FLEXURAL RESPONSE OF HYBRID FIBER REINFORCED CEMENTITIOUS COMPOSITES

by

SAYED MOHAMAD SOLEIMANI

B.Sc. (Civil Engineering), Sharif University of Technology, Tehran, IRAN, 1991

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Sayed Mohamad Soleimani

Department of Civil Engineering

The University of British Columbia
Vancouver, Canada

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ABSTRACT

In spite of the brittleness of concrete, it is a widely used material in construction. In Fiber Reinforced Concrete (FRC), short and randomly distributed fibers abate the nucleation and growth of matrix cracks and bridge them after their creation. This reduces brittleness, and provides sources of strength gain, toughness and ductility. Fibers as reinforcement can be effective in arresting cracks at both macro and micro levels. Most of the FRC used today involves use of a single fiber type. This implies that a given fiber can provide reinforcement only at one level and within a limited range of strain. For an optimal response, therefore, different types of fibers must be combined to make Hybrid Fiber Reinforced Concrete (HyFRC).

The scope of this research was to investigate the flexural response of HyFRC. Up to three different types of fibers were combined in each mix. Hybridization was amongst steel/polypropylene macro fibers and carbon/polypropylene/steel micro fibers. Compressive strength of the matrix was around 55-60 MPa.

The main purpose of this research was to investigate the influence of various hybrid fiber combinations on fresh properties of concrete (i.e. workability) and on mechanical properties including compressive strength and toughness in bending. In this study, 14 different mixes containing only one type of fiber, 12 different mixes containing two kinds of fibers and 5 different mixes containing three kinds of fibers were made as well as plain concrete for reference (32 different mixes in total). For each mixture, six 100x100x350 mm prismatic specimens and six 100x200 mm cylinders were made and tested.

Measuring the VeBe time for each and every mix assessed the workability of FRC/HyFRC. Cylindrical specimens were used to determine the compressive strengths. Beam specimens were used to obtain the load versus deflection curves in third point loading to calculate their flexural toughness and first-crack strengths. Finally, synergistic effects between fibers were observed in the hybrids with enhanced performance of the material over a wider range of deflections.

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to my wife, Nahid

Sometimes I wake up
in the middle of the night
shivering from fright
feeling empty feeling nothing
because I think about how it would be
if you weren't here
And then I wonder ...
if you really know how very much you mean to me
how incredible I think you are
how you are a part of all my emotions
how you are the deepest meaning in my life
Please always know that ...
I love you more than anything else in the world

I will always consider each day with you special
regardless of what events occur in our lives
I will make sure that our relationship flourishes
as I will always love and respect you

Thank you from the bottom of my heart

1. INTRODUCTION

1.1. Fiber Reinforced Concrete (FRC):

Concrete is a brittle material that is also weak in tension. Reinforcing concrete by conventional continuous steel rebars can solve weakness in tension, but concrete remains a brittle material with a very low strain capacity. Reinforcing concrete with randomly distributed fibers of modern materials can improve the ductility and durability. Short randomly distributed fibers abate the nucleation and growth of matrix cracks, and bridge them after their creation thereby providing sources of strength gain, toughness and ductility.

Fiber Reinforced Concrete (FRC) is a concrete made primarily of hydraulic cements, aggregates, and discrete reinforcing fibers. Fibers suitable for reinforcing concrete have been produced from steel, glass, and organic polymers. Naturally occurring asbestos fibers and vegetable fibers, such as sisal and jute, are also used for reinforcement. The concrete matrices may be mortars, normally proportioned mixes, or specifically formulated mixes for a particular application.

The use of fibers to reinforce brittle materials goes back to Biblical times when straw was used in manufacturing of brick. A pueblo house built around 1540 is believed to be the oldest house in the U.S. and is constructed of sun-baked adobe (blocks) reinforced with straw. In more recent times, large-scale commercial use of asbestos fibers in a cement paste matrix began with the invention of the Hatschek process in 1898. This is a wet process in which the fiber is added to a mixture of cement and water and then moulded, cured or hardened to form the finished product. Because it is a wet manufacturing process, the application of basic engineering controls and safe work practices can ensure a safe working environment for workers. Asbestos cement construction products have been widely used throughout the world. However, primarily due to health hazards associated with asbestos fibers, alternate fiber types were introduced throughout the 1960's and 1970's.

In modern times, a wide range of engineering materials (including ceramics, plastics, cement, and gypsum products) incorporate fibers to enhance composite properties. The enhanced properties include *tensile strength, compressive strength,* *elastic modulus, crack resistance, crack control, durability, fatigue life, resistance to impact and abrasion, shrinkage, expansion, thermal characteristics, and fire resistance.*

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

Use of **glass** fibers in concrete was first attempted in the USSR in the late 1950's. It was quickly established that ordinary glass fiber, such as borosilicate E-glass fibers, are attacked and eventually destroyed by the alkalies in the cement paste. Considerable development work was directed towards producing a form of alkali-resistant glass fibers containing zirconia. This led to a considerable number of commercial products. The large use of glass fiber reinforced concrete in the U.S. and Canada is currently for the production of exterior architectural cladding panels.

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

Research on **carbon** fiber reinforced concrete was started in the early 1970's. At the beginning expensive PAN (polyacrylonitrile)-based continuous carbon fibers were used. In the 1980's, inexpensive low-modulus carbon fibers were made from coal and petroleum pitches, called Pitch-based carbon fibers. One of the first successful uses of carbon fibers in construction was the Al-Shaheed monument in Baghdad, Iraq, where CFRC was used for 10,000 m^2 of lightweight cladding tile panels.

Steel fibers, glass fibers, carbon fibers and synthetic (mostly polypropylene) fibers are the main kinds of fibers used today. They can be added in a variety of ways. They can be added to ready mix concrete in a truck and cast in a conventional manner for bulk applications such as highway pavements, slabs, and foundations. They can also be sprayed along with mortar slurry to form thin pre-cast panels. There have also been new developments in fiber reinforced cement systems and research on properties and behavior of cement systems reinforced with carbon, alumina, polyamide, polyethylene, and polyvinyl alcohol fibers.

From all the above discussion, one can conclude that nowadays we have better understanding of fiber-matrix interactions. But, so far, most fiber reinforced concrete used in practice contains only one type of fiber. We know that failure in concrete is a gradual, multi-scale process. The pre-existing cracks in concrete are of the order of microns. Under an applied load, these grow and eventually join together to form macro cracks. A macro-crack propagates stably until it attains conditions of unstable propagation and a rapid fracture is precipitated. The gradual and multi-scale nature of fracture in concrete implies that a given fiber can provide reinforcement only at one level and within a limited range of strains. For an optimal response, therefore, different types of fibers must be combined. This was the major reason that has encouraged researchers over the past 25 years to work on Hybrid Fiber Reinforced Concrete (HyFRC).

1.2. Hybrid Fiber Reinforced Concrete (HyFRC):

Fibers, depending on their size and volume fraction, can be effective at both micro and macro–levels of cracking. Accordingly, fibers used for concrete reinforcement are divided into two broad categories: macro and micro.

Macro-fibers are large fibers, 30-60 mm in length and between 0.5 to 1.0 mm in diameter. Micro-fibers, on the other hand, are fine fibers typically 5-10 mm long and 20 microns in diameter. With their fine size, micro-fibers reinforce the paste and the mortar phases and delay crack coalescence thereby increasing the apparent tensile strength of the composite. Macro-fibers, on the other hand, bridge a fully formed macro-crack and prevent its growth and widening thereby imparting a higher energy dissipation capacity beyond matrix cracking. As was mentioned earlier, for an optimal response, different types of fibers must be combined. This new composite, Hybrid Fiber Reinforced Concrete (HyFRC), can be produced by the following three combinations of fibers [1]:

1. **Hybrids based on fiber constitutive response:** One type of fiber being stronger and stiffer provides adequate first crack strength and ultimate

strength, while the second type of fiber, being relatively flexible leads to improved toughness and strain capacity in the post-crack zone.

2. **Hybrids based on fiber dimensions:** One type of fiber is smaller, so that it bridges micro-cracks and therefore controls their growth. This leads to a higher tensile strength of the composite. The second fiber is larger and is intended to arrest the propagation of macro-cracks and therefore brings about a substantial improvement in the fracture toughness of the composite.

3. **Hybrids based on fiber function:** One type of fiber is intended to improve the fresh and early age properties such as ease of production and plastic shrinkage, while the second fiber leads to improved mechanical properties.

2. LITERATURE SURVEY

Considerable research, development, and applications of FRC are taking place throughout the world. Industry interest and potential business opportunities are evidenced by continued new developments in fiber reinforced construction materials. These new developments are reported in numerous research papers, international symposia, and state-of-the-art reports issued by professional societies. This chapter is a review of some of these papers. Although the idea of hybrids has not been investigated extensively, the concept dates back 27 years when Walton and Majumdar showed the benefits of producing satisfactory composites by using a mixture of organic and inorganic fibers as reinforcement [2].

2.1. Steel Fiber Reinforced Concrete (SFRC):

Properties of freshly mixed SRFC are influenced by fiber geometry and aspect ratio, fiber volume fraction, mix proportions and the fiber-matrix interfacial bond characteristics. Because of fibers' presence in the mix, the degree of compaction influences the compressive strength and other hardened material properties much more than it does for plain concrete. The addition of steel fibers usually reduces the measured slump of the composite as compared to a plain concrete. In most SFRC applications mechanical vibration is required; therefore, workability of SFRC can be assessed by measuring the Vebe time, as described in the British Standards Institution - Standard BS 1881 [3], instead of conventional slump measurement. A study has shown that loss of slump with time for SFRC and plain concrete are similar [4]. Another important thing that must be considered is the "balling" of fibers, which from a practical point of view must be avoided. One can easily say that the greater the aspect ratio of the fibers, the higher the probability of having fiber balling. On the other hand, short fibers with relatively low aspect ratio are not able to interlock and can easily be separated by vibration. Long and thin fibers with a relatively high aspect ratio tend to interlock to form a mat or a ball and it is not easy to separate them by vibration. Ironically, for mechanical improvement in hardened concrete, a high aspect ratio fiber is more desirable, therefore different factors must be considered in designing fibers and mixing them into FRC. The aspect ratio of the fibers, the volume fraction, the fiber shape, the method of introducing fibers into the mixer and the maximum size and overall gradation of the aggregate used in the mix all play important roles. Having larger maximum size aggregate and higher fiber aspect ratio reduces the maximum volume fraction of fibers that can be added to the mix without a tendency to ball.

Dispersion of fibers throughout the mix is very important and we need a uniform dispersion, of course. The following sequences can be used:

1. Fibers can be added to the truck mixer after all other ingredients have been mixed. It is better to add the fibers when the mixer is rotating at full speed. Rate of adding the fibers is important and 100 lbs per minute is a reasonable rate.
2. Fibers can be added to the aggregate stream in the batch plant before the aggregate is added to the mixer. The fibers should be spread out along the belt to prevent bunching of fibers.
3. Fibers can be added on the top of the aggregates after they are weighed in the batcher. The can be added manually or by using a conveyor.

In compression, previous research has shown that the ultimate strength is only slightly affected by the presence of fibers, with observed increases ranging from 0 to 15% for up to 1.5% by volume of fibers [5, 6].

Flexural strength of SFRC increases with increasing fiber volume, and this increase is greater than the increases in either tension or compression. While, in direct tension, 30 to 40% increases have been reported for an addition of 1.5% by volume of steel fibers in mortar and concrete [7, 8], some researchers have reported a 50 to 70% increase in flexural strength due to fiber addition [9].

The preferred technique for determining toughness of FRC is flexural loading. This reflects the stress condition in the majority of applications such as paving, flooring, and shotcrete lining. Quasi-static flexure is also preferable for determining toughness because the results are lower bound values, safe for use in design. Under these flexure conditions, toughness can be demonstrated qualitatively by observing the flexural behavior of simply supported beams. A concrete beam containing steel fibers suffers damage by gradual development of single or multiple cracks with increasing deflection, but retains some degree of structural integrity and post-crack resistance even at a considerable deflection. A similar beam without steel fibers fails suddenly at a small deflection by separation into two pieces.

Zhao et al. divided the methods for determining toughness into four groups [10]:

1. Energy method,
2. Strength method,
3. Energy ratio method,
4. Multi-characteristic point method.

Although toughness is accepted as a good way of measuring the energy absorption capacity of a material, there are disagreements on how it must be measured and used. The influence of specimen size, loading configuration and type of fiber on the mechanical properties of FRC are major concerns. Static third-point bending is used in all of the popularly used tests for toughness measurements. In these methods, the area under the load-deflection response has been used to compute the energy absorption capacity of the specimen. Gopalaratnam et al. mentioned four important factors that can influence the load-deflection response of the specimen [11]:

1. Specimen size, depth of the specimen and its span are the most important parameters;
2. Loading configuration, for example midpoint versus third-point loading;
3. Control of different parameters during the test such as load-point deflection and load; and
4. Rate of loading.

One of the most important conclusions from their work [11] was the method of measuring the specimen deflection, which is used in this research work. The best way to do this is the measurement of the beam center point-deflection in relation to the neutral axis of the beam at its supports.

The two widely used standard test methods, ASTM C 1018 [12] and JSCE Standard SF-4 [13], are based on determining the energy required to deflect and fracture beam specimens under four-point loading. Both methods have caused a great deal of confusion. Banthia and Trottier proposed an alternative method of analyzing the load-deflection curves by calculating post-crack strength values at various deflections [14].

These methods will be discussed in detail later on. Using the best and most meaningful method to analyze the data of this study is important.

Different types of steel fibers were investigated and results can be found in different papers. ASTM C 1018 and JSCE SF-4 were usually used in these reports to show the toughness characteristics of SFRC. As mentioned earlier, because of many concerns with these two methods, their use here has been avoided. In general, one can say that steel fibers, especially the deformed ones, are the best among all fiber types, at least under static loading conditions.

2.2. Polypropylene Fiber Reinforced Concrete (PFRC):

Like other synthetic fibers, fiber volume, fiber geometry, production method and composition of the matrix affect the properties of PFRC. Test data are available for PFRC at different fiber volume percentages. As for other types of FRC, VeBe time or inverted slump cone time are preferred methods to express workability of the freshly mixed PFRC. Satisfactory workability can be maintained by using an appropriate amount of high-range water reducer (superplasticizer) to keep strength and water to cement ratio constant. This will be mandatory when micro fibers at high dosages (i.e. 2.0% by volume) are used.

In compression tests, PFRC cylinders fail in a ductile mode compared to plain concrete cylinders [15]. This is more noticeable when the strength of the concrete is high; in this case plain concrete cylinders shatter into pieces because they are not able to absorb the energy released by the test machine at failure. On the other hand, PFRC cylinders, like most other kinds of FRC cylinders, continue to sustain load and tolerate large deformations without any shattering [15]. High quantities of fiber (i.e. 2.0% by volume) can reduce the workability and therefore produce more entrapped air in the concrete and lower its unit weight. This reduces the compressive strength [16].

First-crack strength and modulus of rupture are not usually increased by adding polypropylene fibers. Some researchers reported that for 1.0, 1.5 and 2.0% by volume of fibrillated polypropylene in concrete, the compressive strength and the flexural strength were lower than those for corresponding plain concrete [17].

Flexural toughness and post crack behavior of PFRC have been reported for different fiber volumes ranging from 0.10 to 2.0 %. The most recently reported results were based on the ASTM C 1018 [12] method. Toughness index values will be affected by the type of loading (mid-point versus third-point loading) and type of testing machine (open-loop versus closed-loop). At higher fiber contents, considerable improvements in toughness indices can be seen for PFRC. Material, length, geometry and bonding characteristics of polypropylene fibers influence the toughness and post-crack behavior of this composite. Polypropylene fiber reinforced beams can sustain loads beyond the first crack load, but at a reduced load level. This post-crack reduction in load carrying capacity decreases as the fiber content increases [15]. For example, in another study, Alhozaimy et al. [18] showed that the flexural toughness increases 44%, 271% and 387% by adding 0.1%, 0.2% and 0.3% volume fraction of fibers, respectively as compared to its value for plain concrete. Some researchers have found that mechanical bonding properties of polypropylene fibers increase for twisted collated fibrillated polypropylene fibers or for fibers with buttons (enlargements) added to the fiber ends as compared to un-deformed polypropylene fibers [19].

Al-Tayyib et al. [20] indicated that water absorption, electrical resistivity and permeability of concrete with various water to cement ratios were not significantly affected by the addition of 0.2% by volume fibrillated polypropylene fiber.

2.3. Carbon Fiber Reinforced Concrete (CFRC):

The aerospace industry developed carbon fibers for their high strength and stiffness properties. Compared with most other synthetic fiber types, carbon fibers are expensive. However, laboratory research has continued to determine the physical properties of CFRC.

Carbon fibers have high tensile strength and elastic modulus. They retain their properties at high temperatures and they are inert to most chemicals. The two main processes for making carbon fibers are based on different starting materials, either polyacrylonitrile or petroleum and coal tar pitch. Polyacrylonitrile (PAN) based carbon fibers are manufactured by carbonizing polyacrylonitrile yarn at high temperatures and aligning the resultant graphite crystallites by a process called "hot-stretching". They are manufactured as either HM (high modulus) fibers or HT (high tensile strength) fibers and are dependent upon material source and extent of hot-stretching for their physical properties. They are available in different forms. Carbon fibers can also be made from petroleum and coal pitch and these pitch-based carbon fibers are less expensive than the PAN-based carbon fibers. Pitch-based carbon fibers are also manufactured in two different ways. General purpose (GP) fibers are made from isotropic (non-oriented fiber structure) pitch and are low in elastic modulus and tensile strength. High performance (HP) fibers, on the other hand, are made from mesophase (highly oriented fibers) pitch and are high in elastic modulus and tensile strength. Carbon fibers are typically produced in tows (strands) that may contain up to 12,000 individual filaments. Tows are commonly pre-spread prior to incorporation in CFRC to facilitate cement matrix penetration and to maximize fiber effectiveness. Brown and Hufford [21] used carbon tow impregnated with polyvinyl acetate (PVA) to obtain a good fiber-matrix bond, and to avoid the difficulty of opening up the spaces between filaments to allow penetration of cement particles. The PVA served as an intermediate medium for achieving chemical bond and an effective stress transfer.

Research on CFRC started in the early 1970's by Ali and Majumdar [22]. They used the expensive PAN-based carbon fibers and their investigation of CFRC was limited to the properties of the materials as reinforcement in a continuous fiber sheet or two dimensional random mats. The extent of their useful work was to characterize the material. The pitch-based carbon fibers usually have a much lower modulus of elasticity and strength, but their price is much lower than that of the PAN fibers. The pitch-based carbon fibers still have superior properties to many other synthetic fibers, and their modulus of elasticity is equal to or greater than that of cement matrix. These two, the combination of their lower price and superior properties, has made them more attractive for cement reinforcement. Nowadays the modulus of elasticity and tensile strength of pitch-based carbon fibers have been increased to those of PAN-based carbon fibers. In this newly developed technology, carbon fibers are a mesophase-pitch-based product offering high-performance properties for a broad range of target applications. They are available in chopped, milled and micronized forms and any form can be supplied coated with sizing agents and/or other post-graphitization treatments. These data are available from producers (e.g. www.carbonfibers.conoco.com). One of these newly available products was used in this research study. Therefore, there are no results from other studies available for comparison with this kind of carbon fiber reinforced concrete.

Different methods can be used to disperse the carbon fibers into individual filaments when preparing CFRC with short fibers. Nishioka et al. [23] introduced two different methods for doing it; fiber separation by a dispenser or a hammermill and mixing with the Omni mixer.

Akihama et al. [24] showed a noticeable improvement in the flexural strength and post-cracking behavior by using short and randomly distributed pitch-based carbon fibers in a paste matrix. They used two different water to cement ratios for their mixes: 0.42 and 0.298. Different volume fractions of fibers were used ranging from 1.72% to 4.03%. It was interesting that reducing the water to cement ratio lead to a reduction in the post-cracking portion of the load-deflection curve, without changing the peak load values.

Both Akihama et al. [24] and Nishioka et al. [23] noted that many of the carbon fibers in their mixes were broken rather than pulled out when the composite was loaded to failure. Nishioka et al. [23] considered that the critical length for pitch-based carbon fiber is in the range of 0.8 to 1.4 mm. It should be noted that the length distribution of the fibers after mixing is quite different from the uniform original length. Usually stiffer fibers break up more than the flexible ones and this shortening of fiber length must be considered for different types of failure: fiber fracture and fiber pull-out.

Finally, Chung concluded in her paper [25] that short pitch-based carbon fiber cement-matrix composites showed attractive tensile and flexural properties, low drying shrinkage, high specific heat, low thermal conductivity, high electrical conductivity, high corrosion resistance and a weak thermoelectric behavior.

2.4. Hybrid Fiber Reinforced Concrete (HyFRC):

As mentioned earlier, Walton and Majumdar [2] can be considered the first researchers who brought up the idea of hybridizing organic and inorganic fibers. They found that some previous studies such as one from Goldfein [26] had shown that the inherent brittleness of cement paste or mortar can be remedied by incorporating very small quantities of organic polymer fibers such as nylon and polypropylene into these matrices. Walton and Majumdar noticed that although polymer fibers improve the impact strength of a cement-based composite, they can not make a significant contribution towards an increase in the tensile strength of the material because of their low modulus of elasticity. Therefore, they concluded that it was necessary to consider the possibilities that might result from the addition of a suitable second fiber to the polymer fiber, for applications where improvements in both tensile strength and resistance against impact are desired. For organic fibers they selected several different types of fibrillated and monofilament polypropylene and monofilament nylon fibers. Then glass, asbestos and carbon fibers were tried as the second fiber. The carbon fiber was in the form of either a chopped-strand mat or a continuous tow. They used pre-mixing and spray-suction methods to produce composites in the form of flat sheets, about 9 mm thick and cut into test specimens 50 mm wide and 152 mm long, and finally found that organic and inorganic fibers work together to produce improvement in both tensile and impact properties. They could also measure the strength of the bond between polymer fibers and cement or concrete. A poor value of the order of 1 MN/m^2 was obtained with polypropylene monofilament.

The most investigated fiber combination so far is that of steel and polypropylene fibers, but other combinations such as steel and carbon, steel and steel, fibrils of polypropylene and AR glass, and carbon and polypropylene have also been investigated. Here a brief review of most of the work done in HyFRC so far is presented.

For concrete structural applications, steel fibers are being used since they possess a high Young's modulus and lead to strong and stiff composites; generally the elongation of low modulus fibers such as polypropylene enables the concrete composites to absorb large amounts of energy and resist better impact and shock loading.

Normal strength concrete and high strength concrete containing different amounts of steel and polypropylene fibers have been investigated by Glavind and Aare [27]. Stress-strain curves in compression were obtained by a deformation controlled test system. Unfortunately, the authors did not mention the properties and characteristics of fibers that had been used in their research. Steel and polypropylene fibers were used in quantities of 0.5% and 1.0% by volume, respectively. In hybrid mixes, 0.5% by volume of steel and 0.5% by volume of polypropylene fibers were used. They showed that for normal strength concrete, hybridization of these two fibers increased the ultimate compressive strain of the composite.

Larsen and Krenchel [28] studied the durability of FRC. In their hybrid composites they mixed high bond polypropylene fibers with a length of 12 mm and average cross section of 30 μm x 140 μm with enlarged end steel fibers with a length of 18 mm and fiber cross section of 0.3 mm x 0.4 mm. Laboratory tests on polypropylene FRC and combined steel and polypropylene FRC showed an increase in fracture energy with age. The fracture energy increase of polypropylene FRC and mixed polypropylene and steel FRC over a period of about two years was 15% and 20%, respectively. Composites with and without polypropylene and steel fibers and combinations of these fibers became stronger and tougher over the years; fracture energy determined from flexural stress-deflection curves showed that after ten years of out-door exposure the fracture energy had increased by approximately 40%.

Another study on a hybrid composite based on steel and polypropylene was performed by Feldman and Zheng [29]. Three types of macro steel fibers, two straight and one deformed, and two different lengths of fibrillated polypropylene fibers were used. They found that the flexural strength (Modulus of Rupture) of the HyFRC slightly decreased as the polypropylene fiber content increased. Also, the compressive strength of the HyFRC decreased as the polypropylene fiber content increased. They also showed that deformed steel fibers were more effective than straight ones in the improvement of the strengths, and for straight fibers, the longer fibers were more effective as compared to the short ones. For HyFRC, the toughness and toughness indices increased as polypropylene fiber content increased, and even increased further by adding steel fibers. Deformed steel fibers were the most effective fibers in improving the toughness and toughness indices because of their better mechanical bonding with the concrete matrix. Therefore, in the hybrid composites, the stronger and stiffer steel fibers improved the ultimate strength, while the more flexible and ductile polypropylene fibers led to improved toughness and strain capacity in the post crack zone.

Hybrid fiber reinforced concrete containing two types of fibers (polypropylene and steel) were tested under repeated loading with a constant hybrid fiber volume fraction of 1% by Komlos et al. [30]. Smooth straight steel fibers with a length of 40 mm and a diameter of 0.4 mm and chopped polypropylene fibers in multifilament fibrillated form with a length of 36 mm were used. Workability, compressive strength, flexural strength and impact strength were investigated before and after cyclic loading. The number of cycles in all tests was 10^5. In both cases, before and after cyclic loading, impact strength increased by increasing the percentage of PP fiber in the HyFRC while the total fiber volume fraction was constant. HyFRC with higher PP fibers showed better post-crack responses too.

Qian and Stroeven [31] investigated the effect of steel-polypropylene hybrid fibers on crack arrest in four-point bending tests on the notched prisms. Mono-filament polypropylene fiber with a length of 12 mm and a diameter of 18 μm and two types of hooked steel fibers with lengths of 30 mm and 40 mm and diameter of 0.3 mm and one plain steel fiber with a length of 6 mm and a diameter of less than 0.1 mm were used. They found a positive synergy between large steel fibers and polypropylene fibers on the load-bearing capacity and fracture toughness in the small displacement range. The critical stress intensity factor, K_{IC}, was improved by using polypropylene fiber in the hybrids. They also found that this synergy disappeared in the large displacement range. The longer and stiffer steel fiber was better than the soft polypropylene fiber and small steel fiber in the aspect of energy absorption capacity in the large displacement range.

The same authors, Qian and Stroeven, investigated the optimization of fiber size, fiber content, and fly ash content in hybrid polypropylene-steel fiber concrete with low fiber content based on general mechanical properties [32]. They used the same fibers as mentioned in the previous paragraph. They found that a certain content of fine particles such as fly ash is necessary to evenly disperse fibers. They again found a synergy effect in the hybrid fibers system. They also found that addition of small steel fibers had a significant influence on the compressive strength, but the splitting tensile strength was only slightly affected. On the other hand, large steel fibers gave rise to opposite mechanical effects. The synergy effect implemented in a hybrid fibers system was found to lead to similar significant improvements that could be realized with a mono-fiber system having a higher total fiber content, provided the different types and sizes of fibers were properly dispersed.

The physical properties and crack resistance of concrete containing macro and micro fibers at early ages, when crack control is crucial, were examined by Kim et al. [33]. They did not provide any information about the fibers they used except the lengths of the fibers. They used steel fibers of 30, 12 and 6 mm in length and polypropylene fibers of 6 and 12 mm in length. They noticed that the resistance to the initiation of the first crack and the toughness for hybrid fiber reinforced concrete were improved remarkably as compared to those of mono fiber composites. They also found that hybrid fiber reinforcement is effective for the control of thermal cracks.

Horiguchi and Sakai [34] studied fracture toughness of steel and polyvinyl alcohol (PVA) hybrid fiber reinforced concrete in compression as well as in flexure. In relation between the toughness index and first crack deflection HyFRC showed greater first crack deflection for the same flexural toughness. They also showed that for a total volume fraction of 1.5% the highest compressive toughness was observed in HyFRC. Pull-out energy was found to be affected more by hooked end fibers than by changes of matrix strength due to temperature changes; the pull-out strength at -20°C was higher than that at 20°C.

A high-modulus polyethylene fiber and a fibrillated polyethylene pulp were used in hybrid fiber reinforced cement composites by Soroushian et al. [35]. They used only fine aggregates (grade 100 silica sand) in the matrices. Dispersing agents and a high-performance mixer were used to insure the uniform dispersion of fibers in the matrix. The high modulus polyethylene fiber is particularly effective in improving the toughness and ductility of the cement-based materials, while the fibrillated polyethylene pulp can be effective in arresting micro-cracks in cementitious matrices under load, thereby increasing the tensile and flexural strengths of the composite material. For impact resistance, the positive effect of each fiber was pronounced in the presence of the other fiber type. For flexural strength and toughness, the combined use of polyethylene fiber and pulp produced desirable results as long as the amounts incorporated were below certain limits. The negative effects of fibers on compressive strength were less pronounced when the two fiber types were used in combination. The interactions between these two fibers in determining the specific gravity, volume of permeable pores, and water-absorption capacity of cementitious materials were either negligible or only moderately significant.

Two types of brittle micro fibers, namely alumina and carbon, in addition to ductile polypropylene fibers were used in another study on hybrid cement-based composites by Mobasher and Li [36]. Two types of hybrid composites (mortar) were manufactured. The first series used 4% alumina and 4% polypropylene and the second series used 4% carbon fibers and 4% polypropylene fibers. Since the two fiber lengths were an order of magnitude different, the mixing in the matrix did not pose a problem. The specimens reinforced with carbon and PP showed better post-peak performance than the specimens reinforced with alumina and PP fibers. Load versus CMOD (Crack Mouth Opening Displacement) response showed that the peak load increased by as much as 75% for both series of hybrids as compared to composite containing only 4% of polypropylene. The increased strength was attributed to the contribution of short alumina and carbon fibers and indicated their ability to transfer load across the faces of the pre-critical crack.

Concrete specimens reinforced by different combinations of carbon-steel, polypropylene-steel and steel-steel hybrid fibers at low volume were tested by Stroeven et al. [37]. Optimum reinforcement compositions were obtained for compression, splitting tension and flexural strengths and for post-peak behavior. They found that fibers increased the flexural strength, but more pronounced were the post-peak improvements. No significant differences were observed either between plain and hooked steel fibers, or between PAN and pitch carbon fibers. The effect of the small carbon fibers on toughness was found negligible. Nevertheless, they showed an increase in material toughness by combining carbon fibers with steel fibers, which was an aspect of synergy. For optimizing these composites, the fibers should be uniformly distributed throughout the material and the composite should be well compacted by vibration. These requirements can be ensured by a sequential mixing procedure, the use of an effective superplasticizer and a sufficiently long duration of vibration. During such production conditions part of the carbon fibers may fracture. They found that among the investigated steel-carbon HyFRC mixtures, those containing a combination of hooked-end steel fibers, and PAN carbon fibers performed the best, especially in the post-peak range. PAN carbon micro fibers significantly improved the pull-out behavior of the steel fibers. This was not observed in case of the hybrid pitch-based carbon and steel fiber composites. In the case of steel-polypropylene HyFRC, they found that the aggregate gradation and the total amount of fine materials should be designed carefully. In this case slump should be kept below 160 mm to ensure proper dispersion of the fibers.

