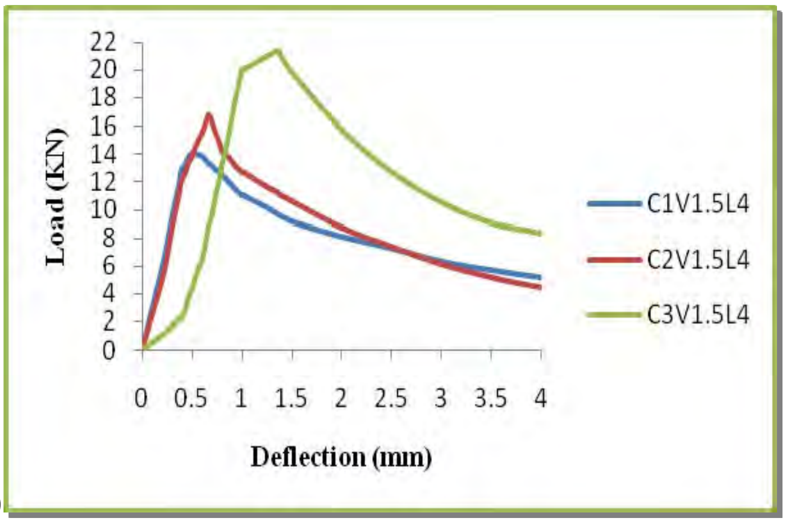
c) 

Fig 5.18 Load versus deflection curves of different concrete grades; a) $V_{f = 0.5}$ b) $V_{f = 1.0}$ c) $V_{f = 1.5}$

5.2.2.3 Location of First Crack Point and Energy Absorption up to Specified Deflections

According to ASTM C 1018 the first crack point is termed as the point at which the curvature first increases sharply and then slope of the curve exhibits a definite change. Due to this subjective definition location of first crack point may vary according to whom the test is performed and evaluated.

In this research work, 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. 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. As a result 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. The first crack location is determined after correcting those curves which are slightly concave and convex upward according to ASTM 1018 suggestion.

For analysis purpose energy absorptions up to the first crack point (δ_{FC}) and a multiple of the first crack points ($3\delta_{FC}$, and $5.5\delta_{FC}$) as outlined in ASTM C 1018, were estimated by calculating the area under the curve up to specified deflections mentioned above. Toughness indices I_5 and I_{10} were also calculated. Obtained results for the three mix series are presented in Table 5.5-5.7.

In mix Series I both the I_5 and I_{10} toughness indices of the plain control mix are found to be 2.76. But fiber inclusion in this mix series has resulted a minimum I_5 and I_{10} values of 4.11 and 5.29 with a relative gain of 48.9 and 91.7% respectively in mix $C_1V_{0.5}L_4$, whereas maximum I_5 and I_{10} values are observed in mix $C_1V_{1.0}L_2$ with I_5 and I_{10} values of 8.72 and 13.47 showing a relative gain of 215.9% and 388% respectively. From the results it was possible to observe an increase in energy absorption up to specified points of deflection when both the fiber length and volume increase. However such a direct relationship was not observed regarding the toughness indices as these values greatly depend on the first crack point. But as shown in Table 5.5 addition of fiber to the concrete has extensively improved the toughness indices.

Table 5.5 Energy Absorption up to Selected Multiples of First Crack Deflection and Toughness Indices for Mix series I.

MIX SERIES I						
Mix Designation	First Crack (δ_{FC}) Location (mm)	Energy Absorption (Joule)			Toughness Index	
		$\delta = \delta_{FC}$	$\delta = 3\delta_{FC}$	$\delta = 5.5\delta_{FC}$	I_5	I_{10}
Control-1	0.41	1.73	4.77	4.77	2.76	2.76
$C_1V_{0.5}L_2$	0.26	1.07	5.14	7.34	4.81	6.88
$C_1V_{0.5}L_4$	0.38	1.62	6.66	8.58	4.11	5.29
$C_1V_{0.5}L_6$	0.37	1.96	9.24	13.67	4.71	6.97
$C_1V_{1.0}L_2$	0.31	0.63	5.5	8.5	8.72	13.47
$C_1V_{1.0}L_4$	0.5	2.93	12.81	20.52	4.37	7.0
$C_1V_{1.0}L_6$	0.51	4.97	24.51	39.37	4.93	7.92
$C_1V_{1.5}L_2$	0.44	1.85	10.29	15.42	5.55	8.31
$C_1V_{1.5}L_4$	0.43	2.89	13.28	22.48	4.59	7.78
$C_1V_{1.5}L_6$	0.4	2.83	19.12	37.99	6.76	13.44

According to the calculated values for Mix Series II shown in Table 5.6 both the I_5 and I_{10} toughness indices are recorded to be 1.94, which is lower than the value obtained for the control mix in Mix Series I. I_5 and I_{10} toughness indices ranging from 3.35 up to 6.12 and from 3.79 up to 10.54 with a relative gain of 72.68 up to 215.5% and 95.4 up to 443.3% respectively was obtained by addition of different fiber length and volume to the concrete mix. Similar to the previous mix series an increase in energy absorption up to specified points of deflection was witnessed when both the fiber length and volume increase.

The I_5 and I_{10} toughness indices of the control mix in Mix series III is 2.67. Table 5.7 shows that, the I_5 and I_{10} toughness indices of the SFRC are higher about 38.2-212.7% and 46.2-239% than the control mix. Similar to the other mix series addition of fiber has considerably improved the toughness indices and also an increase in energy absorption up to specified points of deflection was witnessed when both the fiber length and volume increase.

Table 5.6 Energy Absorption up to Selected Multiples of First Crack Deflection and Toughness Indices for Mix series II.

MIX SERIES II						
Mix Designation	First Crack (δ_{FC}) Location (mm)	Energy Absorption (Joule)			Toughness Index	
		$\delta = \delta_{FC}$	$\delta = 3\delta_{FC}$	$\delta = 5.5\delta_{FC}$	I_5	I_{10}
Control-2	0.31	1.88	3.65	3.65	1.94	1.94
$C_2V_{0.5}L_2$	0.36	2.08	6.96	7.88	3.35	3.79
$C_2V_{0.5}L_4$	0.36	2.40	9.03	12.91	3.76	5.38
$C_2V_{0.5}L_6$	0.32	1.42	8.67	14.92	6.12	10.54
$C_2V_{1.0}L_2$	0.3	2.07	9.55	11.87	4.62	5.74
$C_2V_{1.0}L_4$	0.6	3.51	19.71	32.14	5.62	9.16
$C_2V_{1.0}L_6$	0.6	6.56	26.65	44.73	4.06	6.81
$C_2V_{1.5}L_2$	0.31	2.02	11.81	17.46	5.84	8.63
$C_2V_{1.5}L_4$	0.43	2.61	14.35	21.51	5.50	8.24
$C_2V_{1.5}L_6$	0.6	6.39	32.7	57.77	5.11	9.03

Table 5.7 Energy Absorption up to Selected Multiples of First Crack Deflection and Toughness Indices for Mix series III.

MIX SERIES III						
Mix Designation	First Crack (δ_{FC}) Location (mm)	Energy Absorption (Joule)			Toughness Index	
		$\delta = \delta_{FC}$	$\delta = 3\delta_{FC}$	$\delta = 5.5\delta_{FC}$	I_5	I_{10}
Control-3	0.49	3.66	9.77	9.77	2.67	2.67
$C_3V_{0.5}L_2$	0.35	1.60	9.92	12.22	6.21	7.65
$C_3V_{0.5}L_4$	0.38	2.49	9.20	12.35	3.69	4.96
$C_3V_{0.5}L_6$	0.54	1.56	13.06	22.78	8.35	14.57
$C_3V_{1.0}L_2$	0.45	2.80	12.93	18.98	4.63	6.79
$C_3V_{1.0}L_4$	0.44	3.57	18.36	30.80	5.14	8.62
$C_3V_{1.0}L_6$	0.52	4.86	26.46	47.23	5.45	9.72
$C_3V_{1.5}L_2$	0.37	2.53	12.45	18.59	4.92	7.34
$C_3V_{1.5}L_4$	0.66	6.58	38.96	59.56	5.92	9.05
$C_3V_{1.5}L_6$	0.72	7.9	42.62	67.93	5.40	8.6

As discussed in the literature review pat under section 2.8.1.1 for an ideally elastic-plastic material toughness index value would be equal to the index itself. The toughness indices obtained in this research work for SFRC as shown in Table 5.5-5.7 are by far better than the toughness indices for the control mixes. However depending on amount, type and orientation of fibers, calculated toughness indices of some mix were either higher or lower than the index values and very much variable due to the subjective definition of the first crack point and often the load-deflection curves lack a distinct point as mentioned in the literature due to micro cracking and subsequent multiple cracks before the peak load is reached.. The lower toughness indices for the control mix are due to the fact that plain concrete beams fail immediately after first crack.

5.2.3 Impact Resistance

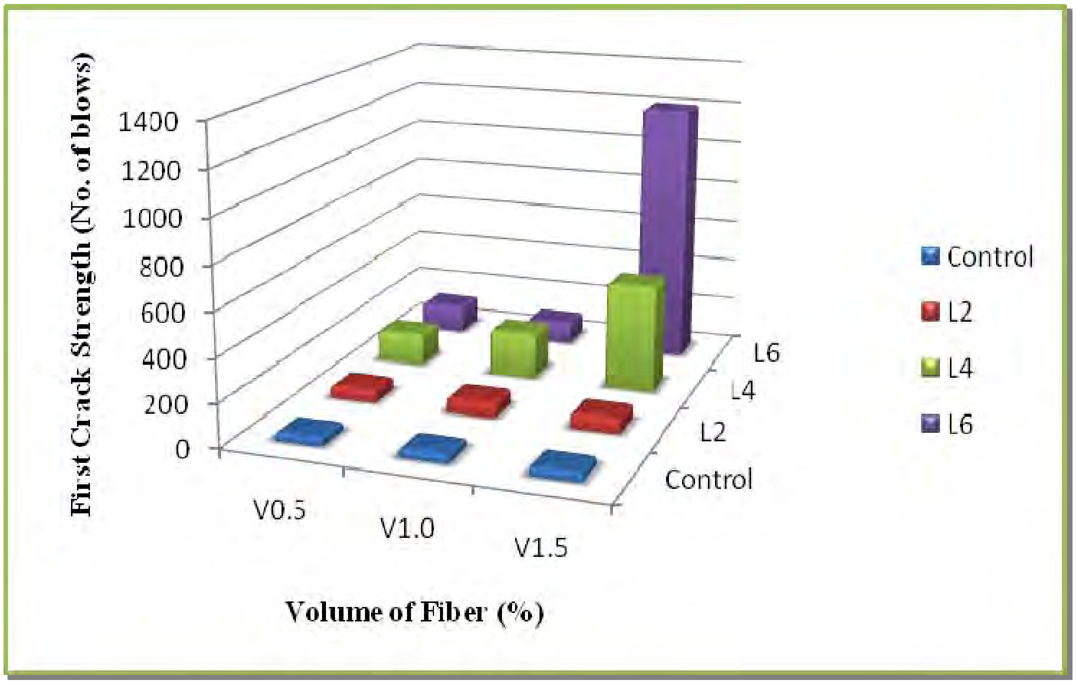
One of the most important properties exhibited by fiber concrete is their high impact strength relative to that of plain concrete. In this research work, impact resistance was determined using drop weight test as described in Chapter 2. By using the repeated drop weight test method the number of blows required to bring the first crack and the ultimate failure was determined and the test results along with the average height of the sample is presented in Table 5.8. As can be witnessed from the test results, fiber inclusion has enormously increased both the first crack and ultimate failure strength. The test results for each mix series are discussed below.

The first crack and ultimate failure strength in terms of number of blows for the control mix in Mix Series I is 40 and 43, respectively. In this mix series only 3 numbers of blows were enough to bring the control mix to the ultimate failure. Number of blows for the first crack and ultimate failure strength ranging from 59-1212 and 72-1432 with a relative gain of 47.5-2930% and 67.4-3,230% respectively were obtained by addition of fibers of different length and volume to the concrete mix. Minimum and maximum numbers of blow were observed in mix $C_1V_{0.5}L_2$ and $C_1V_{1.5}L_6$, respectively. First crack and ultimate failure strengths are raised with raising fiber volume. The comparison of impact test results for this mix series is provided in Fig. 5.17.

Table 5.8 Impact resistance test results

Mix Series I				Mix Series II				Mix Series III			
Mix Designation	Mean Height of sample (mm)	First Crack (No. of Blows)	Ultimate Failure (No. of Blows)	Mix Designation	Mean Height of sample (mm)	First Crack (No. of Blows)	Ultimate Failure (No. of Blows)	Mix Designation	Mean Height of sample (mm)	First Crack (No. of Blows)	Ultimate Failure (No. of Blows)
Control-1	63.97	40	43	Control-2	64.00	115	120	Control-3	63.98	126	129
$C_1V_{0.5}L_2$	63.50	59	72	$C_2V_{0.5}L_2$	64.28	163	181	$C_3V_{0.5}L_2$	65.58	168	179
$C_1V_{0.5}L_4$	63.97	150	180	$C_2V_{0.5}L_4$	63.83	193	222	$C_3V_{0.5}L_4$	64.92	370	397
$C_1V_{0.5}L_6$	62.73	130	169	$C_2V_{0.5}L_6$	63.58	697	753	$C_3V_{0.5}L_6$	64.37	388	416
$C_1V_{1.0}L_2$	64.30	72	87	$C_2V_{1.0}L_2$	64.48	174	190	$C_3V_{1.0}L_2$	65.05	148	166
$C_1V_{1.0}L_4$	63.83	214	241	$C_2V_{1.0}L_4$	63.83	214	241	$C_3V_{1.0}L_4$	64.14	574	657
$C_1V_{1.0}L_6$	64.43	101	153	$C_2V_{1.0}L_6$	64.5	713	810	$C_3V_{1.0}L_6$	65.35	637	862
$C_1V_{1.5}L_2$	63.79	71	90	$C_2V_{1.5}L_2$	63.78	244	292	$C_3V_{1.5}L_2$	64.13	188	212
$C_1V_{1.5}L_4$	64.20	499	566	$C_2V_{1.5}L_4$	64.45	223	312	$C_3V_{1.5}L_4$	64.94	944	1060
$C_1V_{1.5}L_6$	64.54	1212	1432	$C_2V_{1.5}L_6$	64.72	1004	1248	$C_3V_{1.5}L_6$	63.48	1122	1254

a)



b)

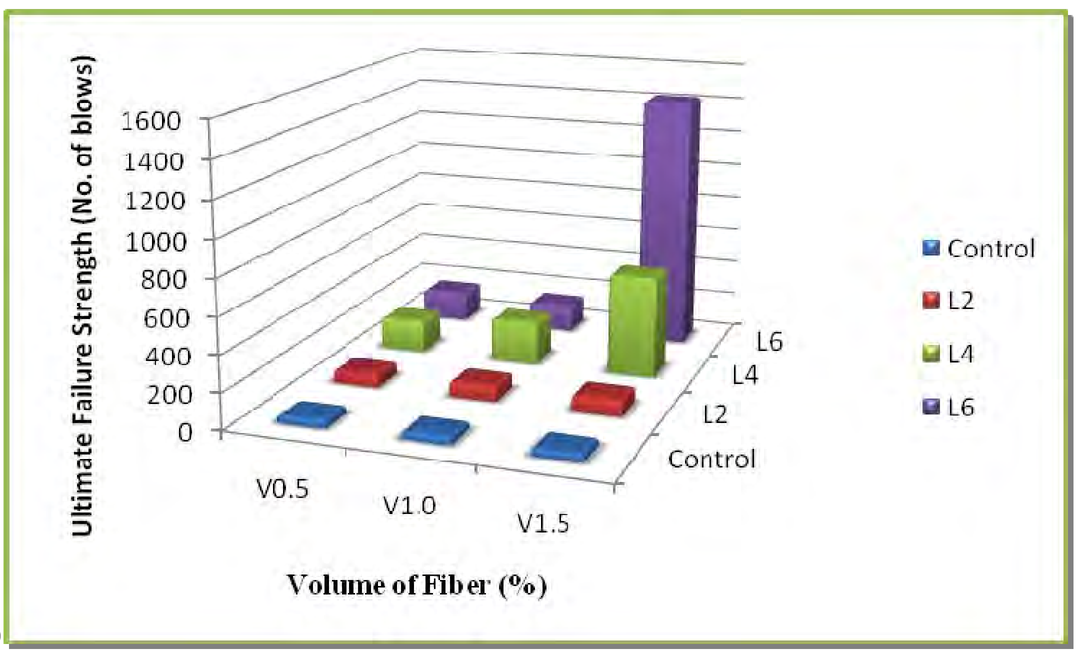
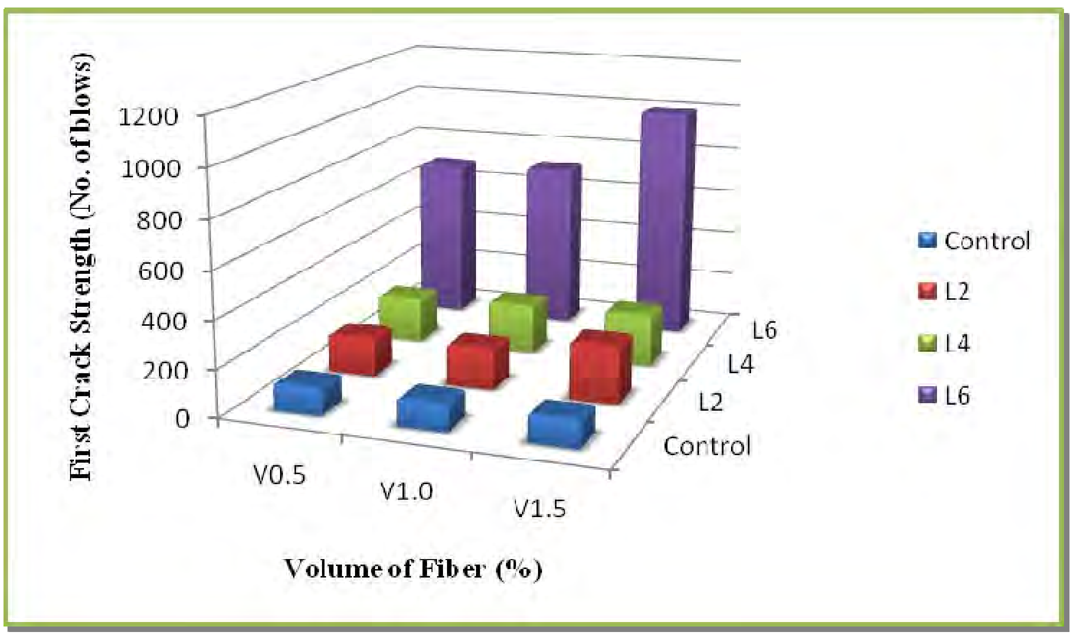


