DEVELOPMENT OF FRP BASED COMPOSITE FIBRE FOR FIBRE REINFORCED CEMENTITIOUS COMPOSITES

by

Mohammed Farooq

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Abstract

This thesis describes a method of development of a novel fibre based on fibre reinforced polymers (FRP), for use fibre reinforcement in concrete. Thermosetting epoxy resin matrix were reinforced with E-glass, S-glass, and Carbon fibre to produce different types of composite fibres. The FRP panels were produced using the Vacuum Infusion technique, and then cut to different fibre sizes. The volume fractions of reinforcements within the FRP fibre were controlled by using woven and unidirectional fabrics. The number of layers of reinforcing fibres were also changed, to obtain the optimal thickness of the fibres.

The FRP material was characterized by means of tensile tests and microscope image analysis. Four different compositions of FRP were produced with tensile strengths ranging from 195 MPa to 950 MPa. The different combinations in geometry broadened the total number of fibres investigated to 12. Single fibre pullout tests were performed to obtain the fundamental fibre-matrix interfacial bond parameters for the different FRP fibres. The FRP fibres, being hydrophilic, along with having a unique rough surface texture, showed a good bond with cement matrix. A bond strength superior to industrially available straight steel fibres and crimped polypropylene fibres has been observed. The 3 best fibres were then chosen to examine the flexural behaviour FRP fibre reinforced concrete beams.

The optimized FRP fibres, one each of Glass FRP and Carbon FRP were then further investigated to study the effect of matrix maturity, temperature, fibre inclination, and loading rate on the fibre-matrix interfacial behaviour using single fibre pullout tests. Scanning Electron Microscope (SEM) analysis was carried out to identify the effect of above-mentioned factors on the surface characteristics of the fibre. An attempt was also made to optimize the fibre-matrix interface to achieve an optimized failure mechanism by coating the fibre with oil.

The ability of the fibre to transfer stresses across a cracked section over extended periods has been investigated by means of fibre-relaxation tests. Finally, to assess durability, the fibres were conditioned at high pH and high temperature after which single fibre pullout, direct tension tests, & SEM analysis were conducted.
Preface

This thesis presents the original, unpublished and independent work carried out by the author, Mohammed Farooq, under the supervision of Dr. Nemy Banthia. The fibre and specimen have been produced, and tested by the author, some testing procedures of which have been developed by Dr. Nemy Banthia.
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<th>Description</th>
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<tbody>
<tr>
<td>ASTM</td>
<td>American Standards for Testing and Measurement</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon Fibre Reinforced Polymer</td>
</tr>
<tr>
<td>C-H</td>
<td>Calcium Hydroxide</td>
</tr>
<tr>
<td>CM</td>
<td>Compression Moulding</td>
</tr>
<tr>
<td>CMC</td>
<td>Ceramic Matrix Composite</td>
</tr>
<tr>
<td>C-S-H</td>
<td>Calcium Silicate Hydrate</td>
</tr>
<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
</tr>
<tr>
<td>ECC</td>
<td>Engineered Cementitious Composites</td>
</tr>
<tr>
<td>EDX</td>
<td>Energy Dispersive X-ray Spectroscopy</td>
</tr>
<tr>
<td>FC</td>
<td>Fibre count</td>
</tr>
<tr>
<td>FSS</td>
<td>Fibre specific surface</td>
</tr>
<tr>
<td>FRC</td>
<td>Fibre Reinforced Concrete</td>
</tr>
<tr>
<td>FRP</td>
<td>Fibre Reinforced Polymer</td>
</tr>
<tr>
<td>GFRP</td>
<td>Glass Fibre Reinforced Polymer</td>
</tr>
<tr>
<td>GPC</td>
<td>Geo-polymer Concrete</td>
</tr>
<tr>
<td>GPC</td>
<td>Geo-polymer Concrete</td>
</tr>
<tr>
<td>HMPE</td>
<td>High molecular weight polyethylene</td>
</tr>
<tr>
<td>HPPE</td>
<td>High-performance polyethylene</td>
</tr>
<tr>
<td>ITZ</td>
<td>Interfacial Transition Zone</td>
</tr>
<tr>
<td>LCM</td>
<td>Liquid Composite Moulding</td>
</tr>
<tr>
<td>LVDT</td>
<td>Linear Variable Differential Transformer</td>
</tr>
<tr>
<td>NCC</td>
<td>Nano-crystalline cellulose</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
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<td>--------------</td>
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</tr>
<tr>
<td>OM</td>
<td>Optical Microscope</td>
</tr>
<tr>
<td>PA or PPA</td>
<td>Polyamide or High performance polyamide</td>
</tr>
<tr>
<td>PAN</td>
<td>Polyacrylonitrile</td>
</tr>
<tr>
<td>PE</td>
<td>Polyethylene</td>
</tr>
<tr>
<td>PEEK</td>
<td>Polyether ether ketone</td>
</tr>
<tr>
<td>PEI</td>
<td>Polyethylenimine</td>
</tr>
<tr>
<td>PET</td>
<td>Polyethylene terephthalate</td>
</tr>
<tr>
<td>PMC</td>
<td>Polymer Matrix Composite</td>
</tr>
<tr>
<td>PP</td>
<td>Polypropylene</td>
</tr>
<tr>
<td>PTFE</td>
<td>Polytetrafluoroethylene</td>
</tr>
<tr>
<td>PVA</td>
<td>Polyvinyl Alcohol</td>
</tr>
<tr>
<td>PVC</td>
<td>Polyvinyl Chloride</td>
</tr>
<tr>
<td>RTM</td>
<td>Resin Transfer Moulding</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>UHMWPE</td>
<td>Ultrahigh molecular weight polyethylene</td>
</tr>
<tr>
<td>VARTM</td>
<td>Vacuum Assisted Resin Transfer Moulding</td>
</tr>
<tr>
<td>VI or VIP</td>
<td>Vacuum Infusion or Vacuum infusion process</td>
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Begin with the name of God, the most Gracious, the most Merciful

I would like to express profound gratitude to my supervisor, Dr. Nemy Banthia for his invaluable support throughout the project. I am thankful for his motivation, freedom, and trusting me with this project. It has been a privilege to work with him.

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I would like to once again thank the Almighty, for guiding me through life.
"If things are not failing, you are not innovating enough"

- Elon Musk
Chapter 1: Introduction

1.1 Understanding the study and its importance

The study begins with the development of a fibre reinforced polymer (FRP) based composite fibre to be used as a short random discrete reinforcement in concrete. Concrete which contain fibres as one of the key ingredients are referred to as fibre reinforced concrete, commonly abbreviated as FRC throughout the world. The use of FRC in the construction industry is well documented; the contribution of fibre in enhancement of cracking resistance, toughness, strength, fatigue life, impact resistance is well known to us by now [1]. The increase ductility along with the aforementioned properties, due the addition of randomly distributed fibres is also observed [2].

The concept of short fibre reinforcement is not new to the engineering world, and the civil construction industry is not the only industry to use these kinds of reinforcements in structures. Several materials, in which, a type of polymer, mostly plastic, is reinforced with short reinforcing fibres to enhance its properties exist. These are referred to as Polymer Matrix Composites or PMC, and are widely used in the marine, automotive, and aerospace industries. The automotive industry also makes use of Ceramic Matrix Composites (CMC), in which high strength carbon fibres are used to increase the toughness of a very strong but brittle ceramic matrix such as silicon carbide. Carbon fibre reinforced silicon carbide is used in making brake pads of sports cars such as Mercedes-Benz C215, Bugatti Veyron, Corvette ZR1, Ferrari 430, and so on.

The fundamental understanding of the word composite is a material made up of different parts or elements. In the context of engineering materials, a composite can be defined as a material that is made from two or more constituent materials which independently have significantly different properties, when combined together make a material whose properties different from the constituent materials. For instance consider a composite of a plastic matrix such as thermosetting polyester reinforced with glass fibre. The glass fibre as we know is flexible and brittle, and the polyester matrix is flexible and has an elasto-plastic constitutive response. The composite made by the combination of these two constituent material, also commonly referred to as Fibre Reinforced Polymer (FRP) is stiff and brittle. Cement paste, mortar, plain concrete, and fibre reinforced...
concrete (FRC) are all composites, however only fibre reinforced concrete falls under the fibre reinforced composites category. FRC, CMC and PMC are all fibre reinforced composites, the difference lies only in the choice of matrix and reinforcing fibre.

The use of various “continuous” fibres as continuous reinforcements in different polymer, cementitious, or other matrices open up a whole new world. Continuous fibre reinforced composites are used to a much greater extent than discrete fibre reinforced composites across all industries. However, the mechanism of strengthening the matrix is different in the case of continuous reinforcements, and therefore the applications of continuous fibre reinforcements and random discrete fibre reinforcement are different and case specific. The study conducted in presented in this thesis limits its study and discussion to short discrete fibre reinforced concrete.

A large variety of fibres are used in concrete worldwide, some of the prominent ones used widely are steel, polyester, polypropylene and glass. While all these fibres have consistently performed well, they have certain drawbacks. The fibres, their mechanism, and performance are briefly discussed in the Section 2.3. This study is an attempt to develop an innovative fibre based on Fibre Reinforced Polymers. The idea is to reinforce a relatively low strength unsaturated resin matrix such as epoxy with a high performance fibre such as glass. The ample matrix and reinforcing materials to choose from, and varying their composition in the composite provide great opportunity to design and manufacture fibres of varying geometries, elastic, physical and chemical properties. The right combination of materials could result in a fibre that could potentially be a game changer in the field of fibre reinforced concrete. The single engineered fibre could enhance the mechanical properties such as toughness, ductility, strength, fatigue life, impact strength; enhance the durability of FRC by reducing shrinkage and permeability of water and other chemical ions; improve fire resistance whilst keeping the overall cost low.

FRP fibre reinforced FRC offers interesting possibilities in the structural and non-structural design of concrete, especially in areas of high seismic activity where the ductility, toughness and energy absorption are of critical importance. The use of these novel materials could also be extended to repair materials and shotcrete. The recent studies emphasising the importance of compatibility of repair material with that of the substrate have in a way influenced and changed our perception of high performance cement based repairs. The compatibility of FRP fibre with cementitious matrix is expected to be much better in a way that the properties, such as modulus can be matched with
that of the repair material and the substrate. The low specific gravity of FRP fibre compared to steel fibres used extensively in shotcrete means that the specific gravity of the FRP fibres is relatively close to the specific gravity of the other constituents of shotcrete. Steel has a much higher momentum when travelling at the same velocity as the other constituents of shotcrete, resulting in losses due to rebound, and possibly even damage to the substrate. FRP fibre with a more compatible specific gravity is expected to embed well in the shotcrete, reducing rebound loss and the damage to substrate.

When we talk of FRC, the general impression that comes to mind is use of fibres in concrete made of hydraulic cement. Fibres can also be used in clay or lime bricks to enhance their properties. They may also be used to increase the stiffness or modulus of flexible pavements made of asphalt. FRP fibres open up prospects for use in polymer concrete, in particular heat cured geopolymer concrete (GPC). FRP requires curing at high temperature to develop, if partly cured FRP fibres can be introduced in GPC and cured together, we might be able to get a strong bond between the completely cured resin and GPC. In FRC, some of the bond strength comes from the interfacial van der Waals forces between cementitious matrix and fibre, which comes as a result of a good adhesive nature of the interface between C-S-H and fibre. If we can make use of the adhesive nature of cementitious matrix and the adhesive nature of resin matrix of the FRP fibre, the efforts towards bond formation could be enhanced. Because the cementitious matrix is water based, it is important that the resin of the FRP fibre be hydrophilic. With a hydrophobic resin, we would fail to use the adhesive nature of cementitious matrix as well as that of the resin. The surface characteristics of the fibre essentially dictate the fibre-matrix interaction while fibre is in fresh state. This fresh state interaction influences the mature behaviour.

The potential of this kind innovative fibre is immense and could lead to numerous possibilities. This research tries to lay a foundation for a novel application of FRP fibres in civil engineering, and pave a way for developing a unique, commercially viable and technologically pioneering FRP fibres.
1.2 Outline of the thesis

The fundamental goal of the project is to develop an innovative macro fibre based on fibre reinforced polymer material for the application as a short random discrete fibre in fibre reinforced concrete. The principal purpose of the fibre would be to enhance the mechanical properties of concrete. The improvement in performance of concrete with respect to durability by reduced shrinkage would be an additional accompanying benefit.

Objective I  Review and Establish method of development of fibre; determine its bond parameters, and study the flexural response.

Objective II  Investigate various factors affecting single fibre pullout.

Objective III  Assess the performance of fibre under sustained loading and deterioration.

The objectives are further divided into smaller milestones for an effective progress tracking. The chapters 4, 5, & 6 of the thesis are outlined based on the aforementioned 3 significant objectives of the project.

Chapter 1  Introduction.
Chapter 2  Literature review and background studies.
Chapter 3  Materials and mix designs.
Chapter 4  Manufacture of Fibre, and Characterization.
Chapter 5  Study of some factors affecting fibre pullout.
Chapter 6  Performance of fibre under Sustained loading and deteriorating conditions.
Chapter 7  Conclusion and Recommendations for future work.

Chapter 1, Introduction

A short chapter, which starts with providing us an underlying idea behind the research work, and discusses the need for the study. The chapter also outlines the project goals and objectives.

Chapter 2, Literature review and background studies,

This chapter acts as a foundation for understanding the concepts and forms the basis of many decisions taken throughout the course of the research. The first half of the chapter provides a
literature survey, starting with the definition of fibre reinforced concrete to discussing an extensive list of fibres currently being used, their popularity, their advantages, and limitations. The second half of the chapter consists of background studies relevant to the research. The concept of fibre reinforced polymers, their use in the construction and repair industry, parameters and the design process of the FRP panels and fibres are then introduced. Discussion on the feasibility of the manufacture of FRP fibre, its materials, and manufacturing techniques conclude this chapter.

Chapter 3, Materials and mix designs

This chapter lists all of the materials used throughout the course of the project. The choice of material used to manufacture the fibre affects the performance of the fibre, the materials used to evaluate the performance of the fibre affect the conditions and behaviour of the experiments, and may influence outcome of the tests. The mix designs used in the project are also given in this chapter.

Chapter 4, Manufacture of fibre and characterization

This chapter is based on working towards the first objective of the project, as mentioned earlier. This involves choosing the material, the manufacturing technique, and designing the fibre reinforced polymer composite to suite the requirements. Such composite fibres are not used in the construction industry, neither any other industry makes use of a similar fibre, hence were needed to be manufactured in the lab facility. Some of the characterization tests are conducted as per ASTM guidelines, and some others which have been developed in the lab, have been discussed in detail. The procedure of mixing, placing and casting the specimen, the test conditions, rate of loading, curing conditions, specifications of the testing machine, and their effect on the test outcomes are also discussed. Direct tensile tests were done on different sizes of the FRP panel to determine the effect of size on the tensile properties.

Once the materials and techniques are decided, the geometry and design of the fibre needs to be optimized with the help of single fibre pullout tests to determine the bond parameters and obtain an efficient fibre. The bond between the different FRP fibres and cementitious matrix were tested through single fibre pullout tests. Based on their material composition, and geometry 15 different fibre types were tested, with each series having 10 replicates to get a reliable set of data. The study was limited to a single mortar mix of normal strength.
Test for Flexural toughness was taken as a test for determining the mechanical behaviour of the FRP fibre reinforced FRC. A single concrete mix of normal strength concrete was used to cast beams of size 100mm x 100mm x 350mm. The beams were cast and tested in accordance with ASTM C1609. Three different FRP fibres based on the composition were tested, at 2 different volume fractions. Unreinforced, and glass fibre reinforced concrete specimen were also cast and tested for reference. The results from the various tests are discussed along with the mechanisms of failure.

Chapter 5, Study of some factors affecting fibre-matrix interfacial behaviour,

The fibres performing best in the earlier section, one each of Glass FRP and Carbon FRP were used in further investigated for service life performance.

For effect of matrix maturity, in terms of matrix curing age, the tests at 1, 3, 7, & 28 days after casting were conducted.

For effect of temperature conditioning, 7 different temperatures in the environmental ranging from -20° C to 130° C were tested.

For effect of fibre inclination and orientation, 2 angles each of inclination were tested.

For effect of dynamic loading on fibre pullout, 2 dynamic, and 3 quasi-static rates of loading were investigated.

Chapter 6, Performance of fibre under sustained loading and deteriorating conditions

This chapter looks at FRP fibres from a durability point of view. Fibre relaxation tests, which constitute the first half of the chapter, involve assessing the ability of the fibre to continue to transfer loads in a cracked section after an initial crack opening, thus preventing a sudden brittle failure (or collapse).

To examine the resistance of the FRP fibre under the alkaline environment of concrete, the fibres were subjected to accelerated deteriorating conditions by immersing in a high pH solution at high temperature. These samples were observed under an optical microscope, a scanning electron microscope (SEM) and energy dispersive x-ray spectroscopy (EDX) analysis was done to see any change in the physical structure on the surface of the fibre. Tensile tests were conducted on the FRP strips to assess any drop in strength. Single fibre pullout tests were also conducted to see if there is any effect of deterioration of fibres on the bond performance.
Chapter 7, Conclusions and Recommendations for future work

This chapter presents the conclusion of the research project, and proposes recommendations for future work.
Chapter 2: Literature Review and Background Studies

2.1 Fibre reinforced cementitious composites

In the most general sense, a concrete which contains fibre as one of the ingredients may be called fibre reinforced concrete. Bentur and Mindess [2] have defined fibre reinforced cement as a material made from hydraulic cement and discrete, discontinuous fibres but containing no coarse aggregate. Fibre reinforced concrete on the other hand has been defined as a material made with hydraulic cement, and aggregates of various sizes, incorporating discrete, discontinuous fibres.

Fibres have been probably been used since the ancient time, with one of its earliest written account occurring in Exodus 5:6 “And Pharaoh commanded the same day the taskmasters of the people, and their officers, saying. Ye shall no more give the people straw to make brick, as heretofore: let them go and gather straw for themselves”. Use of fibre as reinforcement have also been mentioned as early as 5000 years back when Egyptians used straw to reinforce mud bricks [1].

In the modern times, with the origin of cement and concrete, the first interest in Fibre Reinforced Concrete was in the 1960’s. Asbestos, Glass and Steel are the few of the earliest fibres to be used for short discrete reinforcements. The first accounts of random fibre reinforcement was by Dr. Romualdi, Dr. Batson, and Dr. Mandel; the pioneering work of wire reinforced concrete, presented in 1963 and 1964 [3,4]. The earliest documentation of glass fibre for concrete also took place around the same time [5]. Fibre reinforced concrete has come a long way since.

The improvement of fracture toughness of concrete by reinforcement with fibres of various materials has resulted in gradual acceptance of fibre reinforced concrete as a mainstream construction and repair material. The benefits of fire reinforcement of concrete in areas of fracture toughness, energy absorption capacity, long term durability, impact resistance and fatigue endurance are well recognized [1,2]. The advantages of fibres towards improving the electric [6], magnetic [7], and thermal changes [8,9] have also been documented.

In addition to benefits of fibre reinforcement during high impact loading [10,11], seismic loading [12–14] and blast [15,16], the benefits of fibre reinforcement extend to improve the resistance of
the structure to fires, especially in the case of high strength concrete columns, to mitigate fire related accidents and terrorist incidents [17–19].

The use of recycled materials in the production of fibres has further garnered a lot of interest from the sustainability point of view [20].

### 2.2 Current status of fibre reinforced concrete

It has been over 50 years from the time when fibre reinforcement was first introduced in cement based matrices. As of today, there are more than 60 different materials such as steel, polypropylene and polyester are used for making fibres for concrete. Below is a list of some of the earliest reports of various materials used for making fibre in the construction industry.

