MECHANICAL PROPERTIES AND IMPACT RESISTANCE OF HYBRID FIBRE-REINFORCED HIGH STRENGTH CONCRETE

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FACULTY OF ENGINEERING
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KUALA LUMPUR

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DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING SCIENCE

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ABSTRACT

Concrete is the most widely used construction material since it has the lowest ratio between strength to cost as compared to other available materials. Over the years many researchers have been able to overcome the inherent weaknesses of concrete thereby making it significantly more suitable for a wide variety of applications. The introduction of reinforcement by short discrete fibres (steel, nylon and polypropylene) that are randomly distributed can be practiced among other that remedy weaknesses of concrete such as brittleness, low crack growth resistance, low durability, etc. Fibre-reinforced concrete is a composite obtained by adding a single type or a blend of fibres to the concrete mix. The use of one type of fibre alone helps to eliminate or reduce the effects of only a few specific undesirable properties. Based on previous studies, the addition of two types of fibres in a suitable combination would help to improve more properties of concrete amongst the fibres. This aspect of combining the fibres, i.e. hybridizing the fibres in a rational manner to derive maximum benefits, is investigated in a research on very high strength concrete. High performance fibres- reinforced concrete, with matrix strength of about 100 MPa was used. An attempt was made resulting in a concrete mix suitable for practical use, with the required workability, density, etc. This was achieved by making use of proper admixtures including silica fume and superplasticizers. The amount and type of fibres to be used in the hybrid composites were planned such that the strength properties of the hybrid fibres behaviour could be evaluated. The basic properties of the hybridized material evaluated and analyzed extensively were the mechanical properties of the material. The various fibre types used in diverse combinations included macro and micro fibres of steel, nylon and polypropylene. Control mixes and double fibre hybrids were investigated. Along with basic mechanical properties, modified cube compressive, non-destructive test (ultrasonic pulse velocity,

dynamic modulus of elasticity and static modulus of elasticity) and impact resistance tests were also carried out. Results from previous studies indicated that more attractive engineering properties were observed associated with different fibre types when hybridized with macro and micro fibres of steel and nylon demonstrated maximum strength. The volume fraction of macro fibres used for any of the mixes was 0.4% and 0.9% of steel fibres respectively and it appears that this macro fibre volume fraction is high enough to observe maximized strength properties in the hybrids. These amounts of fibres appear to be high enough to make the post peak response of the matrix insensitive to the addition of small dosages (0.1% V_f) of other fibres, such as nylon and polypropylene micro fibres.

ABSTRAK

Konkrit merupakan bahan yang paling banyak digunakan dalam pembinaan kerana mempunyai nisbah yang terendah terhadap kos dan juga kekuatan jika berbanding dengan bahan-bahan lain yang sedia ada. Sepanjang tahun ini, kami telah mampu mengatasi masalah kelemahan konkrit yang bersifat kerapuhan sehingga menjadikan konkrit signifikan lebih sesuai untuk pelbagai aplikasi yang luas. Salah satu perkembangan utama adalah peneguhan bahan dengan serabut diskrit singkat (keluli, nilon dan polipropilena) yang merata dan berorientasikan secara rawak untuk menangani masalah kelemahan konkrit yang bersifat kerapuhan, daya ketahanan yang lemah terhadap masalah pertumbuhan pecahan, daya tahan yang rendah dan lain-lain. Peneguhan serabut dalam konkrit dikenali sebagai komposit yang diperolehi dengan menambah jenis tunggal atau campuran pelbagai jenis serabut yang berlainan ke dalam campuran konkrit. Dengan peneguhan satu jenis serabut saja, hanya dapat membantu untuk menghilangkan atau mengurangkan kesan terhadap beberapa ciri khusus yang tidak diingini. Hal ini diyakini bahawa dengan peneguhan dua jenis serabut dalam kombinasi yang sesuai akan membantu untuk memperbaiki sifat asalan konkrit antara satu sama lain. Aspek menggabungkan serabut, iaitu hibridisasi serabut secara rasional untuk mendapatkan manfaat maksimum akan diselidik dalam projek ini yang bersifat kesangat tinggian kekuatan konkrit. Konkrit prestasi tinggi serabut-diperkuatkan dengan kekuatan matriks daripada 100 MPa digunakan dalam penyelidikan ini. Suatu usaha telah dilakukan untuk menjadikan konkrit sesuai digunakan secara praktikal dengan memastikan konkrit yang digunakan dapat menjalankan kerja mengikut keperluan, kepadatan yang sesuai dan sebagainya. Hal ini dicapai dengan memanfaatkan bahan tambahan yang sesuai termasuk habuk silika dan 'superplasticizer'. Jumlah dan jenis serabut yang akan digunakan dalam komposit hibrida dirancang sedemikian sehingga sifat kekuatan perilaku serabut hibrida boleh dinilai. Di samping itu, bahan hibrida yang

dinilai dan dianalisis secara menyeluruh adalah berasaskan sifat mekanik. Pelbagai jenis serabut yang digunakan dalam kombinasi termasuk serabut makro dan mikro seperti jenis keluli, nilon dan polipropilena. Kawalan dan hibrida campuran serabut ganda juga diselidik. Seiring dengan sifat mekanik asas, tekan kubus diubahsuai, ujian tanpa musnah (kelajuan denyutan ultrasonik, modulus keanjalan dinamik, dan modulus keanjalan statik) dan ujian hentaman juga dipelajari. Penelitian dengan jelas menunjukkan bahawa sifat teknikal lebih menarik dari segi kejuruteraan berkaitan dengan jenis serabut yang berbeza bila hibridisasi dengan serabut makro dan mikro yang berjenis keluli dan nilon telah menunjukkan kekuatan maksimum. Bahagian ruangan serabut makro yang digunakan dalam campuran adalah bernilai 0.4% dan 0.9% masing-masing. Di samping itu, kuantiti serabut yang digunakan adalah cukup tinggi untuk menghasilkan graf respon pasca puncak tidak sensitif terhadap matriks penambahan dos yang kecil (0.1% isipadu serabut) dari serabut lain, seperti serabut nilon dan polipropilena mikro.

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ACKNOWLEDGEMENT

First and foremost, I would like to wish my sincere appreciation to my supervisor, Prof. Madya Ir Dr. Ismail Bin Othman for his valuable guidance, supports and suggestions on this project. He had also given me much guidance and also for providing me with ample amount of knowledge about the field of structural engineering throughout the process on preparing this project which contributed to the success of this project.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol	Description	Unit
A	Cross section area	m^2
Ac	Area of contact	m^2
$A_{surface}$	Area of loading surface	m^2
b	Breadth of the specimen	m
d	Depth of the specimen	m
f_b	Bonding strength	Pa
f_s	Tensile splitting strength	Pa
F	Force	N
g	Gravity acceleration	ms^{-2}
D_f	Density of the fibre material	kg/m^3
d_f	Diameter of a circular fibre	m
E	Energy	Joule
E_a	Mean strain under the upper loading stress	-
E_b	Mean strain under the basic stress	-
E_c	Static modulus of elasticity	GPa
Ed	Dynamic modulus of elasticity	GPa
F	Failure load	KN
l	Length of a circular fibre	m
l_c	Critical length of the fibre	m
m	Mass of fresh concrete	kg
n	Frequency	Hz
ρ	Density of fresh concrete	kg/m^3
S	Spacing of the fibre	m
S_a	Upper loading stress	N/mm ^{2}
S_b	Basic stress	N/mm ^{2}
T	Time	s
v_b	Interfacial bond strength	Pa
V	Volume of container	m^3
V	Velocity	Km/s
V_f	fibre percent by volume of the matrix	% m^3

LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviation	**Compound**
ACI	American Concrete Institute
Al_2O_3	Aluminium oxide
AR	Alkaline resistant
ASTM	American Society for Testing and Materials
BS	British Standard
°C	Degree centigrade
CaO	Calcium oxide
$Ca(OH)_2$	Calcium hydroxide
CSH	Calcium silicate hydrate
DME	Dynamic modulus of elasticity
DOE	Design of experiments
ELE	Engineering Laboratory Equipment
Fe_2O_3	Iron(III) oxide
FRC	Fibre-reinforced concrete
G	Glass fibre
GFRC	Glass fibre-reinforced concrete
H_2O	Water
HPC	High performance concrete
HyFRC	Hybrid fibre-reinforced concrete
MOR	Modulus of Rupture
n	Number of drop
OPC	Ordinary Portland Cement
PCE	Polycarboxylic
PO	Polyster fibre
PP	Polypropylene fibre
PVA	Polyvinyl acetate
V_f	Volume fraction
SEM	Scanning electron microscope
SF	Steel fibre
SFRC	Steel fibre-reinforced concrete
SHRP	Strategic Highway Research Program
SIFCON	Slurry infiltrated fibre concrete

LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviation	**Compound**
SIMCON	Slurry infiltrated mat concrete
SiO_2	Silicon dioxide
SP	Superplasticizer
SSA	Specific surface area
SSD	Saturated surface dry
UPV	Ultrasonic Pulse Velocity

1.0 INTRODUCTION

1.1 Background and Problem Statement

Concrete is the most commonly used construction material in the world due to its versatility, durability and economy. Progress in concrete materials science and technology during the last 30 years has far exceeded that made during the previous 150 years (Benjamin, 2006). Ultra-high-strength concrete (UHSC) is a new class of concrete that has been the result of such development. This new type of concrete is characterized with very high compressive strength; higher than 100 MPa. It is a new kind of concrete with certain characteristics, developed for particular environment; the characteristics are improvement in strength, durability, resistance to various external agents etc.

A very significant development that took place in the history of concrete was the use of rebars in concrete for structural elements. This system was quite efficient in terms of resisting the macro-cracks in concrete and in imparting bending strength in flexural members. The purpose was somehow overcome the low tensile strength of concrete by strategically placing the rebar. Unfortunately, concrete is a brittle material with low tensile strength and strain capacities.

To help overcome the inherent weaknesses of concrete, there has been a steady increase over the past 40 years in the use of fibre-reinforced cements and concretes (FRC). Reinforcement of concrete with short randomly distributed fibres can address some of the concerns related to concrete brittleness and poor resistance to crack growth. Fibres are not added to improve the strength, though modest increases in strength may occur. Rather, their main role is to control the cracking of concrete, and to alter the behaviour of the material once the matrix has cracked, by bridging across these cracks and so providing some post-cracking ductility.

When a matrix is strengthened or reinforced due to short fibres, the following improvements can be observed:

1) Strengthening of the matrix
2) Stress intensity reduction
3) Fibre bonding and frictional pullout
4) Bridging of fibres across cracks and crack face stiffness

Reinforcement of concrete with short randomly distributed fibres can be effective in arresting cracks at both micro and macro-level. At the micro-level, fibres inhibit the initiation and growth of cracks, and after the micro-cracks coalesce into macro-cracks, fibres provide mechanisms that abate their unstable propagation, provide effective bridging, and impart sources of strength gain, toughness and ductility. (Bentur and Mindess, 1990)

Concrete has been under the process of development since a long time. A historical perspective to the development of FRC is given below.

1900	asbestos fibres (Hatschek process)
1950	development of concepts and the science of composite materials
1960	FRC
1970	new initiative for asbestos cement replacement
1980	SFRC, GFRC, PPFRC and Fibre Shotcrete
1990	micromechanics, hybrid systems, wood based fibre systems manufacturing

	techniques, secondary reinforcement, high strength concrete ductility issues, shrinkage crack control
2000+	structural applications, code integration, new products

Almost all FRCs used today commercially involve the use of a single fibre type. Clearly, a given type of fibre can be effective only in a limited range of crack opening and deflection. In recent years, researchers have realized the benefits of combining fibres, in terms of extracting synergy and improving the response of the hybridized material. The benefits of combining organic and inorganic fibres to achieve superior tensile strength and fracture toughness were recognized nearly 25 years ago by Walton and Majumdar (1975). After a long period of relative inactivity there appears to be a renewed interest in hybrid fibre composites and efforts are underway to develop the science and rationale behind fibre hybridization. It is hoped that there is some interaction between the fibres so that the resulting properties exceed the sum of properties provided by individual fibres.

In general, fibre reinforcement is not a substitute for conventional steel reinforcement. Fibre and steel reinforcements play different roles in concrete. The reinforcing bars were added to increase the load-bearing capacity of structural concrete members while fibres are more effective for crack control. There are many applications in which fibres can be used effectively in conjunction with conventional reinforcement to improve the behaviour of structural components, for instance when the concrete is to be subjected to blast or impact loading, or in seismic applications.

Fibres are added to inhibit a propagation of cracks in concrete which occur due to its low tensile strength. The bridging of the fibres across the cracks and the path followed by the crack, for a specimen in pure tension is clearly seen. Figure 1.1 demonstrates ways in which fibres act to absorb energy and control the crack growth.

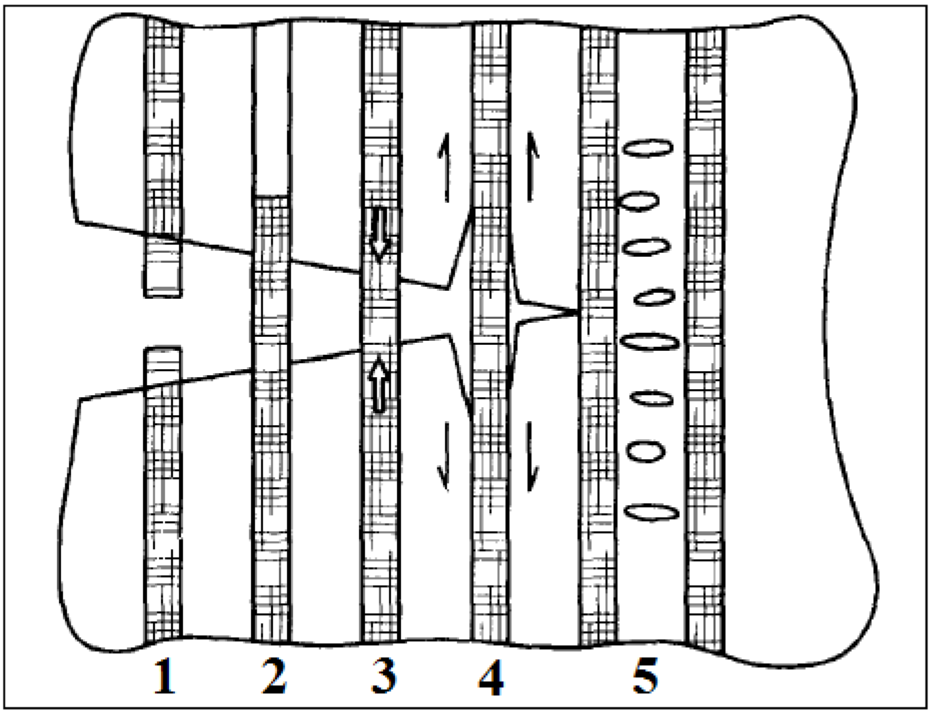


Figure 1.1: Energy-absorbing fibre/matrix mechanisms: 1) fibre failure, 2) fibre pull-out, 3) fibre bridging, 4) fibre/matrix debonding, 5) matrix cracking (Zollo, 1997)

The developments in the recent years have led to FRCs that performs like elasto-plastic materials. The function of the fibres is to lock the coarse aggregate together and prevent the propagation and opening of macro cracks. Also, the different fibre types are being optimized and new ones have been developed to extract maximum benefit from them.

Most of the FRCs used today involves the use of a single fibre type. Such concrete can be effective only in a limited deflection range. The science of hybrid composites where two fibres are combined to achieve enhancement in the basic properties of the material is underdeveloped, yet very significant. One way of achieving more attractive engineering properties is by judiciously hybridizing or combining different kinds of macro and micro fibres.

It has been shown recently (Yew and Othman, 2011; Ding, et al., 2010; Hsie, et al., 2008) that by using the concept of hybridization with two different fibres incorporated in a common cement matrix, the hybrid composite can offer more attractive engineering properties because the presence of one fibre enables the more efficient utilization of the potential properties of the other fibre. However, the hybrid composites studied by previous researchers were focused on cement paste or mortar. The strength properties of hybrid fibre-reinforced in very high strength concrete have not been studied previously. Therefore, hybrid nylon-steel- and polypropylene-steel-fibre-reinforced in very high strength concrete will be investigated.

1.2 Research Objectives

The objectives of this research are listed as below:

(a) To develop very high strength concrete (>100 MPa) mixtures based on traditional concrete mix formulation,

(b) To determine the behaviour of hybrid nylon-steel- and polypropylene-steel-fibre content to be used in FRC through the investigation of hybrid composites based on a very high strength concrete,

(c) To evaluate the effectiveness of hybrid nylon-steel- and polypropylene-steel fibres in concrete through the investigation of mechanical properties compared to plain concrete,

(d) To investigate the impact strength of hybrid nylon-steel- and polypropylene-steel fibres compared to plain concrete.

1.3 Scope of Research

To achieve the research objectives, it is important to study the principal role of fibres in the concrete. This research is to verify the use of hybrid nylon-steel and polypropylene-steel fibres in concrete. Therefore, there were several investigative tests of fresh and hardened concrete properties carried out based on the ACI, ASTM and BS codes. The research targeted quantifying improved engineering properties associated with each mix, and the combinations of 0.5% and 1.0% volume fraction of nylon-steel and polypropylene-steel fibres in each mix was judiciously decided so as to be able to offer more attractive engineering properties to the concrete. Various admixtures were incorporated into the plain concrete and hybrid mixes to make them workable and at the same time keeping them feasible for practical use.

1.4 Outline of Thesis

This thesis is presented in five chapters. Chapter one is the introduction to this research, which describes the background and the problem statement, research objectives and scope of the research. This experiment was carried out to develop a very high strength hybrid fibre-reinforced concrete (HyFRC). In chapter two, a review of literature on the development of FRC and the origin and use of HyFRC is described. The physical and mechanical properties of FRC were also studied and described. Appropriate literatures in the area of HyFRC have been reviewed and reported. Finally, the comparison of data is also presented in tabular form.

Chapter three gives details about the methodology that was adopted to carry out the preparation, materials used, classification, materials properties, test apparatus and testing procedures. The development of HyFRC and further tests that were carried out to study their physical and mechanical properties are explained. The mix design for HyFRC is also given in this chapter. Different amounts and types of fibres to be added to obtain the optimum content are determined. The variations in mix proportions to study the effect of different water to binder ratio (w/b) are also described. The brief testing procedure and the references of relevant codes of practice are summarised.

Chapter four presents the experimental results and discussion on the fresh and hardened properties of various HyFRC. The mechanical properties of HyFRCs are compared and the interpretations of the test results are also discussed. The comparison between the test results of plain concrete and the HyFRC are discussed using tabulated results, graphs and relevant equations. In addition, the test results of non-destructive tests (NDT) carried out on specimens is also discussed. The final chapter of this thesis presents the conclusions arrived after the analysis and discussions of the experimental results. Also, suggestions of some recommendations for further research work are specified. Some of the supporting data and analysis are attached in the Appendix.

2.0 LITERATURE REVIEW

2.1 Introduction

Concrete failure initiates with the formation of micro-cracks, which eventually grow and coalesce together to form macro-cracks. The macro-cracks propagate till they reach an unstable condition and finally result in fracture. Thus, it is clear that cracks initiate at a micro level and lead to fracture through macro cracking. Hybrid fibres reinforcement helps to abate both the micro and macro cracks from forming and propagating.

2.2 Fibre-Reinforced Concrete

Fibre-reinforced concrete (FRC) is defined as a concrete incorporating relatively short, discrete, discontinuous fibres. Generally, the fibres are not added to increase the concrete strength, though modest increases in strength may occur. Instead, the principal role of short dispersed fibres in concrete is to inhibit propagation of cracks in concrete which occur due to its low tensile strength. Fibre will replace large single crack with dense system of micro cracks which implies the improvement of durability and safety of structure (Brandt, 2008; Kartini, et al., 2002; Ramana, et al., 2000).

2.3 Application of FRC

Fibre-reinforced concrete has found many applications. The attention is concentrated on structural concretes for heavy-duty pavements, anti-terrorist shields, high-rise buildings, long-span bridges, dams, pipes, fire protection coatings; spray concretes highway and airfield pavements, and many other kinds of outstanding structures (Brandt, 2008).

Fine fibres control opening and propagation of micro-cracks as they are densely dispersed in cement matrix. Longer fibres up to 50 or 80 mm control larger cracks and contribute to increase the final strength of FRC as shown in Figures 2.1 and 2.2.

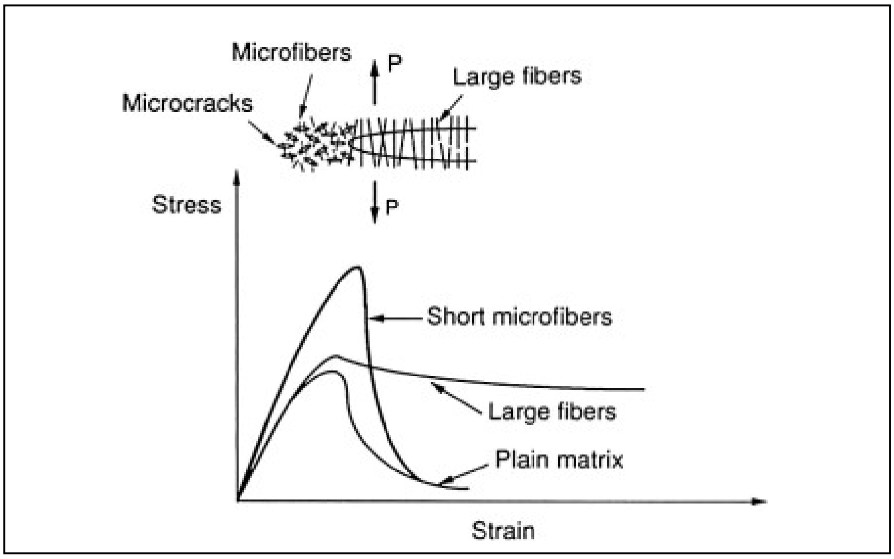


Figure 2.1: Structures of long and short fibres controlling the crack propagation (Betterman, et al., 1995)

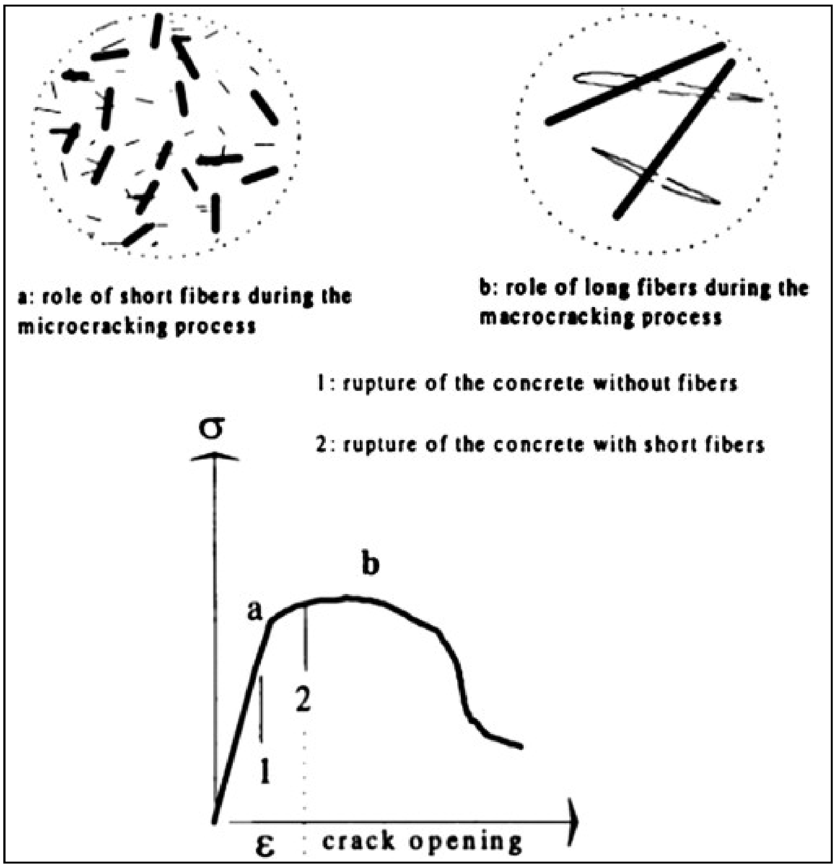


Figure 2.2: Structure of short and long fibres controlling microcracks and its influence on the stress – crack opening curve (Rossi, 1982)

2.4 Characteristics of Fibre

2.4.1 Group of Fibre

Basic groups of fibres applied for structural concretes and classified according to their material are steel fibre of different shapes and dimensions, glass fibres in cement matrices used as alkali-resistant (AR) fibres, synthetic fibres made from polyolefin, polyethylene, polyvinyl alcohol, polypropylene, etc (Brandt, 2008).

2.4.2 Geometrical Properties

Figure 2.3 shows that the properties included the fibre length, diameter or perimeter, cross-sectional shape, and longitudinal profile can be selected. To develop better bond between the fibre and the matrix, the fibre can be modified along its length by roughening its surface or by inducing mechanical deformations. Hence the fibre can be smooth, indented, deformed, crimped, coiled, twisted, with end hooks, end paddles, end buttons, or other anchorage system. In some fibres the surface is etched or plasma treated to improve bond at the microscopic level. Some steel fibres such as ring, annulus, or clip type fibres have also been used and shown to significantly enhance the toughness of concrete in compression (Kim, et al., 2008).

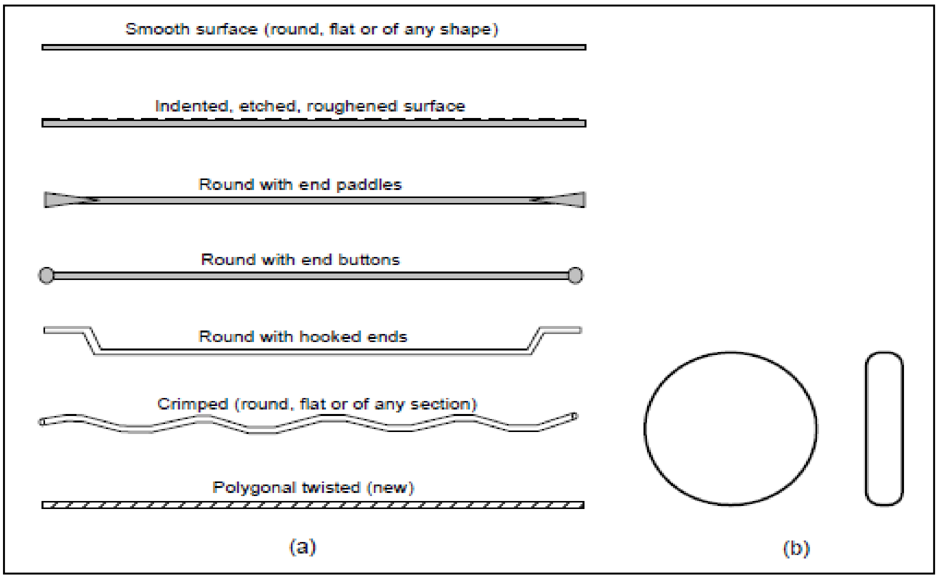


Figure 2.3: (a) Typical profiles of steel fibres commonly used in concrete (twisted fibre is new) (b) Closed loop fibres tried in some research studies (Naaman, 2003).

2.4.3 Mechanical Properties

According to the mechanical properties of fibres, the tensile strength, elastic modulus, stiffness, ductility, elongation to failure, and surface adhesion property are very important characteristic of fibre (Naaman and Reinhardt, 2003).

2.4.4 Physical and Chemical Properties

For the properties, it includes the density, surface roughness, chemical stability, non-reactivity with cement matrix, fire resistance or flammability is taken into consideration when being choose as a material (Naaman and Reinhardt, 2003).

2.4.5 Fibre Material

Fibres are categorized into three main categories (Naaman and Reinhardt, 2003):

1) Natural organic material such as wood, sisal, jute, bamboo, straw, horse hair, etc.
2) Natural mineral material such as asbestos, rock wool, etc.
3) Man-made material such as steel, polymers (synthetic), glass, carbon, metallic, etc.

A number of different types of fibres are used to produce fibre-reinforced concrete of various kinds. The most common ones are steel, organic polymers (primarily polypropylene), glass, carbon, asbestos, and cellulose. These fibres vary considerably in geometry, properties, effectiveness, and cost (Mindess and Boyd, 2002).

For the fibre to be successful as reinforcement it must have the following attributes (Richardson, 2003):

(a) Be easily spread evenly throughout the mix;

(b) Should have sufficient bond with the concrete to transfer any tensile stresses across the concrete;

(c) Should be sufficiently stiff and have a suitable modulus of elasticity so as to limit cracking to acceptable limits;

(d) Provide fracture toughness; and

(e) Should be sufficiently durable to provide service throughout the life of the concrete.

To improve mortars and concrete behaviour, the fibres must be easily dispersed in the mixture, have suitable mechanical properties and must be durable in highly alkaline cement matrix (Silva, et al., 2005).

2.4.6 Fibre Orientation and Fibre Efficiency Factor

Orientation factor or fibre efficiency factor is equal to efficiency with which randomly oriented fibres can carry a tensile force in any one direction. The idea is similar to the bent bars and vertical stirrups provided in beams to resist the inclined diagonal tension stress. If the assumption is perfect, the efficiency factor is $0.41l$, but it can varies between $0.33l$ and $0.65l$ when close to the surface of the specimen, as trawling or leveling can modify the orientation of the fibres (Mindess and Young, 1981).

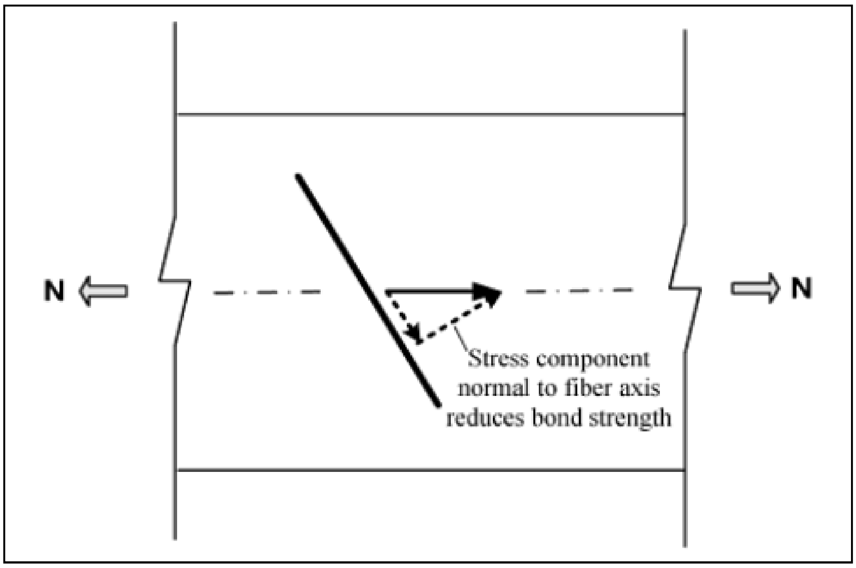


Figure 2.4: Illustration to explain the bond reduction in the uncracked state of the composite due to orientation of fibre (Naaman, 2003)

2.4.7 Spacing Factor

The spacing of fibre is known to affect the development of cracking in matrix. Fibres need to be close enough together so that they effectively intercept any cracks as they propagate through the composite. This is due to reduce of stress intensity factor of the fracture. Fibre acts as crack arrestor, by decreasing the spacing between increasing the tensile strength of the composite (Nawy, et al., 2008).

Several expressions have been developed. One of the expressions is from McKee (1969):

$$S=3\sqrt{\frac{V}{V_f}} \qquad (2.1)$$

Where V is the volume of one fibre element

Another expression is from (Romualdi, 1974) and (Batson, 1976):

$$S=13.8d_f\sqrt{\frac{1.0}{V_f}} \qquad (2.2)$$

Where; s= spacing of the fibre

d_f= diameter of fibre

V_f= fibre percent by volume of the matrix

An expression which takes into account of the fibre length (Mindess and Young, 1981)

$$S=13.8d_f\frac{\sqrt{l}}{V_f} \qquad (2.3)$$

2.5 Synthetic Fibres

Synthetic (polymer) fibres are increasingly being used for the reinforcement of cementitious materials. Some fibres, such as polypropylene and nylon, are used very extensively, and many fibres are available that have been formulated and produced specifically for reinforcement of mortars and concretes.

2.5.1 Nylon Fibre

Nylon fibres are made from nylon and are therefore stronger and bond better into concrete than other synthetic fibres. Nylon fibres exist in various types in the marketplace for use in apparel, home furnishing, industrial, and textile applications. Only two types of nylon fibre are currently marketed for use in concrete, nylon 6 and nylon 66. Nylon 6 begins as pure caprolactam. As caprolactam has 6 carbon atoms, it got the name Nylon 6. Nylon 6 or polycaprolactam is a polymer developed by Paul Schlack at IG Farben to reproduce the properties of nylon 66. Nylon 6 is not a condensation polymer, but instead is formed by ring-opening polymerization. This makes it a special case in the comparison between condensation and addition polymers. Nylon 6 fibres are tough, possessing high tensile strength, as well as elasticity and luster. They are wrinkle-proof and highly resistant to abrasion and chemicals such as acids and alkalis. Nylon 66 is made of hexamethylenediamine and adipic acid, which give nylon 66 a total of 12 carbon atoms. Nylon 66 has a high melting point of 265˚C. This fact makes it resistant to heat and enables it to withstand heat setting for twist retention. Its long molecular chain results in more sites for hydrogen bonds, creating chemical "spring", making it very resilient.