Fig 5.19 Comparison of impact test results of Mix Series I; a) First crack strength b) Ultimate failure strength

In mix series II the first crack and ultimate strength in terms of number of blows for the control mix is 115 and 120 which are higher than the values in mix series nearly by three folds. To bring the control mix from first crack strength to the ultimate failure only 5 numbers of blows were required. However addition of fibers drastically improved both the first crack and ultimate strength. Test results in this mix series indicated that, first crack strength and ultimate failure strength of reinforced mixtures are 41.7-773% and 33.7-940% higher than the control mix. Minimum and maximum numbers of blows for the first crack and ultimate failure were observed in mix $C_2V_{0.5}L_2$ and $C_2V_{1.5}L_6$ respectively. An increase in first crack and ultimate failure strengths are witnessed by increasing both the fiber length and fiber volume. The comparison of impact test results for Mix Series II is presented in Fig. 5.18.

a)


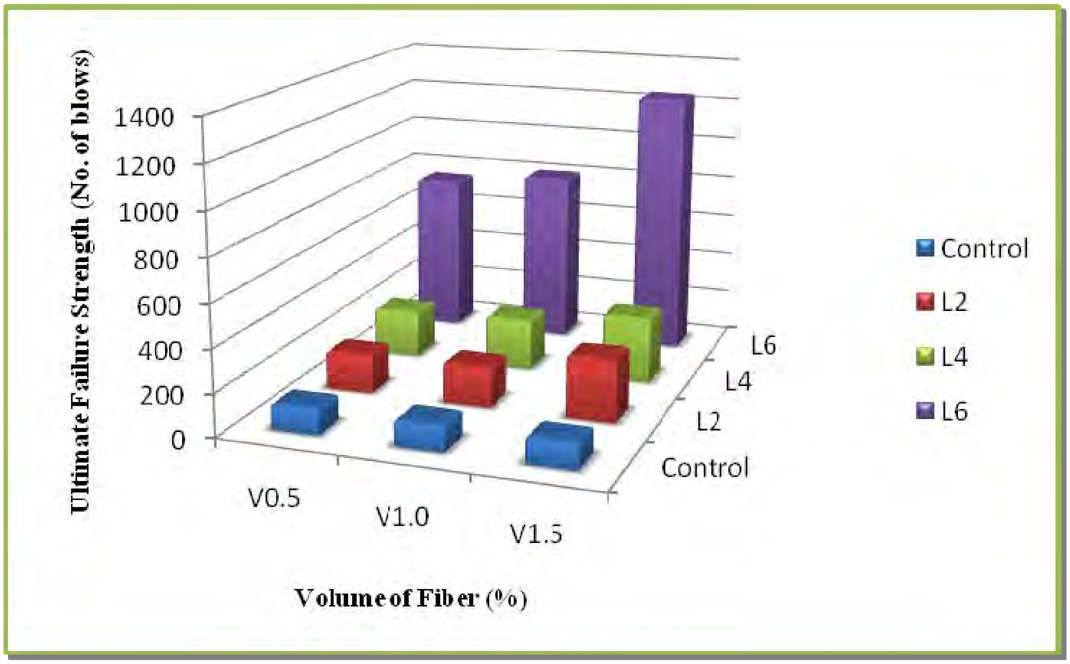
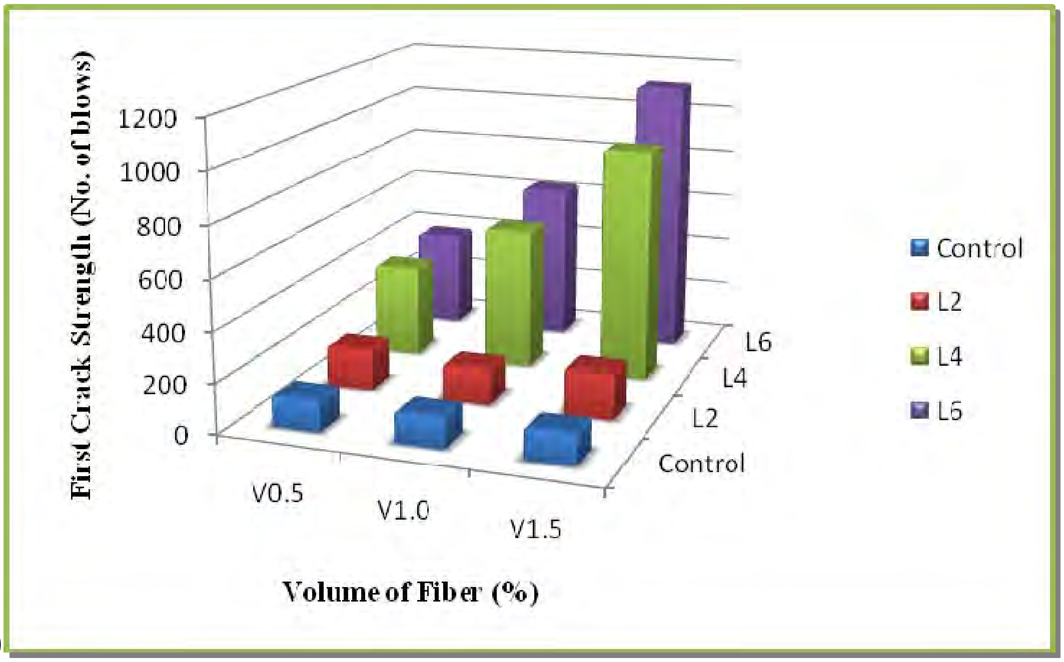
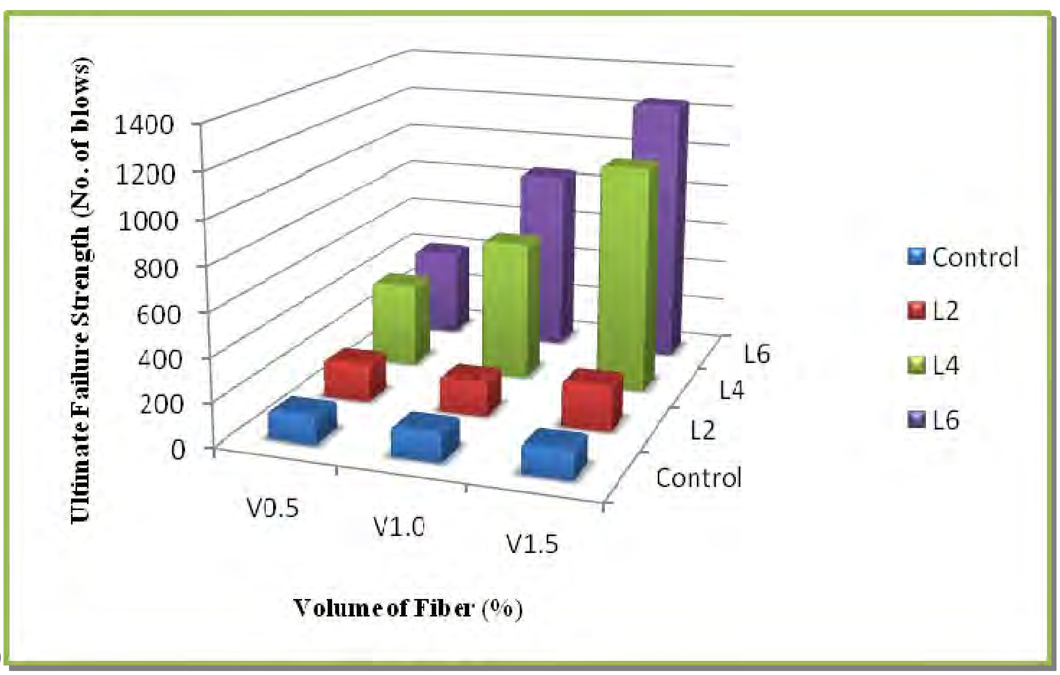
b) 

Fig 5.20 Comparison of impact test results of Mix Series II; a) First crack strength b) Ultimate failure strength

The first crack and ultimate failure strength recorded for the control mix in mix series III is 126 and 129 which are higher than the other two mix series. Similar to mix series I only 3 numbers of blows were sufficient to bring the first crack strength to the ultimate failure. Numbers of blows for the first crack and ultimate failure strength ranging from 168-1122 and 179-1254 with a relative gain of 33.3-790.5% and 38.8-872.1% respectively were obtained by addition of fibers of different length and volume to the concrete mix. Minimum and maximum numbers of blows for the first crack and ultimate failure were observed in mix $C_3V_{0.5}L_2$ and $C_3V_{1.5}L_6$ respectively. Similar to that of mix series II first crack and ultimate failure strength are raised with raising fiber length and volume. The comparison of impact test results for Mix Series III is shown in Fig. 5.19.



a)



b)

Fig 5.19 Comparison of impact test results of Mix Series III; a) First crack strength b) Ultimate Failure Strength

In all the three mix series, it was possible to detect that addition of small quantity of steel fiber can greatly improve the impact resistance of the concrete. For instance addition of only 0.5% by volume of 20mm steel fiber has raised the impact resistance of Mix $C_1V_{0.5}L_2$, $C_2V_{0.5}L_2$ and $C_3V_{0.5}L_2$ by 48, 42 and 33%, respectively. The plain control mixes easily failed (breaks into halves) after the first crack was observed. Only three blows were required to bring Control-1 and Control-3 from mix series I and III to the ultimate failure correspondingly.

Due to their higher aspect ratio and volume of fiber maximum values of first crack and ultimate failure strength was attained in those mixes incorporating 1.5% of 60 mm fiber length, which are $C_1V_{1.5}L_6$, $C_2V_{1.5}L_6$ and $C_3V_{1.5}L_6$. In these mixes the obtained first crack strength values are 30, 9 and 9 times that of the control plain mix belonging to each series, respectively. In addition to this the ultimate failure strength has increased by 33 folds for $C_1V_{1.5}L_6$ and by 10 folds for $C_2V_{1.5}L_6$ and $C_3V_{1.5}L_6$ mixes. From this it can be deduced that utilization of 1.5% fiber volume and 60 mm fiber length is more efficient. This is mainly because of the higher energy required to pull the fibers out of the matrix to reach to the ultimate failure. The relative impact values obtained by adding 1.5% volume of fiber and 60 mm fiber length into the concrete mixture is by far better than the other mechanical properties investigated in this research so far.

The impact test results obtained in this research work are somehow in good conformity with the literature review presented under section 3.2.4.2 where it was stated that based on tests carried out by repeated drop weight test proposed by ACI Committee 544, for fibrous concrete, the number of blows to failure is typically several hundred compared to 30 to 50 for plain concrete.

Even if drop weight test is the simplest of all impact tests, the results obtained as can be seen in Annex I are highly variable. But still the results are useful to ascertain the relative merits of fiber inclusion in terms of impact resistance.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

In this research, the experimental work carried out to evaluate the fresh and hardened properties of SFRC made with fibers extracted from used tyre is studied. On the basis of results obtained by tensile strength of steel fibers, slump tests, compression tests, flexural tests and impact tests, the following conclusions are drawn:

1. The mean tensile strength of the steel fibers recovered from used tyre is lower than the virgin steel fiber (VSF) nearly by half (48.7%) and the test results recorded for the individual samples are highly variable due to the uncontrolled burning temperature used to recover them. However, the obtained results are in good conformity with the experimental results reported by other researchers and meet the requirements specified by ASTM 820. From the test results obtained it is also possible to deduce that, as far as tensile strength is concerned, the steel fibers recovered from used tyres are comparable to industrial steel fibers (ISF).

2. Without the presence of the superplasticizer (SP 430) the SFRC appeared to be relatively stiff, unworkable and the materials tend to “hang together” and resist movement compared to the control mixes. It is almost impossible to work with fibers having higher aspect ratio and volume fraction. Therefore the use of admixture is a must to attain a satisfactory workability and a more uniform distribution of fiber.

3. The incorporation of steel fibers strongly affected the workability of the fresh concrete. The test results indicated that as the fiber length and the volume of fraction increase the workability tend to decrease significantly. In addition it can be realized that when the steel fibers are longer than 40mm and the fiber volumes are 1.0% and higher, it becomes relatively difficult to obtain to consolidate it and consequently, to produce a good fibers dispersion within the cement matrix.

4. A relative compressive strength loss and gain ranging from 0.28-3.68% and 0.08-11.77%, respectively, was obtained by introducing fibers of different length and volume to the concrete. From the results acquired it is possible to deduce that it is unlikely to achieve considerable improvements in compressive strength by steel fiber inclusion and the ultimate strength is only slightly affected by the presence of steel fibers. If what is desired is a strength increase, it is clearly much easier (and much cheaper) simply to redesign the plain concrete mix, primarily by reducing the w/c ratio and by changing the cement type.

5. Fiber inclusion of all lengths and volume fractions resulted in substantial increase in flexural tensile strength values. A similar pattern was exhibited in all mix series with regard to increment in flexural tensile strength when both the fiber length and volume of fibers increased. Compared to the other fiber lengths the relative flexural tensile strength gain by 20mm fiber length is not as such appreciable due to its lower aspect ratio. Utilization of 1.5% fiber volume and 60mm fiber length is found to be more efficient on flexural tensile strength of all mix series.

6. Energy absorption under flexural loading was greatly enhanced with steel fiber reinforcement. And the effect of fiber length, fiber volume and concrete strength is concluded as follow:
    a. An increase in fiber length results a considerable increase in the peak flexural load and ductility. Among the examined specimens those with 60mm fiber length exhibit a stable post peak load-deflection response.
    b. An increase in the volume of fibers increases the peak load and the residual strength after cracking. These effects are especially very much pronounced for 60mm fiber length.
    c. High strength concrete results in a much higher peak load for all fiber volume percentages, but not necessarily ductility.

7. From the results obtained it is possible to deduce that an increase in energy absorption up to specified points of deflection can be observed when both the fiber length and volume increase. However such a direct relationship was not witnessed regarding the toughness

indices as these values greatly depend on the first crack point which is very much subjective. However the reinforced specimens have shown larger values of toughness indices compared to the control specimens.

8. Steel fiber inclusion has enormously increased both the first crack and ultimate failure strength. Furthermore it was possible to detect that addition of small quantity of steel fiber can greatly improve the impact resistance of the concrete. The ultimate failure strength (UFS) has increased with increasing fiber volume and length for all mixes. Due to the higher energy required to pull the fibers out of the matrix to reach to the ultimate failure utilization of 1.5% fiber volume and 60 mm fiber length is more efficient both for first crack and ultimate failure strength.

9. Most of the test results obtained from this research work confirms the experimental results reported in the literature and are comparable with concrete made with industrial steel fibers. As a result steel fiber extracted from used tyres can be considered a promising and potential candidate for SFRC.

6.2 RECOMMENDATIONS

Based on the investigation made the following recommendations are forwarded for studies in purpose of future excellence.

1. The interesting results confirm the promising application of concrete reinforced with steel fibers extracted from used tyres. However, further, research work is still necessary in order to have a more in-depth understanding of the material properties and to evaluate possible practical applications. And also economic evaluation of the adoption of currently available steel fibers extraction technology should be investigated.