Ramanalingam et al. [38] tried to develop a strain-hardening composite using hybrid fibers and high volume fly ash. They presented the results of an experimental program in which a fiber reinforced mortar had been designed with different combinations of fibers to exhibit strain-hardening behavior under flexural loading. Three types of fibers- Polyvinyl Alcohol (PVA) micro fibers with a length of 6 mm and diameter of 14 μm, macro PVA fibers 12 mm long and 0.2 mm in diameter and steel fibers 6 mm long and 0.16 mm in diameter- were used in different combinations as reinforcement for the mortar matrix. They found that the ultimate load of the composite increased with the percentage of steel fibers. On the other hand, the PVA fibers improved post peak response. The results showed that a hybrid composite with the proper volume ratio of high and low stiffness fibers provided significant increases to both ultimate load and post-peak ductility. They concluded that cement mortar reinforced with 1.5% steel and 0.5% macro PVA fibers could be considered as an optimum hybrid fiber reinforced cementitious composite in their study. In the next series of tests, the volume of cement was partly replaced by fly ash in various amounts to study the role of fly ash. They kept the optimum hybrid fibers content constant in all of the tests in these series. When the percentage of replacement by fly ash was increased, both ultimate load and ductility increased. When high volume of fly ash was used (50%), the composite showed a strain-hardening response with multiple cracking. In this case, the first crack toughness decreased whereas the toughness indices increased. In compression, when steel fibers were added to the mortar matrix the strength started increasing significantly. Interestingly, the largest increase in compressive strength was obtained from the optimum hybrid fiber reinforced cementitious composite, as mentioned earlier. Finally, they concluded that a high performance strain-hardening cement composite with multiple cracking could be achieved by reinforcing cement mortar with steel and PVA fibers in hybrid form with high volumes of fly ash.

The effect of hybrid fibers and/or expansive agents on shrinkage and water permeation properties has been investigated by Sun et al. [39]. They used three different sizes of macro steel fibers, one type of micro polypropylene fibers and one type of micro polyvinyl alcohol (PVA) fibers in their hybrid systems. They found that for the concrete reinforced with hybrid steel fibers, the shrinkage strain was lower than with mono-fibers of large size. Also, for the concrete specimens with hybrid of macro steel fibers and micro PVA fibers, or with hybrid of macro steel fibers, micro PVA fibers and micro polypropylene fibers, the shrinkage strains at 28 days were reduced by 39-49%, compared with that of mono macro steel fiber reinforced concrete. They also showed that the addition of an expansive agent improved the interfacial microstructure between aggregate, fibers and hardened cement paste. The shrinkage strains of the concrete matrix with an expansive agent, especially with the combination of hybrid fibers, decreased significantly. This demonstrated that incorporation of expansive agent improved the interface of fiber-matrix and aggregate-matrix, so that fibers of different sizes and types could resist shrinkage and cracking at different scales. Therefore, one can easily conclude that hybrid fibers and expansive agents are beneficial to improvements of concrete in impermeability and durability. Different series of HyFRC specimens were tested for permeability. The total volume fractions were kept constant and the relative water permeation coefficients of the concrete incorporated with hybrid steel fibers were lower than that of mono-fiber reinforced and plain concretes. The concrete reinforced with three sizes of steel fibers provided better improvement for the impermeability than that with two sizes of steel fibers or mono size fiber [39]. In general they showed that concrete with both the expansive agent and hybrid fibers, especially the hybrid fibers of different sizes and types, provided the best results of the shrinkage and permeability resistance.

Two types of micro fibers, carbon and polypropylene, were used and tested in HyFRC under bending and tensile stresses by Qi et al. [40]. Carbon and polypropylene fibers could be effective at different structural levels. When the stress level was relatively low the hybrid fibers would hinder the crack propagation. When the stress level was relatively high, the carbon fibers were debonded from the matrix and eventually fractured. Most of the polypropylene fibers were fractured and produced a large deformation. Different types of fiber failure in carbon-polypropylene HyFRC could be determined by the stress level, the interface bonding strength and the fiber volume fraction etc. They concluded that the strengthening and toughening of the carbon-polypropylene HyFRC were due to the hybrid fibers which could eliminate the crack sources and hinder the crack propagation.

A fatigue damage model for carbon-polypropylene HyFRC was established by Hua et al. [41]. Both carbon and polypropylene were micro fibers. They found that the fatigue life of the carbon-polypropylene HyFRC increased with the increase of fiber volume fraction. But when the volume fraction of the carbon fibers exceeded 1.0% and that of polypropylene exceeded 0.7%, the experimental fatigue life did not increase significantly. They found that the fatigue properties of concrete were improved by using the carbon fiber and the polypropylene fiber and the main reason for that was the hybrid effect that could hinder crack propagation.

Reinforcement of cements with very fine fibers of carbon and steel in mono and hybrid forms was investigated by Banthia and Sheng [42]. They used pitch based carbon fiber with a length of 6 mm and a diameter of 18 μm and micro mild steel fiber with average length of 3 mm and average diameter of 25 μm. The experimental load versus deflection curves for cements reinforced with various volume fractions of mono carbon and mono steel fibers showed significant improvements both in the load carrying capacity as well as in toughness. They also noted that while steel fiber reinforcement produced composites with better load carrying capacities than the carbon fiber, the insignificant differences between elastic and ultimate flexural strengths for the steel fiber composites indicate that the response was essentially linear up to the attainment of the absolute peak load. Carbon-cement composites, on the other hand, have a distinct elastic behavior followed by substantial non-linearity up to the occurrence of the ultimate load. For mono-fiber systems, they concluded that carbon fibers with lower modulus led to a better toughening of the matrix and that of steel fibers caused better strengthening.

Different combinations of hybrid steel-carbon fibers were also tested. Adding steel fibers to a base matrix with 1% carbon fiber caused strengthening and the load versus deflection curve approached the curve for composites with only steel fibers. Similarly, adding carbon fibers to a base matrix with 1% steel fiber produced a response leaning towards the composites carrying only carbon fibers. More steel fibers led to a more prominent improvement in strength and more carbon fibers led to a more pronounced improvement in toughness. At very high dosages of one or the other fiber, however, these fibers appeared to be incompatible.

The permeability of HyFRC under compression was investigated by Horiguchi et al. [43]. Two types of macro and two types of micro steel fibers, one kind of micro polypropylene and two types of galvanized crimped macro steel fibers were used. They showed that the water permeability of plain concrete under compression decreased up to a stress level of 45% of compressive strength, and increased slightly at levels exceeding 45%. In the range of their experiments, it was found that the effects of volume ratio, length and type of micro fiber on the water permeability were not significant. The water permeability of HyFRC had significant correlation with its compressive strength and the unit weight. It was found that the adequate water tightness could be achieved when the corresponding compressive strength was more than 17 MPa and unit weight was more than 2130 kg/m^3.

Water penetration of concrete reinforced with long and short steel fibers was investigated by Horiguchi et al. [44]. For the DIN 1048 water permeability test according to inflow permeation method, it was possible to estimate the permeability of low permeable concrete, whereas the outflow method showed some difficulties for low permeability concrete. The permeability of HyFRC showed a lower value than that of plain concrete.

The strength and toughness of two types of fiber cement corrugated roofing sheets were investigated by Xu et al. [45]. In the hybrid form, they used fibrillated polypropylene networks and alkali resistant glass fibers. No strength or toughness reductions had been found after exposure to natural weather as roofing material on buildings for 6 years for corrugated hybrid sheets. The flexural peak load of hybrid sheets increased by about 20% after a 6-year exposure period, implying that the aging for 6 years of the hybrid sheets was not sufficient for alkali attack of the glass fibers by the cement matrix to become apparent. It was possible that the improved bond between the glass and the cement matrix was a reason for the increased load bearing capacity of the hybrid sheets.

A brief summary of published research on HyFRC is given in Table 2.1.

Researchers	Hybrid Fibers Investigated	Major Findings
Walton et al. [2]	Polypropylene, Nylon, Glass, Asbestos and Carbon	Organic and inorganic fibers work together to produce improvement in both tensile and impact properties.
Glavind et al. [27]	Steel and Polypropylene	Hybridization of these two fibers increased the ultimate compressive strain of the composite.
Larsen et al. [28]	Steel and Polypropylene	After 10 years of out-door exposure the fracture energy of composite containing two fiber had increased by approximately 40%
Feldman et al. [29]	Steel and Polypropylene	In the HyFRC, the stronger and stiffer steel fibers improved the ultimate strength, while the more flexible and ductile polypropylene fibers improved toughness and strain capacity in the post crack zone.
Komlos et al. [30]	Steel and Polypropylene	HyFRC with higher PP fibers showed better post-crack responses and higher impact strengths.
Qian et al. [31]	Steel and Polypropylene	Critical stress intensity factor was improved by using PP fiber in the hybrids and this synergy disappeared in the large displacement range.
Qian et al. [32]	Steel and Polypropylene	A certain content of fine particles such as fly ash is necessary to evenly disperse fibers.
Kim et al. [33]	Steel and Polypropylene	The resistance to the initiation of the first crack and the toughness for hybrid fiber reinforced concrete were improved remarkably as compared to those of mono fiber composites.
Horiguchi et al. [34]	Steel and PVA	HyFRC showed greater first crack deflection for the same flexural toughness.

Table 2.1 Summary of the Hybrid Literature Research

Soroushian et al. [35]	Polypropylene fiber and Polyethylene pulp	Hybrids were beneficial in impact loading and for improving flexural strength and toughness.
Mobasher et al. [36]	Alumina, Carbon and Polypropylene	Load versus CMOD response showed that the peak load increased by as much as 75% for as compared to composite containing only PP.
Stroven et al. [37]	Carbon, Steel and Polypropylene	An increase in material toughness was observed by combining carbon fibers with steel fibers. Also, PAN carbon micro fibers significantly improved the pull-out behavior of the steel fibers.
Ramanalingam et al. [38]	PVA (micro and macro) and Steel	A hybrid composite with proper volume ratio of high and low stiffness fibers provided significant increases to both ultimate load and post-peak ductility.
Sun et al. [39]	Steel Polypropylene and PVA	In concrete reinforced with hybrid steel fibers, the shrinkage strain was lower than that with mono-fiber of large size. Permeability decreased in HyFRC.
Qi et al. [40]	Carbon and Polypropylene	Strengthening and toughening of the carbon-PP HyFRC were due to the hybrid fibers which could eliminate the crack sources and hinder the crack propagation.
Hua et al. [41]	Carbon and Polypropylene	Fatigue properties of concrete were improved by using the carbon fiber and the PP fiber in hybrid forms.
Banthia et al. [42]	Carbon and Steel	In hybrids, more steel fibers leading to a more prominent improvement in strength and more carbon fibers leading to a more pronounced improvement in toughness.
Horiguchi et al. [43]	Steel, Polypropylene and Galvanized Steel	The water permeability of HyFRC had significant correlation with its compressive strength and the unit weight.
Horiguchi et al. [44]	Long and Short Steel	The permeability of HyFRC was lower than that of plain concrete.
Xu et al. [45]	PP and Glass	The flexural peak load of hybrid sheets increased by ageing.

Table 2.1(Continued) Summary of the Hybrid Literature Research

3. OBJECTIVES AND SCOPE

The main objective of this research is to develop high performance hybrid fiber reinforced concretes containing two or three fiber types at various dosage rates. As mentioned in the introduction, hybrid fiber reinforced concrete (HyFRC) has not been investigated extensively, although based on the papers cited earlier in the literature survey, it is clear that the idea of hybridization is sound, well founded and promising. From the limited number of papers in the field of HyFRC, it is also clear that much further research remains to be done. In most cases, the choice of the fibers has been ad-hoc with limited rationale. Therefore, a comprehensive study is needed to compare different combinations of micro-macro, micro-micro, and macro-macro hybrid fibers and then to optimize them.

The focus of this study is to investigate the influence of various fiber combinations on fresh properties of concrete, mainly its workability and on mechanical properties including compressive strength and toughness in bending. As mentioned earlier, HyFRC can be broadly categorized into three different categories. Different types of fibers can be combined based on their different mechanical responses, different dimensions and different functions. In these systems, one type of fiber is usually stronger and stiffer, which improves the first crack strength, while the second type is more flexible and ductile, which leads to improved toughness and strain capacity in the post-cracking stage. The hybrid fiber system needs this combination of different types of fibers to optimize the performance of the composite in the fresh and hardened states with respect to the workability, strength and toughness. In other words, the basic purpose in using hybrid fibers is to control cracks at different size levels and at different curing ages or different loading stages. The large and strong fibers control large cracks and the small and soft fibers control crack initiation and propagation of small cracks. The presence of durable fibers in concrete can increase the strength and/or toughness retention after a certain age while another type is to guarantee the short-term performance during transportation and installation of the structural element.

All these three types of hybrids, as categorized based on fiber response, fiber dimension and fiber function, are studied in this research by combining the following fibers:

- Two types of steel macro fibers with different deformed geometries,
- One type of steel micro fiber, which can be considered as a lower limit for macro fibers with equivalent diameter of 0.25 mm and average length of 6 mm,
- One type of polypropylene macro fiber with deformed geometry,
- One type of polypropylene micro fiber,
- Two types of carbon micro fibers with different properties.

This research investigates the use of hybrid fibers in concrete with compressive strength in the range of 55-60 MPa. Benefits of hybrids, if any, cannot be established without having information on the properties of mono-fiber reinforced concrete. Therefore, for all the above mentioned fibers, fiber reinforced concretes containing only one kind of fiber were also investigated. The maximum total volume fraction of fibers in hybrid-fiber systems was 1.5% and in mono-fiber systems was 1.0%. From a practical point of view, keeping the total volume fraction as low as possible is very important. On the other hand, to gain reasonable results out of fiber addition, the total volume fraction must be above a minimum dosage and this leads us to optimum practical dosages for different mono- or hybrid-fiber systems.

In this study plain concrete was examined as a reference. Fourteen different mixes with only one kind of fiber, 12 different mixes with two kinds of fibers and 5 different mixes with three kinds of fibers were made and examined. Therefore, it is clear that the scope of this project was broad.

4. EXPERIMENTAL WORK

4.1 Mixes

In this study, 32 different mixes were made and examined. All these mixes had the same amounts of sand, aggregate, water and cement. The only difference was the amount and/or the kind of fibers in different mixes. Mixture proportions are given in Table 4.1. For each mixture, six 100x100x350 mm prismatic specimens and six 100x200 mm cylinders were cast in a standard way. Compaction of concretes was achieved by using a vibrating table. The vibration times varied depending on the stiffness of the mixtures. Specimens were de-moulded after 24 hours and stored for an additional 28 days under controlled conditions at 23±3°C and 100% RH.

Table 4.1 Concrete Mix Ingredients

Mix Ingredient	**Amount (kg/m^3)**
Sand	557
Coarse Aggregate, 14 mm maximum size	1113
Cement	400
Water	180

4.2 Materials

Cement

CSA Type 10 (ASTM Type I) normal Portland cement was used throughout the research.

Sand

Saturated Surface-Dry (SSD) clean river sand with a fineness modulus of about 2.5 was used in all mixtures.

Coarse aggregate

Crushed gravel with a maximum size of 14 mm was used in all mixtures.

Superplasticizer

The commercially available Glenium-based high range water reducing admixture "RHEOBUILD 3000FC" (Glenium Polycarboxylate) provided by "Master Builders Technologies" was used in some mixes to achieve adequate workability.

Fibers

Seven different types of fibers were used in this work study. The geometrical and mechanical properties of these fibers are listed in Table 4.2.

Table 4.2 Fibers Properties

Fiber	**Type**	**Dimensions**			**E (GPa)**	**Tensile Strength (MPa)**	**Density (kg/m^3)**	**Cross-Sectional Shape**	**Shape**
		L mm	D	Geometry					
S_1	Steel fiber Novotex	50	1mm	Flat-end	212	1150	7850	Circular	
S_2	Steel fiber Xorex	50	1mm	Crimped	212	1200	7850	Crescent	
S_3	Steel fiber Novocon MD-Φ2	3-10	0.25 mm	Deformed	212	1200	7850	Circular	
CC	Conoco Carbon fiber	12.5	9-11 μm	Straight	232	2100	1900	Circular	
CK	Kureha Carbon fiber	6	18 μm	Straight	30	590	1900	Circular	
HPP	Macro polypropylene	50	1mm	Crimped	3.5	375	900	Rectangular	
mp	Micro polypropylene	12.5	2 denier	Straight	3.5	375	900	Circular	

4.3 Experimental Program

The objective of the research was to compare workability, one of the most important fresh properties of fiber reinforced concrete, compressive strength and flexural toughness, two important hardened properties, among different types of single-, double- and triple-fiber reinforced concrete. Cylinder specimens were used to determine the compressive strengths and beam specimens were tested to obtain the "load versus deflection" curves in third-point loading to calculate their flexural toughness and first-crack strengths. Specimen details are given in Table 4.3.

When carbon fibers were used, they were first wetted with about 2/3 of the total water. Sand and cement were mixed together (dry) in an Omni mixer for a few minutes and then wetted carbon fibers were added and mixed for one minute. This mixture was transferred into a pan-mixer and blended for another minute with the remaining water (about 1/3 of total water) and the coarse aggregate. In HyFRC cases containing carbon fibers, coarse aggregate was mixed (dry) with other fibers in the pan-mixer before transferring the paste containing carbon fibers from the Omni mixer. The mixes that did not contain carbon fibers were mixed directly in the pan-mixer. In these cases, fibers were added to the mixes at the end to ensure that proper fiber dispersion was achieved and fiber balling and clumping did not occur.

In most FRC or HyFRC applications mechanical vibration is required; therefore, workability of FRC/HyFRC can be assessed by measuring the VeBe time, as described in the British Standards Institution - Standard BS 1881 [3], instead of the conventional slump test.

The VeBe time test is a more appropriate test for workability than the slump test, in that it measures the work needed to compact the concrete. The freshly mixed concrete is packed into a similar cone to that used for the slump test. The cone stands within a special container on a platform, which is vibrated at a standard rate, after the cone has been lifted off the concrete. The time taken for the concrete to be compacted is measured. VeBe times range from one second for runny concrete to more than ten seconds for stiff concrete. Unlike the slump test, the VeBe time test gives useful results for stiff concretes. Figure 4.1 shows a schematic of VeBe time test apparatus.

VeBe time test was carried out for all mixes in this study.

Table 4.3 Specimen Details

Specimen Designation	Mix Type	Volume Fraction of Different Fibers							Total Volume Fraction
		S_1	S_2	S_3	CC	HPP	mp	CK	
Control	Plain	-----	-----	-----	-----	-----	-----	-----	-----
1	Single Fiber	0.5%	-----	-----	-----	-----	-----	-----	0.5%
2		1.0%	-----	-----	-----	-----	-----	-----	1.0%
3		-----	0.5%	-----	-----	-----	-----	-----	0.5%
4		-----	1.0%	-----	-----	-----	-----	-----	1.0%
5		-----	-----	-----	0.5%	-----	-----	-----	0.5%
6		-----	-----	-----	1.0%	-----	-----	-----	1.0%
7		-----	-----	-----	-----	1.0%	-----	-----	1.0%
8		-----	-----	-----	-----	-----	1.0%	-----	1.0%
22		0.35%	-----	-----	-----	-----	-----	-----	0.35%
23		-----	0.35%	-----	-----	-----	-----	-----	0.35%
24		-----	-----	-----	-----	0.5%	-----	-----	0.5%
25		-----	-----	-----	-----	-----	0.5%	-----	0.5%
28		-----	-----	0.5%	-----	-----	-----	-----	0.5%
29		-----	-----	-----	-----	-----	-----	0.5%	0.5%
9	Double Fiber	0.35%	-----	-----	0.15%	-----	-----	-----	0.5%
10		-----	0.35%	-----	0.15%	-----	-----	-----	0.5%
11		0.5%	-----	-----	0.5%	-----	-----	-----	1.0%
12		-----	0.5%	-----	0.5%	-----	-----	-----	1.0%
13		-----	-----	-----	0.5%	0.5%	-----	-----	1.0%
14		-----	-----	-----	0.5%	1.0%	-----	-----	1.5%
15		-----	-----	-----	0.5%	-----	0.5%	-----	1.0%
16		-----	-----	-----	0.5%	-----	1.0%	-----	1.5%
21		-----	-----	-----	0.5%	-----	-----	0.5%	1.0%
26		0.5%	-----	-----	-----	0.5%	-----	-----	1.0%
27		-----	0.5%	-----	-----	0.5%	-----	-----	1.0%
30		-----	-----	0.5%	-----	0.5%	-----	-----	1.0%
17	Triple Fiber	0.5%	-----	-----	0.5%	0.5%	-----	-----	1.5%
18		0.5%	-----	-----	0.5%	-----	0.5%	-----	1.5%
19		-----	0.5%	-----	0.5%	0.5%	-----	-----	1.5%
20		-----	0.5%	-----	0.5%	-----	0.5%	-----	1.5%
31		-----	-----	0.5%	-----	0.5%	-----	0.5%	1.5%

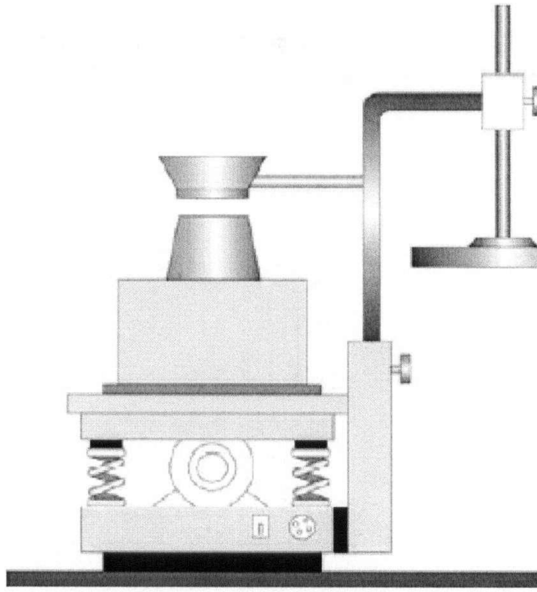

Figure 4.1 VeBe Time Test Apparatus

As mentioned earlier, for each of the 32 mixes investigated, 6 beams (100 x 100 x 350 mm) and 6 cylinders (100 mm in diameter and 200 mm in height) were cast. Cylinder specimens were used to determine the compressive strengths. Figure 4.2 shows the compression test machine with a capacity of 220,000 lb (890 kN) that has been used in this study. The test was performed in accordance with ASTM C 39 [46].

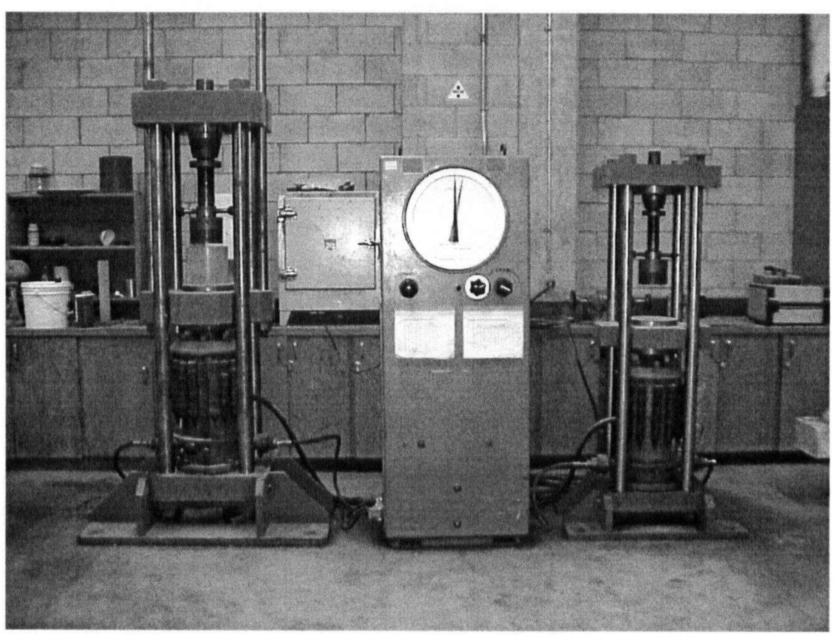

Figure 4.2 Compression Test Machine

Beam specimens were used to obtain the load versus deflection curves in third-point loading to calculate their flexural toughness and first-crack strengths. All beams were tested for flexural toughness using an Instron machine. The method of measuring the specimen deflection is very important and as mentioned earlier the best way of doing this is by measuring of the beam center point-deflection in relation to the neutral axis of the beam at its supports [11]. For the test set-up (Figure 4.3), two Linear Variable Displacement Transducers (LVDTs) were used to record the deflections continuously. These tests were performed in accordance with ASTM C 1018 [12].

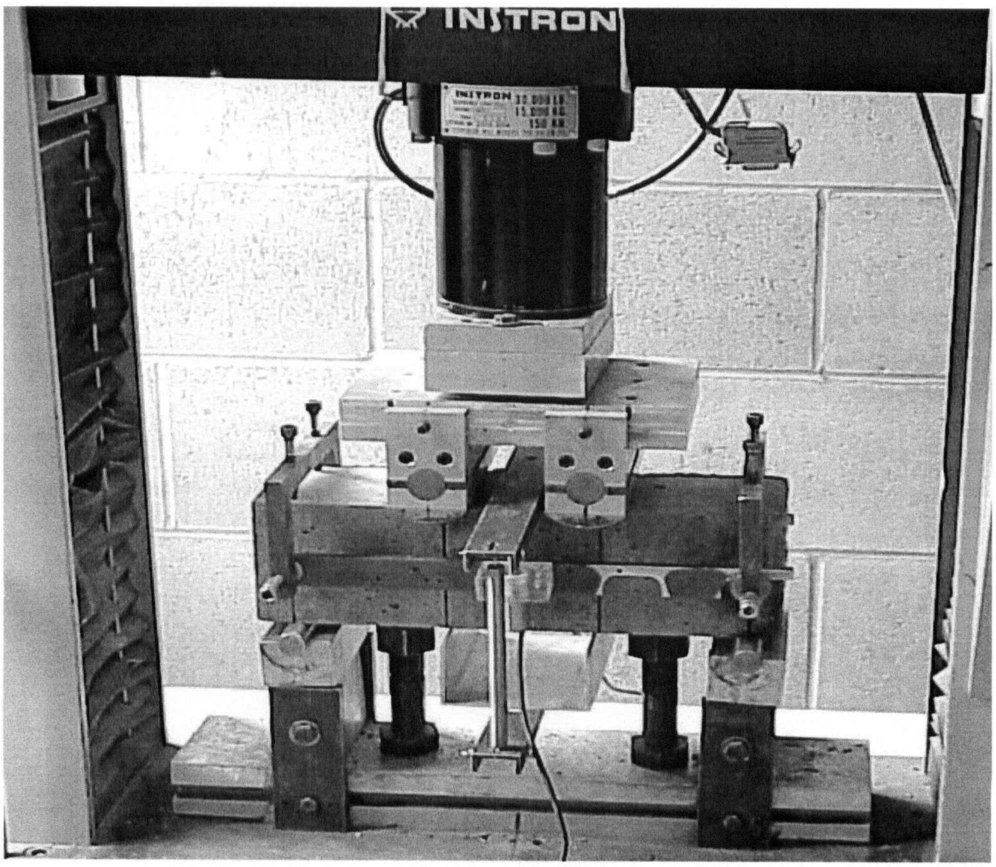

Figure 4.3 Arrangement of Beam for Toughness Test with Instron Machine

4.4 Analysis Scheme

Fiber reinforced concrete, because of its high energy-absorption capability, is a very good material for numerous applications. This energy-absorption capability is referred to as "toughness". There is a great deal of debate over how the toughness of FRC should be characterized. The most common method to measure toughness is to use the load-deflection curve obtained using a simply supported beam loaded at the third points (four-point bending). The two widely used standard test methods are the ASTM C 1018 standard test method [12] and the Japan Society of Civil Engineers (JSCE) standard SF-4 method [13]. In this study, as mentioned earlier, flexural toughness tests were performed in accordance with ASTM C 1018 [12], but the results were analyzed by using the Post Crack Strength (PCS) method as proposed by Banthia and Trottier [14]. The error in the measured deflections due to twisting of the specimen can be minimized by measuring displacements on both sides of the specimen and averaging the measured values. All the measurements in this study were conducted in this way. A special Yoke, as shown in Figure 4.4, was used to support the LVDTs, and the true deflections were recorded.

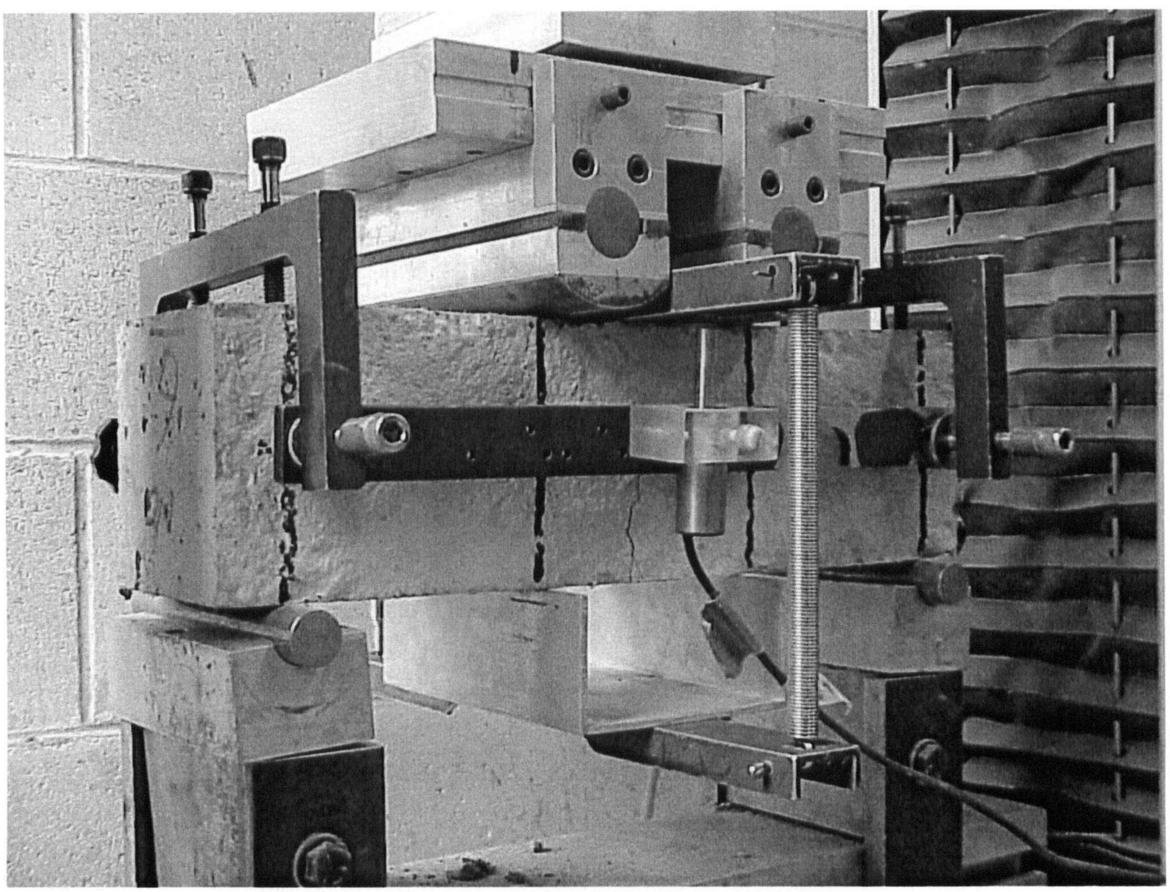

Figure 4.4 Use of a Yoke to Measure True Specimen Deflections

1.4.1 ASTM C 1018 Standard Test Method

This method is based on determining the amount of energy required first to deflect and crack a fiber reinforced concrete beam loaded at its third points, and then to further deflect it to selected multiples of the first-crack deflection. Toughness indices I_5, I_{10}, I_{20}, I_{30}, etc., are then calculated by taking the ratios of the energy absorbed to a certain multiple of first-crack deflection and the energy consumed up to the occurrence of first crack. In general, toughness index of "I_N" can be determined at various deflections using the equation (4.1):

I_N = (Energy absorbed up to a certain multiple of first-crack deflection) / (Energy absorbed up to the fist crack) (4.1)

The subscripts "N" in these indices are based on the elasto-plastic analogy such that, for a perfectly elasto-plastic material, the index "I_N" would have a value equal to "N". Here, the given FRC is compared with a conceptual material that behaves in an ideally elasto-plastic manner. Implicitly, the scheme also assumes that plain concrete is ideally brittle and, hence, the various toughness indices in its case assume a constant value of 1.