It has always been recognized that nylon fibres outperformance other synthetic fibres but it is only in recent years that manufacturing costs have reduced to make them more economical as well. The main application for synthetic fibres is to eliminate early age cracking and any resultant long-term problems. Secondary benefits are increased impact resistance, reduce bleed and improved build in shortcrete. At high dosages, post crack strength can be sufficient to enable replacement of light reinforcement. There can also be minor improvement in concrete properties affected by the improved rheology, for example surface durability.

Synthetic (polymeric) fibres have become increasingly common in recent years. Most synthetic fibres have lower elastic modulus than concrete. At the relatively low fibre volume currently used in industrial practice (<0.5%), they are most effective in reducing the amount of plastic shrinkage cracking, though they also provide some toughening and impact resistance.

Nylons (polyamides) are among the most successful of the synthetic bulk commodity polymers to have emerged from the last century. This success is largely due to the excellent fibre properties of the polymers, particularly nylon-6 (polyamide-6, polycaprolactam) and nylon-6/6 (polyamide-66). Applications for these fibres largely fall into two classes; woven (e.g. in clothing textiles, carpets, parachute 'silk', and sails) and non-woven (e.g. in tyre reinforcement cord, ropes, fishing line, sports racket and guitar ‘strings’, and dental floss).

Nylon fibres are often characterised as having good strength coupled with chemical resilience and low moisture absorbency. These three factors are, however, closely inter-dependent. For instance, whilst it is well known that the amide linkage (–CO–NH–) is susceptible to acid hydrolysis and UV degradation, water absorption can substantially reduce both the glass transition temperature and Young's modulus (Reimschuessel, 1978).

The reason for choosing nylon fibres for the testing programme was one of the cost considerations. The other qualities attributable to non-metal fibre reinforcement are zero reinforcement corrosion, reduction in ion flow and no aging problems (Richardson, et al., 2005).

Nylon fibres appear to be used increasingly in FRC, often as a substitute for polypropylene fibres. For FRC, the nylon fibres are generally produced as a high tenacity yarn that is heat and light stable, and is subsequently cut into appropriate lengths. These fibres typically have a tensile strength of about 800 MPa, and an elastic modulus of about 4 GPa. It should be noted that these fibres are hydrophilic, and can absorb about 4.5% of water; this must be considered if high volume contents of the fibre are being used, rather than the more usual 0.1%-0.2%. Like polypropylene, nylon is chemically stable in the alkaline cement environment.

2.5.2 Polypropylene Fibre

Polypropylene fibres are produced from homopolymer polypropylene resin in a variety of shapes and sizes, and with differing properties. The main advantages of these fibres are their alkali resistance, relatively high melting point (165˚C) and the low price of the material. Their disadvantages are poor fire resistance, sensitivity to fire and other environmental effects. The mechanical properties, in particular modulus of elasticity and bond, can readily be enhanced. A number of different polypropylene fibres for use with cementitious matrices have been developed and are marketed commercially.

Polypropylene fibres are made of high molecular weight isotactic polypropylene. Because of the sterically regular atomic arrangement of the macro-molecule, it can be more readily produced in crystalline form, and then processed by stretching to achieve a high degree of orientation, which is necessary to obtain good fibre properties. Polypropylene fibres can be made in three different geometries, all of which have been used for the reinforcement of cememtitious matrices: monofilaments (Walton and Majumdar, 1975) and (Dave and Ellis, 1979), film (Hannant, et al., 1980) and extruded tape (Krenchel and Jensen, 1980), (Krenchel and Shah, 1985). All three forms have been used successfully for mortar and concrete reinforcement. In this study, the forms of monofilaments have been choosen for research purpose. While both the fibrillated and monofilament polypropylene fibres have essentially the same strength and elastic modulus, it has been suggested that in terms of their ability to arrest cracks, the monofilament fibres are more effective than the fibrillated fibres (Banthia and Nandakumar, 2001).

Monofilament polypropylene fibres are produced by an extrusion process, in which the polypropylene resin is hot drawn through a die of circular cross section. A number of continuous filaments (tows) are produced at one time, and are then cut to the appropriate lengths.

The chemical structure of the polypropylene makes it hydrophobic with respect to the cementitious matrix, leading to reduced bonding with the cement, and negatively affecting its dispersion in the matrix. Thus, most of the polypropylene fibres developed for FRC undergo various proprietary surface treatments to improve the wetting of the fibres in order to overcome these disadvantages. For instance, Zhang et al. (2000) found that treating the fibres with low temperature cascade arc plasma was effective in improving the flexural performance and toughness of polypropylene FRC. Similarly, Tu et al. (1999) found that treating the surface of the fibres with fluorination or oxyfluorination processes improved the performance of the FRC.

2.6 Steel Fibres

Originally steel fibre was added into concrete to prevent crack control, to replace the secondary reinforcement of flat slabs, pavement and tunnel lining, and also some repair works due to its ability in increasing the toughness of cement and concrete. The increase in toughness can prevent or minimize the cracking caused by relative humidity and temperature change. It can also increase the resistance towards dynamic load such as impact, blast or seismic wave. Improves in strength due to fibre is to improve the post-peak load carrying capacity after concrete failure (Bentur and Mitchell, 2008).

The function of adding steel fibres to the concrete is to lock the coarse aggregate together and prevent the propagation and opening of micro cracks. Tensile forces are transferred across the crack by the fibres resulting in lower stress concentrations at the crack-end. This limits crack propagation relative to plain or mesh reinforced concrete. The steel fibres become load carrying and replace conventional reinforcement. Such characteristic of steel fibre is better than other fibres reinforcement in concrete.

Steel fibres may be produced by cutting wire, by shearing sheets, or from a hot-melt extract. The first generation of steel fibres were smooth, but it was soon found that, as a result, they did not develop sufficient bond with the cementitious matrix; modern steel fibres are generally either deformed along their lengths or at their ends to enhance the cement-fibre bond. Though they will rust visibly when exposed at the concrete surface, they appear to be highly durable within the concrete mass.

Fibres come in various sizes and shapes. Round steel fibres, made from low carbon steel or stainless steel, have diameters in the range 0.25 mm to 1.0mm. Flat steel fibres, produced by shearing sheet or flattening round wire, are available in thicknesses ranging from 0.015 mm to 0.04 mm. Crimped and deformed steel fibres are available both in full length or crimped at the ends only. Some fibres are collated to facilitate mixing and placing. A typical volume fraction of steel fibres is 0.25 to 1.50% (of the volume of concrete).

Corrosion of fibres may be a problem with steel fibre-reinforced concrete, although studies seem to indicate that corrosion does not seem to propagate 2.5 mm below the surface (Somayaji, 1995). The properties of steel, nylon and polypropylene fibres vary widely with respect to strength and modulus of elasticity, as shown in Table 2.1.

Table 2.1: Properties of steel, nylon and polypropylene fibres

Fibre type	Specific gravity	Diameter (μm)	Tensile strength (GPa)	Elastic modulus (GPa)	Melting point (˚C)
Steel	7.84	100-1000	0.5-2.6	210	1200
Nylon	1.14	23-400	0.75-1.9	5.17	225
Polypropylene	0.91	20-40	0.4-0.76	4.11	160

2.7 Types of Fibres Hybridization

The character and performance of fibre-reinforced concrete change depend on the properties of concrete and the fibres. The properties of fibres that are usually of interest are fibre concentration, fibre geometry, fibre orientation, and fibre distribution. Moreover, using a single type of fibre may improve the properties of fibre reinforced concrete to a limited level. However the concept of hybridization, adding two or more types of fibre into concrete, can offer more attractive engineering properties as the presence of one fibre enables the more efficient utilization of the potential properties of the other fibre (Sahmaran, et al., 2005).

Optimization of mechanical and conductivity properties can be achieved by combining different kinds, types, and sizes of fibres, such as in case of polypropylene and steel fibres have the attractive advantages of hybrid fibres systems: (Qian and Stroeven, 2000):

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

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

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

In well-designed hybrid composites, there is positive interaction between the fibres and the resulting hybrid performance exceeds the sum of individual fibre performances. This phenomenon is termed "synergy." Many fibre combinations may provide 'synergy' with the most commonly recognized being (Xu, et al., 1998):

1) Hybrids Based on Fibre Constitutive Response:

   One type of fibre is stronger and stiffer and provides reasonable first crack strength and ultimate strength, while the second type of fibre is relatively flexible and leads to improved toughness and strain capacity in the post-crack zone. There is generally a significant difference in the modulus of elasticity of the two types of fibres mentioned above, and ideally they carry load commensurate to the value of strain the material is subjected to.

2) Hybrids Based on Fibre Dimensions:

   One type of fibre is smaller, so that it bridges micro-cracks and therefore controls their growth and delays coalescence. This leads to a higher tensile strength of the composite. The second fibre is larger and is intended to arrest the propagation of macro-cracks and therefore results in a substantial improvement in the fracture toughness of the composite. This is consistent with Banthia's and Shah's (Banthia, et al, 1995) and (Shah, 1991) views mentioned earlier.

3) Hybrids Based on Fibre Function:

One type of fibre is intended to improve the fresh and early age properties such as resistance to plastic shrinkage, while the second fibre leads to improve in the hardened/mechanical properties. When these fibres are hybridized, fresh and hardened properties of the composites are simultaneously enhanced. Some such hybrids are now commercially available where a low (<0.2%) dosage of polypropylene fibre is combined with a higher (~0.5%) dosage of steel fibre. Glavind et al. 1991 tested steel and polypropylene fibre hybrids and reported that hybridization of these two fibres increased the ultimate compressive strain of the composite. Larsen et al. 1991 combined steel and polypropylene fibres in cementitious composites and found that after 10 years of out-door exposure the fracture energy of composites containing two fibres increased by approximately 40%. In view of the above research findings, several control mixes with different V_f of steel and polypropylene were considered in this investigation to establish the effect of variation of fibre modulus on the behavior of concrete in flexural toughness.

2.7.1 Macro and Micro Fibres

Hybrids based on fibre dimensions can be classified as micro and macro; macro fibres generally being 30-60 mm in length as opposed to about 5 mm size for micro fibres. Based on the size of the fibres, micro and macro-cracks can be controlled. The diameter is generally in the range of 0.5 mm for macro fibres and about 20 microns for the micro fibres. Another approach of distinguishing fibres is according to the specific surface area (SSA) of fibre employed. The SSA can be defined as the surface area for a unit mass (Banthia, et al., 1995), and mathematically,

$$\mathrm{SSA}_m = \frac{2(2l+d)}{ldD_f} \tag{2.4}$$

When using fibres based on their size micro or macro) alone, SSA can also be defined as the surface area for a unit volume, and can be written mathematically as,

$$\mathrm{SSA}_\mathrm{v} = \frac{2(2l+d)}{ld} \tag{2.5}$$

Where, l = length of a circular fibre,

d= diameter of a circular fibre, and

D_f= density of the fibre material

As their high SSA, and a small size would indicate, the micro-fibres reinforce cement paste and the mortar phases, thereby delaying crack coalescence and increasing the apparent tensile strength of these phases (Shah, 1991).

In Equation 2.4, note that the diameter of the fibre plays a more important role than its length. Based on this formula, the approximate SSA value for a commonly used steel macro fibre is calculated below.

- Steel macro fibre

  SSA = 2((2*3.5) + 0.05) / (3.5*0.05*7.85)

  SSA = 10.3 cm^2 / gm

Similarly, SSA values for some other fibres are:

Nylon micro fibres = 1526 cm^2 / gm

Polypropylene micro fibres = 441 cm^2 / gm

Arbitrarily speaking, macro fibres have an SSA of roughly 10 cm^2/gm and micro fibres have an SSA greater than 400 cm^2/gm. The micro fibre with a large SSA are expected to reinforce the cement paste and mortar phases, thereby delaying crack coalescence and thus increasing the apparent tensile strength. The function of the macro fibres, on the other hand, is known to bridge across the macro-cracks and induces post-crack ductility in the material.

2.8 Parameters of Fibres Reinforcement

2.8.1 Aspect Ratio (*l/d_f*)

Aspect ratio is equal to ratio of fibre length over diameter or equivalent diameter which is generally less than 100 in between range from 40 to 80 (Kim, et al., 2008). For reasons of workability and dispersion in the matrix, the aspect ratio of most modern fibres is in the range of 50 to 150 (Mindess, et al., 2003).

Both micro and macro fibres may exceed the critical length and hence fracture across a crack. Figure 2.5 shows the stress distribution across the length (l) of a fibre, which determines the pull-out or fibre fracture mechanism. In the Figure, l_c is the critical length of the fibre. When $l < l_c$, fibres fracture and when $l > l_c$, fibres get pulled out. It is therefore the aspect ratio that governs the possibility of fibre fracture, not the SSA.

2.8.2 Critical Length

Figure 2.5 shows the critical length is the minimum fibre length required for the build-up of a stress (or load) in the fibre which is equal to its strength (or failure load) (Mindess and Boyd, 2002).

$$l_c = \frac{d_f}{2v_b}\sigma_f \tag{2.6}$$

Where, d_f= fibre diameter

v_b= interfacial bond strength

σ_f= fibre strength

The effects of fibre length on shear stress transfer and *l*c are shown as below.

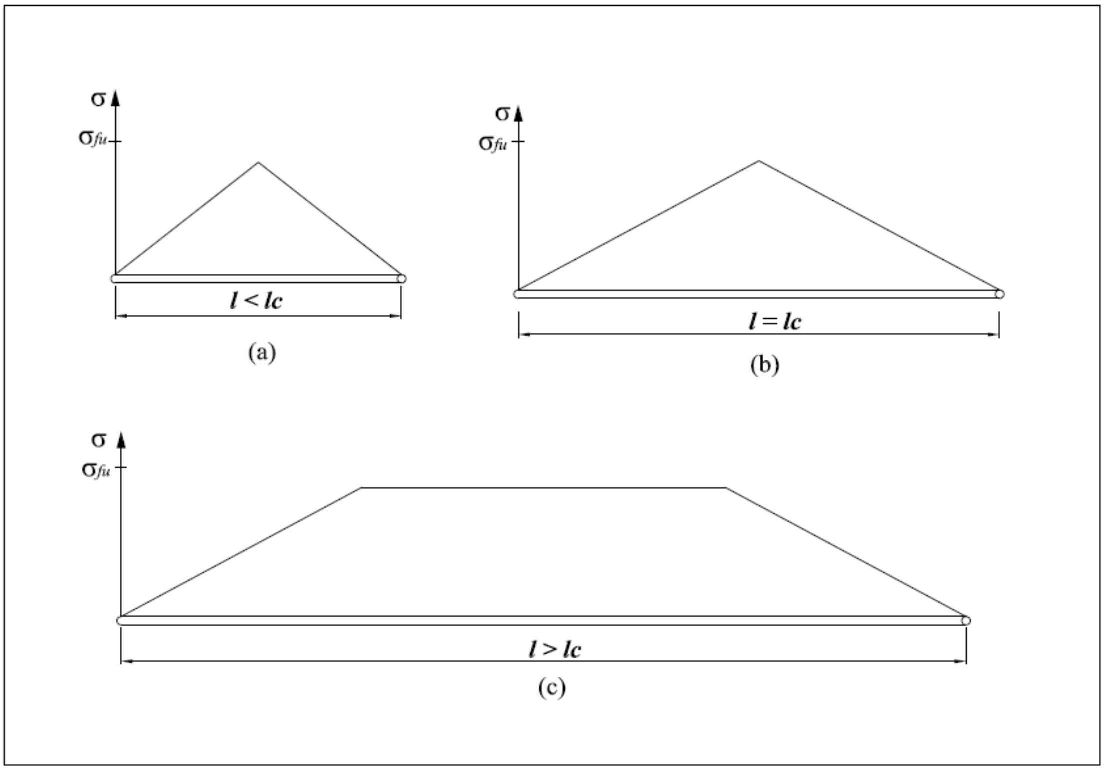


Figure 2.5: Stress profile along a fibre in a matrix as a function of fibre length (Bentur and Mindess, et al., 1990)

Shah et al. (2001) tested permeability characteristics of hybrid composites and demonstrated that fibre hybridization significantly increased the resistance to water ingress. Although the concept of hybrids has shown to have significant promise, almost all studies to date have focused on normal strength matrices. Gupta et al. (2002) showed that the strength of the matrix plays a major role in the optimization of hybrid composites. In this research, the influence of concrete strength is explored further by conducting tests on hybrid composites based on a very high strength concrete.

2.9 Effect on Fresh Concrete Properties

2.9.1 Workability

Fibre tends to stiffen the concrete mix, and make it looks harsh when static, although it may respond well to vibration. The addition of fibres will reduce the workability of the concrete. This can be generally compensated for by increasing the fine-to-coarse aggregate ratio and by increasing the cementitious material content, generally through the addition of pozzolanic materials.

Workability tests based on static conditions, such as the slump test might be misleading due to the fact that FRC is workable when vibrated. Hence tests which consist of dynamic effects are more recommended. There are a number of workability tests; researchers have described that there are 61 workability tests for FRC test yet only a number of test is commonly used (Koehler and Fowler, 2003). The most common tests for workability of FRC are:

1) Slump test (ASTM C143, *Standard Test Method for Slump of Hydraulic Cement Concrete*). It is not a good indicator for the workability of FRC due to static condition. Though according to ACI Committee 544 (2), once it has been established that a particular FRC mixture has satisfactory handling and placing characteristics at a given slump, the slump test may be used as a quality control test to monitor the FRC consistency from batch to batch '
2) Vebe Test (BS 1881: Part 104: 1983 *Method for Determination of Vebe Time*) Vebe Test is suitable for workability properties of fresh FRC because it is a dynamic effect test, but it is not relevant for quality control on site.

3) Walz flow table test (in German DIN 1045 and 1048, and European EN206) it is commonly used in Europian countries. It is a simple test; a metal container which is 200 mm × 200 mm × 400 mm is filled with incompacted concrete then rodded or vibrated. The degree of compaction is calculated as the height of the container divided by the average height of the compacted concrete.

4) Inverted slump cone (ASTM C995, *Standard Test Method for Time of Flow of Fibre-Reinforced Concrete through Inverted Slump Cone*). It is a test specially developed for FRC. It is sensitive to the mobility and fluidity of FRC, and is used for mixes which has a slump of less than 50 mm and it should not be used if the time of flow is less than 8 s; such mixes should be assess by slump test.

2.9.2 Fabrication of Fibre-Reinforced Concrete

Mixing fibres with other constituents can be done in several ways depending on the facilities available and job requirements. The most important factor in mixing is to ensure the fibres are dispersed uniformly and to prevent bleeding, and also fibre balling. There are several factors that lead to segregation and balling such as:

1) Aspect ratio (l/d_f)
2) Volume percentage of fibre
3) Coarse aggregate size, gradation, and quantity
4) Water / cementitious materials ratio and method of mixing

A maximum aspect ratio of l/d_f and a steel fibre content excess of 2% by volume is the cause of non-uniform mix. It is recommended that 9.7mm maximum aggregate size is use in the mixture although conventional mixing procedures can be used. Water-cement ratio varies due to the cementitious pozzolans in cement replacement and the percentage by volume of the matrix (Nawy, et al., 2008).

A workable method can be summarized as follows:

(a) Blend part of the fibre and aggregate before charging into the mixer.

(b) Blend the fine and coarse aggregate in the mixer, add more fibres at mixing speed, then add cement and water simultaneously or add the cement immediately followed by water and additives.

(c) Add the balance of the fibre to the previously charged constituents, and add the remaining cementitious materials and water.

(d) Continue mixing as required by normal practice.

(e) Place the fibrous concrete in the forms. Use of fibres requires more vibrating than required for non-fibrous concrete; although internal vibration is acceptable if carefully applied, external vibration of the formwork and the surface is preferable to prevent segregation of the fibres.

When using transit mix truck or revolving drum mixer, fibres should be added last to the wet concrete. The fibres added should be free of clumps by passing through proper screen. The use of collated fibres held together by water-soluble sizing which dissolves during mixing can solve the clumping problem. After the fibre had been mixed into the mixer, the mixing speed should be set to 3-40 revolutions per minute for proper dispersion of the fibres. Or the fibres may be mix with fine aggregate on conveyor belt during the aggregate adding process to the concrete mix.

Fibre balling or clumping usually occurs before fibres are added to the mix. If they enter the mix free of balls, they will be uniformly dispersed. Fibre balling when mixing might be due to using worn out mixing equipment or over mixing process (Bentur and Mitchell, 2008).

2.10 Effect on Hardened Concrete Properties

2.10.1 Compressive Strength

The normal range of fine content is less than 2%. FRC has shown a little effect on compressive strength (Bentur and Mitchell, 2008). The effect of fibre in concrete can be seen in Figure 2.6 in the compressive test by using steel fibre.

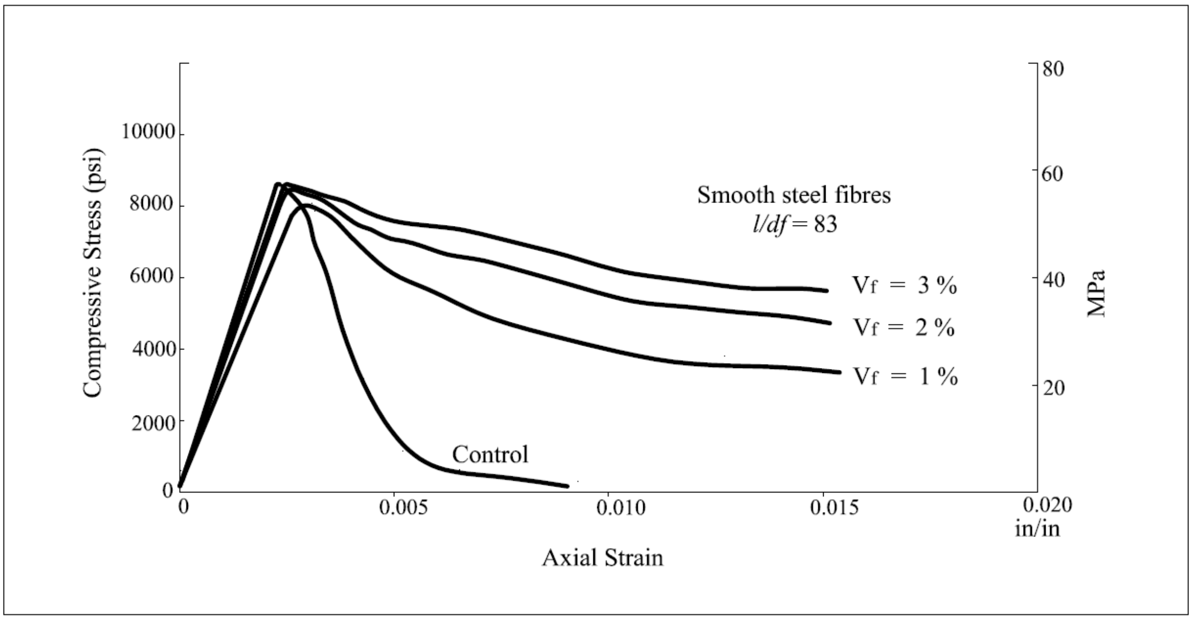


Figure 2.6: Relationship between compressive strain with fibre content

The compressive strength of concrete reinforced with 30mm length of fibres was about 17% higher than the corresponding plain concrete strength (Cachim, et al., 2002).

Tests by Karihaloo et al. (2006) had found an increase in compressive strength from about 120 MPa to about 145 MPa which is approximately 21% on going from 0% to 4% fibres by volume (Farhat, et al., 2007).

Similarly another test has found an increase from about 150 MPa to about 200 MPa which is an increase of 33% on going from no fibres to 4% fibres by volume (Sun, et al., 2001).

Inclusion of plastic fibres in concrete should improve its fracture resistance, but it could have a negative impact on compressive strength and creep behaviour. In general, plastics do not achieve chemical bond with cementitious materials. Compressive strength decreased with increase in the amount of the plastic fibres in concrete, particularly above 0.5% fibre addition by weight. Therefore, in order to maintain a particular compressive strength level, plastic fibre concentration in concrete must be controlled. However, the amount of fibre addition can be increased substantially if particles (fibres) are further processed to improve the bond area and stress transfer capacity of particles (fibres) (Naik, et al., 1996).

Attempts have been done to determine the relationship between extreme high fibre content and compressive strength. It was found that for SIFCON (slurry infiltrated fibre concrete) with fibre content of 10% by volume, the compressive strength had increase roughly 25-50% from its plain concrete matrix. Similarly a test had been done by using SIMCON (slurry infiltrated mat concrete) with fibre volume of 2.16 - 5.39% shows an increase of about 30%. However very high fibre content may lead to difficulties in achieving full compaction consequently porosities in matrix increased (Bentur and Mitchell, 2008).

2.10.2 Splitting Tensile Strength

In low volume of steel fibres, it will increase cylinder splitting tensile strength when the fibres content is increased although it has little effect on compressive strength (Balendran, et al., 2002).

Reinforcement of concrete with short, randomly distributed steel fibres leads to improvements in the tensile strength and tensile and compressive ductility of the materials. This is due to the tendency of propagating microcracks in cementitious matrices to be arrested or deflected by fibres (Choi, et al, 2002).

The addition of 1.5% by volume of fibres may increase the tensile strength by about 45%. Steel fibres have also been shown to increase the shear capacity substantially (Somayaji, 1995).

For steel fibre-reinforced concrete, the mainly three-dimensionally distributed steel fibres can reinforce both the shear failure (oblique cracks) and the splitting failure (vertical cracks) greatly (Ding and Kusterle, 2000).

Other investigations showed that the addition of fibres in conventional FRC can increase the toughness of cementitious matrices significantly; however their tensile strength and especially strain capacity beyond first cracking are not enhanced (Fischer and Li, 2007).

2.10.3 Modulus of Rupture (Flexural Strength)

Fibre tends to increase the flexural strength in the concrete or mortar elements to a much greater extent compare to elements which is subjected to direct tension or compression (ACI Committee 544, 1993). It was shown that in strain hardening fibre reinforced composite, the flexural strength was roughly twice the strength of plain concrete cement (Li and Maalej, 1996).

The first stage involves the first cracking load stage in load deflection diagram, and the second stage is the ultimate controlling stage. Both the first cracking load ultimate flexural capacities were affected by the function of the product of the fibre volume (V_f) and aspect ratio (l/d_f). The principle effect of fibres is to improve the post-peak load carrying capacity of the concrete (i.e. toughness), as shown in Figure 2.7.

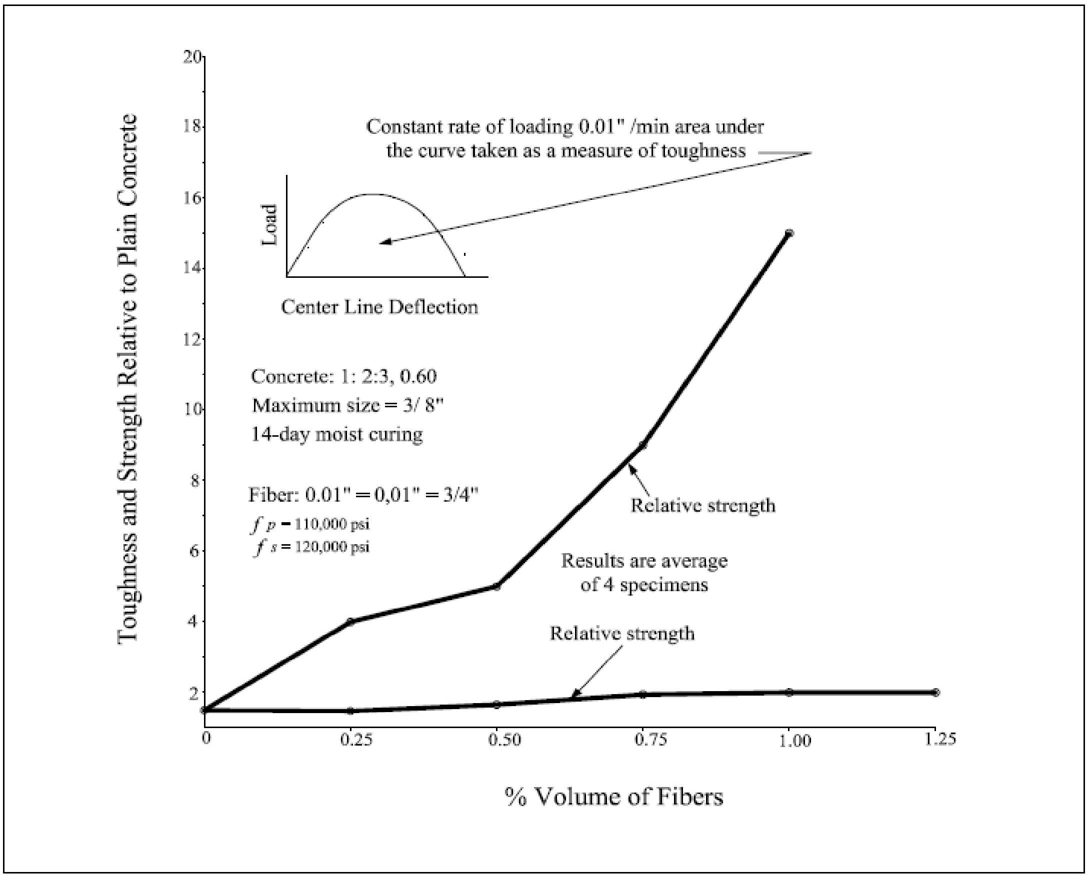


Figure 2.7: Effect of the volume of steel fibres on the strength and toughness of SFRC (Shah and Rangan, 1971)

2.10.4 Concrete Fluidifiers (Superplasticizers)

Superplasticizer (SP) is an admixture that enables the concrete to be workable even produced at very low water-cement ratios (without the need for excessively high cement contents) is critical. Superplasticizer also prevents flocculation of Portland cement particles and reduces inhomogeneities of material such as silica fume by distributing them homogenously. Hence it helps to improve paste strength. The strength of the paste will be limited by the flaws with form the weakest link, introducing SP will help to minimise the inhomogeneities or capillary pores.

2.10.5 Impact Resistance of Fibre-Reinforced Concrete

The impact resistance of plain concrete is considered relatively low. The introduction of fibre into concrete has the effect of improving the concrete performance under dynamic loading sometimes by more than an order of magnitude.

Plain concrete is known for the highly strain rate sensitive in compression (Grote, et al., 2001), tension (Zielinski, et al., 1988), and flexural (Mindess, et al., 1986 and Suaris and Shah, 1982), though the degree of rate sensitivity varies. In fibre-reinforced concrete the situation is more complicated since the matrix, the fibres and the fibre-matrix bind are strain-rate sensitive to different degrees. Hence it is not able to predict the behaviour of fibre-reinforced concrete under impact on the basis of static test result due to the difference in failure mechanisms, also depending on the particular fibre-reinforced concrete and strain rate.

There are several common types of impact test which are:

(a) Instrumented drop weight test- In the test a mass which is raised to a certain height and then let to drop onto the target specimen which may be a beam, a plate or a compression specimen. The system is instrumented with some load cells, accelerometers, strain gauges and displacement transducers.

(b) Swinging pendulum machines- The machines are of the form of Charpy machines. A swinging pendulum strikes the specimen and transferring momentum and reducing high stress rates to the sample. (Suaris and Shah, 1982) and (Gokoz and Naaman, 1981).

(c) Split Hopkinson pressure bar- The fibre reinforced specimen is sandwiched between two elastic bars and very high stress rates can be generated by propagating a pulse through one of the bars, using a striker bar. When the input bar is struck, a well-defined rectangular compression wave is generated. When the wave reaches the specimen, some of it reflects back through the input bar, and some transmits through the specimen to the output bar. This generates very high stresses and stress rates in the specimen. One dimensional wave analysis is then used to obtain the stress vs. strain curves.

(d) Projectile impact- In the test a projectile of some sort is fired at an FRC specimen, using a kind of gun. Hence this initiates a compressive wave which runs through the material to a free edge. The wave is then reflected and is transformed into a tensile wave that propagates in the opposite direction. The principal failure modes are scabbing on the rear side of the specimen, and scabbing on the front. In some cases, complete penetration may occur. The results of the experiments are assessed in terms of the visual damage to the specimen.

(e) Explosive charges- It is a method by generating extremely high stress rates; an explosive charge may be attached directly to the specimen, and then detonated.

(f) Repeated impact drop weight test- A weight of some type is dropped repeatedly onto the specimen, and the number of blows required to cause a specified amount of damage is recorded. This test is inconsistent, and is not now used very much.

(g) Inertial loading- In the initial period of the impact event, a beam or a plate specimen is accelerated, and the inertial force induced in addition to the force required bending the specimen. As a result during this time period, the recorded load is considerably greater than that resisted by the beam. This shows up as an oscillation in the total load vs. time curve.

2.11 Research in Hybrid Fibre-Reinforced Concrete (HyFRC)

2.11.1 Double Fibre Hybrid Composites

Glavind and Aarre (1991) investigated the possibilities of increasing the fracture toughness of high-strength concrete by adding fibres. Tests were conducted with both normal and high-strength concrete containing different amounts of steel and polypropylene fibres and toughness was described by toughness indices. The investigation showed that the addition of steel fibres was effective in increasing the toughness and non-linear load carrying capacity for high-strength concrete. Steel fibres also marginally increase the compressive strength of high strength concrete.