2. In order to better appreciate the improvement given by the addition of steel fibers extracted from used tyres, it would have been great to evaluate the performance of

specimens reinforced with the conventional industrial steel fibers and virgin steel fibers recovered from used tyres.

3. Slump test is inadequate and cannot satisfactorily distinguish the effects of fiber inclusion on the consistency of SFRC. Methods employing dynamic consolidation such as inverted slump cone test or Vebe test should be used in order to attain a clearer view of the effects of fiber inclusion.

4. Since material properties of steel fiber reinforced concrete depend, to a relevant extent, on the bond between the fibers and the matrix, direct or indirect fiber pull out test should be carried out in order to attain a comprehensible view on the behavior of pulling out of a fiber from a matrix already reinforced with steel fiber.

5. Since results from flexural tests on concrete beams are prone to significant experimental errors due to spurious support displacements, machine stiffness, load rate and rocking of specimen on its support it is recommended to use a yoke along with resistive clip gauge.

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

7. The repeated drop weight test used results high drop numbers over thousand for some specimens which make the test difficult to carry out and leads to highly variable results. Therefore, instrumented impact tests should be adopted to evaluate the impact resistance.

8. Further research is proposed in the following areas:

i) Use of SFRC to replace the minimum reinforcement recommended on ground slab for shrinkage and temperature.

ii) Development of rational design procedures to incorporate the properties of SFRC to replace stirrups provided for shear in load carrying beams.

REFERENCES

[1] Jagadish K.S., Venkatarama Reddy B.V. and Nanjunda Rao K.S., Alternative Building Materials and Technologies, First Edition, New Age International Publishers, New Delhi, 2007.

[2] Shetty M.S., Concrete Technology Theory and Practice, Revised Edition, S. Chand and Company LTD., New Delhi, 2005.

[3] ACI Committee 544, State-of-The-Art Report on Fiber Reinforced Concrete, ACI 544 1.R-96

[4] Sidney Mindess, Francis Young J. and David Darwin, Concrete, Second Edition, Prentice Hall, New Jersey, 2003.

[5] Bentur A. and Mindess S., Fibre Reinforced Cementitious Composites, Elsevier, London, 1990.

[6] Waste Management, http://www.brookes.ac.uk/eie/tyres.htm.

[7] Gupta R.K., Civil Engineering Materials & Construction Practices, Jain Brothers, New Delhi, 2006.

[8] Alp Eren Yurtseven, Determination of Mechanical Properties of Hybrid Fiber Reinforced Concrete, 2004.

[9] ACI Committee 544, Measurement of Properties of Fiber Reinforced Concrete, ACI 544.2R-89.

[10] ASTM, standard test method for flexural toughness and first crack strength of fiber-reinforced concrete, ASTM 1018-92.

[11] JSCE, Method of test for flexural strength and flexural toughness for fiber reinforced concrete.

[12] Hannant D.J., Fibre Cements and Fibre Concrete, Wiley, Chichester, 1987.

[13] Balaguru P.N. and Shah S.P., Fiber-Reinforced Cement Composites, McGraw-Hill.

[14] Steel Fiber Reinforced Concrete Ground Slabs, http://www.upetd.up.ac.za/thesis/.

[15] ACI Committee 544, Guide for Specifying, Proportioning, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete, ACI 544.3R-93.

[16] Shanthakumar A. R., Concrete Technology, Oxford University Press, New Delhi, 2007.

[17] ACI Committee 544, Design Considerations for Steel Fiber Reinforced Concrete, ACI 544.4R-88.

[18] WRAP Identifies Opportunities for Tyre-derived Steel and Fiber, http://www.recyclingaction-yorkshire.org.uk./.

[19] California Integrated Waste Management Board, Assessment of Markets for Fiber and Steel Produced From Recycling Waste Tyres, Sacramento, 2003.

[20] https://www.rma.org/scrap_tires/scrap_tire_markets/scrap_tire_characteristics/.

[21] www.coopertire.com/us/en/information/info-construction.asp

[22] Environmental Information Exchange; Waste management, Recycling, Tyres http://www.brooks.ac.uk/eie/tyres.htm.

[23] End of life recycling-the concrete centre, http://www.sustainableconcrete.org.uk/main.

[24] Alielo M. A., Leuzzi F., Centonze G. and Maffezoli A., Use of Steel Fibers Recovered from Waste Tyres as Reinforcement in Concrete: Pull-out, Compressive and Flexural Strength, Elsevier Ltd., 2008.

[25] Tlemat H., Pilakoutus K. and Neocleous K., Stress-Strain Characteristic of SFRC using Recycled Fibers, RILEM 2006.

[26] Tlemat H., Pilakoutus K. and Neocleous K., Flexural Toughness of SFRC Made with Steel Fibers Extracted from Used Tyres, http://www.shef.ac.uk/tyre-recycling/.

[27] FOSROC Product Catalog, Admixtures: SP 430, http://www.FOSROC.com.

[28] RILEM Symposium 1978, Testing and Test Methods of Fiber Cement Composites, The Construction Press Ltd, Lancaster, 1978.

ANNEXES

ANNEX A

CHEMICAL, PHYSICAL AND MECHANICAL PROPERTIES OF THE CEMENT

MESSEBO CEMENT FACTORY
QUALITY CONTROL LABORATORY
QUALITY CERTIFICATE

QC/4/012
Issue-1
Page: 1 of 1

REPORT FOR: **CUSTOMER**

Product Type Portland Pozzolana Cement

Date of Report 9/9/2009

Date of Dispatch 7/5/2009 to 7/10/2009

Report Type: Weekly Report

Parameter		Test method	Unit	Limit	Date of Testing	Measured	Remark
Sulfur content		EN196-2	%	Max 4.0	/5-10/July/2009	2.46	
Chloride Content		EN196-21	%	Max 0.1	/5-10/July/2009	0.01	
LOI		EN196-2	%	Max 5.0	/5-10/July/2009	1.23	
Comprehensive Strength	2 day	EN196-2	N/mm2	Min 10.0	/5-10/July/2009	13.8	
	28 day	EN196-2	N/mm2	Min 32.5	/5-10/July/2009	36.6	
Setting time	initial	EN196-3	Minute	Min 75	/5-10/July/2009	155	
	final	EN196-3	Minute	Max 600	/5-10/July/2009 *	195	
Soundness		EN196-3	mm	Max 10	/5-10/July/2009	1.25	
Specific Surface Area		BS EN196-6	cm2/g	-	/5-10/July/2009	2970	
Heat of Hydration	3 day*	BS 1370	KJ/kg	-	/5-10/July/2009	153	
	28 day	BS 1370	KJ/kg	-	/5-10/July/2009	258	
Percentage of Pozzolana*			%	-	/5-10/July/2009	25 %	
Specific gravity		-	g/cm3	-	/5-10/July/2009	---	

Chemical Analysis result: *SiO2=29.14 Fe2O3=5.91 Al2O3=6.76 CaO=55.86 MgO=1.52 SO3=2.94 LOI=2.31*

Yohannes G. Kidan
Quality Control Manager
Date: 9/9/2009

ANNEX B

SIEVE ANALYSIS RESULTS

Test: Sieve Analysis of Coarse Aggregate

Test Method Used: Project: Msc. Thesis

Sample No.: S.CA.1 Source: Blue Nile Quarry

Tested By: Nasir Bedewi Date: 25-06-09

Table A.C.1 Sieve Analysis Results for Coarse Aggregate

Sieve Size (mm)	Weight of Sieve (g)	Wt. of Sieve & Retained (g)	Weight Retained (g)	Percentage Retained (%)	Cumulative Coarser (%)	Cumulative Passing (%)	Lower Limit (%)	Upper Limit (%)
37.5	1188	1188	0	0.00	0.00	100.00	100.00	
19	1419	1419	0	0.00	0.00	100.00	90.00	100.00
12.5	1166	3645	2479	48.53	48.53	51.47	40.00	80.00
9.5	1171	2682	1511	29.58	78.11	21.89	20.00	55.00
4.75	1194	2222	1028	20.13	98.24	1.76	0.00	10.00
Pan	1060	1150	90	1.76	100.00	0.00	0.00	5.00
FM=2.25								

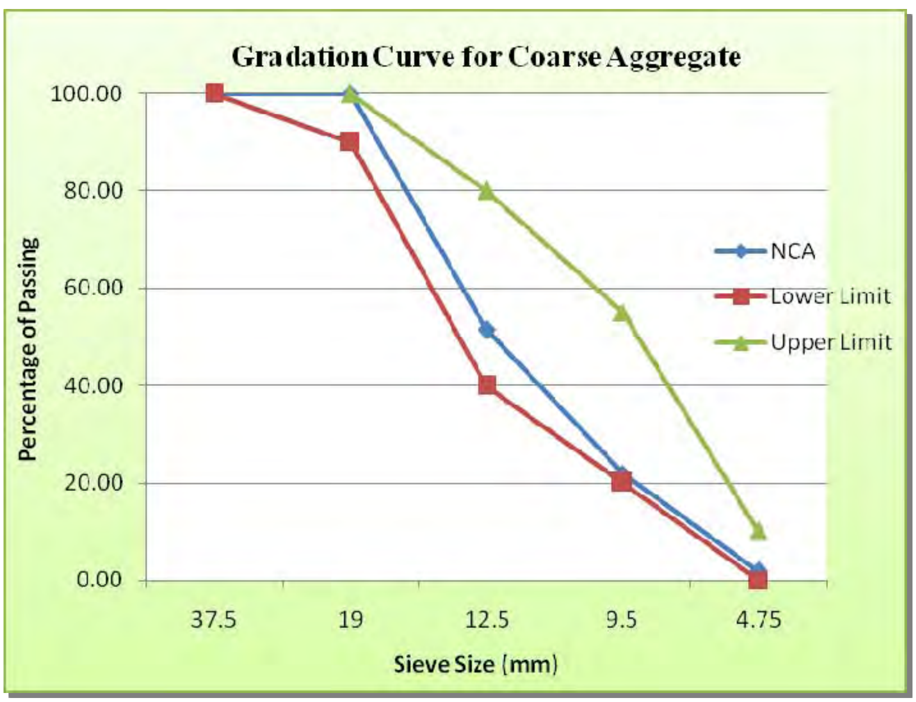


Fig A.C.1 Gradation Curve for Coarse Aggregate

Test: Sieve Analysis of Fine Aggregate

Test Method Used: Project: Msc. Thesis

Sample No.: S.FA.1 Source: Meki

Tested By: Nasir Bedewi Date: 24-06-09

Table A.C.2 Sieve Analysis Results for Fine Aggregate

Sieve Size (mm)	Weight of Sieve (g)	Wt. of Sieve & Retained (g)	Weight Retained (g)	Percentage Retained (%)	Cumulative Coarser (%)	Cumulative Passing (%)	Lower Limit (%)	Upper Limit (%)
9.5	586	586	0	0.00	0.00	100.00	100.00	
4.75	567	576	9	1.80	1.80	98.20	95.00	100.00
2.36	521	535	14	2.80	4.60	95.40	80.00	100.00
1.18	529	584	55	11.00	15.60	84.40	50.00	85.00
0.06	506	719	213	42.60	58.20	41.80	25.00	60.00
0.03	478	627	149	29.80	88.00	12.00	10.00	30.00
0.015	462	512	50	10.00	98.00	2.00	2.00	10.00
Pan	423	431	8	1.60	99.60	0.40		
FM=2.66								

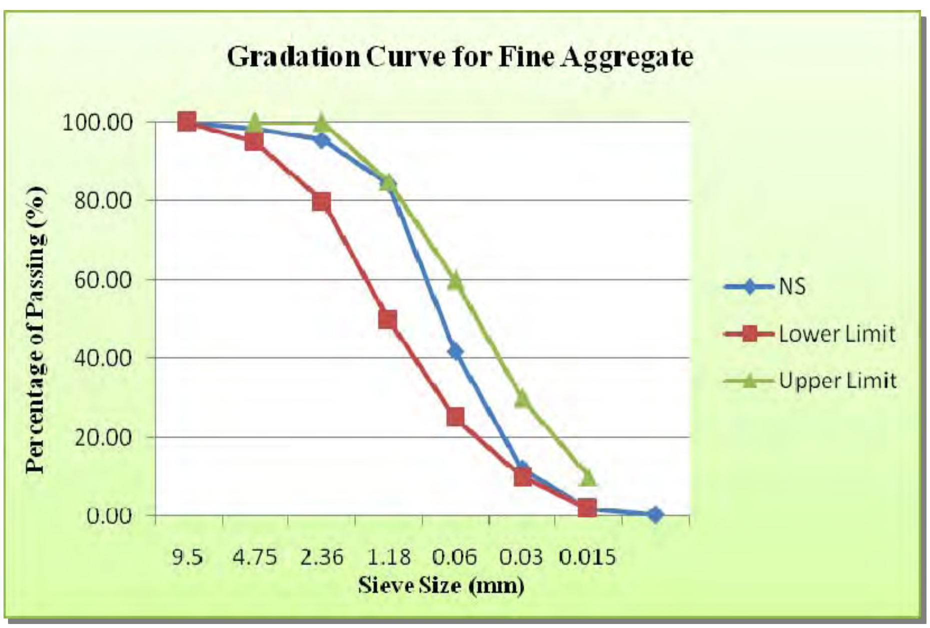


Fig. A.C.2 Gradation Curve for Fine Aggregate

ANNEX C

SPECIFICATION OF THE ADMIXTURE (SP 430)

Conplast SP430*

constructive solutions

High performance superplasticising admixture

Uses

- To provide excellent acceleration of strength gain at early ages and major increases in strength at all ages by significantly reducing water demand in a concrete mix.
- Particularly suitable for precast concrete and other high early strength requirements.
- To significantly improve the workability of site mixed and precast concrete without increasing water demand.
- To provide improved durability by increasing ultimate strengths and reducing concrete permeability.

Advantages

- Major increases in strength at early ages without increased cement contents are of particular benefit in precast concrete, allowing earlier stripping times.
- Makes possible major reductions in water:cement ratio which allow the production of high strength concrete without excessive cement contents.
- Use in production of flowing concrete permits easier construction with quicker placing and compaction and reduced labour costs without increasing water content.
- Increased workability levels are maintained for longer than with ordinary sulphonated melamine admixtures.
- Improved cohesion and particle dispersion minimises segregation and bleeding and improves pumpability.
- Chloride free, safe for use in prestressed and reinforced concrete.

Standards compliance

Conplast SP430 conforms with BSEN 934-2, BS 5075 Part 3 and with ASTM C494 as Type A and Type F, depending on dosage used.

Conplast SP430 complies with the requirements of the United Kingdom Water Fittings Byelaws Scheme and is listed in the Directory of Materials as suitable for use in contact with potable water under its previous name of Conplast 430.

Description

Conplast SP430 is a chloride free, superplasticising admixture based on selected sulphonated napthalene polymers. It is supplied as a brown solution which instantly disperses in water.

Conplast SP430 disperses the fine particles in the concrete mix, enabling the water content of the concrete to perform more effectively. The very high levels of water reduction possible allow major increases in strength to be obtained.

Conplast SP430*

Technical support

Fosroc provides a technical advisory service for on-site assistance and advice on mix design, admixture selection, evaluation trials and dispensing equipment.

Dosage

The optimum dosage of Conplast SP430 to meet specific requirements should always be determined by trial mixes using the materials and conditions that will be experienced in use.

For high strength, water reduced concrete the normal dosage range is from 1.00 to 3.00 litres/100 kg of cementitious material, including PFA, GGBFS and microsilica. For high workability concrete the normal dosage range is from 0.70 to 2.00 litres/100 kg of cementitious material.

Use at other dosages

Dosages outside the typical ranges quoted above can be used to meet particular requirements. Contact Fosroc for advice.

Effects of overdosing

An overdose of double the amount of Conplast SP430 will result in an increase in retardation as compared to that normally obtained. Provided that adequate curing is maintained, the ultimate strength of the concrete will not be impaired by increased retardation and will generally be increased. The effects of overdosing will be further increased if sulphate resisting cement or cement replacement materials are used.

Properties

Appearance	:	Brown liquid
Specific gravity BSEN 934-2)	:	1.18 @ 22°C + 2°C
Water soluble chloride (BSEN 934-2)	:	Nil
Alkali content (BSEN 934-2)	:	Typically less than 55g. Na2O equivalent/litre of admixture

Instructions for use

Mix design

Where the main requirement is to improve strengths, initial trials should be made with normal concrete mix designs. The addition of the admixture will allow the removal of water from the mix whilst maintaining workability. After initial trials, minor modifications to the overall mix design may be made to optimise performance.