The strength remaining in the material is characterized by the residual strength factor (R) derived from the toughness indices. In general, the residual strength factor between indices I_M and I_N (N>M) is expressed as

$$R_{M,N} = C\,(I_N - I_M) \qquad (4.2)$$

where constant C = 100/(N-M) chosen such that for an ideally elasto-plastic material the residual strength factors assume a value equal to the stress at which the elastic-to-plastic transition takes place. Plain concrete, with its ideally brittle response, therefore has residual strength factors equal to zero. Different toughness indices and residual strength factors can be derived from Figure 4.5 as follows:

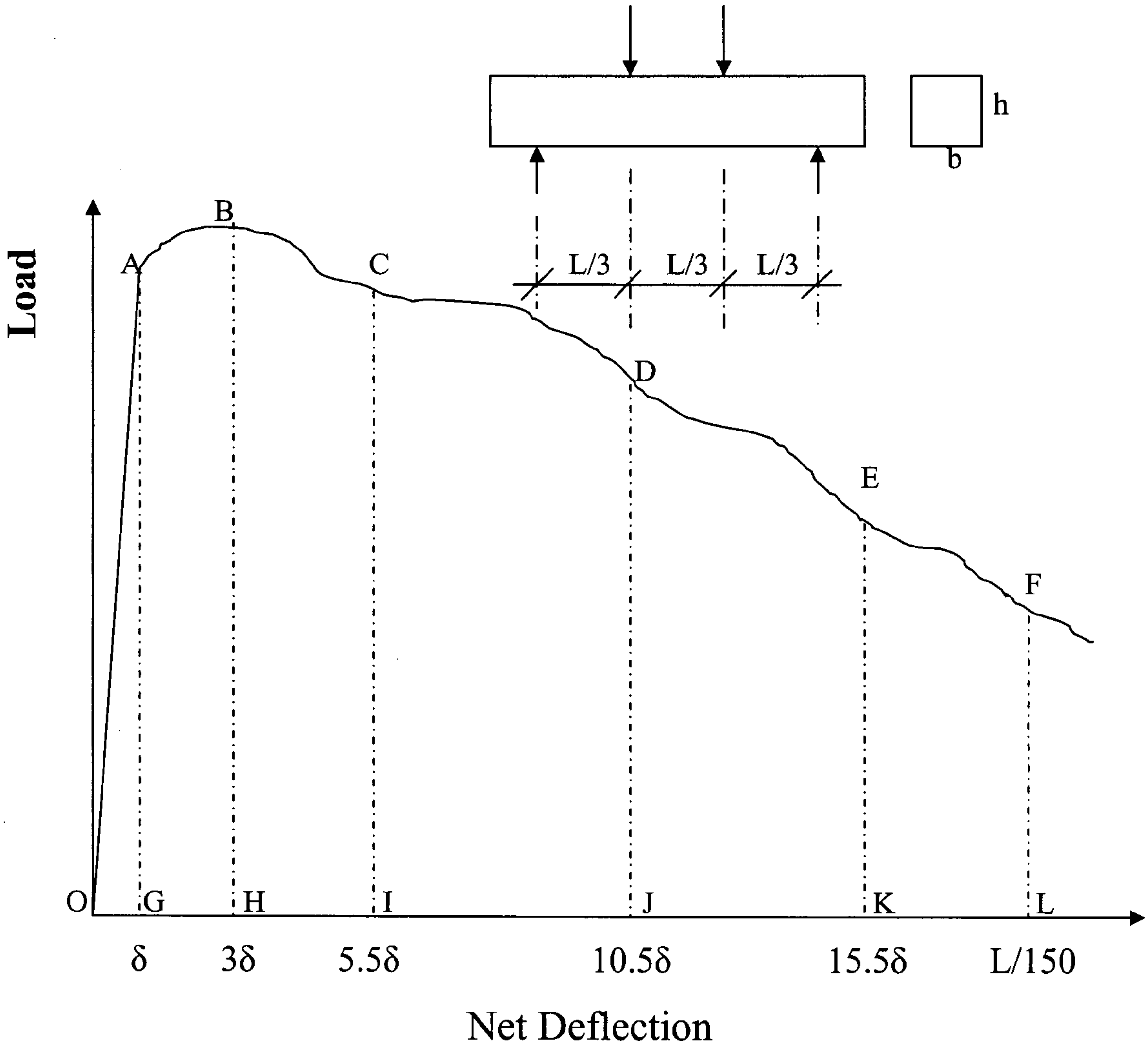

Figure 4.5 ASTM C 1018 and JSCE SF-4 Techniques of Fiber Reinforced Toughness Characterization (*δ = Deflection at First Crack*)

$$I_5 = \frac{Area''OABH''}{Area''OAG''} \tag{4.3}$$

$$I_{10} = \frac{Area''OACI''}{Area''OAG''} \tag{4.4}$$

$$I_{20} = \frac{Area"OADJ"}{Area"OAG"} \quad (4.5)$$

$$I_{30} = \frac{Area"OAEK"}{Area"OAG"} \quad (4.6)$$

$$R_{5,10} = 20(I_{10} - I_5) \quad (4.7)$$

$$R_{10,20} = 10(I_{20} - I_{10}) \quad (4.8)$$

1.4.2 JSCE Standard SF-4 Method

In this technique [48], the area under the load-deflection curve up to a deflection of span/150 is obtained. From this measure of flexural toughness, a flexural toughness factor (FT) is calculated. It may be noted that FT has the units of stress such that its value indicates, in a way, the post-matrix cracking residual strength of the material when loaded to a deflection of span/150. The chosen deflection of span/150 for its calculation is purely arbitrary and is not based on serviceability considerations. A flexural toughness factor (FT) can be derived from Figure 4.5 as follow:

$$FT = \frac{A_{(L/150)} \times L}{(L/150) \times b \times h^2} = \frac{Area"OAFL" \times L}{(L/150) \times b \times h^2} \quad (4.9)$$

According to Banthia and Trottier [14], there are many concerns with the ASTM C 1018 and JSCE test methods. These are briefly discussed below.

1.4.3 Concerns with the ASTM C 1018 Standard Test Method

Measuring true specimen deflections and the instability after the peak load are two major concerns in the ASTM C 1018 test method. An accurate measurement of deflection is very important to characterize toughness of FRC. Settlement of the specimen supports is the biggest source of error in a flexural specimen under a transverse load. The calculation of toughness indices requires an accurate assessment of the first-crack energy, which constitutes the denominator in the definition of the various indices. According to this standard, "Devices such as electronic transducers or mechanical dial gages shall be located either at both loading points, or at the mid-span, to accurately determine the net deflection of the test specimen under load exclusive of any effects due to seating or twisting of the specimen on its supports." The measured displacement of the load points comprises not only the true displacement due to the response of the beam material to the applied stress but also those arising from seating and downward movement of the beam as a rigid body. If not properly considered, the settlement in the supports can lead to a gross overestimation of the first-crack energy and, hence, to erroneous indices. In addition, the identification of first-crack is not so simple, due to the substantial non-linearity of load deflection curves even prior to attaining the peak load. The point of peak load is also the point of instability for the loading machine. If the specimen is not stiff enough, it will experience a sudden unloading and release a large amount of energy. This sudden release of energy has major effects on the load-deflection curves immediately following the peak load. The problem associated with instability can be remedied by using a closed-loop servo controlled test machine. Most commercial laboratories, unfortunately, do not commonly use this kind of sophisticated equipment and this leads to another concern for this test method.

1.4.4 Concerns with the JSCE SF-4 Test Method

Identifying the correct location of the first crack, which is critical and one of the major problems with the ASTM C 1018 method, is not a concern with the JSCE method. Unlike the ASTM C 1018 method, the instability in the load-deflection plot right after the first crack is not of major concern in this method, since the end point deflection of span/150 is too far out in the curve to be affected by the instability in the initial portion. However, there are other limitations and concerns. First of all, FTs are specimen geometry-dependent, which makes an exact correlation with the field performance of

FRC rather difficult. In addition, the end point chosen on the curve at a deflection of span/150 is often criticized for being much greater than the acceptable deflection/serviceability limits. The behavior immediately following the first crack, which may be of importance in many applications, is not indicated in FT in any way. Finally, the technique may be criticized for failing to distinguish between the pre-peak and post-peak behaviors by adopting the smeared approach of using the total area under the curve to calculate FTs.

1.4.5 Banthia and Trottier's Proposed Method (PCS Method)

In order to simplify the approach, a new method has been proposed by Banthia and Trottier [14] wherein identification of first crack is not required. The procedure according to them is as follows (see Figure 4.6):

1. Obtain the load-deflection curve with accurate deflection measurements using a Yoke or a similar device.
2. Locate the peak load and divide the curve into two regions: the pre-peak region (before the occurrence of the peak load) and the post-peak region (after the peak load). Note the value of the load at the peak and measure the area under the curve up to the peak load. This measure of energy is termed pre-peak energy and denoted as E_{pre}.
3. Locate points on the curve in the post-peak region with specimen deflections equal to various fractions of the span L/m_1, L/m_2, etc. The suggested fractions are between L/3000 and L/150. Measure the areas under the curve up to these deflections, denoted as $E_{total,m}$ (measured at a deflection of L/m).
4. Subtract the pre-peak energy, E_{pre}, from the various values of $E_{total,m}$ to obtain the post-peak energy values to a deflection of L/m, referred as $E_{post,m}$.

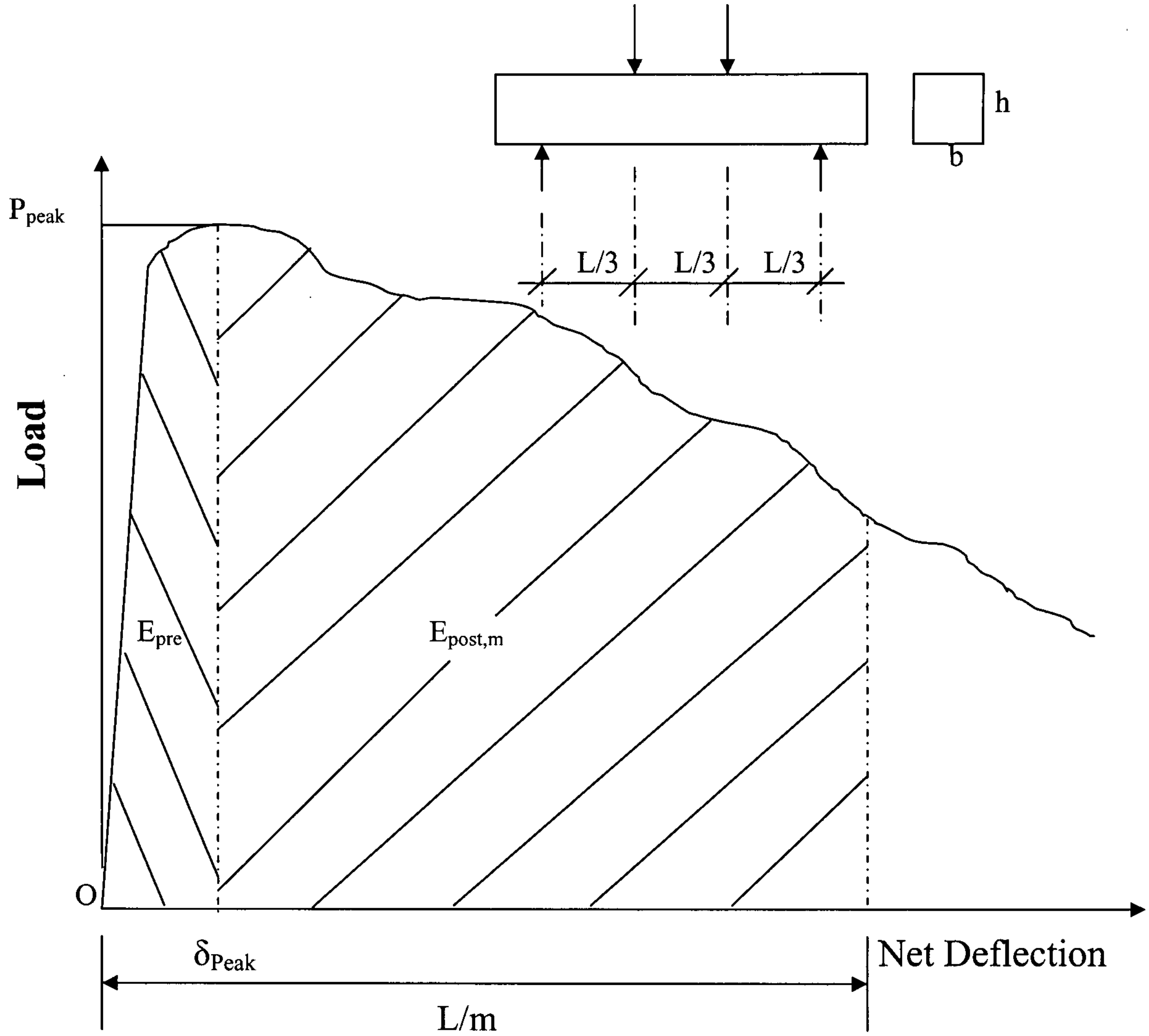

Figure 4.6 PCS Technique (Proposed by Banthia and Trottier)

5. Calculate the post-crack strength (PCS_m) in the post-peak region at the various deflections. The PCS_m at a deflection of L/m, is defined as equation (4.10):

$$PCS_m = \frac{(E_{post,m}) \times L}{(\frac{L}{m} - \delta_{peak}) \times b \times h^2} \qquad (4.10)$$

Comparing equations (4.9) and (4.10), JSCE and PCS methods, for a deflection of L/150, it is observed that the terms $E_{post,m}$ and $A_{(L/150)}$ in the numerator represents the area under the load-deflection curves. The only difference is that the term $E_{post,m}$ does not include a small portion of the pre-peak area. This pre-peak area is negligible compared to the total area up to L/150. In the same way, the terms in the denominator, $(\frac{L}{m} - \delta_{peak})$ and $(L/150)$ are almost the same except for a small difference of δ_{peak}, which is small, compared to L/150. Thus, FT values and PCS values for a deflection of L/150 are almost same. One can also say that the PCS formula is a modification of the JSCE formula. If one is interested in the total energy of the material, the JSCE TF is quite meaningful. But, as mentioned earlier, the PCS formula covers a wide range of deflections from L/3000 to L/150 which is useful for different serviceability conditions.

5. RESULTS

5.1. VeBe Time:

VeBe times, according to the British Standards Institution - Standard BS 1881 [3], were measured for all 32 mixes in this work study. The results are tabulated in Table 5.1. In a few mixes, where the micro fibers content was high, a minimum recommended amount of superplasticizer was used to gain adequate workability. The amount of superplasticizer is given in this Table. Information about this superplsticizer is given in section 4.2.

VeBe times varied from 2 seconds for plain concrete to 27 seconds for HyFRC mix number 15 with 0.5% Conoco carbon fiber and 1.0% micro polypropylene fiber by volume. In the latter, no superplasticizer was used. The chemical structure of the polypropylene makes it "hydrophobic" with respect to the cementitious matrix, leading to reduced bonding with the cement, and negatively affecting its dispersion in the matrix. In addition, micro polypropylene fibers, because of their high value of specific surface area, decrease the amount of available water in the freshly mixed system for enhancing reasonable workability. After this observation in mix number 15, a minimum recommended dosage of superplasticizer was used in mixes 16, 18, 20 and 21, where there were at least 1.0% of micro fibers by volume. For example, usage of superplasticizer in HyFRC mix number 16 with 0.5% by volume Conoco carbon fiber and 1.0% by volume micro polypropylene fiber decreased the VeBe time to 11 seconds (increase in workability) as compared to that of HyFRC mix number 15 with 0.5% by volume Conoco carbon fiber and 0.5% by volume micro polypropylene fiber and VeBe time of 27 seconds. It was also observed that the workability of a mix was adequate as long as the VeBe time was in the range of 2 to 7 seconds. VeBe times were more than 7 seconds for mixes 6, 8, 15, 16, 18, 20, 21 and 31 where micro fibers contents were equal to or higher than 1.0% by volume.

Specimen Designation	Mix Type	Volume Fraction of Different Fibers [1]							Total Volume Fraction	VeBe Time (Sec.)
		S_1	S_2	S_3	CC	HPP	mp	CK		
Control	Plain	-----	-----	-----	-----	-----	-----	-----	-----	2
1	Single Fiber	0.5%	-----	-----	-----	-----	-----	-----	0.5%	3
2		1.0%	-----	-----	-----	-----	-----	-----	1.0%	5
3		-----	0.5%	-----	-----	-----	-----	-----	0.5%	4
4		-----	1.0%	-----	-----	-----	-----	-----	1.0%	5
5		-----	-----	-----	0.5%	-----	-----	-----	0.5%	5
6		-----	-----	-----	1.0%	-----	-----	-----	1.0%	9
7		-----	-----	-----	-----	1.0%	-----	-----	1.0%	5
8		-----	-----	-----	-----	-----	1.0%	-----	1.0%	9
22		0.35%	-----	-----	-----	-----	-----	-----	0.35%	3
23		-----	0.35%	-----	-----	-----	-----	-----	0.35%	3
24		-----	-----	-----	-----	0.5%	-----	-----	0.5%	3
25		-----	-----	-----	-----	-----	0.5%	-----	0.5%	5
28		-----	-----	0.5%	-----	-----	-----	-----	0.5%	3
29		-----	-----	-----	-----	-----	-----	0.5%	0.5%	6
9	Double Fiber	0.35%	-----	-----	0.15%	-----	-----	-----	0.5%	5
10		-----	0.35%	-----	0.15%	-----	-----	-----	0.5%	4
11		0.5%	-----	-----	0.5%	-----	-----	-----	1.0%	7
12		-----	0.5%	-----	0.5%	-----	-----	-----	1.0%	6
13		-----	-----	-----	0.5%	0.5%	-----	-----	1.0%	4
14		-----	-----	-----	0.5%	1.0%	-----	-----	1.5%	7
15		-----	-----	-----	0.5%	-----	0.5%	-----	1.0%	27
16*		-----	-----	-----	0.5%	-----	1.0%	-----	1.5%	11
21**		-----	-----	-----	0.5%	-----	-----	0.5%	1.0%	8
26		0.5%	-----	-----	-----	0.5%	-----	-----	1.0%	4
27		-----	0.5%	-----	-----	0.5%	-----	-----	1.0%	4
30		-----	-----	0.5%	-----	0.5%	-----	-----	1.0%	3
17	Triple Fiber	0.5%	-----	-----	0.5%	0.5%	-----	-----	1.5%	5
18**		0.5%	-----	-----	0.5%	-----	0.5%	-----	1.5%	11
19		-----	0.5%	-----	0.5%	0.5%	-----	-----	1.5%	8
20**		-----	0.5%	-----	0.5%	-----	0.5%	-----	1.5%	15
31		-----	-----	0.5%	-----	0.5%	-----	0.5%	1.5%	8

(1) For fibers definition, please see Table 4.2.

*: Superplasticizer was used. **RHEOBUILD 3000FC** "Master Builders Technologies" **2.8 ml per kg of cement.**

: Superplasticizer was used. **RHEOBUILD 3000FC "Master Builders Technologies" **1.5 ml per kg of cement.**

Table 5.1 VeBe Times for Different Mixes

5.2. Concrete Density:

Hardened concrete densities for all of the 32 mixes were calculated and the results are listed in Table 5.2. These densities are in the range of 2343-2524 kg/m^3. Concrete workability and compactability are the most important parameters responsible for changes in densities. To calculate these densities, all of the beam weights and dimensions for each mix were measured accurately. Minimum density (2343 kg/m^3) belongs to HyFRC mix number 16 with 0.5% by volume Conoco carbon fiber and 1.0% by volume micro polypropylene fiber, note that this mix had a poor workability with a VeBe time of 11 seconds. On the other hand, the maximum density (2524 kg/m^3) belongs to FRC mix number 2 with 1.0% by volume of S_1 (steel fiber, flat-end).

5.3. Compressive Strength:

Four, five or six cylindrical specimens were tested in compression for each mix. The average of these results for each mix, maximum and minimum values of individual specimens and, as a measure of the dispersion or variability of the values, the standard deviation of the results in each group are given in Table 5.3. Compressive strengths of the mixes varied from 40.6 MPa for mix number 16 to 64.3 MPa for mix number 1. The standard deviations of the results were from 0.39 for mix number 1 to 6.28 for mix number 10. In each group, every individual result, except for one specimen in the group of mix number 22, was in the range of 85-115% of average value. Comparison of VeBe times, densities and compressive strengths among the different mixes can be reviewed in Table 5.4.

It can be noted that mix number 16 had the lowest density among all the mixes in this study, and at the same time showed the lowest compressive strength. Micro fibers, especially the combination of micro polypropylene fibers and carbon fibers, decreased the compactability of the concrete and as a result compressive strength decreased. This was confirmed by HyFRC mix number 16 (0.5% by volume Conoco carbon fiber and 1.0% by volume micro polypropylene fiber) with the lowest compressive strength value of 40.6 MPa and HyFRC mix number 15 (0.5% by volume Conoco carbon fiber and 0.5% by volume micro polypropylene fiber) with a compressive strength of 45.2 MPa.

Specimen Designation	Mix Type	Volume Fraction of Different Fibers (1)							Total Volume Fraction	Density (kg/m³)
		S_1	S_2	S_3	CC	HPP	mp	CK		
Control	Plain	-----	-----	-----	-----	-----	-----	-----	-----	2478
1	Single Fiber	0.5%	-----	-----	-----	-----	-----	-----	0.5%	2476
2		1.0%	-----	-----	-----	-----	-----	-----	1.0%	2524
3		-----	0.5%	-----	-----	-----	-----	-----	0.5%	2488
4		-----	1.0%	-----	-----	-----	-----	-----	1.0%	2506
5		-----	-----	-----	0.5%	-----	-----	-----	0.5%	2399
6		-----	-----	-----	1.0%	-----	-----	-----	1.0%	2409
7		-----	-----	-----	-----	1.0%	-----	-----	1.0%	2433
8		-----	-----	-----	-----	-----	1.0%	-----	1.0%	2391
22		0.35%	-----	-----	-----	-----	-----	-----	0.35%	2482
23		-----	0.35%	-----	-----	-----	-----	-----	0.35%	2482
24		-----	-----	-----	-----	0.5%	-----	-----	0.5%	2453
25		-----	-----	-----	-----	-----	0.5%	-----	0.5%	2413
28		-----	-----	0.5%	-----	-----	-----	-----	0.5%	2485
29		-----	-----	-----	-----	-----	-----	0.5%	0.5%	2512
9	Double Fiber	0.35%	-----	-----	0.15%	-----	-----	-----	0.5%	2461
10		-----	0.35%	-----	0.15%	-----	-----	-----	0.5%	2451
11		0.5%	-----	-----	0.5%	-----	-----	-----	1.0%	2462
12		-----	0.5%	-----	0.5%	-----	-----	-----	1.0%	2454
13		-----	-----	-----	0.5%	0.5%	-----	-----	1.0%	2412
14		-----	-----	-----	0.5%	1.0%	-----	-----	1.5%	2421
15		-----	-----	-----	0.5%	-----	0.5%	-----	1.0%	2382
16*		-----	-----	-----	0.5%	-----	1.0%	-----	1.5%	2343
21**		-----	-----	-----	0.5%	-----	-----	0.5%	1.0%	2347
26		0.5%	-----	-----	-----	0.5%	-----	-----	1.0%	2500
27		-----	0.5%	-----	-----	0.5%	-----	-----	1.0%	2499
30		-----	-----	0.5%	-----	0.5%	-----	-----	1.0%	2467
17	Triple Fiber	0.5%	-----	-----	0.5%	0.5%	-----	-----	1.5%	2367
18**		0.5%	-----	-----	0.5%	-----	0.5%	-----	1.5%	2381
19		-----	0.5%	-----	0.5%	0.5%	-----	-----	1.5%	2386
20**		-----	0.5%	-----	0.5%	-----	0.5%	-----	1.5%	2410
31		-----	-----	0.5%	-----	0.5%	-----	0.5%	1.5%	2393

(1) For fibers definition, please see Table 4.2.

*: Superplasticizer was used. **RHEOBUILD 3000FC** "Master Builders Technologies" **2.8 ml per kg of cement.**

: Superplasticizer was used. **RHEOBUILD 3000FC "Master Builders Technologies" **1.5 ml per kg of cement.**

Table 5.2 Hardened-Concrete Density of Different Mixes

Specimen Designation	Mix Type	Volume Fraction of Different Fibers [1]							Total Volume Fraction	Average Comp. Strength (MPa)	Max. Individual Strength (MPa)	Min. Individual Strength (MPa)	Standard Deviation (MPa)
		S_1	S_2	S_3	CC	HPP	mp	CK					
Control	Plain	-----	-----	-----	-----	-----	-----	-----	-----	59.3	63.0	54.2	4.24
1	Single Fiber	0.5%	-----	-----	-----	-----	-----	-----	0.5%	64.3	64.6	63.8	0.39
2		1.0%	-----	-----	-----	-----	-----	-----	1.0%	59.2	64.9	55.6	4.12
3		-----	0.5%	-----	-----	-----	-----	-----	0.5%	57.0	62.6	52.0	3.90
4		-----	1.0%	-----	-----	-----	-----	-----	1.0%	61.0	66.1	53.4	6.00
5		-----	-----	-----	0.5%	-----	-----	-----	0.5%	51.5	54.2	48.5	2.36
6		-----	-----	-----	1.0%	-----	-----	-----	1.0%	47.9	52.2	42.9	3.39
7		-----	-----	-----	-----	1.0%	-----	-----	1.0%	59.0	61.0	56.5	1.64
8		-----	-----	-----	-----	-----	1.0%	-----	1.0%	51.2	53.4	48.0	2.19
22		0.35%	-----	-----	-----	-----	-----	-----	0.35%	52.5	56.5	46.8	4.09
23		-----	0.35%	-----	-----	-----	-----	-----	0.35%	51.6	53.7	47.7	2.40
24		-----	-----	-----	-----	0.5%	-----	-----	0.5%	56.9	60.2	54.5	2.19
25		-----	-----	-----	-----	-----	0.5%	-----	0.5%	57.6	59.6	53.1	2.68
28		-----	-----	0.5%	-----	-----	-----	-----	0.5%	57.5	60.5	55.9	2.06
29		-----	-----	-----	-----	-----	-----	0.5%	0.5%	53.9	59.3	51.4	3.74
9	Double Fiber	0.35%	-----	-----	0.15%	-----	-----	-----	0.5%	50.7	55.4	45.7	3.68
10		-----	0.35%	-----	0.15%	-----	-----	-----	0.5%	43.7	53.7	38.0	6.28
11		0.5%	-----	-----	0.5%	-----	-----	-----	1.0%	54.4	59.9	49.4	4.12
12		-----	0.5%	-----	0.5%	-----	-----	-----	1.0%	49.2	55.1	44.3	4.17
13		-----	-----	-----	0.5%	0.5%	-----	-----	1.0%	52.7	57.9	44.9	4.89
14		-----	-----	-----	0.5%	1.0%	-----	-----	1.5%	52.6	54.2	50.2	1.73
15		-----	-----	-----	0.5%	-----	0.5%	-----	1.0%	45.2	46.3	43.2	1.46
16*		-----	-----	-----	0.5%	-----	1.0%	-----	1.5%	40.6	44.3	37.2	3.23
21**		-----	-----	-----	0.5%	-----	-----	0.5%	1.0%	46.8	50.0	41.2	3.48
26		0.5%	-----	-----	-----	0.5%	-----	-----	1.0%	53.9	56.8	52.2	2.09
27		-----	0.5%	-----	-----	0.5%	-----	-----	1.0%	55.0	58.2	52.8	2.09
30		-----	-----	0.5%	-----	0.5%	-----	-----	1.0%	55.0	57.6	50.0	3.40
17	Triple Fiber	0.5%	-----	-----	0.5%	0.5%	-----	-----	1.5%	49.3	50.5	48.3	0.90
18**		0.5%	-----	-----	0.5%	-----	0.5%	-----	1.5%	48.7	51.7	45.7	2.27
19		-----	0.5%	-----	0.5%	0.5%	-----	-----	1.5%	47.5	50.2	45.4	2.13
20**		-----	0.5%	-----	0.5%	-----	0.5%	-----	1.5%	57.7	59.3	55.6	1.38
31		-----	-----	0.5%	-----	0.5%	-----	0.5%	1.5%	50.3	53.1	47.7	2.21

(1) For fibers definition, please see Table 4.2.

*: Superplasticizer was used. **RHEOBUILD 3000FC** "Master Builders Technologies" **2.8 ml per kg of cement.**

: Superplasticizer was used. **RHEOBUILD 3000FC "Master Builders Technologies" **1.5 ml per kg of cement.**

Table 5.3 Detailed Compressive Strength Test Results for Different Mixes.

Specimen Designation	Mix Type	Volume Fraction of Different Fibers (1)							Total Volume Fraction	VeBe Time (Sec.)	Density (kg/m³)	Comp. Strength (MPa)
		S_1	S_2	S_3	CC	HPP	mp	CK				
Control	Plain	-----	-----	-----	-----	-----	-----	-----	-----	2	2478	59.3
1	Single Fiber	0.5%	-----	-----	-----	-----	-----	-----	0.5%	3	2476	64.3
2		1.0%	-----	-----	-----	-----	-----	-----	1.0%	5	2524	59.2
3		-----	0.5%	-----	-----	-----	-----	-----	0.5%	4	2488	57.0
4		-----	1.0%	-----	-----	-----	-----	-----	1.0%	5	2506	61.0
5		-----	-----	-----	0.5%	-----	-----	-----	0.5%	5	2399	51.5
6		-----	-----	-----	1.0%	-----	-----	-----	1.0%	9	2409	47.9
7		-----	-----	-----	-----	1.0%	-----	-----	1.0%	5	2433	59.0
8		-----	-----	-----	-----	-----	1.0%	-----	1.0%	9	2391	51.2
22		0.35%	-----	-----	-----	-----	-----	-----	0.35%	3	2482	52.5
23		-----	0.35%	-----	-----	-----	-----	-----	0.35%	3	2482	51.6
24		-----	-----	-----	-----	0.5%	-----	-----	0.5%	3	2453	56.9
25		-----	-----	-----	-----	-----	0.5%	-----	0.5%	5	2413	57.6
28		-----	-----	0.5%	-----	-----	-----	-----	0.5%	3	2485	57.5
29		-----	-----	-----	-----	-----	-----	0.5%	0.5%	6	2512	53.9
9	Double Fiber	0.35%	-----	-----	0.15%	-----	-----	-----	0.5%	5	2461	50.7
10		-----	0.35%	-----	0.15%	-----	-----	-----	0.5%	4	2451	43.7
11		0.5%	-----	-----	0.5%	-----	-----	-----	1.0%	7	2462	54.4
12		-----	0.5%	-----	0.5%	-----	-----	-----	1.0%	6	2454	49.2
13		-----	-----	-----	0.5%	0.5%	-----	-----	1.0%	4	2412	52.7
14		-----	-----	-----	0.5%	1.0%	-----	-----	1.5%	7	2421	52.6
15		-----	-----	-----	0.5%	-----	0.5%	-----	1.0%	27	2382	45.2
16*		-----	-----	-----	0.5%	-----	1.0%	-----	1.5%	11	2343	40.6
21**		-----	-----	-----	0.5%	-----	-----	0.5%	1.0%	8	2347	46.8
26		0.5%	-----	-----	-----	0.5%	-----	-----	1.0%	4	2500	53.9
27		-----	0.5%	-----	-----	0.5%	-----	-----	1.0%	4	2499	55.0
30		-----	-----	0.5%	-----	0.5%	-----	-----	1.0%	3	2467	55.0
17	Triple Fiber	0.5%	-----	-----	0.5%	0.5%	-----	-----	1.5%	5	2367	49.3
18**		0.5%	-----	-----	0.5%	-----	0.5%	-----	1.5%	11	2381	48.7
19		-----	0.5%	-----	0.5%	0.5%	-----	-----	1.5%	8	2386	47.5
20**		-----	0.5%	-----	0.5%	-----	0.5%	-----	1.5%	15	2410	57.7
31		-----	-----	0.5%	-----	0.5%	-----	0.5%	1.5%	8	2393	50.3

(1) For fibers definition, please see Table 4.2.