The combination of different fibres for thin walled fibre reinforced cement composites for structural applications, with fibres made of metallic, mineral, polymeric or naturally occurring materials was reported by Ramanalingam et al. (2001). The authors stated that different fibres offer different extent of improvement to the mechanical properties of the matrix, but the most sought-after property in a cement-based composite is the strain hardening response that is associated with multiple cracking. The authors believed that in order to achieve this property, different types of fibres should be suitably combined to exploit their unique properties.

Qi et al. (2000) tested carbon and polypropylene fibre hybrids and found that hybrid fibre-reinforced concrete when tested in tension resulted in de-bonding between the matrix and the fibre and a great number of fibres pulled out. The stress was always first transferred from the matrix to the carbon fibres, due to its high modulus. After some displacement, the polypropylene fibres would carry most of the load and a large deformation would induce failure. In the study, it was also noticed that carbon and polypropylene fibres when used in a combination offered toughening at different structural levels. Significant strengthening and toughening occurred in carbon-polypropylene hybrid fibre-reinforced concrete.

Horiguchi and Sakai (1997) investigated steel and PVA hybrids. They studied the fracture toughness of fibre-reinforced concrete in comparison as well as flexure. Four different types of steel fibre and two types of PVA fibre individually and in combination form were investigated. The toughness of hybrid fibre-reinforced concrete showed different performance from that of mono fibre composites and for the same flexural toughness, the first crack deflection was greater in the hybrids. They also observed that while the compressive strength did not change, the addition of fibres significantly enhanced the compressive toughness. Compressive toughness was found to increase in proportion to the fibre content; the highest compressive toughness occurred for the hybrids. No clear correlation however between the compressive and flexural toughness was noticed.

Feldman and Zheng (1991) also studied hybrid composites containing steel and polypropylene fibres. From their investigation, they concluded that workability of hybrid fibre-reinforced concrete was reduced as steel fibre or polypropylene fibre contents were increased. Deformed fibres were found to be more effective than straight fibres in enhancing the flexural and compressive behaviour of concrete. They also found that in hybrid composites, stronger and stiffer steel fibres improved the ultimate strength, while the more flexible and ductile polypropylene fibres led to improved toughness and strain capacity in the post-crack zone.

A combination of fibres can be very effective, resulting in some form of synergy. Soroushian et al. (1993) reported synergy in hybrid polyethylene fibre reinforced cement composites. They optimized the combined use of two different fibre types (high modulus polyethylene fibre and a fibrillated polyethylene pulp) in cementitious matrices.

It was noted that in the case of impact resistance, the favorable effect of each fibre was further enhanced in the presence of the other fibre. For flexural strength and toughness, the combined use of polyethylene fibre and pulp produced highly desirable results. The authors also noted that the negative effect of fibres on compressive strength was less pronounced when the two fibre types were used in combination.

Qian and Stroeven (2000) investigated the optimization of fibre size, fibre content and fly ash content in hybrid polypropylene-steel fibre concrete with low fibre contents. They found that the presence of fine particles of an admixture helped fibre dispersion and that different sizes of steel fibres contributed to different mechanical properties. Additions of a smaller fibre had a significant influence on the compressive strength, but splitting tensile strength was only slightly affected. The authors found that the optimum dosage of polypropylene fibre was 0.15% and concluded that synergy existed in their hybrid fibre composites.

2.11.2 Other Properties of HyFRC

The benefits of hybridizing fibres are observed not only in flexural and compressive toughness but also in the other properties. The interaction between polyethylene fibre and pulp in controlling the specific gravity, volume of permeable voids, and water absorption capacity of continuous materials has been found to be either negligible or only moderately significant (Komlos, et al., 1995).

Schaumann et al. (2008) conducted experimental and modeling studies on polypropylene and steel fibres, in beams with or without conventional stirrups. In general, fibres proved to be more effective in high-strength concrete than in normal strength concrete based on ultimate load and overall ductility. Steel fibres were found to be far more effective than polypropylene fibres. In tests, where a combination of fibres and stirrups was used, a slightly increase in ultimate load with major improvements in ductility were noted in comparison to beams made of plain concrete.

In another investigation (Group 6), floor slabs were tested under static loading. They were related to the toughness characteristics by testing beams according to ASTM C 1399. A 30 MPa plain concrete slab and slabs containing fibre reinforcement (fibre contents of 0.25% and 0.35%) were examined. The fibres used in the investigation were macro steel and micro polypropylene. From the acquired data, maximum peak load, flexural strength and the average residual strength from the beam specimens was calculated. The authors proposed to relate the residual strength of FRC to an increase in structural capacity of slabs.

Durability studies were conducted by Larsen and Krenchel (1991), who examined steel, AR-glass, synthetic (polypropylene) and natural (sisal and paper pulp cellulose) fibre-reinforced concrete for exposure to climatic conditions. They concluded that natural and glass fibres lose strength and ductility when subjected to normal out-doors exposure. They also investigated a combination of what they believed to be the best fibres (steel and polypropylene), and found that the ductility and fracture energy of the composites were increased significantly even after a very long period of exposure. The researchers concluded that fracture energy for composites will change with time, depending on the type of reinforcement and the matrix.

Under repeated loading, fibre-reinforced concrete containing several volume fractions of two types of fibres, polypropylene and steel fibre content led to balling, while the increase in polypropylene fibre content led to a harsh mix. The fracture and impact energy, as well as toughness and ductility were found to be substantially improved by an increase in the volume fraction of polypropylene fibres.

In an investigation by Sun et al. (2001), shrinkage and water permeation properties of high-performance concrete with expansive agents and hybrid fibres (steel, polyvinyl alcohol and polypropylene fibres) were studied. Test results indicated that the hybrid fibres of different types and sizes could reduce the size and amount of cracking at different levels.

Kim and Sakai (1997) investigated hybrid fibre-reinforced concrete containing micro and macro fibres to enhance the resistance to cracking by thermal stresses. The physical properties and crack resistance at early ages were examined. In this investigation, steel fibres and polypropylene fibres of 6, 12, and 30 mm in length were used. It was concluded that hybrid fibre-reinforced concrete had high resistance to thermal cracks and it was possible to control these cracks. In the case of steel fibres, crack resistance improved monotonically with fibre volume in the range of 0.1-2.5%. However, for polypropylene fibres, 0.3% was the optimum volume fraction.

Synergy in cement-based hybrids is not only in terms of toughness but also in terms of other secondary properties such as electrical conductivity. This is evident from the research carried out by Banthia et al. (1992), where synergy was observed in electrical conductivity due to the use of carbon (micro) and steel (micro) fibres. Electrical resistivity measurements were conducted on cement pastes reinforced with conductive micro-fibres of carbon and steel both in mono and hybrid forms, using a high frequency alternating current. Although carbon fibres themselves are far less conductive than steel fibres, cement composites with carbon fibres were found to be far better conductors than those with steel fibres. It was concluded that, more than the conductivity of the material itself, it is the size and the distributions of the fibre in a composite were found to have conductivities better than their equivalent mono-fibre systems. Improvements in conductivity with carbon fibre were by almost three orders of magnitude as opposed to one order of magnitude increase for steel fibres. Increase in conductivity with increase in the volume fraction of the fibres was also noticed for steel and carbon fibres, but the increase in conductivity because of steel fibres was lower than that due to carbon fibres. They concluded that the two fibres in a hybrid composite had an interactive behavior rather than a purely additive behavior.

To summarize then, it is clear that the concept of hybridizing fibres is a sound one and significant improvements have been reported by various investigators. It is also clear that the influence of concrete matrix strength is not well understood. Equally essential is to develop some rational guidelines for fibre hybridization, and some such attempts were made in this thesis.

2.12 Experiments by Sivakumar and Santhanam (2007)

The effect of a hybrid combination of metallic and non-metallic fibres was investigated by Bentur and Mindess (1990), Komlos et al. (1995), Yao et al. (2003) and Sivakumar and Santhanam (2007b). The fibres used by Sivakumar and Santhanam (2007) were hooked steel, polypropylene, polyster and glass (Table 2.2). The concrete strength was 60 MPa and its workability was 75-125 mm.

Table 2.2: Physical and mechanical properties of various fibres used (Sivakumar and Santhanam, 2007)

Property	Hooked steel	Polypropylene	Glass	Polyster
Length (mm)	30	20	6	12
Diameter (mm)	0.5	0.10	0.01	0.05
Aspect ratio	60	200	600	240
Specific gravity	7.8	0.9	2.72	1.35
Tensile strength (MPa)	1700	450	2280	970
Elastic modulus (GPa)	200	5	80	15
Failure strain (%)	3.5	18	3.6	35

The volume fractions of various fibres used in mixtures are given in Table 2.3. The following specimens were prepared: 100 mm cubes (compression tests), 100 mmx200 mm cylinders (split tensile strength tests) and 100x100x500 mm beam specimens (flexural tests). The results for the compressive, split tensile and flexural strengths and modulus of elasticity for all the mixtures are presented in Table 2.4. An enhancement in the compressive strength compared to control concrete occurred for the steel fibre concrete and all hybrid fibre concretes. The maximum increase in the compressive strength was only of the order of 15%. The concretes with individual non-metallic fibres did not register any increase in the compressive strength. For all fibre concrete mixtures, there was a corresponding increase in the modulus of elasticity as compared to the control concrete. The split tensile strengths of hybrid fibre concretes were found to be higher as compared to reference and mono-steel fibre concrete. The hybrid fibre concretes containing steel and polypropylene (HSPP3 and HSPP6) showed the highest split tensile strength among all concretes. The glass fibres, possibly owing to their short lengths did not perform as well as the other two non-metallic fibres.

Table 2.3: Dosage of different fibre combination used (Sivakumar and Santhanam, 2007)

Mixture	Volume fraction of hooked end (%)	Volume fraction of non-metalic fibre (%)	Fibre dosage (kg/m³)				Total fibre dosage (kg/m³)
			S	PP	PO	G	
C1	-	-	-	-	-	-	-
HST2	0.50	-	39.98	-	-	-	39.98
HSPP3	0.38	0.12	27.22	1.34	-	-	28.56
HSP04	0.38	0.12	27.22	-	1.82	-	29.04
HSGL5	0.38	0.12	27.22	-	-	3.84	31.06
HSPP6	0.25	0.25	19.44	2.26	-	-	21.70
HSPO7	0.25	0.25	19.44	-	3.36	-	22.8
HSGL8	0.25	0.25	19.44	-	-	6.77	26.21
HSPP9	0.12	0.38	9.36	3.41	-	-	12.77
HSPO10	0.12	0.38	9.36	-	5.14	-	14.50
HSGL11	0.12	0.38	9.36	-	-	10.32	19.68
PP12	-	0.50	-	4.5	-	-	4.5
PO13	-	0.50	-	-	6.72	-	6.72
GL14	-	0.50	-	-	-	13.62	13.62

Note: S-steel fibre, PP- polypropylene fibre, PO- polyster fibre, G- glass fibre.

The flexural testing results are presented in Figure 2.8 and Table 2.4. Compared to concrete without fibres, all fibre-reinforced concretes showed an appreciable increase in flexural strength. Among all fibre concretes, a hybrid combination of steel and polyester showed the maximum flexural strength. The reason could be due to a smaller length and high aspect ratio of polyester fibres, which gave a high reinforcement index. A steel-polypropylene and steel glass combination showed a reasonable increase in the flexural strength compared to plain and mono-steel fibre concrete.

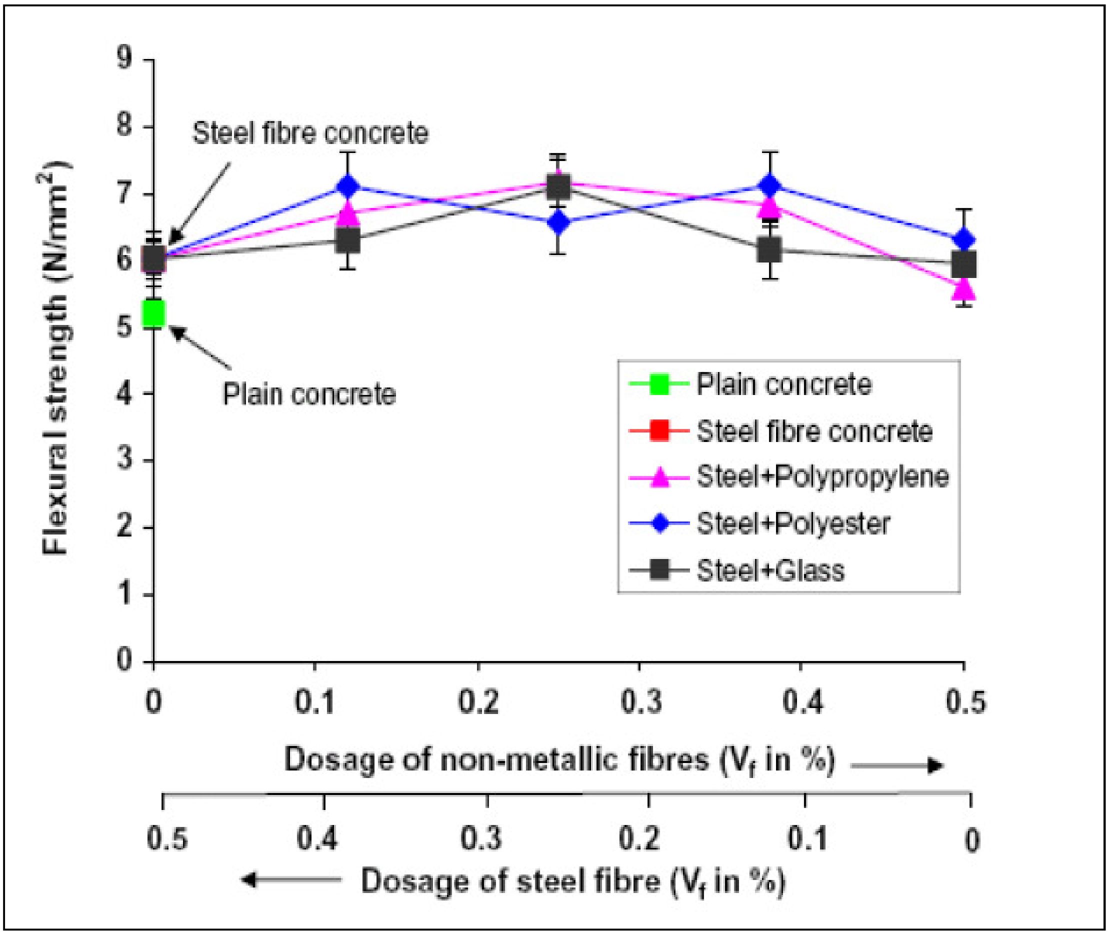


Figure 2.8: Flexural strength of various hybrid fibre contents (Sivakumar and Santhanam, 2007)

Table 2.4: Compressive loading tests of various fibre contents (Sivakumar and Santhanam, 2007)

Mixture	Mean compressive strength (MPa)	Mean split tensile strength (MPa)	Mean modulus of elasticity (GPa)	Ultimate flexural strength (MPa)
C1	56.1	4.1	31.1	5.2
HST2	59.2	5.2	33.2	6.0
HSPP3	61.1	5.3	34.8	6.7
HSP04	62.4	5.2	35.2	7.1
HSGL5	59.2	5.3	34.1	6.3
HSPP6	64.7	5.5	35.1	7.3
HSPO7	58.6	5.4	35.6	6.6
HSGL8	60.3	4.9	34	7.1
HSPP9	63.4	4.9	35.5	6.8
HSPO10	64.2	5	35.6	7.1
HSGL11	62	4.8	34.8	6.2
PP12	56.1	4.4	33.1	5.6
PO13	55.1	4.7	34.8	6.3
GL14	57.8	4.3	33.7	6.0

2.13 Dynamic Experiments

There are laboratory tests available for determining the dynamic properties and impact resistance of steel-fibre-reinforced concrete. These may be broadly categorized into drop weight impact tests and projectile impact tests (Suaris and Shah 1984). A number of experimental studies on the impact behaviour of SFRC have been carried out and all of these studies, regardless of the test method employed, demonstrated that the impact resistance of SFRC is, in general, substantially higher than that of plain concrete. Song et al. (2004) applied the drop weight impact test method to evaluate the impact resistance of concrete and found that, by adding 1.5% by volume of steel fibres to plain concrete, the average number of blows required to produce the first crack could be increased by 418% and the average number of blows required to cause failure could be increased by 518%. On the other hand, Ong et al. (1999) applied the projectile impact test method using a projectile with a hemispherical nose and found that the amounts of impact energy required to cause failure of concrete slabs, each containing 1% or 2% by volume of steel fibres, were respectively 100% and 136% higher than that of plain concrete.

According to Bonzel and Dahms (1981), the impact resistance of fibrous concrete is significantly higher (Figure 2.9). It grows with increasing fibre dosage.

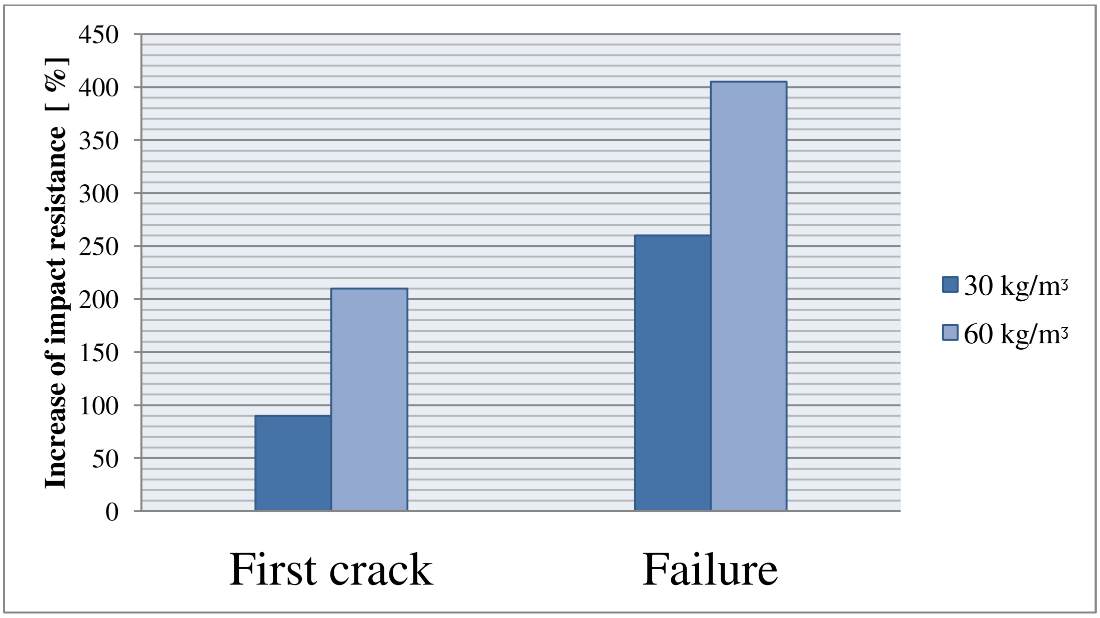


Figure 2.9: Increase of impact resistance with respect to plain concrete and different volume fraction of steel fibres (Bonzel and Dahms, 1981)

3.0 MATERIALS AND METHODOLOGY

3.1 Introduction

In the Strategic Highway Research Program (SHRP), high performance concrete (HPC) was initially defined by three requirements:

- Maximum water-cementitious material ratio of 0.35
- Minimum durability factor of 80% after 300 cycles of freezing and thawing
- Minimum compressive strength of either:
  - (a) 21 MPa within 4 hours after placement;
  - (b) 34 MPa within 24 hours;
  - (c) 69 MPa within 28 days,

"High performance" in high performance concrete may imply high strength, high durability and/or other characteristics needed for a specific application. In this context, toughness is another property implying high performance, specifically for fibre reinforced concrete and the toughness tests provide a quantitative measure of this property.

3.2 Materials

In the process of fibre-reinforced concrete (FRC) production, all raw materials have to be careful inspected to avoid any flaws or defects. The properties of main raw material such as nylon fibre, polypropylene fibre, steel fibre, cement, silica fume, coarse aggregate, fine aggregate, water, and superplasticizer have been identified. There are two main section of testing including the fresh and hardened concrete tests. The procedures of tests, the essential apparatus and the properties of materials are given in detail below, as shown in Figure 3.1.

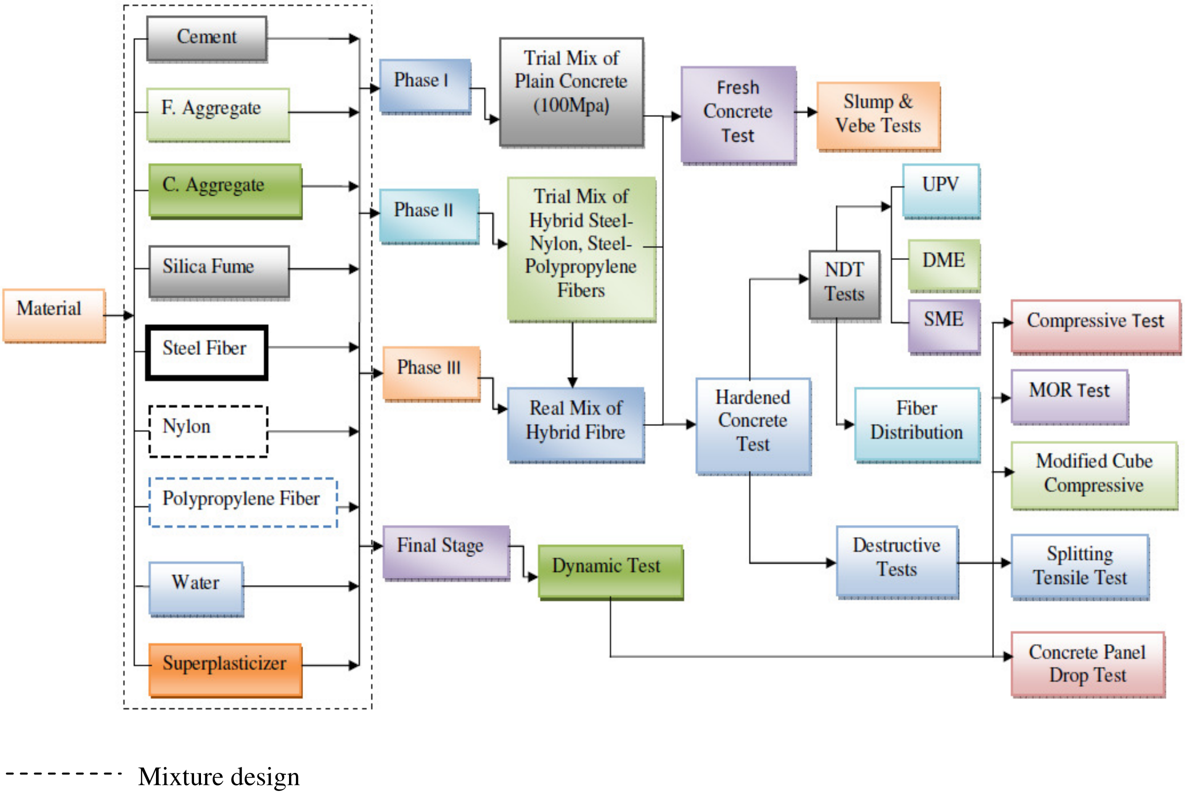


Figure 3.1: The Flow Chart of Materials and Methodology

3.2.1 Cement

For the research work, cement used in the mixing is Ordinary Portland Cement Type 1 (OPC). The cement was manufactured by Tasek Corporation Berhad. The brand of the cement is Tasek Cement which has fulfilled the requirement stated in Malaysian Standard MS 522 which is loosely based on the British standard BS 12. It is a leading brand in the construction industry and is extensively used in projects of all sizes. The colour of it is brownish grey. It is stored in an airtight steel drum to prevent from moisturization before use. A typical chemical composition of cement is shown in Table 3.1.

Table 3.1: A typical chemical composition of cement used below

Compositions and properties of cement	***Ordinary Portland Cement (OPC)***
SiO_2 (% by wt)	21.28
CaO (% by wt)	5.60
$Al_2 O_3$ (% by wt)	3.36
Fe_2O_3 (% by wt)	64.64
MgO (% by wt)	2.06
SO_3 (% by wt)	2.14
Total Alkalis	0.05
Insoluble Residue	0.22
Loss on Ignition	0.64
Modulus	
Lime Saturation Factor	0.92
Silica Modulus	2.38

3.2.2 Coarse Aggregate

Coarse aggregates make up about 70-80% of volume of concrete. Particle from rock fragments are the most common of aggregate. Therefore, its selection and proportioning should be concerned properly in order to control the quality of the concrete. The aggregate material must be strong, durable and inert to give satisfactory performance and the sizes must be appropriate to fulfill the intended application. The coarse aggregate used during the experiment was crushed granite with maximum size of 19 mm (3/4") obtained from a quarry site. It was angular in shape and rough surface texture. In this study, coarse aggregate was obtained in Selangor from Hanson Quarry of Cheras. The crushed granite was kept inside laboratory which are sheltered from rain or other humid source. This is to ensure that the moisture content does not vary in each casting. To get the maximum size of 19 mm coarse aggregate, a 19 mm sieve was used to remove the unwanted materials such as leaves, branches of tree and larger size of aggregate. Then, it was dried in an open air for not less than 24 hours. It is to prevent the moisture content in the aggregate affecting the concrete production.

There are three tests were done to investigate the coarse aggregate, sieve analysis, specific gravity and water absorption. According to test of BS822: Clause:11, the result of sieving analysis showed that the coarse aggregate is in the range of 15mm to 25mm nominal size. The fineness modulus of coarse aggregate is 4.92. Besides, according to test of BS882:Clause 19, the properties of coarse aggregate are:

Table 3.2: Properties of coarse aggregate

PROPERTIES OF COARSE AGGREGATE	***STANDARD VALUE***
Specific Gravity (SSD)	2.75
Specific Gravity (Oven dry)	2.73
Specific Gravity (Apparent)	2.79
Water absorption (%)	0.72
Moisture content (%)	0.26
Finess modulus	4.92

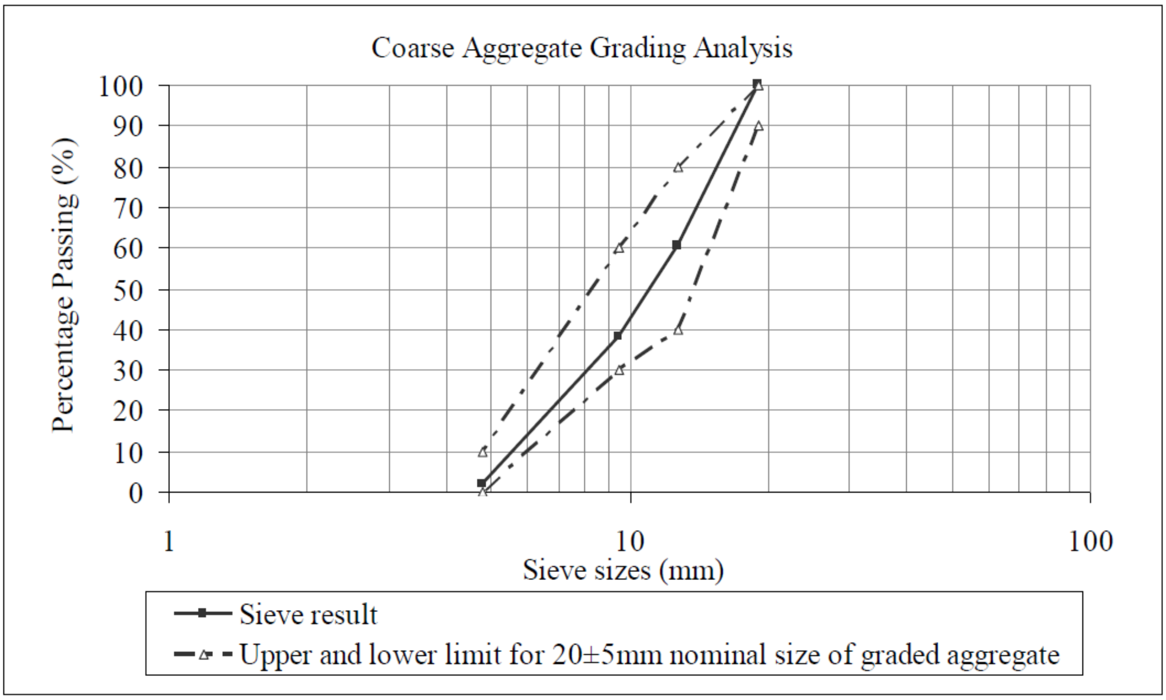


Figure 3.2: Sieving analysis of coarse aggregate

3.2.3 Fine Aggregate

The fine aggregate used in the experiment is mining sand available from Hanson Quarry Selangor. The mining sand with a maximum size of 5 mm was used as fine aggregate. The sand was stored in a shaded area and sheltered from rain to ensure that the sand was saturated surface dry. After sieving using size of 4.75 mm and below, the fine aggregate was dried in an open air before use.

Several tests were done to determine the properties of the fine aggregate. These included specific gravity and water absorption, and the sieve analysis. According to BS812:Clause 21, the fine aggregates was certified in Zone 2 as shown in Figure 3.3. The finess modulus is 3.00. Besides, according to BS812:Clause 28, and BS822:Clause 11, the properties of t fine aggregate are :

Table 3.3: Properties of fine aggregate

PROPERTIES OF FINE AGGREGATE	***STANDARD VALUE***
Specific Gravity (SSD)	2.52
Specific Gravity (Oven Dry)	2.48
Specific Gravity (Apparent)	2.58
Water absorption (%)	1.45
Mositure content (%)	0.62
Finess modulus	3.00

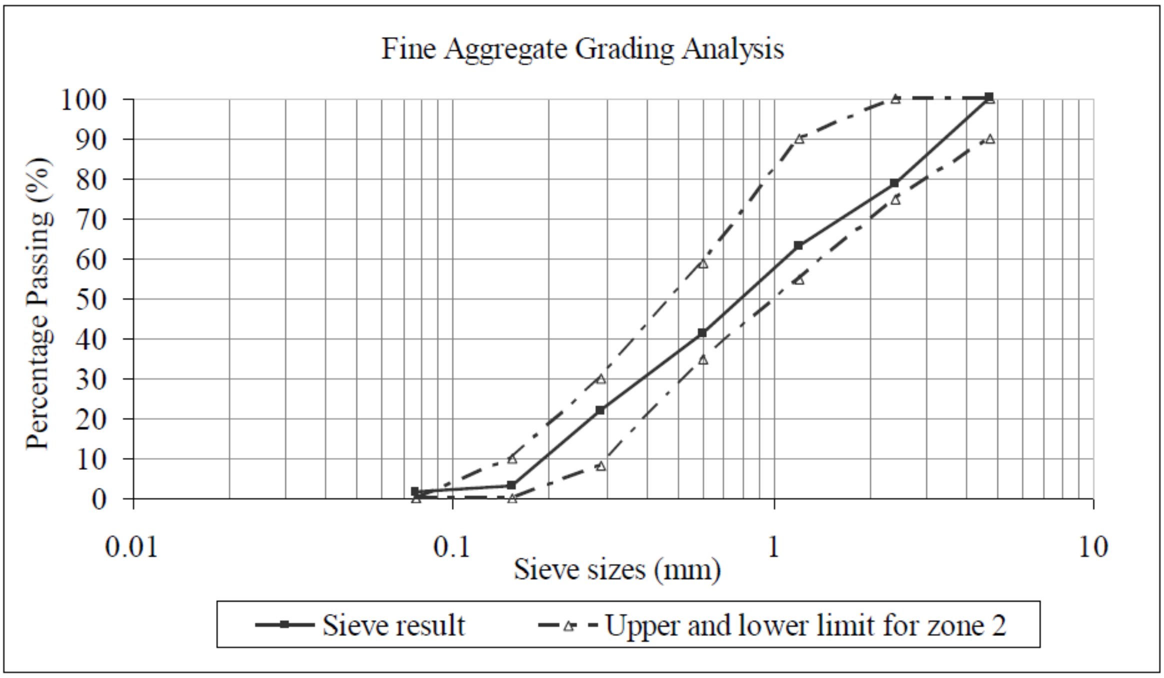


Figure 3.3: Sieving analysis of coarse aggregate.

3.2.4 Water

Water at a temperature of 27 ℃ was used for concrete mixing and curing. The water used for concrete mixing and curing was free from any impurities to ensure that the strength and durability of the concrete are not affected. In the lab, the water filter was set up as the cleanliness of the mixing water was remaining high. The specific gravity of the water for mixing was assumed as 1.0.

3.2.5 Superplasticizer

One of the serious shortcomings of fibre-reinforced concrete is that the workability is greatly reduced due to the addition of fibres. This problem can be corrected by adding admixtures such as superplasticizers. Superplastisizers (high-range water reducers) are added to a concrete mix (with a low to normal slump and low water-cementing materials ratio) to help increase its slump and flowability. Superplastisized concrete unfortunately entraps more air than conventional concrete, but most of this air is generally lost during transportation and casting using vibrators. In this study, GLENIUM ACE 388 (RM) SURETEC procured from BASF Company was used to increase the workability of fresh concrete and to aid in the strength improvement of the hardened concrete.