*Table 2-1 Some of the earliest accounts of various fibres used in the construction industry*

<table>
<thead>
<tr>
<th>Year</th>
<th>Type</th>
<th>Category</th>
<th>Note</th>
<th>Reference</th>
</tr>
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<td>Steel Wire</td>
<td>Metallic</td>
<td>Welded wires like a mesh</td>
<td>[4]</td>
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<td>1968</td>
<td>Steel</td>
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<td></td>
<td>[21]</td>
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<td>Asbestos</td>
<td>Mineral</td>
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<td></td>
</tr>
<tr>
<td>1968</td>
<td>Plastics</td>
<td>Synthetic</td>
<td></td>
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<td></td>
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<tr>
<td>1971</td>
<td>Jute</td>
<td>Natural</td>
<td></td>
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</tr>
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<td>Composite</td>
<td>Rod as primary reinforcement</td>
<td>[24]</td>
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<td>Chopped steel wire and fibreglass</td>
<td>Metallic &amp; Mineral</td>
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<td>[25]</td>
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<td>1972</td>
<td>Steel fibre</td>
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<td>[26,27]</td>
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<tr>
<td>1972</td>
<td>Polycrystalline Alumina</td>
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</tr>
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<td>---------------------</td>
<td>------------</td>
<td>---------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>1974</td>
<td>Glass</td>
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<td>Vegetable fibre</td>
<td>[34]</td>
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<td>1978</td>
<td>Carbon fibre</td>
<td>Synthetic</td>
<td></td>
<td>[35]</td>
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<tr>
<td>1979</td>
<td>Kevlar</td>
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<td></td>
<td>[36]</td>
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<tr>
<td>1979</td>
<td>Water reed</td>
<td>Natural</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1979</td>
<td>Elephant grass</td>
<td>Natural</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1979</td>
<td>Plantain</td>
<td>Natural</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1979</td>
<td>Musamba</td>
<td>Natural</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1979</td>
<td>Wood</td>
<td>Natural</td>
<td></td>
<td>[37]</td>
</tr>
<tr>
<td>1984</td>
<td>Polyester</td>
<td>Synthetic</td>
<td></td>
<td>[38]</td>
</tr>
<tr>
<td>1987</td>
<td>Polyacrylonitrile</td>
<td>Synthetic</td>
<td></td>
<td>[39]</td>
</tr>
<tr>
<td>1989</td>
<td>Polyethylene</td>
<td>Synthetic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1989</td>
<td>Nylon</td>
<td>Synthetic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1989</td>
<td>Aramid</td>
<td>Synthetic</td>
<td>Kevlar 49 &amp; Kevlar 149</td>
<td>[40]</td>
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<td>1991</td>
<td>Acrylic</td>
<td>Synthetic</td>
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<td></td>
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<tr>
<td>1991</td>
<td>Rayon</td>
<td>Synthetic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1995</td>
<td>Polyvinyl Alcohol</td>
<td>Synthetic</td>
<td></td>
<td>[41]</td>
</tr>
<tr>
<td>1995</td>
<td>Sisal &amp; Bagasse</td>
<td>Natural</td>
<td></td>
<td>[42]</td>
</tr>
<tr>
<td>1993</td>
<td>Cellulose</td>
<td>Natural</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1993</td>
<td>Fibre Reinforced Polymer</td>
<td>Composite</td>
<td>As continuous rods</td>
<td>[43]</td>
</tr>
<tr>
<td>1993</td>
<td>Wollastonite fibre</td>
<td>Mineral</td>
<td>CaSiO3 mineral</td>
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<tr>
<td>1993</td>
<td>Calcium/Alumina fibre</td>
<td>Mineral</td>
<td></td>
<td>[44]</td>
</tr>
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<td>1995</td>
<td>Glass Fibre Reinforced Polymer</td>
<td>Composite</td>
<td>As continuous rods</td>
<td>[45]</td>
</tr>
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<td>Year</td>
<td>Type</td>
<td>Category</td>
<td>Note</td>
<td>Reference</td>
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<td>-------------------------------</td>
<td>--------------</td>
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<td>Composite</td>
<td></td>
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<td></td>
<td>[52]</td>
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<td>2003</td>
<td>PP + Carbon</td>
<td>Hybrid</td>
<td>Introduction of Hybrid fibre reinforcement systems</td>
<td>[53]</td>
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<tr>
<td>2003</td>
<td>Carbon + Steel</td>
<td>Hybrid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td>Steel + PP</td>
<td>Hybrid</td>
<td></td>
<td></td>
</tr>
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<td>[55,56]</td>
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<td>Natural</td>
<td></td>
<td>[57]</td>
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<tr>
<td>2011</td>
<td>Palm leaves</td>
<td>Natural</td>
<td></td>
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<tr>
<td>2010</td>
<td>Nano &amp; Micro cellulose</td>
<td>Natural</td>
<td></td>
<td>[58]</td>
</tr>
<tr>
<td>2013</td>
<td>Recycled nylon</td>
<td>Recycled/Synthetic</td>
<td></td>
<td>[59]</td>
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<tr>
<td>2013</td>
<td>Expanded Polystyrene</td>
<td>Synthetic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>Copolymer Polypropylene/polyethylene</td>
<td>Composite Synthetic</td>
<td>Blended macro synthetic fibre</td>
<td>[60]</td>
</tr>
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<td>2013</td>
<td>Loofah fibre</td>
<td>Natural</td>
<td>Natural fibre</td>
<td>[61]</td>
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<tr>
<td>2013</td>
<td>Basalt fibre</td>
<td>Mineral</td>
<td>Extruded basalt rock</td>
<td>[62]</td>
</tr>
<tr>
<td>2014</td>
<td>Expanded Vermiculite</td>
<td>Mineral</td>
<td>Si mineral</td>
<td>[63]</td>
</tr>
</tbody>
</table>

While numerous fibres, many of which have been listed in the Table above, have been tried out, only a handful of them are suitable for fibre reinforced applications and an even smaller number is used in practice owing to the economical and sustainability consideration. While steel fibres are the most widely used fibre, especially in structural applications, their widespread use has been restricted by the hardships involved in handling. Their susceptibility to corrosion is another issue that needs to be addressed, and may be a major issue for slab on grade, bridge decks, and industrial floors where there is a high chance of chemical attack from de-icing salts and ground water [64]. Consider a reinforcing steel rod of diameter 12mm and length 1000mm, and a steel fibre of...
diameter 1mm and length 50mm. The surface area of the steels fibres equivalent to the volume of the steel rod is about 240 times the surface area of the steel rod. In other words, steel fibres are roughly 240 times more likely to corrode than a steel rod for the same volume. Apart from corrosion, the susceptibility of steel fibres interaction with the electromagnetic fields, and a lower specific strength compared to the polymer fibres further have restricted the use of steel fibres.

The excellent bond of glass fibre with cementitious material gives the composite an excellent strengthening effect [65]. While most mineral glass fibres exhibit high mechanical properties, and hence are used for various structural and non-structural applications, some concerns with durability and alkaline stability exist. A number of attempts at improving the alkaline stability with alkali resistant glass and application of alkali resistant coating have been reported [66,67].

Another mineral fibre that is gaining popularity is Basalt fibre. The structure and manufacture of basalt fibres is similar to that of glass fibre, but with lesser energy consumed and no additives, making it a lower cost material compared to glass or carbon [68,69]. Improvement in mechanical properties such as flexural strength, fracture energy, and abrasion resistance in cement concrete and geopolymer concrete have been reported [68,70–73] Similar to the glass fibres, the basalt fibres have shown susceptibility to alkaline environment, undergoing chemical degradation leading to loss of strength [74].

Various natural fibres such as wood, sisal, coconut, sugarcane bagasse, palm, and vegetable fibres, among many others have been tried. However, their durability, and varying quality remain major causes for concern [75]. This has given rise to development of a large assortment of synthetic fibres of a variety properties. Some of which are polyolefin, acrylic, aramid, and carbon fibres. In order to achieve adequate reinforcement, the fibres should have a high tensile strength and tensile modulus [76]. Synthetic Polymer fibres from the polyolefin family such as polypropylene (PP) and polyethylene (PE), along with fibres from polyester family such as polyethylene terephthalate (PET) have gained much popularity of late because of their comparatively simple manufacture, low cost, and ease of handling. Many polymeric fibres are in fact made out of recycled plastics such as polyethylene terephthalate (PET)[77–79] and polypropylene (PP) [76,80], making the concrete system a little more sustainable [20]. The polymeric fibres are used largely in non-structural application, to prevent propagation, and bridging of cracks caused most commonly due to shrinkage, and creep in concrete. Polypropylene fibres are also used to some extent where
enhancement in mechanical properties and structural strengthening is required [81–84]. Of late, polyvinyl alcohol (PVA) polymer fibres have gained popularity, with development of engineered cementitious composites (ECC) [85–87]. PVA fibres however, coming as a product from the petroleum industry, are quite expensive. The need for coating the PVA fibres to prevent fibre fracture in many cases increases the overall cost of fibre, limiting its use to some demanding applications.

There has been a fair share of innovation in modifying the geometry of the fibres to increase the resistance to fibre pullout. The most common ones are hooked, sinusoidal, and crimped; however, many others like flat ends, cone ends, twisted, sinusoidal ends etc. also exist [88]. Several embossing techniques have also been successfully tried out in order to improve the frictional resistance to fibre pullout [78, 89]. Numerous surface modification techniques such as plasma treatments [90–95] surface coating [66, 96–98], and other surface modifications [99] etc. have also been examined.

2.3 Mechanism of fibre reinforcement & failure theory

In a brittle matrix composite, such as fibre reinforced cementitious composite, the matrix has a low strain capacity. In the case of tensile or flexural loading, due to the low strain capacity of the brittle matrix, it cracks early in the process, immediately transferring the load to the fibres, which are then expected to carry the load. If the load on the member is exceeding the capacity of the fibre reinforcements, the fibres would start pulling out of the matrix at the cracked section, consuming energy in the process, preventing a catastrophic failure. If the composite isn’t well designed, and the fibres are excessively well bonded, it may result in fibres fracturing immediately when the stresses are transferred. Therefore, the bond-slip mechanism of the composite is of prime importance. Two key aspects emerge: one, the stress transfer mechanism during fibre pullout, and second, different failure mechanisms that may take place once the stresses have crossed their respective limits. Several bond failure mechanisms, depending on the fibre characteristics, matrix characteristics, interfacial characteristics and stress states may come into play.
2.3.1 Stress transfer

The most widely accepted fibre-matrix stress transfer mechanism is based on the shear lag theory, as described by Greszczuk [100]. The shear lag theory assumes that the extensional stresses in the matrix are negligible relative to those in the fibre and that the shear stresses in the fibre are small compared to those in the matrix [101]. Greszczuk’s theory states that the complete fibre-matrix debonding of a sudden catastrophic nature takes place when the maximum interfacial stress exceeds the interfacial bond strength. Assuming idealized stress distribution, the interfacial bond strength can be computed by using the formula:

\[
\tau_{\text{max}} = \frac{P_{f,\text{max}}}{\pi \times d_f \times I_e}
\]

Where

- \(\tau_{\text{max}}\) is the maximum idealized bond stress,
- \(P_{f,\text{max}}\) is the maximum load at which debonding takes place,
- \(d_f\) is the diameter of the fibre, and
- \(I_e\) is the length of the fibre embedded in the matrix (the embedded length).

\[\text{Equation 2-1}\]

However, in reality, the debonding is not sudden or catastrophic. The theory by Lawrence & Laws et al. [102,103] considers a frictional resistance, which is solely responsible for resistance to pullout after the initial debonding has taken place, which can contribute significantly to the total resistance.
of fibre pullout. In other words, the initial resistance to fibre pullout is offered by the elastic bond between the fibre and matrix; the elastic bond is broken as a result of fibre pullout (or fibre slip), which point onwards, the resistance to pullout is by frictional resistance. In such cases, interfacial bond shear strength may be calculated as a function of amount of fibre pullout (or fibre slip $x$) by modifying the above Equation 2-1 to get:

$$
\tau_x = \frac{P_{f,x}}{\pi \cdot d_f \cdot l_e}
$$

Equation 2-2

Where $\tau_x$ is the idealized bond stress at slip $x$  
$P_{f,x}$ is the load at slip $x$  
$d_f$ is the diameter of the fibre, and  
$l_e$ is the length of the fibre embedded in the matrix (the embedded length)

The stress distribution at the interface, based on both, complete debonding, and partial debonding may be graphically represented as shown in the Figure 2.2 below [104].

Figure 2-2 (a) describes the uncracked section, the fibre enters the matrix at the two ends.

Figure 2-2 (b) & (c) represents the pure elastic bond, and pure frictional bond of completely debonded fibre-matrix interface respectively.

Figure 2-2 (d) & (e) represents the combination of elastic and frictional bond active after partial debonding. Figure 2.2 (d) represents a scenario when the elastic bond strength is larger than the frictional bond strength in debonded region, and Figure 2.2 (e) represents the scenario where the elastic bond is smaller than the frictional bond strength.

The Figure 2-3 below shows the stress transfer distribution in a cracked section. The non-liner elastic bond stress distribution is the maximum at the point where the fibre enters the crack surface.
Figure 2-2 Fibre-Matrix Interfacial Stress transfer theory in an uncracked section (Bartos, 1981 [104])

Figure 2-3 Fibre-Matrix Stress transfer theory in a cracked section (Bartos, 1981 [104])
While the above holds good in a general sense, in some fibres systems in which it is difficult to define the perimeter, such as in the case of a bundle of glass fibres, or with fibres of non-uniform cross section, a shear flow, i.e. a shear force per unit length may be used in place of shear stress. Debonding thus occurs when the maximum elastic shear flow exceeds the shear resistance per unit length of the fibre bond. Any suitable theoretical model of fibre pullout process may be used for such fibres, by considering concepts of shear flow and shear flow resistance [101].

Laws [105] further went on to add that in principle, it is possible to calculate the bond parameters from pull out tests, but the results only apply to the conditions of pull out and not necessarily reflect or predict the behaviour of the composite. The single fibre pullout tests therefore are only to understand the fundamental behaviour of the fibre-matrix interface. While a fibre may show excellent performance in terms of interfacial bond strength, it may or may not be reflected in the performance of the composite. However, superior performance of a composite requires a good fibre-matrix interfacial bond. A good single fibre pullout response may therefore be considered as a pre-requisite to a worthy composite response.

2.3.2 Failure types and crack bridging mechanism

The crack arrest mechanism for FRC is similar to the aggregate, when the crack tip approaches the aggregate, the aggregate absorbs energy and arrests the crack. Similarly, the fibre arrests the crack, and even acts as crack bridges, thereby absorbing energy till failure.

The failure and energy absorption mechanisms are briefly described below.

**Fibre pullout:**

When the interfacial shear stress between the matrix and fibre exceeds the bond shear capacity of the straight fibre-matrix system, additional energy absorption occurs. This however takes place only when the tensile stress in the fibre has not reached the tensile capacity of the fibre. It is possible that the fibre may undergo partial pullout, and still be able to transmit some reduced load, which may in turn prevent collapse. If the composite is to fail, this is the most preferable mode of failure, as it absorbs the maximum amount of energy before failure or collapse.
**Fibre bridging:**

As seen from Figure 2-5, the fibre bridging mechanism is responsible for arresting the progress of the crack and controlling crack width. The stresses responsible for causing the propagation of crack are then partially carried by the bridging fibre. The external stress that is either responsible for the crack, or is a result of the crack, may be absorbed by slippage of fibre.

**Fibre-matrix debonding:**

This type of failure is most often encountered with polymer matrix composites, as opposed to cementitious composites, and is often a result of incompatibility of the fibre and matrix. In either brittle matrix composites, or ductile matrix composites, when there is a large mismatch in modulus or strain capacity, and when the load is applied in the direction of alignment of fibres, the chances of fibre-matrix debonding occurs.
The interfacial zone (ITZ) between the fibre and the matrix is the weakest component of the system. In some scenarios, it is possible that propagation of crack may either change its course and advance through the ITZ or create smaller cracks that propagate.  

Fracture of fibre:

When the tensile stresses generated within the body of the fibre are higher than the tensile strength, the fibre undergoes brittle and catastrophic fracture. This type of failure is often seen in the case of PVA fibres, and many efforts to reduce the bond between fibre and matrix have been made. This kind of failure is not desirable, as it reduces the energy absorption and negates the very purpose of fibre reinforcement at all.

Matrix cracking:

As it is shown in Figure 2-8, effective crack bridging process often results in matrix cracking. As the fibres are being stressed because of the crack mouth opening on one side, the stresses developed in the fibre are transferred to the adjoining matrix on the
other side of the fibre. These stresses transferred to the adjoining matrix are generally tensile in nature, which undergo micro-cracking, absorbing energy in the process.

![Figure 2-8 Sketch of typical matrix cracking](image)

**Fibre-matrix damage:**

Often with deformed fibres, or fibres with a rough surface such as ribbed steel fibres, the pullout is accompanied by abrasion damage to the adjoining matrix [106]. The cracking and micro-cracking of the adjoining matrix as shown in Figure 2-9, absorbs energy in the process.

Another form of matrix damage has been observed in PVA fibres, in which the adjoining matrix damages the softer fibre due to abrasion causing delamination within the fibrils of the fibre [98]. Although the abrasion of fibre does involve energy absorption, and is often considered a good sign with respect to compatibility of fibre with the matrix, excessive abrasion can damage the fibre and reduce its capacity, and cause stress concentrations that can rupture the fibre before complete pullout.

![Figure 2-9 Sketch of typical fibre-matrix damage](image)
Bearing & anchorage action:

Among the different attempts to improve the performance of fibre reinforced composites, geometric deformations have been the most efficient, which is reflected in their widespread use and popularity. In the case of deformed fibres as shown in Figure 2-10, the deformation in the fibre acts as a bearing surface which provides the anchorage holding the fibre and resisting pullout.

![Figure 2-10 Sketch showing typical bearing action in deformed fibres](image)

Plastic deformation:

The ductile nature of steel fibres, and most polymeric fibres, allows for the fibre to deform as it is being pulled out of concrete, as shown in Figure 2-11 [106–110]. While fibres with hooked ends deform only till the hook is straightened, the crimped fibres undergo plastic deformation till the entire fibre is pulled out. Energy is consumed during the plastic deformation. This is true in the case of straight steel & polymeric fibres as well, when they are being pulled out an inclined angle from the crack surface.

![Figure 2-11 Sketch showing plastic deformation of deformed fibre](image)
Snubbing friction:

In the case of fibres that are inclined to the cracked surface, a large snubbing friction at the point where fibre enters the cement matrix is generated. Snubbing friction in turn develops tensile stress in the matrix in the close vicinity of the point where fibre enters the matrix. This large snubbing friction causes cracks in the matrix, and sometimes the stresses generated are high enough to cause matrix crushing. While these cracking and crushing do absorb energy, they also reduce the contact area holding the fibre in place, and may cause a sudden failure.

![Sketch showing matrix crushing due to snubbing friction action](image)

*Figure 2-12 Sketch showing matrix crushing due to snubbing friction action*

The type of fracture depends not only on the surface characteristics, but may also be governed by the length of the embedment [111]. Finally, the performance of a cracked fibre reinforced composite in terms of load transfer can be said to depend primarily on two aspects, [44]:

1. There is adequate resistance or energy absorption by the fibres to pull-out.
2. There are adequate number of fibres to participate in the stress transfer process.
2.3.3 Factors affecting fibre pullout

Fibre characteristics

1. Fibre material: First and the foremost constituent influencing the composite behaviour is the type of fibre used. Fibres of various materials have been discussed earlier in the Section 2.2. The material used, being hydrophobic or hydrophilic is one of the essential factor, that affects the single fibre pullout behaviour [112].

2. Fibre geometry: The size and shape of the fibre allows for optimization of the bond-slip response to achieve maximum toughness and energy absorption in the composite. The most popular modifications in geometry is by providing a mechanical anchorage at the ends, or throughout the fibre. A new parameter deformation ratio may be defined to quantify the effect of deformation on a fibre on the bond-slip performance [113,114]. Other geometrically modified fibres include improving the roughness of the fibre by making indentations [89], and ribbed fibres [106].

Matrix characteristics

3. Matrix composition: It is generally accepted that a matrix of higher strength has a higher pullout resistance than the lower strength matrices. This has been verified by Banthia [115], where a general reduction in pullout strength has been observed with an increase in water-cement ratio (and therefore reduced strength). He also reported improvement in fibre-matrix bond with addition of silica fume.

Environmental conditions

4. Curing age and temperature: A definite increase in bond-slip resistance with increase in curing time and matrix maturity is reported. A direct correlation between peak fibre pullout load and matrix strength development by accelerating curing (water bath at 38°C) has been reported [115].

5. Test temperature: At low temperatures, due to freezing of water in cement matrix has been reported to have an improved fibre-matrix interface during quasi static loading [116]. Due to the temperature dependent mechanical performance of most polymeric fibres, an increase in temperature can be expected to modify the fibre pullout and interfacial performance.
Loading conditions

6. **Loading rate**: The improved mechanical properties of the constituent materials, the cementitious matrix, and fibre under dynamic loading conditions are well known to us. A definite increase in fibre-matrix interfacial strength using different rates of dynamic loading, different types of fibres have been reported by various researchers [109,115,117–119].

7. **Loading angle**: Due to the random 3-D orientation of fibres at cracked surface, several studies have been done to investigate the inclined pullout behaviour of fibres from cementitious matrix [120–122]. Attempts have been made to use the inclined fibre pullout performance to predict the flexural behaviour of fibre reinforced concrete [123–125].

2.4 FRP composites in construction and repair industry

The construction industry may be considered as a late adopter of the fibre reinforced polymer (FRP) technology. The comparatively sluggish incorporation of FRP composites in the construction industry has been attributed largely on the lack of investment in research and development post the world war years [14,126,127]. The aerospace & aviation industry, along with the defence industry are seen as the pioneers in development and addition of FRP technology in their use. Early introduction of polymer composites began in the 1960’s, with the production of specific resins, catalysts, and accelerators and technologies were developed to facilitate manufacture of composites by relatively straightforward open mould methods [14]. The key changes that were instrumental in use of FRP in civil engineering were [127]:

a) Development of techniques such as Pultrusion, resin transfer moulding, semi-automatic manufacturing of large components leading to possibility of low cost FRP manufacturing.
b) Reduced material demand in the defence industry.
c) Design of new FRP elements in conjunction with conventional structural materials.
d) Need for non-corrosive reinforcement.

Soon after, the industry started to accept FRP as a viable building material, and used it in select projects such as a sandwich polymer composite / aluminium skeletal dome manufactured in the UK, for erection in Benghazi, Libya in 1968, and an all polymer composite roof structure for Dubai
airport in 1972 [14]. During the early days, FRP was used essentially for innovative structural shapes, for innovative roof shapes in particular, that were not possible using the conventional materials such as concrete, and semi load bearing partition walls. By mid-1980s, the aspiration to use FRP materials as a structural component to replace conventional materials in aggressive and hostile environment had begun [126].

One of the first iconic FRP constructions was the Aberfeldy footbridge in Scotland, completed in 1992, which apart from the aluminium connections required to attach the stay cables to the deck, is entirely made of FRP. The bridge was strengthened in 1997, for additional load carrying capacity, is standing tall, showing no signs of structural deficiency. However, smaller impact loads have had localized damage, exposing the fibres, which could potentially be a cause for accelerated deterioration of reinforcing glass fibres if left unattended [128]. Since then, numerous bridges have been constructed, either as all composite FRP systems, or as hybrid systems. Many of these bridges built have been discussed by Keller [129].