ANNEX D

SPECIFICATION OF VIRGIN STEEEL FIBER (BEAD WIRE)

SUPPLIER:	BEAD WIRE SPECIFICATION: ROUND BEAD WIRE ø 0, 89 mm			CUSTOMER: MAT-ATC CODE:25.1	
Construction: Round bead wire diameter 0,89 mm					
Coating	Bronze				
SPECIFICATION	**UNIT**	**VALUE TARGET**	**TOLERANCE**	**TEST METHOD**	**NOT**
Nominal diameter	[mm]	0,89	+/- 0,025	MP 066	
Nominal weight per length	[g/m]	4,884	-	MP 061	
PHYSICAL MECHANICAL PROPERTIES					
✓ Tensile Strength min.	[MPa]	1900	-	MP 068	
✓ Nominal breaking force min.	[N]	1182		MP 068	*
✓ Elongation at break	[%]	6-9	-	MP 068	
Stiffness-number of bends	-	13	-	MP 065	
Stiffness-number of torsions	-	25	-	MP 060	
Mass of Bronze coating	[g/kg]	0,30-0,95	-	MP 046	
Copper content	[%]	97-99,5	-	MP 046	
Straightness	[cm/3m]	50	-	MP 072	
Weight of reelless coil or metal reel	[kg]	350-450	-	-	
Overall width of reelless coil	[mm]	280-295	-	-	
Overall width of metal reel	[mm]	343	-	-	
Adhesion /stand. comp./ min.	[N/25mm]	300	-	MP 053	

CONDITION OF STOCKING:

Temperature: *Recommended 5-35°C*

Humidity: *Protection against moisture and UV radiation is trough packing, which can not be destructed.*

PERIOD OF GUARANTEE:

The six months from date of expedition, in case that are keeping condition of stocking and packing and material is not destructed.

NOTICE:

Testing is according laboratory guidebook or according separate agreement with supplier.

**- critical parameter for tyre safety.*

Issue date:

SUPPLIER

CUSTOMER

Prepared by : Research and development department MATC
Date :19/02/07

ANNEX E

INDUSTRIAL STEEL FIBERS DATA SHEET

Xorex® Steel Fiber

PRODUCT SPECS

PRODUCT USE

MIXING • Xorex steel fibre can be added before, during or after the batching of the concrete. Materials, batching requirements, mixings and testing procedures should comply with the applicable sections of ASTM C1116 and ASTM C1436.

PLACING • Xorex steel fibre can be pumped and placed using conventional equipment. Hand screeds, laser screeds and vibratory screeds can be used.

FINISHING • Conventional finishing techniques and equipment can be used when finishing Xorex steel fibre concrete. In some cases an extra bull float process is advised and lowering the angle of the floating blades will help to minimize fibre exposure on the surface. SI Concrete Systems personnel can help to determine the best solution for your job.

REFERENCE DOCUMENTS

ASTM A820 • Standard Specification for Steel Fibres for Fibre-Reinforced Concrete.

ASTM C1018 • Standard Test Method for Flexural Toughness and First-Crack Strength of Fibre-Reinforced Concrete.

ASTM C1116 • Standard Specification for Fibre-Reinforced Concrete and Shotcrete.

ASTM C1399 • Average Residual Strength of Fibre Reinforced Concrete.

ASTM C1436 • Standard Specification for Materials for Shotcrete.

ACI 506 • Guide for Shotcrete.

ACI 544-3R • Guide for Specifying, Proportioning, Mixing, Placing, and Finishing Steel Fibre Reinforced Concrete.

TECHNICAL INFORMATION

FIBER	XOREX
Minimum Tensile Strength	829MPa (120,000psi)
Fiber Length	25, 35, 50 & 63mm (1.0, 1.5, 2.0 & 2.5in.)
Average Equivalent Diameter	1.0mm (0.040in.)
Average Aspect Ratio	25,35,50&63
Deformation	Continuously deformed circular segment.
Appearance	Bright and clean wire.

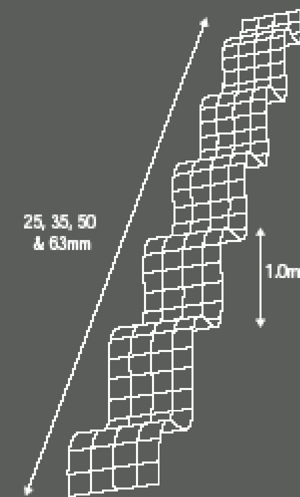
PACKAGING

Xorex steel fibre is packaged in 25kg (55lb), five ply, paper and polyethylene lined bags. Also available in 800kg bulk bags on request.

SAFETY

It is recommended that gloves and eye protection be used when handling or adding Xorex steel fibre to concrete.

DIMENSIONS



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MATRIX CS-1.0 cut sheet steel fibres

PRODUCT DATA SHEET

TECHNICAL INFORMATION

FIBER	MATRIX – CS 1.0
ASTM Specification	ASTM A820 Type II
Material Type	Low Carbon, cut sheet steel
Tensile Strength	414 – 828 Mpa (60 – 120 ksi)
Fiber Length	25.0 mm (1.0") also available in 3/4", & 1.5"
Average Thickness	.33 – .60 mm (0.13 – .025")
Average Aspect Ratio	<60
Specific Gravity	7.85
Modulus of Elasticity	29.0 x 10⁶ @ 70° F (20° C)
Melting Point	2760° F (1516° C)
Deformations	Continuously deformed cut sheet fibres
Appearance	Bright and clean cut sheet steel
Packaging	50lb. boxes

SAFETY

FRC recommends that gloves and eye protection be used when handling or adding MATRIX cut sheet steel fibres.

REFERENCE DOCUMENTS

ACI 302.1R	* Guide for Concrete Floor and Slab Construction.
ACI 360R-92	* Design of Slabs on Grade.
ACI 544-1R	* Fiber Reinforced Concrete
ACI 544-3R	* Guide for Specifying, Proportioning, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete.
ACI 506	* Guide for Shotcrete.
ASTM A820	* Standard Specification for Steel Fibers for Fiber-Reinforced Concrete.
ASTM C94	* Standard Specification for Ready-Mixed Concrete.
ASTM C1018	* Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete.
ASTM C1116	* Standard Specification for Fiber-Reinforced Concrete and Shotcrete.

MIXING – PLACING – FINISHING – TESTING

- **Mixing** - MATRIX CS fibres can be added during or after the batching of concrete. In some instances CS can be added before the concrete is batched. Mixing should conform to ASTM C94 standard specification for ready-mixed concrete.
- **Placing** - MATRIX steel fibres can be pumped and placed using conventional equipment. Hand screeds can be used, but vibratory and laser screeds are recommended to provide added compaction and bury surface fibers.
- **Finishing** - Normal finishing equipment & techniques can be used when finishing MATRIX fibers. Troweling blades should be kept at a flat angle for as long as possible to insure a fibre free surface.
- **Testing** - Sample testing on jobsite shall conform to ASTM C1072. Measuring materials, toughness, and workability shall be governed by ASTM C1116 & ASTM C1018

NOVOCON® XR

PRODUCT DATA SHEET

NOVOCON® XR STEEL FIBERS

Novocon XR (formerly Xorex®) steel fiber is a leading low carbon, cold drawn steel wire fiber concrete reinforcement. It is evenly distributed in concrete mixtures to provide improved mechanical bonding capacity exceeding most performance specifications for enhancing concrete's shear strength, fatigue endurance, impact resistance and flexural toughness. Novocon XR has been used in over 150 million square feet (15 million square meters) of slabs on ground for industrial floors. It is a reliable, cost efficient concrete reinforcement that is designed to be easy to mix, place and finish.

FEATURES & BENEFITS

- Complies with ASTM A820.
- Variable equivalent diameter and a continuously deformed shape provide reinforcement resulting in tighter, more stable joints.
- Improves the impact resistance, fatigue endurance and shear strength of concrete.
- Provides crack width control.
- Manufactured in 1.5 in and 2 in (38 mm and 50 mm) lengths to meet specific applications.
- Provides uniform, multi-directional concrete reinforcement.
- Requires less labor to incorporate into concrete applications than rebar or wire mesh.
- Offers greater project scheduling accuracy.
- No special equipment is needed to mix, place or finish.
- Compatible with all types of cements and concrete mixtures.
- Backed by our team of concrete experts who carefully analyze each project and provide steel fiber design recommendations to help ensure maximum product performance and cost efficiency.

PRIMARY APPLICATIONS

- Commercial and Industrial Slabs On Ground • Shotcrete
- Composite Metal Decks • Overlays • Airport Pavements • Highway Pavements
- Hydrodynamic Structures • Equipment Foundations • Precast

COMPLIANCE

- Novocon XR steel fiber concrete reinforcement complies with ASTM A820.
- Materials, batching requirements, mixing and testing procedures should comply with the applicable sections of ASTM C 1116/C 1116M and ASTM C 1436.

CHEMICAL AND PHYSICAL PROPERTIES

Fiber Length	1.5 in and 2 in (38 mm and 50 mm)
Equivalent Diameter	0.045" (1.14 mm)
Aspect Ratio	34 and 44
Tensile Strength	140-180 Kpsi (966-1242 MPa)
Deformation	Continuously deformed circular segment
Appearance	Bright and clean wire

DO SPECIFY NOVOCON XR FIBERS:

- For temperature/shrinkage and flexural reinforcement
- Increased crack resistance, ductility, energy absorption or toughness
- Improved impact resistance
- Improved fatigue endurance and shear strength
- Improved durability

DO NOT SPECIFY NOVOCON XR FIBERS:

- Replacing structural levels of steel reinforcement

PROPEX® | THE ADVANTAGE CREATORS™

CONCRETE SYSTEMS

ANNEX F

DOE MIX DESIGN DATA SHEET

Table A.F.1 Mix Design Data sheet for Mix Series I.

Mix Design Data Sheet for Mix Series I (C-25)				
Stage	Item		Reference or Calculation	Values
1	1.1	Characteristic strength	Specified	Compressive 25 N/mm^2 at 28 days Proportion defective 5 Percent
	1.2	Standard deviation	Fig. 3	- N/mm^2 or no data 8 N/mm^2
	1.3	Margin	C1	(k = 1.64) 1.64 x 8 = 13.12 N/mm^2
	1.4	Target mean strength	C2	25 + 13.12 = 38.12 N/mm^2
	1.5	Cement type	Specified	OPC
	1.6	Aggregate Type: Coarse		Crushed
		Aggregate Type: Fine		Uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	0.57 } Use the lower value
	1.8	Maximum Free water/cement ratio		0.53 }
2	2.1	Slump or V-B	Specified	Slump 10-30 mm or V-B 6-12 s
	2.2	Maximum aggregate Size	Specified	20 mm
	2.3	Free-water Content	Table-3	180 kg/m^3
3	3.1	Cement Content	C3	180 ÷ 0.53 = 339.6 kg/m^3
	3.2	Maximum cement content	Specified	_____ kg/m^3
	3.3	Minimum cement content	Specified	_____ kg/m^3 Use if greater than item 3.1 and calculate item 3.4
	3.4	Modified free-water/cement ratio		_____
4	4.1	Relative density of aggregate (SSD)		2.70 **Known**/ assumed
	4.2	Concrete density	Fig. 5	2445 kg/m^3
	4.3	Total aggregate content	C4	2445 - 339.6 - 180 = 1925.4 kg/m^3
5	5.1	Grading of fine aggregate	BS 882	Zone 2
	5.2	Proportion of fine aggregate	Fig. 6	34 percent
	5.3	Fine aggregate content		1925.4 x 0.34 = 654.6 kg/m^3
	5.4	Coarse aggregate content		1 925.4 - 654.6 = 1270.8 kg/m^3

Quantities	**Cement (kg)**	**Water (kg or lit)**	**Fine Aggregate (kg)**	**Coarse Aggregate (kg)**
Per m^3 (to the nearest 5 Kg)	339.6	180	655	1270
Degree of absorption (%)			2.38	0.35
Adjustment for moisture content	**340**	**200**	**640**	**1265**
Per trial mix of **0.056** m^3	19.04	11.2	35.84	70.84

Table A.F.2 Mix Design Data sheet for Mix Series II.

Mix Design Data Sheet for Mix Series II (C-40)				
Stage	Item		Reference or Calculation	Values
1	1.1	Characteristic strength	Specified	Compressive 40 N/mm^2 at 28 days Proportion defective 5 Percent
	1.2	Standard deviation	Fig. 3	- N/mm^2 or no data 8 N/mm^2
	1.3	Margin	C1	(k = 1.64) 1.64 x 8 = 13.12 N/mm^2
	1.4	Target mean strength	C2	40 + 13.12 = 53.12 N/mm^2
	1.5	Cement type	Specified	OPC
	1.6	Aggregate Type: Coarse		Crushed
		Aggregate Type: Fine		Uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	0.45 } Use the lower value
	1.8	Maximum Free water/cement ratio		0.42
2	2.1	Slump or V-B	Specified	Slump 10-30 mm or V-B 6-12 s
	2.2	Maximum aggregate Size	Specified	20 mm
	2.3	Free-water Content	Table-3	180 kg/m^3
3	3.1	Cement Content	C3	180 ÷ 0.42 = 428.57 kg/m^3
	3.2	Maximum cement content	Specified	_____ kg/m^3
	3.3	Minimum cement content	Specified	_____ kg/m^3 Use if greater than item 3.1 and calculate item 3.4
	3.4	Modified free-water/cement ratio		_____
4	4.1	Relative density of aggregate (SSD)		2.71 **Known**/ assumed
	4.2	Concrete density	Fig. 5	2452 kg/m^3
	4.3	Total aggregate content	C4	2452 – 428.57 - 180 = 1843.43 kg/m^3
5	5.1	Grading of fine aggregate	BS 882	Zone 2
	5.2	Proportion of fine aggregate	Fig. 6	32 percent
	5.3	Fine aggregate content		1843.43 x 0.32 = 589.9 kg/m^3
	5.4	Coarse aggregate content		1843.43 – 589.9 = 1253.53 kg/m^3

Quantities	**Cement (kg)**	**Water (kg or lit)**	**Fine Aggregate (kg)**	**Coarse Aggregate (kg)**
Per m^3 (to the nearest 5 Kg)	430	180	590	1255
Degree of absorption (%)			2.38	0.35
Adjustment for moisture content	**430**	**198.43**	**575**	**1250**
Per trial mix of **0.056** m^3	24.08	11.11	32.2	70

Table A.F.2 Mix Design Data sheet for Mix Series II.

Mix Design Data Sheet for Mix Series III (C-60)				
Stage	Item		Reference or Calculation	Values
1	1.1	Characteristic strength	Specified	Compressive 60 N/mm^2 at 28 days Proportion defective 5 Percent
	1.2	Standard deviation	Fig. 3	- N/mm^2 or no data 8 N/mm^2
	1.3	Margin	C1	(k = 1.64) 1.64 x 8 = 13.12 N/mm^2
	1.4	Target mean strength	C2	60 + 13.12 = 73.12 N/mm^2
	1.5	Cement type	Specified	OPC
	1.6	Aggregate Type: Coarse Aggregate Type: Fine		Crushed Uncrushed
	1.7	Free-water/cement ratio	Table 2, Fig 4	0.327 Use the lower value
	1.8	Maximum Free water/cement ratio		
2	2.1	Slump or V-B	Specified	Slump 10-30 mm or V-B 6-12 s
	2.2	Maximum aggregate Size	Specified	20 mm
	2.3	Free-water Content	Table-3	180 kg/m^3
3	3.1	Cement Content	C3	180 ÷ 0.33 = 550.5 Kg/m^3
	3.2	Maximum cement content	Specified	_____ kg/m^3
	3.3	Minimum cement content	Specified	_____ kg/m^3 Use if greater than item 3.1 and calculate item 3.4
	3.4	Modified free-water/cement ratio		_____
4	4.1	Relative density of aggregate (SSD)		2.72 **Known**/ assumed
	4.2	Concrete density	Fig. 5	2459 kg/m^3
	4.3	Total aggregate content	C4	2459 – 550.5 - 180 = 1728.5 kg/m^3
5	5.1	Grading of fine aggregate	BS 882	Zone 2
	5.2	Proportion of fine aggregate	Fig. 6	30 percent
	5.3	Fine aggregate content		1728.5 x 0.30 = 518.5 kg/m^3
	5.4	Coarse aggregate content		1728.5 – 518.5 = 1210 kg/m^3

Quantities	**Cement (kg)**	**Water (kg or lit)**	**Fine Aggregate (kg)**	**Coarse Aggregate (kg)**
Per m^3 (to the nearest 5 Kg)	550	180	520	1210
Degree of absorption (%)			2.38	0.35
Adjustment for moisture content	**550**	**198.43**	**510**	**1205**
Per trial mix of **0.056** m^3	30.8	11.11	28.56	67.48

ANNEX G

COMPRESSIVE STRENGTH TEST RESULTS

Table A.G.1 7^{th} Day Compressive Strength Results for Mix Series I.