For historical reasons, polynaphthalene sulfonate superplastisizers have been most commonly used in North America and Japan, while polymelamine superplasticizers are commonly used in Europe (Aitcin and Mindess, 1988). In the case of high strength concrete, where fine mineral admixtures such as silica fume are used, it is very important to have an effective superplasticizer which would accommodate the high demand of workability in the mix.

For this study a superplasticizer added during the casting is an innovative based superplasticiser with super retention technology. Due to a specifically tailored constitution of the active material, this admixture shows formerly unknown adsorption characteristics to cement. As a result, polycarboxylic ether (PCE) provides exceptional good early strength development. While conventional admixture for high early strength concomitantly suffer from high workability loss over time and eventually lower final strength, polycarboxylic ether (PCE) overcomes this dependency and provides much improved slump retention and vastly increased final strength of concrete. It is formulated to comply with ASTM C494 (1998) for Type F and G admixtures.

The normally recommended dosage rate is 0.75-1.2. litres per 100 kg of cement. To ensure proper handling and storage of the material, the superplasticizer must be stored in a place where the temperature is not below 0℃. In case the product freezes, increase the temperature of the product to 30 ℃ and remix. The storage incompatibility of the material is with strong oxidising agents, alkalis and acids. It must avoid contact with metal such as iron. The superplasticizer was diluted before mixing with the concrete. Polycarboxylic ether (PCE) is a liquid admixture to be added to the concrete during the mixing process. The best results are obtained when the admixture is added after all the other components are already in the mixer and after the addition of at least 80% of the total water. Furthermore it is not recommended to add superplasticizer together with dry aggregate or cement, as it lowers the plasticising effect or water reduction ability.

3.2.6 Mineral Admixtures- Silica Fume

High-strength concretes generally contain one or more supplementary cementitious materials such as fly ash, silica fume, blast furnace slag, metakaolin, etc. Until a few years ago, 40 MPa concrete was considered to be high strength, but today, using silica fume, concrete with compressive strength in excess of 100 MPa can be readily produced. It enables to achieve very flowable concrete without segregation and very high compressive strengths in the range of 70-120 MPa. Silica fume also lubricates the concrete and increases pumpability. The advantages of using additives such as silica fume facilitate production, cost saving benefit, and increases durability. It is interesting to note that the use of about 10% silica fume in high-performance concretes with very low water/binder ratios results in a significant decrease in the superplastisizer dosage required for a given workability (Rougerson and Aitcin, 1994). The silica fume used for this research investigation was procured from Scancem Materials Sdn. Bhd.

Silica fume is a filtered powder generated from the reduction of high purity quartz – ferrosilicon metals or silicon metals. Silica fume consists primarily of very fine smooth spherical silicon dioxide particles with an extremely high surface area. Silica fume's chemical and physical typical composition is shown in Table 3.4 in comparison with OPC cement and fly ash.

Table 3.4: Chemical and physical composition of cementitious materials

	Unit	OPC	Fly Ash	Silica Fume
SiO_2	%	17-25	40-55	90-98
CaO	%	60-67	1-5	0.2-0.7
Al_2O_3	%	2-8	20-30	0.4-0.9
Fe_2O_3	%	0-6	5-10	1-2
Other	%	1-8	4-15	2-3
S.G	-	3150	2100	2200
Bulk density	Kg/m^3	1400	900-1000	550-650
Surface Area	m^2/kg	200-500	200-600	20,000

Silica fume improves concrete through two mechanisms:-

1) Pozzolanic effect:

When water is added to OPC, hydration occurs forming two products, as shown below:

$$OPC + H_2O \longrightarrow CSH\ (\text{Calcium silicate hydrate}) + Ca\,(OH)_2 \qquad (3.1)$$

In the presence of silica fume, the silicon dioxide from the silica fume will react with the calcium hydroxide to produce more aggregate binding CSH as follows:-

$$Ca(OH)_2 + SiO_2 + H_2O \longrightarrow CSH \qquad (3.2)$$

The reaction reduces the amount of calcium hydroxide in the concrete. The weaker calcium hydroxide does not contribute to strength. When combine with carbon dioxide, it forms a soluble salt which will leach through the concrete causing efflorescence, a familiar architectural problem. Concrete is also more vulnerable to sulphate attack, chemical attack and adverse alkali-aggregate reactions when high amounts of calcium hydroxide is present in concrete.

2) Microfiller effect:

Silica fume is an extremely fine material, with an average diameter 100x finer than cement (Figure 3.4). At a typical dosage of 8% by weight of cement, approximately 100,000 particles for each grain of cement will fill the water spaces in fresh concrete (Figure 3.5). This eliminates bleed and the weak transition zone between aggregate and paste found in normal concrete. This microfiller effect will greatly reduced permeability and improves the paste-to-aggregate bond of silica fume concrete compared to conventional concrete.

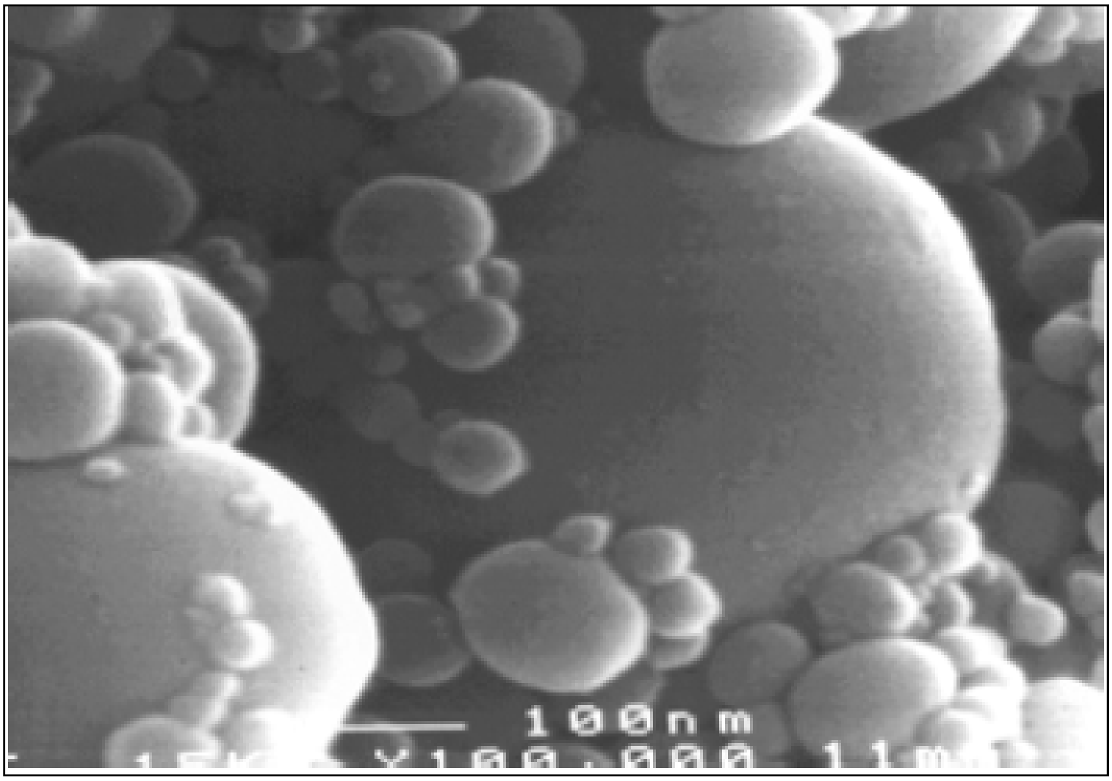


Figure 3.4: Silica Fume is 100x finer than cement and the particles are spherical (SEM photo)

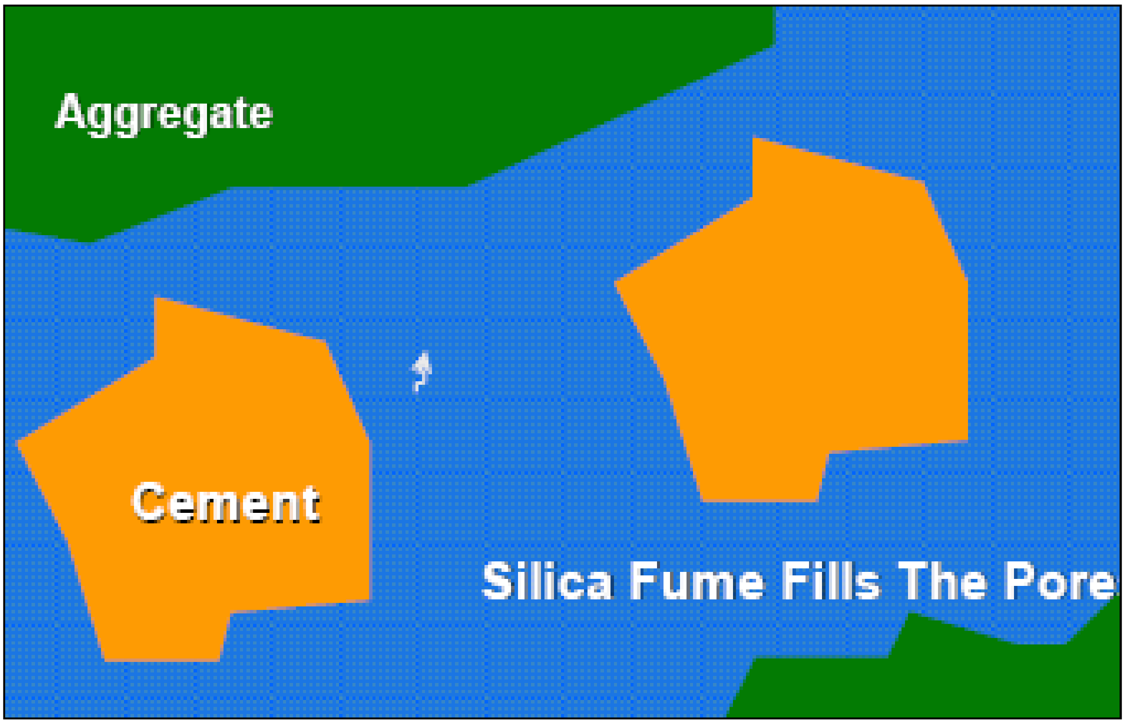


Figure 3.5: Approximately 100,000 Silica Fume particles fill the space between cement grains

The silica reacts rapidly (Figure 3.6) providing high early age strengths and durability. The efficiency of silica fume is 3-5 times that of OPC and consequently vastly improved concrete performance can be obtained.

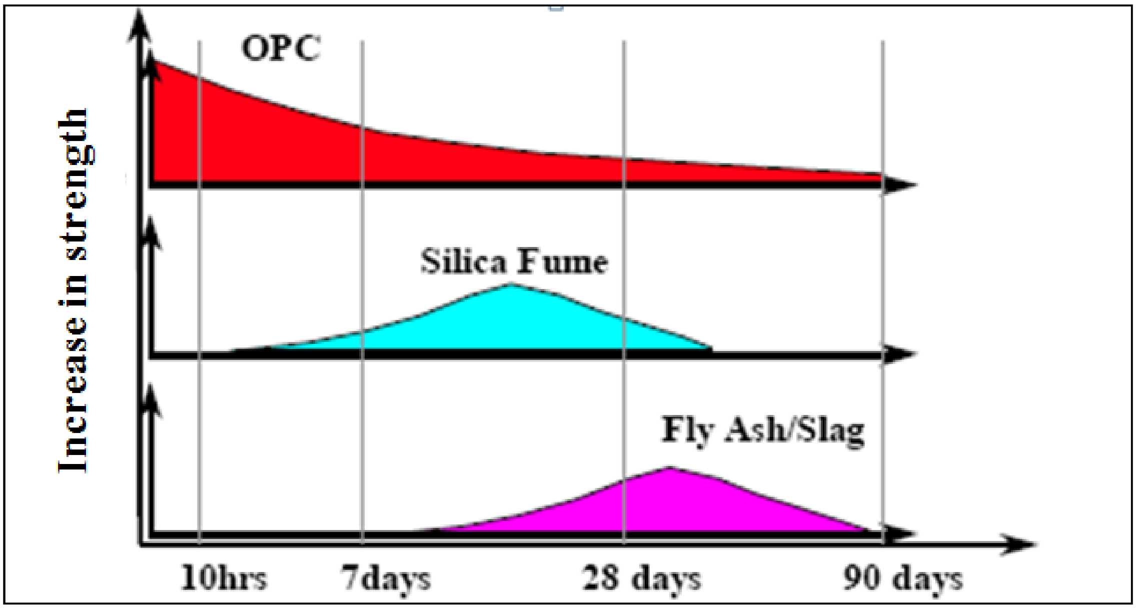


Figure 3.6: Silica fume contributes predominantly to strength between 3-28 days

3.2.7 Fibre (Steel, Nylon and Polypropylene)

3.2.7.1 Steel Fibre (Fig 3.7)

The steel fibre used during casting is obtained from Scancem Materials. The steel fibres are made from hard drawn low carbon steel, in accordance to ASTM A820.90 Type 1 and have a tensile strength of 1200 MPa. It has a length of 35 mm and aspect ratio of 65. The specific gravity of the steel fibres is 7.84. There are hooks at both ends of the steel fibre to enhance the bonding between steel and concrete. The percentage volume fraction of nylon, polypropylene and steel fibres were added into the concrete based on the optimum fibre content in the proportion of 0.1% to 0.4% and 0.1% to 0.9%. The steel fibre used for this research investigation was procured from Scancem Materials Sdn. Bhd.

3.2.7.2 Nylon Synthetic Fibre (Fig 3.8)

Nylon fibre is 100% pure virgin nylon 6 fibre, supplied as a filamentized fibre bundle. Its ability to absorb about 4% moisture (i.e. 25 ml of water per cubic metre of concrete at recommended dosage) gives an enhanced bond to the concrete matrix. Nylon has a tensile strength which is 896 MPa. For concrete, the length of nylon fibres used is 19mm. The specific gravity and modulus of elasticity of nylon are 1.14 and 5.17 GPa, respectively. The melting temperature of nylon is about 225˚C. The main application for synthetic fibres is to eliminate early age cracking and any resultant long-term problems. The Nycon fibres called nylon 6 used for this research investigation were procured from Scancem Materials Sdn. Bhd.

3.2.7.3 Polypropylene Synthetic Fibre (Fig 3.9)

Polypropylene fibres are produced from homopolymer polypropylene resin. Polypropylene has a tensile strength of 413 MPa. For concrete, the length of polypropylene fibres used was 12 mm for concrete. The specific gravity and modulus of elasticity of polypropylene are 0.91 and 4.11 GPa, respectively. Polypropylene fibres are known for their high alkali resistivity, and therefore would be expected to retain their strength in the highly alkaline matrix. Sensitivity to UV radiation is not expected to be critical since the polymer is protected by the matrix. The melting temperature of polypropylene is about 165˚C. The SikaFibre-M used for this research investigation was procured from Sika kimia Sdn. Bhd.

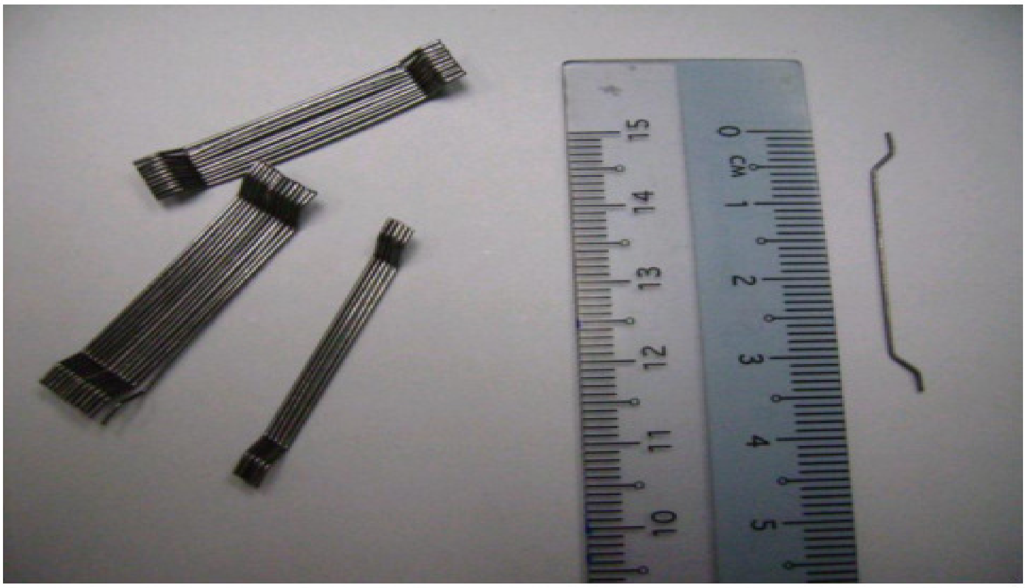


Figure 3.7: Steel fibre (35 mm length)

Figure 3.8: Nylon fibre (19 mm length)

Figure 3.9: Polypropylene fibre (12 mm length)

3.2.8 Fibre Distribution of Nylon and Polypropylene

The in-concrete distribution of nylon and polypropylene fibres was approximated through the distribution of these fibres in the mixing water. To approximate the distribution, 3 g of nylon and polypropylene fibres were respectively introduced into a 6 x 80 cm cylindrical glass measure filled with 1000 g of the mixing water. After the introduction, the measure was stoppered, vigorously agitated, and allowed to stand for 3 hours as shown in Figure 3.10, It was observed that the nylon fibres had a more marked dispersion in the mixing water compared to polypropylene, implying that the nylon fibres distributed themselves more thoroughly throughout the concrete.

Figure 3.10: Nylon (left) and polypropylene (right) fibres distribution

3.3 Mix Design

Mix design can be defined as the selection of ingredients and their proportions. It involves the process of choosing the correct proportion of cement, chemical and mineral admixtures, fine and coarse aggregate and water to produce concrete that is as economical as possible with certain minimum properties such as strength, durability and a required consistency.

Department of Environment, (DOE) method was used to determine the properties of concrete such as workability, strength, density, thermal characteristics, and durability requirements. In DOE method the properties most usually specified are:

1) The workability of the fresh concrete
2) The compressive strength at a specific age

3) The durability, by means of specifying the minimum cement content and/ or maximum free-water/ cement ratio, and in some cases requiring the use of selected types of materials

The concrete mix was designed to achieve Grade 100 at 28 days. The workability was maintained in the range of 20-220 mm slump. To make sure the concrete achieve the required workability, superplasticizer was added into the concrete mix without changing the water content. Thus, the water-to-cement ratio could be maintained and the strength of the concrete would be more consistent.

3.4 Sample Preparation

In concrete sample preparation, the work can be divided into three phases. The first phase is mixing the plain concrete without fibre as it achieved 97 MPa. For the second phase, the concrete trial mix was done to determine the optimum proportion of nylon fibre to give the highest value of strength. Then, the optimum percentage of nylon fibre was carried on from phase II to the real mix of phase III. In the real mix of phase III, the steel fibre was added to enhance the ability of the nylon fibre in concrete where it could offer better engineering properties to the concrete. The proportions of both fibres were different as to obtain the better quality of FRC through several concrete investigation tests. All ingredients of the concrete mixes were prepared according to the calculated mix design proportion and mixed with a laboratory 190 litres capacity concrete drum mixer.

3.4.1 Sample Preparation of Plain Concrete (Phase I)

In the first stage of the concrete preparation, the plain concrete without fibres achieved the compressive strength of 97 MPa at 28 days. The workability is to meet the requirement in the range 180-220 mm in slump test. The mix proportions is as shown in the Table 3.5:

Table 3.5: Design mixture of Grade 97

Item	Trial Mix 1 (kg/m³)
Cement Content	406
Silica Fume	45
Free Water Requirement	131
Fine Aggregate Content	903
19mm Aggregate Content	935
Superplastisizer	Polycarboxylic ether (PCE) (0.45-0.82 litre)
Water/(cement + silica fume) ratio	0.29

3.4.2 Sample Preparation of Hybrid Fibres Trial Mix (Phase II)

For the mixing in phase II, nylon, polypropylene and steel fibres were added into the concrete at different percentages such as 0.1%, and 0.2% volume fraction of nylon and polypropylene fibres and 0.8% and 0.9% steel fibres volume fraction of the concrete. At the early stage, the work was focused on the workability of the concrete. Then it was followed by the compressive strength, flexural strength and splitting tensile tests. For each of the concrete cube the compressive strength was tested at 1, 3, 7 and 28 days. The flexural strength and splitting tensile strength for different percentage of fibres were tested at 28 days. Type of test and details are shown in Table 3.6.

Table 3.6: Hardened test carried out for each mixture of concrete

No.	Test	Specimen Type	Dimension	Testing age (Days)			
				1	3	7	28
1	Compressive	cube	100x100x100 mm	4	4	4	4
2	Flexural	prism	100x100x500 mm	-	-	-	8
3	Splitting tensile	split cylinder	Ø=150xL=300 mm	-	-	-	8

3.4.3 Sample Preparation of Real Mix (Phase III)

For real mix in phase III, the steel fibres was added as supplement to nylon fibres. In the first stage, the concrete was casted based on the optimum content of nylon and polypropylene fibres resulting from phase II. The optimum of 0.1% volume fraction of the nylon and polypropylene fibres were determined and added to 0.4% and 0.9% volume fraction of steel fibre of the concrete volume. In the second stage, the concrete was casted using the optimum content of hybrid fibres that was determined from the result of 0.5% and 1.0% volume fraction of HyFRCs. At the early stage of study, the fresh concrete properties of workability (slump test and Vebe test) and density were determined. In this phase, the samples that were prepared are shown in Table 3.7.

Table 3.7: Type of tests and samples for the real mix concrete (Phase III)

No.	Tests	Specimen shape	Size(mm)	Testing age (Days)			
				1	3	7	28
I. Non-destructive Tests							
1	Ultrasonic pulse velocity	cube	150 x 150 x 150	4	4	4	4
2	Dynamic modulus of elasticity	prism	100 x 100 x 500	-	-	-	3
3	Static modulus of elasticity	cylinder	150 dia x 300 length	-	-	-	3
II. Destructive Tests							
1	Compressive strength	cube	100 x 100 x 100	4	4	4	4
2	Modulus of rupture	prism	100 x 100 x 500	-	-	-	8
3	Modified cube compressive strength	portion of broken prism	-	-	-	-	8
4	Tensile splitting strength	cylinder	150 dia x 300 length	-	-	-	8

3.4.4 Final Stage of Sample Preparation

In this stage slabs with dimension of 600×600×50 mm were casted with plain concrete content of 0% fibre and 0.1% V_f of nylon and polypropylene fibres to 0.4% and 0.9% V_f of steel fibres of the hybrid fibres reinforced concrete. The slabs were used for impact test using a modified concrete panel drop test machine. The test for the fibre-reinforced concrete with different fibre content was carried out at 28 days from the date of the concrete was casted. In this phase, details of the slabs are shown in Table 3.8.

Table 3.8: Impact test carried out for each mixture

No.	Test	Specimen Type	Dimension	Testing age			
				1	3	7	28
1	Impact test	small scale slab	600x600x50 mm	-	-	-	3

3.5 Fresh Concrete Test

3.5.1 Slump Test

The slump test (Figure 3.11) is a simple, quick and cheap test to perform. It is almost universally used for nearly all types of medium to high workability concrete. This test is also very useful in detecting variations in uniformly of a mix of given nominal proportions. There are also some differences in practice with its use in different countries, mostly following to the British and American standards.

The British and European Standards specify that the slump should be measured to the highest point of the concrete, whereas the American standard specifies measurement to the displaced original centre of the top surface of the concrete. The same test on the same concrete can give different values depending on where it is performed.

The principle of slump test is based on measuring a flow property of concrete under self-weight after standard compaction. It is not only suitable for medium and high workability concrete; it is also sensitive to small changes in water content. Furthermore it is very simple and suitable for site use. The only problem is it is heavily operator dependent.

At the start of the test, a mould was placed on a smooth, horizontal, rigid and non-absorbent surface that is free from vibration and shock. The apparatus used is a cone with bottom diameter 200 mm and with a height of 300 mm together with a 600 mm long tamping rod. It was important to ensure that the internal surface of the mould was clean and damp but free from superfluous moisture. Firstly the cone was filled with concrete in three equal layers, and each layer is compacted with 25 strokes of the tamping rod. Then the cone is slowly raised and the concrete is allowed to slump under its own weight. The slump is measured using the upturned cone and slump rod as a guide. (Figure 3.11) In the test, the BS 1881 Part 102 was followed and hence the slump is measured to the highest point of the concrete. The apparatus of slump test is shown in Figure 3.12.

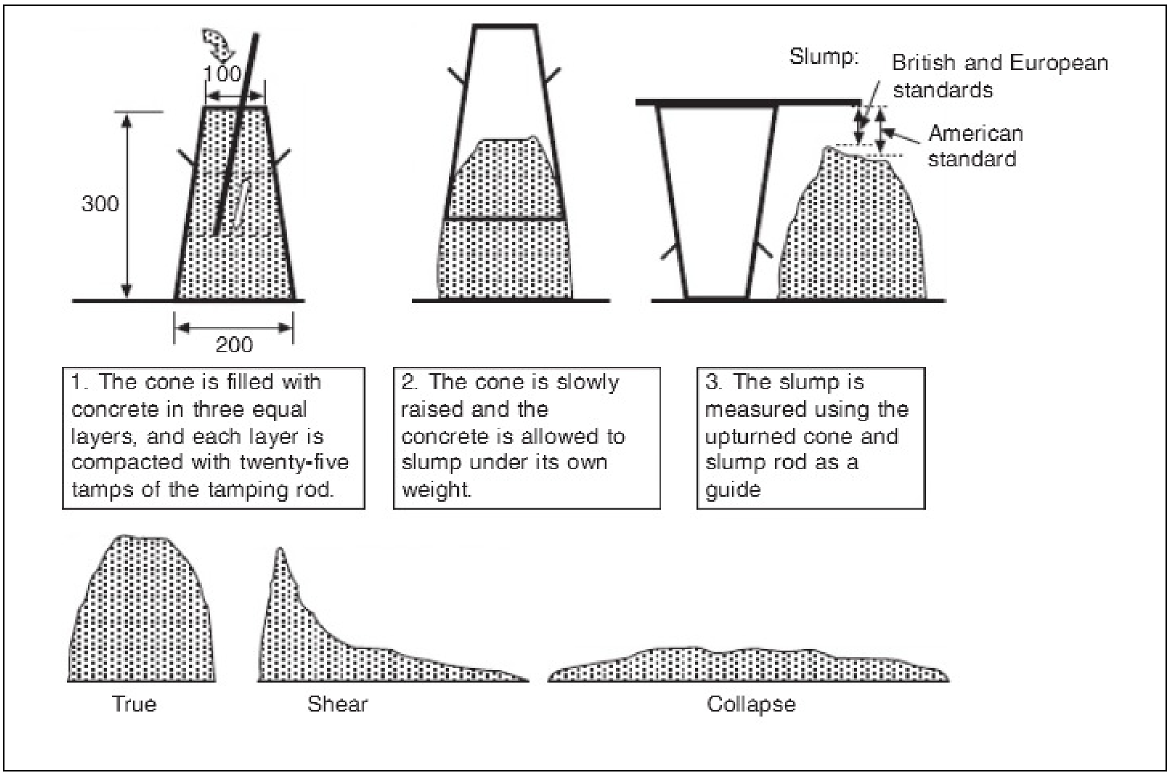


Figure 3.11: The slump test (BS 1881 Part 102: 1983; BS EN 12350-2: 2000; ASTM C143-90a).

Figure 3.12: Determination of slump using the slump test

3.5.2 Vebe Test

Vebe test is shown in Figure 3.11 BS 1881: Part 104: 1983 described the method for determination of Vebe time. It measures the amount of work (time at constant vibration) for full compaction.

It is suitable for very low and low workability mixes and it shows a greater relation to concrete placing conditions than slump. Vebe test is more complex than other methods which requires standard vibrating equipment and sometimes difficult to define end point.

In this test, the time for the concrete shape to change from cone shape to compacted concrete is taken. The duration time is defined as Vebe time and it is stated in the nearest 0.5 second. This test is very sensitive to the consistency, flow and compactable changes of the concrete. Therefore, there is a relationship between the concrete workability of this test at lab with that on site. This test is similar with the method of concrete casting at site.

The mould was hold firmly against the surface below with the funnel, that in position at the top whilst it was filled in three layers of concrete, each approximately one-third of the height of the mould when tamped. Each layer was tamped with 25 strokes by using a 16 mm diameter, 600 mm long tamping steel rod in a way of gravity falling. Each layer was tamper to its full depth, ensuring that the tamping rod through the second and top layers into the layer immediately below. After the top layer has been tamped, the funnel was removed and the concrete level striked off with the top of the mould with a sawing and rolling motion of the tamping rod. With the mould still held down, from the surface below was cleaned off any concrete which may have fallen onto it or leaked from the lower edge of the mould.

When the filling was completed, the top surface was leveled. The cone was removed from the concrete by raising it vertically, slowly, and carefully, in 5-10 seconds without any lateral or twisting motions. Immediately after the cone was removed, the glass plate holder was put onto the concrete in gentle motion. This was then vibrated at a controlled frequency and amplitude until the lower surface of the transparent disc was completely covered with grout. The duration time of the concrete to be compacted was taken as Vebe time. The apparatus of Vebe test is shown in Figure 3.14.

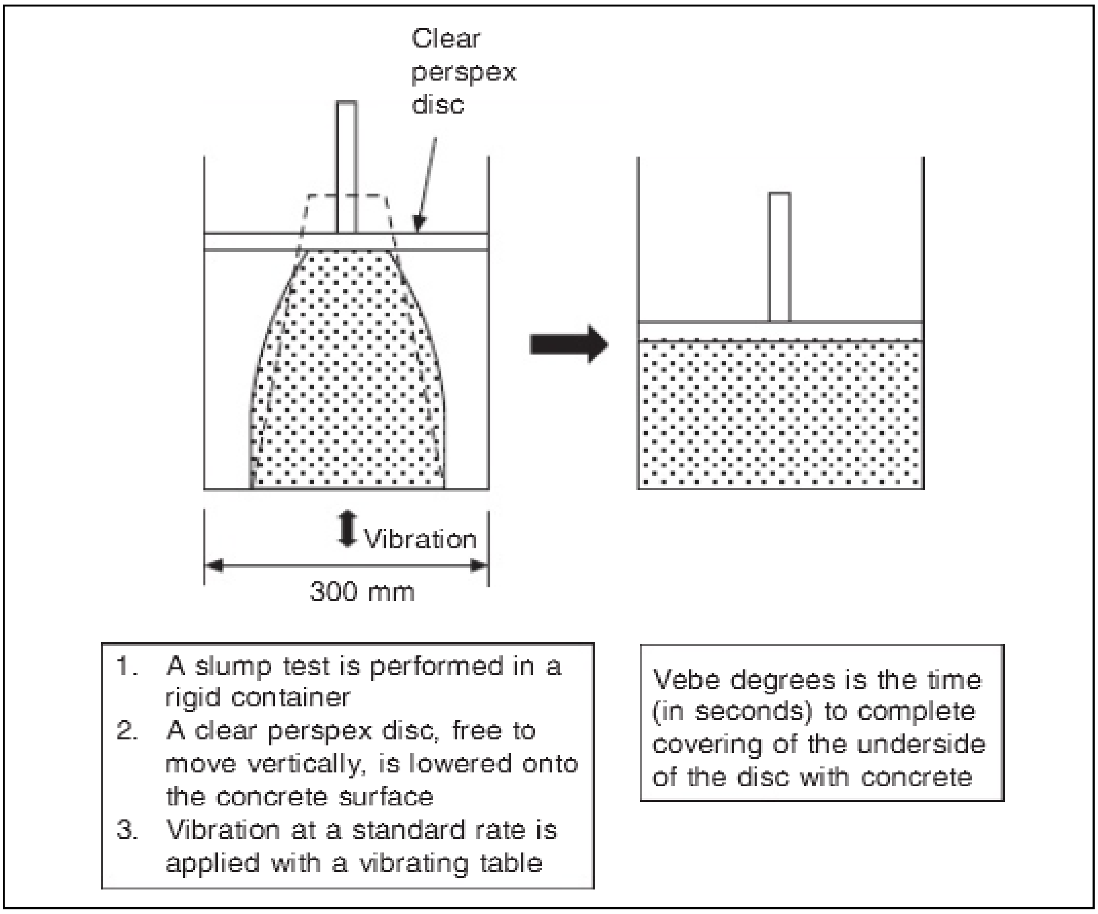


Figure 3.13: The Vebe test (BS 1881 Part 104: 1983, BS EN 12350-3: 2000)

Figure 3.14: Apparatus of Vebe test

3.5.3 Density of Fresh Concrete

Density of fresh concrete can be measured in accordance with BS1881: Part 107:1983. It can be obtained by weighing the compact fresh concrete in a standard container of known volume and mass. The top of the container was cleaned of any excess concrete. The concrete density of fresh concrete was determined as follows:

$$\rho = \frac{m}{V} \qquad (3.1)$$

Where, ρ =density of fresh concrete in kg/m^3

m= mass of fresh concrete in unit kg

V= in unit m^3

3.6 Hardened Concrete Test (Non-Destructive Tests)

3.6.1 Ultrasonic Pulse Velocity Test

The test procedure is given in BS1881: Part 203:1986. The Ultrasonic Pulse Velocity (UPV) Test is based on the measurement of speed of a sound wave with the density of its propagation. Generally, the speed of ultrasonic pulses traveling in a solid material depends on the elastic properties and density of the specimen.