Figure 2-13 Use of FRP composites in Civil Engineering, (Hollaway 2003, [126])
FRP has garnered a lot of interest as rehabilitation and retrofit material owing to the resin’s excellent adhesion bond with old concrete, and high specific strength/modulus. The FRP components are either used in the form of an externally bonded plate, or as a near surface mounted FRP rod to strengthening RC beams in flexure [130–134]. Several research articles, books, state-of-the-art papers, and review papers by leading researchers, Meier [130], Nanni et al. [135], Teng et al. [132,133], Hollaway et al. [131], Rizkalla et al. [134], and many others [136–138] exist.

FRP as primary rod is a comparatively new system, with a lot of ongoing work. Most FRP rebar, with cost in mind, are made by pultrusion of glass fibres through a polyester resin. Due to the low hydrophilicity of resin, generally, some form of surface or geometric modification is needed to improve the bond with cementitious matrix, the most common of which are listed below:

a) Ribbed
b) Sandblasted
c) Spirally wound

For use of FRP as reinforcing bars, because it is inside the concrete, making it impossible for visual observation for degradation or damage, durability and stability of GFRP rods are of the main concern. Good amount of research has been done in the field of durability analysis of FRP bars. Extensive amount of independent works by leading researchers Nanni et al. [46,139], Benmokrane et al. [49,140], Uomoto [141], Davalos et al. [142,143], Bakis et al. [144], review paper by Ceroni et al. [145], and collaborative work at SIMTReC (Centre for Structural innovation and monitoring technologies, formerly known as ISIS Intelligent sensing for innovative structures), led by Mufti et al. [146–149], among many others on the durability [139,150–153] and applicability of FRP rebar in concrete are available [154–156].

FRP hybrid systems are those in which a system comprising of FRP composites and traditional materials such as concrete/steel etc. are combined optimally [126]. A hybrid beam with concrete in the compression area with FRP composite material in the tension area has been developed and is regarded one of the key future materials [157,158]. Another type of hybrid material is a hollow FRP tube which is filled with concrete, for use as columns without any internal reinforcement [159–161].
2.5 FRP fibre for FRC

The macro fibres used in FRC are roughly about 30 to 60 mm in length and about 400-1000 µm in diameter. It is also well known across disciplines that a fibre with higher aspect ratio performs better, as there is more surface for surface activity such as bonding. Keeping these in mind, in this research, the target dimensions of FRP fibre were decided to be about 50mm in length, and about 0.5mm in diameter.

2.5.1 Review of prospective materials

A large collection of materials, both for reinforcing the FRP fibre as well as the matrix of the FRP fibre exist. A discussion of advantages and limitations of an extensive set of materials has been done in this section.

2.5.1.1 Reinforcing materials:

E glass family

E glass is a material of calcia-alumina-silicate glass family, and the commonly made glass fibre is by extruding alumina-borosilicate glass. It is the most popular reinforcing fibre used in the composites industry owing to its good engineering properties and relatively low cost. However, the properties of E glass can vary depending on the manufacturer, composition, diameter, and geometry; and has a strength of anywhere between 2000 MPa to 3500 MPa and elastic modulus of around 70 GPa. For example, while the website of AZO materials [162] list the strength of the E glass at 1950 to 2050 MPa, the data sheet of E glass manufactured by Saint Gobain Vetrotex lists the filament tensile strength to be 3400 MPa [163]. The impregnated strand tensile strength (calculated on fibre cross section) of the same fibre manufactured by Saint Gobain Vetrotex is 2400 MPa. Hence it should be well understood before the commencement of the project, that the same E glass fibre would behave in different way depending on testing conditions, and the behavior of composite will be different from the behavior of individual yarns or fibres.
E glass is used widely in many industries, for not only its elastic properties, but also for thermal and electrical insulation. The versatile application, good compatibility with resin matrices at a relatively very low cost makes it so popular.

E glass fibre is many times referred to as just glass fibre, and is used widely in marine industries, manufacture of insulating walls and as discrete fibres in concrete (Glass Fibre Reinforced Concrete).

The only issue with E glass is its susceptibility to deterioration in alkaline environments. Environmental attack of moisture for example has been reported to degrade the strength of glass fibre, initiate micro-cracks in the resin, degrade the fibre matrix interface and also cause swelling of the composite [153]. The loss in mechanical properties of glass fibres independently as well as in composites in concrete has also been well documented [142,145,151,164]. Efforts have been made towards making a new kind of glass fibre that is resistant to corrosion and other durability issues in presence of an alkaline environment. Such glass fibres are Alkali resistant glass, E-CR glass (Electrical Chemical Resistance glass), C-glass (Corrosion resistant glass) etc.

**S glass family**

S glass stands for high strength glass, sometimes is also considered to stand for stiff glass. It is very similar to E glass in the way that it visually looks and handles similar to E glass, but is made of a slightly different chemical composition. The surface properties of S glass fibres are also identical to E glass, meaning they will have an as good bond with Polyester, Vinyl ester, or Epoxy resin matrices. The difference between E glass and S glass lies in their elastic properties. S glass is considered to have about 15-20% greater modulus and about 30-40% higher tensile strength than E glass. The commonly available S glass is actually S-2 glass to be precise, but these terms are often used interchangeably. S-2 glass is second generation S-glass.

The comparison of glass fibre compositions is shown in Table 2-2 below [165].
Table 2-2 Composition of Glass fibres, % by weight

<table>
<thead>
<tr>
<th>Component</th>
<th>E Glass</th>
<th>S Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon dioxide</td>
<td>52-56%</td>
<td>64-66%</td>
</tr>
<tr>
<td>Calcium oxide</td>
<td>16-25%</td>
<td>Trace</td>
</tr>
<tr>
<td>Aluminum oxide</td>
<td>12-16%</td>
<td>24-26%</td>
</tr>
<tr>
<td>Boron oxide</td>
<td>5-10%</td>
<td>-</td>
</tr>
<tr>
<td>Sodium and Potassium oxides</td>
<td>0-2 %</td>
<td>Trace</td>
</tr>
<tr>
<td>Magnesium oxide</td>
<td>0-5%</td>
<td>9-11%</td>
</tr>
</tbody>
</table>

Carbon fibre

Carbon fibre, also known as graphite fibre is a high strength high modulus fibre, about 5-10 um in diameter and composed of mainly carbon atoms. The atomic structure of carbon fibre is similar to that of graphite, both of which are made of graphene sheets. Graphene is a thin layer of pure carbon that are bonded to each other in a hexagonal arrangement. While in graphite, the graphene sheets are linked to each other with weak Van der Waals forces, on the case of carbon fibre, the graphene sheets are haphazardly folded or crumpled together (Figure 2-15).

The cost of carbon fibres still remains very high, which restricts the use in different applications. In the market, it is available for roughly ten times the price of E glass, which makes carbon much less popular among low to medium strength applications, however, is the material of choice for high performance parts such as in the aerospace and aviation, automobile, high performance sports goods, etc.
Once again, as in the case of glass, the strength does depend on the manufacturer, depending on the quality of precursor PAN used, which also affects the cost of the final product. Carbon fibres are also classified on the basis of their relative tensile modulus, ranging from low modulus carbon fibre at around 200 GPa to intermediate modulus carbon fibre around 250-350 GPa, to ultra-high modulus carbon fibre above 450 GPa. However, the most readily available carbon fibre have strength ranging from 2500 MPa to 4000 MPa, and have modulus ranging from 230 GPa to 450 GPa.

**Aramid fibres (Kevlar)**

Kevlar is the most popular of the organic Aramid fibres developed by DuPont. Other Aramid fibres, which also have similar properties are Nomex which is also developed by DuPont. Twaron and Technora are other similar aramids developed in Japan by Teijin.
Kevlar or other Aramid fibres are like glass and carbon, high strength, and high modulus fibres. While the strength of Kevlar is similar to carbon and glass, the modulus of Kevlar is roughly between the higher modulus carbon fibre and lower modulus glass fibres.

The cost of Kevlar is higher than glass, which again restricts the use to specific high performance applications such as ballistics, sports gear, automobiles etc.

Aramid fibres tend to absorb moisture, and are susceptible to ultra-violet radiation, raising durability concerns. In the case where an aramid fibre reinforced panel is damaged, and the fibres are surfaced and open to moisture, the fibre likely is attacked by moisture, and undergoes degradation.

**Polyethylene (Spectra or Dyneema)**

Ultra-high molecular weight polyethylene (UHMWPE), also referred to as high-performance polyethylene (HPPE) or high modulus polyethylene (HMPE), are a new series of organic fibres developed under the brand names Spectra and Dyneema. It is composed of extremely long chains of polyethylene, the molecular weight of the chains reach up to 6 million atomic mass units. The major advantage of these polyethylene fibres are that they possess a very high resistance to abrasion. It also is very smooth to touch with a very low coefficient of friction, which makes the fibres slightly tricky to handle. The other crucial property of UHMWPE is its very low specific gravity of as low as 0.97. Strength of UHMWPE can be up to 2500 MPa, compared to the steel of highest strength, which has a strength of up to 1600 MPa. The low specific gravity of the Dyneema fibre, compared to steel which as a specific gravity of 7.85, makes the specific strength of Dyneema much higher, as much as 10 to 15 times as that of steel. Its high specific strength has fascinated its use in ballistic resistant armour, ballistic resistant vehicles, bullet proof vests etc.

Other fibres such as boron fibre, and basalt fibre are also considered, but due to their limited availability, only the 5 fibres described above were emphasised upon. Other new innovative fibres such as lignin carbon fibre, nano-crystalline cellulose (NCC) were also considered. However, these fibres are still in the research phase, and have not been made available commercially in the market.
2.5.1.2 Matrix materials:

Epoxy resin

Epoxy is the most commonly used resin system in the composites industry, including the aerospace, aviation, automobile, recreational and high performance sports goods, among many others. The good understanding of uncured and cured resin properties, good compatibility with most fibres, metals, and other materials makes it a material of choice for most applications. It also has excellent adhesion and resistance to chemicals and other solvents. However, the costs involved are on the higher side, as compared to other resins.

Polyester (Thermoset)

Polyester is the second most widely used resin, after epoxy. It is cheap, and has a flexible cure process, meaning a reasonably good degree of cure can be achieved even if the ideal conditions such as an autoclave or oven are not available. This makes it a good choice for large components such as turbine blades, boats, water slides, water pools, pipes etc.

While the cost is low, the material properties are lower than that of epoxy resin. It also has a higher shrinkage as compared to epoxy, and is seldom used with carbon fibre.

There are health and safety concerns with the use of polyester resin, which is why, in most cases, the manufacture of polyester parts is restricted to factories, where health and safety issues are dealt with, compared to epoxy, which is often also used by individuals. The polyester resin generally requires a fume hood or such, because of the styrene emissions, which pose a health and environment hazard.

Vinyl ester (Thermoset)

Vinyl ester occupies the space in between epoxy and polyester, in terms of material properties, and cost. Vinyl ester has a lower viscosity as compared epoxy and polyester, and a faster cure cycle as well, and hence can be used in components or parts in which speedy manufacturing cycles are required.

Like the polyesters, there also have health and safety concerns with the emission of styrene, and therefore, the use is restricted to factories or industries with appropriate facilities.
Other thermoplastic resins

Thermoplastic resins make up roughly about 10% of all the resin used in the composites industry. They are rather cheap, and have a higher ductility or strain to failure, as compared to most thermosetting resins. The ductile nature increases its toughness, and imparts an improved impact resistance.

Their application is limited by the temperature sensitivity, often very high viscosity, and susceptibility of certain thermoplastics towards chemical attacks. The change of state from a liquid phase to a solid phase involves no chemical reaction, and is only rearrangement of molecules depending on the temperature. Therefore theoretically, the production cycles are much faster and continuous. However, the setup costs and operating costs are often quite high.

Several thermoplastic resins such as high performance polyamide (PA or PPA, nylon), polyether ether ketone (PEEK), polyethylenimine (PEI), polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), polycarbonate etc. have been considered for this project.

2.5.2 Parameters of FRP composite fibre

To characterize the composition of a composite material, the parameters often used are volume fraction of fibres in the composite, and the volume fraction of resin. Although volume fraction of voids has shown to of some importance, for the ease of calculations, it is generally not considered. Also for ease of calculation, a full transfer of stress from the resin the reinforcing fibres is considered. They are generally referred as –

\[
\begin{align*}
V_f & – volume \ of \ fibres \\
V_m & – volume \ of \ matrix \\
V_v & – volume \ of \ voids \\
V & – Volume \ of \ composite \ part \ or \ panel
\end{align*}
\]

\[
\begin{align*}
v_f & – volume \ fraction \ of \ fibres \\
v_m & – volume \ fraction \ of \ matrix \\
v_v & – volume \ fraction \ of \ voids
\end{align*}
\]
\[ v_f = \frac{\text{volume of fibres}}{\text{total volume of panel}} = \frac{V_f}{V_p} \quad \text{Equation 2-3} \]

\[ v_m = \frac{\text{volume of matrix}}{\text{total volume of panel}} = \frac{V_m}{V_p} \quad \text{Equation 2-4} \]

\[ v_v = \frac{\text{volume of void}}{\text{total volume of panel}} = \frac{V_v}{V_p} \quad \text{Equation 2-5} \]

If \( V_v \) is considered 0, (ideal case) i.e. there are no voids in the panel (which although unlikely, is often negligible), the panel consists of fibres and matrix alone.

\[ V_f + V_m = V_p \quad \text{Equation 2-6} \]

\[ v_f + v_m = 1 \quad \text{Equation 2-7} \]

The volume fractions is limited by the material type and manufacturing technique. A basic lay-up technique makes a panel of low fibre volume fractions, in the range of 15-20\%, while to increase the volume fraction of fibre to up to 50-60\%, a much improved and sophisticated compression moulding or autoclave curing may be required.

Along with the volume fractions, the direction of fibres reinforcement is the other key parameter that defines the performance of the composite part. This orthotropic quality of composite materials sets it apart from other building materials, making it possible to tailor fit the material depending on the applications; inserting reinforcement where required.

The direction of the reinforcing fibre may be limited by primarily the materials being used. For instance for tubular pressure vessels, where the loading is essentially radial, a unidirectional reinforcing mat is best suited. In the construction of the hull of a boat, woven fabrics with near equal reinforcements in two perpendicular directions are used, to resist the complex loading that it may encounter during its service life. On a Table top or counter top, a chopped strand mat may be used, where the stresses expected are low and in arbitrary directions. Many at times, in a complex structural element, a hybrid of different reinforcing materials are used to optimize the capacity to suite the requirements. In a structural I-beam for example, unidirectional fabrics are primarily used in the flanges, where the stresses are mostly tensile or compressive, and the web
may made of woven fabrics cast at 45° to maximize the shear capacity. Some woven fabrics may also be used in the flanges in addition to the regular unidirectional fabrics for added stiffness where required, especially in cases where torsional loads are expected.

Generally, a composite panel is made of a set of layers, and the properties are met as a designed combination of these layers. In thin sections, addition or removal of one layer makes a significant difference to the performance of the composite panel. The exceptions are in assembly of the thick fuselage sections of the jet aircrafts (Boeing 787), where automated fibre placement technique is used, in which case the thin layers of fibres are negligible when compared to the overall thickness of the part. In these cases, the fibre may be oriented in the desired directions to a desired thickness.

It might also be noteworthy to know that the stress distribution within the cross section of the panel is not equal, owing to the non-homogenous cross section. For example, a mere increase in cross section area of the member does not imply an increase in the load carrying capacity in the same proportion. For a given volume fraction of reinforcing fibres, the change in cross sectional area is due to the addition or removal of one or more layers of reinforcing fabric. In such cases, the axial strength and stiffness remain same, although the load carrying capacity of the panel changes. Any change in the cross section without a change in number of reinforcing layers, the change in area must come from the change in matrix volume thereby changing the volume fractions of the panel, which in turn changes the axial strength and stiffness of the panel.

The properties of a laminate can be estimated if we know the properties of the constituent fibre and matrix materials. The most widely used method is the rule of mixtures, although in recent times with the advent of high computational power, complex finite element models are also used for important applications. For the purpose of this research, rule of mixtures provides a sufficiently good estimate.

### 2.6 Review of FRP manufacture techniques

An FRP composite is manufactured in a number of ways, depending essentially on the requirements of the finished product, starting from the simple wet layup technique to the complex automated
fibre placement technique. Some of these popular techniques and their applicability in this project are described below:

- Simple Techniques:
  - Wet lay-up
  - Pre-preg lay-up
  - Spray-up

- Complex Techniques:
  - Liquid composite moulding
    - Resin transfer moulding
    - Vacuum infusion
    - Light resin transfer moulding
  - Compression moulding
  - Bladder moulding
  - Pultrusion
  - Filament winding
  - Automated Fibre Placement

The time and requirements of curing depends on the type of resin, and degree of polymerization required. Generally curing is done in one of the following conditions:

1. At room temperature, at atmospheric pressure
2. In an oven, at high temperature and atmospheric pressure
3. In an autoclave, at high temperature and high pressure.
2.6.1 Wet lay-up

In the wet lay-up process, the mould, which is generally a flat aluminum or glass plate is first coated with release agent and sometimes with a gel coat (for better quality finish of the composite panel). The reinforcing fibres, generally in the form of mats or fabrics, both of woven and unidirectional kind, are placed on the mould. The resin is poured on the fibre reinforcements, and the wet composite is rolled or wiped with a squeegee to spread the resin uniformly throughout, and eliminate voids. Care is taken such that the squeegee is used uniformly over the area, gently pushing outward from the centre, so we are not introducing new air pockets towards the centre but pushing them away from the edges. Ample amount of resin is poured to ensure complete saturation of the fabric. When a composite of relatively high thickness is required, it is recommended to first saturate some layers of the fabric, then add more layers. Once the panel is cured, it may be easily peeled off of the mould.

Although this is a fairly simple technique, the removal of voids using a squeegee is dependent on the skill of the worker. This hinders consistency within the panel, and its reproducibility.

2.6.2 Pre-preg lay-up

Pre-preg fibres are those fibres or fabrics which are pre-impregnated with a B-stage resin. B-stage resin is a partially cured resin, enough to have some structural stability, but remaining flexible enough to be able to be draped in complex shapes. The totally uncured resin, also known as the green stage resin is in the form of a liquid and would seep out of the fabric, and therefore only partially cured fabrics are used.

Similar to the wet layup, these are placed on moulds coated with release agents. A squeegee is often used to remove the voids, and sometimes vacuum is applied to compact the Prepreg and squeeze out the air voids to a greater degree. Excessive resin may also be removed by squeezing or vacuuming technique.

Pre-preg fabrics require special attention, since they consist of partially cured resin. Care must be taken that the B-stage resin does not cure, and therefore the Pre-preg fabrics have a limited shelf
life, and are required to be kept in cold storage. The manufacturing technique is very simple and we can get good uniformity among the panels, however the high cost limits its application to very high performance parts.

2.6.3 Spray up

As the name suggests, in the spray up technique, the fibre and unsaturated liquid resin are sprayed simultaneously over the mould. It is one of the techniques used in manufacture of boats, canoes, etc. This technique is widely used in marine industry and in manufacture of precast products where the parts do not have very high mechanical requirements. The performance is similar in all directions, however structural performance is low due to the use of random alignment of short discontinuous fibres as opposed to aligned continuous ones. This method has also been adapted for used in the construction industry for repair and retrofit of structures [169–174]. The significant difference in spray up is that chopped short fibres are used, instead of continuous fabrics or mats used in other techniques described above. While the spraying velocity of the materials does offer some compaction, additional compaction may be achieved by rolling using a squeegee. This is a fast process, although a highly skilled operator is required to spray the material. This process also poses some health safety and environment concerns.

2.6.4 Liquid composite moulding (LCM)

Liquid Composite Moulding refers to the manufacturing technique in which the liquid unsaturated resin is injected into a dry fabric which is placed between a mould and a counter mould, with the help of an external force such as injection pressure, vacuum pressure, or a combination of both. LCM can be broadly classified into 3 categories, (a) Vacuum infusion, (b) Resin transfer moulding, and (c) Light resin transfer moulding, depending on the mould and resin injection method.
2.6.4.1 Vacuum infusion (VI)

In vacuum infusion technique, dry fabric is placed between a solid mould, generally made of a metal or an alloy, and a membrane counter mould, generally made of nylon or sometimes polyethylene. The vacuum bag is sealed at the edges, and resin is drawn from an inlet pipe(s), under vacuum suction applied at the outlet end. In this method, to prevent the consumables such vacuum bag & pipes to get attached to the composite part, a peel ply is used, which can be easily peeled off after curing.

2.6.4.2 Resin transfer moulding (RTM)

In RTM, both the mould and counter mould are made of a rigid metal or alloy. The dry fabric is placed between the mould and counter mould, and the resin is pushed through an inlet pipe under a high pressure of around ~100-700 kPa (~15-100 psi). A peel ply is not required in the process, and therefore the composite part has a smooth surface on both sides. Sometimes additional vacuum pressure is applied at the outlet to assist with the flow of resin.

2.6.4.3 Light resin transfer moulding (LRTM)

LRTM adapts principles from vacuum infusion and resin transfer moulding. It uses a semi rigid tool such as in vacuum infusion process, and a semi flexible counter mould, which is sealed off at the edges. The injection pressure is lesser than in the case of RTM, at typically range from 1-2 atmospheres (~100-200 kPa or ~15-30 psi). LRTM has advantages over RTM and VI process, that the processing costs are lower, and composite part has two finished smooth surfaces.