Concrete Grade C-25										
Mix Desig.	Cube No.	Dimensions (cm)			Weight (g)	Volume (cm^3)	Unit Weight (g/cm^3)	Failure Load (kN)	Actual Comp. Strength (MPa)	Corrected Comp. Strength (MPa)
		L	W	H						
C-1	Cu-4	14.97	14.99	15.17	8273	3404.15	2.430	398.0	17.69	17.53
	Cu-5	15.08	14.98	15.16	8247	3424.62	2.408	408.9	18.17	17.89
	Cu-9	14.95	15.00	15.28	8273	3426.54	2.414	403.3	17.69	17.65
	Mean				8264.33	3418.44	2.418	403.40	17.85	17.69
$C_1V_{0.5}L_2$	Cu-8	15.00	15.04	15.09	8474	3404.30	2.489	405.0	18.00	17.89
	Cu-6	15.30	15.29	15.32	8858	3583.91	2.472	407.1	18.09	17.37
	Cu-9	15.00	14.99	15.18	8457	3413.22	2.478	396.6	17.63	17.42
	Mean				8596.33	3467.15	2.480	402.90	17.91	17.56
$C_1V_{0.5}L_4$	Cu-1	14.98	14.99	15.17	8425	3406.43	2.473	411.2	18.27	18.09
	Cu-6	14.89	14.90	15.20	8396	3372.29	2.490	412.2	18.31	18.21
	Cu-3	14.99	14.99	15.16	8411	3406.45	2.469	402.9	17.91	17.73
	Mean				8410.67	3395.06	2.477	408.77	18.16	18.01
$C_1V_{0.5}L_6$	Cu-6	15.02	15.04	15.16	8427	3424.66	2.461	400.5	17.80	17.59
	Cu-9	14.98	15.00	15.16	8452	3406.45	2.481	421.0	18.71	18.54
	Cu-8	15.02	14.95	15.05	8349	3379.46	2.471	408.0	18.13	18.05
	Mean				8409.33	3403.52	2.471	409.83	18.21	18.06
$C_1V_{1.0}L_2$	Cu-1	15.10	15.00	15.07	8478	3413.36	2.484	398.7	17.72	17.52
	Cu-2	14.99	14.99	15.12	8445	3397.47	2.486	390.8	17.37	17.24
	Cu-8	15.01	14.98	15.11	8499	3397.48	2.502	395.0	17.55	17.42
	Mean				8474.00	3402.77	2.490	394.83	17.55	17.39
$C_1V_{1.0}L_4$	Cu-1	14.98	14.99	15.17	8552	3406.43	2.511	412.0	18.31	18.13
	Cu-4	15.27	15.23	15.42	9111	3586.11	2.541	407.5	18.11	17.31
	Cu-7	14.98	15.04	15.24	8547	3433.56	2.489	395.2	17.56	17.31
	Mean				8736.67	3475.36	2.513	404.90	17.99	17.58
$C_1V_{1.0}L_6$	Cu-5	14.99	14.99	15.15	8535	3404.21	2.507	410.8	18.26	18.09
	Cu-6	15.05	14.97	15.09	8468	3399.75	2.491	394.4	17.53	17.37
	Cu-7	14.91	15.16	15.15	8477	3424.44	2.475	412.1	18.31	18.24
	Mean				8493.33	3409.47	2.491	405.77	18.03	17.90
$C_1V_{1.5}L_2$	Cu-1	14.98	14.99	15.15	8594	3401.94	2.526	413.5	18.38	18.22
	Cu-3	15.01	14.99	15.16	8606	3411.00	2.523	410.8	18.26	18.05
	Cu-6	15.02	14.98	15.15	8611	3408.74	2.526	422.2	18.76	18.55
	Mean				8603.67	3407.23	2.525	415.50	18.47	18.28
$C_1V_{1.5}L_4$	Cu-1	15.05	15.10	15.14	8698	3440.64	2.528	459.3	20.41	20.16
	Cu-3	15.00	14.99	15.15	8567	3406.48	2.515	487.2	21.65	21.44
	Cu-4	14.99	14.98	15.12	8507	3395.20	2.506	473.6	21.04	20.90
	Mean				8590.67	3414.11	2.516	473.37	21.03	20.83
$C_1V_{1.5}L_6$	Cu-1	15.00	15.03	15.23	8548	3433.60	2.490	416.0	18.49	18.21
	Cu-3	14.99	15.01	15.17	8530	3413.25	2.499	416.2	18.50	18.30
	Cu-6	15.01	15.29	15.57	9071	3573.36	2.539	441.2	19.61	18.88
	Mean				8716.33	3473.40	2.509	424.47	18.87	18.46

Table A.G.2 7th Day Compressive Strength Results for Mix Series II.

Concrete Grade C-40										
Mix Desig.	Cube No.	Dimensions (cm)			Weight (g)	Volume (cm^3)	Unit Weight (g/cm^3)	Failure Load (kN)	Actual Comp. Strength (MPa)	Corrected Comp. Strength (MPa)
		L	W	H						
C-2	Cu-1	14.98	15.03	15.22	8421	3426.77	2.457	580.4	25.80	25.46
	Cu-2	14.99	15.00	15.07	8322	3388.49	2.456	586.5	26.06	25.96
	Cu-3	14.97	14.99	15.08	8292	3383.96	2.450	589.1	26.18	26.10
	Mean				8345.00	3399.74	2.455	585.33	26.01	25.84
$C_2V_{0.5}L_2$	Cu-4	15.29	15.26	15.40	8968	3593.21	2.496	636.3	28.28	27.02
	Cu-5	14.99	14.99	15.08	8399	3388.48	2.479	623.2	27.69	27.57
	Cu-7	15.00	15.04	15.11	8448	3408.82	2.478	638.9	28.39	28.19
	Mean				8605.00	3463.50	2.484	632.80	28.12	27.59
$C_2V_{0.5}L_4$	Cu-3	15.29	15.05	15.26	8622	3511.55	2.455	614.8	27.31	26.35
	Cu-6	15.27	15.02	15.26	8522	3499.96	2.435	626.5	27.84	26.89
	Cu-8	15.06	15.00	15.28	8623	3451.75	2.498	649.2	28.85	28.21
	Mean				8589.00	3487.75	2.463	630.17	28.00	27.15
$C_2V_{0.5}L_6$	Cu-2	15.24	15.23	15.40	8996	3574.42	2.517	660.9	29.38	28.16
	Cu-3	15.27	15.26	15.34	8928	3574.53	2.498	645.1	28.67	27.54
	Cu-9	15.06	15.04	15.16	8531	3433.78	2.484	641.0	28.48	28.08
	Mean				8818.33	3527.58	2.500	649.00	28.84	27.93
$C_2V_{1.0}L_2$	Cu-1	14.98	14.97	15.18	8530	3404.12	2.506	648.4	28.81	28.51
	Cu-2	14.99	15.00	15.07	8552	3388.49	2.524	651.1	28.94	28.82
	Cu-3	15.01	14.98	15.27	8591	3433.46	2.502	639.0	28.39	27.88
	Mean				8557.67	3408.69	2.511	646.17	28.71	28.41
$C_2V_{1.0}L_4$	Cu-2	14.99	14.98	15.03	8574	3374.99	2.540	669.8	29.76	29.73
	Cu-5	15.06	15.30	15.14	8791	3488.53	2.520	649.2	28.85	28.47
	Cu-7	15.20	14.95	15.21	8633	3456.32	2.498	658.5	29.27	28.48
	Mean				8666.00	3439.95	2.519	659.17	29.29	28.89
$C_2V_{1.0}L_6$	Cu-2	14.98	15.02	15.15	8550	3408.74	2.508	610.8	27.15	26.91
	Cu-3	15.00	15.01	15.22	8531	3426.78	2.490	620.8	27.59	27.19
	Cu-7	15.03	15.01	15.27	8567	3444.92	2.487	608.6	27.08	26.52
	Mean				8549.33	3426.81	2.495	613.40	27.27	26.87
$C_2V_{1.5}L_2$	Cu-1	14.98	14.99	15.10	8689	3390.71	2.563	660.3	29.35	29.19
	Cu-4	14.98	15.10	15.21	8614	3440.47	2.504	634.5	28.20	27.85
	Cu-9	15.02	14.90	15.06	8604	3370.40	2.553	637.4	28.32	28.18
	Mean				8635.67	3400.53	2.540	644.07	28.62	28.41
$C_2V_{1.5}L_4$	Cu-2	15.00	15.02	15.19	8667	3422.31	2.533	695.5	30.90	30.52
	Cu-3	15.29	15.21	15.42	9233	3586.09	2.575	724.8	32.21	30.74
	Cu-6	15.30	15.26	15.31	9104	3574.55	2.547	729.0	32.40	31.12
	Mean				9001.33	3527.65	2.551	716.43	31.84	30.80
$C_2V_{1.5}L_6$	Cu-1	15.00	15.00	15.21	8675	3422.25	2.535	614.1	27.28	26.92
	Cu-3	14.99	15.00	15.23	8679	3424.47	2.534	646.2	28.72	28.31
	Cu-5	15.01	15.00	15.23	8631	3429.03	2.517	647.1	28.76	28.31
	Mean				8661.67	3425.25	2.529	635.80	28.25	27.84

Table A.G.3 7th Day Compressive Strength Results for Mix Series III.

Concrete Grade C-60										
Mix Desig.	Cube No.	Dimensions (cm)			Weight (g)	Volume (cm^3)	Unit Weight (g/cm^3)	Failure Load (kN)	Actual Comp. Strength (MPa)	Corrected Comp. Strength (MPa)
		L	W	H						
C-3	Cu-3	15.00	14.98	15.25	8387	3426.68	2.448	948.5	42.15	41.46
	Cu-5	14.99	15.00	15.15	8368	3406.48	2.456	981.9	43.64	43.24
	Cu-9	15.01	15.05	15.28	8447	3451.76	2.447	970.7	43.14	42.32
	Mean				8400.67	3428.30	2.450	967.03	42.98	42.34
$C_3V_{0.5}L_2$	Cu-3	15.21	15.26	15.46	9026	3588.34	2.515	1004.2	44.63	42.71
	Cu-5	14.98	14.99	15.08	8479	3386.22	2.504	974.2	43.29	43.13
	Cu-6	15.08	15.32	15.21	8714	3513.90	2.480	956.5	42.51	41.70
	Mean				8739.67	3496.15	2.500	978.30	43.48	42.51
$C_3V_{0.5}L_4$	Cu-1	14.96	14.98	15.05	8481	3372.72	2.515	976.4	43.40	43.37
	Cu-7	15.05	14.99	15.28	8549	3447.16	2.480	971.7	43.18	42.25
	Cu-8	15.06	14.99	15.18	8552	3426.88	2.496	957.8	42.57	41.90
	Mean				8527.33	3415.58	2.497	968.63	43.05	42.51
$C_3V_{0.5}L_6$	Cu-1	15.02	15.02	15.11	8517	3408.82	2.499	967.0	42.98	42.61
	Cu-5	15.30	15.24	15.45	8992	3602.51	2.496	999.1	44.39	42.27
	Cu-6	15.00	15.09	15.08	8518	3413.36	2.495	976.6	43.41	43.17
	Mean				8675.67	3474.90	2.497	980.90	43.59	42.68
$C_3V_{1.0}L_2$	Cu-1	14.99	14.98	15.18	8578	3408.67	2.517	1003.1	44.58	44.08
	Cu-5	15.01	14.99	15.38	8646	3460.50	2.498	990.1	44.00	42.89
	Cu-9	15.02	14.99	15.23	8616	3429.03	2.513	1019.9	45.33	44.58
	Mean				8613.33	3432.73	2.509	1004.37	44.64	43.85
$C_3V_{1.0}L_4$	Cu-2	15.00	15.00	15.25	8596	3431.25	2.505	977.4	43.46	42.73
	Cu-3	15.00	15.00	15.12	8586	3402.00	2.524	1002.0	44.53	44.18
	Cu-9	15.03	14.96	15.28	8593	3435.69	2.501	976.3	43.38	42.51
	Mean				8591.67	3422.98	2.510	985.23	43.79	43.14
$C_3V_{1.0}L_6$	Cu-1	15.00	15.00	15.07	8638	3390.75	2.548	998.2	44.36	44.16
	Cu-3	15.00	15.00	15.08	8545	3393.00	2.518	1006.8	44.75	44.51
	Cu-6	15.00	15.00	15.10	8565	3397.50	2.521	984.5	43.75	43.47
	Mean				8582.67	3393.75	2.529	996.50	44.29	44.04
$C_3V_{1.5}L_2$	Cu-1	15.00	14.98	15.09	8662	3390.72	2.555	1019.2	45.29	45.03
	Cu-2	15.00	14.97	15.24	8698	3422.14	2.542	1019.6	45.31	44.60
	Cu-5	14.99	14.99	15.09	8635	3390.72	2.547	1037.5	46.11	45.87
	Mean				8665.00	3401.20	2.548	1025.43	45.57	45.17
$C_3V_{1.5}L_4$	Cu-6	15.04	14.99	15.24	8720	3435.85	2.538	973.9	43.28	42.49
	Cu-7	15.04	14.97	15.23	8660	3429.02	2.526	976.6	43.40	42.64
	Cu-9	15.05	15.08	15.25	8825	3461.05	2.550	976.0	43.38	42.52
	Mean				8735.00	3441.97	2.538	975.50	43.35	42.55
$C_3V_{1.5}L_6$	Cu-4	15.00	15.00	15.22	8796	3424.50	2.569	970.3	43.11	42.50
	Cu-5	15.26	15.26	15.47	9305	3602.46	2.583	1040.3	46.23	44.07
	Cu-7	15.08	14.95	15.17	8690	3420.02	2.541	1011.6	44.96	44.22
	Mean				8930.33	3482.33	2.564	1007.40	44.77	43.60

Table A.G.4 28th Day Compressive Strength Results for Mix Series I.

Concrete Grade C-25										
Mix Desig.	Cube No.	Dimensions (cm)			Weight (g)	Volume (cm^3)	Unit Weight (g/cm^3)	Failure Load (kN)	Actual Comp. Strength (MPa)	Corrected Comp. Strength (MPa)
		L	W	H						
C-1	Cu-6	15.00	14.97	15.30	8452	3435.62	2.460	660.8	29.37	28.79
	Cu-7	15.00	14.96	15.28	8382	3428.83	2.445	636.3	29.28	27.76
	Cu-8	14.96	15.04	15.28	8372	3437.98	2.435	630.7	28.03	27.59
	Mean				8402.00	3434.14	2.447	642.60	28.89	28.05
$C_1V_{0.5}L_2$	Cu-4	14.98	14.99	15.12	8466	3395.20	2.494	625.1	27.78	27.60
	Cu-5	15.00	15.29	15.14	8926	3472.36	2.571	640.9	28.48	28.22
	Cu-7	14.99	15.24	15.19	8979	3470.12	2.588	639.7	28.43	28.09
	Mean				8790.33	3445.89	2.551	635.23	28.23	27.97
$C_1V_{0.5}L_4$	Cu-2	15.00	15.00	15.21	8447	3422.25	2.468	640.5	28.46	28.07
	Cu-4	15.29	15.33	15.10	9003	3539.38	2.544	665.6	29.58	28.83
	Cu-5	15.25	15.27	15.54	9018	3618.76	2.492	656.3	29.18	27.69
	Mean				8822.67	3526.80	2.501	654.13	29.07	28.20
$C_1V_{0.5}L_6$	Cu-4	15.00	15.00	15.14	8406	3406.50	2.468	627.8	27.89	27.64
	Cu-5	15.28	15.20	15.40	8920	3576.74	2.494	663.5	29.48	28.20
	Cu-7	15.03	14.97	15.13	8517	3404.24	2.502	656.3	29.17	28.86
	Mean				8614.33	3462.49	2.488	649.20	28.85	28.23
$C_1V_{1.0}L_2$	Cu-3	14.99	14.99	15.09	8521	3390.72	2.513	618.1	27.47	27.33
	Cu-4	15.02	15.32	14.97	9059	3444.69	2.630	648.2	28.81	28.83
	Cu-7	14.92	15.10	14.98	8499	3374.87	2.518	618.1	27.47	27.66
	Mean				8693.00	3403.43	2.554	628.13	27.92	27.94
$C_1V_{1.0}L_4$	Cu-5	14.92	15.27	15.00	9101	3417.43	2.663	619.6	27.53	27.69
	Cu-8	15.00	15.28	15.04	8608	3447.17	2.497	657.3	29.21	29.14
	Cu-9	14.99	15.28	15.07	8664	3451.74	2.510	687.8	30.57	30.45
	Mean				8791.00	3438.78	2.557	654.90	29.10	29.09
$C_1V_{1.0}L_6$	Cu-1	15.00	15.19	15.02	8471	3422.31	2.475	635.2	28.23	28.19
	Cu-3	15.02	15.19	15.02	8582	3426.87	2.504	621.9	27.64	27.57
	Cu-8	15.01	15.19	14.99	8512	3417.75	2.491	616.5	27.40	27.40
	Mean				8521.67	3422.31	2.490	624.53	27.76	27.72
$C_1V_{1.5}L_2$	Cu-2	14.97	15.00	15.20	8600	3413.16	2.520	661.2	29.39	29.06
	Cu-4	15.32	15.27	15.46	9152	3616.66	2.531	673.0	29.91	28.41
	Cu-5	15.25	15.26	15.36	9111	3574.50	2.549	687.9	30.57	29.37
	Mean				8954.33	3534.77	2.533	674.03	29.96	28.95
$C_1V_{1.5}L_4$	Cu-2	15.00	14.99	15.11	8656	3397.48	2.548	702.8	31.23	31.01
	Cu-8	15.03	14.96	15.13	8547	3401.96	2.512	714.1	31.74	31.40
	Cu-9	15.01	14.92	15.15	8572	3392.83	2.527	719.4	31.97	31.64
	Mean				8591.67	3397.43	2.529	712.10	31.65	31.35
$C_1V_{1.5}L_6$	Cu-7	15.27	15.34	15.02	9158	3518.31	2.603	668.6	29.71	29.15
	Cu-8	15.02	15.13	15.04	8553	3417.88	2.502	640.7	28.47	28.36
	Cu-9	15.03	15.20	14.96	8605	3417.70	2.518	600.4	26.68	26.70
	Mean				8772.00	3451.30	2.541	636.57	28.29	28.07

Table A.G.5 28th Day Compressive Strength Results for Mix Series II.