Before the test can be started, a zero reading should established for the apparatus, since the indicated measurement was influenced by a time delay due to both transmission of the pulse through the transducers material and transmission of electrical signal along the transducer cables. Concrete cubes of size 150mm x 150mm x 150mm were tested at 1, 3, 7 and 28 days.

The apparatus incorporated a suitable time delay adjustment so that the indicated readings may be made independent of this effect. The time delay adjustment was made while the transducers were coupled to the opposite ends of a reference bar for which the transit time was accurately known (bar with transit time 26μs was used).

Then, the transducers were arranged in direct transmission. The direct transmission arrangement was used since the transfer of energy between the transducers was at its maximum and the accuracy of velocity determination was therefore governed principally by the accuracy of the path length measurement. The ultrasonic pulses generated at the transmitting transducer were ensured to pass into the concrete and were then detected by the receiving transducer. It was essential that there was adequate acoustical coupling between the concrete surfaces; the finish was sufficiently smooth to ensure good acoustical contact by the use of a coupling medium and by pressing the transducer against the concrete surface. Thus, grease was used in this test. The apparatus of UPV test is shown in Figure 3.15.

Generally, a pulse of longitudinal vibrations is produced by an electroacoustical transducer which was held in contact with one surface of the concrete under test. After traversing a known path length, L in concrete, the pulse of vibrations is converted into an electrical signal by a second transducer. Electronic timing circuits enable the transit time, T of the pulse to be measured. Ultrasonic Pulse Velocity, V, in km/s for the concrete could be calculated as given below:

$$\text{Ultrasonic Pulse Velocity, } V = \frac{L}{T} \qquad (3.2)$$

Where, L = length of specimen, mm

T = time taken to travel from the transmitter to the receiver, in μs

Figure 3.15: Apparatus of Ultrasonic Pulse Velocity test

3.6.2 Dynamic Modulus of Elasticity Test

Dynamic modulus of elasticity, (DME) was tested according to BS1881: Part 209: 1990. Concrete prisms with dimension of 100mm x 100mm x 500mm were used and tested by using an "ERUDITE"-Resonant Frequency Tester at the age of 28 days.

Before running the DME test, the length and density were tested immediately just after removal from water, whilst still saturated. The surface water and grit were wiped off the specimen. Later the prism was clamped and balanced at its canter on the fixed support. After that, contact was made between the vibrating part of the exciter and the center of one end face of the specimen by means of a weak adhesive. The contact was made between a piezo-electric vibration pick-up and the opposite end of the specimen in a similar way, as shown in Figure 3.16. The axis of the transducers was ensured in the centre and normal to the end faces of the specimen.

The frequency at which this vibration occurs relates largely on the dynamic modulus of density, elasticity and length of the specimen. The exciter was driven by a variable frequency oscillator with a range of 100-10000 Hz imparts an alternative force to the specimen, and the response was sensed by pick-up, amplified, and their amplitude was measured by an appropriate indicator. The amplitude of vibration was monitored by the indicator until the resonant frequency was obtained at the maximum deflection of the indicator.

The dynamic modulus of elasticity in kN/mm ² is given by the equation:

$$\text{Dynamic modulus of elasticity, } Ed = \frac{4n^2 L^2 \rho}{10^{15}} \quad (3.3)$$

Where, n= frequency at maximum deflection of indicator (Hz)

L= length of the specimen (mm)

ρ = density of the specimen (kg/m^3)

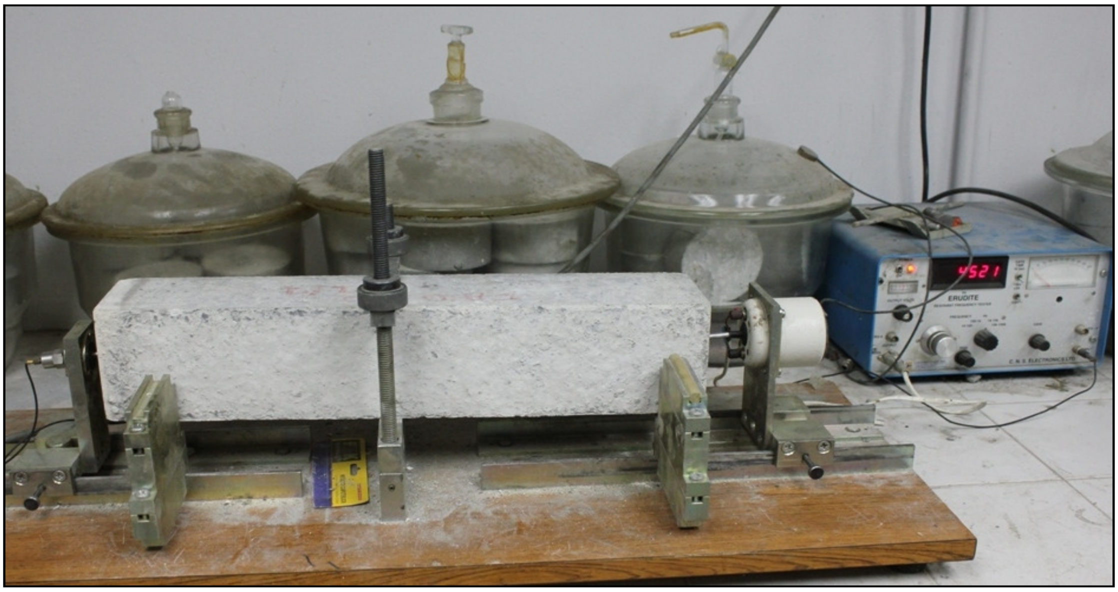


Figure 3.16: Apparatus of dynamic modulus of elasticity test

3.6.3 Static Modulus of Elasticity Test

Static modulus of elasticity was tested according to BS1881:Part121:1983. The concrete cylinders used for this test were 150 mm diameter and 300 mm in length and tested at 28 days. An extensometer was attached to the test cylinder. Then, the concrete cylinder was placed centrally on the lower platen of the testing machine as shown in Figure 3.17. The upper block slowly bear on the specimen, and the block gently rotated by hand so that uniform seating was obtained.

Before the test started, reading at dial gauge should set to zero first. Then, load was applied at a pace of 4.418 kN/s. Upon reaching a load of about 20% of ultimate load, the load was reduced to zero, and the dial gauge reading noted. If the dial gauge reading was not zero, the loading of 20% steps were repeated until the dial gauge, upon unloading, was zero. The final loading cycle was started and the loading was continued until maximum. The dial gauge was read when it reached the basic stress, S_a and the upper loading stress, S_b.

The static modulus of elasticity is given as:

$$\text{Static modulus of elasticity, } E_c = \frac{S_a - S_b}{\varepsilon_a - \varepsilon_b} \tag{3.4}$$

Where, S_a = upper loading stress, N/mm² ($S_a = F_c/3$)

S_b = basic stress, N / mm² (0.5 N/mm²)

ε_a = mean strain under the upper loading stress, mm

ε_b = mean strain under the basic stress, mm

F_c = Compression load, N

Figure 3.17: Apparatus for static modulus of elasticity test

3.7 Hardened Concrete Test (Destructive Tests)

3.7.1 Compressive Test

The compressive strength test of 100×100×100 mm cube specimens at 1, 3, 7 and 28 days was determined according to BS1881:Part116:1983 by using an ELE (Engineering Laboratory Equipment) testing machine with a load capacity of 3000kN.

According to the BS1881:Part116:1983, the cube, sample was placed with the cast faces in contact with the platens of the testing machine as shown in Figure 3.18. The load on the cube was applied at a constant rate of stress (2.4 KN/s) until the specimen failed.

Concrete is a material with non-linearity in the stress-strain relation. At high stress rate, the strain increased progressively. At near failure state, the movement of the pressure plate of the testing machine was increased. Failure on the sample approached when the loading rate was decreased. The maximum load applied to the cube was recorded. By dividing the load at failure by surface area of the sample, the compressive strength was obtained. Compressive strength formula was indicated as:

$$\text{Compressive strength, } P=\frac{F}{A} \tag{3.5}$$

Where, F= failure load (KN)

$A_{surface}$ = area of loading surface (mm^2)

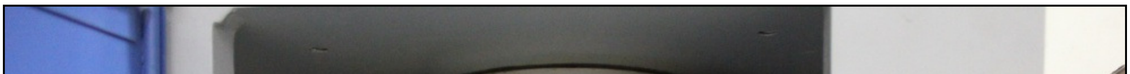


Figure 3.18: Apparatus of cube compressive test

3.7.2 Modulus of Rupture Test

Modulus of rupture (MOR) or flexural strength test was carried out in accordance with BS1881:Part118:1983. According to the code a plain concrete beam (100mm×100mm×500mm) is subjected to flexure using symmetrical two-point loading until failure occurs. Figure 3.19 shows the point loads are spaced at one-third of the span; hence the test for both of apparatus is also called a third-point loading test or two-point loading. An ELE machine of 3000 KN capacity was used to determine the average of MOR. Whilst, INSTRON 5582 was used to evaluate the results by comparing flexural strengths of plain concrete prisms with hybrid fibre reinforced concrete prisms by plotting curves of Flexure Load (KN) versus Flexure Extension (mm).

For two-point loading a constant bending moment is produced in the zone between the upper roller bearings. Hence this induces a symmetrical triangular stress distribution along vertical sections from compression above the neutral axis at mid-height to tension below the neutral axis. The maximum tensile stress at the bottom of the test beam is known as the modulus of rapture or flexural strength.

All the specimens subjected to water curing were tested immediately on removal from the water whilst they were still wet. Specimens for testing at 24 hours were tested in the moist condition. Specimens previously used for non-destructive tests were not remain out of water for more than 15 minutes and were returned to water curing for at least 15 minutes before testing.

The surfaces of the support and loading rollers were wiped clean. Surface water and grit on the specimens were also wiped off. The test specimen was placed in the flexural machine correctly with the longitudinal axis of the specimen centered at right angles to the rollers. A sawn specimen was placed in the machine so that the original finished surface was in tension. The original surface may not therefore be oriented with its position in the structure. After that, that packing was not used between the specimen and the roller. Furthermore, load was not applied to the specimen until all loading and supporting rollers were in even contact with the test specimen.

Then, the load was applied steadily and without shock at such a rate as to increase the stress at a rate of 0.05 mm/min (INSTRON 5582-100 KN capacity) or 0.067 KN/s (ELE 3000 KN capacity) respectively. The loading rates were applied based on the strength of the concrete. If the concrete is categorise as low strength concrete the lower rate was used. Similarly high strength concrete will require higher loading rate. Once adjusted, the rate of loading was maintained without change until failure occured. The maximum load read on the scale was recorded as the breaking load.

$$\text{Modulus of rupture, } f_{cr,} = \frac{FL}{bd^2} \qquad (3.6)$$

Where, F= maximum breaking load (KN)

L= distance between the lower supporting rollers (mm)

b= breadth of the specimen (mm)

d = depth of the specimen (mm)

Figure 3.19: Apparatus of ELE 3000 KN capacity (left) and INSTRON 5582-100 KN capacity (right) used for prism flexural tests

3.7.3 Modified Cube Compressive Strength Test

The failure parts from the prism beam after flexural strength test were used in the modified cube test. This test was done according to BS1881: Part119: 1983. Test specimen of part of beam was placed between the additional plates, and load was applied without any shock, continuously increased at a pace of 2.4 KN/s. The specimen was carefully marked and placed in a suitable jig such as that shown in Figure 3.20. The specimen and auxiliary platens were ensured to be located correctly. The specimen was centered carefully on the lower platen of the machine so that it did not touch the jig supports.

Equivalent cube compressive strength was determined as follows:

$$\text{Modified Cube Compressive Strength} = \frac{F}{A_c} \tag{3.7}$$

Where, F = maximum load, in KN

Ac = area of contact of the additional platens, in mm^2

Figure 3.20: Apparatus of modified cube compressive strength test

3.7.4 Splitting Tensile Test

The tensile splitting strength was tested according to BS1881: Part 117:1983. The specimen used was concrete cylinder of 150mm in diameter and 300 mm in length and placed with its horizontal axis between the platens of the machine. A narrow strip of plywood as shown in Figure 3.21 was placed between concrete cylinder and the platen to prevent high local compressive stresses at load lines. Without shock, the load was applied and increased continuously at a nominal rate within the range 0.02 N/ (mm^2.s). The rate was maintained, once adjusted, until failure. The maximum load applied to the specimen was recorded.

This method was simple to perform and produce more uniform results compared to other tensile strength tests. Load was increased slowly until by indirect tension in the form of splitting along the vertical diameter at a pace of 1.767 kN/s. The horizontal tensile splitting strength in N/mm ^{2} is expressed as follows:

$$\text{Tensile splitting strength}, f_s = \frac{2P}{\pi d l} \qquad (3.8)$$

Where, P= compressive load on the cylinder (KN)

l= length of the cylinder, (mm)

d= diameter (mm)

Figure 3.21: Apparatus of cylinder splitting tensile strength test

3.8 Impact Test

There are no standard test method to evaluate the impact properties of fibre-reinforced concrete and plain concrete, although there are many test procedures used in different laboratories such as instrumented drop weight impact tests using machines of various sizes.

A repeated drop weight impact test was conducted. It is the simplest test among all the impact tests. A weight is dropped repetitively on the same spot on the specimen as shown in Figure 3.22. Test is based on the modification of ACI Committee 544, 'Measurement of properties of fibre-reinforced concrete'. A steel rammer which weighs

6.50 kg was put to a height of 64.0 cm from the small scale slab surface and let to free fall from the height repeatedly. The number of drops when the first crack occurs and when the small scale slab breaks respectively were recorded. The energy that the specimens absorbed until it broke was calculated as:

$$E = \sum_{i=1}^{n} mgh \qquad (3.9)$$

Where, m = mass of steel rammer (kg)

g = gravity acceleration as $9.81 ms^{-2}$

h = drop height to the surface of small scale slab (m)

n = number of drops

Figure 3.22: Apparatus of concrete panel drop test

4.0 RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, fresh and hardened properties of various fibre reinforced composites are described and tested. To characterize their strength properties and test behaviour, the compressive strength test, splitting tensile strength test, modified cube compressive strength test, flexural strength test, impact resistance test and comparison of flexural load-flexure extension curves were carried out and the results were analyzed.

4.2 Mixture Design

The first part of this research study involves the development of an initial mixture design based on traditional concrete mix formulations with compensation for expected behaviour (increased water demand, reduced aggregate size, etc). From this base mix, adjustments were then made in order to optimize the strength. The variables include the types of materials being used in the matrix, and the mixture proportions. The mixtures were evaluated based on compressive strength, as determined according to BS1881:Part116:1983 using an ELE (Engineering Laboratory Equipment) testing machine with a load capacity of 3000 KN. The mixtures were also evaluated qualitatively based on rheological properties. The addition of the fibres tends to decrease the workability of the concrete, but the workability must remain within practical limits to ensure proper placement. The proportioning of the initial mixture involved many trials in order to develop a material that would be workable without segregation.

The initial mixture design was Trial Mix 1 containing standard Type 1 cement interground with silica fume. Silica fume has been used to improve the bond pullout energy of fibres in high performance concrete by Chan and Chu (2004). Other benefits of silica fume concrete include lower permeability, and higher compressive strength (Holland, 2005). From the initial mixture design, influence of superplasticizer type and dosage on the workability and strength play an important role in this investigation (Mahmud, et al., 2007). Therefore, different types of superplasticizer were used.

In Trial Mix 2, Viscocrete-2077 superplasticizer was added to the mixture in order to improve the workability. The second refinement to the mixture design was a reduction in the water to cement ratio to 0.43. In order to maintain the desired workability in Trial Mix 3, a high grade superplasticizer, Viscocrete-2088 was used. By decreasing the water to cement ratio to 0.36, the concrete strength, including the bond and compressive strength were increased (Mahmud, et al., 2009). Trial Mix 3 was then utilized for all of the initial testing. However, as the project progressed, the water to cement ratio was again reduced to 0.29. This was done because even with the lower water to cement ratio of Trial Mix 3, the fibres were still failing to bond. The bonding could be improved by reducing the water to cement ratio, further improving the performance of the material. However, there is a practical limit at which a lower water to cement ratio results in a concrete that is not workable. It was determined through this research program that the limit for this mixture occurs around a water to cement ratio of 0.29. The resulting mixture design, Trial Mix 4 which utilizes GLENIUM ACE 388 (RM) SURETEC was used for the later testing in this project. The mixture designs for percentage of superplasticizer used and workability attained for all of these variations are shown in Table 4.1.

Table 4.1: Mixture design summary

Item	Trial Mix 1	Trial Mix 2	Trial Mix 3	Trial Mix 4
Cement (kg)	406	406	406	406
Silica Fume (kg)	45	45	45	45
Fine Aggregate* (kg)	904	904	904	904
Coarse Aggregate* (kg)	935	935	935	935
Water (kg)	203	194	163	131
Water/(cement + silica fume)	0.45	0.43	0.36	0.29
SP (% of cementitious content)	1.7	1.9	2.0	1.1
Fibre	0	0	0	0
Slump (mm)	80	50	50	220
Superplasticizer	Sikament E-163X	Viscocrete-2077	Viscocrete-2088	GLENIUM ACE 388 (RM) SURETEC

* Aggregate weight is given at SSD condition

4.3 Compressive Tests of Preliminary Mixture Designs

Each of the mixtures discussed above was evaluated to determine its compressive strength. Compressive strength was examined as this better indicated the effectiveness of the fibres. The results from each of the initial mixtures tested following BS1881:Part116:1983 are summarized in Figure 4.1. The figure shows the compressive capacity for each of the initial mixture designs at 28 days. The compressive strength increased significantly with each adjustment to the mixture. The increments were due to the improvement of the bonding strength of the concrete paste itself. Combining water with a cementitious material forms a cement paste by the process of hydration. The cement paste glues the aggregate together, fills voids within it and allows it to flow more freely. Less water in the cement paste will yield a stronger, more durable concrete; more water will give a free-flowing concrete with a higher slump. As compared to the traditional superplasticizers, GLENIUM ACE 388 (RM) SURETEC improves the engineering properties such as early and ultimate compressive strength, very high workability and improves surface appearance.

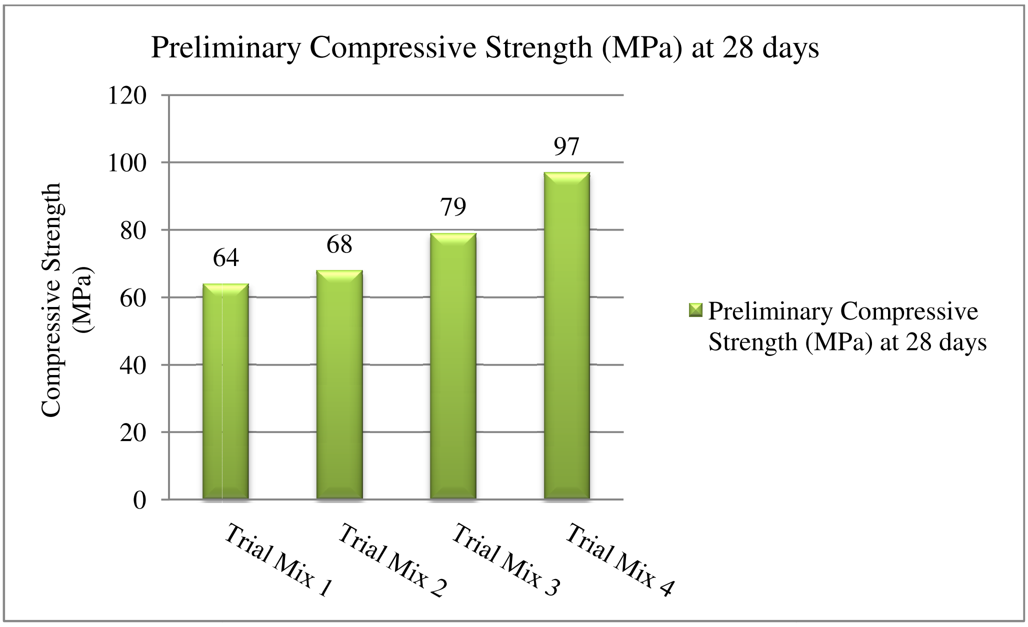


Figure 4.1: Compressive capacity of preliminary mixture designs

4.4 Properties of Fresh Concrete Test

4.4.1 Fresh Concrete Density

Table 4.2: The properties of fresh concrete with different percentage of fibres

Type of concrete and percentage of fibre (%)	Density (kg/m³)	Temperature (°C)
OPC	2437	30.0
0.1% Nylon + 0.4% SF	2486	29.0
0.1% Polypropylene + 0.4% SF	2480	29.0
0.1% Nylon + 0.9% SF	2562	28.5
0.1% Polypropylene + 0.9% SF	2551	28.5

As shown in Table 4.2, the fresh concrete density with different percentage of fibre is ranged between 2437 kg/m³ to 2562 kg/m³. The hybrid fibre-reinforced concrete with 0.1% nylon + 0.9% steel fibres has the highest density value (2562 kg/m³) compared to 0.1% polypropylene + 0.9% steel fibre reinforced concrete (2551 kg/m³). This phenomenon is due to the density of nylon fibre (1140 kg/m³) which is higher than that of polypropylene fibre (910 kg/m³).

4.4.2 Fresh Concrete Temperature

The temperature of the fresh concrete is almost the same in the range of 28.5 °C to 30.0 °C (Table 4.2). The temperature of the mix depends on the ambient temperature and the reactions that occur in the concrete mixes. Fresh OPC had a higher temperature. As the ambient temperature is almost the same for all mixtures, the heat evolved during the reactions of cement and aggregates influenced the mix temperature. The concrete with higher content of cement on touching area with aggregates; it extends the chemical reactions that evolve higher heat energy and results in the higher temperature in the OPC mix.

4.4.3 Workability of Fresh Concrete

The workability of concrete determines the ease and homogeneity with which it can be mixed, placed, consolidated and finished. It is a way to understand the behavior of concrete and to recognize the requirements of workability on site. For this study, the slump and Vebe tests were carried out.

The workability of concrete was fixed within a range of 20-220 mm for the slump test and 3.0-9.0 sec for the Vebe test. From the experiment, the amount of superplasticizer needed for plain concrete was 1.1%. The amount of superplastisizer needed increased to 1.8% and 2.0% in total volume fraction for 0.5% and 1.0% V_f of hybrid fibre (nylon + steel) reinforced concrete, respectively as shown in Table 4.3 and Figure 4.2.

Table 4.3: Workability of concrete with different percentage of various fibres

Type of concrete and percentage of fibre (%)	Workability		Amount of SP (% of cementitious content)
	Slump (mm)	Vebe (s)	
OPC	220	3.0	1.1
0.4% V_f steel fibre	200	4.0	1.3
0.9% V_f steel fibre	170	6.0	1.6
0.1% V_f nylon + 0.4% V_f steel fibres	30	8.0	1.8
0.1% V_f polypropylene + 0.4% V_f steel fibres	30	8.0	1.8
0.1% V_f nylon + 0.9% V_f steel fibres	20	9.0	2.0
0.1% V_f polypropylene + 0.9% V_f steel fibres	20	9.0	2.0

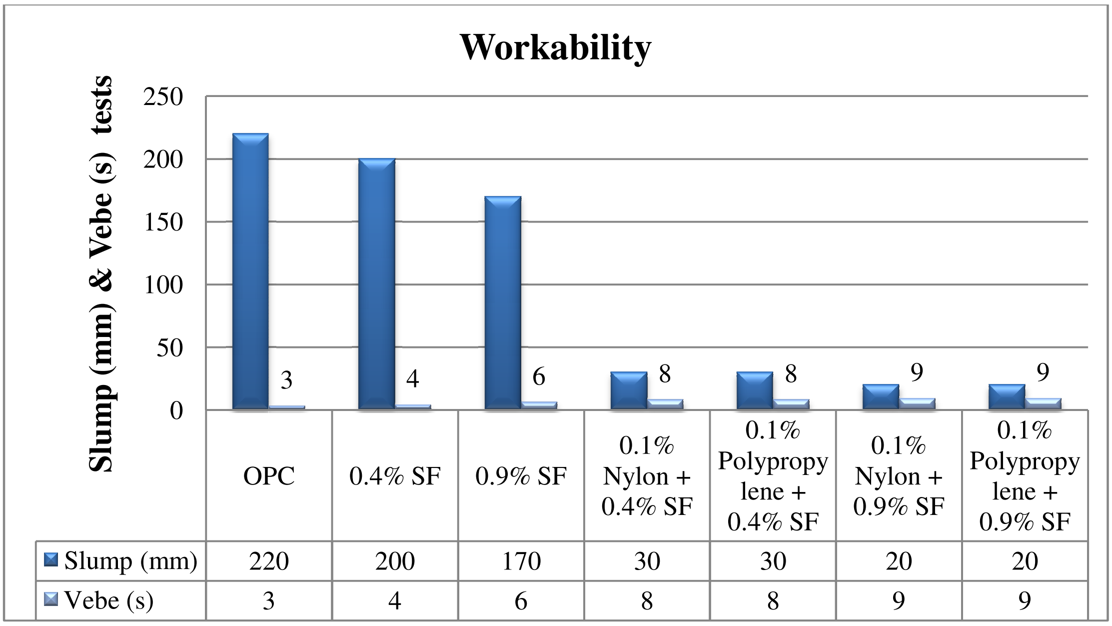


Figure 4.2: Slump and Vebe tests for concrete containing different % of fibres content

From Table 4.3, workability based on the slump and Vebe tests of the concrete show a decreasing pattern when the fibre content was increased, especially for hybrid fibres. The highest slump was achieved by the control mix which did not contain any fibre. Meanwhile, the Vebe time was increased with the addition of 0.1% of nylon and polypropylene fibres. The highest value was obtained when 0.1% nylon + 0.9% steel fibres and 0.1% polypropylene + 0.9% steel fibres were added, which is the lowest concrete workability to be compacted.

Therefore, it could be concluded that increase of nylon and polypropylene fibre content will decrease the workability of the concrete. The fibre prevented fresh concrete from being consolidated easily. The reason of lower slump is that adding hybrid fibres can form a network structure in concrete, which restrains the mixture from segregation and flow. The friction between the individual particles in the concrete and the mould increased with the addition of fibre due to the high content and large surface area of the fibres. The internal friction increase with fibre content and the amount of work done will eventually increase. The fibres absorb more cement paste to wrap around, and the viscosity of mixture reduces the slump test (Chen and Liu, 2005).

In order to improve the workability of the fresh concrete, superplasticizer was added into the concrete where the water to cement ratio was maintained. The superplastisizer acts as a lubricant to increase the fluidity and workability without affecting the properties of the concrete.

4.5 Hardened Concrete Test (Destructive)

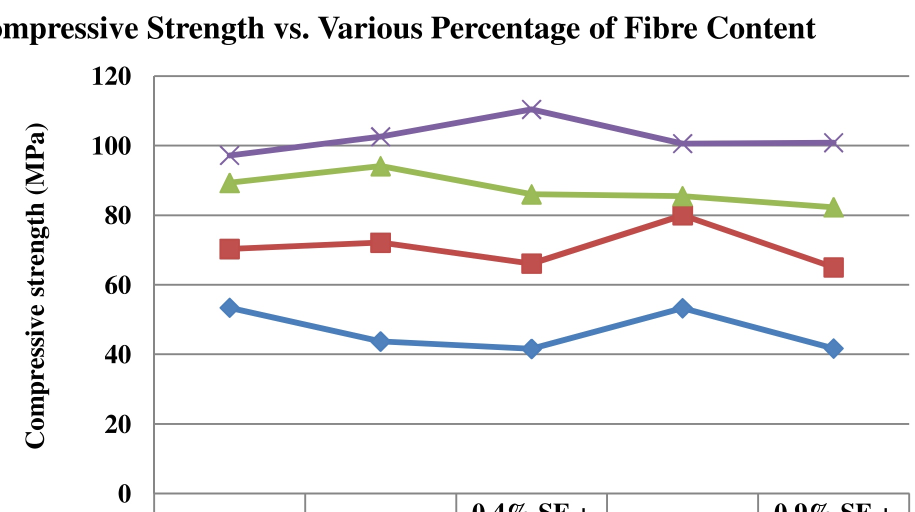
4.5.1 Compressive Strength

Compressive test is the most common hardened concrete test because of the intrinsic importance of compressive strength in structural design. The compressive strength of concrete is considered as the most valuable property of hardened concrete because it gives an overall view of the quality of concrete.

During the compression test, the 100×100×100 mm plain concrete failed instantly at maximum load and shattered into pieces when the first crack occurs; the failure is of brittle nature. For fibre-reinforced concrete, even after the first crack the concrete did not disintegrate and was still able to sustain compressive forces because the concrete was held together by the fibres.

By visual inspection, it was found that some of the tested HyFRC and plain concrete specimens had cubical failure. The pattern of plain concrete failure was symmetrical and regular. Failure was explosive. On the other hand, fibre-reinforced concrete is more ductile compared to plain concrete as shown in Figure 4.3. The compressive strength versus various percentages of fibre content is presented in Figure 4.4.

Figure 4.3: Failed 100×100×100 mm cube specimens



	OPC	0.4% SF + 0.1% Nylon	0.4% SF + 0.1% Polypropylene	0.9% SF + 0.1% Nylon	0.9% SF + 0.1% Polypropylene
Compressive strength (MPa) 1 day	53.4	43.7	41.6	53.3	41.7
Compressive strength (MPa) 3 days	70.3	72.1	66.1	80.0	65.0
Compressive strength (MPa) 7 days	89.3	94.1	86.0	85.5	82.3
Compressive strength (MPa) 28 days	97.2	102.6	110.4	100.6	100.8

Figure 4.4: Compressive strength vs. various % of fibre content

In this investigation, 8 cubes per mix were tested in compression on the 1^{st}, 3^{rd}, 7^{th} and 28^{th} days according to BS1881:Part116:1983. The average compressive strength of all the mixes combined was approximately 102 MPa. As expected, not much change was observed in the compressive strength of concrete with addition of fibres. This is in accordance with previously published data by Morris and Garret (1981) and Mangat and Azari (1984), where the strength gain was between 0 and 25%.

As shown in Figure 4.4, the compressive strength of the 0.5% hybrid polypropylene-steel-fibre-reinforced concrete (FRC) improved by 13.6% over the non-fibrous control counterpart, followed by the 0.5% hybrid nylon-steel FRC at 5.5%. The improvement came principally from the fibres interacting with the advancing cracks and showed the highest values of compressive strength compared to 1.0% hybrid polypropylene-steel and nylon-steel FRC. It is even higher compared to OPC control concrete, which is 3.7% and 3.5% improvement compared to 1.0% hybrid polypropylene-steel and nylon-steel FRC, respectively. The increment of fibre content is not significant and it was proved that the addition of fibres may not increase much compressive strength of the concrete. This may be due to the fibre balling or clogging within the 1.0% hybrid polypropylene-steel and nylon-steel FRCs. The higher fibre content might have caused voids resulting in decreased compressive strength.

When withstanding an increasing compression load, several distinct stages can be defined. During the first stage, micro-crack kinks develop randomly throughout the specimen. It is due to the heterogeneity of the specimen. Since the hardened cement paste and aggregates have different stiffness, local tensile stresses develop and further micro cracking occurs. Next, these micro-cracks join together forming macro-cracks that run parallel to the direction of the applied stress, thus blocking the forward propagation of the crack. The blunting, blocking, and even diverting of the crack allowed the fibrous concrete cubes to withstand additional compressive load, thus upgrading its compressive strength over the non-fibrous control concrete.

4.5.2 Second Stage of Compressive Strength

The purpose of the test is to evaluate whether the addition of fibres to a concrete mix adversely affects the compressive strength. Especially for HyFRC cubes, there are two stages of recording of compressive strength. The first stage of record is termed as "First Crack", explicitly the ultimate compressive strength. The second stage of record is the record of “Residual Strength”, specifically to continue loading after the first crack until failure. Figure 4.5 shows the results of residual compressive strength.