2.6.5 Compression moulding (CM)

Compression Moulding is similar to RTM, in the way that they both have rigid moulds, except in the case of compression moulding, the edges are not sealed. After the reinforcement fabric is placed on the mould, resin is poured. The mould and counter mould are then pressed together against each other, causing the excess resin along with the air voids to be removed from the unsealed side edges.
2.6.6 Bladder moulding

Bladder moulding is a process that uses an inflatable bladder and an outside mould to create a part, typically using a pre impregnated reinforcements.

2.6.7 Pultrusion

In Pultrusion, the dry reinforcing material, which maybe either tow of fibres or a woven fabric, are pulled through a resin bath. Once passed through the resin bath, the reinforcing material impregnated with resin is pulled through an orifice, which gives the composite it’s cross sectional shape, to the heated die chamber, where the resin cures and polymerizes. The pultruded composite may then be cut to the desired length.

This type of manufacturing is very well suited for the mass production of a composite FRP bars. It is slightly more complex than the techniques described in earlier sections, and involves a high cost for the setup of the system. But once the machinery is setup, composites can be produced continuously and uniformly.

2.6.8 Filament winding and tube rolling

In the filament winding technique, a reinforcing tape or tow is continuously wound around a mandrel in a controlled pattern. The dry reinforcement may either be wound around the mandrel, and then saturated with resin after winding is complete, known as the dry-winding process, or the reinforcement may be saturated in resin just before winding, known as the wet-winding process.

Tube rolling process typically involves wrapping of a pre-impregnated reinforcement around a circular mandrel.
2.6.9 Automated fibre placement

Automated fibre placement is an advanced technique used widely in the aviation & aerospace industry. The fibre placed using a head mounted either on a robotic arm or a gantry system, to reinforce a large composite part wholly, which would not be possible by hand lay-up. This technique generally uses prepreg fibres or prepreg fabrics, which can be precisely placed at the required position. Curing generally requires an autoclave. The cost of setup of such machinery incurs very high cost, limiting its use mainly to the aerospace industry.

2.7 Choice of manufacturing technique

The consideration of the different manufacturing techniques in reference to the requirements of the FRP fibre envisioned are discussed below:

- **Wet lay-up:** No control over thickness or volume fractions, high void content, and poses health and safety concerns.

- **Pre-preg lay-up:** Expensive, low shelf life and demanding storage requirements.

- **Spray-up:** Low volume fractions in the direction of loading.

- **Vacuum infusion:** Low setup cost, Uniform and reproducible composite parts.

- **RTM:** High setup costs, suitable for complex shapes. More than necessary to make a flat composite panel.

- **LRTM:** Setup costs slightly higher than vacuum infusion process.

- **Compression moulding:** High setup costs, suitable for complex shapes. More than necessary to make a flat composite panel.

- **Bladder moulding:** Suitable for hollow shapes. More than necessary to make a flat composite panel.
**Pultrusion:** High setup costs.
Faster and better quality control, compared to others.
Possibility of higher volume fractions compared to others mentioned above.

**Filament winding:** Suitable for prismatic shapes. More than necessary to make a flat composite panel.

**Automated fibre placement:** Very high setup costs, suitable for complex shapes. More than necessary to make a flat composite panel.

Boutier et al. [175] in their experimental study have compared the different LCM techniques in detail, based on their performance, setup and operational costs, production scale, and size. While Pultrusion may be the better way of manufacturing the fibre at a large scale, a quick, relatively low cost vacuum infusion technique could be used to produce the fibres at a small scale in the laboratory.
Chapter 3: Materials and Mix Designs

3.1 FRP materials and consumables

3.1.1 Reinforcing fibres

A total of 4 types of reinforcing fibres, as shown in Figure 3-1 were used to make the FRP panels.

Figure 3-1 Reinforcing fabrics used in the project (a) woven glass fabric, (b) woven carbon fabric, (c) unidirectional glass fibre tape, & (d) unidirectional carbon fibre tape
3.1.1.1 Woven glass fabric

Woven E glass fabric, of the type generally referred to in the market as style E 3733, shown in Figure 3-1 (a) was the first fabric to be used as the reinforcing fabric for FRP panels. These are the lowest cost FRP reinforcing fibres available. The style E 3733 refers to loose plain type of weaving. The technical specifications of the fabric are as follows –

1. Thickness – 0.0078” or ~0.2mm
2. Areal density – 5.8 oz/sq.yd. or ~200gsm
3. Weave type – 18 X 18 plain

3.1.1.2 Unidirectional glass fibre

Unidirectional S glass tape of width 12 inches as shown in Figure 3-1 (c) was used for making FRP panels. The technical specifications of the fabric are as follows –

1. Thickness – 0.009” or ~0.23mm
2. Areal density – 4 oz/sq.yd. or ~135gsm
3. Weave type – Unidirectional with fine spider web of polymer fibrils holding the fibre in place.

3.1.1.3 Woven carbon fibre

Woven carbon fibre with twill weaving pattern, as shown in Figure 3-1 (b) was used for making the FRP panels. The basic technical specifications of the fabric are as follows:

1. Thickness – 0.012” or ~0.32mm
2. Areal density – 5.7 oz/sq.yd or ~195gsm
3. Weave type – 2 X 2 twill with 3k carbon fibres.

3.1.1.4 Unidirectional carbon fabric

Unidirectional carbon fibre tape of width 12 inches, as shown in Figure 3-1 (d) was used to cast FRP panels. The basic technical specifications area as follows –
1. Thickness – 0.01” or ~0.26mm
2. Areal density – 4.8 oz/yd2 or ~ 165 gsm
3. Weave type – Unidirectional with fine spider web of polymer fibrils holding the fibre in place.

3.1.2 FRP resin

Epoxy was chosen as the only resin used as the matrix for the FRP panels. The multifunctional epoxy resin with cycloaliphatic amine based hardener was manufactured by Rhino Linings Corporation.

The trade name of the resin-hardener system used is Rhino epoxy 1411 resin with hardener rhino 4111, which was used in the ratio 100:30 (Resin: Hardener).

The basic properties of cured neat resin, as provided by the manufacturer are as follows:

1. Glass transition temperature Tg: 90°C
2. Tensile strength: 10.3 ksi ~ 70 MPa
3. Tensile modulus: 465 ksi ~ 3.2 GPa
4. Ultimate elongation: 7.4% to 7.5 %

3.1.3 Release agent

Water based Polytetrafluoroethylene (PTFE) (Teflon like) release agent was used on the Aluminium moulds for easy peeling off of the FRP panel. The release agent is manufactured by Airtech international incorporated, and is sold by the name commercial Release all® Safelease 30, rated to 450°F (~232°C) curing temperature.
3.1.4 Peel ply, vacuum bag & flow medium

Nylon based peel ply pre-coated with silicone release agent having thickness 0.0045” (~0.11mm), manufactured by Airtech International Incorporated was used. The product is sold by the name Bleeder lease® B, and is rated to temperature of 450°F (~232°C).

Nylon based vacuum bag of high elasticity having thickness 0.002” (~0.05mm), manufactured by Airtech International Incorporated was used for manufacturing the FRP panels. The product is sold by the name Ipplon® KM1300, and is rated to the temperature 420°F (~212°C).

Polypropylene based flow medium, manufactured by Airtech International Incorporated has been used. It is sold by the name Greenflow 75, and is rated to temperature 302°F (~150°C).

3.1.5 Tacky tape

A multipurpose sealant tape with high tack, manufactured by Airtech International incorporated has been used for sealing the sides of the vacuum bag during the production of the FRP panels.

3.1.6 Plastic tube & spiral wrap tube

Spiral wrap of diameter 3/8th inch, and plastic tube of diameter 3/8th inch made out of food grade polyethylene was used in manufacturing the FRP panels. The tape is sold by the name AT-200Y, and is rated to maximum cure temperature of 400°F (~204°C).

3.1.7 Moulds

A flat Aluminum mould was used to cast the FRP panel on.

3.2 Tabbing Materials for FRP tests

Two types of materials have been used for two different sizes of FRP samples.
Aluminium sheets of thickness 1/32” (~0.8mm) were used for tabbing the fibre sized FRP specimen.

Electrical grade fiberglass laminate (GPO3), also known as polyester-grade industrial laminate of thickness 1/16” (~1.6mm) was used to tab FRP strips for tensile strength tests. These laminates are rated to a temperature of 265°F (~130°C), and have tensile strength in the range of 10-15 ksi (~70-105MPa).

Epoxy glue of make JB weld, rated to a temperature of 600°F (~315°C) was used for tabbing.

### 3.3 Materials for Cementitious Composites

#### 3.3.1 Cement

General purpose Type 10 of make Quikrete was used for all the tests.

#### 3.3.2 Aggregates

River sand was used as fine aggregate to cast mortar and concrete specimen. The fine aggregate had a specific gravity of 2.62.

Crushed natural stone nominal maximum size 12mm was used as coarse aggregate for casting concrete specimen. The coarse aggregate had a specific gravity of 2.7.

#### 3.3.3 Water

Clean potable tap water was used as the water for mixing.

#### 3.3.4 Mould release agent

Organic biodegradable, canola based, reactive form release agent of make Green Release was used to coat the moulds prior to casting the mortar and concrete specimen.

#### 3.3.5 Moulds

All the moulds were made of PVC material.
3.3.6 Glass fibres

Glass fibre used for comparison were Alkali resistant glass chopped strands from OCV Reinforcements of the following properties:

- Length: 35 mm
- Thickness: 0.2 mm
- Width: 1.1 mm
- Specific Gravity: 2.58

3.4 Mix designs

3.4.1 Mortar

Mortar with water to cement ratio of 0.35, with equal parts of cement and sand were used for casting the specimen. The mortar had a compressive strength of 60 MPa at 7 days.

3.4.2 Concrete

Concrete with the following mix design was used for casting the specimen.

*Table 3-1 Mix design for concrete*

<table>
<thead>
<tr>
<th>Water</th>
<th>Cement</th>
<th>Fine Aggregate</th>
<th>Coarse Aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>199.0 kg/m³</td>
<td>360.8 kg/m³</td>
<td>869.6 kg/m³</td>
<td>911.5 kg/m³</td>
</tr>
</tbody>
</table>

The concrete had a compressive strength of 25 MPa at 7 days, and 35 MPa at 28 days.

No chemical or mineral admixtures were used, for mortar or concrete specimen.
Chapter 4: Manufacture of Fibre and Characterization

4.1 Manufacture of FRP composite fibre

Various FRP manufacturing techniques have been discussed earlier in the Section 2.7. The vacuum infusion technique, limitations and improvisations associated with our project requirements in particular are discussed in this section. While Pultrusion is perhaps the only way of manufacturing a composite part which extends essentially in one direction, the simplest form that can be made using other techniques including the vacuum infusion technique is a flat FRP panel. These panels need to be cut or trimmed to a size suitable for being used as a short discrete fibre in fibre reinforced concrete.

The target fibre dimensions were:

- Diameter: 0.5mm
- Length: 50 mm

4.1.1 Manufacture of FRP panel: vacuum infusion technique

Stepwise procedure of the vacuum infusion technique is described below:

1. The flat aluminum or alloy mould is cleaned, so that there aren’t even small dust particles. This is essential in creating a leak free vacuum bag.

2. The mould release agent applied, in order to prevent the epoxy resin to stick to the mould. (Fig 4-1 (a)).

3. The reinforcing fabric and a layer of peel ply are placed on the mould in the regular infusion process. In this project, an extra layer of peel ply was placed between the mould and the reinforcements (Fig 4-1 (b), 4-1 (c)). Sometimes an additional flow medium is also placed at the top in cases when the thickness of the reinforcements is small. The flow medium assists the flow of resin (Fig. 4-1(d)).
4. Inlet & outlet tubes are placed at the two edges as shown in Figure 4-1 (d). The entire setup is then covered with vacuum bag which acts as the counter-mould. Spiral wrap is used to allow for uniform flow into and out of the reinforcements.

5. The vacuum bag is then sealed off using a tacky tape. The outlet is connected to the catch pot, which is in turn connected to a vacuum pump (Fig. 4-1 (e)).

6. A vacuum test is done to check for leaks. This is done by pinching off the inlet tube. The vacuum pump is then switched on, to create a vacuum inside the bag. Once vacuum is created, the vacuum pump is switched off, and the change in pressure inside the vacuum is measured for about 10 minutes (Fig. 4-1 (e)).

7. Once vacuum is setup in the system, the degassed resin and hardener are mixed in the resin pot and introduced through the inlet. The resin is drawn under vacuum pressure, and infuses into the reinforcing fabric (Fig. 4-1 (f), 4-1 (g)).

8. Once the resin has saturated the reinforcing fabric, the inlet channel is pinched off. The outlet is still connected to the catch pot, the setup still under vacuum.

9. The setup is left undisturbed for 24 hours, after which it is separated from resin pot and catch pot. It is cured in the oven at 65°C for 4 hours and 85°C for another 2 hours.

10. Once cured, the peel plies on both sides are then peeled off carefully ensuring no damage to the FRP panel.
Figure 4-1 Steps involved in Vacuum infusion process
4.1.2 Adaptation of technique to our requirements

While the target was to produce a fibre of a circular cross section, the vacuum infusion technique produces a flat panel which is cut to fibre sizes, giving the fibre a rectangular cross section. The thickness of the fibre is governed by the amount of reinforcing material and the technique of manufacture. In this project, the thickness of the fibres of different compositions varies from 0.3mm to 0.9mm. The width of the fibre depends on the ability to cut the fibre. Practically, the lowest width possible is about 1.2 to 1.5 mm.

As mentioned in the earlier section, a layer of peel ply was placed between the mould and the reinforcements, which is not placed in the regular infusion processes. The peel ply gives a rough finish to the surface of the composite part, and in most applications, a rough surface is not desired. Often the surface is polished with epoxy to give the part a glossy look. In our case however, a rough surface means a better bond behaviour with cementitious material. To get a rough surface on both sides, the reinforcing fabric is placed between two peel plies, instead of having just the one peel ply on top of the reinforcing fabric.

4.1.3 Cutting FRP panels to make FRP fibre

2 types of panels were manufactured using the infusion technique. The first one was using a woven fabric, which have fibres running in both the directions. The effort for cutting the panel is moderate in both directions. The second type of panel was made using a unidirectional fabric. For these panels, the effort required for cutting along the direction of fibres is less, but the effort for cutting perpendicular to the direction of fibres is high.

Also both, woven as well as unidirectional panels were cast using 2 types of materials, glass and carbon. The effort required for cutting the carbon fibre reinforced polymer panel (CFRP panel) was higher than glass fibre reinforced polymer panel (GFRP panel).

Several tools were tried for cutting the panels. Even the sharp blades were found to be difficult for making narrow cuts. Besides, without a precise guiding mechanism, it is not possible to cut in a straight line. A mechanical saw was used for cutting the FRP panel. While the cuts were very clean,
the effort required to make a single fibre was high. Practically not a feasible option. A pair of good quality scissors were also tried, while cutting was possible, making precise cuts was not possible.

A stack paper cutter as shown in Figure 4-2 (a) was tried, and worked well with most of the panels. Sheet metal scissors also known as sheet metal snips or shears were used to cut the unidirectional panels in the direction perpendicular to the fibres into 50 mm wide strips. These strips were then cut into fibre sizes using the paper stack cutter.

4.2 Characterization of FRP panel and fibre

4.2.1 Methods and experimental setup

4.2.1.1 Volume fractions

Vacuum infusion can produce FRP panels of good quality with reasonable consistency among different batches. There may however be minor variation caused because of inconsistent vacuum compression among different batches, and in different regions of the same batch. The volume fraction of the composite may be calculated using the formula:

\[ V_f = \frac{\rho_s}{\rho_f \cdot t} \]  

\textit{Equation 4-1}
Where \( \rho_s \) = superficial density or areal weight of the reinforcement in gsm or g/m\(^2\)

\[ \rho_f = \text{density of fibre material in g/m}^3 \]

\[ t = \text{thickness of FRP panel in m} \]

4.2.1.2 Microscopic images

The fibre samples were observed under an optical and scanning electron microscope.

Optical microscope

An optical microscope of make Meiji, mounted on an arm boom was used to observe the FRP fibres under a magnifications ranging from 2x to 4.5x. A 2 megapixel camera mounted on the axis of the microscope was used to take pictures, using the Motic Image plus 2.0 ML Software. The measurements such as fibre width were made using the Motic live imaging module. The source of external light was by using lamps attached to an 18” flex arm, the setup of which was made by Fiber Optic Company.

Scanning electron microscope (SEM)

A Hitachi SU1510 Scanning electron microscope was used to take microscopic images of fibres and interface samples. The specifications of the SEM are as defined below:

In addition to the SEM, the Energy-Dispersive X-Ray Spectroscopy comes with the same machine.

Table 4-1 Specifications & Settings of the SEM used

<table>
<thead>
<tr>
<th>Specifications of the SEM</th>
<th>3 nm @ 30kV (High Vacuum mode)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution</td>
<td>15 nm @ 3kv (High Vacuum mode)</td>
</tr>
<tr>
<td>Secondary electron resolution</td>
<td>4 nm @ 30kV (Variable Pressure mode)</td>
</tr>
</tbody>
</table>
### Setting used for taking pictures of fibres (For Section 4.2.2.2 & Section 6.2.2.3)

<table>
<thead>
<tr>
<th>Setting</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working distance</td>
<td>15mm</td>
</tr>
<tr>
<td>Current</td>
<td>60 mA</td>
</tr>
<tr>
<td>Voltage</td>
<td>15 kV</td>
</tr>
<tr>
<td>Lighting</td>
<td>Component</td>
</tr>
<tr>
<td>Pressure used</td>
<td>30 Pa</td>
</tr>
<tr>
<td>Mode</td>
<td>BSE imaging</td>
</tr>
</tbody>
</table>

### 4.2.1.3 Tensile behaviour

#### Specimen preparation

The performance of the composite or FRP was measured by means of a tensile test. Tensile loading, along with some shear loading are the two predominant kinds of loading that we can expect on the fibre in concrete. The thickness of each panel ranges from 0.3mm to 0.7mm, which makes it difficult to keep the sample held in between the jaws of the regular friction grips. There is also a chance of causing damage to the FRP panel at the grips. Therefore, commercially available Aluminum or Fibreglass sheets are often used as tabbing material, which are then secured in place by the friction grips. Fibreglass tabbing is preferred compared to Aluminum, as the rough fibreglass surface can be easily glued using epoxy glue onto the FRP panels produced in the laboratory. Electrical grade fibreglass of thickness 1/16” (~1.6mm) was used for tabbing. The tabbing process is described with the help of the Figure 4-3 below.
1. The 1/16” (~1.6mm) thick fibreglass sheet (tabbing material) is cut into strips of 1” or 2.5 cm using a saw or shears.

2. These strips are then glued onto the edge of the FRP sheet produced, such that the strips are perpendicular to the direction of fibres or the direction of loading as shown in Figure 4-3 (a). A clear gauge length of 10cm is maintained between the two tabs.

3. The circular Table saw is used to cut the FRP panel with fibreglass tabs to narrow strips of width about 1cm as shown in Figure 4-3 (b).

Figure 4-3 Preparation of specimen for tensile testing. (All dimensions are in mm)
Test setup and procedure

The tests were performed on a vertically mounted strain controlled Instron universal testing machine in accordance with ASTM D3039-14 [176]. The hydraulic powered Instron machine was equipped with a load cell of 250 kN. The tests were conducted at a constant displacement rate of 0.035 mm/sec (2mm/minute). The displacement was measured by measuring the cross-arm displacement. A DASYlab program was used to acquire the data and store it in ascii format. The data is further analysed to obtain the strength, strain, and other elastic properties.

Inevitably due to the nature of the test, there arises some eccentricity due to misalignment in the machine while placing the specimen in the grips. Misalignment and eccentricity can cause high variations in the data, and even result in premature failures in the FRP specimen. Care is taken to minimize the misalignment, by visually aligning the long axis of the specimen with the axis of the machine. At least 10-12 specimen were tested to obtain the average tensile response of the FRP specimen. The Figure 4-4 below show the grips used for the test.

![Figure 4-4](a) Friction grips for tensile tests of (b) GFRP and (c) CFRP strips

4.2.1.4 Single fibre pullout

Specimen preparation

Single fibre pullout tests were performed to assess the bond of the fibre with cementitious matrix. To test the bond, dogbone shaped specimen as shown in Figure 4-3 below were cast and tested.
A mortar of normal strength, using equal parts of general purpose cement and fine river sand, with water to cement ratio of 0.35 was used for all tests. The mixing and placing the cement mortar was as per ASTM C305 [177]. Water is first poured into the mixing bowl, after which cement is added. They are mixed for about 30 seconds to get a consistent cement paste, after which gradually sand is added while the mixer is rotating. Once all the sand is added, it is allowed to mix for another 30 seconds. The speed of the mixer is then increased, and mixing continued for about 30 seconds. The mixer is then stopped, the excess mortar collected on the sides is scraped off and allowed to stand for another minute. Mixing is resumed, and the process is completed after another 60 seconds of mixing ensuring a uniform mortar is obtained.