*: Superplasticizer was used. **RHEOBUILD 3000FC** "Master Builders Technologies" **2.8 ml per kg of cement.**

: Superplasticizer was used. **RHEOBUILD 3000FC "Master Builders Technologies" **1.5 ml per kg of cement.**

Table 5.4 Comparison of VeBe Time, Density and Compressive Strength among Different Mixes.

HyFRC mix number 10 (0.35% by volume S_1 fiber and 0.15% Conoco carbon fiber) also showed a low compressive strength (43.7 MPa). Improper compaction of the cylindrical specimens can be considered as the main reason here, as indicated by the high value of standard deviation (6.28 MPa in Table 5.3). Among the five cylinders, compressive strengths varied from 38.0 MPa to 53.7 MPa. Clearly, proper vibration plays an important role in FRC and HyFRC. Compressive strengths of the different mixes can be compared in Figure 5.1.

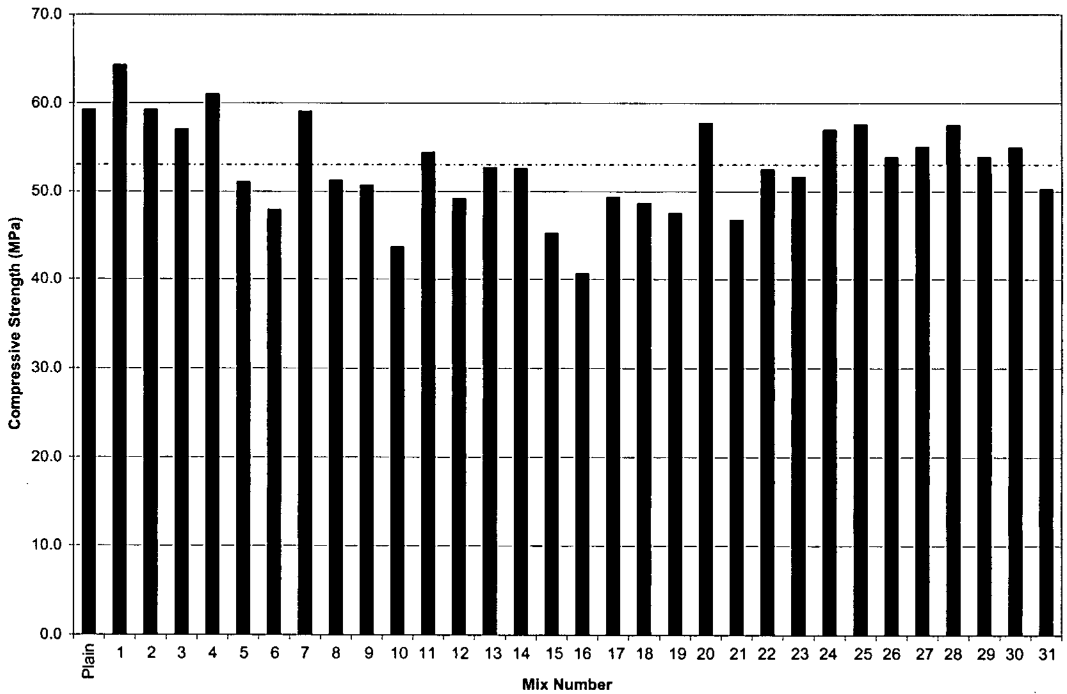

Figure 5.1 Compressive Strengths of Different Mixes

Figures 5.2 to 5.7 show tested cylinders of different mixes. Cylinders failed in a brittle manner except for FRCs or HyFRCs containing micro polypropylene fibers (e.g. FRC mix #8 in Figure 5.3 and HyFRC mix #18 in Figure 5.7). Micro carbon fiber did not improve the brittleness of concrete cylinders (Figure 5.2). FRC or HyFRC cylinders containing macro fibers such as HPP, S_1 and S_2 failed in a brittle manner but did not split (Figures 5.4, 5.5 and 5.6). One should note that these tests are open-loop tests and inherently produce a brittle response.

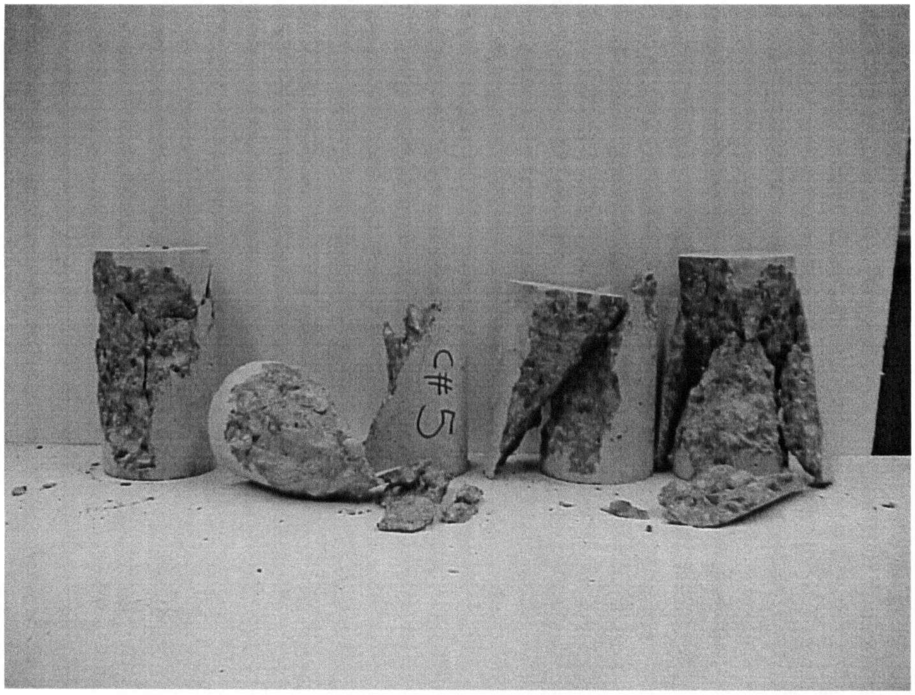

Figure 5.2 Tested Cylinders of Mix #5 (0.5% CC)

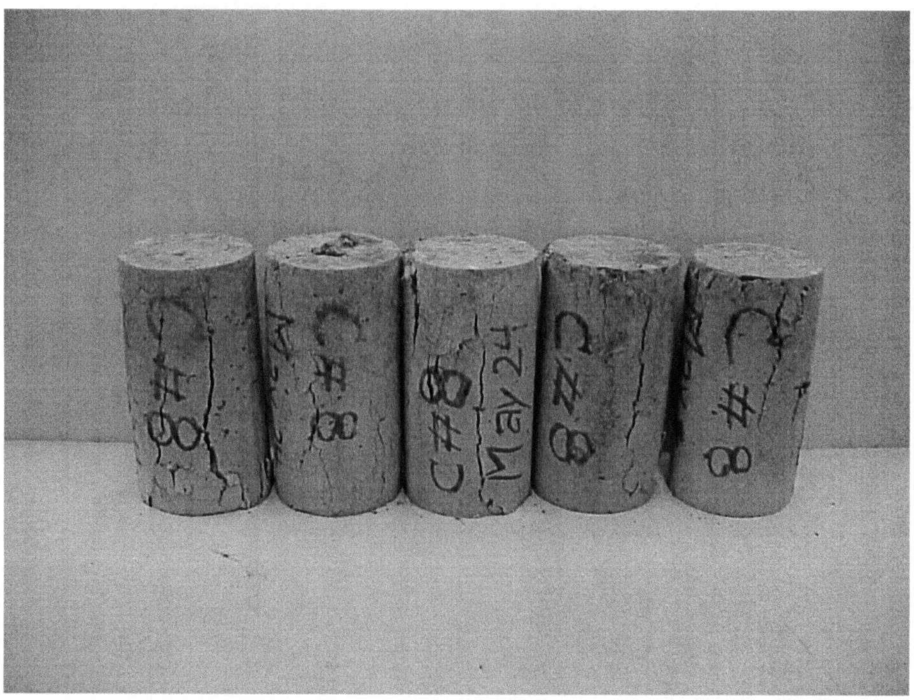

Figure 5.3 Tested Cylinders of Mix #8 (1.0% mp)

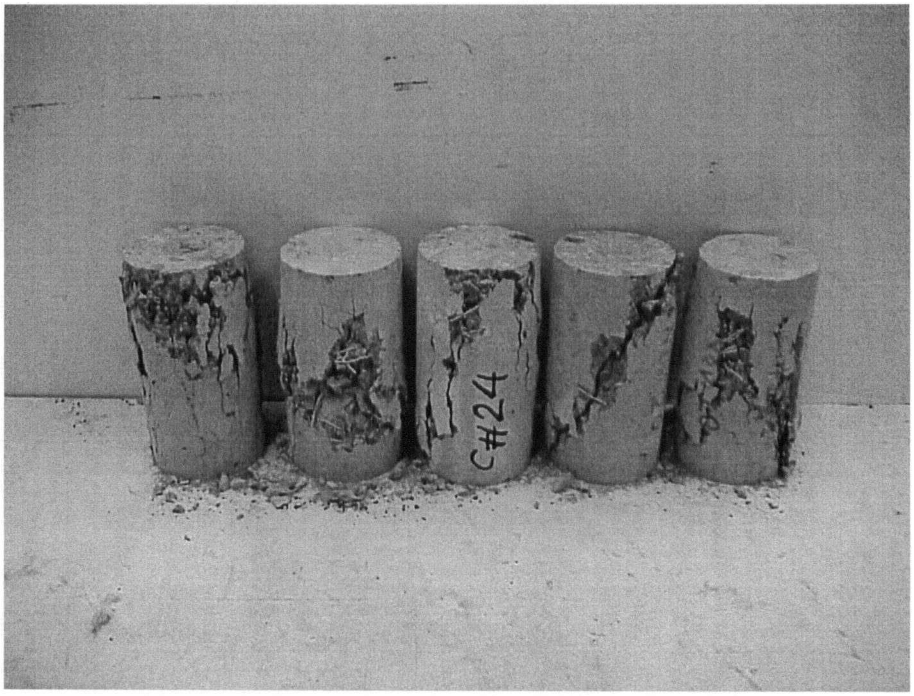

Figure 5.4 Tested Cylinders of Mix #24 (0.5% HPP)

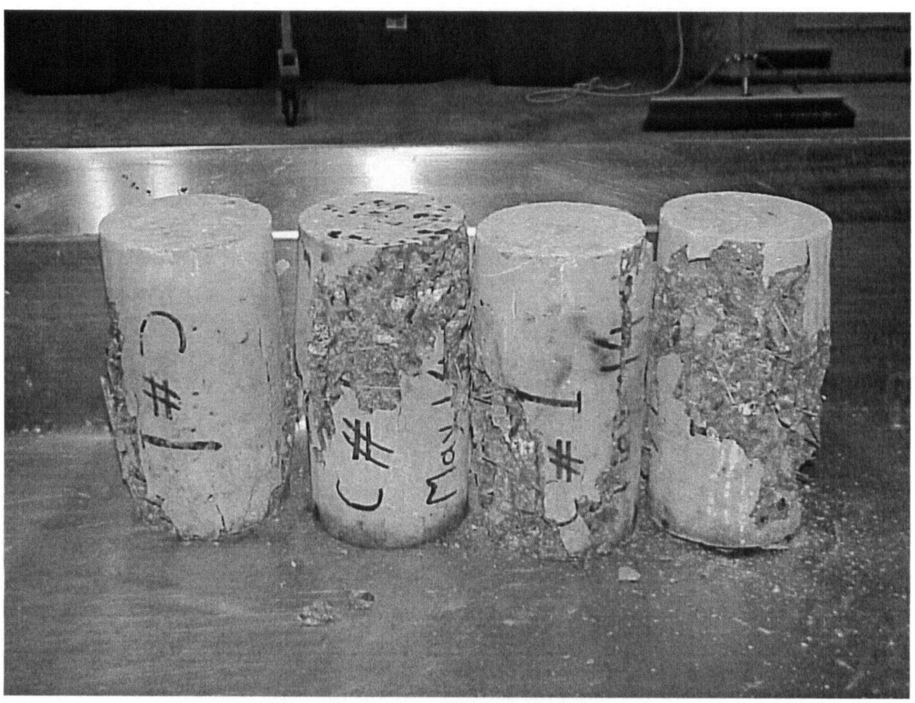

Figure 5.5 Tested Cylinders of Mix #1 (0.5% S_1)

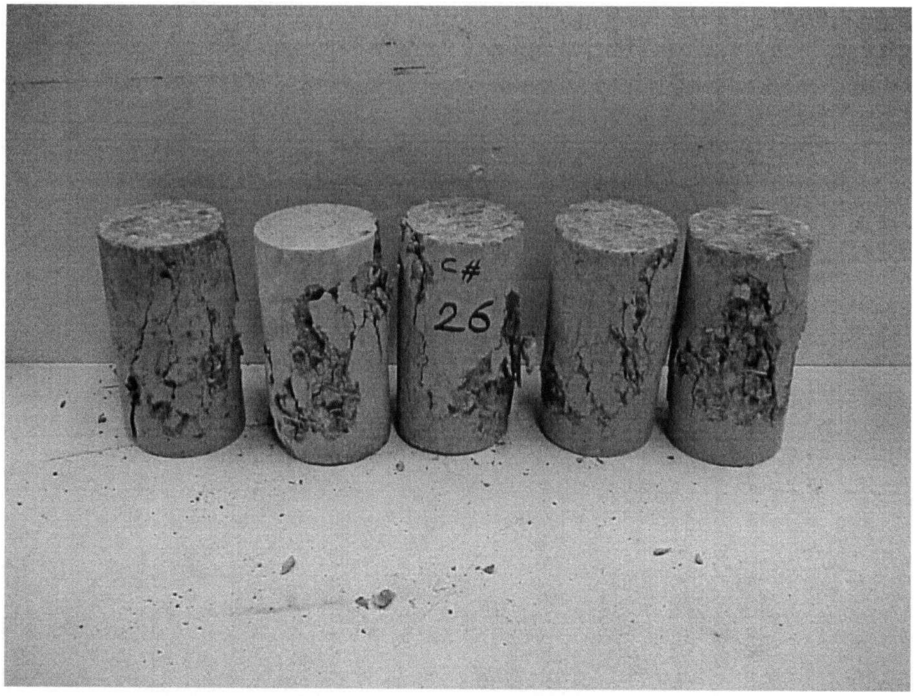

Figure 5.6 Tested Cylinders of Mix #26 (0.5% S_1 + 0.5% HPP)

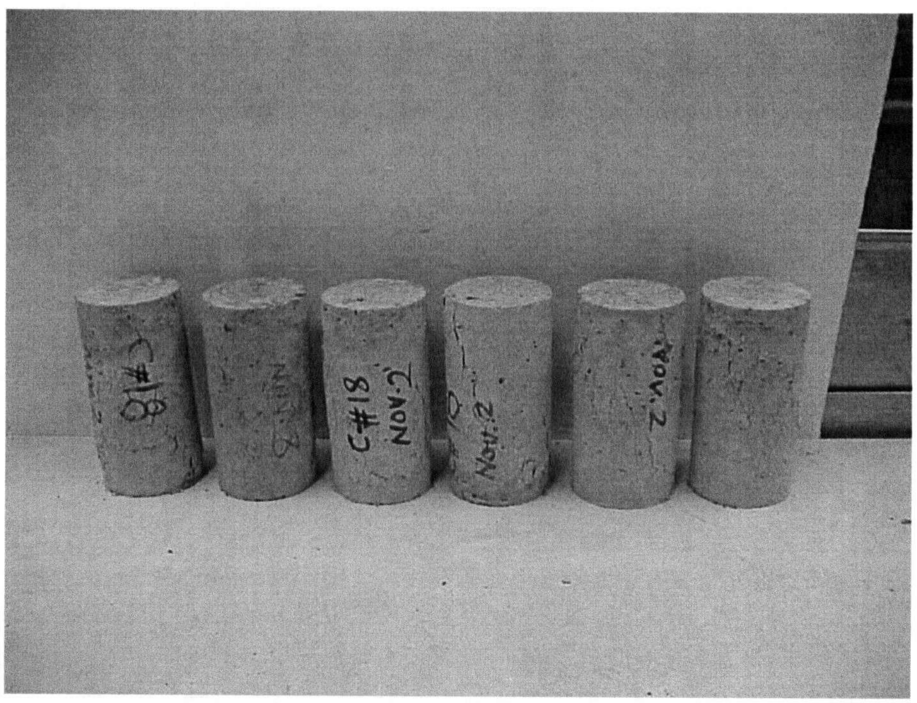

Figure 5.7 Tested Cylinders of Mix #18 (0.5% S_1 + 0.5% mp + 0.5%CC)

5.4. Flexural Toughness and First-Crack Strength:

All the beam specimens (100 x 100 x 350 mm) were tested in flexure in third-point loading, as shown in Figure 5.8.

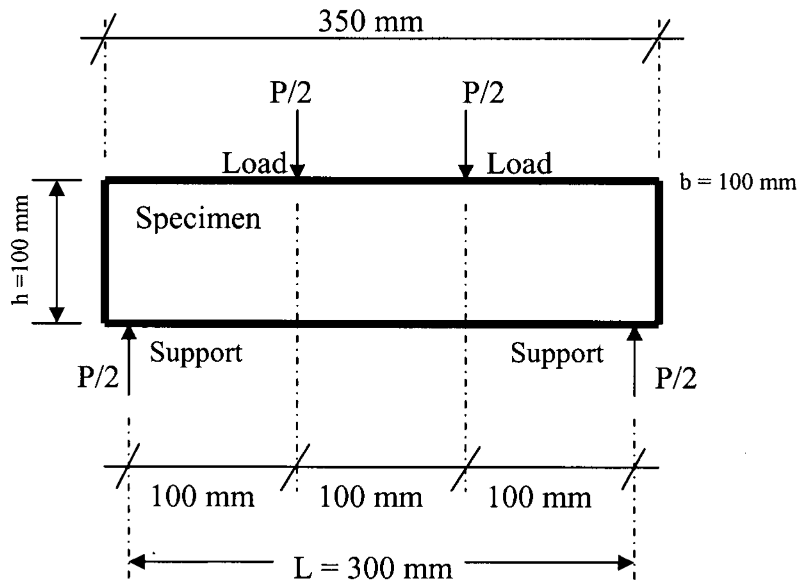

Figure 5.8 Diagrammatic View of Third-Point Loading Apparatus for Flexure Test of Concrete

The cast specimens were tested turned on their sides with respect to their position as molded. This provided smooth, plane and parallel faces for loading. Specimens were loaded at a cross arm rate of 0.1 mm/minute. The theoretical maximum tensile strength, or *modulus of rupture*, **R**, was then calculated from the simple beam bending formula for third-point loading:

$$R = \frac{\left(\frac{P}{2} \times \frac{L}{3}\right) \times \frac{h}{2}}{\frac{bh^3}{12}} \longrightarrow R = \frac{PL}{bh^2} \qquad (5.1)$$

where P is the maximum total load indicated, L the span length, b the specimen breadth, and h the specimen height. Equation (5.1) holds only if the beam breaks in the middle third of the beam (between the two interior loading points). If the beam breaks outside the middle third of the beam by less than 5% of the span length, equation (5.1) should be replaced by:

$$R = \frac{\left(\frac{P}{2} \times a\right) \times \frac{h}{2}}{\frac{bh^3}{12}} \longrightarrow R = \frac{3Pa}{bh^2} \qquad (5.2)$$

where a is the average distance between the point of fracture and the nearest support. Note that in the latter one moment arm is considered a instead of L/3.

In this project, every single specimen broke in the middle third of its span and therefore, equation (5.1) was used to calculate the modulus of rupture. Due to the fact that the simple flexure formula [Equation (5.1)] assumes that the stress varies linearly through the depth of the beam, this calculated modulus of rupture tends to overestimate the true tensile strength by about 50% [47]. Concrete has a nonlinear stress-strain curve and the above mentioned assumption is not true, especially near failure where the stress block is more nearly parabolic than triangular. However, MOR (modulus of rupture) values calculated by formulae (5.1) or (5.2) remain very useful, since concrete members are often loaded in bending in addition to axial tension. The values obtained from a flexure test are a good representation of the concrete property, and are of interest.

Modulus of rupture of each individual specimen was calculated and the average value for each mix, the maximum and minimum values of individual result in each group and the standard deviations of results are tabulated in Table 5.5.

When the flexural toughness tests were carried out, beams that were brittle failed in an unstable manner. In addition, the tests were carried out under open-loop conditions and therefore, the load versus deflection curves would look like that shown in Figure 5.9. The curve in this Figure shows the test result of one specimen in the group of "C#1". This curve indicates that a large amount of energy was absorbed by the specimen as it failed. The line "CD" in this curve is misleading if one considers what really takes place during failure. During the specimen loading, a large amount of elastic energy will be stored in the specimen and in the testing machine. This energy keeps accumulating as crack formation continues. Up to the peak value in this curve, the micro-cracked concrete is still maintaining a stable structure. Once the coalesced main crack reaches its critical length, it continues to grow even if the applied load is decreasing.

Specimen Designation	Mix Type	Volume Fraction of Different Fibers (1)							Total Volume Fraction	Ave. of Modulus of Rupture (MPa)	Max. of Individual Results (MPa)	Min. of Individual Results (MPa)	Standard Deviation (MPa)
		S_1	S_2	S_3	CC	HPP	mp	CK					
Control	Plain	-----	-----	-----	-----	-----	-----	-----	-----	5.62	6.36	5.04	0.4782
1		0.5%	-----	-----	-----	-----	-----	-----	0.5%	6.33	7.03	5.29	0.6457
2		1.0%	-----	-----	-----	-----	-----	-----	1.0%	6.47	6.69	6.11	0.2537
3		-----	0.5%	-----	-----	-----	-----	-----	0.5%	5.73	6.37	5.44	0.3484
4		-----	1.0%	-----	-----	-----	-----	-----	1.0%	6.96	7.56	6.17	0.5712
5		-----	-----	-----	0.5%	-----	-----	-----	0.5%	5.71	6.25	5.05	0.4224
6	Single Fiber	-----	-----	-----	1.0%	-----	-----	-----	1.0%	6.52	7.06	5.77	0.4656
7		-----	-----	-----	-----	1.0%	-----	-----	1.0%	5.24	5.73	4.74	0.4507
8		-----	-----	-----	-----	-----	1.0%	-----	1.0%	5.03	5.87	4.21	0.5789
22		0.35%	-----	-----	-----	-----	-----	-----	0.35%	5.86	6.20	5.39	0.4121
23		-----	0.35%	-----	-----	-----	-----	-----	0.35%	5.15	5.47	4.83	0.2329
24		-----	-----	-----	-----	0.5%	-----	-----	0.5%	4.84	6.05	4.26	0.7084
25		-----	-----	-----	-----	-----	0.5%	-----	0.5%	5.46	6.15	4.70	0.4806
28		-----	-----	0.5%	-----	-----	-----	-----	0.5%	6.63	7.38	6.03	0.6095
29		-----	-----	-----	-----	-----	-----	0.5%	0.5%	6.41	6.92	6.04	0.3763
9		0.35%	-----	-----	0.15%	-----	-----	-----	0.5%	5.33	5.74	4.67	0.4185
10		-----	0.35%	-----	0.15%	-----	-----	-----	0.5%	6.05	6.88	4.93	0.6533
11		0.5%	-----	-----	0.5%	-----	-----	-----	1.0%	6.07	6.59	5.06	0.5255
12		-----	0.5%	-----	0.5%	-----	-----	-----	1.0%	6.14	6.45	5.38	0.4452
13		-----	-----	-----	0.5%	0.5%	-----	-----	1.0%	5.68	6.11	4.95	0.4604
14	Double Fiber	-----	-----	-----	0.5%	1.0%	-----	-----	1.5%	6.06	6.27	5.68	0.2305
15		-----	-----	-----	0.5%	-----	0.5%	-----	1.0%	5.11	5.79	4.52	0.5423
16*		-----	-----	-----	0.5%	-----	1.0%	-----	1.5%	5.45	5.98	4.96	0.4043
21**		-----	-----	-----	0.5%	-----	-----	0.5%	1.0%	5.39	5.99	4.84	0.4392
26		0.5%	-----	-----	-----	0.5%	-----	-----	1.0%	6.52	7.25	5.81	0.4597
27		-----	0.5%	-----	-----	0.5%	-----	-----	1.0%	6.46	6.77	5.92	0.3039
30		-----	-----	0.5%	-----	0.5%	-----	-----	1.0%	6.54	6.96	5.81	0.4363
17		0.5%	-----	-----	0.5%	0.5%	-----	-----	1.5%	5.50	6.37	4.90	0.5941
18**	Triple Fiber	0.5%	-----	-----	0.5%	-----	0.5%	-----	1.5%	6.65	7.74	6.05	0.6189
19		-----	0.5%	-----	0.5%	0.5%	-----	-----	1.5%	5.65	6.36	5.27	0.4023
20**		-----	0.5%	-----	0.5%	-----	0.5%	-----	1.5%	6.74	7.17	6.48	0.2680
31		-----	-----	0.5%	-----	0.5%	-----	0.5%	1.5%	6.38	6.77	6.03	0.2667

(1) For fibers definition, please see Table 4.2.

*: Superplasticizer was used. **RHEOBUILD 3000FC** "Master Builders Technologies" **2.8 ml per kg of cement.**

: Superplasticizer was used. **RHEOBUILD 3000FC "Master Builders Technologies" **1.5 ml per kg of cement.**

Table 5.5 Modulus of Rupture Values and Ttheir Variability among Different Mixes.

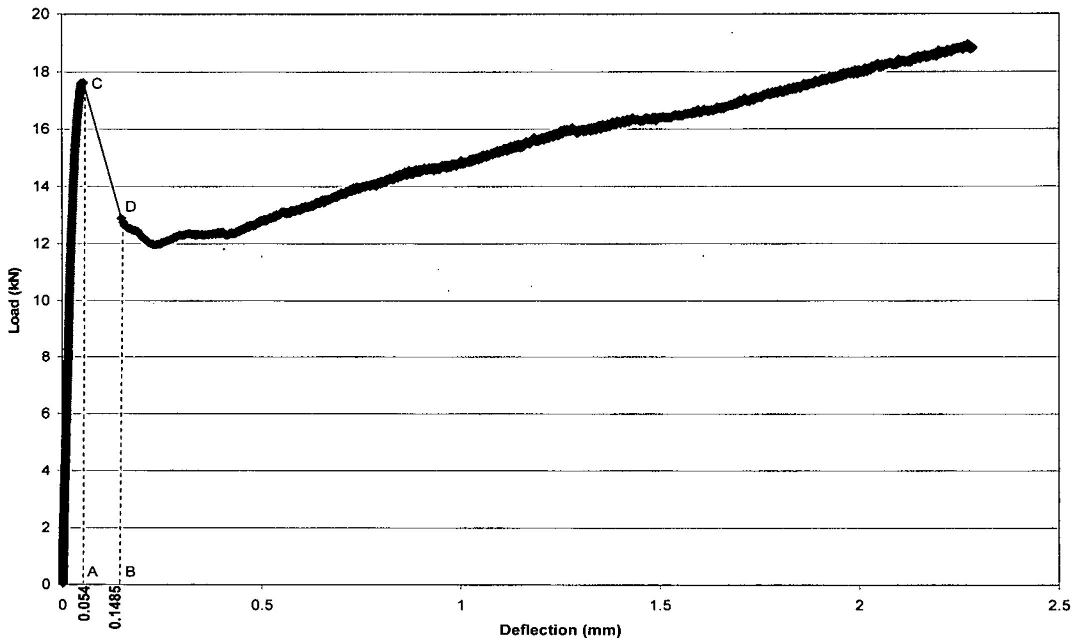

Figure 5.9 Load versus Deflection Curve after an Open-Loop Test (One of the Beams in C#1)

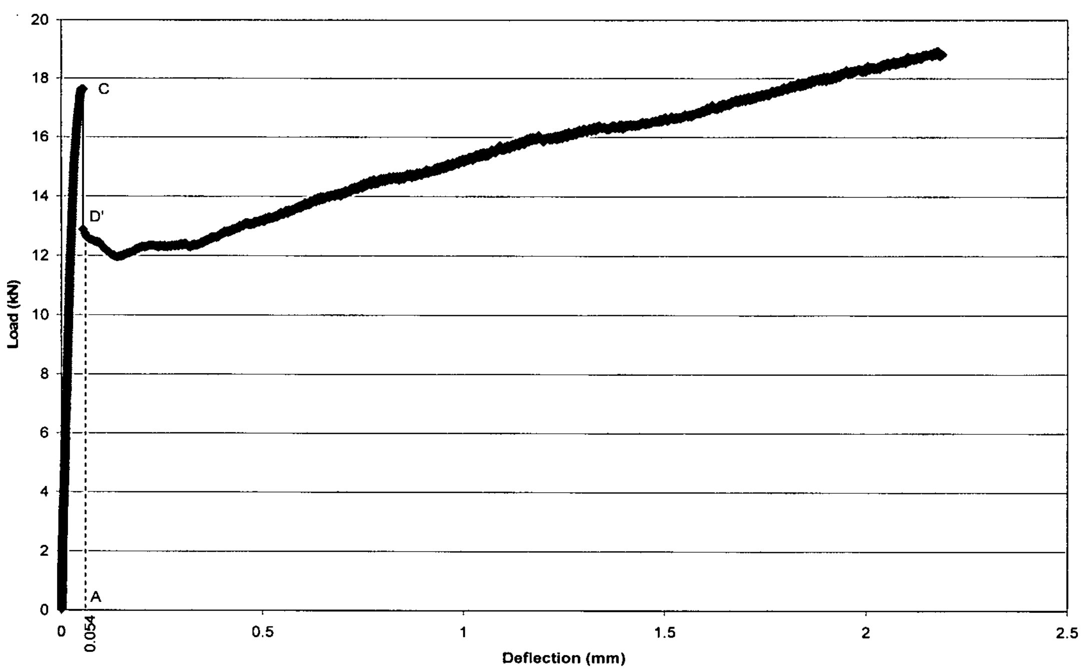

Figure 5.10 Modified Load versus Deflection Curve (Instability Portion Is Removed)

In open-loop test setups where large amounts of energy have been stored, the reduction in applied load causes the sudden release of this stored energy producing the sudden unstable growth of a single crack. This event occurs rapidly, much faster than the rate of data acquisition, and therefore, the post-peak energy (the area under the load-deflection curve) in Figure 5.2 would contain a large portion (ABDC) corresponding to the energy originally stored in the machine. The misinterpretation caused by this observation can be counteracted by shifting back the point D to point D', as shown in Figure 5.10. Therefore such a modified load-deflection curve is deemed to be close enough to the one that would otherwise be produced in a closed-loop test machine.

This method was used to modify the load-deflection curves for specimens which underwent unstable failures. These resulting curves and data points were then used to determine toughness parameters.

Figures 5.11 to 5.42 show individual load-deflection curves for mixes which had been tested in this program. In each Figure an average curve is provided which will be used to compare different behavior of mixes under flexure in the following chapters. Figure 5.43 shows the dispersion of macro steel fibers in a tested beam broken in two halves (mix number 4 with 1.0% S_2) and Figure 5.44 shows micro polypropylene fibers bridging a macro crack in a tested beam.