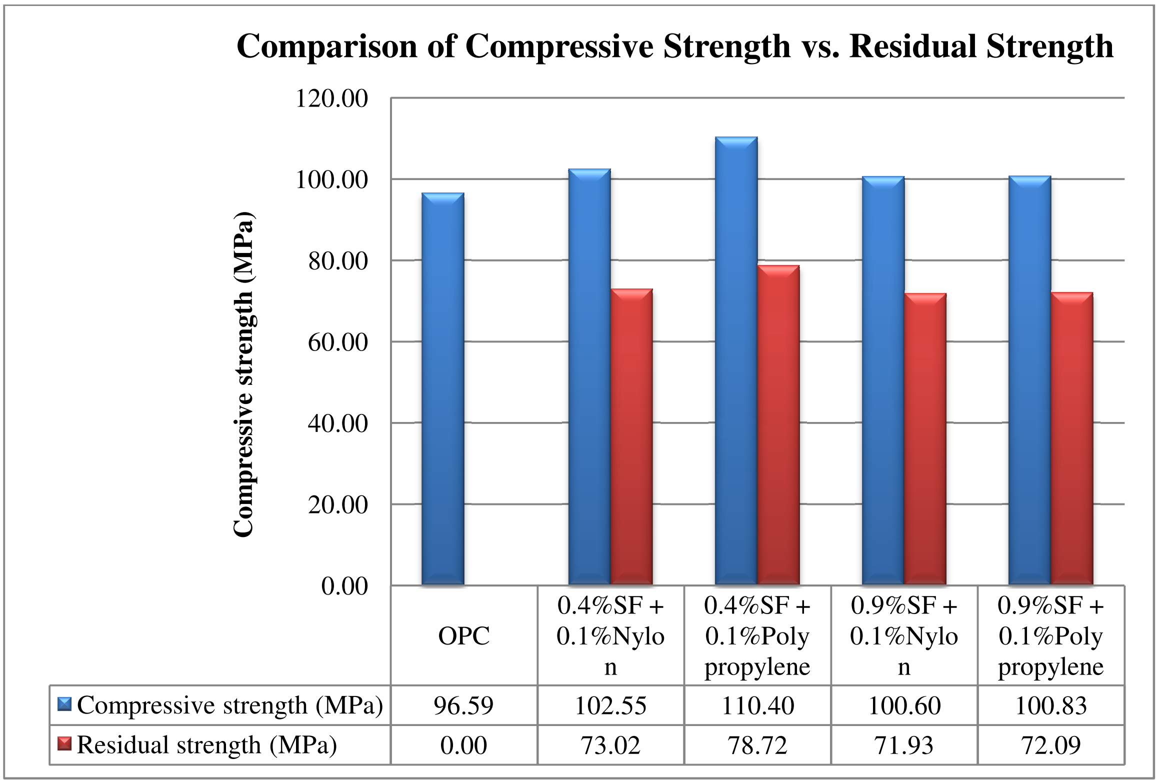


Figure 4.5: Comparison of compressive strength vs. residual strength

From Figure 4.5, it could be noted that the second stage of compressive strength of OPC is zero while for HyFRC with 0.5% and 1.0% steel-polypropylene and steel-nylon fibre, the second stage of compressive strength is approximately 71.4% compared to the first stage of recording compressive strength respectively.

Addition of fibres increases the ease of concrete compression due to the flexibility of the hybrid fibres. This result in drastic improvements in the residual compressive strength compared to plain concrete. The improvement is due to the shape and surface bonding of the fibres in the concrete. The steel fibres have hooks which may helps in the mechanical bonding between the fibre and the cement matrix. Hence it will enhance the compressive toughness of the HyFRC.

4.5.3 Modulus of Rupture (MOR)

The tensile stress that is reached at the bottom fibre, known as modulus of rupture, is an important requirement to understand the tensile strength of fibre-reinforced concrete compared to plain concrete. When a concrete specimen is subjected to bending, the tensile behaviour will govern its strength because concrete is a tension-weak material. In the first stage, micro-cracks become randomly distributed throughout the specimen and eventually, they begin to join together to form macro-cracks, cracking being localized. The final stage begins when the newly formed macro-cracks start to propagate and then quickly lead to unstable propagation and failure.

In this study, even though no definite increase in the compressive strength was noted with the addition of hybrid fibres, there was a clear increase in the MOR of the material under two point bending. In Figure 4.5, the MOR of hybrid mixes are compared with their corresponding control. It proves that HyFRC concrete had significantly increased modulus of rupture.

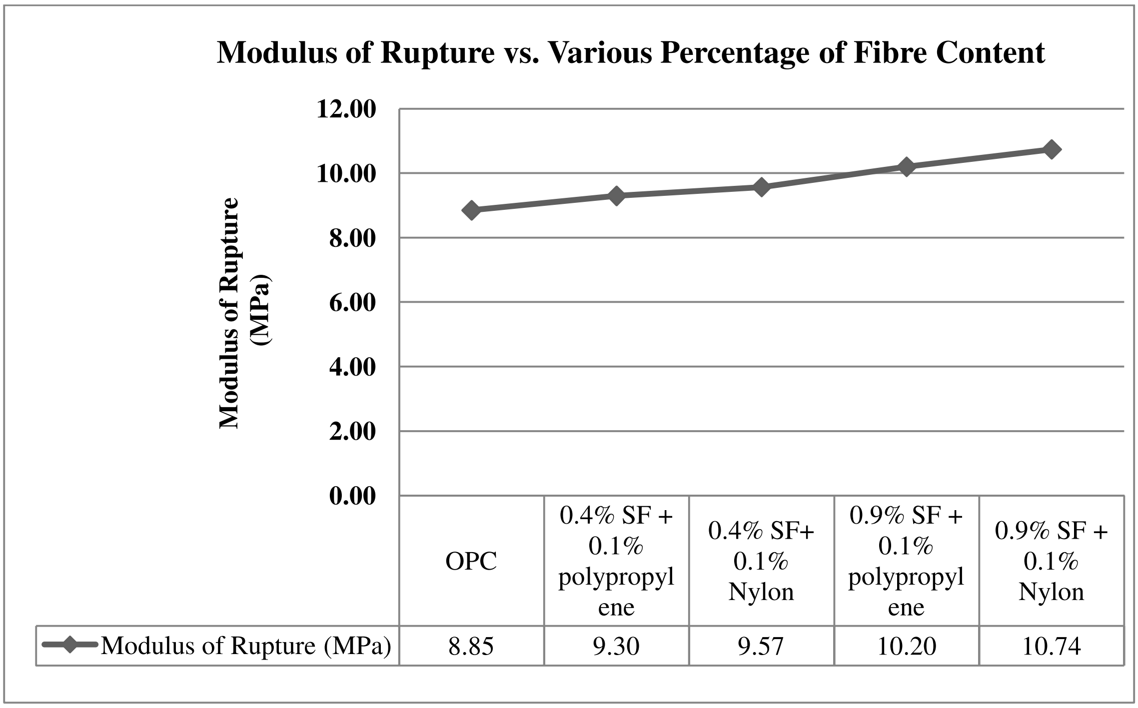


Figure 4.6: Effect of different fibre content on flexural strength of concrete

Figure 4.6 shows the flexural strength at 28 days, there was some variation in the flexural strength of the mixes, ranging from a maximum of 10.74 MPa to a minimum of 8.85 MPa. The HyFRC mixes had higher flexural strength compared to OPC control concrete. The highest value of MOR of the 1.0% hybrid nylon-steel FRC was a 21.4% increase over the nonfibrous control concrete. The increase resulted primarily from the fibres intersecting the cracks in the tension half of the reinforced prism. These fibres accommodated the crack face separation by stretching themselves, thus providing an additional energy-absorbing mechanism and also stress relaxing the micro- and macro-cracked region neighboring the crack-tip.

The MOR of 0.5% and 1.0% hybrid nylon-steel-fibre-reinforced concrete (FRC) slightly higher over the 0.5% and 1.0% hybrid polypropylene-steel FRC. It could be found that, hybrid nylon-steel has higher tensile strength properties compared to hybrid polypropylene-steel FRC. Factors that affect the flexural strength are length-diameter ratio, volume fraction, bond strength and orientation of fibre (Hannant, et al., 1978). Virtually the surface of fibre was observed to be mechanically treated (e.g. crimped, hooked-end, indented etc.); hence the bonding between the cement matrix and the fibre was strong. As a result, the strength of the concrete was improved. The tensile stress is also improved with increasing fibre content. As stated for compressive strength, the hybrid fibre additions made bearable differences in the variability carried by the MOR for 1.0% V_f of HyFRC, compared to the plain concrete and 0.5% V_f of HyFRC counterpart.

Fibres are added to inhibit a propagation of cracks in concrete which occur due to its low tensile strength. Plain concrete specimens usually fail catastrophically by a single crack which results in separation into two pieces (Figure 4.7a). The flexural strength of hybrid steel-nylon fibres concrete showed some improvement.

Figure 4.7b shows a HyFRC can be effective in arresting cracks at both micro and macro-levels. It demonstrates the ways in which hybrid fibres act to absorb energy and control the crack growth.

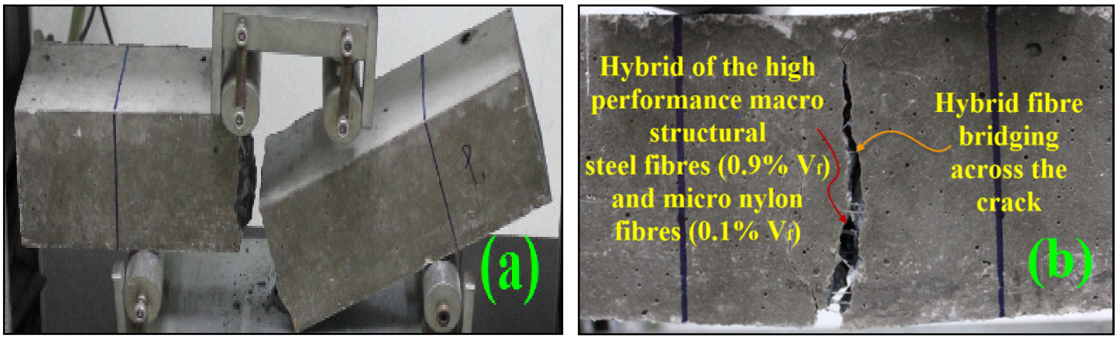
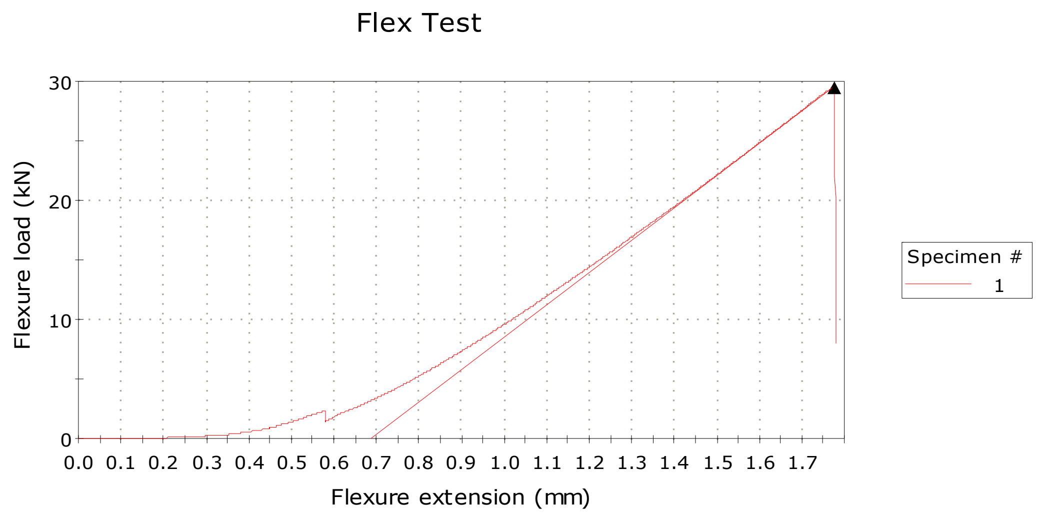


Figure 4.7: (a) Crack in concrete element subjected to bending without fibres and (b) with fibres

4.5.4 Comparison of Flexure Load-Flexure Extension Plots

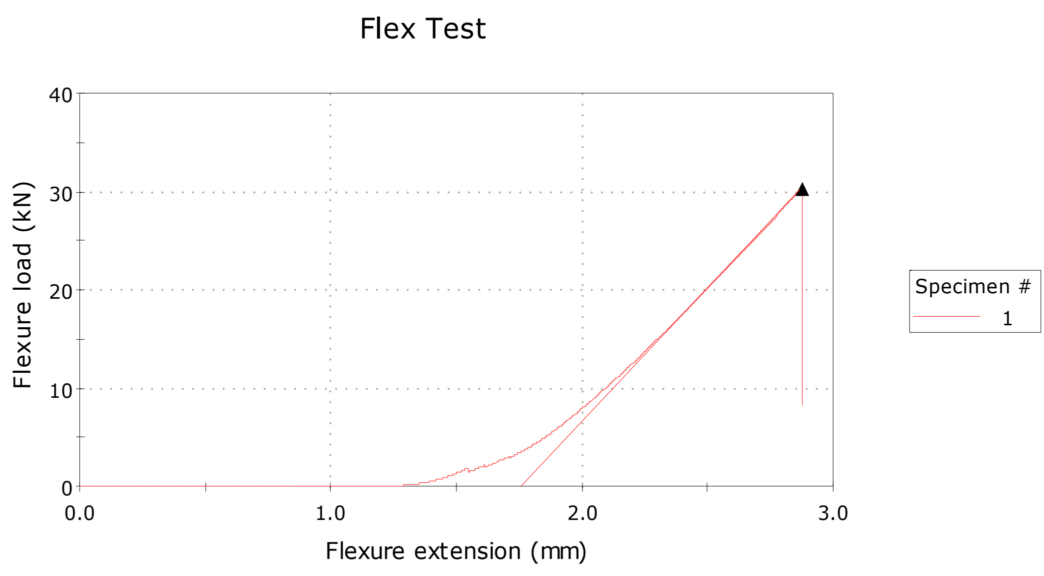
One of the defining points on the load-deflection curve of FRC under flexure is the point of first crack, which corresponds to the modulus of rupture. This is the point at which the load-deflection curve first becomes nonlinear (ASTM C 1018-97). Fibre reinforcement is effective only after the point of first-crack (Furlan and Hanai, 1997). Flexure load-flexure extension plot for plain concrete is presented in Figure 4.8. The instability during testing occurs due to the sudden release of energy after a specimen reaches the peak load. The figure shows that the curve is consistent.



	Specimen Name	Width (mm)	Thickness (mm)	Maximum Flex Load (kN)	Extension at Max Flex Load (mm)	Modulus of Rupture (MPa)
1	Plain concrete	100.3	100.5	29.5	1.7	8.7
Mean*		100.3	100.5	29.5	1.7	8.7
S.Dev*		-----	-----	-----	-----	-----
Minimum*		100.3	100.5	29.5	1.7	8.7

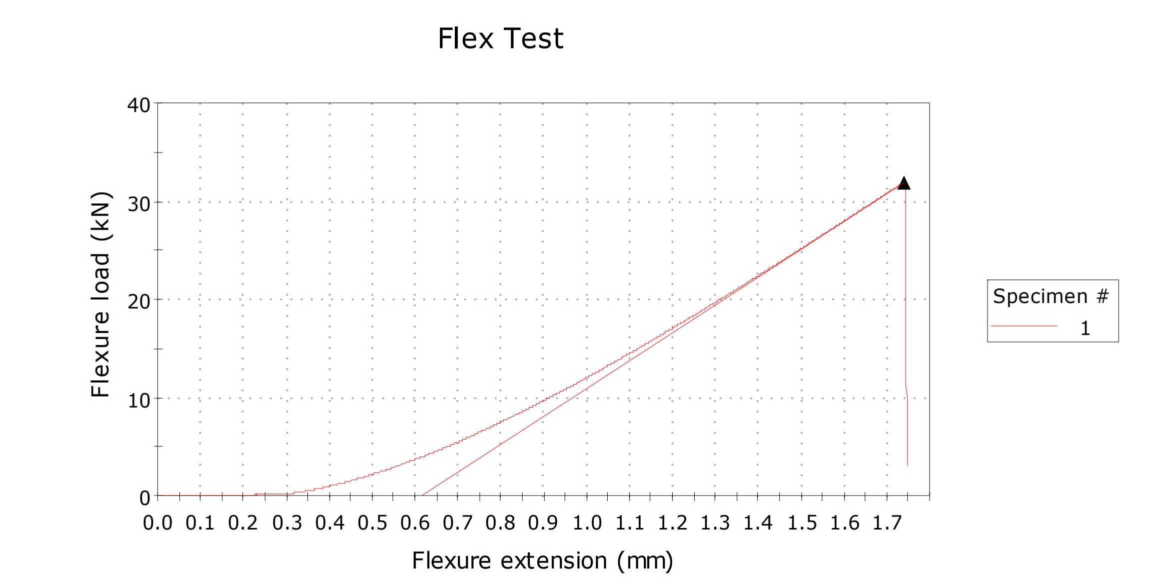
*The results is computerised.

Figure 4.8: Flexure load vs. flexure extension- plain concrete



	Specimen Name	Width (mm)	Thickness (mm)	Maximum Flex Load (kN)	Extension at Max Flex Load (mm)	Modulus of Rupture (MPa)
1	0.4% SF + 0.1% polypropylene	101.2	100.8	30.2	2.9	8.8
Mean*		101.2	100.8	30.2	2.9	8.8
S.Dev*		-----	-----	-----	-----	-----
Minimum*		101.2	100.8	30.2	2.9	8.8

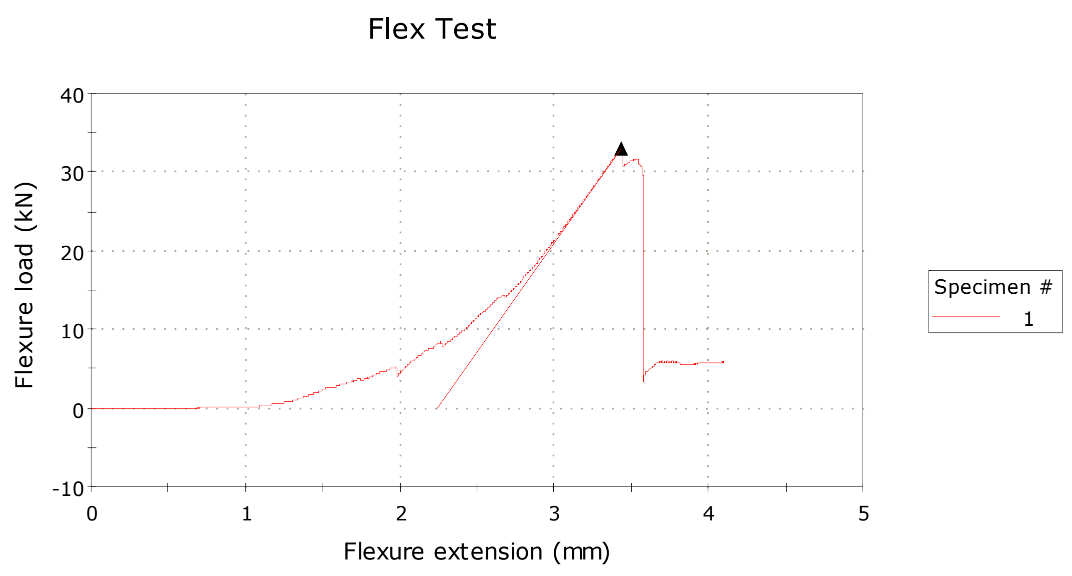
Figure 4.9: Flexure load vs. flexure extension- 0.5% HyFRC of steel-polypropylene



	Specimen Name	Width (mm)	Thickness (mm)	Maximum Flex Load (kN)	Extension at Max Flex Load (mm)	Modulus of Rupture (MPa)
1	0.4% SF + 0.1% nylon	101.4	100.8	31.9	1.8	9.3
Mean*		101.4	100.8	31.9	1.8	9.3
S.Dev*		-----	-----	-----	-----	-----
Minimum*		101.4	100.8	31.9	1.8	9.3

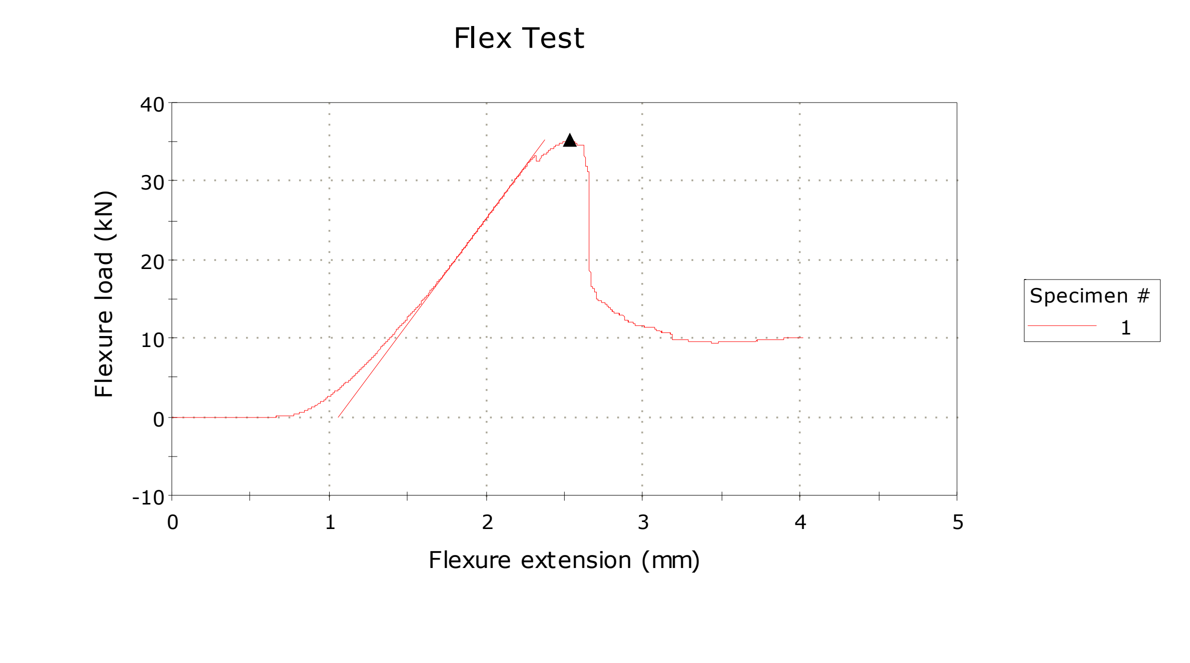
Figure 4.10: Flexure load vs. flexure extension- 0.5% HyFRC of steel-nylon

Figures 4.9 and 4.10 show the response of 0.5% HyFRCs mixes. The load carrying capacity (after the peak) of 0.5% HyFRC is quite similar to plain concrete. However, HyFRC with 0.5% steel-nylon and 0.5% steel-polypropylene both showed slightly higher MOR compared to plain concrete.



	Specimen Name	Width (mm)	Thickness (mm)	Maximum Flex Load (kN)	Extension at Max Flex Load (mm)	Modulus of Rupture (MPa)
1	0.9% SF+ 0.1% polypropylene	101.2	100.4	33.1	3.4	9.7
Mean*		101.2	100.4	33.1	3.4	9.7
S.Dev*		-----	-----	-----	-----	-----
Minimum*		101.2	100.4	33.1	3.4	9.7

Figure 4.11: Flexure load vs. flexure extension- 1.0% HyFRC of steel-polypropylene



	Specimen Name	Width (mm)	Thickness (mm)	Maximum Flex Load (kN)	Extension at Max Flex Load (mm)	Modulus of Rupture (MPa)
1	0.9% SF + 0.1% nylon	100.2	100.4	35.2	2.5	10.5
Mean*		100.2	100.4	35.2	2.5	10.5
S.Dev*		-----	-----	-----	-----	-----
Minimum*		100.2	100.4	35.2	2.5	10.5

Figure 4.12: Flexure load vs. flexure extension-1.0% HyFRC of steel-nylon

The content of steel macro fibres was further increased to 0.9% for 1.0% volume fraction of HyFRC and the flexure load-flexure extension plots are presented in Figures 4.11 and 4.12. It can be noted that the amount of instability after the peak reduced drastically with 0.9% steel fibre by volume. A further increase in the volume fraction resulted in load carrying capacities exceeding the peak load with large extensions. Large improvements in the flexural response were observed when 1.0% V_f of HyFRC was compared with OPC and 0.5% V_f of HyFRC, respectively.

4.5.5 Splitting Tensile Test

Direct testing of concrete in uniaxial tension is more difficult than steel or timber. Since concrete is a brittle material, it is difficult to grip and align. Therefore, the indirect cylinder splitting tensile test is used to determine the tensile strength of concrete. In the splitting tension test, a concrete cylinder, of the type used for compression tests, is placed with its axis horizontal between the platens of a testing machine, and the load is increased until failure by indirect tension in the form of splitting taking place along the vertical diameter. Figures 4.13 shows the failed specimens and Figure 4.14 showed that addition of various percentage of fibre content into concrete significantly increased the splitting tensile strength.

Figure 4.13: Failed 100×200 mm cylinder specimens

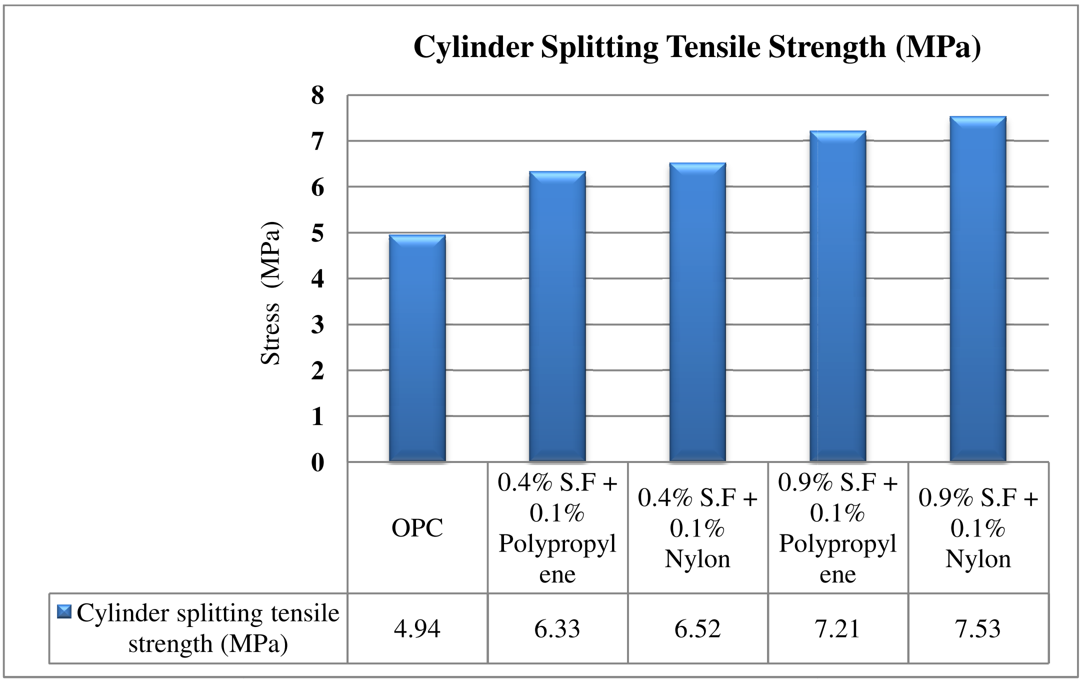


Figure 4.14: Splitting tensile strength vs. % of concrete containing various fibre content

Figure 4.14 showed that the percentage improvement in splitting tensile strengths of the 1.0% hybrid nylon-steel- and polypropylene-steel FRCs were 52.4% and 46.0 %, respectively than that of the unreinforced control concrete. On the other hand, the percentage improvement of 0.5% hybrid nylon-steel- and polypropylene-steel FRCs was 32.0% and 28.1% at the 28th day, respectively. Once the splitting occurred and continued, the fibres bridging across the split portions of the matrix acted through the stress transfer from the matrix to the fibres, and thus, gradually supported the entire load. The stress transfer improved the tensile strain capacity of the hybrid fibre-reinforced concretes. Therefore, reinforced concrete with the addition of hybrid nylon-steel- and polypropylene-steel fibres had increased splitting tensile strength compared to the unreinforced control counterpart.

During the splitting tensile test, it could be observed that the OPC specimen broke cleanly into two pieces while HyFRC specimens were still held together. This indicates that the HyFRC have better performance compared to the OPC. This result is consistent with the statement that the splitting tensile strength of fibre-reinforced concrete behaved in proportion to the number of fibres intersecting the fracture surfaces (Potrzebowski, 1983).

According to Chen et al. (2002), reinforcement of concrete with fibres leads to improvements in the tensile strength of the materials. This is due to the tendency of propagating macro-cracks in cementitious matrices to be arrested or deflected by fibres. From the Figure 4.14, it could be found that the tensile strength of concrete with nylon-steel FRC is higher than concrete with polypropylene-steel FRC. It is because the nylon fibre has higher tensile strength than the polypropylene fibre referring to the Table 2.1. In addition, It could be concluded that the nylon-steel FRCs are providing the better bonding compare to the polypropylene-steel FRCs in concrete.

4.5.6 Modified Cube Compressive Strength

The modified cube test is a compression test to determine the development of compressive strength with age, using portions of beams broken in flexural. The end parts of the beam were left unbroken and they were usually square in cross-section. An 'equivalent' cube can be obtained by applying load through a square steel plate of the same size as the cross section of the beam.

Table 4.4: Modified cube compressive strength of FRC with different % of fibres

Concrete Type and Fibre content (%)	Actual Cube Strength (MPa)	Modified Cube Strength (Mpa)	Actual Cube Strength / Modified Cube Strength
OPC	97.2	101.3	0.96
0.4% SF + 0.1% Nylon	102.6	103.3	0.99
0.4% SF + 0.1% Polypropylene	110.4	114.5	0.96
0.9% SF + 0.1% Nylon	100.6	101.9	0.99
0.9% SF + 0.1% Polypropylene	100.8	103.3	0.98

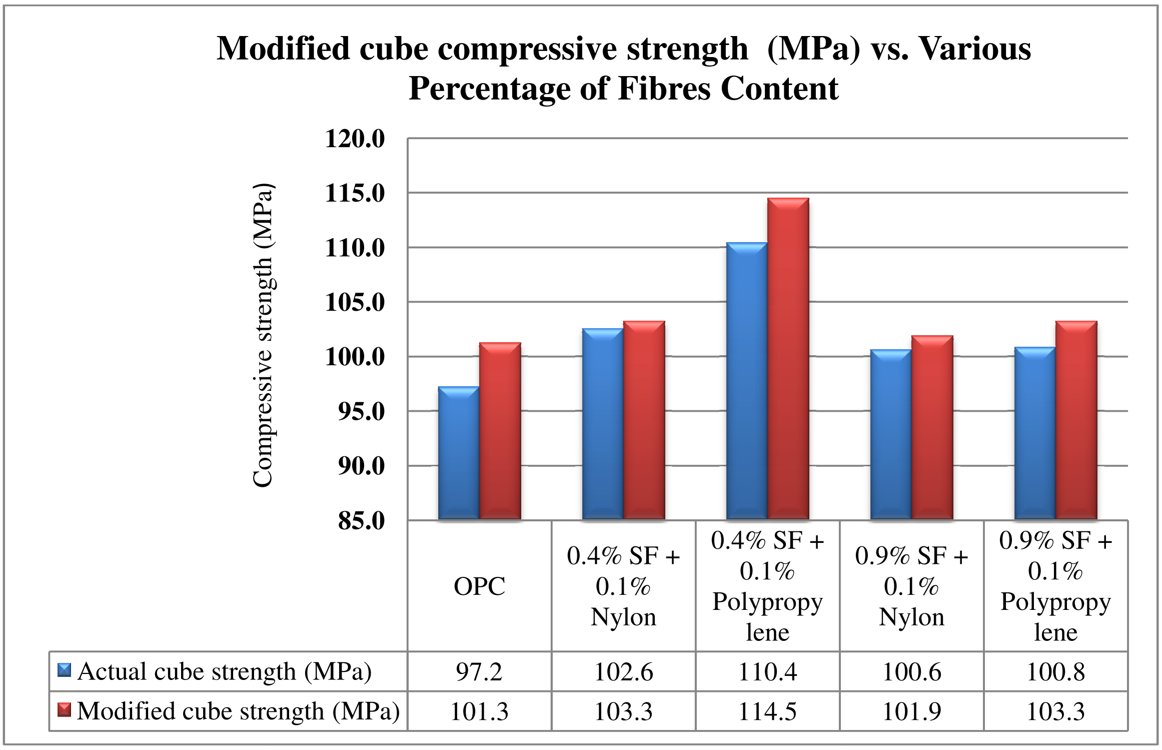


Figure 4.15: The modified cube compressive strength of concrete containing various % of fibres content

From Table 4.4 and Figure 4.15, it was found that the value of modified cube compressive strength is slightly higher compared to the value of ordinary compressive strength.

Compared to plain OPC the fibre reinforced concrete does not show significant difference in compressive strength using this test. By the 28th day, the modified cube strength of OPC was 101.3 MPa. Strength for low volume fraction (0.5%) of hybrid nylon-steel- and polypropylene-steel- FRCs was 103.3 MPa and 114.5 MPa, respectively. Besides that, for 1.0% hybrid nylon-steel- and polypropylene-steel- FRCs the strength were 101.9 MPa and 103.3 MPa, respectively. It was found that the strength for most of the cubes were slightly increased compared to the actual cube test. Nevile (1996) stated that the average compression strength of modified cube test is 5% higher than that of a cast cube of the same specimen size. The measured strength of specimen with a larger cross-sectional area is greater than the strength of actual cube strength due to the so called wall effect. For HyFRCs, the improvements came principally from the fibres interacting with the advancing cracks. Both the ability to hold the matrix together and the compression toughness were increased. The ratio between actual cube strength and modified cube strength determined in Table 4.4 can be used as reference in estimating the actual cube strength based on an unbroken part of a beam.

4.5.7 Ultrasonic Pulse Velocity

The UPV method is known as the transit time method which involves measuring the time taken for an ultrasonic pulse to travel through a known distance in concrete, from which the velocity is calculated. It is one of the non-destructive tests frequently used to predict strength of concrete by detection of the voids inside the concrete. The method consists of measuring the time of travel of an ultrasonic pulse passing through the concrete being tested. Comparatively higher velocity is obtained when concrete quality is good in terms of density, uniformity, homogeneity etc.