![Dogbone Specimen Schematics](image)

*Figure 4-5 Schematics of dogbone sample*

The dogbone shaped specimen, as shown in Figure 4-5, consists of two halves, which are separated by a 0.5 mm thick plastic separator. The fibre is pierced through this thin plastic separator, which holds the fibre in position. The plastic sheet in turn is secured in the grooves in the mould dividing the dogbone specimen in two equal halves. The moulds were made of poly vinyl chloride (PVC), and were oiled prior to pouring the mortar. Mortar is then poured carefully in both halves of the dogbone to fill about half the height. The moulds are vibrated slightly on a Table vibrator for about 20-30 seconds, care is taken so that the fibre is still in position and alignment during and after vibration. Mortar is then poured to fill up the dogbone shaped specimen to fill up, then vibrated lightly for about 60-90 seconds. The specimen are then covered with a plastic film immediately after casting to avoid any loss of moisture while in plastic state. They are de-moulded
the next day, labelled and moist cured in a curing room at 23° and 95% relative humidity for 6 days.

![Figure 4-6 Pictures of steps involved in casting of dogbone specimen](image)

The only means of connection of the two halves of the dogbone specimen are through the bond with the fibre. The two ends are pulled, the stresses are transferred from the matrix to the fibre in the form of shear stress acting on the bonding surface of the fibre. This bond shear stress induces tensile stress in the body of the fibre. Failure of these dogbone specimen can be considered when there is zero or minimal resistance to separation of the two ends of the dogbone specimen. Among the failure types discussed in Section 2.3.2, the dogbones failed in predominantly the following types:

a) Fibre pullout

b) Fibre fracture

c) Matrix spalling (in inclined fibre pullout only)
Test setup and procedure

The tests were conducted on an electric powered screw driven horizontally mounted machine equipped with a 2000 lbs (~900 N) load cell. An LVDT was used to measure the displacement or the crack width opening. The grips of machine are designed in the shape of a dogbone, as shown in Figure 4-7, such that the points of contact were away from the point where fibre enters the matrix. This is important, since the point where fibre enters the matrix is of critical importance, therefore must be kept free of interferences [115].

![Horizontal setup for single fibre pullout tests](image)

*Figure 4-7 Horizontal setup for single fibre pullout tests*

The quasi-static pullout test was conducted with pullout rate of 2.4 mm/minute. A DASYlab program was used to acquire the load and slip data in asci format which is later processed to obtain the pullout load-slip curve.

Bond stress is computed by distributing the experimentally determined load over the area of bonding of the FRP fibre with the matrix. Experimentally obtained pullout load-slip curves are integrated to quantify the total pullout energy dissipated by the fibre-matrix interface during the pullout process. Once the pullout energy is known, the equivalent bond strength is calculated using the following [178]:

$$
\tau_{eq} = \frac{8 * E_p}{\pi * d_f * L_f^2}
$$

*Equation 4-2*
Where \( \tau_{eq} \) is the equivalent bond strength, \( E_p \) is the fibre pullout energy, \( d_f \) is equivalent diameter of fibre and \( L_f \) is the total length of the fibre.

For fibres that are non-circular in diameter, a generalized equation may be used

\[
\tau_{eq} = \frac{8 \times E_p}{P \times L_f^2}
\]

\( \text{Equation 4-3} \)

Where \( P \) is the perimeter of the fibre.

The equation may also be modified to change the circular perimeter \( P_{cir} = \pi d_f \) to rectangular perimeter \( P_{rec} = 2^*(t+w) \) where \( w \) is fibre width and \( t \) is fibre thickness. The equation therefore becomes

\[
\tau_{eq} = \frac{8 \times E_p}{2 \times (t + w) \times L_f^2}
\]

\( \text{Equation 4-4} \)

8-10 specimen were tested to obtain the average curves shown in the results and discussion section.

4.2.1.5 Flexural test (ASTM C1609)

Flexural tests were done in accordance with ASTM C1609 [179]. At least 3 beams of size 100mm x 100mm x 350mm were tested.

Specimen preparation

A normal strength concrete of compressive strength 40 MPa was used throughout. Type 10 General use (ASTM Type I), cement, fine river sand, and crushed stone coarse aggregate of maximum nominal size 10mm (0.4") were used. No chemical admixtures or secondary cementitious material were used.
The specific gravity of the FRP fibres were computed using the pycnometer method. While the standard test method for specific gravity of plastics is supposed to be measured as per as per ASTM D792 (by weighing the plastic fibres in water), the specific gravity was indirectly measured using ASTM D854, which is the standard test method for specific gravity of soil solids by water pycnometer method. The experimental results were then compared with the rule of mixture estimates as shown in Table 4-2:

**Table 4-2 Specific Gravity of FRP fibres**

<table>
<thead>
<tr>
<th>Fibre type</th>
<th>GFRP Bi-directional</th>
<th>GFRP Uni-directional</th>
<th>CFRP Uni-directional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated specific gravity</td>
<td>1.60</td>
<td>1.49</td>
<td>1.29</td>
</tr>
<tr>
<td>Rule of mixtures estimate</td>
<td>1.60</td>
<td>1.52</td>
<td>1.27</td>
</tr>
</tbody>
</table>

An oil based mould release agent was used to oil the moulds before mixing the concrete. Concrete mixing, placing, and curing was carried out in accordance with ASTM C192 [180]. A drum mixer was used to mix about 12 liters of concrete for 3 beams. The materials, including the fibres were weighed separate pans. The mixer was dampened using a wet cloth before mixing the ingredients. Coarse aggregate and fine aggregate were added to the mixer and dry mixed for about a minute. The cement was then added and dry mixed again for about a minute. The water and fibres were then gradually added simultaneously while the mixer was rotating. After all the ingredients were added, concrete was mixed for another 3 minutes to ensure complete mixing and consistent mixing of the ingredients. Due to the low workability, the moulds were filled in 3 layers. A Table vibrator was used to consolidate the concrete after every 1/3rd placement of concrete. Once the excess concrete is struck off, the surface is finished using a trowel. To prevent evaporation of water from the free surface, a thin sheet of plastic is placed immediately after finishing the surface.

The specimen were allowed to set, and de-moulded after 24 hours. They were then moist cured in a curing room, at 23° C with 95% relative humidity for 6 days, and were removed no more than 10 minutes before the test.

Along with FRP fibre reinforced concrete specimen, unreinforced beam specimen, and glass fibre reinforced concrete beams were also cast for comparison.
Test setup and procedure

The specimen were tested after moist curing after 7 days in a closed loop Instron universal testing machine as per ASTM C1609 as shown in Figure 4-8 & 4-9 below:

*Figure 4-8 Third point bending test as per ASTM C1609*

*Figure 4-9 Schematics of flexural beam tested as per ASTM C1609.*
An average of 2 LVDT measurements were used for determining the mid-span deflection. The rate of loading was set to

0.05 mm/minute up to a deflection of L/600
0.10 mm/minute from a deflection of L/600 to a deflection of L/300
0.15 mm/minute from a deflection of L/300 to a deflection of L/150 or failure whichever occurred earlier

Where \( L \) = clear span of the beam \( = 300 \text{mm in our case} \)

From the data acquired, the peak load, and residual loads at a deflection of L/600 and L/150 were determined. The flexural strength corresponding to the above deflections are calculated as per the formula:

\[
f = \frac{P \times L}{b \times d^2}
\]

Where
- \( f \) = Flexural strength
- \( P \) = Load
- \( L \) = Clear Span
- \( b \) = average width of beam
- \( d \) = average depth of beam

The load deflection curve is then integrated from deflection 0 to deflection L/150 to obtain the area under the curve, which gives us the flexural toughness of the beam. In other words, it gives us the energy absorbed by the fibre reinforced concrete specimen during the duration of the test from mid-span deflection 0 to L/150.

The equivalent flexural strength ratio \( \% \) is obtained by using the following formula:
\[
R_{T,150}^D = \frac{150 \times T_{150}^D}{f \times b \times d^2} \times 100\% \\
Equation 4-6
\]

*Where:* \( R_{T,150}^D \) = Equivalent flexural strength ratio \\
\( T_{150}^D \) = Flexural toughness

### 4.2.2 Results and discussion

#### 4.2.2.1 Volume fractions

A reasonable consistency was observed in most of the FRP panels. The volume fractions for the 4 kinds of FRP panels produced are described in the Table 4-3.

*Table 4-3 Summary of volume fractions of FRP panels produced.*

<table>
<thead>
<tr>
<th></th>
<th>GFRP Bi-directional</th>
<th>GFRP Uni-directional</th>
<th>CFRP Bi-directional</th>
<th>CFRP Uni-directional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>0.28 &amp; 0.7</td>
<td>0.35-0.5</td>
<td>0.45</td>
<td>0.4-0.6</td>
</tr>
<tr>
<td>Volume Fraction of Fibre ( V_f ) (%)</td>
<td>31%</td>
<td>22-30%</td>
<td>25%</td>
<td>18-25%</td>
</tr>
<tr>
<td>Effective ( V_f ) (%)</td>
<td>16%</td>
<td>22-30%</td>
<td>13%</td>
<td>18-25%</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>1.67</td>
<td></td>
<td>1.33</td>
<td></td>
</tr>
</tbody>
</table>

The unidirectional fabrics, especially unidirectional S-Glass fibre had varying thickness and even some gaps in between. In such cases, we can expect a greater variation in thickness and volume fractions. The difference in volume fractions does change in the elastic properties of FRP which are discussed further in Section 4.2.2.3.
4.2.2.2 Microscopic images

Optical microscope

The unique surface texture shown in Figures 4-10 & 4-11 comes as a result of the production technique. The rough pattern comes from the peel ply we used in the manufacturing process. During infusion, the peel ply are wetted by the resin completely. When peel ply are peeled off of the FRP panel, it leaves an impression on the panel, thereby creating the pattern on the FRP panel.

Figure 4-12 shows the edge of the Unidirectional CFRP fibre. As we can see, there is minimal damage to the fibre at the edges in the cutting process.

![Microscopic images](image1)

Figure 4-10 Microscopic images of the surface of (a) CFRP and (b) GFRP fibres

![Microscopic image](image2)

Figure 4-11 Microscopic image of the Longitudinal profile of CFRP fibre
Figure 4-12 Microscopic image of the cut section of the CFRP fibre, focusing on the edge

Scanning electron microscope

SEM images were taken on GFRP and CFRP unidirectional fibres at the 200x, 500x and 2000x magnifications. The images are shown below:

Figure 4-13 SEM Images of GFRP fibres at (a) 200x, (b) 500x & (c) 2000x magnifications

The SEM images are at a higher magnification and more detailed than the OM images. The pattern on the surface observed in the OM images can be more clearly seen in the SEM images. Because of the natural lighting, shadow & reflection in the OM images, we get a better depth perception in OM images as compared to the SEM images.
Figure 4-14 SEM Images of CFRP fibres at (a) 200x, (b) 500x & (c) 2000x magnifications

As we can see, there is no distinct difference between the GFRP and CFRP fibres on the surface. No distinct difference is expected, as the manufacturing technique is identical. Shown below are FRP fibres at a lower magnification, and a different lighting to emphasize the depth perception and show a 3D effect.

Figure 4-15 SEM image at lower magnification of 50x with 3D mode lighting. Left: Undamaged CFRP fibre, Right: Damaged GFRP fibre

For the CFRP fibre in the above Figure 4-15 (left), we can see the crater like depressions, consistent with the OP image of the profile of the fibre, shown in Figure 4-10. We can also see some exposed fibres at the edges. In the Figure 4-15 (right), is the SEM image of a GFRP fibre which was damaged earlier. Note the separation of fibres along the length of the crack.
4.2.2.3 Tensile behaviour

Average tensile response of CFRP and GFRP specimen are shown in the Figures 4-15 and 4-16, and have been summarized in the Table 4-4

<table>
<thead>
<tr>
<th></th>
<th>Glass-Bi</th>
<th>Glass-Uni</th>
<th>Carbon-Bi</th>
<th>Carbon-Uni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Vf in direction of loading (%)</td>
<td>16%</td>
<td>22-30%</td>
<td>13%</td>
<td>22-30%</td>
</tr>
<tr>
<td>Strength (MPa)</td>
<td>194</td>
<td>578</td>
<td>398</td>
<td>953</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>4.0</td>
<td>9.9</td>
<td>6.6</td>
<td>19.9</td>
</tr>
</tbody>
</table>

We can see that the CFRP panel is roughly twice as strong and about twice as stiff as the GFRP panel, both in the unidirectional and bidirectional FRP panels. Furthermore, the unidirectional FRP strips have roughly twice the number of reinforcing fibres in the direction of loading as compared to the woven FRP strips. Consequently, for both GFRP and CFRP, the unidirectional FRP strips are twice as strong and have twice the elastic modulus as the woven FRP strips.

Figure 4-16 Average tensile response of woven FRP panels
The response of FRP specimen are generally lower than the values estimated by the rule of mixtures, as rule of mixtures does not take into account the voids and defects in the composite. The strength and moduli, as expected are slightly lower than the values estimated with the rule of mixtures.

Additionally, the drop in strength can also be attributed to the eccentricity that might have developed during the test process. Another reason might be the fact that the matrix of the panel might get slightly damaged while making the cut with the saw.

The third reason for the inconsistent strength, especially in the case of unidirectional GFRP panel might be the fact that the reinforcing fibre is of uneven pattern and thickness. A woven fabric is often of a very uniform pattern making a uniform thickness of the fabric and thereby the panel. The unidirectional fabric on the other hand, is generally held in place with the help of very thin organic film which during manufacture gel into the resin. Sometimes these plastic films are not strong enough to hold firmly in place the unidirectional fibres. This lack of uniformity in thickness causes variability in volume fractions of the composite resulting in variable tensile response. The variations in thickness of the FRP panel can be easily rectified in case of large scale production, where a better quality control over the manufacturing technique is possible.
4.2.2.4 Single fibre pullout

To assess the interfacial properties of FRP fibre reinforced cementitious composites, series of single fibre pullout tests were conducted to determine the bond parameters comprising of peak bond strength, pullout energy, and average equivalent bond strengths. The woven fabric FRP panels are considerably easier to produce and handle, thus the initial tests were conducted on FRP fibres made of woven GFRP and CFRP panels. Almost all the specimen made using fibres made out of woven glass or carbon fibre reinforced composite underwent fibre fracture before initiating a pull out. The fibres would experience normal stresses exceeding the strength before the interfacial stresses could attain large enough shear stresses to initiate pullout. The Figures 4-18 (a) & (b) show the specimen which underwent fibre fracture and fibre fracture after partial pullout respectively. Various cross sectional geometries have been tried out with the intention of initiating pullout, but barring one or two specimen, premature failure has been observed in all of the woven GFRP and woven CFRP based fibres. As a result of fibre fracture, the energy absorption of the pullout process is very low, and therefore wouldn’t completely serve the purpose of fibre reinforcement in concrete. These however are the characteristics of pullout testing, not necessarily indicating the fibre would undergo premature failure in a fibre reinforced cementitious composite.

Fibre pullout in this kind of specimen could be initiated by using different materials and manufacturing processes to increase the volume fraction of reinforcing fabric, thereby increasing the strength and modulus. On the upside, fibre fracture indicated that the interfacial bond between fibre and cementitious matrix is considerably strong; stronger than that of other popular polymeric and steel fibres.

Unidirectional fabrics were then used to produce FRP panels, which result in panels with significantly superior performance in the direction of alignment of fibres. The rough surface of the fibre seen under the microscope in Figures 4-10 to Figure 4-15, is one of the vital contributors to the superior interfacial behaviour of the fibre-matrix interface comes from the manufacturing technique. Hence, the manufacturing technique is not changed.
The increase in tensile capacity of the FRP fibre allowed for development of higher interfacial stresses between the fibre and matrix, allowing the study of bond-slip behaviour in detail. Complete fibre pullout is observed in all of the unidirectional CFRP based single fibre dogbone specimen and most GFRP based single fibre dogbone specimen.

Table 4-5 illustrates some of single fibre pullout curves.

We can see from test samples S2 to test sample S11, that all exhibit premature failure due to fibre fracture. In one of the specimen in test sample S7, a fibre pullout is observed. However, the geometry of the fibre, 0.7mm thickness, 2.8mm width and 50mm length is rather impractical. An exceedingly high volume fraction of fibres would have to be used to get sufficient number of crack-bridging fibres in the fibre reinforced cementitious composites. The idea behind trying such sizes were to establish roughly the peak and post peak bond strength. The maximum bond strength can then be used to estimate a minimum tensile strength that is required to avoid premature fibre fracture.
### Table 4-5 Summary of different single fibre pullout tests

<table>
<thead>
<tr>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2</td>
</tr>
<tr>
<td>S6</td>
</tr>
<tr>
<td>S7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material:</th>
<th>E Glass, Bidirectional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions (mm):</td>
<td>0.7 * 1.6 * 50</td>
</tr>
<tr>
<td>Max Interfacial Stress:</td>
<td>1.96 MPa</td>
</tr>
<tr>
<td>Failure Type:</td>
<td>All fractured</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material:</th>
<th>E Glass, Bidirectional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions (mm):</td>
<td>0.28 * 2.5 * 50</td>
</tr>
<tr>
<td>Max Interfacial Stress:</td>
<td>1.06 MPa</td>
</tr>
<tr>
<td>Failure Type:</td>
<td>All fractured</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material:</th>
<th>E Glass, Bidirectional</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions (mm):</td>
<td>0.7 * 2.8 * 50</td>
</tr>
<tr>
<td>Max Interfacial Stress:</td>
<td>2.18 MPa</td>
</tr>
<tr>
<td>Failure Type:</td>
<td>All but one fractured</td>
</tr>
</tbody>
</table>
Sample  S8
Material:  E Glass, Bidirectional
Dimensions (mm):  0.28 * 1.5 * 50
Max Interfacial Stress:  0.66 MPa
Failure Type:  All fractured

Sample  S9
Material:  E Glass, Bidirectional
Dimensions (mm):  0.25 * 1.35 * 30
Max Interfacial Stress:  1.15 MPa
Failure Type:  All fractured

Sample  S11
Material:  Carbon, Bidirectional
Dimensions (mm):  0.45 * 1.8 * 50
Max Interfacial Stress:  3.24 MPa
Failure Type:  All fractured
### Sample S12
- **Material:** Carbon, Bidirectional
- **Dimensions (mm):** 0.45 * 5 * 50
- **Max Interfacial Stress:** 2.52 MPa
- **Failure Type:** 50% fractured, 50% pulled out

![Graph](image1)

### Sample S13
- **Material:** Carbon, Unidirectional
- **Dimensions (mm):** 0.5 * 1.6 * 50
- **Max Interfacial Stress:** 3.28 MPa
- **Failure Type:** All pulled out

![Graph](image2)

### Sample S14
- **Material:** Carbon, Unidirectional
- **Dimensions (mm):** 0.5 * 5 * 50
- **Max Interfacial Stress:** 1.9 MPa
- **Failure Type:** All pulled out

![Graph](image3)
Samples S13 to S16, all of which are composed of unidirectional carbon and unidirectional S glass fibres show a pullout behaviour. The pullout curves of S13 and S15 are discussed further with the help of Figure 4-19 and 4-20.
The wavelike curves seen in the above Figures 4-19 & 4-20 are unique to FRP fibres. Other steel and polymeric fibres tested using the same setup do not show such undulations. A closer examination of these undulations reveal that the peak to peak length of the undulations is roughly about 250µm. This is most likely caused because of the rough but uniform surface of the fibre,
illustrated in the Figure 4-21. To concur, we found that the crest to crest length on the surface of the fibre is about 250µm as well. The Figure 4-21 below shows a sketch of the magnified section of the fibre-matrix interface.

![Figure 4-21 Sketch of the fibre-matrix interface](image)

The Figure 4-22 illustrates an idealized and simplified single fibre pullout response of the of the FRP fibres produced in this project. The load is generally normalized with respect to the bond area to obtain bond stress as described in Section 4.2.1.4 of this document. We can relate the simplified idealized FRP fibre pullout to the different failure scenarios observed with our samples.

![Figure 4-22 Simplified idealized single FRP fibre pullout curve](image)

As we can see from Figure 4-23 below, the roughness or the deformity helps in additional anchorage at the micro level. For smooth surface fibres, the area 1 shown in the Figure 4-22 above, represents the energy absorbed due to the resistance in fibre pullout because of the elastic bond
between the fibre and the matrix, much similar to the elastic bond that exists between the matrix and aggregate. In the case of FRP fibres produced in this project, the area 1 denotes of a combination of an elastic bond between the matrix and the fibre, and a micro-bearing mechanism due to surface deformation of the fibre. Figure 4-23 shows an SEM image of the interior of the dogbone specimen having a unidirectional CFRP fibre. Note the surface roughness leading to a bearing type of action, which can also be seen using an optical microscope shown in Figure 4-11. Also note the damage on the fibre and interface due to abrasion during fibre pullout.

![SEM image of CFRP Fibre-Matrix interface in the interior of the dogbone specimen after fibre pullout test.](image)

The samples S2 to S11 undergo a failure during this mechanism, when the normal tensile stress in the fibre exceeds the strength, while the interfacial stress is still lower bond strength.

Once the interfacial stresses reach the elastic capacity, there is a sudden release in energy accompanied by a sudden relaxation in the fibre. However, this relaxation occurs only for a fraction of the second, after which the frictional component of the fibre pullout stresses the fibre again. This is represented by the area 2 in the Figure 4-23.
Once the load exceeds the peak interfacial elastic limit, the frictional resistance to slip is offered. The chemical behavior, fibre surface interaction with fresh cement matrix are also of importance as they determine the quality of microstructure in the immediate vicinity of the fibre. We can expect the hydrophobic fibres to have a wider and more porous ITZ compared to hydrophilic fibre, and the hydrophilic nature of epoxy used in the FRP fibres produced in this project helps the interfacial bond in the elastic and to some extent the frictional regions by densification of the ITZ microstructure. The surface deformation of the fibre adds to the frictional resistance, giving it a unique stick-slip kind of response during fibre pullout.