Concrete Grade C-40										
Mix Desig.	Cube No.	Dimensions (cm)			Weight (g)	Volume (cm^3)	Unit Weight (g/cm^3)	Failure Load (kN)	Actual Comp. Strength (MPa)	Corrected Comp. Strength (MPa)
		L	W	H						
C-2	Cu-5	15.00	15.01	15.16	8339	3413.27	2.443	915.7	40.69	40.27
	Cu-6	15.05	14.98	15.15	8411	3415.55	2.463	943.0	41.91	41.36
	Cu-7	15.04	14.92	15.11	8377	3390.64	2.471	942.6	41.89	41.48
	Mean				8375.67	3406.49	2.459	933.77	41.50	41.03
$C_2V_{0.5}L_2$	Cu-1	15.02	15.19	15.02	8339	3426.87	2.433	922.2	40.99	40.88
	Cu-2	15.02	15.07	14.99	8411	3393.01	2.479	919.1	40.84	40.82
	Cu-3	15.01	15.17	15.05	8377	3426.91	2.444	927.4	41.22	41.05
	Mean				8375.67	3415.60	2.452	922.90	41.02	40.92
$C_2V_{0.5}L_4$	Cu-1	15.00	14.98	15.14	8513	3401.96	2.502	963.3	42.81	42.42
	Cu-7	15.01	15.01	15.24	8618	3433.57	2.510	953.3	42.37	41.67
	Cu-9	15.00	15.00	15.15	8536	3408.75	2.504	919.2	40.85	40.45
	Mean				8555.67	3414.76	2.505	945.27	42.01	41.51
$C_2V_{0.5}L_6$	Cu-1	15.00	14.99	15.13	8496	3401.98	2.497	929.2	41.29	40.94
	Cu-4	15.29	15.25	15.17	8961	3537.23	2.533	976.8	43.41	42.11
	Cu-8	14.99	15.12	15.16	8547	3436.00	2.487	947.4	42.11	41.69
	Mean				8668.00	3458.40	2.506	951.13	42.27	41.58
$C_2V_{1.0}L_2$	Cu-4	15.00	14.98	15.20	8630	3415.44	2.527	946.5	42.07	41.51
	Cu-6	15.05	15.06	15.25	8690	3456.46	2.514	927.3	41.21	40.40
	Cu-7	15.04	15.06	15.19	8630	3440.57	2.508	960.5	42.69	42.04
	Mean				8650.00	3437.49	2.516	944.76	41.99	41.32
$C_2V_{1.0}L_4$	Cu-3	15.02	14.99	15.10	8587	3399.76	2.526	1012.6	45.00	44.65
	Cu-8	15.02	15.05	15.14	8606	3422.41	2.515	979.3	43.52	43.06
	Cu-9	15.01	15.04	15.24	8660	3440.44	2.517	989.6	43.98	43.26
	Mean				8617.67	3420.87	2.519	993.83	44.17	43.66
$C_2V_{1.0}L_6$	Cu-1	14.99	15.00	15.12	8565	3399.73	2.519	918.9	40.83	40.54
	Cu-5	15.01	14.98	15.14	8533	3404.23	2.507	936.5	41.61	41.21
	Cu-8	14.99	14.99	15.13	8518	3399.71	2.506	939.6	41.75	41.43
	Mean				8538.67	3401.22	2.510	931.67	41.40	41.06
$C_2V_{1.5}L_2$	Cu-3	15.03	14.97	15.17	8661	3413.24	2.537	953.7	42.38	41.83
	Cu-6	15.01	15.11	15.19	8679	3445.11	2.519	963.4	42.82	42.25
	Cu-8	15.00	15.06	15.15	8635	3422.39	2.523	937.7	41.67	41.26
	Mean				8658.33	3426.91	2.527	951.59	42.29	41.78
$C_2V_{1.5}L_4$	Cu-1	14.98	15.00	15.09	8693	3390.72	2.564	995.2	44.23	44.03
	Cu-5	15.22	15.26	15.39	9216	3574.44	2.578	995.8	44.26	42.51
	Cu-7	15.26	15.27	15.37	9181	3581.52	2.563	1061.8	47.19	45.27
	Mean				9030.00	3515.56	2.569	1017.60	45.23	43.94
$C_2V_{1.5}L_6$	Cu-2	14.99	14.99	15.30	8712	3437.91	2.534	950.6	42.25	41.45
	Cu-7	15.03	14.99	15.23	8744	3431.31	2.548	962.7	42.78	42.06
	Cu-8	15.02	15.05	15.06	8570	3404.33	2.517	959.1	42.63	42.40
	Mean				8675.33	3424.52	2.533	957.47	42.55	41.97

Table A.G.6 28th Day Compressive Strength Results for Mix Series III.

Concrete Grade C-60										
Mix Desig.	Cube No.	Dimensions (cm)			Weight (g)	Volume (cm^3)	Unit Weight (g/cm^3)	Failure Load (kN)	Actual Comp. Strength (MPa)	Corrected Comp. Strength (MPa)
		L	W	H						
C-3	Cu-1	14.97	14.98	15.14	8507	3395.15	2.506	1342.4	59.66	59.23
	Cu-6	14.99	14.98	15.13	8420	3397.44	2.478	1342.2	59.63	59.18
	Cu-8	15.02	15.06	15.25	8480	3449.57	2.458	1300.9	57.82	56.79
	Mean				8469.00	3414.06	2.481	1328.50	59.04	58.40
$C_3V_{0.5}L_2$	Cu-2	15.20	15.38	15.23	9045	3560.41	2.540	1384.2	61.51	59.79
	Cu-4	15.06	15.13	14.95	8473	3406.47	2.487	1341.2	59.51	59.57
	Cu-8	15.01	15.15	15.05	8528	3422.39	2.492	1300.9	60.36	57.59
	Mean				8682.00	3463.09	2.507	1342.10	60.46	58.98
$C_3V_{0.5}L_4$	Cu-4	14.98	15.10	14.97	8496	3386.18	2.509	1373.5	61.04	61.25
	Cu-6	14.92	15.21	15.02	8479	3408.54	2.488	1353.4	60.15	60.39
	Cu-9	15.10	15.22	15.03	8577	3454.22	2.483	1355.3	60.23	59.72
	Mean				8517.33	3416.32	2.493	1360.73	60.47	60.45
$C_3V_{0.5}L_6$	Cu-7	15.00	15.05	15.02	8510	3390.77	2.510	1261.3	56.05	55.98
	Cu-8	15.02	15.24	14.99	8560	3431.28	2.495	1279.9	56.88	56.85
	Cu-9	15.09	15.23	15.02	8515	3451.91	2.467	1267.7	56.33	55.93
	Mean				8528.33	3424.65	2.490	1269.63	56.42	56.25
$C_3V_{1.0}L_2$	Cu-3	14.99	15.12	14.98	8557	3395.20	2.520	1400.9	62.26	62.39
	Cu-4	15.00	15.40	15.05	9152	3476.55	2.632	1311.3	58.28	58.09
	Cu-7	15.00	15.21	14.93	8673	3406.28	2.546	1371.0	60.93	61.22
	Mean				8794.00	3426.01	2.566	1361.07	60.49	60.56
$C_3V_{1.0}L_4$	Cu-4	14.99	15.21	15.14	8825	3451.89	2.557	1358.0	60.35	59.84
	Cu-5	15.02	15.43	15.08	9145	3494.92	2.617	1348.6	59.94	59.54
	Cu-8	15.02	15.25	15.02	8670	3440.41	2.520	1402.9	59.89	62.19
	Mean				8880.00	3462.40	2.564	1369.83	60.06	60.52
$C_3V_{1.0}L_6$	Cu-4	15.01	14.99	15.08	8638	3393.00	2.546	1332.4	59.20	58.86
	Cu-5	15.04	15.13	15.06	8545	3426.98	2.493	1348.6	59.93	59.54
	Cu-7	15.28	15.40	15.28	8565	3595.57	2.382	1402.9	62.35	60.09
	Mean				8582.67	3471.85	2.474	1361.30	60.49	59.50
$C_3V_{1.5}L_2$	Cu-3	14.98	15.11	14.97	8705	3388.43	2.569	1381.4	61.40	61.60
	Cu-6	15.05	15.13	15.01	8685	3417.87	2.541	1423.6	63.27	63.02
	Cu-8	15.01	15.06	15.02	8679	3395.28	2.556	1411.6	62.74	62.61
	Mean				8689.67	3400.53	2.555	1405.53	62.47	62.41
$C_3V_{1.5}L_4$	Cu-1	15.00	15.18	15.00	8748	3415.50	2.561	1314.7	58.43	58.43
	Cu-2	14.98	15.17	14.99	8698	3406.43	2.553	1326.4	58.95	59.07
	Cu-8	15.00	15.22	14.92	8764	3406.24	2.573	1342.9	59.18	60.00
	Mean				8736.67	3409.39	2.563	1328.00	58.85	59.17
$C_3V_{1.5}L_6$	Cu-1	14.98	15.27	15.01	8742	3433.46	2.546	1358.9	60.39	60.44
	Cu-6	14.97	15.23	15.04	8612	3429.02	2.512	1373.2	61.03	60.99
	Cu-9	14.98	15.17	14.96	8601	3399.61	2.530	1381.2	61.39	61.63
	Mean				8651.67	3420.69	2.529	1371.10	60.94	61.02

Table A.G.7 56th Day Compressive Strength Results for Mix Series I.

Concrete Grade C-25										
Mix Desig.	Cube No.	Dimensions (cm)			Weight (g)	Volume (cm^3)	Unit Weight (g/cm^3)	Failure Load (kN)	Actual Comp. Strength (MPa)	Corrected Comp. Strength (MPa)
		L	W	H						
C-1	Cu-1	14.98	15.01	15.30	8330	3440.20	2.421	757.7	33.67	33.06
	Cu-2	15.07	15.01	15.43	8243	3490.28	2.362	777.0	34.53	33.42
	Cu-3	15.00	15.00	15.49	8289	3485.25	2.378	765.5	34.02	32.95
	Mean				8287.33	3471.91	2.387	766.73	34.07	33.14
$C_1V_{0.5}L_2$	Cu-1	14.99	15.20	15.10	8429	3440.50	2.450	713.7	31.72	31.53
	Cu-2	14.97	15.09	14.99	8402	3386.20	2.481	750.7	33.36	33.45
	Cu-3	14.97	15.10	15.00	8355	3390.71	2.464	751.1	33.38	33.45
	Mean				8395.33	3405.80	2.465	738.50	32.82	32.81
$C_1V_{0.5}L_4$	Cu-7	15.02	14.95	15.17	8450	3406.41	2.481	787.9	35.02	34.58
	Cu-8	15.04	15.13	15.28	8524	3477.04	2.452	806.0	35.82	35.07
	Cu-9	15.03	14.98	15.21	8415	3424.52	2.457	798.4	35.48	34.92
	Mean				8463.00	3435.99	2.463	797.43	35.44	34.86
$C_1V_{0.5}L_6$	Cu-1	14.81	15.09	15.33	8470	3425.99	2.472	799.0	35.53	35.19
	Cu-2	14.93	15.05	15.23	8406	3422.13	2.456	794.9	33.33	34.96
	Cu-3	14.99	15.00	15.12	83.69	3399.73	0.025	788.0	35.02	34.77
	Mean				5653.23	3415.95	1.651	793.97	34.63	34.97
$C_1V_{1.0}L_2$	Cu-5	15.31	15.30	15.07	8997	3530.04	2.549	751.1	33.38	32.55
	Cu-6	15.10	15.09	15.09	8527	3438.39	2.480	727.4	32.32	31.92
	Cu-9	15.02	15.09	15.02	8440	3404.31	2.479	757.2	33.65	33.56
	Mean				8654.67	3457.58	2.503	745.23	33.12	32.68
$C_1V_{1.0}L_4$	Cu-2	14.98	15.18	14.99	8515	3408.67	2.498	735.6	32.69	32.76
	Cu-3	14.98	15.14	14.96	8489	3392.89	2.502	739.4	32.86	32.99
	Cu-6	14.99	15.25	15.00	8573	3428.96	2.500	738.7	32.82	32.85
	Mean				8525.67	3410.17	2.500	737.90	32.79	32.87
$C_1V_{1.0}L_6$	Cu-2	15.03	15.17	15.00	8403	3420.08	2.457	740.4	32.90	32.84
	Cu-4	14.97	15.04	15.00	8404	3377.23	2.488	746.0	33.15	33.22
	Cu-9	14.99	15.27	14.95	8553	3422.01	2.499	743.3	33.03	33.17
	Mean				8453.33	3406.44	2.482	743.23	33.03	33.08
$C_1V_{1.5}L_2$	Cu-7	14.95	14.99	15.19	8626	3404.09	2.534	771.1	34.26	33.96
	Cu-8	15.00	15.01	15.15	8657	3411.02	2.538	794.1	35.29	34.94
	Cu-9	15.06	15.04	15.20	8677	3442.84	2.520	798.8	35.50	34.90
	Mean				8653.33	3419.32	2.531	788.00	35.02	34.60
$C_1V_{1.5}L_4$	Cu-5	15.04	15.02	15.09	8472	3408.84	2.485	862.2	38.32	37.99
	Cu-6	14.99	14.99	15.13	8506	3399.71	2.502	848.8	37.72	37.43
	Cu-7	15.06	15.13	15.03	8637	3424.70	2.522	865.9	38.48	38.25
	Mean				8538.33	3411.09	2.503	858.97	38.17	37.89
$C_1V_{1.5}L_6$	Cu-2	15.30	15.50	15.13	9081	3588.08	2.531	768.9	34.17	33.22
	Cu-4	15.32	15.50	15.10	9060	3585.65	2.527	757.7	33.68	32.75
	Cu-5	15.00	15.20	14.90	8545	3397.20	2.515	758.4	33.71	33.93
	Mean				8895.33	3523.64	2.524	761.67	33.85	33.30

Table A.G.8 56th Day Compressive Strength Results for Mix Series II.