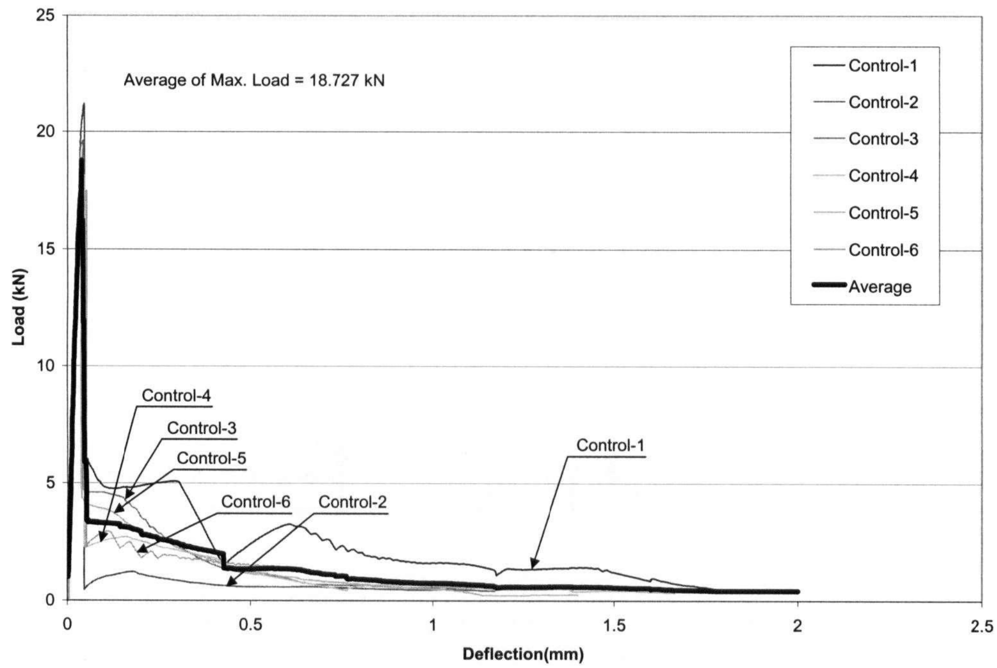

Figure 5.11 Plain Concrete Beams without Fiber

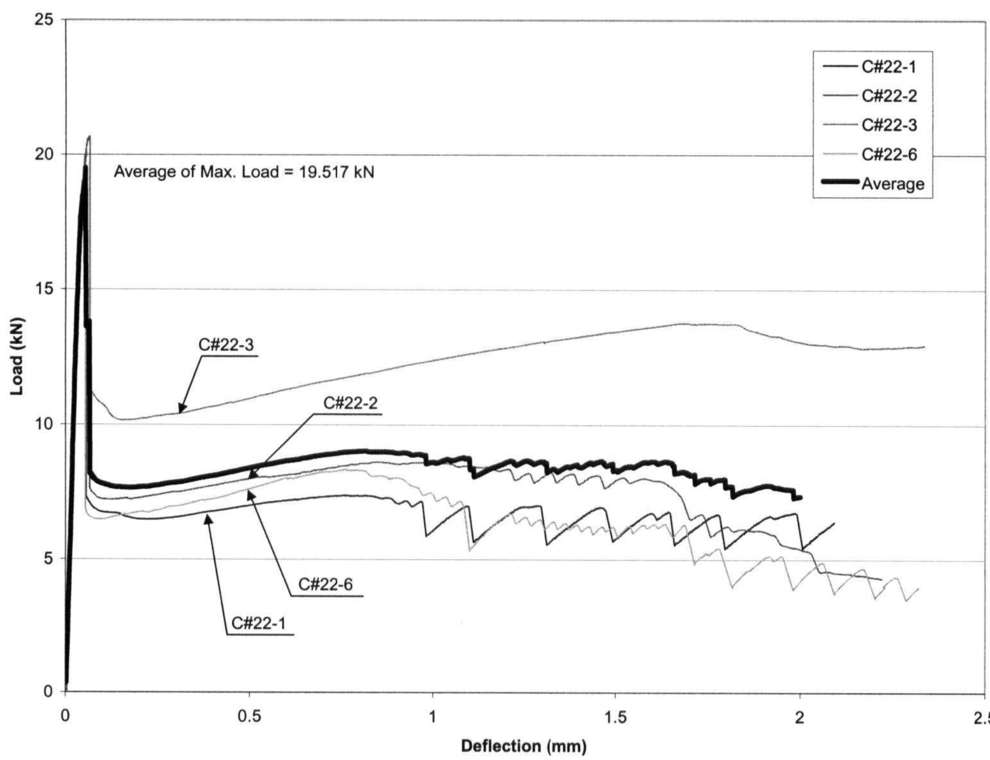

Figure 5.12 FRC Beams with "***0.35% S_1***" (Steel Fiber-Flat End)

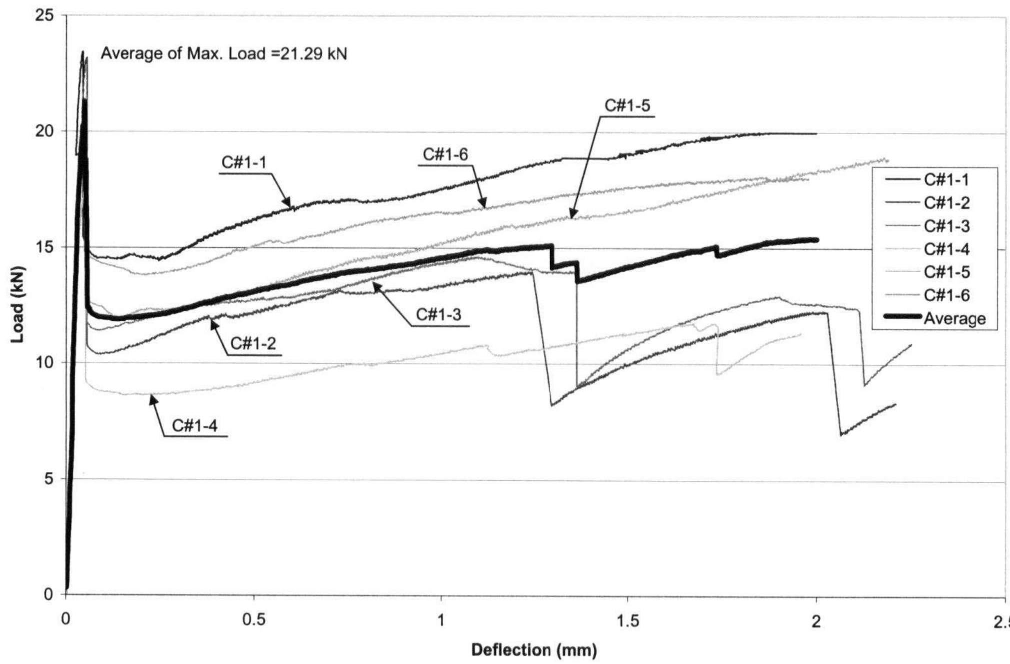

Figure 5.13 FRC Beams with "***0.5% S*** $_{1}$" (Steel Fiber-Flat End)

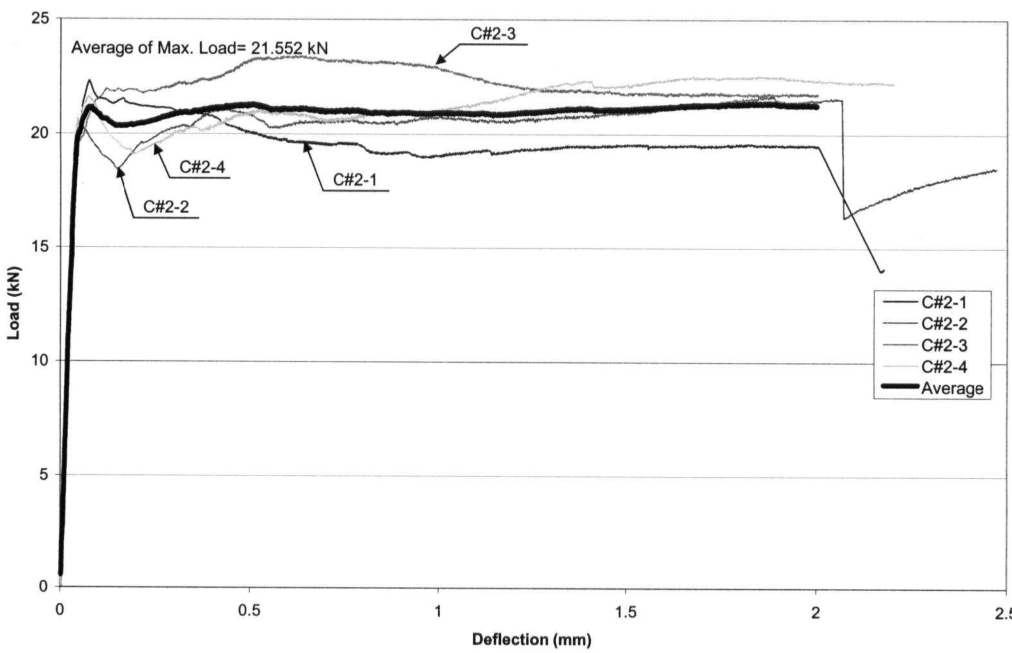

Figure 5.14 FRC Beams with "***1.0% S*** $_{1}$" (Steel Fiber-Flat End)

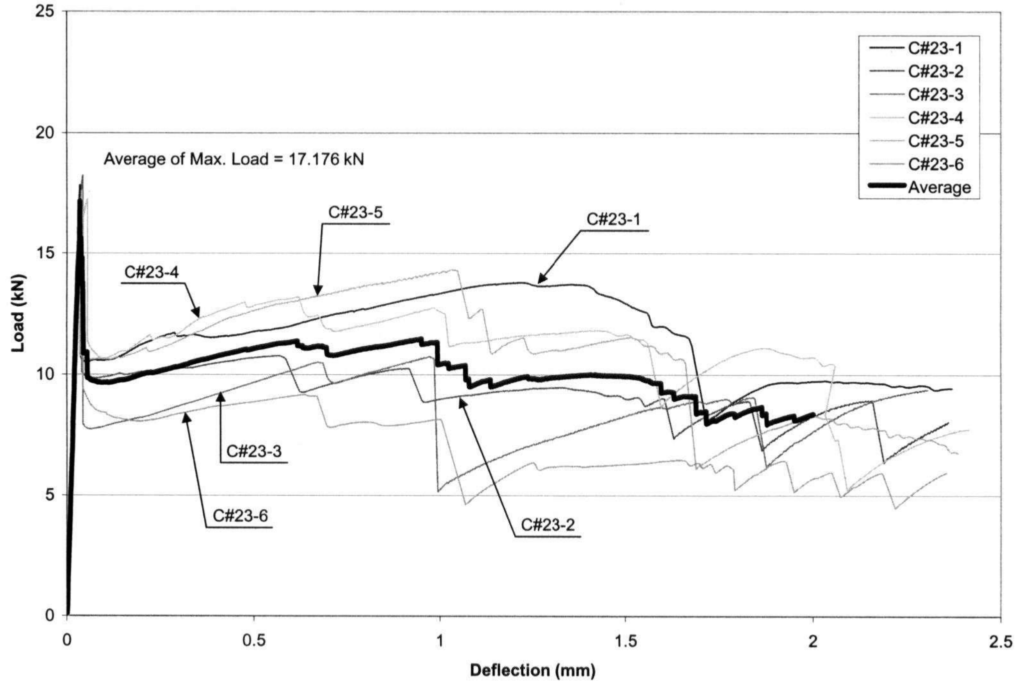

Figure 5.15 FRC Beams with "***0.35% S₂***" (Steel Fiber-Crimped)

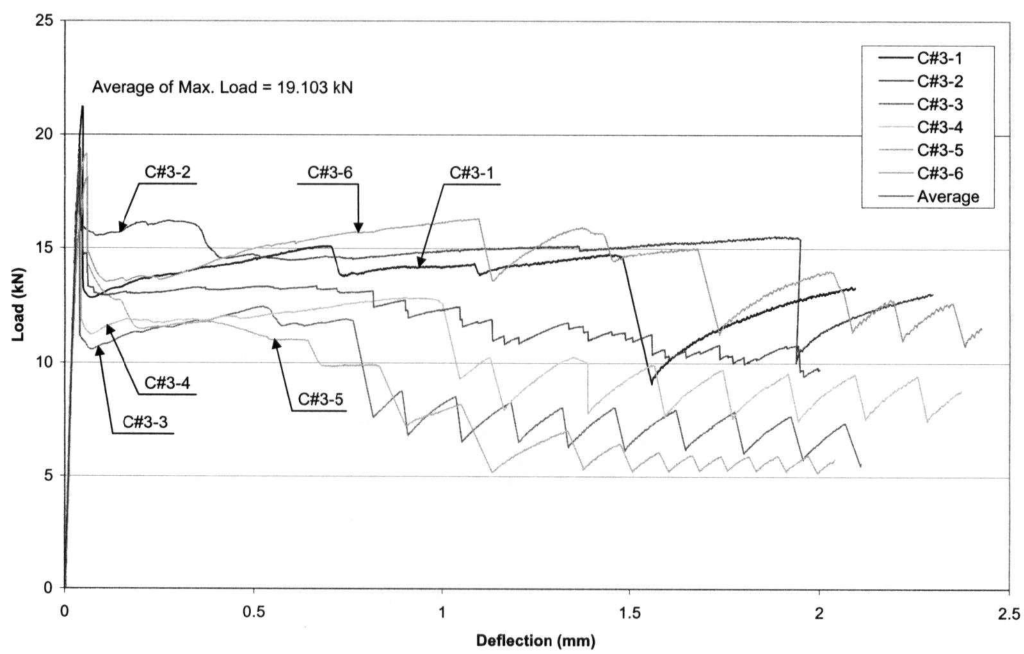

Figure 5.16 FRC Beams with "***0.5% S₂***" (Steel Fiber-Crimped)

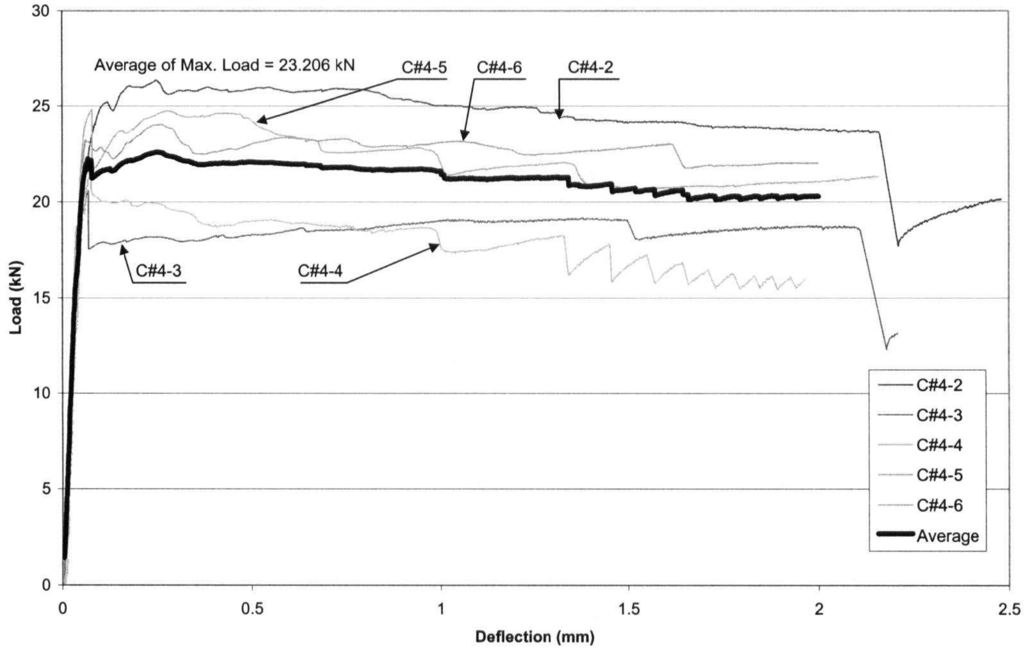

Figure 5.17 FRC Beams with "***1.0% S_2***" (Steel Fiber-Crimped)

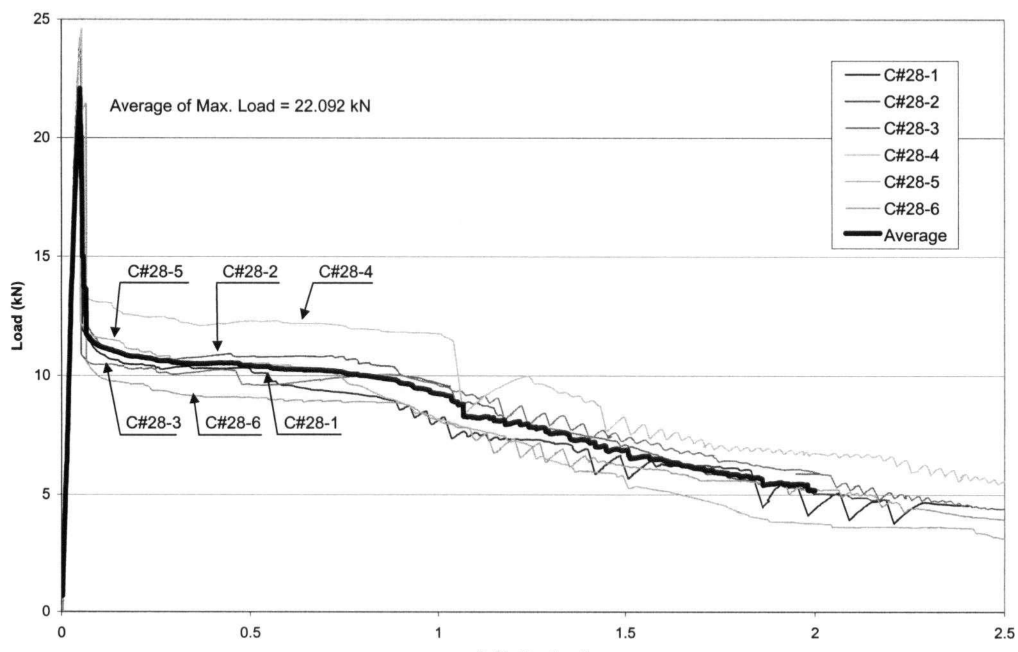

Figure 5.18 FRC Beams with "***0.5% S_3***" (Steel Fiber-Deformed)

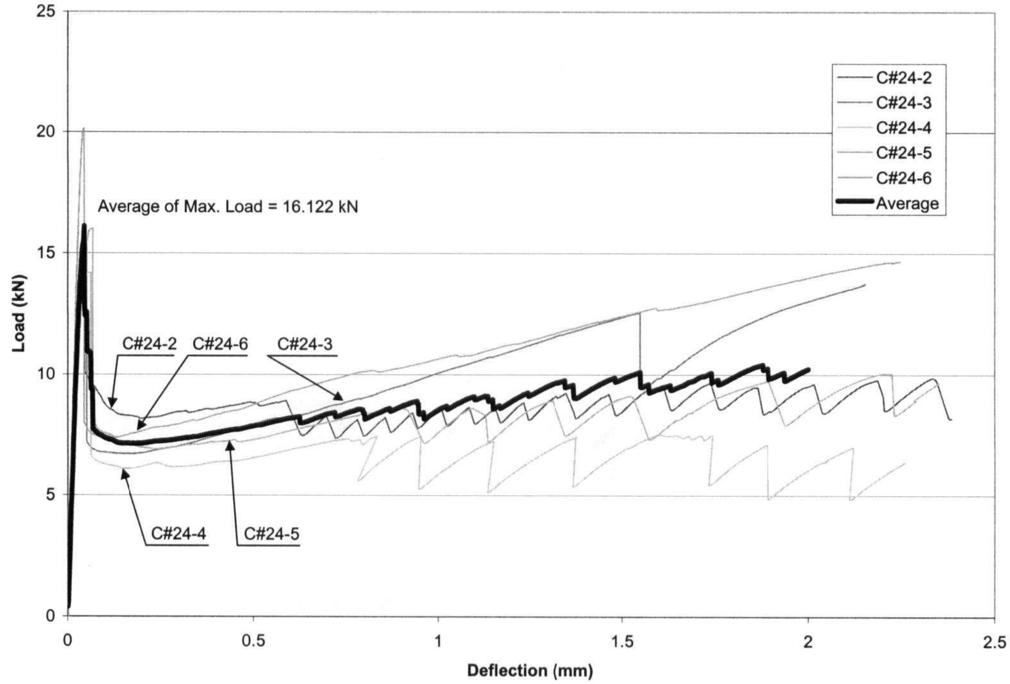

Figure 5.19 FRC Beams with "*0.5% HPP*" (Macro Poly-Crimped)

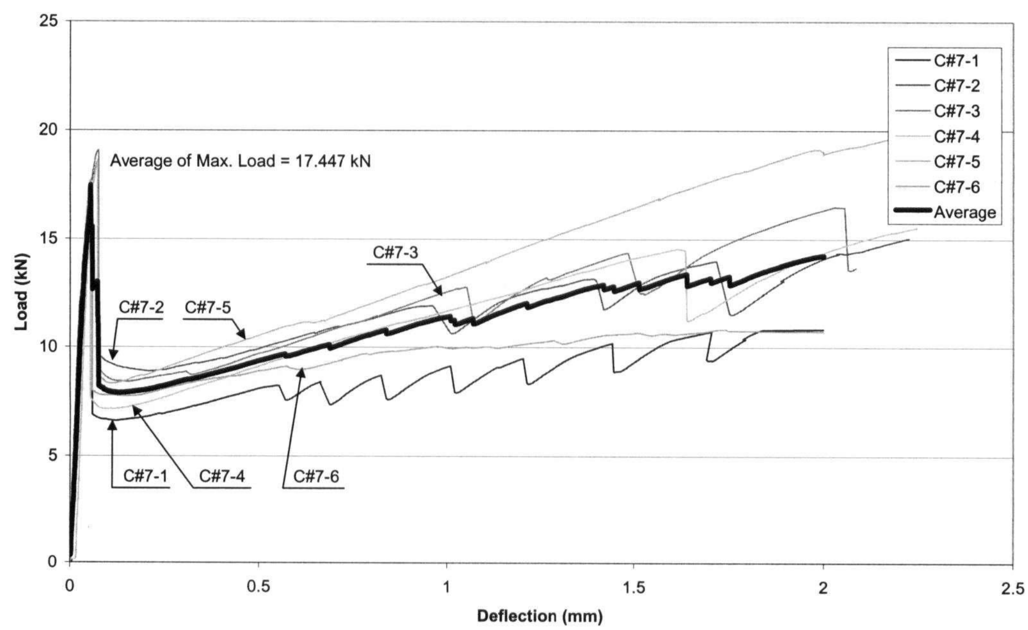

Figure 5.20 FRC Beams with "*1.0% HPP*" (Macro Poly-Crimped)

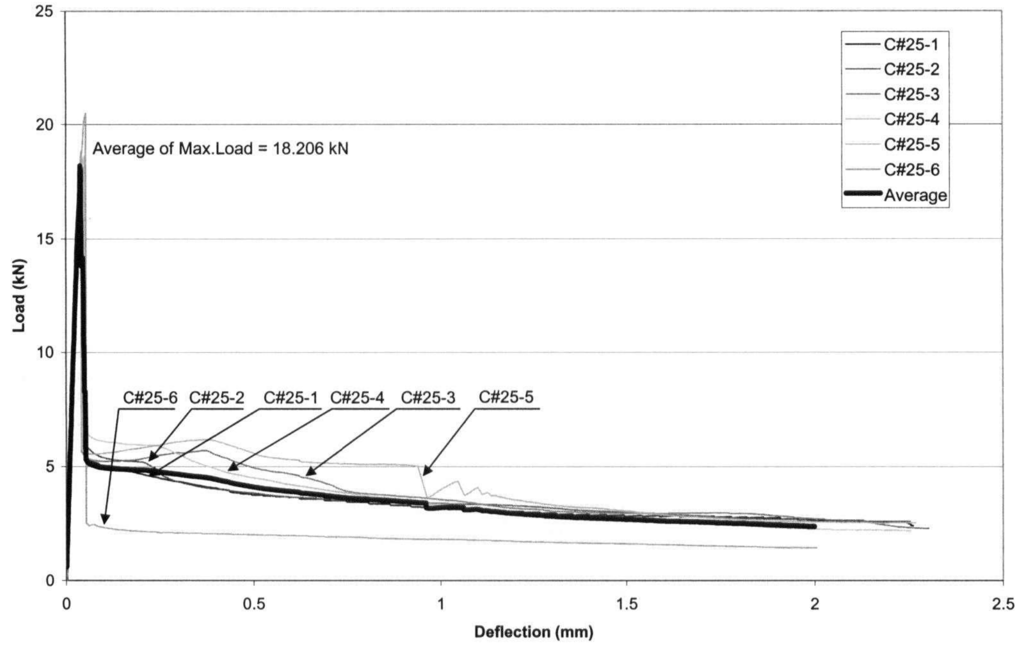

Figure 5.21 FRC Beams with "***0.5% mp***" (Micro Poly)

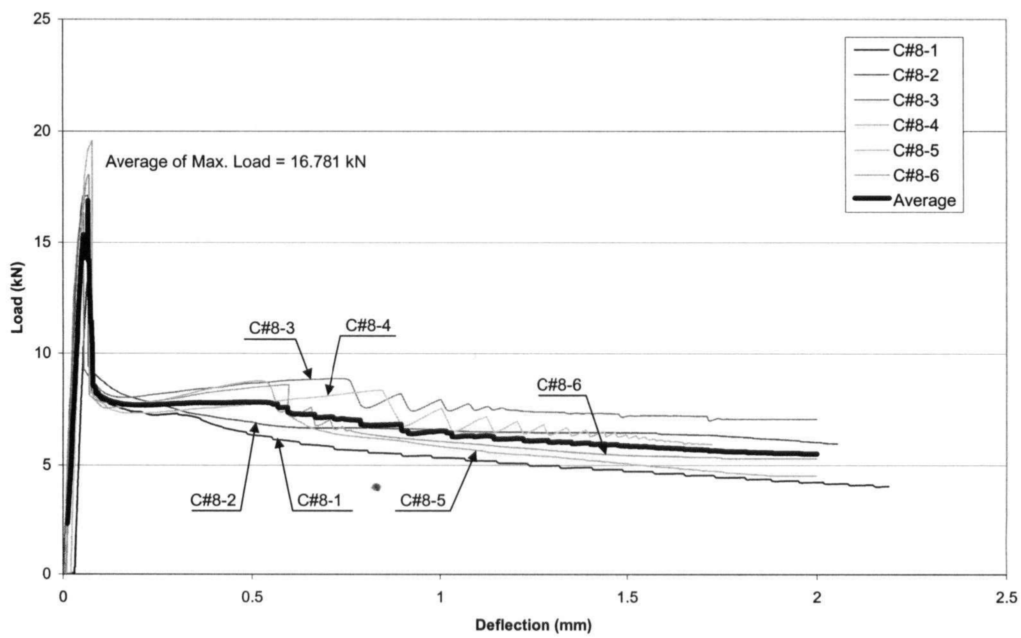

Figure 5.22 FRC Beams with "***1.0% mp***" (Micro Poly)

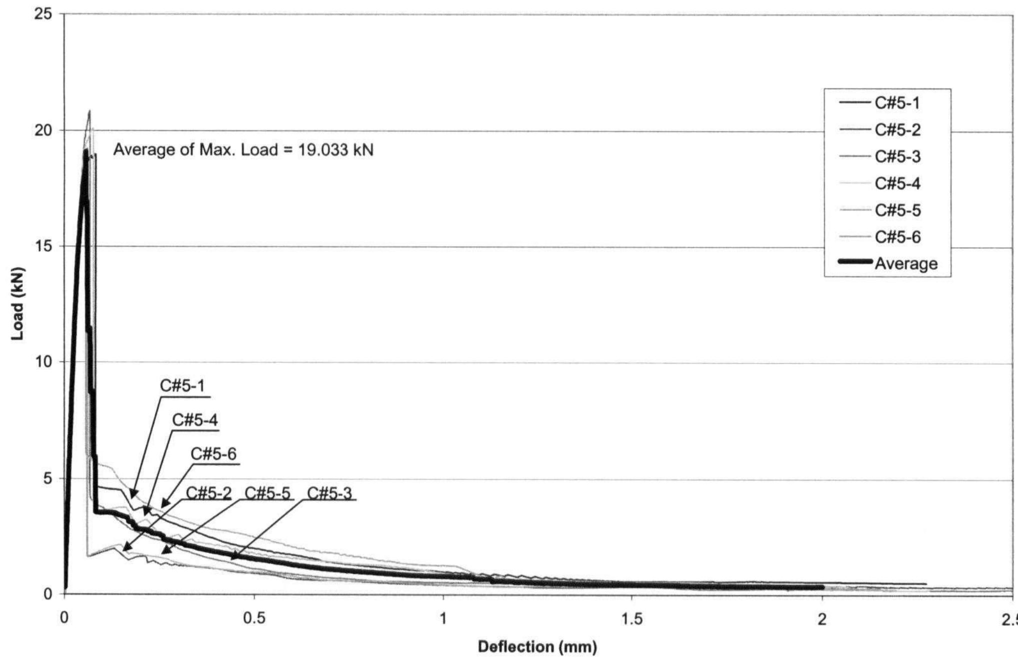

Figure 5.23 FRC Beams with "***0.5% CC***" (Conoco Carbon Fiber)

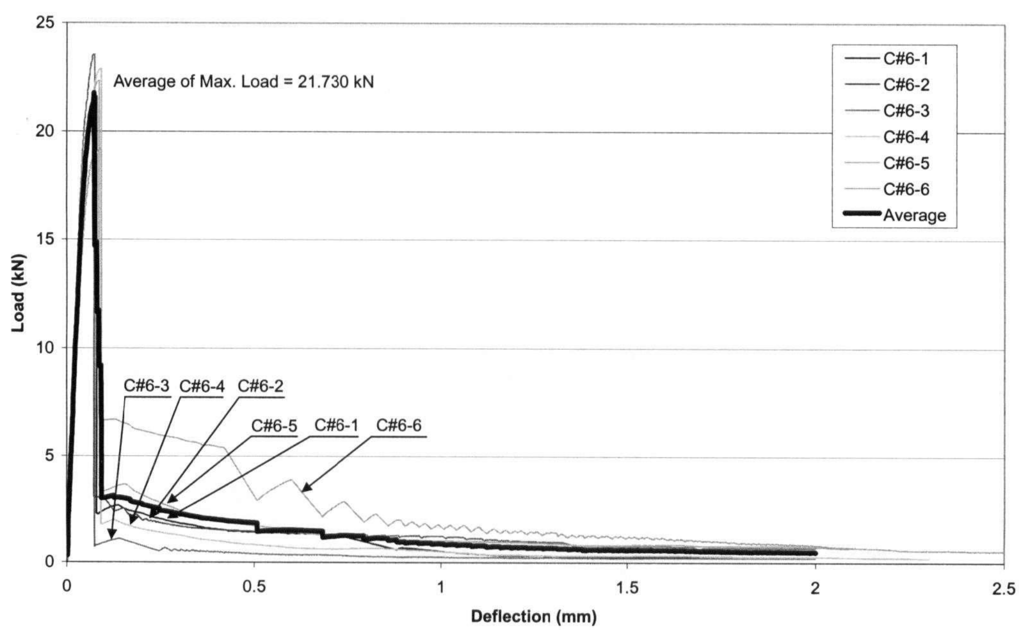

Figure 5.24 FRC Beams with "***1.0% CC***" (Conoco Carbon Fiber)