Table 4-6, Figures 4-24 & 4-25 describe the behaviour of FRP fibres in comparison to commercially available steel and polypropylene fibres.

<table>
<thead>
<tr>
<th></th>
<th>Instances of Fibre Fracture</th>
<th>Pullout Energy</th>
<th>Peak bond stress</th>
<th>Equivalent bond stress</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>St-Straight</strong></td>
<td>0%</td>
<td>726</td>
<td>0.78</td>
<td>0.61</td>
</tr>
<tr>
<td><strong>GFRP</strong></td>
<td>30%</td>
<td>1040</td>
<td>3.32</td>
<td>0.94</td>
</tr>
<tr>
<td><strong>PP-Crimped</strong></td>
<td>0%</td>
<td>1051</td>
<td>2.16</td>
<td>1.22</td>
</tr>
<tr>
<td><strong>CFRP</strong></td>
<td>0%</td>
<td>2022</td>
<td>3.1</td>
<td>1.6</td>
</tr>
<tr>
<td><strong>St-Hooked</strong></td>
<td>0%</td>
<td>1459</td>
<td>3.38</td>
<td>2.1</td>
</tr>
</tbody>
</table>

We can see, the performance of FRP fibres is far superior to straight steel fibres, and at par with the deformed polypropylene fibres. Although it may appear the hooked steel fibre has a higher energy absorption, the peak performance of the FRP fibres, and the energy absorption at low crack openings match the hooked steel fibres. It is evident, much can be gained by optimizing the composition and geometry of the FRP fibres, perhaps surpassing steel fibres in both mechanical and durability aspects.
The variability observed in single fibre pullout tests conducted using FRP fibres made in this project and other industrially available fibres are shown below in Figure 4-26 & Figure 4-27. The standard deviation of bond stress of FRP fibres is comparable to the standard deviation of bond stress industrially produced steel and polypropylene fibres.
Figure 4-26 Standard deviation of bond strength of single fibre pullout test at different fibre slip with different fibres

Due to the higher average value of bond stress in hooked steel fibres, we see a corresponding decrease in coefficient of variation, due to a larger denominator. Similarly, due to a low value of average bond stress at large slip of 10mm, the coefficient of variation of is higher for all fibres. The cause of variation include slight misalignment, variation in ingredients, variation in size of fibre, variation in curing conditions and human error while casting. While the above reason are valid for all fibre types, for FRP fibre in particular the variation in fibre quality and fibre size is most significant.
4.2.2.5 Flexural test (ASTM C1609)

Three different sets of beam specimen using 3 different kinds of FRP fibres were tested for assessing the flexural behavior of FRP fibre reinforced concrete. Additionally, unreinforced beams and beams reinforced with glass fibres were also cast. The composition of the 5 sets of specimen are:

Table 4-7 Composition of FRP fibre reinforced concrete used for flexural tests

<table>
<thead>
<tr>
<th></th>
<th>Batch 1</th>
<th>Batch 2</th>
<th>Batch 3</th>
<th>Batch 4</th>
<th>Batch 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>UR</td>
<td>GFRP-0.5%</td>
<td>GFRP-1%</td>
<td>CFRP-1%</td>
<td>Glass Fibre 1%</td>
</tr>
<tr>
<td>Fibre type</td>
<td>Unreinforced</td>
<td>Bi-directional GFRP</td>
<td>Uni-directional GFRP</td>
<td>Uni-directional CFRP</td>
<td>AR Glass fibre</td>
</tr>
<tr>
<td>Volume fraction</td>
<td>0%</td>
<td>0.5%</td>
<td>1%</td>
<td>1%</td>
<td>1%</td>
</tr>
</tbody>
</table>

Figure 4-28 Average load-deflection curves of flexural response of FRP fibre reinforced concrete
Table 4-8 Summary of parameters of flexural response of FRP fibre reinforced concrete

<table>
<thead>
<tr>
<th></th>
<th>$P_{\text{max}}$</th>
<th>$f_{\text{max}}$</th>
<th>$P_{600}$</th>
<th>$f_{600}$</th>
<th>$P_{150}$</th>
<th>$f_{150}$</th>
<th>$T_{150}$</th>
<th>$R_{T,150}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kN</td>
<td>MPa</td>
<td>kN</td>
<td>MPa</td>
<td>kN</td>
<td>MPa</td>
<td>N-mm</td>
<td>%</td>
</tr>
<tr>
<td>UR</td>
<td>12.923</td>
<td>3.877</td>
<td>0.542</td>
<td>0.163</td>
<td>0.050</td>
<td>0.015</td>
<td>1389</td>
<td>5%</td>
</tr>
<tr>
<td>GFRP 0.5%</td>
<td>16.930</td>
<td>5.079</td>
<td>0.645</td>
<td>0.194</td>
<td>0.094</td>
<td>0.028</td>
<td>1909</td>
<td>6%</td>
</tr>
<tr>
<td>GFRP 1%</td>
<td>14.084</td>
<td>4.225</td>
<td>1.615</td>
<td>0.484</td>
<td>0.733</td>
<td>0.220</td>
<td>3975</td>
<td>14%</td>
</tr>
<tr>
<td>CFRP 1%</td>
<td>14.320</td>
<td>4.296</td>
<td>3.369</td>
<td>1.011</td>
<td>1.646</td>
<td>0.494</td>
<td>6879</td>
<td>24%</td>
</tr>
<tr>
<td>Glass fibre 1%</td>
<td>16.120</td>
<td>4.835</td>
<td>8.054</td>
<td>2.416</td>
<td>3.973</td>
<td>1.192</td>
<td>13355</td>
<td>41%</td>
</tr>
</tbody>
</table>

Where $P_{\text{max}}$ = Maximum load

$f_{\text{max}}$ = Maximum flexural strength

$P_{600}$ = Residual load at deflection of L/600

$f_{600}$ = Residual strength at deflection of L/600

$P_{150}$ = Residual load at deflection of L/150

$f_{150}$ = Residual strength at deflection of L/150

$T_{150}$ = Area under the load vs. net deflection of curve 0 to L/150. This area represents the energy absorbed by the specimen during the test.

$R_{T,150}$ = Equivalent flexural strength ratio

It can be seen from the Figure 4-28 and Table 4-8, there is an improvement in flexural toughness in terms of energy absorption in the case of FRP fibre reinforced specimen over unreinforced specimen. There is an increase of about 200% in flexural toughness by addition of 1% GFRP fibres, and about 400% in flexural toughness by addition of 1% CFRP fibres. However, one may reason that the success of FRP fibre reinforcement in increasing the flexural toughness is rather unsatisfactory, in contrast to the impressive single fibre bond slip response. The flexural response is
quite evidently inferior to the glass fibre reinforced concrete at the same volume fractions, and possibly inferior to some of the synthetic polypropylene and PET fibres, in spite of the bond strength of FRP fibres being higher than that of synthetic fibres.

The three most decisive factors that distinguish the performance of FRP fibre reinforced concrete as compared to steel and other synthetic fibre reinforced concrete lie in the intrinsic properties of fibre.

Due to the random orientation of the fibres in the cross section of the fibres, there are practically no fibres that are aligned perfectly in the directional perpendicular to the crack. In other words, almost all of the fibres are inclined at an angle to the crack surface.

The Figure 4-29 below is a sketch of the pullout process when the fibre is at an angle to the crack surface and the direction of loading. This inclination of the fibre causes a very high amount of snubbing friction at the point A where the fibre meets the crack surface. In the plane A-B, due to the bending in the fibre and angular loading, large bending and shear stress are developed. This snubbing friction and bending action damages the fibre. The effect of inclination of FRP fibres are further discussed in the Section 5.2.3.

![Inclined fibres at crack section](image)

Figure 4-29 Inclined fibres at crack section

The two key elements that come into play are ductility and flexibility. Every part of the fibre embedded inside the cement matrix is required to pass through the set path undergoing bending. Steel and other thermoplastic polymer fibres such as polypropylene, polyester, nylon etc. are both ductile and flexible, which allows for the fibre to deform and slip out. As a result of the ductile
behavior, energy is absorbed in the process of plastic deformation as well as the frictional resistance along the length of the fibre and snubbing friction action at point A. FRP although is a high in modulus and strength material, it is a brittle material. Flexibility of the fibre determines the ease with which it can pass through the inclination. Glass fibres are about 15µ in diameter whereas the carbon fibres are about 7-10µ. This small size allows the fibres to be flexible, therefore undergo bending with ease. But when these fibres are used to reinforce flexible epoxy resin to make FRP composites, the composite nature causes the fibres to bend about the global axis of the FRP composite and not the local axis of the fibres. This plummets the flexibility of the FRP fibres, making them inflexible and brittle.

![Figure 4-30 Magnified sketch of inclined fibre at crack Left: Development of shear stresses; Right: Development of bending stresses.](image)

The third factor is the slightly larger size of the FRP fibre, as compared to other macro fibres, for instance the AR glass fibres used in this study. Consequently, the number fibres bridging the cracks is on an average lower as compared to other macro fibres which are roughly half or a third in size in terms of cross sectional area. Fewer fibres of higher cross sectional area means lower bond area which is absorbing energy.

The Figures 4-31 to 4-35 below show the distribution of fibres in the cracked section of the different fibre reinforced beams after flexural tests.
Figure 4-31 Fibre distribution in GFRP fibre 0.5% reinforced beam specimen

Figure 4-32 Fibre distribution in GFRP fibre 1% reinforced beam specimen

Figure 4-33 Fibre distribution in CFRP fibre 1% reinforced beam specimen
At this point, the effect of size of the fibres can be estimated by bringing in the two parameters fibre count (FC) and fibre specific surface (FSS). The fibre count is the number of fibres per unit volume of FRC at particular volume fraction. The fibre specific surface is the surface area of the fibres present in a unit volume of FRC at a particular volume fraction. The fibre count can be estimated using the nomograph shown in Figure 4-36 below [44]:
For volumetric calculations of a fibre with rectangular cross section, the equivalent diameter of the fibre may be taken as the diameter of fibre of equal volume as original fibre. Therefore, the average equivalent diameter for a typical FRP fibre of cross section 1.5mm width and 0.5mm thickness is calculated to be 0.98mm. For comparison, the equivalent diameter of glass fibre strand of width 1.1mm and thickness 0.5mm is calculated to be 0.50mm.

The fibre count estimated using the nomograph, and the corresponding fibre specific surface is shown in Table 4-9 below:
**Table 4.9 Comparison of size effect of fibre on fibre distribution**

<table>
<thead>
<tr>
<th>Fibre type</th>
<th>FRP fibre</th>
<th>Glass fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre size</td>
<td>1.5 mm width, 0.5 mm thickness</td>
<td>1.1 mm width, 0.2 mm thickness</td>
</tr>
<tr>
<td>Fibre equivalent diameter</td>
<td>0.98 mm</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Fibre length</td>
<td>50 mm</td>
<td>50 mm (say)</td>
</tr>
<tr>
<td>Fibre count per cm³</td>
<td>~0.024</td>
<td>0.1</td>
</tr>
<tr>
<td>Fibre bond area (as per actual fibre size)</td>
<td>200 mm²</td>
<td>130 mm²</td>
</tr>
<tr>
<td>Fibre specific surface</td>
<td>4.8 mm²</td>
<td>13 mm²</td>
</tr>
</tbody>
</table>

As we can see, an increase in fibre size largely reduces the theoretical number of fibres present in a unit volume responsible for crack bridging mechanism. Please note, the test performed were using glass fibre of length 35 mm, shown in the Figures 4-34 & 4-35 above. The above Table is computed to emphasise on the effect of cross sectional size on fibre distribution, and does not represent the fibre distribution shown in the Figures. The fibre count of glass fibre of length 35 mm used in the tests are 0.143 and whereas the fibre specific surface area remained same at 13 mm².

In general terms, an increase in the shear strength of the fibre would definitely increase the overall toughness of the composite beam. However, the failure mechanism is likely still going to be fibre fracture in the cracked area. The additional energy absorption would be coming essentially from 2 reasons:

   a) Increased energy required to rupture the fibre.

   b) Energy absorption by matrix micro-cracking and possible spalling in the region of high snubbing friction.

The increase in energy absorbed is going to be limited, and would not be at par with the fibre pullout mechanism seen in steel fibre reinforced and certain polymer fibre reinforced composites.
Chapter 5: Study of some factors affecting fibre-matrix interfacial behaviour.

5.1 Methods and experimental setup

5.1.1 Effect of matrix maturity

Regular dogbone specimen, as described in Section 4.2.1.4 were prepared. While all the other tests are done after curing the specimen for 7 days at 23°C at 95% relative humidity, additional tests were conducted at 1, 3, & 28 days.

The strength gain of the matrix was also studied for the period in the form of split tensile strength, and compressive strength of cylinders of size 75mm diameter and 150mm height.

5.1.2 Effect of temperature

To investigate the effect of temperature on fibre-matrix bond behaviour, regular dogbone specimen, as described in Section 4.2.1.4 were cast and cured for 7 days. After 7 day curing, the specimen were transferred to oven (or freezer) for 7 days. Keeping the specimen in the oven (or freezer) for 7 days gives ample time for the temperature to take significant effect on the matrix, the fibre, and the fibre-matrix interface. Each specimen was removed from the oven, just before the tests, which were conducted at room temperature. Each dogbone pullout test takes about 12-15 minutes. It is assumed that the change in temperature at the fibre-matrix interface is negligible during the time of the test. The temperatures used in this study are -20°, 20° (room temperature), 50°, 80°, 100°, and 130° Celsius.

Additionally, fibre samples were kept in the oven at 80° and 130° Celsius, and observed under an optical microscope and SEM to investigate any changes in epoxy on the surface of the fibres.
5.1.3 Effect of fibre inclination

In a fibre reinforced concrete specimen, the fibres are randomly oriented. The chances of the fibre being aligned normal to the crack surface are close to none. Most of the fibres are embedded at an inclination to the crack surface, the pullout mechanism of which is considerably different from a straight fibre pullout. This has been discussed earlier in detail while discussing the mechanism of failure in the fibre reinforced concrete beam in the Section 4.2.2.5. Tests were therefore done to investigate the behaviour fibres pullout at different angles to the crack surface.

Dogbone specimen similar to those used in the other tests were cast, except the fibres were inclined to the loading direction, instead of being aligned. The casting and testing of the regular dogbone specimen (with fibres aligned in the direction of loading, normal to the crack surface) have been discussed in detail in the Section 4.2.1.4.

![Figure 5-1 Casting of inclined fibre pullout dogbone specimen](image)

In this case however, a polystyrene foam part (packing peanut) was used to hold the fibre at the required inclination, as shown in Figure 5-1 (b). Mortar was then carefully poured into one half of
the dogbone piece, up to about half the height and vibrated to ensure the position of the fibre is as desired. Mortar was then poured to fill up one half of the dogbone, vibrated, and allowed to set overnight, as shown in Figure 5-1 (c). Next day, the polystyrene foam parts used to hold on to the fibres were removed, and the mortar was placed in 2 layers, as placed with the other half of the dogbone to ensure similar level of compaction. Figure 5-1 (d) & (e) show a closer look at the dogbone specimen cast on one side; the inclination as we can see, is maintained well.

The specimen were cured and tested at 7 days, in the same manner as regular dogbone specimen are tested, as described in the Section 4.2.1.4.

**5.1.4 Effect of loading rate**

To investigate the effect of loading rate, 3 quasi static tests and 2 dynamic tests were conducted. The quasi static tests were conducted at 0.008 mm/sec (slow quasi-static), 0.04 mm/sec (regular quasi-static) and 0.08 mm/sec (fast quasi static). These tests were performed on the same horizontally mounted machine, as described in the Section 4.2.1.4, the speed of the loading head being controlled by the motor.

Dynamic fibre pullout tests were conducted on vertically mounted machine which uses air pressure in a pressurised chamber to generate a dynamic force. The speed of the test depends on the pressure inside the chamber and to some extent on the feedback experienced from the pullout process. Dogbone shaped grips, similar to the horizontally mounted machine were used to grip the specimen in the dynamic setup as well. A high precision laser displacement meter was mounted on the grips to obtain the fibre slip. The pressure inside the chamber was set between 2 and 20 bar (200 kPa to 2000 kPa), to obtain the two dynamic loading rates. The displacement rates were maintained at ~750-800 mm/sec and ~2200-2400 mm/sec.

For both quasi static and dynamic tests, regular dogbone specimen as described in Section 4.2.1.4 were used.
5.1.5 Influence of oil coating

To investigate the bonding mechanisms, aligned and inclined fibre pullout tests were conducted after coating the fibres with oil. The form release agent, as described earlier in the Section 3.3.4 was used to coat the fibres. The fibres were dipped and allowed to rest for sufficient time, more than about 10-15 minutes, in order to coat the fibres, before preparing the single fibre pullout specimen. A locally available canola oil, was used. Oil coating forms a barrier film that inhibits the bonding of fresh concrete to fibre [181].
Only preliminary tests were done to assess the change in bond-slip performance of FRP fibres, and hence only one set of fibres, fully saturated (surface coated) were examined. Figure 5-3 below shows the oil coating process. The fibres were fully dipped in the oil, allowed for the surface to saturate them, and then placed on soft tissue kimwipes, to absorb the excess oil just before being placed in the dogbone specimen.

5.2 Results and discussion

5.2.1 Effect of matrix maturity

It is well known that the bond between the fibre and the matrix depends on the intrinsic properties of the matrix itself. A number of tests have been done to study the effect of matrix characteristics on the bond performance [89,115,182,183]. Tests were conducted at 1, 3, 7 and 28 days; the average results obtained from 10 specimen are shown in Figures 5-4, 5-5 & 5-6 and Table 5-1 below:
Table 5-1 Summary of effect of curing age on bond parameters of GFRP and CFRP single fibre pullout

<table>
<thead>
<tr>
<th></th>
<th>Instances of Fibre Fracture</th>
<th>Pullout Energy</th>
<th>Peak bond stress</th>
<th>Equivalent bond stress</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GFRP</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Day</td>
<td>0%</td>
<td>737</td>
<td>2.1</td>
<td>0.66</td>
</tr>
<tr>
<td>3 Days</td>
<td>10%</td>
<td>867</td>
<td>2.71</td>
<td>0.77</td>
</tr>
<tr>
<td>7 Days</td>
<td>30%</td>
<td>1040</td>
<td>3.3</td>
<td>0.93</td>
</tr>
<tr>
<td>28 Days</td>
<td>50%</td>
<td>895</td>
<td>2.9</td>
<td>0.80</td>
</tr>
<tr>
<td><strong>CFRP</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Days</td>
<td>0%</td>
<td>1434</td>
<td>2.5</td>
<td>1.18</td>
</tr>
<tr>
<td>3 Days</td>
<td>0%</td>
<td>1677</td>
<td>2.46</td>
<td>1.38</td>
</tr>
<tr>
<td>7 Days</td>
<td>0%</td>
<td>2022</td>
<td>3.01</td>
<td>1.66</td>
</tr>
<tr>
<td>28 Days</td>
<td>0%</td>
<td>2542</td>
<td>2.9</td>
<td>2.09</td>
</tr>
</tbody>
</table>

It can be seen from the Figures 5-4, 5-5, 5-6 and the Table 5-1, as expected, there is a general increase in bond parameters with increase curing time. The difference is more prominent in CFRP than in CFRP fibre pullout. Another observation that can be made from the graphs is that there isn’t a radical change in the peak bond stress across different curing ages. Also we can see GFRP fibres and CFRP fibres have dissimilar developments in the interfacial bond, although their surface characteristics are similar.
In the case of GFRP fibres, we can see from the graphs, there isn’t a much difference in the performance of specimen on next day of casting compared to mature specimen. We know from earlier tests, GFRP fibres are stressed to their maximum. This is evident from the fact that about 30% of GFRP single fibre pullouts after 7 days of curing show fibre fracture.
We know, that the most efficient fibre is the one in which fibre slip or fibre pullout takes place at loads just under the tensile capacity of the fibre. The peak bond stress of 3.32 MPa after 7 days of curing corresponds to an internal normal tensile stress of roughly ~550MPa, which is close to the tensile strength of ~600MPa. The interfacial bond developed in the first few days is sufficient to create normal stresses within the fibre to its capacity. Therefore, increasing the curing time to 28 days does not significantly increase the overall toughness and in fact more number of fibres undergo fracture. This can be verified by the fact that in the case of specimen tested at 28 days, about 50% of the samples underwent premature fibre fracture, as compared to 30% at 7 days, 10% at 3 days.
and none of the specimen underwent premature fibre fracture at 1 day. The development of fibre-matrix bond in this case is therefore limited by the strength of the fibre.

With CFRP fibres on the other hand, even after 28 days of curing, samples do not show any fibre fractures, thereby illustrating that an increase in intrinsic properties of the matrix improves the bond between the fibre and matrix, and increases the pullout energy. Contrary to the GFRP fibres, CFRP fibres show a steady improvement in equivalent bond strength and pullout energy, with curing age. In the case of CFRP fibres, the fibres in all scenarios do not exceed two thirds of the tensile capacity. The overall bond performance in this case is not limited by the strength of the fibre, but by the fibre-matrix interface. An improvement in the fibre-matrix interface would therefore improve the overall bond performance of the composite.

In general, the performance of the fibre does increase with an increase in curing time for the first few days, which has been seen earlier in the case of surface deformed polymeric fibres reported by Singh et al. [89]. After the first few days, the development of strength is dependent on the properties of fibre. There isn’t a major change in the peak bond stress, indicating there isn’t any major improvement in the interface. The superior performance comes essentially from the post peak region, due to the strengthening of the microstructure in close surrounding of fibre.