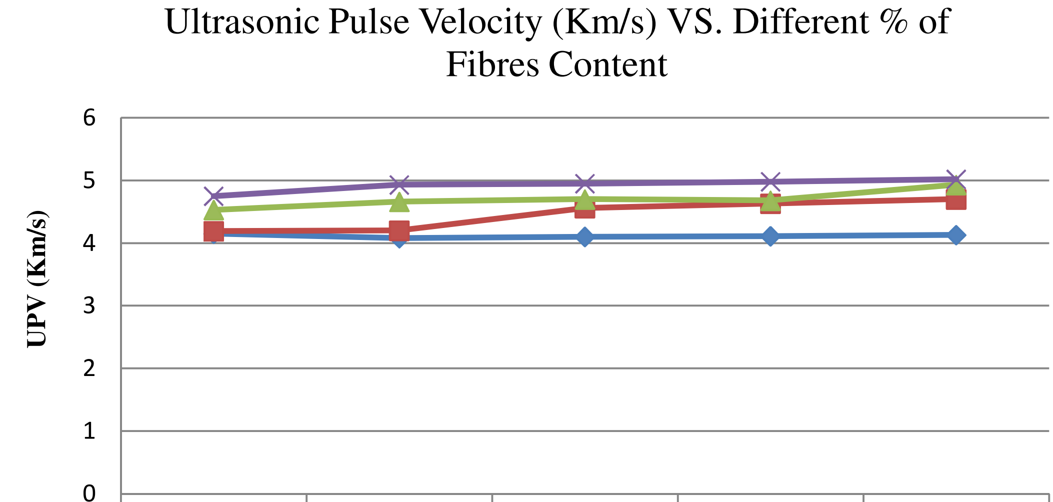
The quality of concrete in terms of uniformity, incidence or absence of internal flaws, cracks segregation is characterized as shown in Table 4.5. The guidelines have been evolved for characterizing the quality of concrete in structures in terms of the ultrasonic pulse velocity.

Table 4.5: Characterizing the quality of concrete (after Neville 1996)

Pulse Velocity (Km/s)	Concrete Quality (Grading)
Above 4.5	Excellent
3.5 to 4.5	Good
3.0 to 3.5	Medium
Below 3.0	Doubtful

Table 4.6: Ultrasonic Pulse Velocity of concrete with different % of fibres

Type of concrete and percentage of fibres	Ultrasonic pulse velocity (Km/s)			
	Age of Testing (days)			
	1	3	7	28
OPC	4.15	4.19	4.53	4.75
0.4% SF + 0.1% polypropylene	4.08	4.20	4.66	4.93
0.4% SF + 0.1% nylon	4.10	4.56	4.70	4.95
0.9% SF + 0.1% polypropylene	4.11	4.63	4.68	4.98
0.9% steel + 0.1% nylon	4.13	4.70	4.93	5.02



	OPC	0.4% SF + 0.1% polypropylene	0.4% SF + 0.1% nylon	0.9% SF + 0.1% polypropylene	0.9% SF + 0.1% nylon
1st	4.15	4.08	4.1	4.11	4.13
3rd	4.19	4.2	4.56	4.63	4.7
7th	4.53	4.66	4.7	4.68	4.93
28th	4.75	4.93	4.95	4.98	5.02

Figure 4.16: Development of UPV f concrete with different percentage of fibres content

Figure 4.16 shows that the FRC with hybrid 0.9% steel and 0.1% nylon fibres has the highest value of UPV at 5.02 km/s on the 28th day. The results indicate that the FRCs with hybrid 1.0% fibres have the lowest voids content compared to the other concrete mixes. The steel, nylon and polypropylene fibres with its flexibility and low aspect ratio enable the concrete to be compacted well and have low voids content. The hybrid FRC with 0.4% steel + 0.1% nylon fibres and 0.4% steel + 0.1% polypropylene fibres had UPV values of 4.95 km/s and 4.93 km/s, respectively. However, the lowest UPV value is that of OPC at 4.75 km/s.

The results show that the UPV of all the concrete mixes increases with the age of the concrete. The increase in UPV with age is closely related to the ratio of gel to space ratio phenomenon. After period of hydration, it produces much gel that may fill up the void space. The ratio of gel to space thus increased consequently. Since the pulse of velocity through voids is slower than through solid matter, therefore, the UPV of the concrete is increased with age. Furthermore, it is important that efficient curing is necessary to get a good concrete.

4.5.8 Dynamic Modulus of Elasticity

The dynamic modulus of elasticity is a function of compressive strength and concrete density. This is a laboratory test on prepared specimens, and can be used to assess progressive changes in the specimen.

The test is used to determine the deterioration of concrete after freezing or thaw damage. It also acts as a test to determine the sulfate resistance of concrete. The dynamic modulus of elasticity can be used for studying specimens which undergo chemical attack. It is therefore particularly useful for generating data in durability testing.

Table 4.7: Dynamic modulus of elasticity of concrete with different % of fibres

Type of concrete and percentage of fibres	Dynamic modulus of elasticity, E_d (GPa) (28 days)
OPC	54.8
0.4% SF + 0.1% polypropylene	56.1
0.4% SF+ 0.1% nylon	55.7
0.9% SF + 0.1% polypropylene	55.2
0.9% SF + 0.1% nylon	54.9

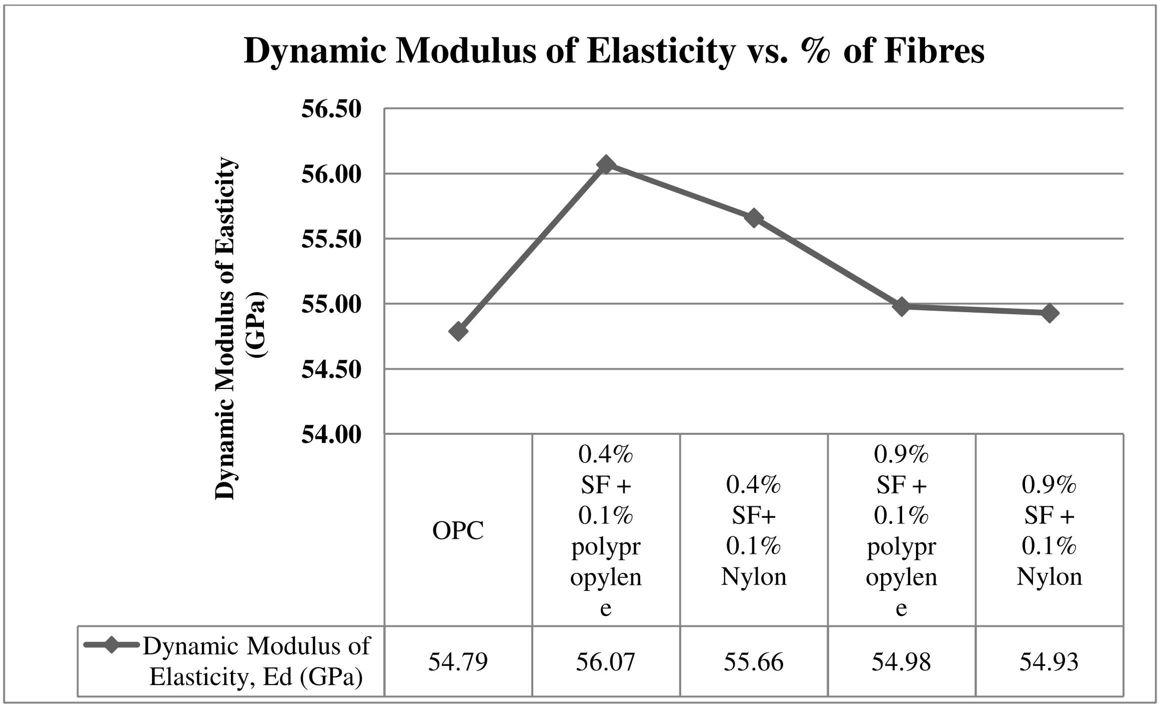


Figure 4.17: The dynamic modulus of elasticity with various % of fibres

According to Figure 4.17, the HyFRC with 0.5% polypropylene-steel fibres exhibits the highest value of dynamic modulus of elasticity at 56.1 kN/mm² at 28th day. The results of the test range from 54.8 kN/mm² to 56.1 kN/mm². Like compressive strength, the dynamic modulus of elasticity depends on the porosity of concrete. Since the hybrid fibres are thin and short, it could be dispersed randomly in the concrete. Thus, the concrete with hybrid fibres could be compacted well without much porous spaces compared to non-fibrous control concrete. On the other hand, HyFRCs with 1.0% fibres showed a lower dynamic modulus of elasticity compared to 0.5% HyFRCs. As the addition of hybrid fibres may reduce the workability of the mix and will cause balling or mat. It was found that the inclusion of 1.0% V_f of HyFRCs led to fibres balling. However, the value of dynamic modulus of elasticity of 1.0% HyFRCs is still higher compared to OPC.

Dynamic modulus of elasticity is affected by the porosity of the concrete. The dimension of fibres is thin and short. Therefore, fibres can be dispersed randomly within the concrete and compacted easily. Hence the void in the concrete would be small. From the Figure 4.17, it could be found that for nylon-steel and polypropylene-steel at higher dosage (e.g. 1.0%), the dynamic modulus value decreased because of the fibre content increase, fibre balling may occur and this will reduce workability because the compaction was difficult to achieve. As a result gaps or voids can be developed in the concrete matrix.

4.5.9 Static Modulus of Elasticity

The static modulus of elasticity of concrete is largely controlled by the volume and modulus of aggregate. It is a static loading test to check the quality of the concrete. Cylinder-shaped specimens are used for the test.

Table 4.8: Static modulus of elasticity of concrete with different % of fibres

Type of concrete and percentage of fibres (%)	Static modulus of elasticity (GPa)
OPC	52.7
0.4% SF + 0.1% polypropylene	51.6
0.4% SF + 0.1% nylon	48.0
0.9% SF + 0.1% polypropylene	45.4
0.9% SF + 0.1% nylon	45.1

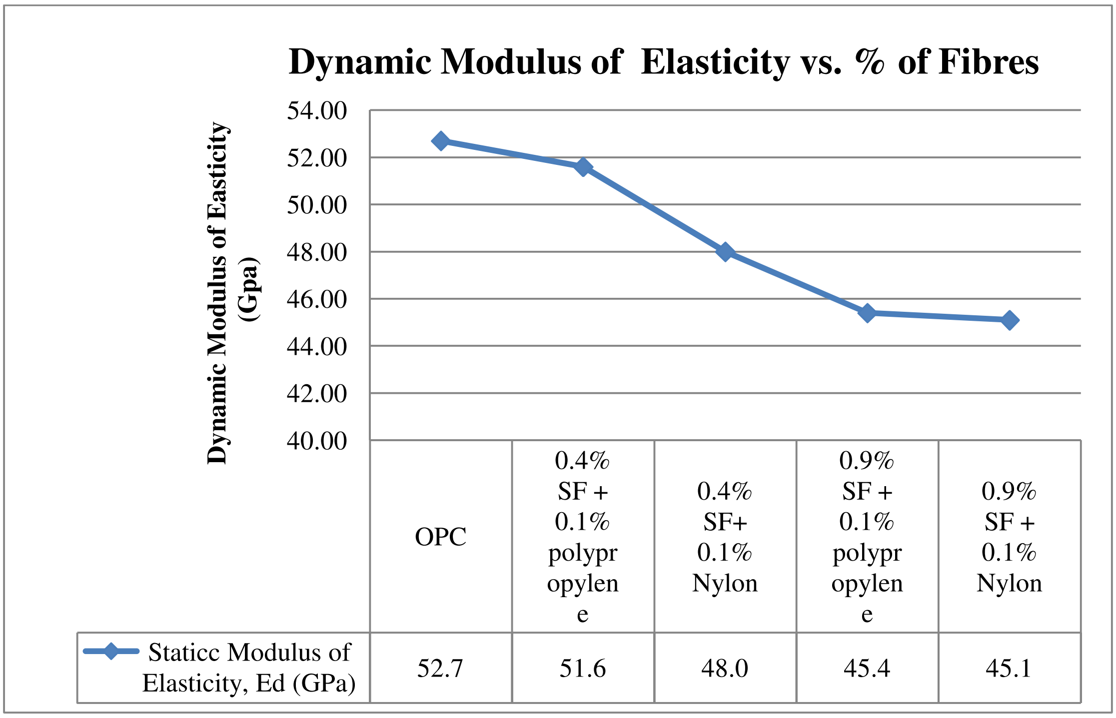


Figure 4.18: Static modulus of elasticity of concrete with various % of fibres

From Table 4.8, it can be noted that the values of static modulus of elasticity ranges from 48.0 kN/mm² to 52.7 kN/mm². Figure 4.18 shows that the OPC has the highest modulus value of 52.7 kN/mm² with reference to 97.2 MPa compressive strength at 28 days. The value of modulus of elasticity of hybrid fibres with reference to compressive strength is proportional when the hybrid fibres content increase from 0.5% to 1.0%. However, the value of static modulus of elasticity decreases when the hybrid fibres are added into the concrete. Referring to Figure 4.17 and Figure 4.18, the average of static modulus of elasticity of 0.5% HyFRCs are showing the highest value. When the hybrid fibres content increase to 1.0%, it reduces the value of static modulus of elasticity. This may be due to the inclusion of nylon and propylene fibres with low modulus of elasticity which caused the concrete to become less elastic.

4.6 Impact Test

Fibre is usually added to concrete so that the concrete is able to sustain high impact load and energy. In this test, the numbers of blows until the first crack on the side, first crack on the top surface and failure mode occurs were determined. The energies absorbed by the FRC were calculated by assuming friction effects are negligible.

Table 4.9: Results of impact test for concrete with different % of fibre content

Type of concrete and percentage of steel fibre (%)	Number of blows (Mean)			Energy absorbed (Joule)
	First-crack (side of slabs)	First-crack (top surface of slabs)	Failure	
OPC	3	4	4	163
0.4% SF + 0.1% polypropylene	14	16	32	1305
0.4% SF + 0.1% nylon	32	33	40	1632
0.9% SF + 0.1% polypropylene	305	306	539	21996
0.9% SF + 0.1% nylon	321	323	582	23751

*All the tests were carried out on the 28th day after the concrete has been cast

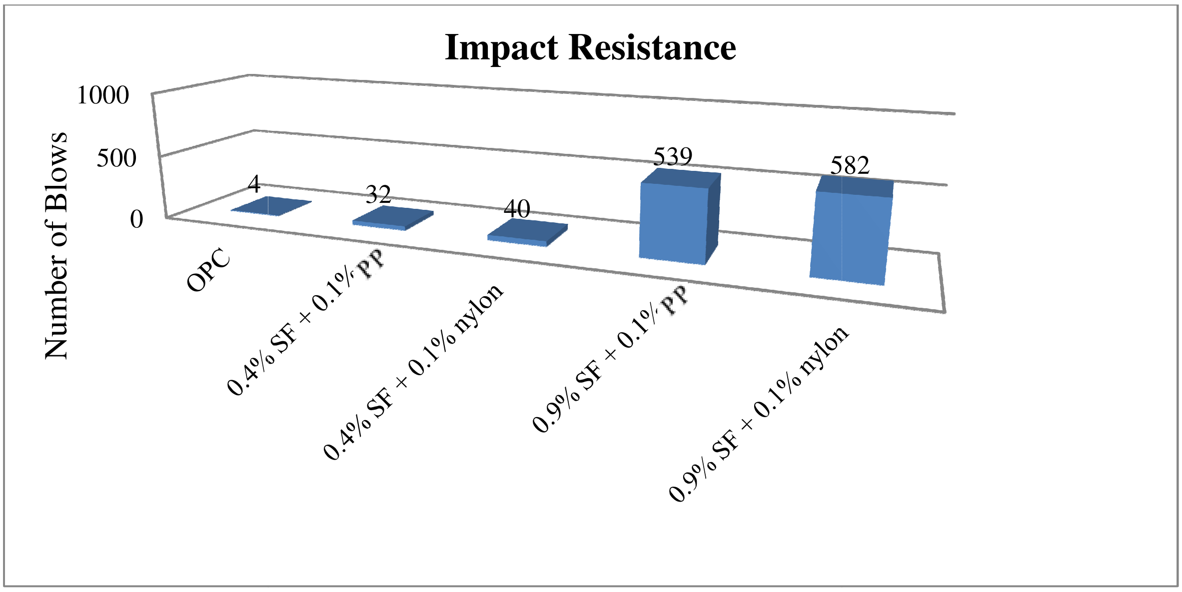


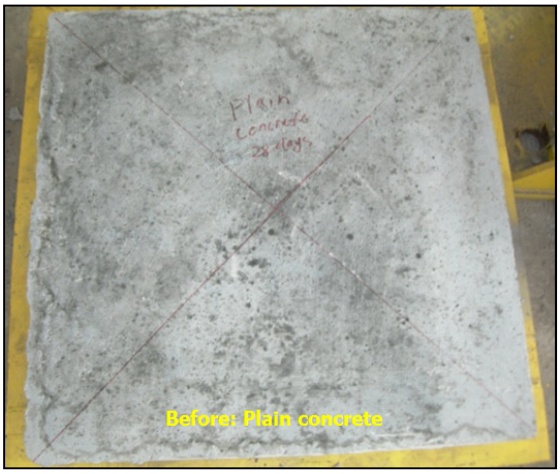
Figure 4.19: The results of impact resistance of concrete with different % of fibre content

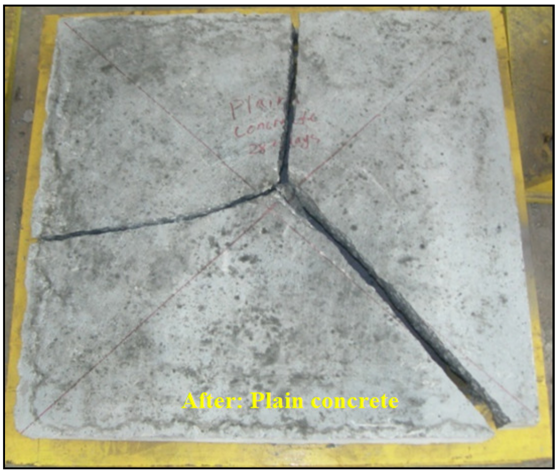
The evaluation of the 15 slabs in this work is shown in Table 4.9 and Figure 4.19. According to the evaluation, the number of blows for mean first-crack (side of slabs) and at failure for the HyFRC slabs with 0.5% nylon-steel increased 967% and 900%, respectively, over the plain control slabs, whereas for the hybrid FRC slabs with 0.5% polypropylene-steel the increase were 367% and 700%, respectively. The mean first-crack (side of slabs) and failure strengths of HyFRC slabs with 1.0% nylon-steel increased 10600% and 14450%, respectively, over the plain control slabs, whereas the improvement percentage of 1.0% HyFRC slabs with polypropylene-steel were 10067% and 13375%, respectively. All these figures emphasize the benefit of hybrid fibre additions and showed that the hybrid nylon-steel FRC outperforms the hybrid polypropylene-steel FRC.

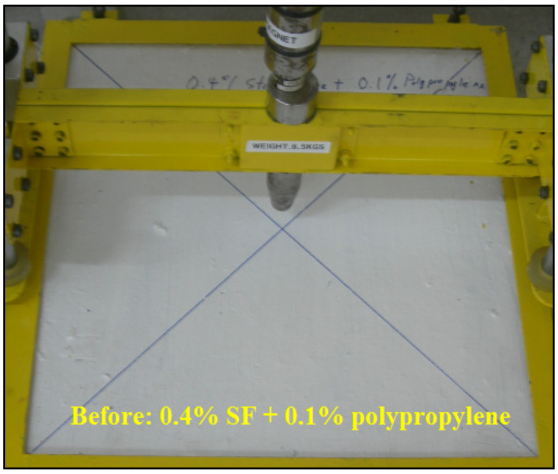
The impact test results showed that the plain OPC concrete could only sustain 4 blows before breaking into three big pieces. The slab did not show any plastic deformation and failed instantly on the 4th blow. The failure pieces were not interconnected with each other after failure.

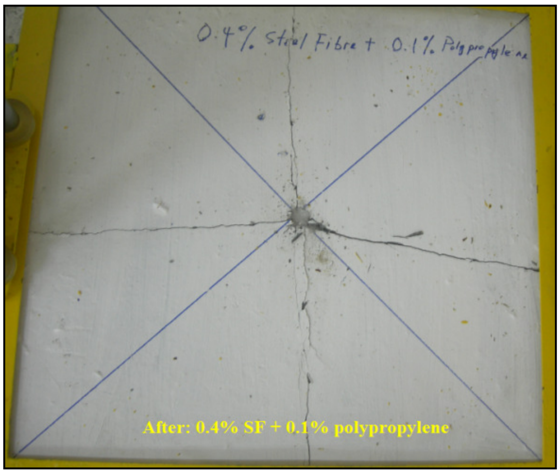
For HyFRC with 0.5% polypropylene-steel and nylon-steel fibre content, the small scale slab developed the first crack on the side of the slab on the 14th and 32nd blow, respectively and the first surface crack was detected on the 16th and 32nd and blow, respectively. The HyFRC with 0.5% nylon-steel was able to receive 40 blows before failure fully occurred compared to 32 blows for HyFRC with 0.5% polypropylene-steel. When failure occurred, the fractured small scale slab was still interconnected by the fibres. The FRC is said to exhibit ductile failure as shown in Figure 4.20. It is clearly seen that the small scale slab could still receivw impact after post-cracking; hence inclusion of hybrid fibres greatly improved the toughness of the small scale slab.

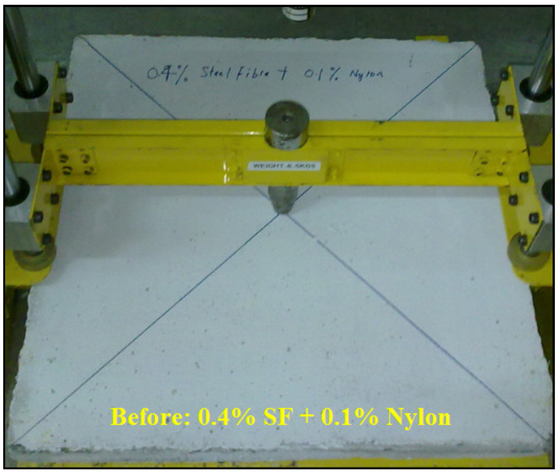
The FRC slab with hybrid 1.0% nylon-steel and polypropylene-steel fibre content developed the first crack on the side of the slab on the 321st and 305th blow, respectively while the first surface crack was detected on the 582nd and 539th blow, respectively. However, the 1.0% hybrid nylon-steel fibre slab was still able to receive 259 blows before failure compared to 233 blows for the 1.0% hybrid polypropylene-steel slab. This is due to the smaller dimensions of the nylon and polypropylene fibres, which bridge micro-cracks and therefore controls their growth and delays coalescence as shown clearly in Figure 4.7. This enables the composite to have higher tensile strength. At the same time, the hooked end of the steel fibre is larger and is intended to arrest the propagation of macro-cracks and therefore results in a substantial improvement in the fracture toughness of the composite. The mean value for nylon-steel HyFRC was higher than that of the polypropylene-steel HyFRC, indicating that the hybrid nylon-steel fibres addition was more effective than its polypropylene-steel counterpart in delaying the ultimate failure.

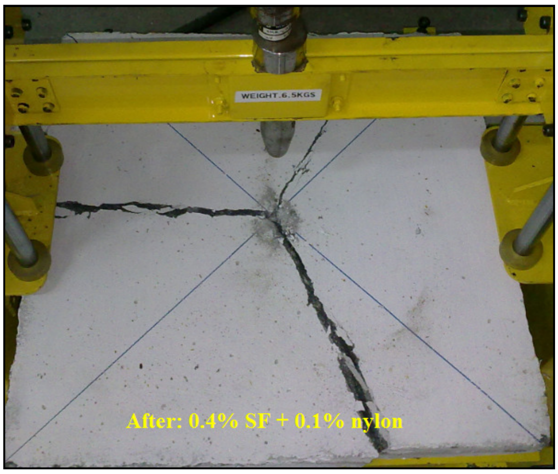

Before: Plain concrete


After: Plain concrete


WEIGHT 6.5KGS
Before: 0.4% SF + 0.1% polypropylene


0.4% Steel Fibre + 0.1% Polypropylene
After: 0.4% SF + 0.1% polypropylene


0.4% Steel Fibre + 0.1% Nylon
Before: 0.4% SF + 0.1% Nylon


WEIGHT 6.5KGS
After: 0.4% SF + 0.1% nylon

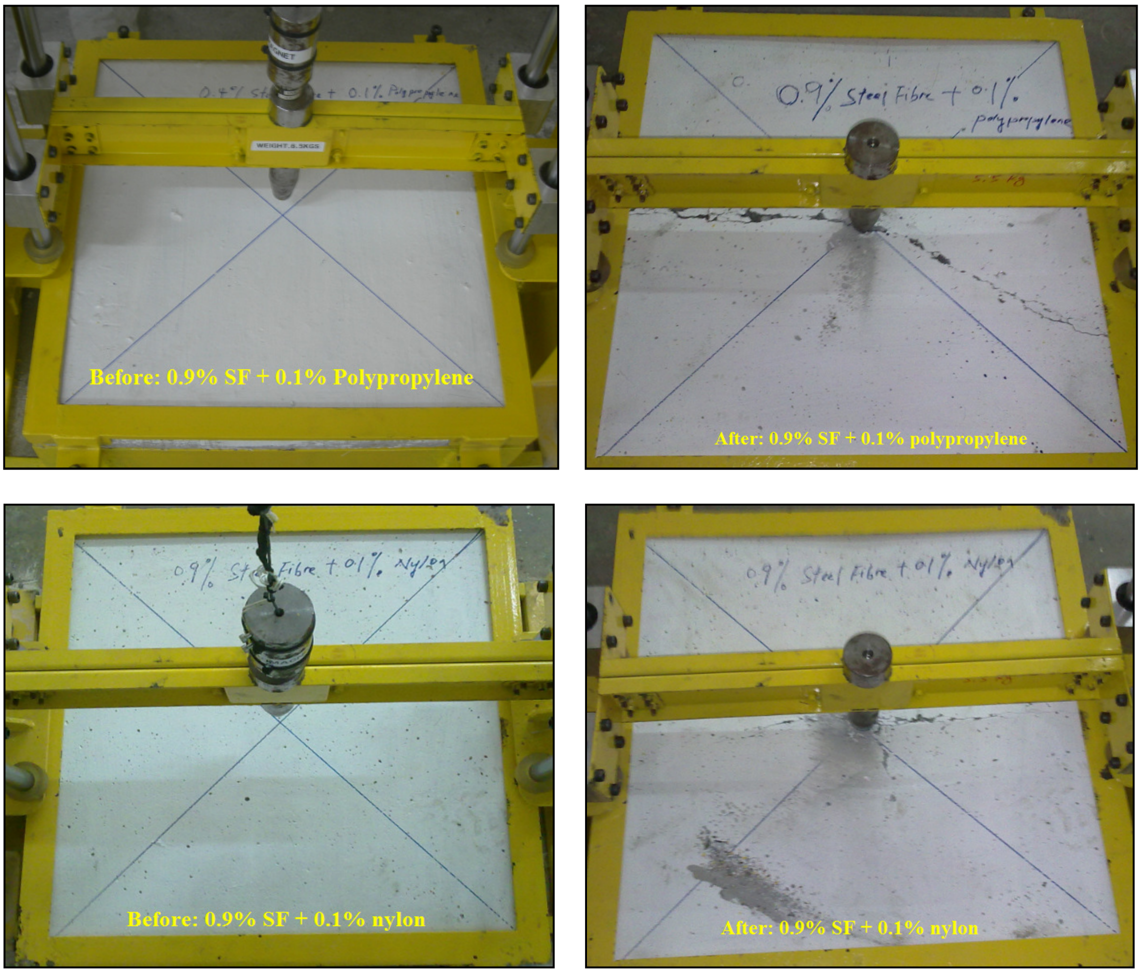


Figure 4.20, continued: Failure mode of plain concrete and different percentage of HyFRCs

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The primary objective of this research program which was to develop high performance hybrid fibre reinforced composites with desirable fresh and hardened properties was obtained. Through analysis of the results, the fibre content used in the FRC has played an important role in enhancing the strength properties of concrete. Hybrid fibre-reinforced concrete utilizes two complementary fibres to improve the properties of concrete. Hybrid fibres of nylon-steel and polypropylene-steel concrete are used to provide improved engineering properties in HyFRCs. There is a positive interaction between the fibres and the resulting hybrid performance exceeds the sum of plain concrete performance. The result showed that the hybrid nylon-steel FRC may give better performance compared to hybrid polypropylene-steel FRC. Within the scope of the work in this study, the following conclusions can be drawn:

1. Workability

The slump and the Vebe time of the mixes were measured as indicators of workability in terms of miscibility, placeability, and property improvements. As the fibre content increases, a lower slump and also higher Vebe time were measured. Thus, for a fixed volume fraction of fibres, the use of micro fibres in the hybrid composites adversely affected the workability. This is expected because the micro fibres have a larger surface area for a given volume fraction than macro fibres.

2. Compressive strength

Some inconsistencies in the compressive strengths were noticed. HyFRC provided the highest value of compressive which is slightly higher than OPC. However, the concrete strength is decreased much when the hybrid fibre content is more than 1.0%. Therefore, in order to maintain a particular compressive strength level. Hybrid fibre concentration in concrete must be controlled.

3. Modified cube test

In the modified cube test, addition of different content of fibre did not improve the compressive strength of the equivalent concrete cube. However, HyFRCs modified cubes with nylon-steel and polypropylene-steel developed higher strength compared to actual cube and plain OPC concrete. This is due to the superior mechanical bonding with cement matrix in HyFRC.

4. Splitting tensile strength

The HyFRCs of nylon-steel and polypropylene-steel clearly show improvement in terms of splitting tensile strength compared to plain concrete. It can be concluded that the increase of fibre content is consistent to the improvement in the splitting tensile strength. The splitting tensile strength of HyFRC was clearly enhanced with the increase of hybrid fibre content. In the primary stage of cracking of concrete, there are numerous nylon and polypropylene fibres bridging the micro-cracks and preventing the expansion of the cracks. When the tensile stress is applied to the specimens, the stress was transferred to the steel fibres, which are geometrical and stronger and have hooked ends, so they can arrest the propagating macro-cracks and substantially improve the splitting tensile strength.

5. Modulus of Rupture (MOR)

Although the addition of micro fibres did not have any effect on the compressive strength of the mix, there was a clear improvement in the MOR of the material under two point loading. Most of the hybrid composites when compared with non-fibrous control concrete showed an increase in the value of MOR by about 12.5%.

6. Comparison of flexure load vs. flexure extension plots

The instability at the peak load is a function of the matrix strength in the flexure load vs. flexure extension curve tests. This unstable release of energy was reduced when fibres were present. It can be concluded that the post peak response of the hybrid composites was reduced.

For HyFRC mixes containing 0.5% volume fraction of nylon-steel and polypropylene-steel, the flexure load vs. flexure extension response followed a softening trend after the peak load. This was expected because of the low modulus of the fibre content that require large strains to attain stresses approaching the strength, as the cracks become wider.

For HyFRC with 1.0% volume fraction of nylon-steel and polypropylene-steel, there was an increase in the load carrying capacity after the peak. The results indicated that the instability at the peak load reduced with the addition of higher amounts of fibre. A high volume fraction of the fibres may be responsible for increasing the effort required for compaction which, in turn, adversely affected the strength and flexural response of the material.

7. Impact Test

The use of HyFRC significantly increases the energy required to cause failure under the impact resistance test when compared with non-fibrous control concrete. HyFRC is more effective at resisting spalling, and more resistant to permanent deflection. It has the ability to absorb energy and also to sustain a higher number of drops till failure. Consequently, it can be concluded that the impact resistance of concrete was significantly improved by addition of different fibre content.

8. Static and dynamic modulus of elasticity

The inclusion of hybrid nylon-steel and polypropylene-steel fibres in concrete may give a negative impact to the elastic modulus of concrete. Increasing the fibre content affected the static and dynamic modulus of elasticity of HyFRC such that it has either an increasing or decreasing trend having strengths greater or smaller as compared to that of plain concrete. It could be concluded that, the value of static modulus of elasticity is proportional to HyFRC specimens with reference of compressive strength at 28 days. However, they increase the strength properties and minimize potential for early cracking in the concrete.

9. Ultrasonic pulse velocity

From the results of the tests carried out, it could be concluded that the grade of concrete meets the requirement of excellent concrete quality. The ultrasonic pulse velocity of the OPC and HyFRCs were both 4.5 Km/s.

5.2 Recommendations for Further Research

This project also leads to the conclusion that more research is required in order to fully understand the behaviour of this material.