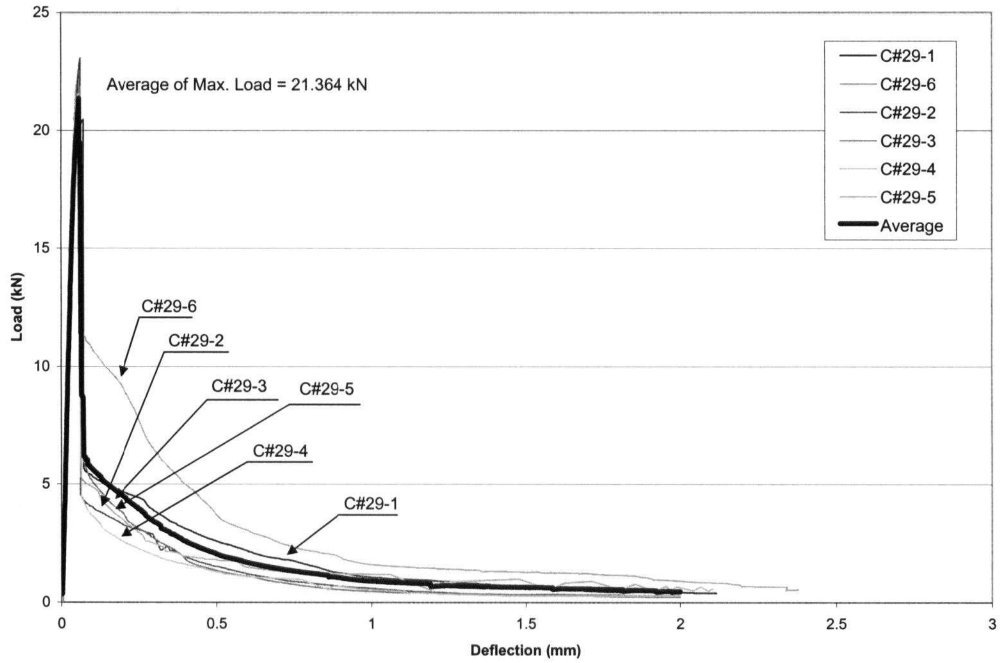

Figure 5.25 FRC Beams with "***0.5% CK***" (Kureha Carbon Fiber)

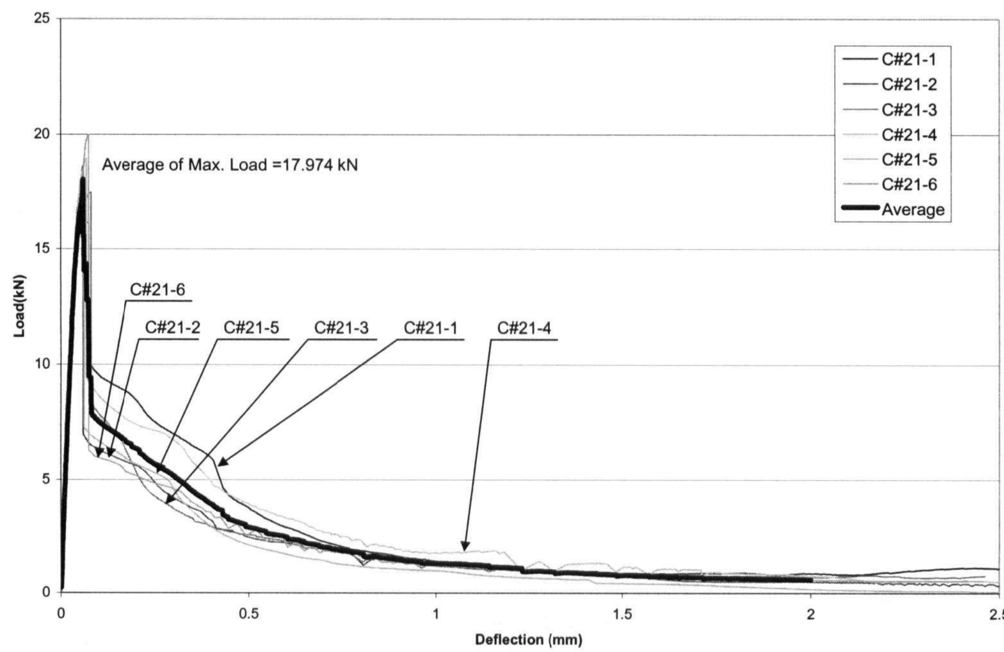

Figure 5.26 HyFRC Beams with "***0.5% CK + 0.5%CC***"

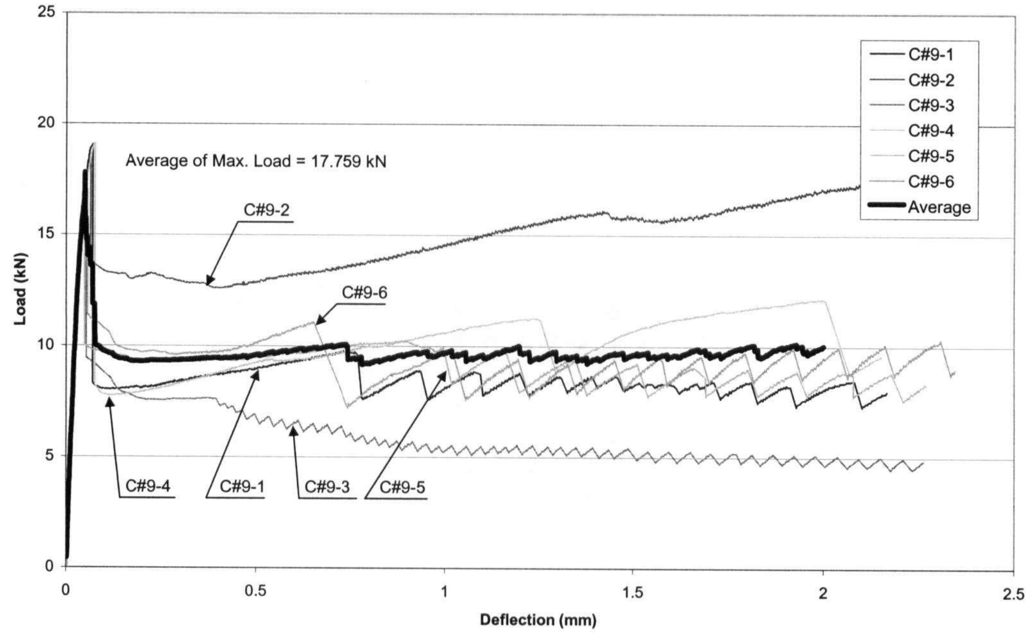

Figure 5.27 HyFRC Beams with "$\mathbf{0.35\%\ S_1 + 0.15\%CC}$"

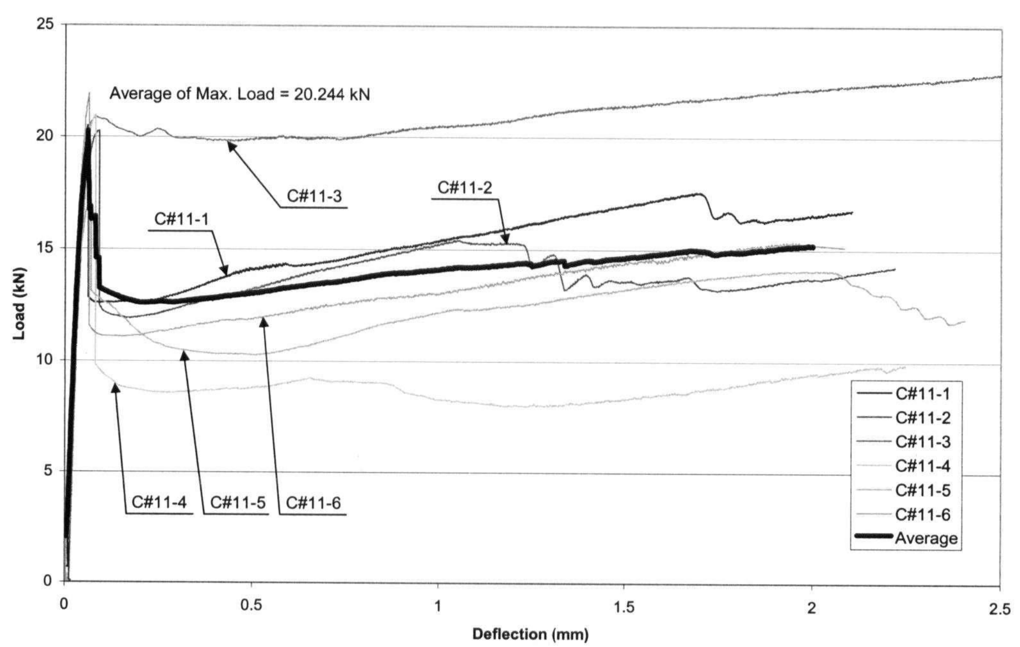

Figure 5.28 HyFRC Beams with "$\mathbf{0.5\%\ S_1 + 0.5\%CC}$"

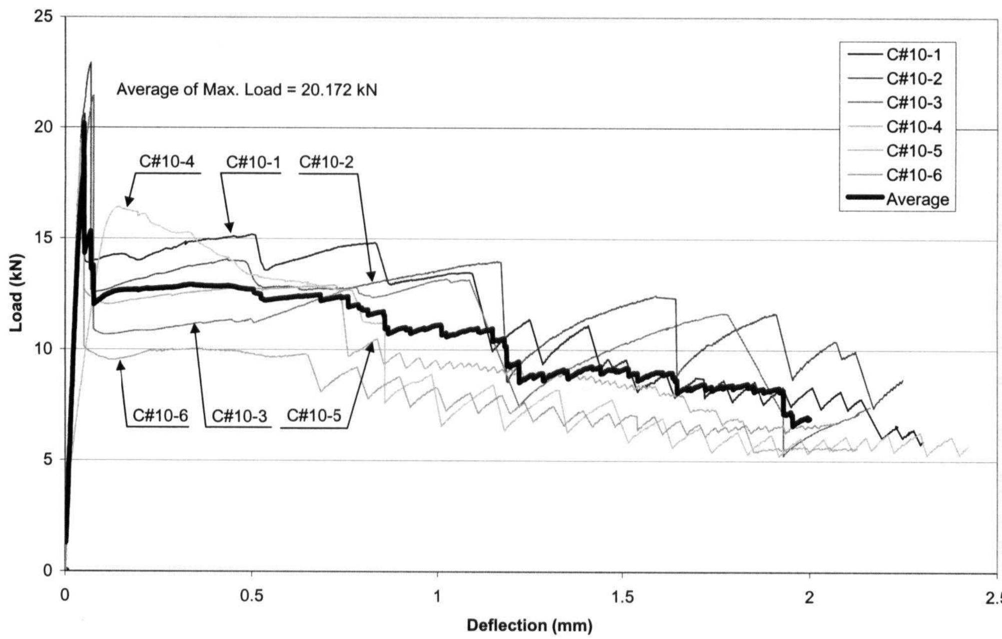

Figure 5.29 HyFRC Beams with "***0.35% S_2 + 0.15%CC***"

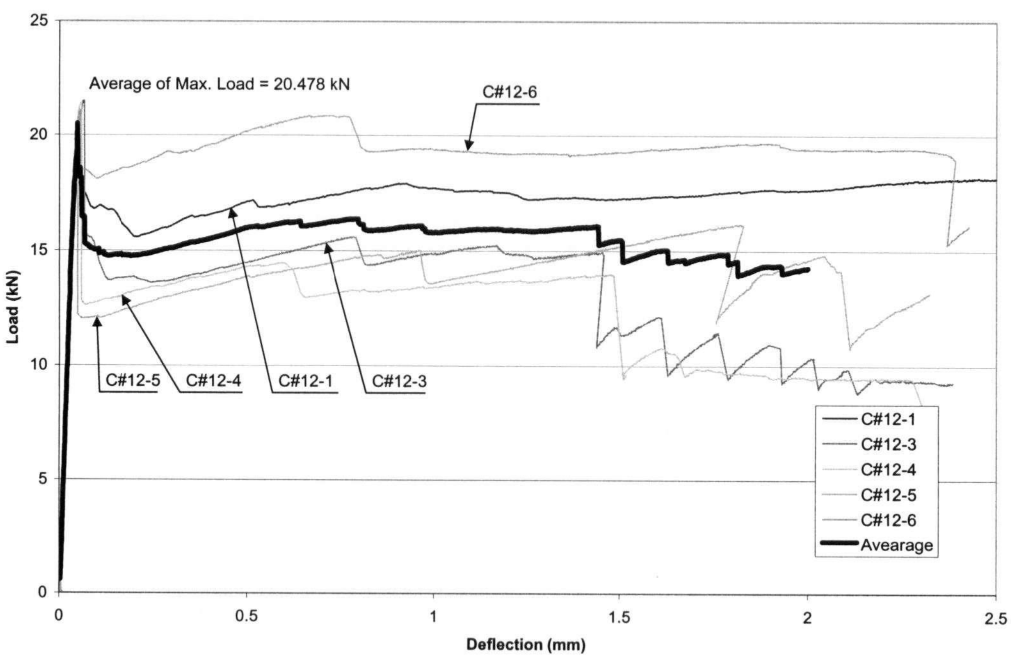

Figure 5.30 HyFRC Beams with "***0.5% S_2 + 0.5%CC***"

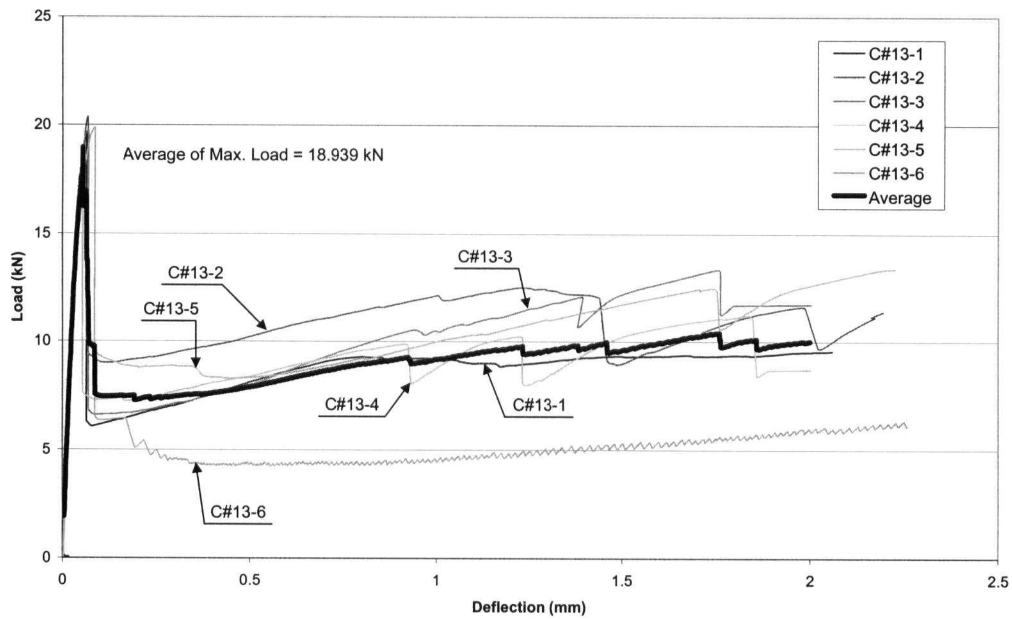

Figure 5.31 HyFRC Beams with "***0.5% HPP + 0.5%CC***"

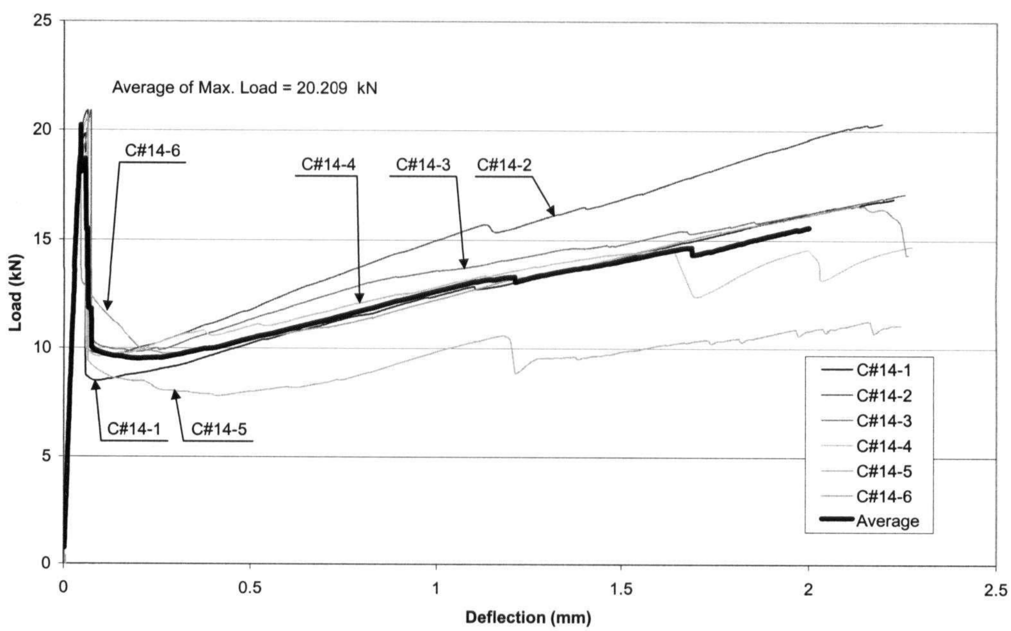

Figure 5.32 HyFRC Beams with "***1.0% HPP + 0.5%CC***"

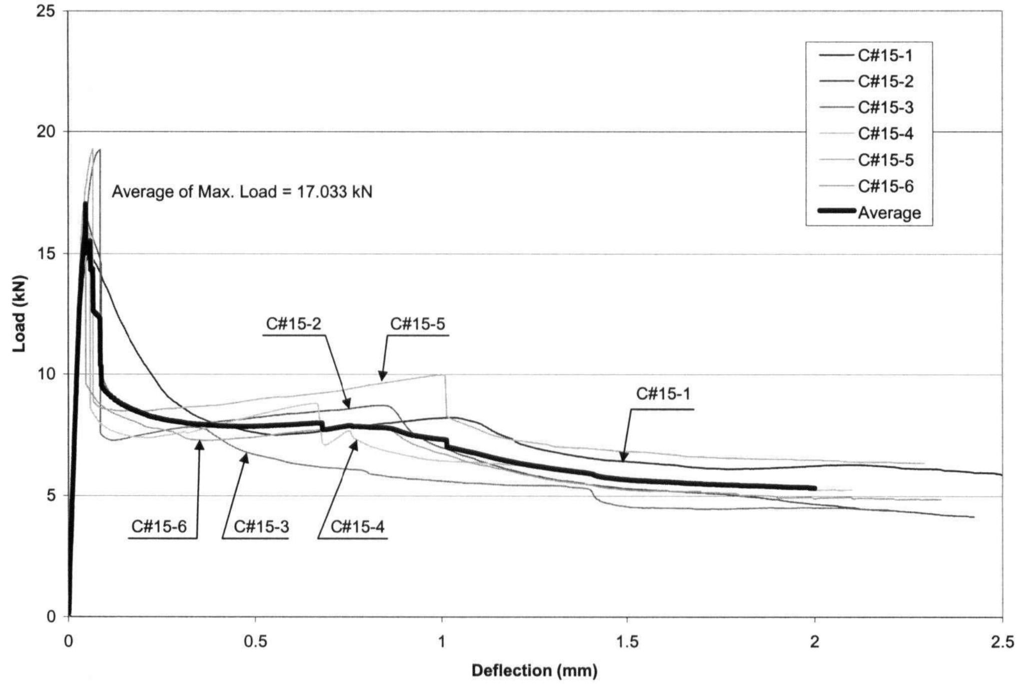

Figure 5.33 HyFRC Beams with "***0.5% mp + 0.5%CC***"

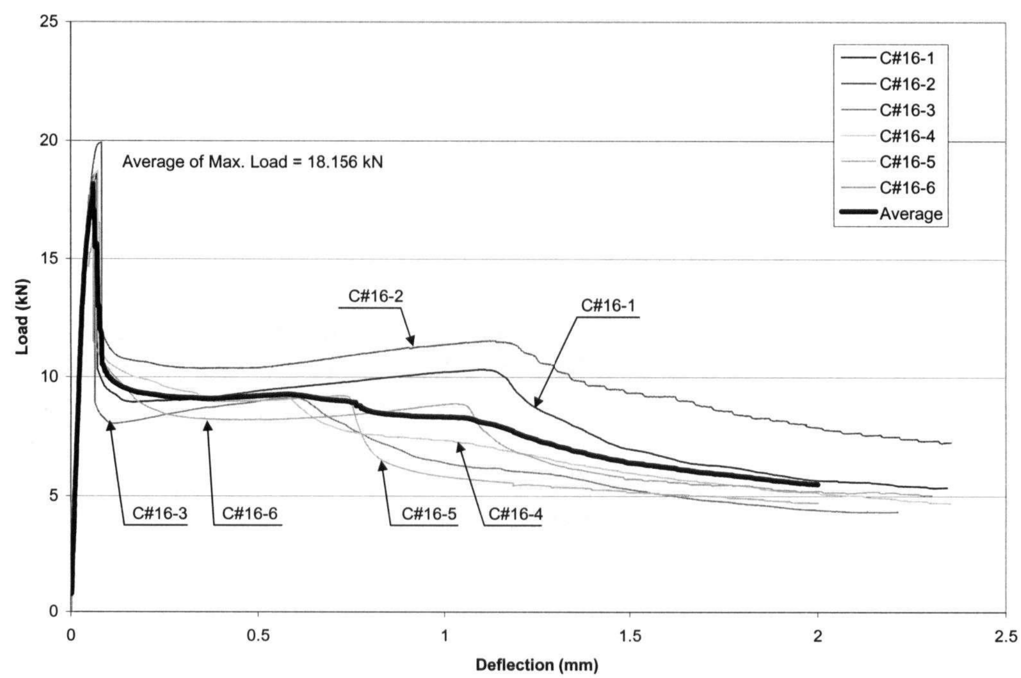

Figure 5.34 HyFRC Beams with "***1.0% mp + 0.5%CC***"

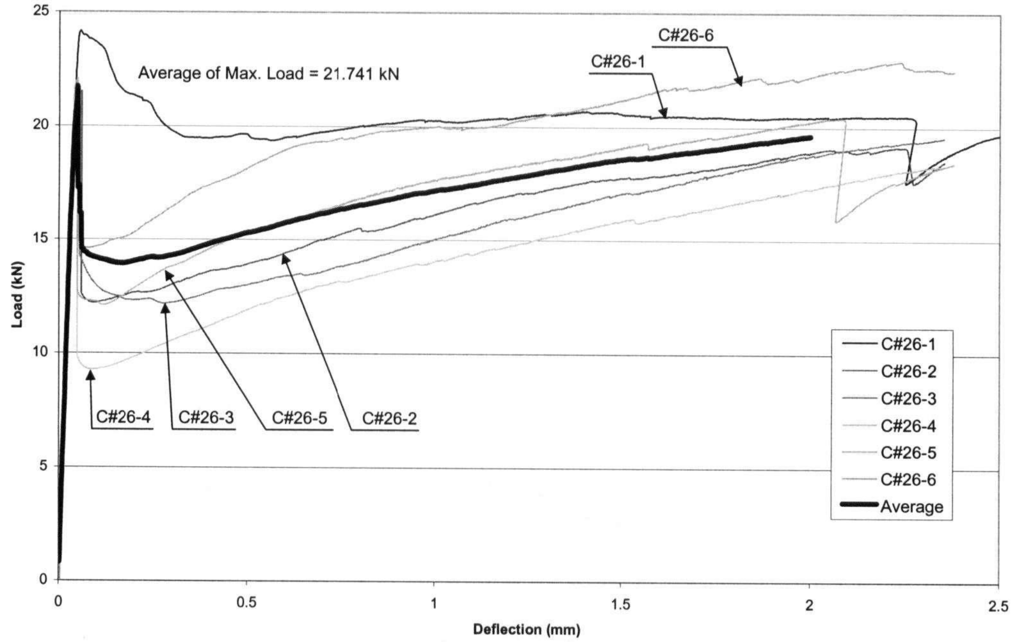

Figure 5.35 HyFRC Beams with "***0.5% S_1 + 0.5%HPP***"

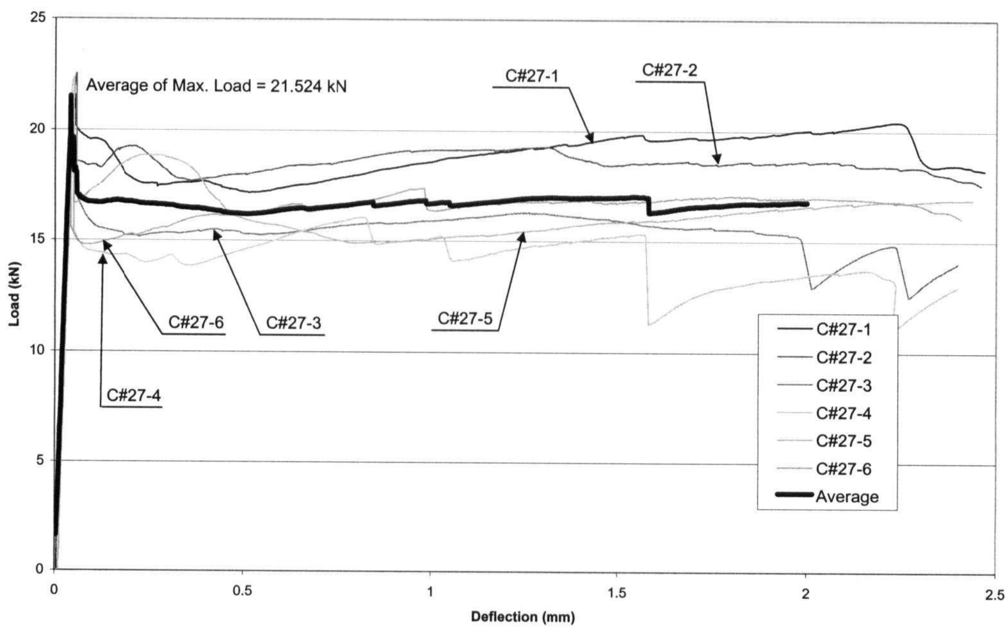

Figure 5.36 HyFRC Beams with "***0.5% S_2 + 0.5%HPP***"

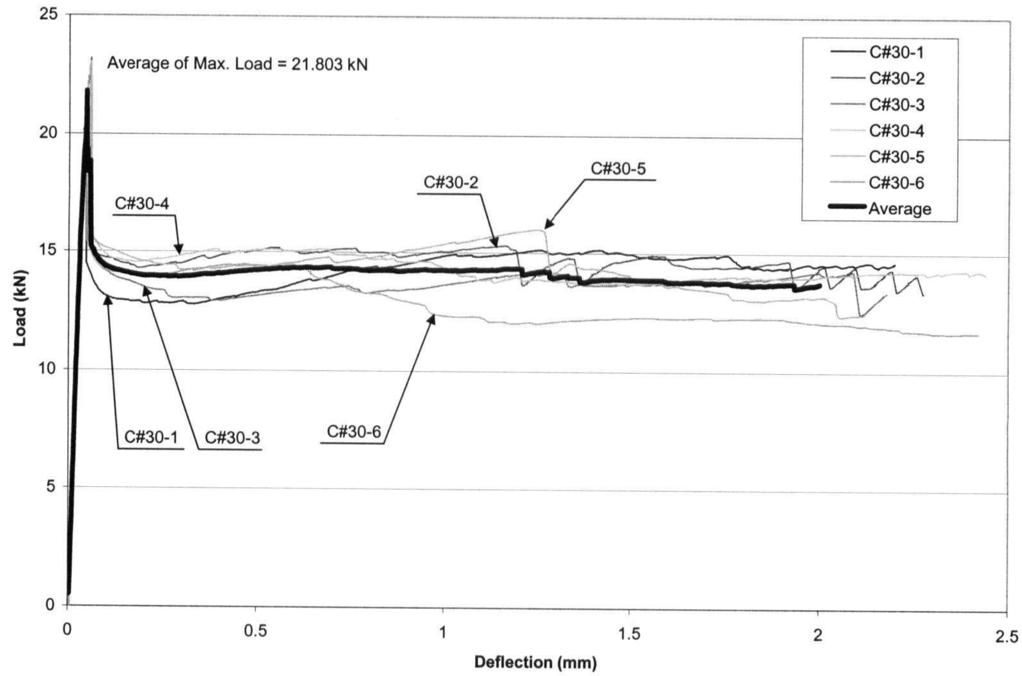

Figure 5.37 HyFRC Beams with "***0.5% S_3 + 0.5%HPP***"

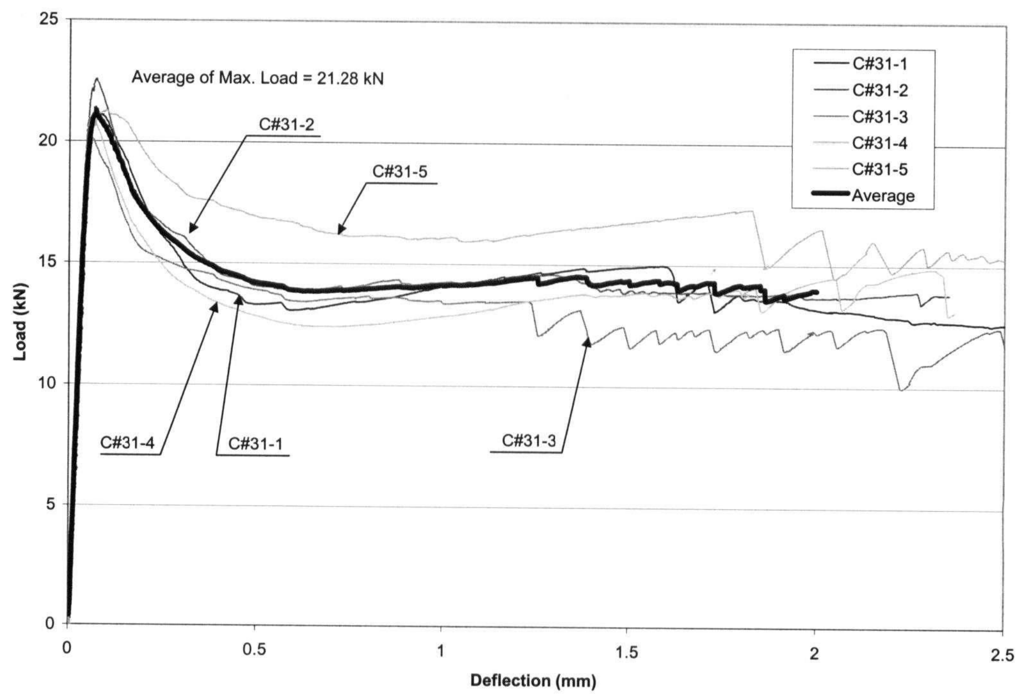

Figure 5.38 HyFRC Beams with "***0.5% S_3 + 0.5%HPP + 0.5%CK***"

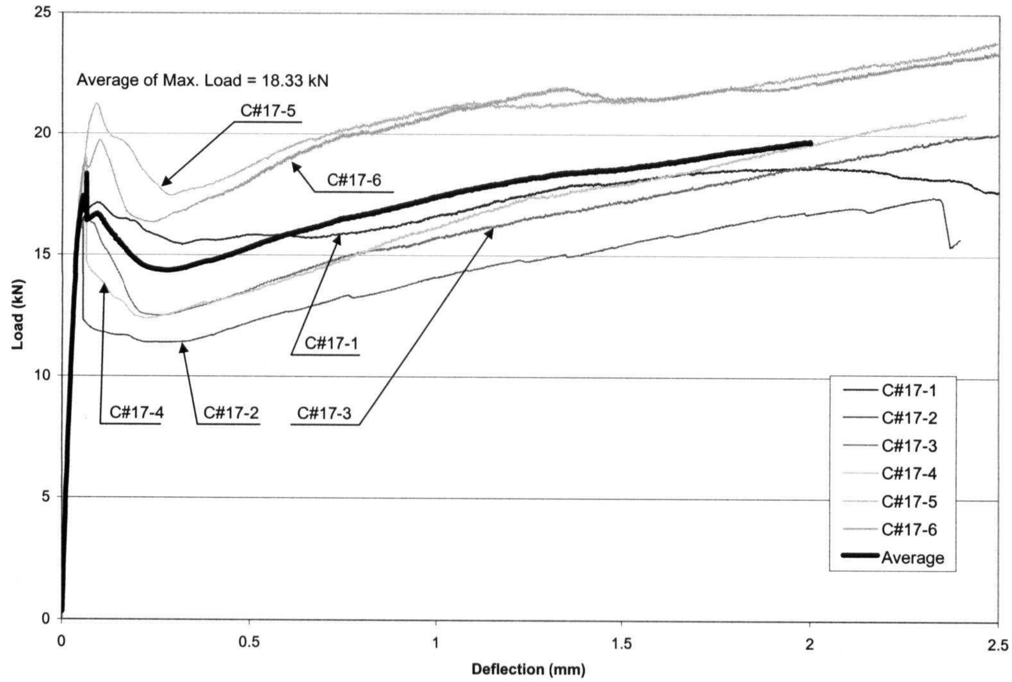

Figure 5.39 HyFRC Beams with "***0.5% S_1 + 0.5%HPP + 0.5%CC***"