### 5.2.2 Effect of temperature

To study the effects of environmental conditions on the fibre-matrix bond, a series of tests were conducted. Many tests have been conducted by various researchers to assess the effect of temperature on fibre-matrix bond [89,116]. The summary of our test results (average of 10 specimen) are shown in Table 5-2 and Figures 5-8, 5-9, & 5-10 below.

At -20°C (-4°F), the overall performance of cementitious-composites is improved, largely due to the freezing of the capillary and gel pores [184] [185]. Better bond between concrete and steel reinforcement has also been reported in [186]. A similarly superior response can be seen from Figure 5-8, 5-9, & 5-10, and Table 5-2 indicating a considerable increase in bond strength and energy absorption. A greater failure resistance can be expected by the strengthening of the interface due to the freezing of capillary water near the ITZ. Due to freezing of pore water, microstructure in the close vicinity of the fibre is strengthened due to reduced porosity, resulting in a greatly
superior frictional resistance as seen from the Figures, as compared to the specimen tested at room temperature. The superior performance of fibre reinforcement at sub-zero temperatures is consistent with the similar response of steel fibre pullout, reported by Banthia et al. [115]. The third interesting observation is in the fibre itself, which depicts tensile strength much higher than those at room temperature. This can be verified by the fact that FRP composite have a higher strength and a higher modulus for up to 50°C below freezing [187], after which while the modulus continues to increase with a decrease in temperature, the strength gradually starts to decrease. The change in strength and modulus below freezing is accompanied by an increased brittleness. However, in the case of GFRP fibres, a greater percentage of specimen undergo fibre fracture at -20°C, indicating although there is an increase in fibre tensile capacity, it is not enough to overcome the high resistance to pullout caused by the frozen micro-pores in the cement matrix. In the case of CFRP fibres, the fibres are loaded to an internal normal stress of about ~750-800 MPa, which is still lower than the tensile capacity at room temperature (~1000 MPa).

Table 5-2 Summary of single fibre pullout bond parameters at different temperatures

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Instance of Fibre Fracture</th>
<th>Pullout Energy</th>
<th>Peak bond stress</th>
<th>Equivalent bond stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFRP Fibre</td>
<td>-20°C 60%</td>
<td>1723.5</td>
<td>5.94</td>
<td>1.53</td>
</tr>
<tr>
<td></td>
<td>20°C 30%</td>
<td>1049.4</td>
<td>3.32</td>
<td>0.93</td>
</tr>
<tr>
<td></td>
<td>50°C 30%</td>
<td>886.5</td>
<td>2.62</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>80°C 25%</td>
<td>1472.7</td>
<td>3.89</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td>100°C 0%</td>
<td>990</td>
<td>2.49</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>130°C 0%</td>
<td>486</td>
<td>1.92</td>
<td>0.43</td>
</tr>
<tr>
<td>CFRP Fibre</td>
<td>-20°C 0%</td>
<td>4220</td>
<td>5.09</td>
<td>3.46</td>
</tr>
<tr>
<td></td>
<td>20°C 0%</td>
<td>2106</td>
<td>3.07</td>
<td>1.73</td>
</tr>
<tr>
<td></td>
<td>50°C 0%</td>
<td>1727</td>
<td>2.29</td>
<td>1.42</td>
</tr>
<tr>
<td></td>
<td>80°C 0%</td>
<td>2547</td>
<td>4.11</td>
<td>2.09</td>
</tr>
<tr>
<td></td>
<td>100°C 0%</td>
<td>1323</td>
<td>2.57</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>130°C 0%</td>
<td>943</td>
<td>3.37</td>
<td>0.77</td>
</tr>
</tbody>
</table>
**Figure 5-8** Average bond stress-slip graphs of GFRP fibre pullout at different temperatures

**Figure 5-9** Average bond stress-slip graphs of CFRP fibre pullout at different temperatures
At elevated temperatures on the other hand, the extent of the effect of temperature is considerably less as compared to the low temperatures mentioned earlier. While at high temperatures, there is a reduction in the mechanical properties of concrete itself, there is also a considerable degradation to the fibre. The glass transition temperature of epoxy used for making the FRP fibres is 90° C. From the Figures and Table above, we can see that there are practically no differences in bond responses at 50° C and at room temperatures which was around 20° C. As we increase the temperature further to 80° C, very close to the glass transition temperature of epoxy, we see an improvement in bond performance in both the case of GFRP fibres as well as CFRP fibres. This may be because of thermal expansion of the fibre, allowing for a better adhesion with the matrix. Another reason could simply be the accelerated hydration reaction at the elevated temperature. The beneficial effect starts to diminish as we increase the temperature further. At 130° C, there is a distinct decline of bond performance. This can be explained by the deterioration of the fibre at such high temperatures, which can be observed in the Figures 5-11 & 5-12. The chemical breakdown in concrete at 130° C and loss of bound water in the matrix, near the ITZ in particular, could also add to the reduced performance of the fibre-matrix bond.
Further, to understand the effect of temperature on fibres, the fibres were observed under a microscope after subjecting to an elevated temperature of 80°C and 130°C in the oven for 7 days. The SEM images of FRP fibres kept in the oven at 80°C for 7 day clearly show in Figure 5-11, micro-cracking on the surface. Note that this is only a surface crack in the matrix, and there isn’t any separation of reinforcing fibres. This is different from the cracking seen after damage, as seen in Figure 4-14 in Section 4.2.2.2. The micro-cracks in the FRP fibres kept at 130°C in the oven, as seen in Figure 5-12 are considerably wider. The widest crack observed was 34 microns wide, observed on CFRP fibre after 130°C heat.
Another vital point to note is that the FRP fibres kept at 130°C appear flatter, and the depth of roughness is much reduced. This is consistent with the glass transition temperature of epoxy used, which was about 90°C. Once the glass transition temperature is crossed, the epoxy starts to behave like a gel, and gets moulded into a flatter shape. This flatness of the fibre further explains the drop in bond strength as discussed earlier.

It was also observed that while the fibres in the specimen subjected to a temperature of 130°C had turned black, become very soft and flimsy, the specimen subjected to -20°C had become stiff and brittle. Another observation that can be made is that cracks propagate mostly at the free edges at the ends of the fibre samples. We know, there is a large difference in coefficient of thermal expansion (CTE) of epoxy and the reinforcing fibres. While epoxy expands at about 45-65 micro-strains/°C, Glass fibre expands at about 1.5-3 (S Glass) and ~5 micro-strains/°C. Carbon fibre has near zero CTE, ranging around -0.6 micro-strains/°C. Therefore, the cracks are observed only in the direction parallel to the fibre reinforcement, as a result of restraining action of the reinforcing fibres in direction perpendicular to the reinforcements [188].

5.2.3 Effect of fibre inclination

We know that fibre orientations in fibre reinforced cementitious composites are 3-D random in nature. Therefore, the likelihood of fibres being aligned normal to the crack opening is rather low. The aligned fibre pullout is perhaps not the best representative of the crack bridging mechanism in the full scale structures. This has encouraged several researchers to study the behaviour of inclined fibre pullout from cement matrix [120–122]. The studies on effect of fibre inclination has been used by various researchers to predict the flexural behaviour of the fibre reinforced cementitious composites [123–125]. The inclination of the fibre has briefly been discussed earlier in the Section 4.2.2.5 as well. To validate the theory of fibre fracture discussed in the Section 4.2.2.5, inclined fibre pullout tests were conducted.

The pullout behaviour of inclined fibre depends not only on the fibre-matrix interface, but also on the elastic properties of the fibre. The two key elements being flexibility and ductility. Fibre reinforced polymers are very well known to be brittle materials. While the reinforcing fibres, be it glass fibre or carbon fibre, are very flexible due to their small diameter (7-15 µm). However, when
the composite is subjected to bending, the reinforcing fibres are bent about the global axis of the composite as shown in Figure 5-13. This turns the flexible fibres and flexible epoxy resin to act as an essentially rigid composite part. The Reinforcing Fibres 1 and 2 as shown in the figure are bent about the global axis of bending, which is the centre line of the FRP composite. This causes the reinforcing fibres to experience very large elastic strains, and lead to local failures as shown in the Figure 5-13.

![Figure 5-13 Sketch of reinforcing fibres inside a bent FRP fibre](image)

The flexibility of the fibre can be associated as a function of its elastic modulus (E), and moment of inertia (or second moment of area) (I).

\[
\text{Bending Rigidity} \propto E \times I
\]

\textit{Equation 5-1}

Having a flexible (low bending rigidity) fibre, the fibre would be able to slip out of the cementitious matrix at varying angles undergoing elastic deformation, as in the case of glass and carbon microfibres.

The other way for fibre pullout would be for the fibre to be ductile, in which case, the fibre would slip out of the cementitious matrix at varying angles undergoing plastic deformation, as in the case of most polymeric and steel fibres.
Because of their rectangular cross section, the fibres behave differently upon bending about two different axis of rotation due to the difference in geometry.

Fibres have long been assumed to be essentially a 1 dimensional structural element, due to their identical bending properties about all their cross sectional axes. FRP fibre however, have a large, non-negligible difference in the bending properties. Therefore, tests have been performed with the fibre being inclined about both the longitudinal planes. The Figure 5-14 below shows the alignment and orientation of specimen showing fibre pullout. The Table 5-4 and Figures 5-15, 5-16, & 5-17 below show the average performance of 10 specimen having fibre at different orientations and inclination angles.

Figure 5-14 Left: Vertically inclined fibres, Right: Horizontally inclined fibres
### Table 5-3 Summary of inclination angles

<table>
<thead>
<tr>
<th></th>
<th>Aligned</th>
<th>Low Inclination</th>
<th>Inclined Horizontally</th>
<th>Inclined Vertically</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>20°-25°</td>
<td>40°-45° about the width of fibre</td>
<td>40°-45° about the thickness of fibre</td>
<td></td>
</tr>
</tbody>
</table>

### Table 5-4 Summary of Single fibre inclined pullout

<table>
<thead>
<tr>
<th></th>
<th>Instances of Fibre Fracture</th>
<th>Pullout Energy</th>
<th>Peak bond stress</th>
<th>Equivalent bond stress</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GFRP fibre</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aligned</td>
<td>30%</td>
<td>1050</td>
<td>3.32</td>
<td>0.93</td>
</tr>
<tr>
<td>Low Inclination 20°-25°</td>
<td>30%</td>
<td>1053</td>
<td>3.19</td>
<td>0.94</td>
</tr>
<tr>
<td>Inclined Horizontally 40°-45°</td>
<td>90%</td>
<td>675</td>
<td>3.32</td>
<td>0.60</td>
</tr>
<tr>
<td>Inclined Vertically 40°-45°</td>
<td>100%</td>
<td>594</td>
<td>3.29</td>
<td>0.53</td>
</tr>
</tbody>
</table>

|                |                             |                |                  |                        |
| **CFRP fibre** |                             |                |                  |                        |
| Aligned        | 0%                          | 2106           | 3.30             | 1.73                   |
| Low Inclination 20°-25° | 0%                     | 2401           | 4.17             | 1.97                   |
| Inclined Horizontally 40°-45° | 100%            | 1219           | 3.77             | 1.00                   |
| Inclined Vertically 40°-45° | 100%            | 999            | 3.93             | 0.82                   |
Figure 5-15 Average bond stress-slip graphs of GFRP single fibre pullout at different angles of inclination

Figure 5-16 Average bond stress-slip graphs of CFRP single fibre pullout at different angles of inclination
We can see from the graphs, at low inclinations, the effect of inclination is minimal, and the fibres pullout the same manner as an aligned fibre would pullout. When the inclination is increased to about 45°, a change in failure mechanism can be seen. The fibres are undergoing premature fibre fracture. This is different from fibre fracture that we have observed in aligned fibre pullout specimen of bi-directional (woven) glass and carbon FRP fibres, which have a lower tensile strength, as discussed in Section 4.2.2.4. In the earlier case, the fibres would fracture in the early stage, when the fibre is held in the matrix by the elastic bond. However, in the unidirectional glass and carbon FRP fibres used throughout the project, when subjected to fibre pullout at an inclination, the fibre fracture is often after it has crossed the elastic limit. In other words, the fibre fractures in most cases, after initiating pullout. This is accompanied by matrix spalling in the region C, as shown in the Figure 5-18 below.

The matrix spalling is a result of a high snubbing friction at the point at which the fibre enters the matrix. Due to the angle of loading, and confinement of the cementitious matrix, the plane AB on the fibre, as sown in Figure above is subjected to large bending and shear stresses.
In the case of horizontally inclined fibres, in which the inclination is about the thickness of the fibre, the modulus of rigidity is much higher, as both, the elastic modulus and the moment of inertia are high. This fibre due to its elastic properties, is therefore expected to offer the maximum resistance to inclined fibre pullout. The vertically inclined fibres, in which the fibres are inclined about their thickness, have a lower bending stiffness, and thus are more flexible. While it is expected the fibres will slip out with lesser effort, the rough surface characteristics come into play. As a result of the rough texture, there is a high resistance to pullout, which can be seen from the results obtained. While low inclination of 20°-25° has no effect on pullout, irrespective of the orientation, when the inclination is increased to about 40°-45°, almost all the specimen, GFRP, CFRP, horizontally inclined, vertically inclined, all undergo a brittle fibre fracture, thus reducing the average energy absorbed, and equivalent bond strength.

5.2.4 Effect of loading rate

The enhanced load bearing response of concrete under high strain rates is well known to us. The increase in compressive strength, modulus of elasticity, and flexural strength are some of the key areas in consideration during seismic design of structures [189,190]. A number of studies have been carried out to assess the behaviour of fibre reinforcement under impact and dynamic loading [191], including low dynamic loading rates [115], different fibre types under dynamic loading rates [110,192], and high strength fibres [193]. An improved interfacial bond performance has been
correlated to the improvements in flexural and tensile responses at higher loading rates. Single fibre pullout tests have been conducted using the FRP fibres produced in this project to understand the effect of loading rates on bond behaviour. Apart from an increased rate of loading as in the dynamic case, a lower quasi static loading rate has also been used. The results have been shown in Table 5-6 and Figures 5-19, 5-20, & 5-21 below.

Table 5-5 Rates of loading used in the tests

<table>
<thead>
<tr>
<th>Rate</th>
<th>5x</th>
<th>10x</th>
<th>10,000x</th>
<th>30,000x</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.008 mm/s</td>
<td>0.04 mm/s</td>
<td>0.08 mm/s</td>
<td>800 mm/s</td>
<td></td>
</tr>
<tr>
<td>2,400 mm/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5-6 Summary of bond parameters of single FRP fibre pullout at different loading rates

<table>
<thead>
<tr>
<th>Loading Rate</th>
<th>Instances of Fibre Fracture</th>
<th>Pullout Energy</th>
<th>Peak Bond stress</th>
<th>Equivalent bond strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFRP fibre</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x</td>
<td>20%</td>
<td>1031</td>
<td>2.93</td>
<td>0.92</td>
</tr>
<tr>
<td>5x</td>
<td>20%</td>
<td>1049</td>
<td>3.32</td>
<td>0.93</td>
</tr>
<tr>
<td>10x</td>
<td>30%</td>
<td>1054</td>
<td>2.78</td>
<td>0.94</td>
</tr>
<tr>
<td>10,000x</td>
<td>0%</td>
<td>1539</td>
<td>5.42</td>
<td>1.37</td>
</tr>
<tr>
<td>30,000x</td>
<td>0%</td>
<td>1175</td>
<td>5.80</td>
<td>1.04</td>
</tr>
<tr>
<td>CFRP fibre</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x</td>
<td>0%</td>
<td>2725</td>
<td>2.66</td>
<td>2.24</td>
</tr>
<tr>
<td>5x</td>
<td>0%</td>
<td>2096</td>
<td>3.07</td>
<td>1.72</td>
</tr>
<tr>
<td>10x</td>
<td>0%</td>
<td>1736</td>
<td>3.10</td>
<td>1.42</td>
</tr>
<tr>
<td>10,000x</td>
<td>0%</td>
<td>2642</td>
<td>4.39</td>
<td>2.17</td>
</tr>
<tr>
<td>30,000x</td>
<td>0%</td>
<td>1219</td>
<td>4.74</td>
<td>1.00</td>
</tr>
</tbody>
</table>
The regular rate of loading used for quasi static tests, is represented in this section as speed 10x, which corresponds to 0.08 mm/second. 2 higher and 2 lower loading rates were used in the tests,
as represented in the Table 5-5 above. Because the dynamic pullout test is performed using a setup that air in a pressurized chamber to apply a sudden uniaxial load, the rate of loading is dependent on the feedback from the test specimen experienced by the loading head. Thus, even though the same pressure was maintained, there was a slight variation in loading rates, of up to about 15%. Therefore, a much higher number of specimen, around 50 for each fibre type were used to get reliable data.

![Figure 5-21 Comparison of peak bond stress and equivalent bond strength of FRP fibres at different rates of loading](image)

We can see there is a definite increase in peak bond performance in both, GFRP and CFRP fibres under dynamic loading conditions. Interestingly, the number of fibres undergoing premature fibre fracture also were reduced to zero, in spite of the normal stresses in the fibres being in the order of 900 MPa, considerably higher than the tensile capacity of the GFRP fibres of around 600 MPa under quasi static conditions. The increased tensile strength of the FRP fibres under dynamic loading conditions, is consistent with the literature [194–196]. As seen with polymeric and steel fibres [110,115,122,191–193], a superior interfacial performance is observed in the case of dynamic loading rates. This is beneficial, as a low crack opening performance is a key factor towards performance based seismic design of structures, aimed at preventing collapse. While the two dynamic loading rates demonstrate similar performances at low crack widths, we observe a drop in the total energy
absorbed (or equivalent bond strength) very high loading rates, although there are no specimen undergoing fibre fracture.

At the other end of the spectrum, when the loading rate was lowered, there was a steady increase in the equivalent bond strength (or total energy absorbed), due to an increased load carrying capacity at high crack widths in the case of CFRP fibre pullout specimen. No such change was noticed in GFRP fibre pullout, which showed identical response in all three quasi-static loading rates.

Overall, GFRP shows considerable change in peak bond stress with change in loading rates, whereas the equivalent bond strength values are similar. On the other hand, CFRP fibres show smaller, but steady increase in peak bond strength with increase in loading rate, and have a lower variation in the equivalent bond strength values.

### 5.2.5 Influence of oil coating

It is well known that in most common polymer fibre–cementitious composite systems, the interfacial chemical bond between the fibre and cementitious matrix is low, and ample resources have been spent to develop numerous techniques to improve the interface. The situation where fibre fracture has been most famously observed in the case of PVA fibres. The situation of FRP fibres is quite similar in the sense of failure mechanism, where many fibres are rupturing before pullout is initiated. Particularly in the case of inclined fibres, fibre rupture is the predominant cause of failure. The key lies in the optimization of the interface between the fibre and the cementitious matrix. Several successful attempts have been made to change the mechanism of failure of PVA fibres from brittle fibre fracture to a tough fibre pullout, improving by far the mechanical properties of the cementitious composites [86, 96, 98, 197].

The average response obtained from 10 samples for single FRP fibre pullout are shown in Table 5-7, and Figures 5-22 to Figure 5-26 below.
A similar improved response can be observed in the case of FRP fibres, under inclined pullout conditions. The three critical performance parameters, the peak bond strength, the equivalent bond stress (energy absorbed), and the fraction of fibres undergoing premature fracture have all been affected by the oil coating.

It must be noted that in this section, for inclined fibres (horizontally and vertically), the average curves represent the average of 10 to 12 replicates, irrespective of the failure mechanism. Because premature fibre fracture takes place in about 75-80% of specimen, and fibre fracture takes place after about 6mm pullout in the rest of the specimen, the average curves resemble closely to the premature failure mechanism, rather than the fibre pullout mechanism.
Figure 5-22 Average bond stress-slip graphs of coated & uncoated vertically inclined FRP fibres

Figure 5-23 Average bond stress-slip graphs of coated & uncoated horizontally inclined FRP fibres
It can be seen from Figures 5-22 to 5-26, and Table 5-7, that in the case of inclined fibres, the average equivalent bond strength (and average energy) absorbed by the coated fibres is considerably higher than the uncoated fibres. This is of particular interest, as in fibre reinforced cementitious cracked section, where the fibres are randomly oriented, almost all fibres are stressed at an angle. Both in the case of horizontally inclined, and vertically inclined pullout specimen, the equivalent bond strength has been increased by almost a factor of 2 in the case of GFRP fibres.
Almost all the specimen with oil coating resulted in a tougher fibre pullout response, instead of a brittle (and sudden) fibre fracture, thereby, serving the purpose of fibre reinforcement. The application of the particular type of oil, the reaction between the hydroxides in the concrete, to form a barrier film that inhibits the bonding of fresh concrete, should theoretically eliminate the chemical bond between the fibre and cementitious matrix. Either case, the film reduced the snubbing friction resisting the pullout of the inclined fibre. The reduction in snubbing friction also eliminated matrix splitting at the point of entry of the fibre.

The film, in addition to reducing or eliminating the chemical bond between the fibre and matrix, also reduced the frictional resistance, allowing the fibre to pull out easily. This can be seen more prominently in the case of aligned fibre pullout, where the peak bond stress, and post peak behaviour of oil coated fibres is considerable lower than that of uncoated fibres.