1. In this investigation, the effect of denier size of the micro fibres on toughness could not clearly be established. Future studies must explore this aspect further.
2. Introduce different shapes and aspect ratio of fibres into concrete to get better performance in strength properties,

3. Greater synergy may also be expected at low matrix strengths, and this aspect needs to be explored.
4. Study on the durability aspects of the hybrid FRC. Durability of concrete in many structures has been a major concern, and durability of concrete is intimately related to its permeability, porosity and sorptivity.
5. Investigate the fire resistance of the hybrid FRC as the nylon, polypropylene and steel fibres may be softened or melted at high temperatures.
6. Investigate the impact resistance of the OPC and the hybrid FRC such as vibration or seismic impacts.
7. Toughness test should be carried out to determine the ability of the hybrid FRC to carry load after failure. The hybrid fibres were observed to be able to carry load after the first crack during the flexural test. Hence this work can determine the amount of strength it can carry post-cracking.
8. Study the effect of different fibre combinations or dosage on improving the mechanical properties of hybrid fibre-reinforced concrete. `

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APPENDICES

1.0 Compressive Strength

Plain Concrete

1 day	b	d	t	Mass	Max Load	Stress 1	Stress 2	Density
sample	(mm)	(mm)	(mm)	(kg)	(kN)	(N/mm^2)	(N/mm^2)	(kg/m³)
1	101.20	101.40	101.40	2.50	546.6	53.27	NA	2402.61
2	100.60	101.51	101.30	2.50	545.8	53.45	NA	2416.71
3	100.20	101.00	101.24	2.50	531.8	52.55	NA	2440.05
4	100.20	101.12	101.48	2.50	549.6	54.24	NA	2431.34
Average						**53.38**	NA	**2422.68**

3 days	b	d	t	Mass	Max Load	Stress 1	Stress 2	Density
sample	(mm)	(mm)	(mm)	(kg)	(kN)	(N/mm^2)	(N/mm^2)	(kg/m³)
1	100.20	101.40	101.25	2.50	706.1	69.50	NA	2430.18
2	100.20	101.20	101.00	2.50	698.0	68.83	NA	2441.01
3	100.40	101.35	101.30	2.50	727.6	71.50	NA	2425.34
4	100.31	101.10	101.10	2.50	702.2	69.24	NA	2438.34
Average						**69.77**	NA	**2433.72**

7 days	b	d	t	Mass	Max Load	Stress 1	Stress 2	Density
sample	(mm)	(mm)	(mm)	(kg)	(kN)	(N/mm^2)	(N/mm^2)	(kg/m³)
1	100.10	100.30	101.00	2.50	896.2	89.26	NA	2465.38
2	100.21	101.50	101.30	2.50	913.4	89.80	NA	2426.35
3	100.30	100.80	101.20	2.50	910.3	90.04	NA	2443.42
4	100.20	100.70	101.40	2.50	868.3	86.05	NA	2443.46
Average						**88.79**	NA	**2444.65**

28 days	b	d	t	Mass	Max Load	Stress 1	Stress 2	Density
sample	(mm)	(mm)	(mm)	(kg)	(kN)	(N/mm^2)	(N/mm^2)	(kg/m³)
1	100.10	101.10	101.20	2.50	1001.1	98.92	NA	2441.04
2	100.20	101.00	101.00	2.50	972.9	96.13	NA	2445.85
3	100.10	100.80	101.00	2.50	944.6	93.62	NA	2453.15
4	100.20	100.90	101.10	2.50	987.1	97.63	NA	2445.85
Average						**96.58**	NA	**2446.47**

0.4% SF + 0.1% nylon

1 day	b	d	t	Mass (kg)	Max Load	Stress 1	Stress 2	Density (kg/m³)
sample	(mm)	(mm)	(mm)		(kN)	(N/mm^2)	(N/mm^2)	
1	100.10	100.80	101.20	2.53	450.3	44.63	-	2477.68
2	100.30	101.20	101.00	2.52	430.9	42.45	-	2458.09
3	100.20	101.20	101.20	2.53	450.6	44.44	-	2465.42
4	100.30	101.00	100.40	2.52	441.5	43.58	-	2477.68
Average						**43.77**	-	**2469.72**

3 days	b	d	t	Mass (kg)	Max Load	Stress 1	Stress 2	Density (kg/m³)
sample	(mm)	(mm)	(mm)		(kN)	(N/mm^2)	(N/mm^2)	
1	100.12	100.20	101.20	2.53	740.3	73.79	-	2492.02
2	100.10	100.40	101.00	2.52	716.8	71.32	-	2482.63
3	100.21	100.40	101.10	2.53	721.8	71.74	-	2487.28
4	100.10	100.40	101.20	2.52	721.6	71.80	-	2477.72
Average						**72.16**	-	**2484.91**

7 days	b	d	t	Mass (kg)	Max Load	Stress 1	Stress 2	Density (kg/m³)
sample	(mm)	(mm)	(mm)		(kN)	(N/mm^2)	(N/mm^2)	
1	100.10	100.20	101.10	2.53	952.5	94.96	-	2494.98
2	100.21	100.30	101.00	2.52	936.6	93.18	-	2482.37
3	100.10	100.20	100.80	2.53	949.4	94.66	-	2502.41
4	100.30	100.20	100.60	2.52	938.7	93.40	-	2492.49
Average						**94.05**	-	**2493.06**

28 days	b	d	t	Mass (kg)	Max Load	Stress 1	Stress 2	Density (kg/m³)
sample	(mm)	(mm)	(mm)		(kN)	(N/mm^2)	(N/mm^2)	
1	100.30	100.10	100.40	2.53	1024.1	102.00	72.61	2509.87
2	100.10	100.30	101.00	2.52	1036.8	103.27	73.55	2485.10
3	100.40	100.10	100.50	2.52	1013.4	100.84	71.77	2494.98
4	100.12	100.10	101.00	2.53	1043.1	104.08	74.13	2499.45
Average						**102.55**	**73.02**	**2497.35**

0.4% SF + 0.1% polypropylene

1 day	b	d	t	Mass (kg)	Max Load	Stress 1	Stress 2	Density (kg/m³)
sample	(mm)	(mm)	(mm)		(kN)	(N/mm^2)	(N/mm^2)	
1	100.10	100.80	101.20	2.53	419.4	41.57	-	2477.68
2	100.30	101.00	101.00	2.53	426.4	42.09	-	2472.73
3	100.20	101.10	101.20	2.53	437.0	43.14	-	2467.86
4	100.20	101.00	100.40	2.52	405.8	40.10	-	2480.15
Average						**41.72**	-	**2474.61**

3 days	b	d	t	Mass (kg)	Max Load	Stress 1	Stress 2	Density (kg/m³)
sample	(mm)	(mm)	(mm)		(kN)	(N/mm^2)	(N/mm^2)	
1	100.55	100.20	101.00	2.53	698.5	69.33	-	2486.28
2	100.21	100.60	101.00	2.53	680.1	67.46	-	2484.79
3	100.10	100.80	100.80	2.53	652.1	64.63	-	2487.51
4	100.20	100.60	100.40	2.52	641.2	63.61	-	2490.01
Average						**66.26**	-	**2487.15**

7 days	b	d	t	Mass (kg)	Max Load	Stress 1	Stress 2	Density (kg/m³)
sample	(mm)	(mm)	(mm)		(kN)	(N/mm^2)	(N/mm^2)	
1	100.20	100.50	101.20	2.53	861.3	85.53	-	2482.60
2	100.10	100.40	101.00	2.53	889.1	88.47	-	2492.48
3	100.10	100.80	101.20	2.53	867.4	85.97	-	2477.68
4	100.10	100.70	100.40	2.52	859.0	85.22	-	2490.02
Average						**86.30**	-	**2485.69**

28 days	b	d	t	Mass (kg)	Max Load	Stress 1	Stress 2	Density (kg/m³)
sample	(mm)	(mm)	(mm)		(kN)	(N/mm^2)	(N/mm^2)	
1	102.00	100.30	101.20	2.53	1141.7	111.60	79.55	2443.65
2	100.10	100.60	101.00	2.52	1087.0	107.94	76.98	2477.69
3	100.30	100.20	101.20	2.53	1118.8	111.32	79.35	2487.55
4	100.30	101.00	100.40	2.53	1121.8	110.74	78.98	2487.51
Average						**110.40**	**78.72**	**2474.10**

0.9% SF + 0.1% nylon

1 day	b	d	t	Mass (kg)	Max Load	Stress 1	Stress 2	Density (kg/m³)
sample	(mm)	(mm)	(mm)		(kN)	(N/mm^2)	(N/mm^2)	
1	100.20	100.30	100.20	2.60	531.9	52.93	-	2581.89
2	100.30	101.20	100.30	2.60	545.2	53.71	-	2553.82
3	100.20	101.20	100.20	2.60	532.8	52.54	-	2558.92
4	100.20	101.00	100.40	2.59	547.5	54.10	-	2549.04
Average						**53.32**	-	**2560.92**

3 days	b	d	t	Mass (kg)	Max Load	Stress 1	Stress 2	Density (kg/m³)
sample	(mm)	(mm)	(mm)		(kN)	(N/mm^2)	(N/mm^2)	
1	101.00	100.20	100.20	2.60	803.2	79.37	-	2563.99
2	100.20	101.10	100.30	2.60	817.5	80.70	-	2558.90
3	100.10	101.00	100.20	2.60	819.4	81.05	-	2566.55
4	100.20	100.60	100.40	2.58	796.7	79.04	-	2549.30
Average						**80.04**	-	**2559.69**

7 days	b	d	t	Mass (kg)	Max Load	Stress 1	Stress 2	Density (kg/m³)
sample	(mm)	(mm)	(mm)		(kN)	(N/mm^2)	(N/mm^2)	
1	100.30	100.80	100.20	2.60	851.7	84.24	-	2566.52
2	100.20	100.10	101.30	2.60	884.4	88.18	-	2558.95
3	100.10	100.20	100.20	2.59	844.5	84.20	-	2577.09
4	100.10	101.00	100.40	2.60	862.8	85.34	-	2561.44
Average						**85.49**	-	**2566.00**

28 days	b	d	t	Mass (kg)	Max Load	Stress 1	Stress 2	Density (kg/m³)
sample	(mm)	(mm)	(mm)		(kN)	(N/mm^2)	(N/mm^2)	
1	102.00	100.30	100.20	2.60	1057.8	103.40	73.91	2536.32
2	100.10	101.00	100.40	2.60	1016.1	100.50	71.85	2561.44
3	100.20	100.20	100.20	2.59	981.9	97.80	69.95	2574.52
4	100.10	101.00	100.40	2.60	1018.1	100.70	72.01	2561.44
Average						**100.60**	**71.93**	**2558.43**

0.9% SF + 0.1% polypropylene

1 day	b	d	t	Mass (kg)	Max Load	Stress 1	Stress 2	Density (kg/m³)
sample	(mm)	(mm)	(mm)		(kN)	(N/mm^2)	(N/mm^2)	
1	100.20	100.10	100.20	2.59	435.2	43.39	-	2577.09
2	100.20	101.00	100.70	2.59	417.1	41.21	-	2541.45
3	100.10	100.20	100.15	2.59	426.7	42.54	-	2578.38
4	100.20	101.00	100.30	2.58	402.8	39.80	-	2541.73
Average						**41.74**	-	**2559.66**

3 days	b	d	t	Mass (kg)	Max Load	Stress 1	Stress 2	Density (kg/m³)
sample	(mm)	(mm)	(mm)		(kN)	(N/mm^2)	(N/mm^2)	
1	101.00	100.10	100.30	2.58	655.1	64.80	-	2544.27
2	100.10	101.10	101.00	2.59	670.0	66.20	-	2533.92
3	100.20	101.00	100.28	2.59	678.6	67.05	-	2552.09
4	100.30	100.40	100.20	2.58	624.6	62.03	-	2556.92
Average						**65.02**	-	**2546.80**

7 days	b	d	t	Mass (kg)	Max Load	Stress 1	Stress 2	Density (kg/m³)
sample	(mm)	(mm)	(mm)		(kN)	(N/mm^2)	(N/mm^2)	
1	100.10	100.20	100.60	2.59	846.9	84.44	-	2566.85
2	100.30	100.10	101.00	2.59	835.1	83.18	-	2554.13
3	100.10	100.30	101.20	2.58	815.7	81.24	-	2539.24
4	100.10	100.40	100.35	2.58	807.4	80.34	-	2558.20
Average						**82.30**	-	**2554.61**

28 days	b	d	t	Mass (kg)	Max Load	Stress 1	Stress 2	Density (kg/m³)
sample	(mm)	(mm)	(mm)		(kN)	(N/mm^2)	(N/mm^2)	
1	100.10	100.30	101.20	2.59	1026.1	102.20	73.09	2549.08
2	100.10	101.00	101.00	2.59	1016.1	100.50	71.84	2536.43
3	100.30	100.20	101.20	2.58	994.7	98.97	70.79	2536.71
4	100.20	101.00	100.40	2.59	1028.8	101.66	72.67	2549.04
Average						**100.83**	**72.09**	**2542.82**

2.0 Comparison of compressive strength vs. residual strength

Fibre content (%)	**Compressive strength (Mpa)**	**Residual strength (Mpa)**
OPC	96.59	0.00
0.4%SF + 0.1%Nylon	102.55	73.02
0.4%SF + 0.1%Polypropylene	110.40	78.72
0.9%SF + 0.1%Nylon	100.60	71.93
0.9%SF + 0.1%Polypropylene	100.83	72.09

3.0 Modulus of Rupture (MOR)

Plain Concrete	Specimen Name	Width (mm)	Thickness (mm)	Maximum Flex Load (KN)	Stress (Nmm-2)
1	OPC 1	101.74	100.6	31.49	9.18
2	OPC 2	101.23	100.52	31.10	9.12
3	OPC 3	102.25	100.62	30.15	8.74
4	OPC 4	101.74	100.45	30.22	8.83
5	OPC 5	101.33	100.25	30.00	8.84
6	OPC 6	101.45	100.54	29.4	8.60
7	OPC 7	101.64	100.64	29.95	8.73
8*	OPC 8	100.30	100.50	29.516	8.74
	Average				**8.85**

***Result of flexural load vs. flexure extension**

0.4% SF + 0.1% Nylon	Specimen Name	Width (mm)	Thickness (mm)	Maximum Flex Load (KN)	Stress (Nmm-2)
1	0.4 SF + 0.1 N	101.16	100.3	35.16	10.36
2	0.4 SF + 0.1 N	101.32	100.4	31.67	9.30
3	0.4 SF + 0.1 N	102.21	100.55	33.08	9.60
4	0.4 SF + 0.1 N	101.24	100.35	31.96	9.40
5	0.4 SF + 0.1 N	101.22	100.20	32.25	9.52
6	0.4 SF + 0.1 N	101.35	100.42	31.92	9.37
7	0.4 SF + 0.1 N	101.25	100.54	33.20	9.73
8*	0.4 SF + 0.1 N	101.40	100.80	31.88	9.28
	Average				**9.57**

***Result of flexural load vs. flexure extension**

0.4% SF + 0.1% Polypropylene	Specimen Name	Width (mm)	Thickness (mm)	Maximum Flex Load (KN)	Stress (Nmm-2)
1	0.4 SF + 0.1 P	101.12	100.35	32.08	9.45
2	0.4 SF + 0.1 P	101.22	100.25	31.12	9.18
3	0.4 SF + 0.1 P	102.10	100.40	31.38	9.15
4	0.4 SF + 0.1 P	101.33	100.30	31.46	9.26
5	0.4 SF + 0.1 P	101.20	100.20	32.45	9.58
6	0.4 SF + 0.1 P	101.42	100.32	31.26	9.19
7	0.4 SF + 0.1 P	101.24	100.44	32.20	9.46
8*	0.4 SF + 0.1 P	101.20	100.80	31.28	9.13
	Average				**9.30**

***Result of flexural load vs. flexure extension**

0.9% SF + 0.1% Nylon	Specimen Name	Width (mm)	Thickness (mm)	Maximum Flex Load (KN)	Stress (Nmm-2)
1	0.9 SF + 0.1 N	101.12	100.32	35.36	10.42
2	0.9 SF + 0.1 N	101.22	100.64	36.66	10.73
3	0.9 SF + 0.1 N	101.31	100.45	35.46	10.41
4	0.9 SF + 0.1 N	100.84	100.25	36.24	10.73
5	0.9 SF + 0.1 N	101.22	100.26	37.30	11.00
6	0.9 SF + 0.1 N	100.94	100.43	36.62	10.79
7	0.9 SF + 0.1 N	101.32	100.24	36.60	10.79
8*	0.9 SF + 0.1 N	100.20	100.40	37.16	11.04
	Average				**10.74**

***Result of flexural load vs. flexure extension**

0.9% SF + 0.1% Polypropylene	Specimen Name	Width (mm)	Thickness (mm)	Maximum Flex Load (KN)	Stress (Nmm-2)
1	0.9 SF + 0.1P	101.11	100.38	35.16	10.35
2	0.9 SF + 0.1P	101.12	100.56	34.12	10.01
3	0.9 SF + 0.1P	101.13	100.65	35.06	10.27
4	0.9 SF + 0.1P	100.34	100.66	35.12	10.36
5	0.9 SF + 0.1P	101.12	100.46	35.23	10.36
6	0.9 SF + 0.1P	100.76	100.42	34.22	10.10
7	0.9 SF + 0.1P	101.12	100.44	34.30	10.09
8	0.9 SF + 0.1P	101.20	100.40	34.26	10.08
	Average				**10.20**

***Result of flexural load vs. flexure extension**

4.0 Splitting Tensile Strength

Plain Concrete

No	diameter (mm)				Average	Height (mm)		Average	Load	Stress (Nmm-2)
	1	2	3	4		1	2			
1	100.96	99.60	98.24	100.10	99.73	200.10	200.00	200.05	160.70	5.13
2	100.24	101.08	99.72	101.92	100.74	200.00	210.00	205.00	154.20	4.75
3	99.65	99.28	100.28	98.08	99.32	200.00	200.50	200.25	160.10	5.12
4	100.17	99.74	100.40	98.92	99.81	201.00	200.00	200.50	154.20	4.91
5	99.00	100.20	98.80	101.00	99.75	200.00	199.00	199.50	153.20	4.90
6	101.50	97.10	98.50	100.90	99.50	199.00	200.00	199.50	154.20	4.95
7	101.03	99.20	100.16	99.73	100.03	200.90	200.50	200.70	153.20	4.86
8	102.33	100.21	99.19	101.12	100.71	197.80	198.00	197.90	154.50	4.93
									Average	**4.94**

0.4% SF + 0.1% polypropylene

No	diameter (mm)				Average	Height (mm)		Average	Load (KN)	Stress (Nmm-2)
	1	2	3	4		1	2			
1	100.50	100.10	98.88	100.10	99.90	210.00	200.00	205.00	198.90	6.18
2	100.20	100.30	99.98	101.12	100.40	200.00	199.00	199.50	201.20	6.39
3	99.86	99.88	100.18	100.02	99.99	200.00	200.50	200.25	199.20	6.33
4	99.89	99.94	100.20	99.89	99.98	200.00	199.00	199.50	200.20	6.39
5	99.96	100.10	99.90	100.60	100.14	200.50	200.00	200.25	198.80	6.31
6	100.50	98.70	99.80	100.60	99.90	200.00	200.50	200.25	200.30	6.37
7	100.30	99.70	99.89	100.30	100.05	200.20	200.50	200.35	198.60	6.31
8	100.20	100.30	100.02	100.12	100.16	198.00	199.00	198.50	199.40	6.38
									Average	**6.33**

0.4% SF + 0.1% nylon

No	diameter (mm)				Average	Height (mm)		Average	Load (KN)	Stress (Nmm-2)
	1	2	3	4		1	2			
1	100.10	100.12	99.88	99.96	100.02	200.00	205.00	202.50	208.20	6.54
2	100.12	99.96	99.99	100.10	100.04	200.00	200.00	200.00	206.20	6.56
3	100.02	100.12	100.10	100.20	100.11	200.00	200.30	200.15	199.80	6.35
4	100.01	99.98	100.20	99.90	100.02	200.00	200.05	200.03	203.10	6.46
5	99.98	100.04	100.10	99.90	100.01	200.50	200.00	200.25	205.80	6.54
6	99.97	98.90	100.20	100.12	99.80	199.90	200.05	199.98	200.20	6.39
7	100.10	99.79	99.97	100.30	100.04	200.10	199.90	200.00	208.60	6.64
8	100.15	99.98	99.98	100.10	100.05	200.10	200.00	200.05	209.40	6.66
									Average	**6.52**

0.9% SF + 0.1% polypropylene

No	diameter (mm)				Average	Height (mm)		Average	Load (KN)	Stress (Nmm-2)
	1	2	3	4		1	2			
1	100.20	100.15	98.80	100.05	99.80	205.00	200.20	202.60	233.20	7.34
2	100.10	100.20	99.90	100.12	100.08	200.00	199.80	199.90	220.60	7.02
3	99.86	99.88	100.18	100.02	99.99	200.00	200.15	200.08	231.50	7.37
4	99.89	99.94	100.20	99.89	99.98	205.00	199.00	202.00	221.10	6.97
5	99.96	100.10	99.90	100.60	100.14	200.50	200.00	200.25	225.20	7.15
6	100.50	98.70	99.80	100.60	99.90	199.90	200.20	200.05	231.00	7.36
7	100.30	99.70	99.89	100.30	100.05	199.60	200.00	199.90	230.20	7.33
8	100.20	100.30	100.02	100.12	100.16	198.00	199.00	198.50	224.10	7.18
									Average	**7.21**

0.9% SF + 0.1% nylon

No	diameter (mm)				Average	Height (mm)		Average	Load (KN)	Stress (Nmm-2)
	1	2	3	4		1	2			
1	99.98	100.10	100.20	99.98	100.07	199.95	200.10	200.03	236.80	7.53
2	100.10	99.80	99.96	100.12	100.00	200.00	199.99	200.00	234.50	7.46
3	100.10	99.90	99.98	100.10	100.02	199.96	200.10	200.03	235.60	7.50
4	100.20	99.70	100.10	99.96	99.99	200.10	199.98	200.04	237.80	7.57
5	100.10	99.90	99.98	99.98	99.99	199.99	200.04	200.02	235.60	7.50
6	100.10	98.99	99.90	100.13	99.78	200.10	200.04	200.07	231.00	7.37
7	100.06	99.75	99.96	100.23	100.00	200.06	199.98	200.02	240.60	7.66
8	100.05	99.96	99.70	99.98	99.92	199.98	200.05	200.02	241.10	7.68
									Average	**7.53**

5.0 Calculation of Static Modulus of Elasticity in Compression (Code: BS1881:Part121:1983)

Specimen: Plain concrete

Average compressive strength from Cube Test (28 days) , fcu	96.60	N/mm^2
Height of Cylinder, H	298.80	mm
Dia of Cylinder, d	149.90	mm
Area of Cylinder (3.14 x d^2/4)	17647.90	mm^2
Basic Stress(Minimun Stress), σ_b	0.50	N/mm^2
Maximun Applied Stress, σ_a= (1/3f_{cu}) *0.8	25.76	N/mm^2
Minimum Applied Load (σ_b x Area), $\mathbf{P_b}$	8.82	kN
Maximun Applied Load (σ_a x Area), $\mathbf{P_a}$	454.61	kN
Load Increment, c = (P_a-P_b) /8 (Interval = 8)	55.72	kN
Strain Coefficient, (0.002/150) x 1/2	6.667E-06	

Load	Load Estimated (kN)	Applied Load (kN)	Gauge Reading 1st cycle		Gauge Reading 2nd cycle		Stress (N/mm2)	Strain	Modulus fo Elasticity, Ec (N/mm2)
Pb	8.82	8.8	0 Sec	1.00	0 Sec	0.00	0.50	0.000003	**52734.90**
			30 Sec	1.00	30 Sec	0.00			
			60 Sec	1.00	60 Sec	0.00			
Pb+c	64.55	64.1	9		11.00		3.63	0.000067	
Pb+2c	120.27	120	19		22.00		6.80	0.000137	
Pb+3c	175.99	176	28		32.50		9.97	0.000202	
Pb+4c	231.72	231	37		41.00		13.09	0.000260	
Pb+5c	287.44	290	46		49.50		16.43	0.000318	
Pb+6c	343.16	343	55		56.00		19.44	0.000370	
Pb+7c	398.89	399	64.5		64.50		22.61	0.000430	
Pa	454.61	455	0 Sec	74.50	0 Sec	70.00	25.78	0.000483	
			30 Sec	74.50	30 Sec	70.50			
			60 Sec	74.50	60 Sec	70.50			

Specimen: 0.4% SF + 0.1% nylon

Average compressive strength from Cube Test (28 days) , fcu	102.55	N/mm^2
Height of Cylinder, H	299.70	mm
Dia of Cylinder, d	150.61	mm
Area of Cylinder ($3.14 \times d^2/4$)	17815.48	mm^2
Basic Stress(Minimun Stress), σ_b	0.50	N/mm^2
Maximun Applied Stress, $\sigma_a = (1/3f_{cu}) *0.8$	27.35	N/mm^2
Minimum Applied Load (σ_b x Area), $\mathbf{P_b}$	8.91	kN
Maximun Applied Load (σ_a x Area), $\mathbf{P_a}$	487.19	kN
Load Increment, c = (P_a-P_b) /8 (Interval = 8)	59.79	kN
Strain Coefficient, (0.002/150) x 1/2	6.667E-06	

Load	Load Estimated (kN)	Applied Load (kN)	Gauge Reading 1st cycle		Gauge Reading 2nd cycle		Stress (N/mm2)	Strain	Modulus fo Elasticity, Ec (N/mm2)
Pb	8.91	8.91	0 Sec	1.00	0 Sec	1.00	0.50	0.000007	**48035.16**
			30 Sec	1.00	30 Sec	1.00			
			60 Sec	1.00	60 Sec	1.00			
Pb+c	68.69	68.7	10		9.50		3.86	0.000065	
Pb+2c	128.48	128.5	19		19.00		7.21	0.000127	
Pb+3c	188.27	188.2	28		29.00		10.56	0.000190	
Pb+4c	248.05	248	40		40.50		13.92	0.000268	
Pb+5c	307.84	307	53.5		50.50		17.23	0.000347	
Pb+6c	367.62	367.6	65.5		62.00		20.63	0.000425	
Pb+7c	427.41	427.6	76		73.00		24.00	0.000497	
Pa	487.19	487.19	0 Sec	85.00	0 Sec	84.00	27.35	0.000566	
			30 Sec	85.00	30 Sec	85.00			
			60 Sec	85.00	60 Sec	85.00			

Specimen: 0.4% SF + 0.1% polypropyle

Average compressive strength from Cube Test (28 days) , fcu	110.40	N/mm^2
Height of Cylinder, H	299.60	mm
Dia of Cylinder, d	149.80	mm
Area of Cylinder (3.14 x d^2/4)	17624.37	mm^2
Basic Stress(Minimun Stress), σ_b	0.50	N/mm^2
Maximun Applied Stress, σ_a= (1/3f_{cu}) *0.8	29.44	N/mm^2
Minimum Applied Load (σ_b x Area), $\mathbf{P_b}$	8.81	kN
Maximun Applied Load (σ_a x Area), $\mathbf{P_a}$	518.86	kN
Load Increment, c = (P_a-P_b) /8 (Interval = 8)	63.76	kN
Strain Coefficient, (0.002/150) x 1/2	6.667E-06	

Load	Load Estimated (kN)	Applied Load (kN)	Gauge Reading 1st cycle		Gauge Reading 2nd cycle		Stress (N/mm2)	Strain	Modulus fo Elasticity, Ec (N/mm2)
Pb	8.81	8.8	0 Sec	1.00	0 Sec	1.00	0.50	0.000007	**51643.77**
			30 Sec	1.00	30 Sec	1.00			
			60 Sec	1.00	60 Sec	1.00			
Pb+c	72.57	72	10		10.00		4.09	0.000067	
Pb+2c	136.32	136	20		20.00		7.72	0.000133	
Pb+3c	200.08	300	29		29.00		17.02	0.000193	
Pb+4c	263.84	263	41		40.00		14.92	0.000270	
Pb+5c	327.59	327	54		55.00		18.55	0.000363	
Pb+6c	391.35	391	65		64.00		22.19	0.000430	
Pb+7c	455.11	455	76		75.00		25.82	0.000503	
Pa	518.86	518	0 Sec	85.00	0 Sec	84.50	29.39	0.000566	
			30 Sec	85.00	30 Sec	85.00			
			60 Sec	85.00	60 Sec	85.00			

Specimen: 0.9% SF + 0.1% polypropylene

Average compressive strength from Cube Test (28 days) , fcu	100.83	N/mm^2
Height of Cylinder, H	299.80	mm
Dia of Cylinder, d	149.96	mm
Area of Cylinder (3.14 x d^2/4)	17662.04	mm^2
Basic Stress(Minimun Stress), σ_b	0.50	N/mm^2
Maximun Applied Stress, σ_a= (1/3f_{cu}) *0.8	26.89	N/mm^2
Minimum Applied Load (σ_b x Area), $\mathbf{P_b}$	8.83	kN
Maximun Applied Load (σ_a x Area), $\mathbf{P_a}$	474.90	kN
Load Increment, c = (P_a-P_b) /8 (Interval = 8)	58.26	kN
Strain Coefficient, (0.002/150) x 1/2	6.667E-06	

Load	Load Estimated (kN)	Applied Load (kN)	Gauge Reading 1st cycle		Gauge Reading 2nd cycle		Stress (N/mm2)	Strain	Modulus fo Elasticity, Ec (N/mm2)
Pb	8.83		0 Sec	1.00	0 Sec	1.00	0.00	0.000007	**45411.74**
			30 Sec	1.00	30 Sec	1.00			
			60 Sec	1.00	60 Sec	1.00			
Pb+c	67.09	67	10		10.00		3.79	0.000067	
Pb+2c	125.35	125	21		21.00		7.08	0.000140	
Pb+3c	183.61	183	31		31.00		10.36	0.000207	
Pb+4c	241.86	241	43		43.00		13.65	0.000287	
Pb+5c	300.12	300	55		54.00		16.99	0.000363	
Pb+6c	358.38	358	66		65.00		20.27	0.000437	
Pb+7c	416.64	416	77		76.00		23.55	0.000510	
Pa	474.90	475	0 Sec	89.00	0 Sec	90.00	26.89	0.000599	
			30 Sec	90.00	30 Sec	90.00			
			60 Sec	90.00	60 Sec	90.00			

Specimen: 0.9% SF + 0.1% nylon

Average compressive strength from Cube Test (28 days) , fcu	100.60	N/mm^2
Height of Cylinder, H	299.60	mm
Dia of Cylinder, d	149.98	mm
Area of Cylinder (3.14 x d^2/4)	17666.75	mm^2
Basic Stress(Minimun Stress), σ_b	0.50	N/mm^2
Maximun Applied Stress, σ_a= (1/3f_{cu}) *0.8	26.83	N/mm^2
Minimum Applied Load (σ_b x Area), $\mathbf{P_b}$	8.83	kN
Maximun Applied Load (σ_a x Area), $\mathbf{P_a}$	473.94	kN
Load Increment, c = (P_a-P_b) /8 (Interval = 8)	58.14	kN
Strain Coefficient, (0.002/150) x 1/2	6.667E-06	

Load	Load Estimated (kN)	Applied Load (kN)	Gauge Reading 1st cycle		Gauge Reading 2nd cycle		Stress (N/mm2)	Strain	Modulus fo Elasticity, Ec (N/mm2)
Pb	8.83	8.8	0 Sec	1.00	0 Sec	1.00	0.50	0.000007	**45054.68**
			30 Sec	1.00	30 Sec	1.00			
			60 Sec	1.00	60 Sec	1.00			
Pb+c	66.97	67	11		11.00		3.79	0.000073	
Pb+2c	125.11	125	22		22.00		7.08	0.000147	
Pb+3c	183.25	183	33		33.00		10.36	0.000220	
Pb+4c	241.39	241	44		44.00		13.64	0.000293	
Pb+5c	299.52	299	55		54.00		16.92	0.000363	
Pb+6c	357.66	357	65		64.00		20.21	0.000430	
Pb+7c	415.80	415	76		76.00		23.49	0.000507	
Pa	473.94	474	0 Sec	88.00	0 Sec	88.00	26.83	0.000591	
			30 Sec	89.00	30 Sec	89.00			
			60 Sec	89.00	60 Sec	89.00			

6.0 Dynamic Modulus of Elasticity

Dynamic Modulus of Elasticity (GPa)					
	Hz			Average	**Ed (GPa)**
Plain concrete	4738	4741	4746	4742	**54.79**
0.4% SF +Polypropylene	4753	4754	4757	4755	**56.07**
0.4% SF +Nylon	4730	4730	4734	4731	**55.66**
0.9% SF +Polypropylene	4644	4640	4643	4642	**54.98**
0.9% SF +Nylon	4635	4627	4628	4630	**54.93**

7.0 The Results of Impact Resistance With Different % of fibres

Percentage of fibre (%)	Number of blows												Energy absorb (Joule)
	First crack (side of small cube)			Average	First crack (surface of small cube)			Average	Failure mode			Average	
OPC	3	2	4	**3**	4	4	4	**4**	4	4	4	**4**	**163**
0.4% SF + 0.1% P	13	14	15	**14**	15	16	17	**16**	31	33	32	**32**	**1305**
0.4% SF + 0.1% N	32	30	34	**32**	34	32	36	**34**	41	40	39	**40**	**1632**
0.9% SF + 0.1% P	306	301	308	**305**	305	306	307	**306**	535	540	542	**539**	**21996**
0.9% SF + 0.1% N	322	320	321	**321**	324	322	323	**323**	579	586	581	**582**	**23751**

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AWARDS AND RECOGNITIONS

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