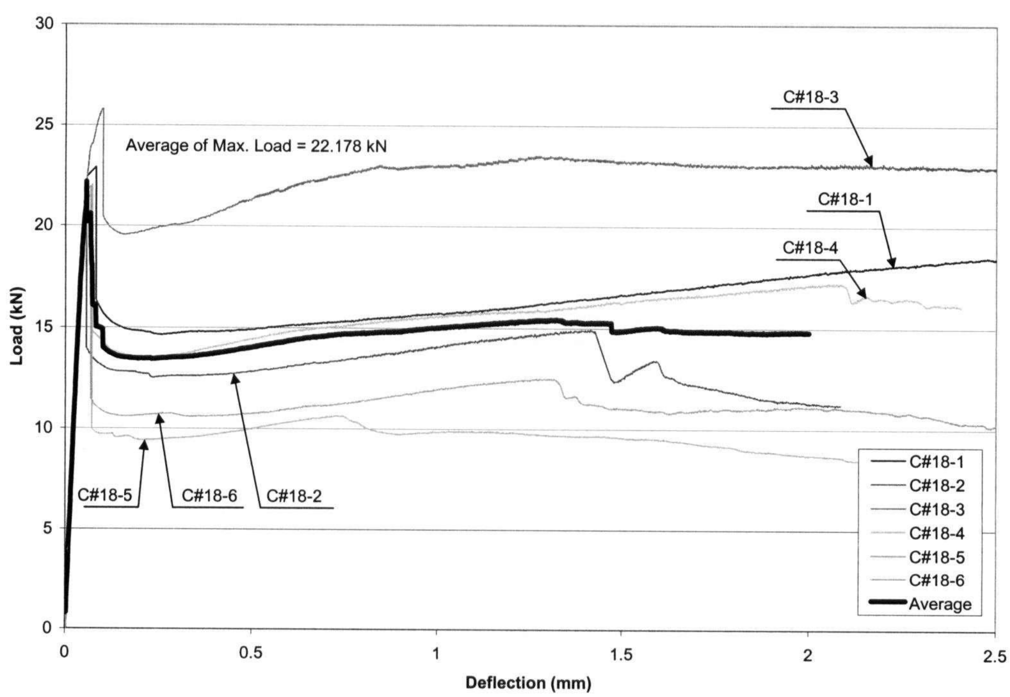

Figure 5.40 HyFRC Beams with "***0.5% S_1 + 0.5%mp + 0.5%CC***"

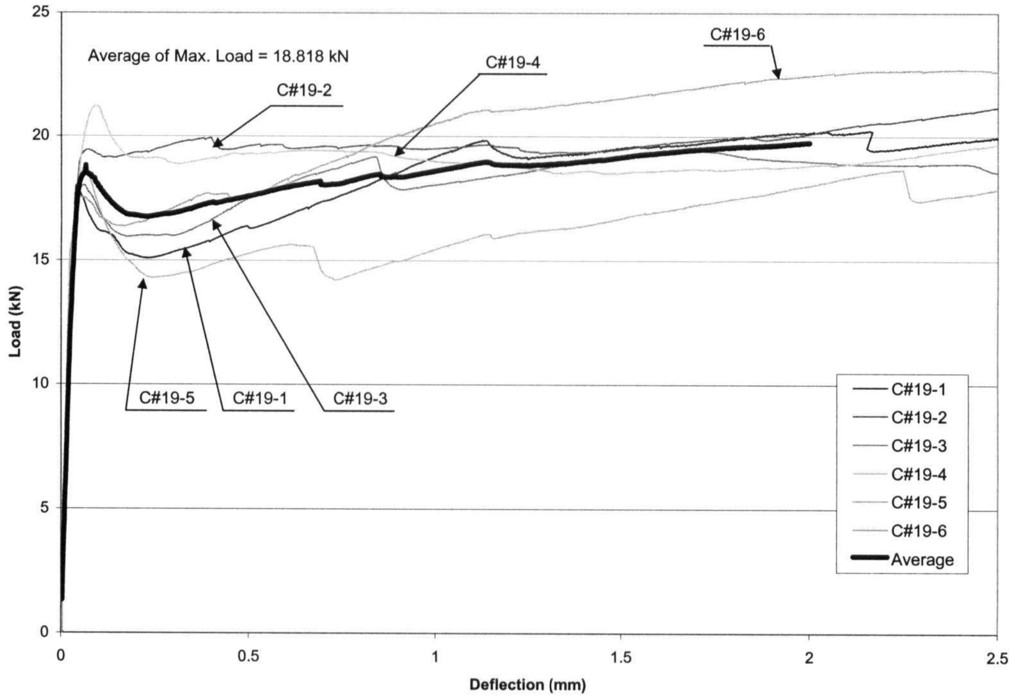

Figure 5.41 HyFRC Beams with "***0.5% S_2 + 0.5%HPP + 0.5%CC***"

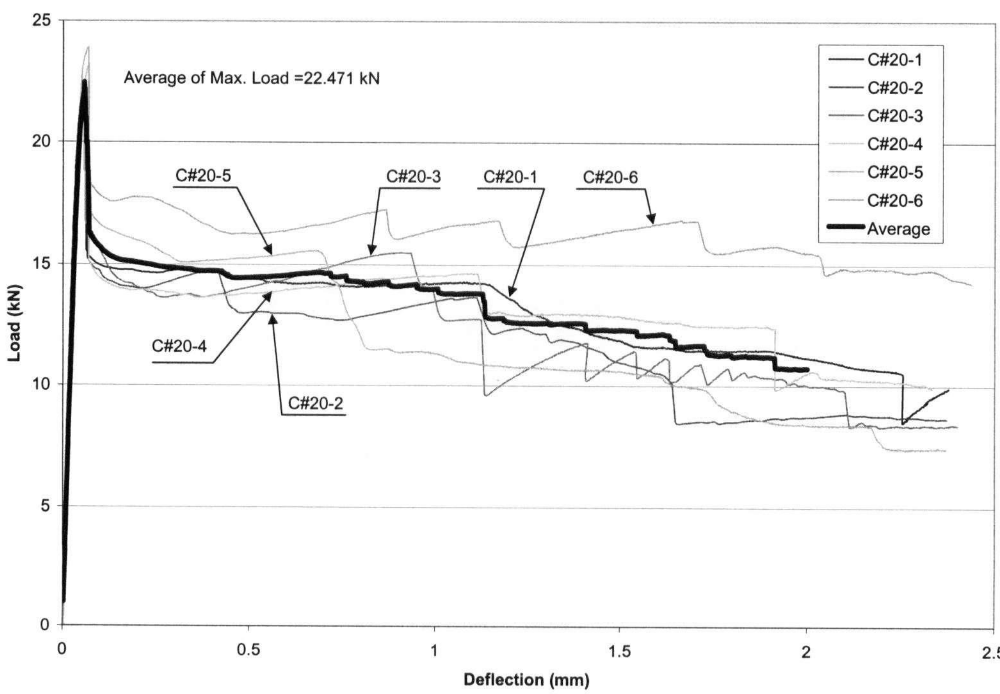

Figure 5.42 HyFRC Beams with "***0.5% S_2 + 0.5%mp + 0.5%CC***"

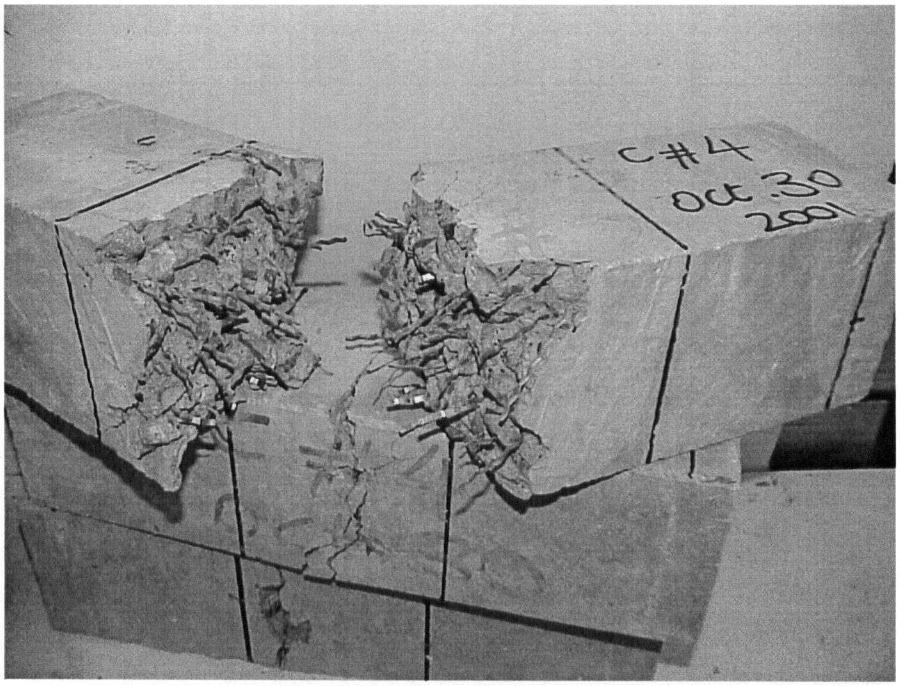

Figure 5.43 FRC Beams with "*1.0% S_2*"

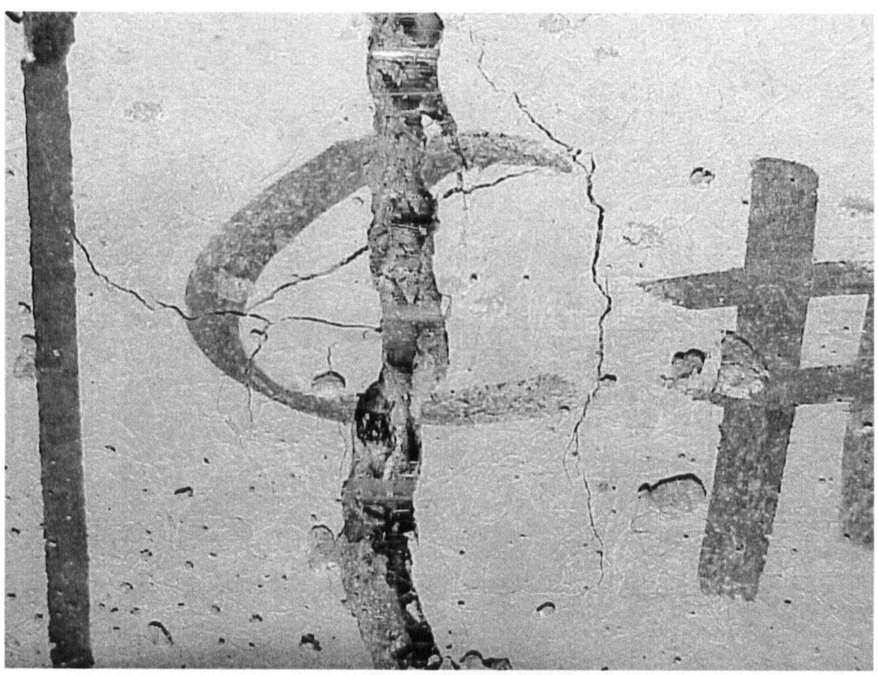

Figure 5.44 Micro Polypropylene Fibers Bridging a Macro Crack in a FRC Tested Beam

6. DISCUSSION

6.1 First-Crack Strength (Modulus of Rupture):

As mentioned in Chapter 5, average Modulus of Rupture (MOR) values of the six specimens in each mix were calculated and the results are given in Table 5.5. Among all the mixes, FRC mix number 4 (1.0% by volume S_2 fiber) showed highest first crack strength (6.96 MPa). On the other hand, FRC mix number 24 (0.5% by volume of HPP fiber) demonstrated the lowest first-crack strength (4.84 MPa) and the highest variability among its individual results (Standard Deviation of 0.7084 MPa). First-crack strength of plain concrete without fiber was 5.62 MPa. HyFRC mix number 14 (0.5% by volume Conoco carbon fiber and 1.0% by volume HPP fiber), on the other hand, demonstrated the lowest variability in its results (Standard Deviation of 0.2305 MPa).

Almost 64% of FRC specimens (i.e. with one kind of fiber), 67% of HyFRC specimens containing two kinds of fibers and 80% of HyFRC specimens containing three kinds of fibers had first-crack strengths higher than that of plain concrete.

HyFRC mix number 10 (0.35% by volume S_2 fiber and 0.15% by volume of Conoco carbon fiber), with a lower compressive strength (43.7 MPa) compared to that of plain concrete (59.3 MPa), surprisingly showed a higher first-crack strength (6.05 MPa).

6.2 Flexural Toughness:

Toughness of FRC and HyFRC can be characterized by three different methods: ASTM C 1018 standard test method, JSCE standard SF-4 method and PCS method, as discussed in chapter 4. As mentioned earlier, the results of this study were analyzed by using the "Post Crack Strength" (PCS) method as proposed by Banthia and Trottier [14]. However, in the following sections, one of the load versus deflection curves is chosen and analyzed according to ASTM C 1018 and JSCE SF-4 as well. After that, PCS values of all test results are calculated and discussed.

6.2.1 ASTM C 1018 Standard Test Method

The load versus deflection curve of specimen No.5 in FRC mix number 1 (C#1-5) with 0.5% by volume of S_1 fiber is shown in Figure 6.1. The calculations of toughness indices requires an accurate assessment of the first-crack energy which constitutes the denominator in the definition of the various indices as defined in section 4.4.1. It is, at least in principle, easy enough to measure net deflections accurately. However, defining first crack is a much more difficult problem conceptually. In ASTM C 1018, first crack is defined as "the point on the load-deflection curve at which the form of the curve first becomes nonlinear." Implicit in this definition is the assumption that the fiber reinforced concrete is a linearly elastic material up to first crack. However, it has long been known that, when looked at in detail, the σ-ε curve for concrete is nonlinear at about 10% of ultimate stress, though it is often approximated as being linear up to about 50% of the ultimate stress. In fact, even before it is loaded, concrete contains micro-cracks, and some of these begin to grow as soon as the concrete is loaded. Thus, the phrase "first-crack deflection" has no fundamental meaning. This is seen clearly in the curve of Figure 6.2, which is highly nonlinear everywhere; note that in this figure, the true load-deflection curve (the wavy line) has been replaced by a simple curve.

Figure 6.2 shows the initial ascending part of the curve in Figure 6.1, which has been magnified to locate the first crack. Based on the ASTM C 1018 definition, the first crack may be placed at point "A" where the deflection is 0.021 mm. Points "B" and "C" corresponding to deflections of 0.034 mm and 0.053 mm, respectively, can also be chosen as the first crack points. On comparing these deflection values with the range of deflections suggested in the standard of between 0.038 to 0.064 mm, it is apparent that only one of the chosen deflections, point "C", is in this range.

In Table 6.1, the indices are calculated based on the three possible locations of the first crack at points "A", "B", and "C" corresponding to first-crack deflections of 0.021, 0.034, and 0.053 mm, respectively. Notice that, based on where the first crack is assumed to occur, extreme variations in the index values may occur. Even if standardized equipment with high precision is used as in this case, the placement of first crack is highly objective; this is bound to lead to large variations between operators and laboratories. This was a major concern for rejecting this method to analyze and compare the results of this study.

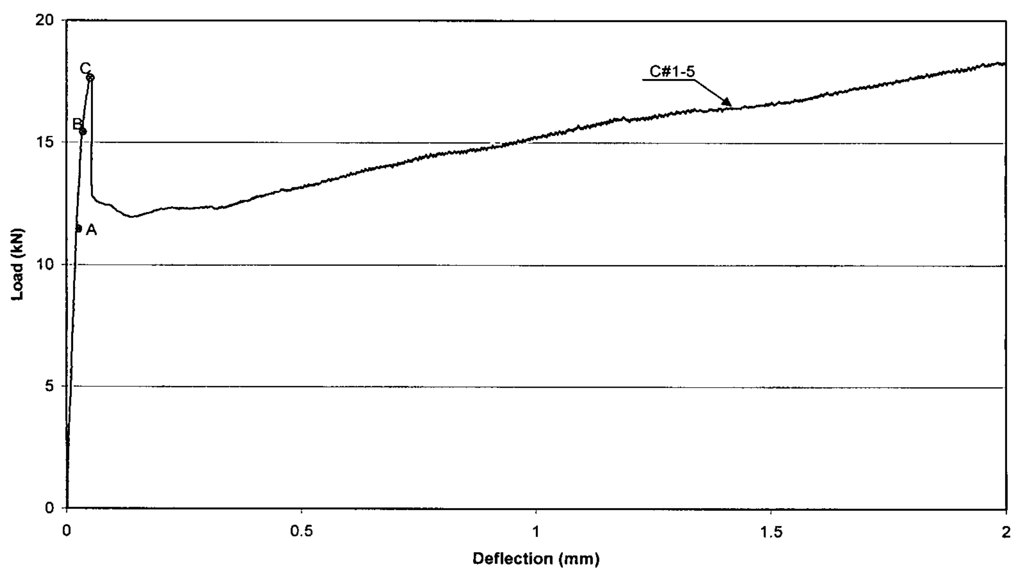

Figure 6.1 Load versus Deflection Curve of a Selected Specimen (C#1-5)

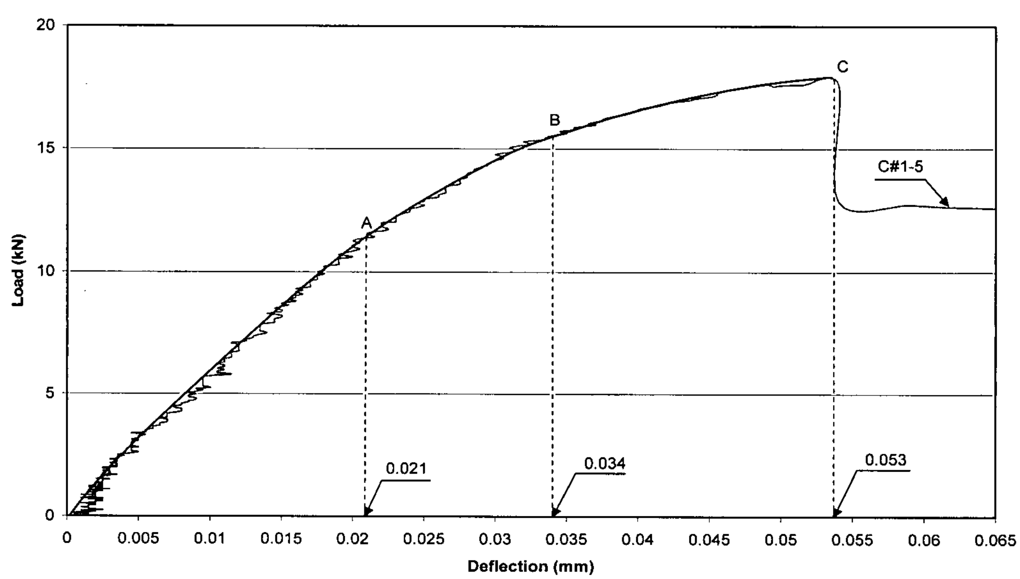

Figure 6.2 Magnified Initial Portion of the Curve in the Figure 6.1

Toughness Indices	Location of First-Crack Point		
	0.021 mm, Point A	0.034 mm, Point B	0.053 mm, Point C
I_5	5.99	4.12	3.01
I_{10}	11.31	7.49	5.55
I_{20}	21.60	14.44	10.89
I_{30}	32.11	21.81	16.67

Table 6.1 Toughness Indices as Affected by First-Crack Placement

6.2.2 JSCE Standard SF-4 Method

The flexural toughness factor (FT) for the previously mentioned specimen (specimen C#1-5) is calculated according to the equation (4.9) and is equal to 4.51 MPa:

$$FT = \frac{A_{(L/150)} \times L}{(L/150) \times b \times h^2}$$

$$= \frac{30.094 kN.mm \times 300 mm}{(300/150) mm \times 100 mm \times (100)^2 mm^2} \times 1000 N/kN = 4.51 N/mm^2 = 4.51 MPa$$

As mentioned earlier, this method gives only one number as a flexural toughness factor (FT) and the behavior of FRC or HyFRC immediately following the first crack, which may be of importance in many applications, is not indicated in FT in any way. Therefore, the PCS method was used to analyze the results in this study.

6.2.3 Banthia and Trottier's Proposed Method (PCS Method)

In this method, there is no ambiguity in either identifying the peak load on the curve or in calculating the pre-peak energy absorbed. Post-crack strength (PCS_m) in the post-peak region at the various deflections for every specimen was calculated by using equation (4.10). A large range of deflections from L/3000 (300/3000 = 0.1 mm) to L/150 (300/150 = 2 mm), which is quite useful for different serviceability conditions, was considered to calculate PCS values. Post-crack strengths (PCS_m) for the previously mentioned specimen (specimen C#1-5) were calculated according to the equation (4.10) and results are listed in Table 6.2.

PCS_m	L/m (mm)	PCS_m Value (MPa)
PCS_{3000}	0.1	3.684
PCS_{1500}	0.2	3.699
PCS_{1000}	0.3	3.676
PCS_{750}	0.4	3.712
PCS_{600}	0.5	3.741
PCS_{400}	0.75	3.886
PCS_{300}	1.0	4.019
PCS_{200}	1.5	4.293
PCS_{150}	2.0	4.541

Table 6.2 Post-Crack Strengths (PCS_m) for Specimen C#1-5

Comparing equation (4.9) with (4.10), for a deflection of L/150, it is observed that the terms $E_{post,m}$ and $A_{(L/150)}$ in the numerator represent the area under the load-deflection curves. The only difference is that the term $E_{post,m}$ does not include a small portion of the pre-peak area. This pre-peak area is negligible compared to the total area up to L/150. In the same way, the terms in the denominator, ($L/M-\delta_{peak}$) and L/150 are almost the same except for a small difference of δ_{peak}, which is small, compared to L/150 (which is 2 mm in case of a 300 mm span). Thus, FT values and PCS_{150} values (PCS values for a deflection of L/150) are almost the same. For the previously mentioned specimen, FT was equal to 4.51 MPa and PCS_{150} equal to 4.541 MPa.

PCS values of mixes in this study were calculated and results are given in Table 6.3.

Table 6.3 PCS_m Values and Modulus of Ruptures (MPa) for Different Mixes

Mix	MOR	PCS_{3000} (L/m=0.1)	PCS_{1500} (L/m=0.2)	PCS_{1000} (L/m=0.3)	PCS_{750} (L/m=0.4)	PCS_{600} (L/m=0.5)	PCS_{400} (L/m=0.75)	PCS_{300} (L/m=1.0)	PCS_{200} (L/m=1.5)	PCS_{150} (L/m=2.0)
Plain	*5.620*	1.064	1.009	0.929	0.847	0.747	0.614	0.519	0.396	0.304
1	*6.320*	3.646	3.621	3.613	3.665	3.702	3.829	3.944	4.086	4.184
2	*6.470*	6.900	6.228	6.202	6.235	6.255	6.276	6.285	6.287	6.308
3	*5.730*	5.363	4.729	4.372	4.244	4.177	4.106	4.053	3.849	3.687
4	*6.960*	6.242	6.574	6.675	6.638	6.645	6.612	6.600	6.233	6.388
5	*5.710*	1.053	0.999	0.896	0.807	0.736	0.606	0.518	0.386	0.322
6	*6.520*	0.877	0.910	0.820	0.762	0.709	0.591	0.512	0.406	0.342
7	*5.236*	2.488	2.404	2.425	2.480	2.534	2.686	2.818	3.103	3.266
8	*5.030*	2.474	2.387	2.355	2.343	2.345	2.298	2.216	2.085	1.983
9	*5.330*	3.011	2.887	2.847	2.845	2.850	2.875	2.862	2.859	2.877
10	*6.052*	3.440	3.804	3.797	3.824	3.831	3.776	3.668	3.370	3.121
11	*6.070*	4.195	3.882	3.838	3.835	3.841	3.907	3.983	4.086	4.225
12	*6.143*	4.691	4.478	4.487	4.522	4.568	4.667	4.697	4.718	4.625
13	*5.680*	2.240	2.245	2.221	2.232	2.251	2.341	2.443	2.591	2.701
14	*6.063*	3.046	2.933	2.901	2.928	2.958	3.077	3.225	3.496	3.734
15	*5.110*	3.055	2.783	2.646	2.573	2.525	2.464	2.419	2.237	2.083
16	*5.450*	5.277	4.417	3.780	3.473	3.303	3.098	2.985	2.765	2.532
17	*5.499*	4.855	4.756	4.545	4.495	4.503	4.595	4.731	4.981	5.176
18	*6.650*	3.970	4.107	4.084	4.099	4.118	4.199	4.261	4.370	4.393
19	*5.645*	5.606	5.242	5.152	5.160	5.168	5.226	5.316	5.439	5.544
20	*6.741*	4.668	4.665	4.581	4.548	4.496	4.458	4.389	4.209	4.012
21	*5.390*	2.281	2.158	1.935	1.774	1.586	1.261	1.044	0.786	0.635
22	*5.855*	2.404	2.326	2.324	2.351	2.373	2.460	2.518	2.529	2.496
23	*5.153*	2.946	2.942	2.978	3.030	3.087	3.172	3.208	3.128	2.993
24	*4.837*	2.303	2.193	2.173	2.192	2.222	2.300	2.364	2.497	2.611
25	*5.462*	1.555	1.486	1.464	1.437	1.402	1.316	1.243	1.118	1.027
26	*6.522*	4.349	4.230	4.240	4.276	4.327	4.481	4.630	4.881	5.097
27	*6.457*	4.959	5.021	5.024	5.000	4.970	4.951	4.966	4.999	4.996
28	*6.628*	3.444	3.367	3.284	3.259	3.234	3.180	3.114	2.847	2.571
29	*6.409*	1.780	1.588	1.410	1.258	1.125	0.893	0.740	0.557	0.455
30	*6.541*	4.426	4.312	4.252	4.247	4.241	4.258	4.269	4.253	4.222
31	*6.384*	6.446	5.735	5.378	5.128	4.940	4.660	4.538	4.457	4.390

In the following sections test results of hybridization among different macro and micro fibers will be reviewed and discussed. Their PCS values will also be compared and discussed, as and when appropriate

Figures 6.3, 6.5, 6.7, 6.9, 6.11, 6.13, 6.15, 6.17, 6.19, 6.21, 6.23, 6.25, 6.27, 6.29 show and compare the load versus deflection curves of different mixes which have been tested in this study. Each curve represents an average of six tested beams. Figures 6.4, 6.6, 6.8, 6.10, 6.12, 6.14, 6.16, 6.18, 6.20, 6.22, 6.24, 6.26, 6.28, 6.30 show and compare Modulus of Rupture (MOR) of different mixes as well as their PCS values at different L/m ratios.