The optimal oil content used in the references [86,96,98,197] is in the range of 1.2% to 2% by weight of the fibres. Another key parameter to consider is the surface area of the fibres, or more precisely, the surface area to volume ratio, which is often used to assess the surface activity of fibres. A quick comparison of the geometry of PVA fibres and FRP fibres is carried out in the Table 5-8 below.
Table 5-8 Comparison of geometry & oil content of PVA fibre and FRP fibre

<table>
<thead>
<tr>
<th>Fibre type</th>
<th>PVA fibre</th>
<th>FRP fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral dimension</td>
<td>39 micron diameter</td>
<td>1.5 mm wide, 0.5 mm thick (Equivalent dia: 0.98mm)</td>
</tr>
<tr>
<td>Length</td>
<td>12 mm</td>
<td>50 mm</td>
</tr>
<tr>
<td>Surface Area</td>
<td>1.48 mm²</td>
<td>200 mm²</td>
</tr>
<tr>
<td>Volume</td>
<td>0.01433 mm³</td>
<td>37.5 mm³</td>
</tr>
<tr>
<td>Surface area to Volume ratio (Specific surface)</td>
<td>103</td>
<td>4</td>
</tr>
<tr>
<td>Aspect ratio (L/d&lt;sub&gt;eq&lt;/sub&gt;)</td>
<td>~300</td>
<td>~50</td>
</tr>
<tr>
<td>Oil Content</td>
<td>1.2% to 2% by weight</td>
<td>Surface saturated</td>
</tr>
</tbody>
</table>

The oil content in the coated PVA fibres is considerably less than the single attempt made here to coat FRP fibres, which further magnifies considering the vast differences in surface area to volume ratios of the two fibres. The performance of FRP fibres in these tests may be regarded as the worst, in regards to the excess oil on the surface of the fibres; and these fibres still perform better than the uncoated fibres at inclined fibre pullout tests.

These tests are a proof of concept to demonstrate the feasibility of oil coating the FRP fibres to improve mechanism and performance of the fibres, and possibly improve the overall performance of FRP fibre reinforced cementitious materials.
Chapter 6: Performance of fibre under sustained loading & deteriorating conditions

6.1 Method and experimental setup

6.1.1 Relaxation of FRP fibre

Once deformed beyond matrix cracking, the loads carried by the fibres bridging the matrix relax with time. We understand the relaxation and creep behaviour of the fibre and the matrix individually, but in a composite, the relaxation is largely at the interface. To assess the relaxation of the fibre-matrix interface, a series of tests were conducted at room temperature and at an elevated temperature of 60°C.

To investigate the relaxation of the fibre, a dogbone specimen, moist cured for 7-10 days was used. The tests were done in the horizontally mounted screw driven electric motor powered dogbone pullout machine, the same one used in earlier single fibre pullout tests. The specimen is subjected to axial tensile loading, till the load reached about 250 N (~55-60 lbs). This is about 70-80% of the average peak pullout load. Once this load is reached, the motor was immediately stopped. The fibre slip was sustained, while the fibre carried a load about 70-80% of its peak load. The specimen was kept at this stage for about 3 days, giving ample time for the specimen to relax. The motor is then switched on again, to observe a trend, if any, in the post relaxation performance of the fibre-matrix bond. With time, the fibre tends to lose the load transferring ability, due to the relaxation in the fibre, and the fibre-matrix interface. The drop in load carried by the dogbone specimen, at a sustained slip is recorded, and relaxation graph is plotted.

It may be noted that unavoidably there is also machine relaxation in the process, which is added on to the fibre-matrix bond relaxation. Therefore the data acquired by the data acquisition system is a combination of the relaxation of fibre-matrix bond and the relaxation of the machine [198,199]. To isolate the machine relaxation, the test is conducted using a rigid dogbone shaped mortar specimen at loads identical to the ones used in fibre dogbone specimen. Assuming that the relaxation of machine and relaxation of fibre-matrix bond are independent of each other, at a
given load, the total relaxation measured would be a simple summation of relaxation of fibre-matrix bond and relaxation of the machine.

Relaxation of deformed polypropylene fibres were also tested as a comparison to the FRP fibres.

6.1.2 Durability studies

For assessing the durability of the FRP samples, a series of tests were performed after subjecting it to accelerated deterioration. Samples were kept immersed in a solution of high pH of ~12.4 at an elevated temperature of 50 degrees Celsius. A supersaturated solution of limewater was used as a high pH solution, maintaining a pH of ~12.4, covered with plastic wrap, to seal any loss in moisture, kept in the oven at 50˚ Celsius. The fibres were allowed to condition, and were tested at 7 and 28 days.

6.1.2.1 Tensile test after subjecting to accelerated deterioration

The specimen used were similar as that discussed in Section 4.2.1.3. Once the samples were tabbed at the ends and ready for testing, they were immersed in high pH limewater in a tray, sealed off using plastic wrap and kept in the oven at 50˚ Celsius. The specimen are removed after 7 or 28 days of conditioning, wiped dry and tested.

The Instron machine with vertical arrangement of capacity 250kN, same as one used in Section 4.2.1.3 was used. The test was conducted in accordance to the standard ASTM D3039 with rate of loading, as discussed earlier, at 2mm/minute.

6.1.2.2 Single fibre pullout after subjecting to accelerated deterioration

The fibres were subjected to accelerated deterioration by immersion in high pH limewater in a tray kept sealed in the oven at 50˚ Celsius, as discussed earlier. The fibres were allowed to deteriorate for 7, and 28 days, after which they were removed from the immersed high pH solution and dried using paper towels. The fibres were kept in the oven for another 2 hours to ensure they were
surface dry, similar to other fibres not subjected to deterioration. This was done so that there is no excess surface water on the FRP fibre, which could influence the fibre-matrix interaction and behaviour. In the results section (section 6.2.2), these fibres are referred to as “GFRP 7 Day-Fibre” meaning GFRP as fibre type, conditioned for 7 days as fibre specimens.

In addition to conditioning the fibres, strips of FRP panels were also subjected to accelerated deterioration in identical conditions as described. In the results section (Section 6.2.2), these fibres are referred to as “GFRP-7Day-Panel” meaning GFRP type of fibre, conditioned for 7 days as a panel sized specimen. After 7 days, the strips were towel dried, and cut to fibre sized specimen. These tests were conducted to assess the influence of surface deterioration and edge deterioration.

The FRP specimen conditioned as fibres, and FRP specimen conditioned as strips, were also used for identical single fibre pullout tests. Dogbone specimen similar to the ones discussed in Section 4.2.1.4 were cast and tested after 7 days of moist curing. The same test setup with the same settings and rate of loading, similar to the rest of the tests, as discussed in Section 4.2.1.4 was used to conduct the tests.

### 6.1.2.3 SEM-EDX image analysis of accelerated deterioration

The SEM-EDX image analysis was done using the same machine as described in Section 4.2.1.2, using the same settings used for SEM-EDX image analysis for characterization. The setting has already been described in the same Section 4.2.1.2.

### 6.2 Results and discussion

#### 6.2.1 Studies of relaxation of FRP fibre

The relaxation behaviour of single FRP fibre reinforced composites at room temperature are shown below in Figures 6-1 & 6-2. The tests were performed on a strain controlled screw driven machine. The fibres, PP, GFRP, and CFRP were all strained till the load in the specimen reached to 50 ±5lbs, at which time strain was kept constant and sustained for the next 3 days. The Figure 6-1 clearly shows the relaxation of polypropylene fibres, FRP fibres, and the relaxation of the machine.
The machine relaxation was subtracted from the total relaxation to get the net relaxation of the fibre relaxation specimen, and is shown in Figure 6-2. It can be seen from the Figure 6-2, that the loss of load carrying capacity is the highest in polypropylene fibres, and least in CFRP fibres. The
FRP fibres show hardly any relaxation or loss in transmissibility of load, as compared to the polypropylene fibres, which lose more than half of their capacity in the first few hours.

Polypropylene fibre, even though crimped, have a smooth surface. First of all, the chemical bond in polypropylene fibres is rather low, and most resistance to pullout comes from the bearing areas of the crimped geometry. Secondly, once pullout is initiated, due to the smooth surface of the fibre, the frictional resistance to pullout is low. Therefore, when the high strains are sustained for long periods, slippage occurs which enhances relaxation of the fibre. In the case of FRP fibres, the required interfacial stresses are developed before any fibre pullout has taken place. The micro-bearing anchorage holds the fibres in place, preventing fibre slippage and minimizing any relaxation at the interface. If the micro-bearing anchorage completely prevents any relaxation at the fibre-matrix interface, the relaxation of the setup is likely coming entirely from relaxation of the fibre. The relatively high tensile modulus of FRP fibres further supports continuous load transmission extended periods after crack opening.

6.2.2 Durability studies

6.2.2.1 Tensile test after subjecting to accelerated deterioration

The most fundamental property to be investigated for durability of the fibre is with the test to assess the loss in tensile strength of the FRP material after accelerated deterioration. The average response of 10-12 specimen of tensile tests of FRP strips after subjecting to accelerated deterioration are shown below in Figures 6-3 and 6-4.

*Table 6-1 Summary of tensile tests conducted after accelerated deterioration*

<table>
<thead>
<tr>
<th></th>
<th>Average Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regular</td>
</tr>
<tr>
<td>GFRP</td>
<td>578</td>
</tr>
<tr>
<td>CFRP</td>
<td>955</td>
</tr>
</tbody>
</table>
We can see from the Figures, there is a definite decrease in strength in the case of GFRP fibres after accelerated deterioration. After 7 days of accelerated deterioration, there is about a 20% drop in tensile strength, which increases to 33% after 28 days of accelerated deterioration. Glass fibre is known to be susceptible to moisture, hydroxides, [62,153,200,201] and seawater [202]. The drop
in strength is therefore in GFRP strips is not surprising. CFRP fibres on the other hand, show no change in tensile properties after deterioration.

The FRP material conditioned to accelerated deterioration at a high pH of 12.4 kept at an elevated temperature of 50°C; conditions which the fibres will likely not experience during their service life. However, further tests are required to assess long term durability of the fibres.

**6.2.2.2 Single fibre Pullout after subjecting to accelerated deterioration**

In the previous section, we have seen the influence of accelerated deterioration on the intrinsic elastic properties of FRP composites. The interfacial bond behaviour between the FRP fibre and the cementitious matrix depends on the surface characteristics of the fibre, apart from the tensile behaviour of the fibre. To assess the surface modification or surface deterioration due to an alkaline attack on epoxy of the FRP composite, single fibre pullout tests were conducted. The average of pullout response of 10 replicates the results are shown in Table 6-2, Figures 6-5, 6-6, & 6-7.

*Table 6-2 Summary of single fibre pullout tests of FRP fibre after accelerated deterioration*

<table>
<thead>
<tr>
<th></th>
<th>Fibre Fracture</th>
<th>Pullout Energy</th>
<th>Peak bond stress</th>
<th>Equivalent bond stress</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GFRP</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regular</td>
<td>30%</td>
<td>1053</td>
<td>3.32</td>
<td>0.94</td>
</tr>
<tr>
<td>7 Day-Panel</td>
<td>40%</td>
<td>1224</td>
<td>2.23</td>
<td>1.09</td>
</tr>
<tr>
<td>7 Day-Fibre</td>
<td>40%</td>
<td>1269</td>
<td>3.76</td>
<td>1.13</td>
</tr>
<tr>
<td>28 Day-Fibre</td>
<td>10%</td>
<td>823.5</td>
<td>3.38</td>
<td>0.73</td>
</tr>
<tr>
<td><strong>CFRP</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regular</td>
<td>0%</td>
<td>2096</td>
<td>3.07</td>
<td>1.73</td>
</tr>
<tr>
<td>7 Day-Panel</td>
<td>0%</td>
<td>1706</td>
<td>2.28</td>
<td>1.40</td>
</tr>
<tr>
<td>7 Day-Fibre</td>
<td>0%</td>
<td>1677</td>
<td>2.41</td>
<td>1.38</td>
</tr>
<tr>
<td>28 Day-Fibre</td>
<td>0%</td>
<td>1521</td>
<td>2.58</td>
<td>1.25</td>
</tr>
</tbody>
</table>
Figure 6-5 Average bond stress-slip graphs of GFRP fibre pullout after different stages of accelerated deterioration

Figure 6-6 Average bond stress-slip graphs of CFRP fibre pullout after different stages of accelerated deterioration
Polymer fibres in concrete have been known to degrade due to the highly alkaline nature of matrix in the cementitious composites [55,56,75,76,203–208]. The polymers are often an attack of hydrolysis, in which, the hydroxyl ions attack the functional groups of the polymer chain, and initiates a reaction.

We can see from Figures 6-5, 6-6, & 6-7, and Table 6-2 that GFRP fibres show variation in peak bond stress and equivalent bond strength with different degrees of deterioration. While it is clear from the previous section, the performance of the FRP itself after 28 days of accelerated deterioration is reduced, fibre-matrix interfacial performance after 7 days of conditioning is not much different from the unconditioned specimen. Interestingly, only about 10% of the specimen of GFRP fibres conditioned to 28 days underwent fibre fracture, compared to 30% of the specimen of unconditioned GFRP fibres. In spite of a lower tensile capacity, as seen in earlier section, fewer fibres undergoing fracture indicates that the bond between the FRP fibre and cementitious matrix is inferior. The normal tensile stresses developed inside the fibre due to the resistance to pullout is lesser than the lowered tensile capacity.

In the case of CFRP fibres, there is a small decrease in peak bond stress, as well as equivalent bond strength. This drop however, is small, considering the harsh conditions that the fibres were subjected to. Statistically speaking, the drop in bond behaviour of CFRP fibres is insignificant.
In both, CFRP and GFRP fibres, pullout response of both types, fibre sized specimen, and panel specimen, after 7 days of identical deterioration show similar equivalent bond strength (energy absorbed). Therefore, assumptions of deterioration at the edge of the FRP fibres, where glass and carbon reinforcing fibres are exposed, are not confirmed.

6.2.2.3 SEM-EDX image analysis of accelerated deterioration

The fibre specimen, after accelerated deterioration of 28 days were observed under the SEM microscope to examine any morphological changes on the surface of the fibres. To represent the true nature of the fibres after deterioration, the specimen were only cleaned using a stirrer in a water bath for about 20 minutes, in order to remove the particles that are lightly adhered to the surface of fibres. The fibres were not cleaned in an ultrasonic water bath, to make sure we are not missing any damaged particles from the fibre.

The SEM images, as seen in Figures 6-8 to Figure 6-11, show the surface in the middle of the fibre.

Figure 6-8 images of Unconditioned (Left) and Conditioned (Right) CFRP fibres at 200x magnification
Figure 6-10 SEM images of Unconditioned (Left) and Conditioned (Right) GFRP fibres at 200x magnification
In Figure 6-8, & Figure 6-10, FRP fibres at low magnification (200x), we see many adhered particles which appear as white amorphous particles or white fluffy balls. With EDX confirmation, it was determined these are lime (calcium oxide/calcium hydroxide) particles adhered to the surface of the fibres.

A higher magnification (2000x), as seen in Figures 6-9 & 6-11, show no change in microstructure or morphology. The particle seen in Figure 6-9 (left), is a flake of pure carbon that is attached to the fibre, as confirmed by the EDX spot analysis. The white amorphous particles on the conditioned fibres are adhered particles of lime, the same as seen at lower magnification. In the unconditioned GFRP fibre seen at high magnification (in Figure 6-11: left), notice some contaminants which appear as white spots, adhered to the surface around and under the flake of epoxy. The surface of the same fibre shows a kind of sheet adhered to it, EDX analysis on which showed the chemical composition identical to the chemical composition of epoxy.

Overall, the SEM images show some lime particles adhered to all the conditioned fibres, but do not show any effects of alkaline attack on the surface.
Chapter 7: Conclusions and Recommendations for Future Work

7.1 Conclusions

The purpose of this study was to develop a composite macro-fibre based on FRP, which is able to provide structural and non-structural benefits by an effective crack bridging mechanism. GFRP and CFRP fibres were successfully made by cutting the FRP panels produced using vacuum infusion technique to the required size. Different compositions leading to strengths ranging from 195MPa to 950 MPa were produced. Single fibre pullout tests were conducted to investigate the FRP fibre-matrix interfacial bond performance. The effects of matrix maturity, temperature, angle of fibre inclination, rate of loading and oil-coating on the fibre-matrix interfacial bond performance has also been investigated. Post-crack load-carrying ability of the fibre reinforced composite has been studied with fibre relaxation tests. Finally, to assess the durability of the FRP fibres, change in tensile strength and bond strength after accelerated deterioration has been examined.

The findings of the project have been accomplishing and encouraging.

a) A composite FRP can be effectively made using simple and readily available ingredients. While in the laboratory, an effective volume fraction of fibre of up to 30% leading to a tensile strength in comparison to steel was achieved, the fibres can be mass produced with superior uniform quality.

b) The single fibre pull-out performance of FRP fibres has been superior to commercially available straight fibres, and matches up with widely used deformed fibres. The unique texture contributes with a micro-bearing action in the pre-pullout stage. The same texture contributes to improving the frictional resistance during fibre pullout.

c) The superior single fibre pullout was been successfully translated to flexural response. The inability to initiate fibre pullout at the cracked section leads to fibre fractures resulting in a low flexural response. To confirm the response of fibre at loading other than the alignment of fibre, further investigation of inclined fibre pullout tests were done. We observe brittle
fibre fracture in most specimen, which explains the lacklustre flexural post-crack response. The fibre fracture may be attributed to a combination of a low shear strength, poor flexibility and ductility, and a high snubbing friction owing to the rough texture.

d) The premature fracture of the fibre before pullout can be rectified by interface modification between the fibre and the cementitious matrix. A coating of oil has been used to successfully change the mechanism from a brittle fibre fracture to a tough, energy absorbing fibre pullout. The overall energy absorption of oil-coated specimen in spite of losing most part of chemical bond between fibre and matrix is still better than non-coated specimen subjected to an inclined pullout.

e) The FRP fibre pullout is largely unaffected by changes in temperature. The performance at low temperatures of -20°C is superior than at room temperature, however, GFRP fibres showed a brittle fibre fracture in many specimen. On the other end of the spectrum, the fibres performed well till 100°C, after which there was a drop in bond performance. The SEM and OM images also showed slight deterioration near the edge on the surface of fibres after 7 days exposure at 130°C.

f) At dynamic rates of loading, interestingly, not only does resistance to pullout increase by up to 2 times, the tensile capacity of the fibre itself increases. The performance of the fibre and its cementitious composites may be expected to better under dynamic loading as compared to quasi static loading.

g) As a result of mechanical anchorage and a relatively high tensile modulus, the relaxation of the fibre is a minimum and about 3 times lesser than that of a deformed polypropylene fibre. This opens up applications in the mining industry.

h) High resistance to deterioration in harsh alkaline environments, and performance independent of temperatures well above 20°C gives the FRP fibres a clear advantages over other commercially available polymeric fibres. The susceptibility of steel fibres to corrosion leaves a void in applicability of FRC in many scenarios such marine environments. The FRP fibres are ideal in such cases.
The fibre places itself in between steel and other polymer fibres in terms of tensile properties, and along with one of a kind surface texture, the fibre will hold an exclusive position in the market. The invention and commercialization of such fibres provides an excellent business opportunity.

7.2 Recommendation for future work

The FRP fibre has performed above expectations is majority of the criteria investigated but needs additional work. The advancements made during the project in the last 2 years have been fulfilling and promising. The project has laid the foundation for a novel application for FRP composites in civil engineering, and has paved the way for innovation in developing unique, commercially viable and technologically pioneering FRP fibres.

Some of the recommendations for future work are listed below:

a) Pultruded FRP fibre

The Pultrusion manufacturing technique may be able to solve more than one problem that we have encountered in this study.

The concern of low flexibility of the FRP fibre can to some extent be alleviated using the Pultrusion technique for manufacturing the fibre. The minimal size to which FRP fibres could be made using the vacuum infusion technique have been made in this study, which is still quite large. The geometry of the fibre can be optimized using the Pultrusion technique.

A higher volume fraction of fibre can be employed using the Pultrusion technique, which would lead to a more compact, highly uniform, superior quality fibre.

The third advantage of Pultrusion is in optimization of the fibre-matrix interface. The rough texture hinders fibre pullout, leading to a brittle fracture, especially in the case of inclined fibre pullout.

b) Interface optimization

The bond between the FRP fibre and cementitious matrix as we have seen is exceptional. In the case of GFRP fibres especially, the high resistance to pullout at times leads to brittle
fracture. We have seen in most inclined pullout cases, fibre fracture is the predominant mode of failure. This problem can be mitigated by optimizing the interface to suit the capacity of the fibres. Oil-coating has proven to be an effective measure in optimizing the interface. We have seen many such cases with PVA fibres, where a brittle fibre fracture type of failure has been successfully changed to tough energy absorbing ductile mechanism as seen in ECC. The preliminary studies in this project have shown promising results with oil-coating. A slip hardening response may be obtained by an optimized interface.

c) Alternate materials

As we know, carbon fibre is one among the most expensive high performance fibres. A search for a more sustainable and economically viable alternative must be in place. Glass fibre, which has been tried out in this project has shown promising results.

A polyester resin matrix would change the surface interaction between the FRP fibre and cementitious matrix, whilst reducing the overall cost. A polyester resin, which is hydrophobic in nature could very well solve the issue with having too strong a bond with cementitious matrix.

d) Thermoplastic resin FRP fibre

Like the polyester resins, other thermoplastic resin systems such as polypropylene, polyethylene terephthalate, polycarbonate, etc. are all hydrophobic and will modify the interfacial interaction between FRP fibre and cementitious matrix. However, these thermoplastic resins require special manufacturing techniques, and hence are often limited to factories. Possibly, the ductile elasto-plastic nature of these thermoplastic resins may be able to impart some amount of ductility onto the FRP fibre.
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