Concrete Grade C-40										
Mix Desig.	Cube No.	Dimensions (cm)			Weight (g)	Volume (cm^3)	Unit Weight (g/cm^3)	Failure Load (kN)	Actual Comp. Strength (MPa)	Corrected Comp. Strength (MPa)
		L	W	H						
C-2	Cu-2	15.03	15.08	15.14	8482	3431.52	2.472	1062.9	47.14	46.71
	Cu-4	14.99	14.98	15.09	8333	3388.46	2.459	1060.3	47.12	46.87
	Cu-8	15.00	14.95	15.22	8467	3413.09	2.481	1075.0	47.78	47.09
	Mean				8427.33	3411.02	2.471	1066.07	47.35	46.89
$C_2V_{0.5}L_2$	Cu-6	15.02	14.84	15.08	8450	3361.28	2.514	1097.8	40.99	48.47
	Cu-8	15.00	15.00	15.09	8502	3395.25	2.504	1101.9	40.84	48.68
	Cu-9	15.02	15.05	15.07	8486	3406.59	2.491	1072.4	41.22	47.38
	Mean				8479.33	3387.71	2.503	1090.70	41.02	48.18
$C_2V_{0.5}L_4$	Cu-2	14.99	15.00	15.11	8498	3397.48	2.501	1055.1	42.81	46.58
	Cu-4	14.98	15.10	14.97	8524	3386.18	2.517	1086.9	42.37	48.47
	Cu-5	15.01	15.15	15.09	8513	3431.49	2.481	1044.1	40.85	46.10
	Mean				8511.67	3405.05	2.500	1062.03	42.01	47.05
$C_2V_{0.5}L_6$	Cu-5	15.33	15.30	15.45	9090	3623.78	2.508	1098.5	41.29	46.38
	Cu-6	15.01	14.99	15.17	8536	3413.25	2.501	1109.7	43.41	48.73
	Cu-7	15.04	14.99	15.07	8541	3397.53	2.514	1102.4	42.11	48.64
	Mean				8722.33	3478.19	2.508	1103.53	42.27	47.92
$C_2V_{1.0}L_2$	Cu-5	15.00	15.02	15.15	8545	3413.30	2.503	1069.8	47.54	47.08
	Cu-8	15.03	15.09	15.18	8702	3442.86	2.528	1094.1	48.62	47.95
	Cu-9	15.01	14.92	15.21	8077	3406.27	2.371	1080.2	48.01	47.31
	Mean				8441.33	3420.81	2.467	1081.37	48.06	47.45
$C_2V_{1.0}L_4$	Cu-1	14.96	15.18	15.22	8639	3456.35	2.499	1137.9	50.57	49.98
	Cu-4	15.03	14.98	15.15	8614	3411.01	2.525	1127.8	50.12	49.53
	Cu-6	15.01	15.03	15.13	8687	3413.33	2.545	1098.1	48.81	48.35
	Mean				8646.67	3426.90	2.523	1121.27	49.83	49.29
$C_2V_{1.0}L_6$	Cu-4	15.00	15.00	15.20	8598	3420.00	2.514	1085.7	48.25	47.62
	Cu-6	14.90	15.05	15.30	8500	3430.95	2.477	1101.6	48.96	48.32
	Cu-9	15.00	15.10	15.20	8573	3442.80	2.490	1056.6	46.96	46.34
	Mean				8557.00	3431.25	2.494	1081.30	48.06	47.43
$C_2V_{1.5}L_2$	Cu-2	14.98	14.98	15.13	8652	3395.18	2.548	1089.9	48.43	48.09
	Cu-5	15.29	15.24	15.37	9225	3581.51	2.576	1141.7	50.74	48.58
	Cu-7	15.00	15.03	15.19	8715	3424.59	2.545	1079.5	47.98	47.38
	Mean				8864.00	3467.09	2.556	1103.70	49.05	48.02
$C_2V_{1.5}L_4$	Cu-4	15.00	15.01	15.06	8650	3390.76	2.551	1164.6	51.76	51.55
	Cu-8	14.99	15.01	15.15	8673	3408.75	2.544	1142.8	50.79	50.32
	Cu-9	15.06	15.15	15.14	8764	3454.33	2.537	1161.3	51.60	50.93
	Mean				8695.67	3417.94	2.544	1156.23	51.38	50.94
$C_2V_{1.5}L_6$	Cu-4	15.00	15.00	15.40	8674	3465.00	2.503	1126.1	50.04	48.75
	Cu-6	15.10	15.07	15.20	8739	3458.87	2.527	1122.7	49.89	48.92
	Cu-9	15.10	14.90	15.10	8538	3397.35	2.513	1135.3	50.46	49.79
	Mean				8650.33	3440.41	2.514	1128.03	50.13	49.15

Table A.G.9 56th Day Compressive Strength Results for Mix Series III.

Concrete Grade C-60										
Mix Desig.	Cube No.	Dimensions (cm)			Weight (g)	Volume (cm^3)	Unit Weight (g/cm^3)	Failure Load (kN)	Actual Comp. Strength (MPa)	Corrected Comp. Strength (MPa)
		L	W	H						
C-3	Cu-2	14.98	14.98	15.20	8398	3410.89	2.462	1520.0	67.50	66.76
	Cu-4	14.96	14.98	15.14	8404	3392.89	2.477	1476.0	65.60	65.17
	Cu-7	15.01	14.99	15.27	8430	3435.75	2.454	1492.0	66.32	65.10
	Mean				8410.67	3413.17	2.464	1496.00	66.47	65.67
$C_3V_{0.5}L_2$	Cu-1	14.98	15.17	15.04	8476	3417.79	2.480	1481.7	65.83	65.77
	Cu-7	14.98	15.07	15.00	8489	3386.23	2.507	1503.1	66.68	66.89
	Cu-9	15.07	15.14	15.02	8522	3426.96	2.487	1495.1	66.45	66.05
	Mean				8495.67	3410.33	2.491	1493.30	66.32	66.24
$C_3V_{0.5}L_4$	Cu-2	14.97	15.21	14.99	8543	3413.13	2.503	1448.5	64.36	64.55
	Cu-3	14.99	15.23	15.00	8513	3424.47	2.486	1459.3	64.86	64.90
	Cu-5	15.04	15.16	14.98	8523	3415.54	2.495	1495.9	66.48	66.40
	Mean				8526.33	3417.71	2.495	1467.90	65.23	65.28
$C_3V_{0.5}L_6$	Cu-2	14.98	15.24	15.01	8524	3426.71	2.488	1492.8	56.05	66.39
	Cu-3	14.97	15.33	15.06	8521	3456.12	2.465	1481.0	56.88	65.69
	Cu-4	15.01	15.45	15.31	9103	3550.46	2.564	1478.2	56.33	64.32
	Mean				8716.00	3477.76	2.506	1484.00	56.42	65.47
$C_3V_{1.0}L_2$	Cu-2	15.26	15.30	15.23	9129	3555.87	2.567	1506.1	62.26	64.80
	Cu-6	15.05	15.12	15.02	8440	3417.89	2.469	1537.7	58.28	68.02
	Cu-8	15.04	15.12	15.08	8567	3429.26	2.498	1540.4	60.93	67.92
	Mean				8712.00	3467.68	2.512	1528.07	60.49	66.92
$C_3V_{1.0}L_4$	Cu-1	14.98	15.08	15.20	8625	3433.66	2.512	1526.1	67.62	67.02
	Cu-6	15.02	15.15	15.22	8735	3463.36	2.522	1520.3	67.30	66.50
	Cu-7	14.99	15.01	15.18	8668	3415.50	2.538	1567.4	69.65	68.88
	Mean				8676.00	3437.50	2.524	1537.93	68.19	67.47
$C_3V_{1.0}L_6$	Cu-2	15.03	15.06	15.15	8615	3429.23	2.512	1556.9	69.20	68.37
	Cu-8	15.00	15.10	15.17	8638	3436.01	2.514	1598.1	71.02	70.23
	Cu-9	15.05	14.96	15.06	8525	3390.73	2.514	1561.6	69.40	68.90
	Mean				8592.67	3418.65	2.513	1572.20	69.87	69.17
$C_3V_{1.5}L_2$	Cu-4	14.97	15.04	15.15	8737	3411.00	2.561	1554.1	69.06	68.52
	Cu-7	15.01	15.26	15.01	8759	3438.08	2.548	1494.8	66.43	66.35
	Cu-9	14.91	15.27	15.01	8648	3417.41	2.531	1516.2	67.24	67.75
	Mean				8714.67	3422.17	2.547	1521.70	67.58	67.54
$C_3V_{1.5}L_4$	Cu-3	15.05	15.29	15.00	8783	3451.72	2.545	1485.7	66.03	65.81
	Cu-4	14.97	15.29	14.98	8735	3428.79	2.548	1485.3	66.01	66.23
	Cu-5	14.98	15.22	15.23	8770	3472.37	2.526	1497.6	66.56	65.64
	Mean				8762.67	3450.96	2.539	1489.53	66.20	65.90
$C_3V_{1.5}L_6$	Cu-2	15.29	15.54	15.38	9398	3654.39	2.572	1513.5	66.66	64.36
	Cu-3	15.00	15.33	14.98	8858	3444.65	2.572	1549.8	68.88	68.97
	Cu-8	15.12	15.43	15.07	8780	3515.86	2.497	1543.7	68.60	67.75
	Mean				9012.00	3538.30	2.547	1535.67	68.05	67.03

ANNEX H

FLEXURAL TENSILE STRENGTH TEST RESULTS

Table A.H.1 28th Day Flexural Tensile Strength Results for Mix Series I.

Concrete Grade C-25										
Mix Desig.	**Beam No.**	**Dimensions (cm)**			**P (kN)**	**M (N.m)**	**I (m^4)**	**C (mm)**	**σ (MPa)**	**σ Gain (%)**
		L	**W**	**H**						
C_1	B-1	30.00	10.00	10.00	10.8	108.00	833.33	50.0	6.48	
	B-2	30.00	10.00	10.00	9.8	98.00	833.33	50.0	5.88	
	Mean				**10.30**	**103.00**	**833.33**	**50.00**	**6.18**	
$C_1V_{0.5}L_2$	B-1	30.00	10.00	10.00	11.9	119.00	833.33	50.0	7.14	**10.68**
	B-2	30.00	10.00	10.00	10.9	109.00	833.33	50.0	6.54	
	Mean				**11.40**	**114.00**	**833.33**	**50.00**	**6.84**	
$C_1V_{0.5}L_4$	B-1	30.00	10.00	10.00	11.9	119.00	833.33	50.0	7.14	**12.62**
	B-2	30.00	10.00	10.00	11.3	113.00	833.33	50.0	6.78	
	Mean				**11.60**	**116.00**	**833.33**	**50.00**	**6.96**	
$C_1V_{0.5}L_6$	B-1	30.00	10.00	10.00	15.5	155.00	833.33	50.0	9.30	**32.52**
	B-2	30.00	10.00	10.00	11.8	118.00	833.33	50.0	7.08	
	Mean				**13.65**	**136.50**	**833.33**	**50.00**	**8.19**	
$C_1V_{1.0}L_2$	B-1	30.00	10.00	10.00	12.1	121.00	833.33	50.0	7.26	**16.02**
	B-2	30.00	10.00	10.00	11.8	118.00	833.33	50.0	7.08	
	Mean				**11.95**	**119.50**	**833.33**	**50.00**	**7.17**	
$C_1V_{1.0}L_4$	B-1	30.00	10.00	10.00	13.6	136.00	833.33	50.0	8.16	**27.67**
	B-2	30.00	10.00	10.00	12.7	127.00	833.33	50.0	7.62	
	Mean				**13.15**	**131.50**	**833.33**	**50.00**	**7.89**	
$C_1V_{1.0}L_6$	B-1	30.00	10.00	10.00	14.9	149.00	833.33	50.0	8.94	**63.11**
	B-2	30.00	10.00	10.00	18.7	187.00	833.33	50.0	11.22	
	Mean				**16.80**	**168.00**	**833.33**	**50.00**	**10.08**	
$C_1V_{1.5}L_2$	B-1	30.00	10.00	10.00	14.3	143.00	833.33	50.0	8.58	**30.58**
	B-2	30.00	10.00	10.00	12.6	126.00	833.33	50.0	7.56	
	Mean				**13.45**	**134.50**	**833.33**	**50.00**	**8.07**	
$C_1V_{1.5}L_4$	B-1	30.00	10.00	10.00	14.9	149.00	833.33	50.0	8.94	**39.81**
	B-2	30.00	10.00	10.00	13.9	139.00	833.33	50.0	8.34	
	Mean				**14.40**	**144.00**	**833.33**	**50.00**	**8.64**	
$C_1V_{1.5}L_6$	B-1	30.00	10.00	10.00	22	220.00	833.33	50.0	13.20	**121.84**
	B-2	30.00	10.00	10.00	23.7	237.00	833.33	50.0	14.22	
	Mean				**22.85**	**228.50**	**833.33**	**50.00**	**13.71**	

Table A.H.2 28th Day Flexural Tensile Strength Results for Mix Series II.

Concrete Grade C-40										
Mix Desig.	**Beam No.**	**Dimensions (cm)**			**P (kN)**	**M (N.m)**	**I (m^4)**	**C (mm)**	**σ (MPa)**	**σ Gain (%)**
		L	**W**	**H**						
C_2	B-1	30.00	10.00	10.00	12.9	129.00	833.33	50.0	7.74	
	B-2	30.00	10.00	10.00	13.5	135.00	833.33	50.0	8.10	
	Mean				**13.20**	**132.00**	**833.33**	**50.00**	**7.92**	
$C_2V_{0.5}L_2$	B-1	30.00	10.00	10.00	14.4	144.00	833.33	50.0	8.64	**5.30**
	B-2	30.00	10.00	10.00	13.4	134.00	833.33	50.0	8.04	
	Mean				**13.90**	**139.00**	**833.33**	**50.00**	**8.34**	
$C_2V_{0.5}L_4$	B-1	30.00	10.00	10.00	13.7	137.00	833.33	50.0	8.22	**9.09**
	B-2	30.00	10.00	10.00	15.1	151.00	833.33	50.0	9.06	
	Mean				**14.40**	**144.00**	**833.33**	**50.00**	**8.64**	
$C_2V_{0.5}L_6$	B-1	30.00	10.00	10.00	16.3	163.00	833.33	50.0	9.78	**16.67**
	B-2	30.00	10.00	10.00	14.5	145.00	833.33	50.0	8.70	
	Mean				**15.40**	**154.00**	**833.33**	**50.00**	**9.24**	
$C_2V_{1.0}L_2$	B-1	30.00	10.00	10.00	13.9	139.00	833.33	50.0	8.34	**6.82**
	B-2	30.00	10.00	10.00	14.3	143.00	833.33	50.0	8.58	
	Mean				**14.10**	**141.00**	**833.33**	**50.00**	**8.46**	
$C_2V_{1.0}L_4$	B-1	30.00	10.00	10.00	16.9	169.00	833.33	50.0	10.14	**21.21**
	B-2	30.00	10.00	10.00	15.1	151.00	833.33	50.0	9.06	
	Mean				**16.00**	**160.00**	**833.33**	**50.00**	**9.60**	
$C_2V_{1.0}L_6$	B-1	30.00	10.00	10.00	23.3	233.00	833.33	50.0	13.98	**58.71**
	B-2	30.00	10.00	10.00	18.6	186.00	833.33	50.0	11.16	
	Mean				**20.95**	**209.50**	**833.33**	**50.00**	**12.57**	
$C_2V_{1.5}L_2$	B-1	30.00	10.00	10.00	14.7	147.00	833.33	50.0	8.82	**9.85**
	B-2	30.00	10.00	10.00	14.3	143.00	833.33	50.0	8.58	
	Mean				**14.50**	**145.00**	**833.33**	**50.00**	**8.70**	
$C_2V_{1.5}L_4$	B-1	30.00	10.00	10.00	19.1	191.00	833.33	50.0	11.46	**40.15**
	B-2	30.00	10.00	10.00	17.9	179.00	833.33	50.0	10.74	
	Mean				**18.50**	**185.00**	**833.33**	**50.00**	**11.10**	
$C_2V_{1.5}L_6$	B-1	30.00	10.00	10.00	24.6	246.00	833.33	50.0	14.76	**86.74**
	B-2	30.00	10.00	10.00	24.7	247.00	833.33	50.0	14.82	
	Mean				**24.65**	**246.50**	**833.33**	**50.00**	**14.79**	

Table A.H.3 28th Day Flexural Tensile Strength Results for Mix Series III.

Concrete Grade C-60										
Mix Desig.	**Beam No.**	**Dimensions (cm)**			**P (kN)**	**M (N.m)**	**I (m^4)**	**C (mm)**	**σ (MPa)**	**σ Gain (%)**
		L	**W**	**H**						
C_3	B-1	30.00	10.00	10.00	14.7	147.00	833.33	50.0	8.82	
	B-2	30.00	10.00	10.00	14.4	144.00	833.33	50.0	8.64	
	Mean				**14.55**	**145.50**	**833.33**	**50.00**	**8.73**	
$C_3V_{0.5}L_2$	B-1	30.00	10.00	10.00	14.9	149.00	833.33	50.0	8.94	**1.37**
	B-2	30.00	10.00	10.00	14.6	146.00	833.33	50.0	8.76	
	Mean				**14.75**	**147.50**	**833.33**	**50.00**	**8.85**	
$C_3V_{0.5}L_4$	B-1	30.00	10.00	10.00	14.9	149.00	833.33	50.0	8.94	**4.12**
	B-2	30.00	10.00	10.00	15.4	154.00	833.33	50.0	9.24	
	Mean				**15.15**	**151.50**	**833.33**	**50.00**	**9.09**	
$C_3V_{0.5}L_6$	B-1	30.00	10.00	10.00	16.3	163.00	833.33	50.0	9.78	**5.50**
	B-2	30.00	10.00	10.00	14.4	144.00	833.33	50.0	8.64	
	Mean				**15.35**	**153.50**	**833.33**	**50.00**	**9.21**	
$C_3V_{1.0}L_2$	B-1	30.00	10.00	10.00	15.7	157.00	833.33	50.0	9.42	**6.53**
	B-2	30.00	10.00	10.00	15.3	153.00	833.33	50.0	9.18	
	Mean				**15.50**	**155.00**	**833.33**	**50.00**	**9.30**	
$C_3V_{1.0}L_4$	B-1	30.00	10.00	10.00	18.8	188.00	833.33	50.0	11.28	**37.46**
	B-2	30.00	10.00	10.00	21.2	212.00	833.33	50.0	12.72	
	Mean				**20.00**	**200.00**	**833.33**	**50.00**	**12.00**	
$C_3V_{1.0}L_6$	B-1	30.00	10.00	10.00	21.8	218.00	833.33	50.0	13.08	**47.08**
	B-2	30.00	10.00	10.00	21	210.00	833.33	50.0	12.60	
	Mean				**21.40**	**214.00**	**833.33**	**50.00**	**12.84**	
$C_3V_{1.5}L_2$	B-1	30.00	10.00	10.00	19.2	192.00	833.33	50.0	11.52	**30.24**
	B-2	30.00	10.00	10.00	18.7	187.00	833.33	50.0	11.22	
	Mean				**18.95**	**189.50**	**833.33**	**50.00**	**11.37**	
$C_3V_{1.5}L_4$	B-1	30.00	10.00	10.00	26.3	263.00	833.33	50.0	15.78	**54.98**
	B-2	30.00	10.00	10.00	18.8	188.00	833.33	50.0	11.28	
	Mean				**22.55**	**225.50**	**833.33**	**50.00**	**13.53**	
$C_3V_{1.5}L_6$	B-1	30.00	10.00	10.00	23.8	238.00	833.33	50.0	14.28	**84.88**
	B-2	30.00	10.00	10.00	30.0	300.00	833.33	50.0	18.00	
	Mean				**26.90**	**269.00**	**833.33**	**50.00**	**16.14**	

ANNEX I

IMPACT TEST RESULTS

Table A.I.3 Impact Test Results for Mix Series I.

Concrete Grade C-25							
Mix Desig.	**Sample No.**	**Sample Height (mm)**	**Standard Deviation**	**First Crack No. Of blows**	**Standard Deviation**	**Ultimate Failure No. Of blows**	**Standard Deviation**
C_1	1	62.28	1.07	44	2.50	46	2.63
	2	63.68		39		45	
	3	64.50		39		41	
	4	64.60		39		41	
	Mean	63.77		40		43	
$C_1V_{0.5}L_2$	1	64.00	0.58	40	23.73	51	25.86
	2	64.00		87		101	
	3	63.00		71		86	
	4	63.00		39		49	
	Mean	63.50		59		72	
$C_1V_{0.5}L_4$	1	65.00	1.34	111	40.09	136	48.53
	2	64.45		199		242	
	3	64.41		165		194	
	4	62.00		124		147	
	Mean	63.97		150		180	
$C_1V_{0.5}L_6$	1	62.56	1.08	77	48.32	106	63.55
	2	63.30		110		145	
	3	63.77		144		169	
	4	61.30		190		256	
	Mean	62.73		130		169	
$C_1V_{1.0}L_2$	1	64.00	0.48	45	21.79	57	23.13
	2	64.20		66		83	
	3	65.00		97		112	
	4	64.00		78		95	
	Mean	64.30		72		87	
$C_1V_{1.0}L_4$	1	64.00	0.62	167	56.42	194	55.72
	2	63.00		195		224	
	3	64.50		296		322	
	4	63.80		198		225	
	Mean	63.83		214		241	
$C_1V_{1.0}L_6$	1	63.40	1.20	139	38.06	197	42.15
	2	64.70		74		109	
	3	66.00		128		179	
	4	63.60		63		125	
	Mean	64.43		101		153	
$C_1V_{1.5}L_2$	1	63.16	0.82	43	25.75	56	29.71
	2	65.00		64		75	
	3	63.50		70		112	
	4	63.50		105		118	
	Mean	63.79		71		90	
$C_1V_{1.5}L_4$	1	62.50	1.86	364	126.41	467	111.29
	2	66.00		623		698	
	3	62.70		420		481	
	4	65.60		589		618	
	Mean	64.20		499		566	
$C_1V_{1.5}L_6$	1	63.70	0.61	1131	111.36	1342	131.65
	2	65.13		1357		1593	
	3	64.80		1240		1483	
	4	64.53		1118		1308	
	Mean	64.54		1212		1432	

Table A.I.3 Impact Test Results for Mix Series II.

Concrete Grade C-40							
Mix Desig.	**Sample No.**	**Sample Height (mm)**	**Standard Deviation**	**First Crack No. Of blows**	**Standard Deviation**	**Ultimate Failure No. Of blows**	**Standard Deviation**
C_1	1	62.28	1.07	44	2.50	46	2.63
	2	63.68		39		45	
	3	64.50		39		41	
	4	64.60		39		41	
	Mean	**63.77**		**40**		**43**	
$C_1V_{0.5}L_2$	1	64.00	0.58	40	23.73	51	25.86
	2	64.00		87		101	
	3	63.00		71		86	
	4	63.00		39		49	
	Mean	**63.50**		**59**		**72**	
$C_1V_{0.5}L_4$	1	65.00	1.34	111	40.09	136	48.53
	2	64.45		199		242	
	3	64.41		165		194	
	4	62.00		124		147	
	Mean	**63.97**		**150**		**180**	
$C_1V_{0.5}L_6$	1	62.56	1.08	77	48.32	106	63.55
	2	63.30		110		145	
	3	63.77		144		169	
	4	61.30		190		256	
	Mean	**62.73**		**130**		**169**	
$C_1V_{1.0}L_2$	1	64.00	0.48	45	21.79	57	23.13
	2	64.20		66		83	
	3	65.00		97		112	
	4	64.00		78		95	
	Mean	**64.30**		**72**		**87**	
$C_1V_{1.0}L_4$	1	64.00	0.62	167	56.42	194	55.72
	2	63.00		195		224	
	3	64.50		296		322	
	4	63.80		198		225	
	Mean	**63.83**		**214**		**241**	
$C_1V_{1.0}L_6$	1	63.40	1.20	139	38.06	197	42.15
	2	64.70		74		109	
	3	66.00		128		179	
	4	63.60		63		125	
	Mean	**64.43**		**101**		**153**	
$C_1V_{1.5}L_2$	1	63.16	0.82	43	25.75	56	29.71
	2	65.00		64		75	
	3	63.50		70		112	
	4	63.50		105		118	
	Mean	**63.79**		**71**		**90**	
$C_1V_{1.5}L_4$	1	62.50	1.86	364	126.41	467	111.29
	2	66.00		623		698	
	3	62.70		420		481	
	4	65.60		589		618	
	Mean	**64.20**		**499**		**566**	
$C_1V_{1.5}L_6$	1	63.70	0.61	1131	111.36	1342	131.65
	2	65.13		1357		1593	
	3	64.80		1240		1483	
	4	64.53		1118		1308	
	Mean	**64.54**		**1212**		**1432**	

Table A.I.3 Impact Test Results for Mix Series III.

Concrete Grade C-60							
Mix Desig.	**Sample No.**	**Sample Height (mm)**	**Standard Deviation**	**First Crack No. Of blows**	**Standard Deviation**	**Ultimate Failure No. Of blows**	**Standard Deviation**
C_3	1	61.80	1.50	107	15.10	110	15.04
	2	64.20		143		146	
	3	64.80		123		127	
	4	65.10		131		134	
	Mean	**63.98**		**126**		**129**	
$C_3V_{0.5}L_2$	1	65.70	0.53	159	59.34	170	63.73
	2	66.00		217		234	
	3	64.80		207		220	
	4	65.80		87		93	
	Mean	**65.58**		**168**		**179**	
$C_3V_{0.5}L_4$	1	65.05	1.01	400	44.55	452	80.96
	2	65.91		327		291	
	3	63.52		337		378	
	4	65.21		416		468	
	Mean	**64.92**		**370**		**397**	
$C_3V_{0.5}L_6$	1	64.29	0.83	193	215.01	219	221.21
	2	65.03		531		587	
	3	63.23		216		231	
	4	64.94		613		627	
	Mean	**64.37**		**388**		**416**	
$C_3V_{1.0}L_2$	1	63.70	0.93	189	49.97	204	48.79
	2	65.80		164		181	
	3	65.40		163		183	
	4	65.30		75		94	
	Mean	**65.05**		**148**		**166**	
$C_3V_{1.0}L_4$	1	62.94	0.98	539	142.02	591	142.46
	2	64.08		620		712	
	3	64.21		400		498	
	4	65.34		738		825	
	Mean	**64.14**		**574**		**657**	
$C_3V_{1.0}L_6$	1	64.78	0.45	634	80.16	774	131.29
	2	65.54		651		942	
	3	65.24		729		1003	
	4	65.83		534		729	
	Mean	**65.35**		**637**		**862**	
$C_3V_{1.5}L_2$	1	60.50	2.46	116	92.05	137	90.36
	2	64.80		143		169	
	3	65.30		322		342	
	4	65.90		172		201	
	Mean	**64.13**		**188**		**212**	
$C_3V_{1.5}L_4$	1	63.74	0.95	674	253.31	738	262.26
	2	66.02		1041		1190	
	3	65.20		813		971	
	4	64.81		1249		1339	
	Mean	**64.94**		**944**		**1060**	
$C_3V_{1.5}L_6$	1	64.07	0.57	1326	158.91	1471	150.42
	2	63.71		943		1213	
	3	63.41		1079		1124	
	4	62.73		1138		1207	
	Mean	**63.48**		**1122**		**1254**	

ANNEX J

PHOTGRAPHIC PRESENTATION

Fig. A.J-1 Defective Bead Wires to be Burn

Fig. A.J-2 Extracted Steel Fibers

Fig. A.J-3 Steel Fiber Ready to be Weighed

Fig. A.J-4 Weighing the Steel Fiber

Fig. A.J-5 Steel fibers ready to be cut

Fig. A.J-6 Cutting the Steel Fiber

Fig. A.J-7 Cutting the Steel Fiber

Fig. A.J-8 Cutting the Steel Fiber

Fig. A.J-9 Steel fiber ready for the mix

Fig. A.J-10 Steel fiber ready for the Mix

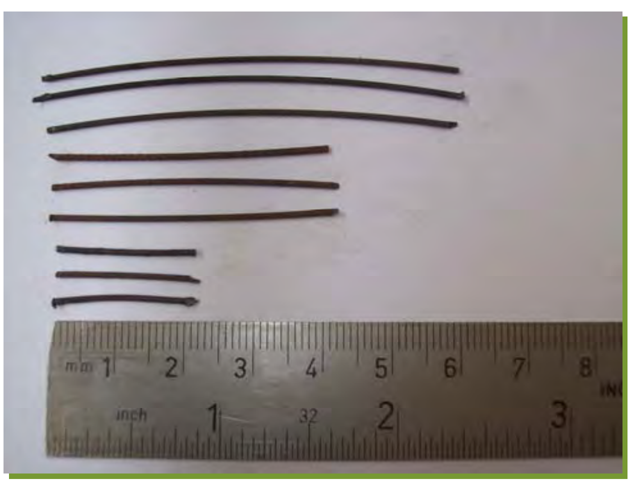

Fig. A.J-11 Steel fiber of different length

Fig. A.J-12 Test machine for tensile strength of steel fibers

Fig. A.J-13 Washing the Coarse Aggregate

Fig. A.J-14 Washing the Fine Aggregate

Fig. A.J-15 Drying the Aggregates

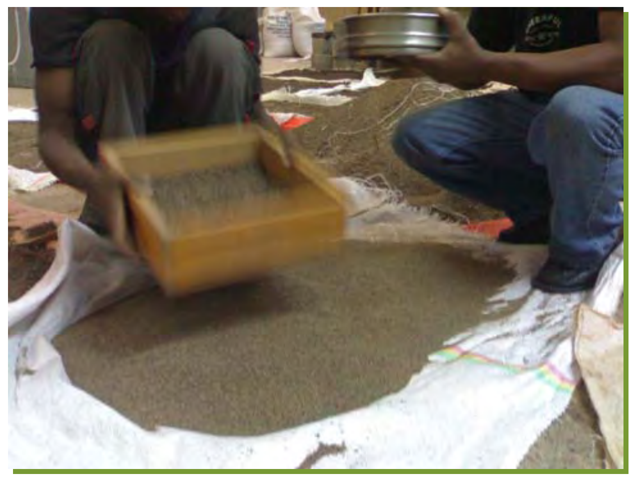

Fig. A.J-16 Sieving the Fine Aggregate

Fig. A.J-17 Water Adjustment for Coarse Agg.

Fig. A.J-18 Bringing the Aggregates to SSD

Fig. A.J-19 Bringing the Aggregates to SSD

Fig. A.J-20 Dry Mixing

Fig. A.J-21 Cleaning Beam Mould

Fig. A.J-22 Assembling Beam Mould

Fig. A.J-23 Oiling cube moulds

Fig. A.J-24 Weighing cube mould

Fig. A.J-25 SFRC Ready to be Casted

Fig. A.J-26 SFRC Ready to be Casted

Fig. A.J-27 Distribution of Fibers in SFRC

Fig. A.J-28 Preparing the Slump

Fig. A.J-29 Slump for Plain Concrete

Fig. A.J-30 Slump for SFRC

Fig. A.J-31 Casting Cube Samples

Fig. A.J-32 Casting a Beam Sample

Fig. A.J-33 Steel Fibers in the Beam Mould

Fig. A.J-34 Casting a Cylinder Sample

Fig. A.J-35 Trimming a Beam Sample

Fig. A.J-36 Casted Samples after Trimming

Fig. A.J-37 Casted Samples

Fig. A.J-38 Samples Ready to be Cured

Fig. A.J-39 Curing the Samples

Fig. A.J-40 Curing the Samples

Fig. A.J-41 Measuring Dimension of a Cube

Fig. A.J-42 Weighing a Cube Sample

Fig. A.J-43 Compressive Strength Machine

Fig. A.J-44 Crushing a Cube Sample

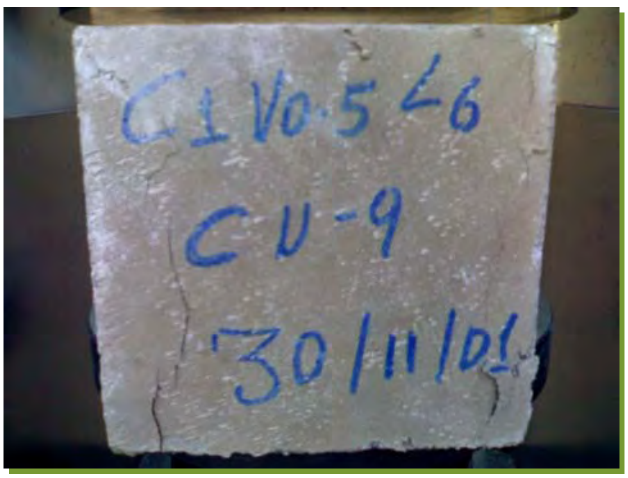

Fig. A.J-45 Failure Mode of a Cube Sample

Fig. A.J-46 UTM Machine for Flexure Test

Fig. A.J-47 Two Point Loading Flexural Test

Fig. A.J-48 A Beam Failed in Flexure

Fig. A.J-49 Cutting the Cylinder Samples

Fig. A.J-50 Greasing a sample for Impact test

Fig. A.J-51 The Instrument for Impact test

Fig. A.J-52 Ultimate Failure of a Plain Sample

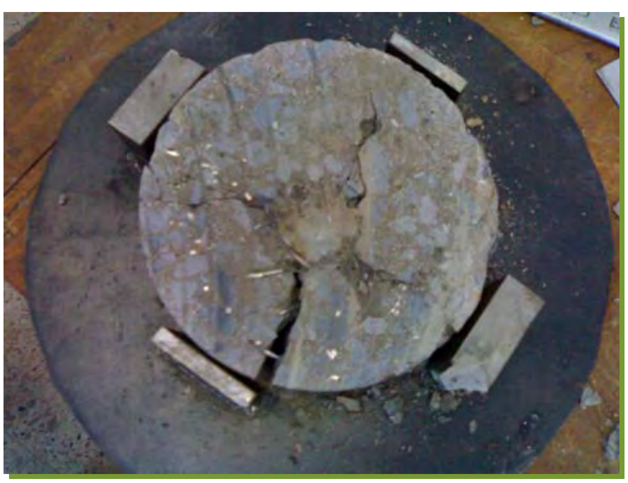

Fig. A.J-53 Ultimate Failure of SFRC Sample

Fig. A.J-54 Ultimate Failure of SFRC Sample

Fig. A.J-53 Distribution of steel fibers in a cube

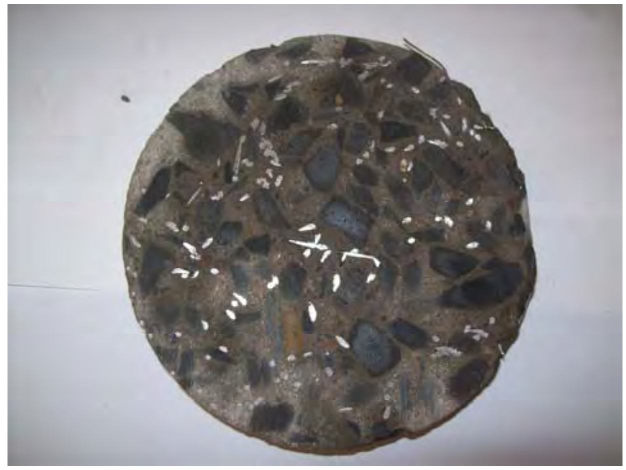

Fig. A.J-54 Distribution of fibers in a disc