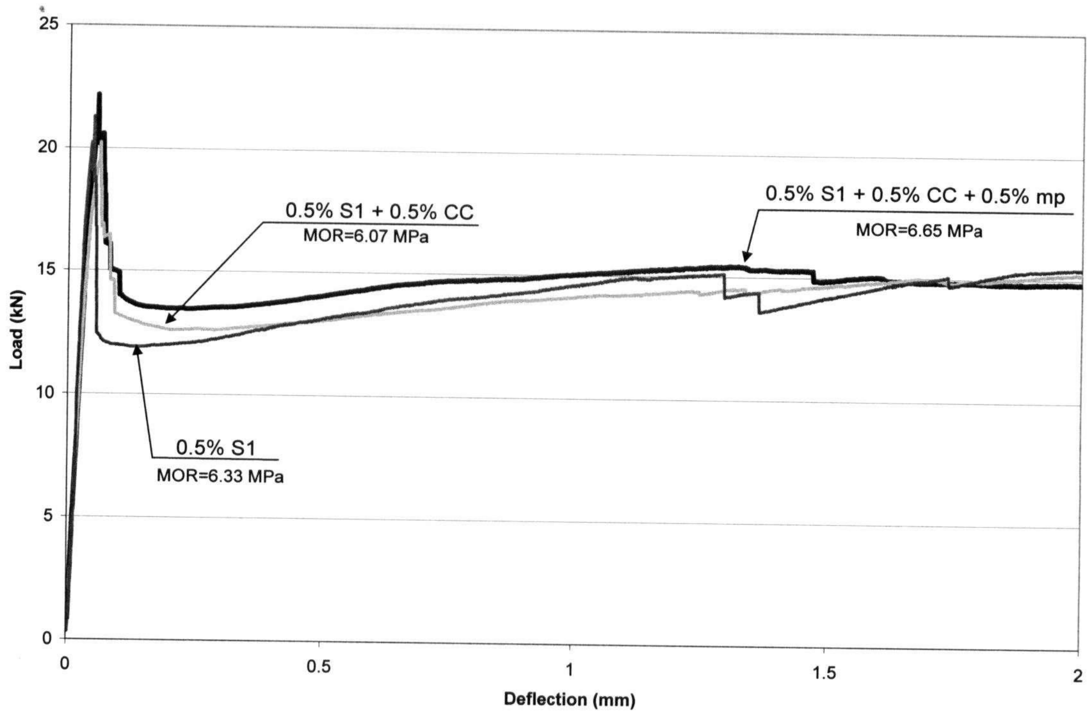

Figure 6.3 S_1, mp and CC Fibers

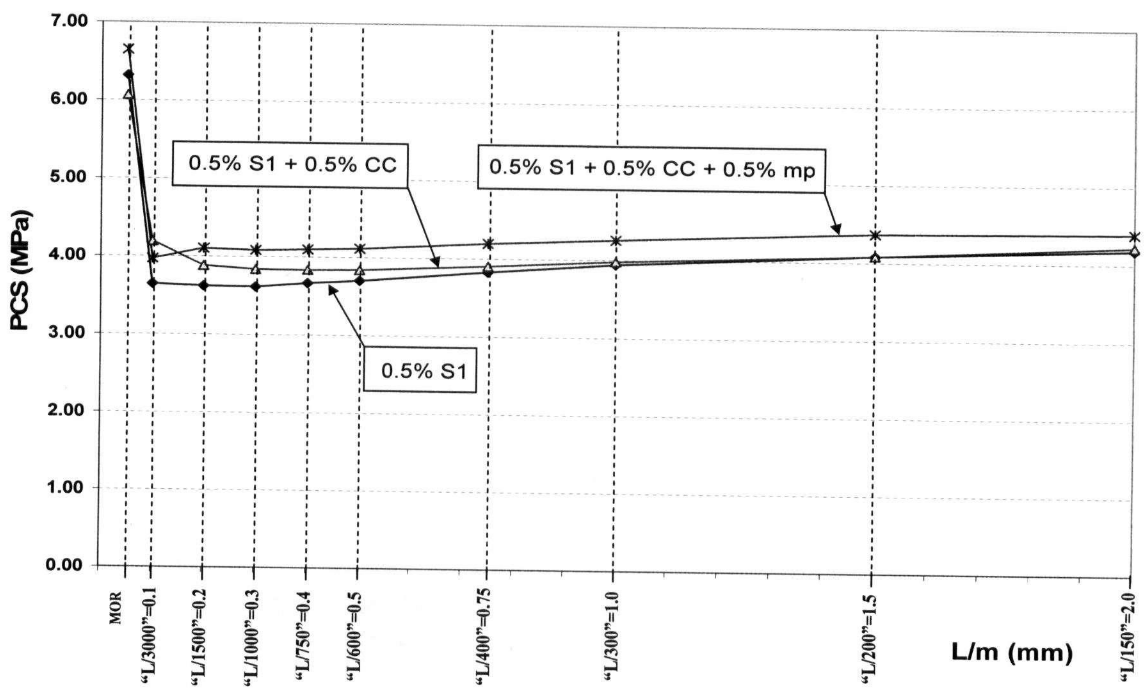

Figure 6.4 PCS - S_1, mp and CC Fibers

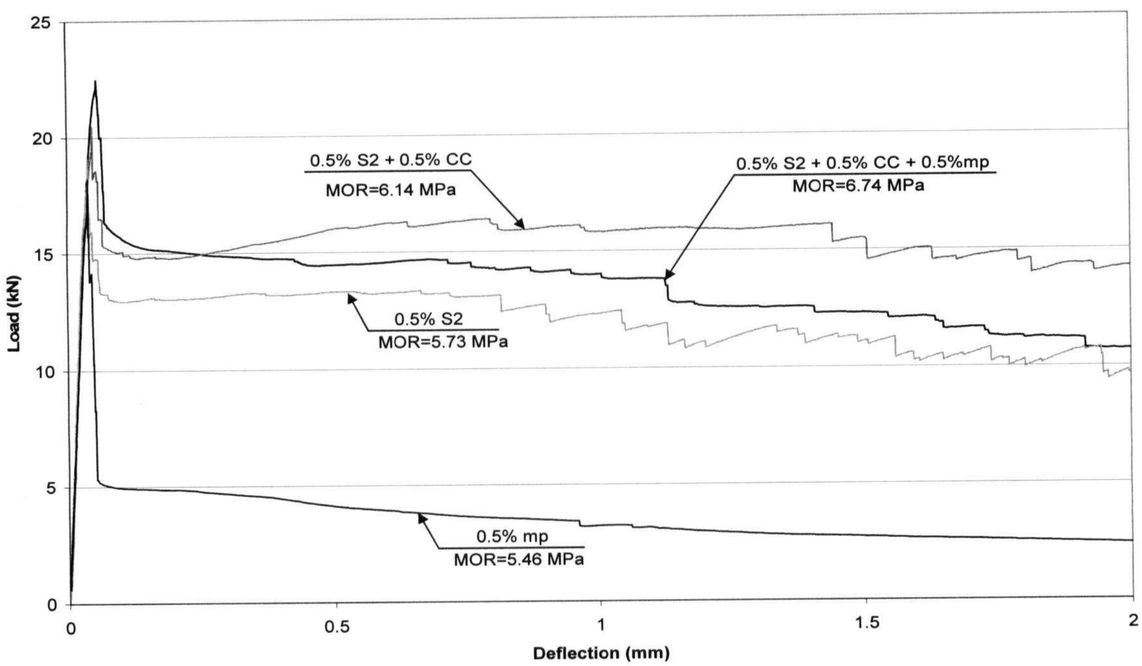

Figure 6.5 S_2, mp and CC Fibers

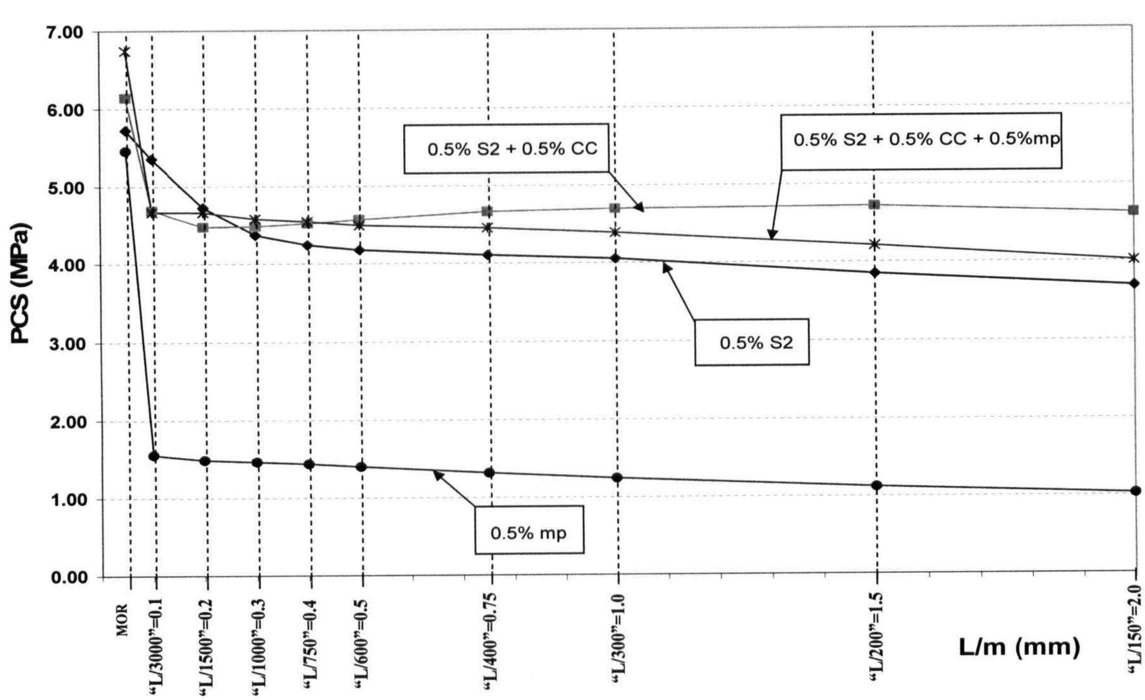

Figure 6.6 PCS - S_2, mp and CC Fibers

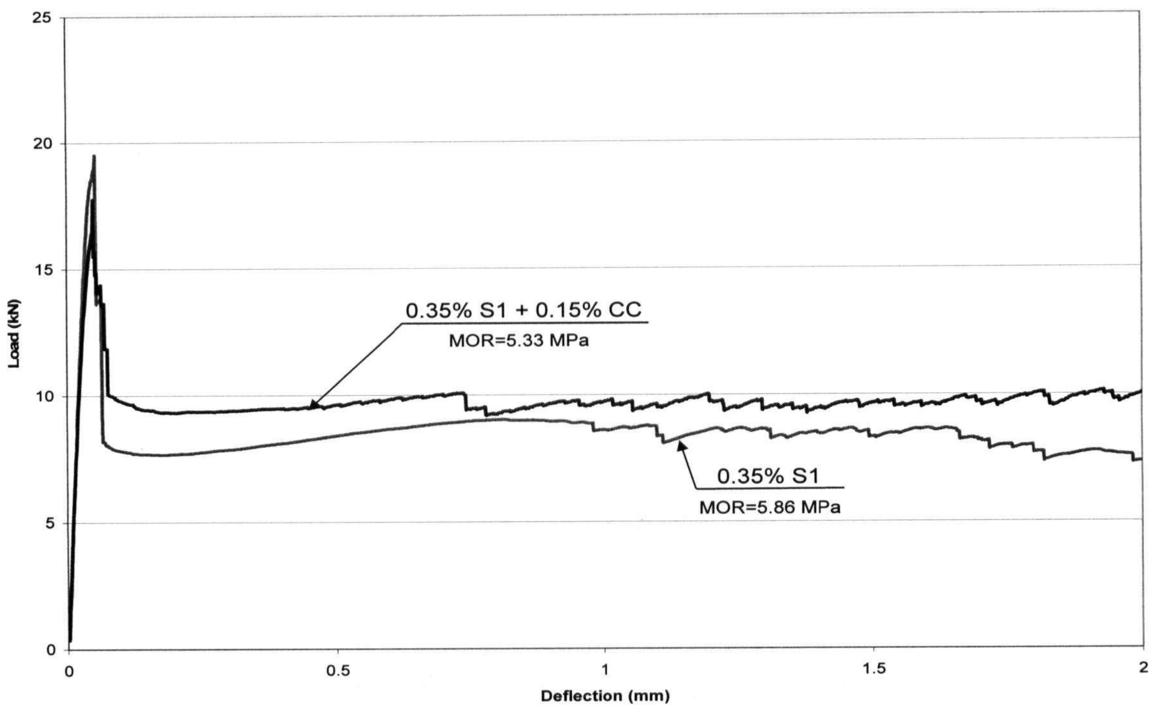

Figure 6.7 S_1 and CC Fibers

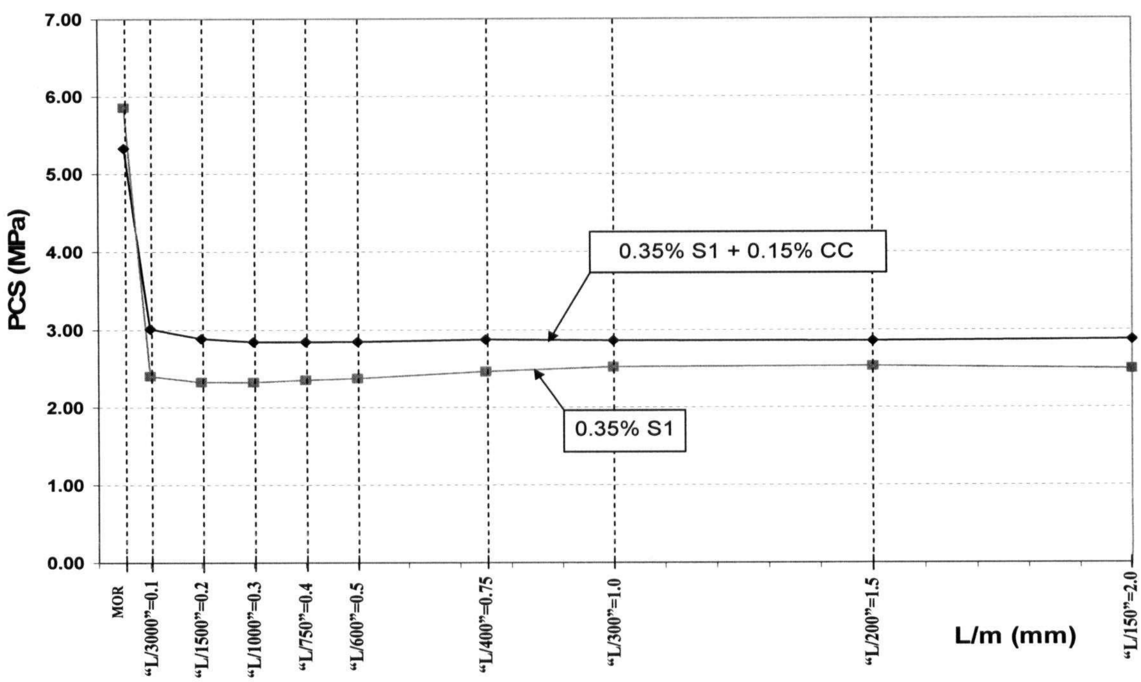

Figure 6.8 PCS - S_1 and CC Fibers

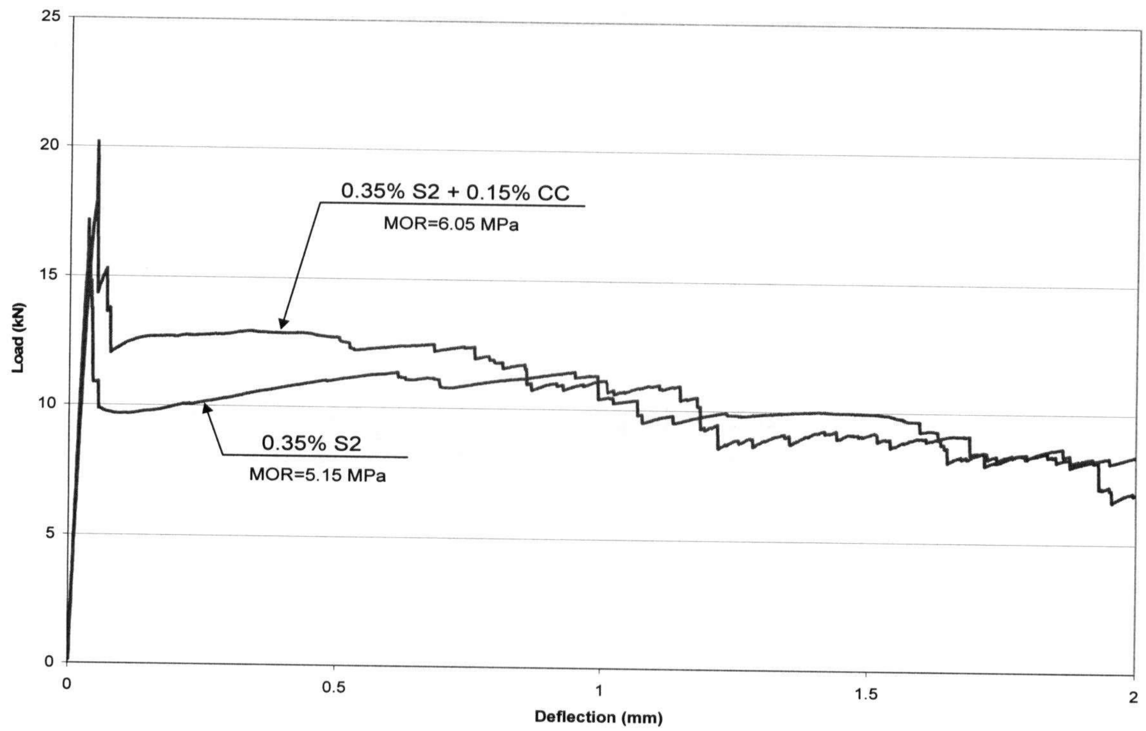

Figure 6.9 S_2 and CC Fibers

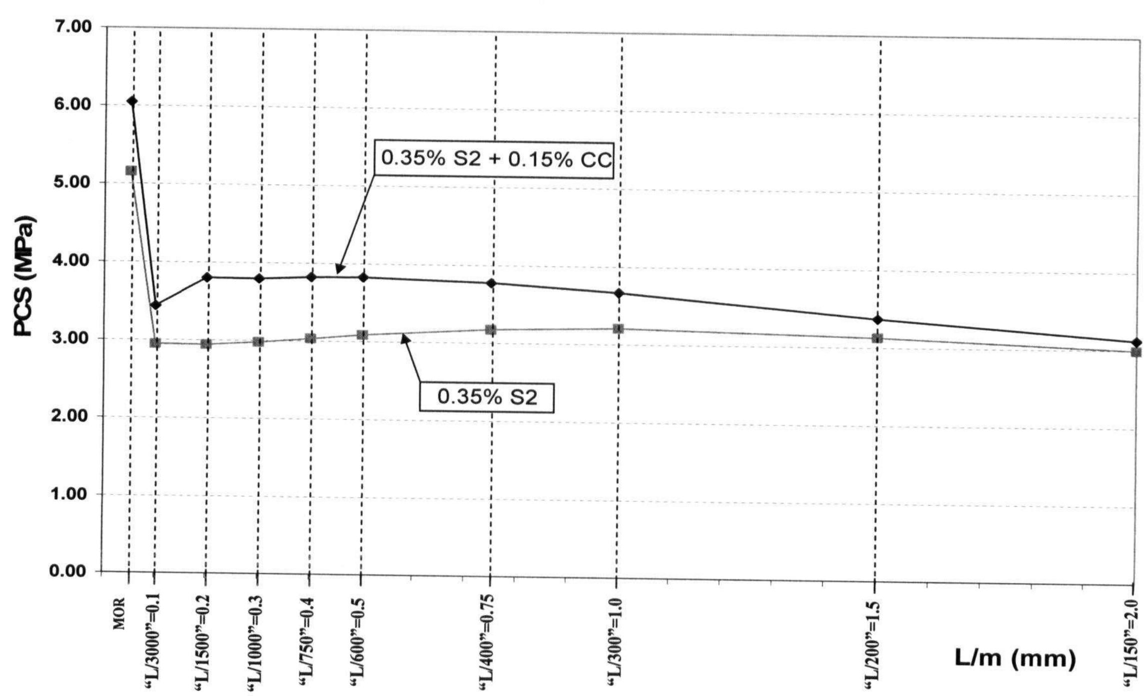

Figure 6.10 PCS – S_2 and CC Fibers

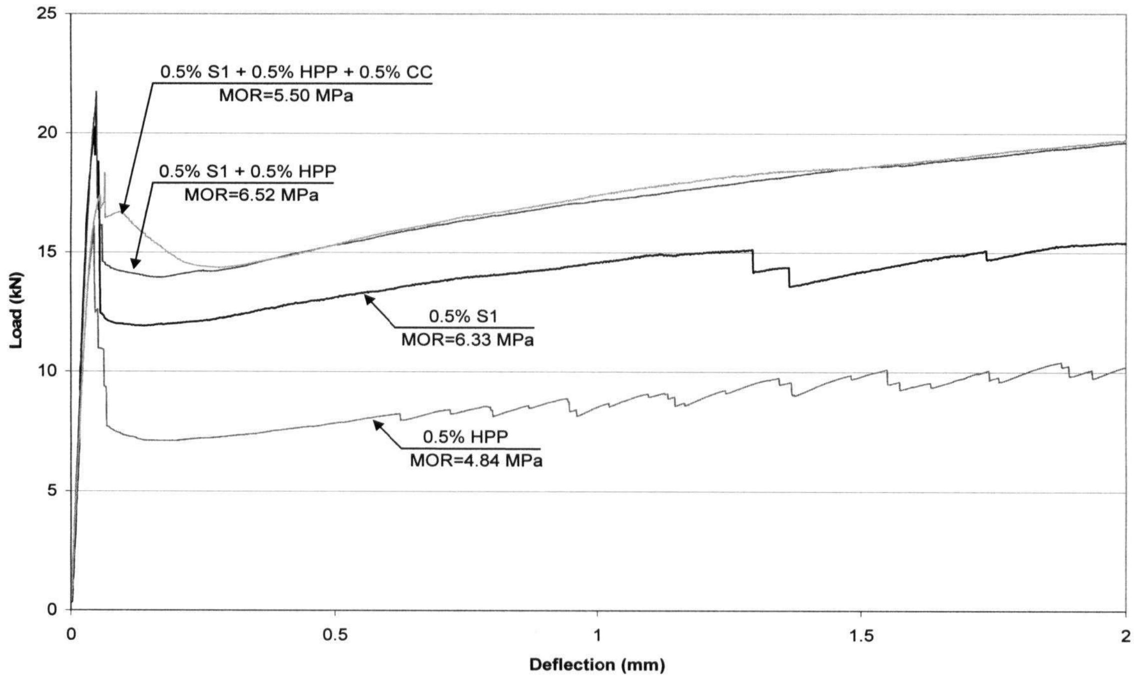

Figure 6.11 S_1, HPP and CC Fibers

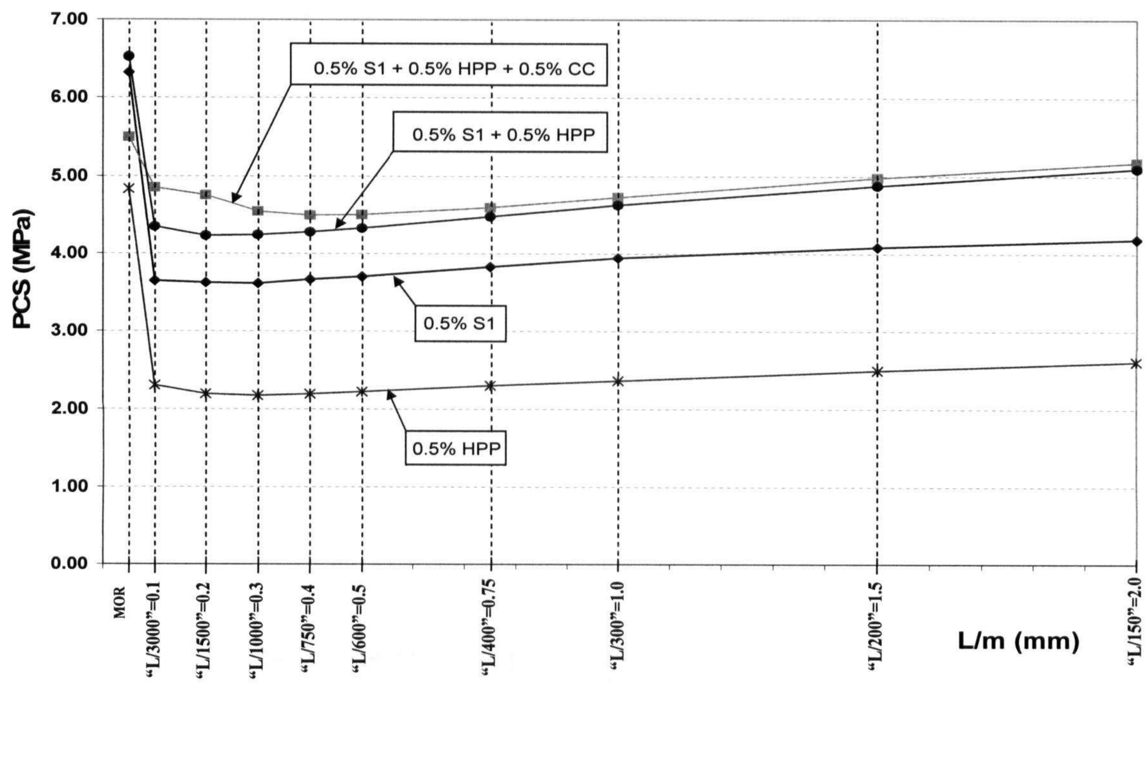

Figure 6.12 PCS - S_1, HPP and CC Fibers

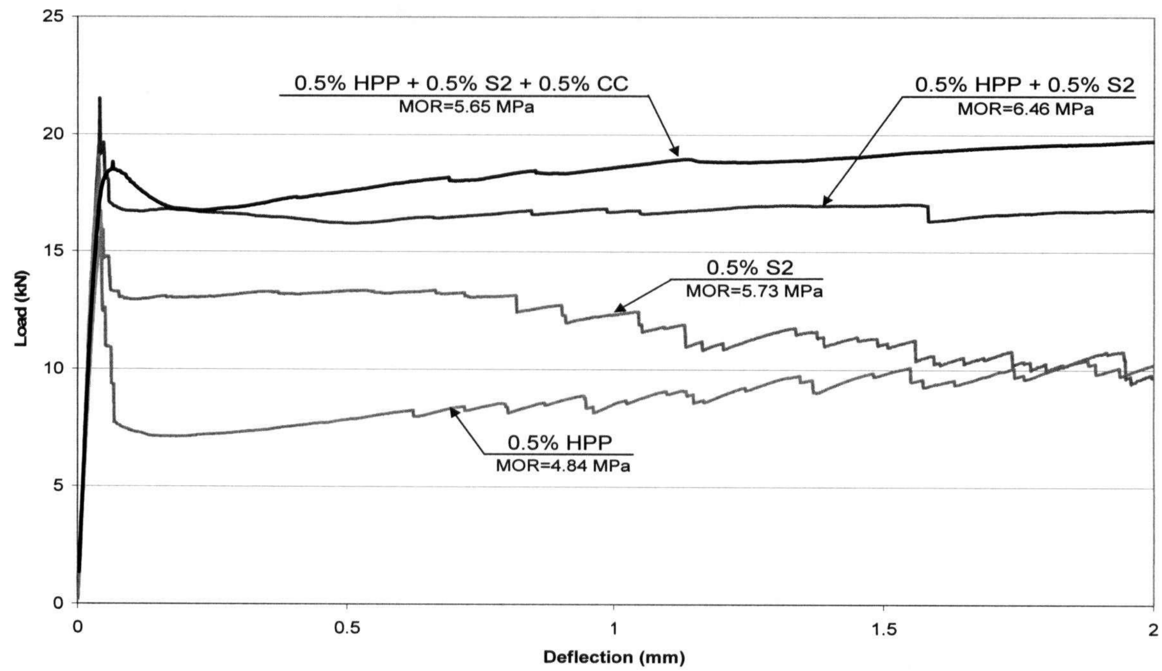

Figure 6.13 S_2, HPP and CC Fibers

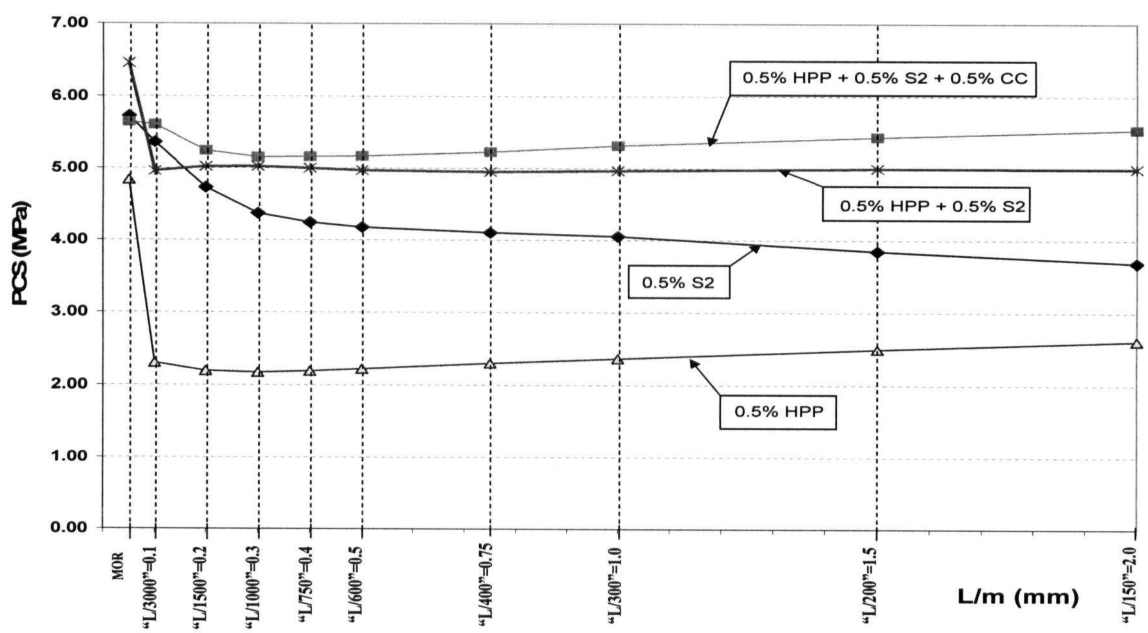

Figure 6.14 PCS – S_2, HPP and CC Fibers

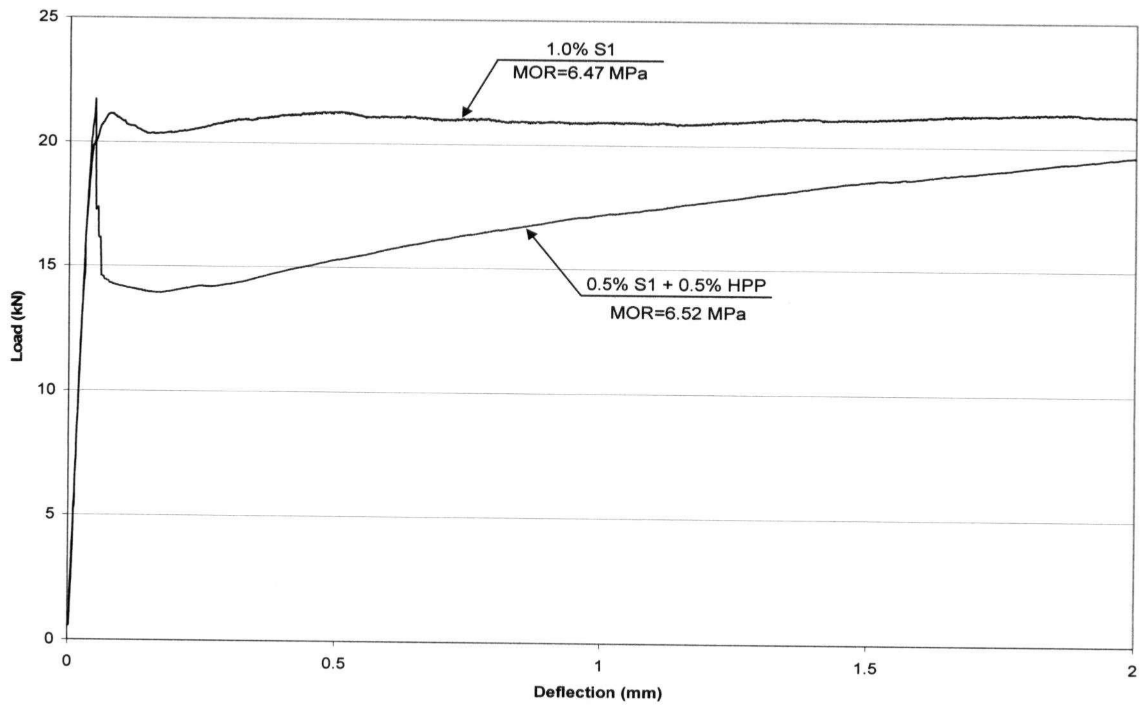

Figure 6.15 S_1 and HPP Fibers

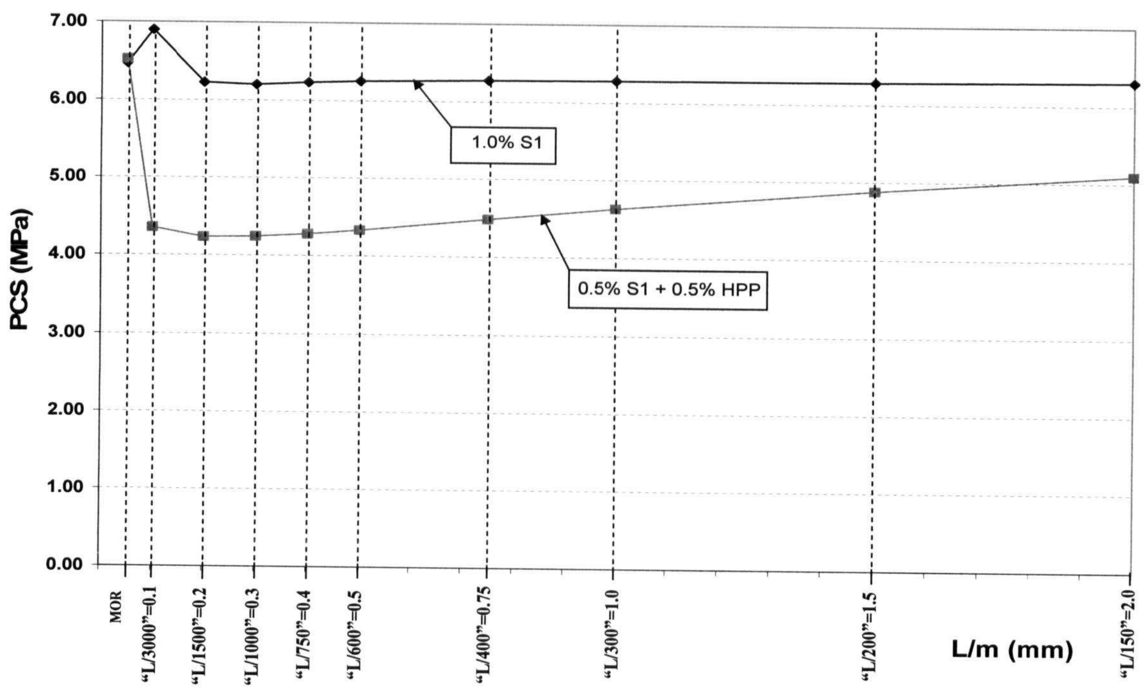

Figure 6.16 PCS - S_1 and HPP Fibers

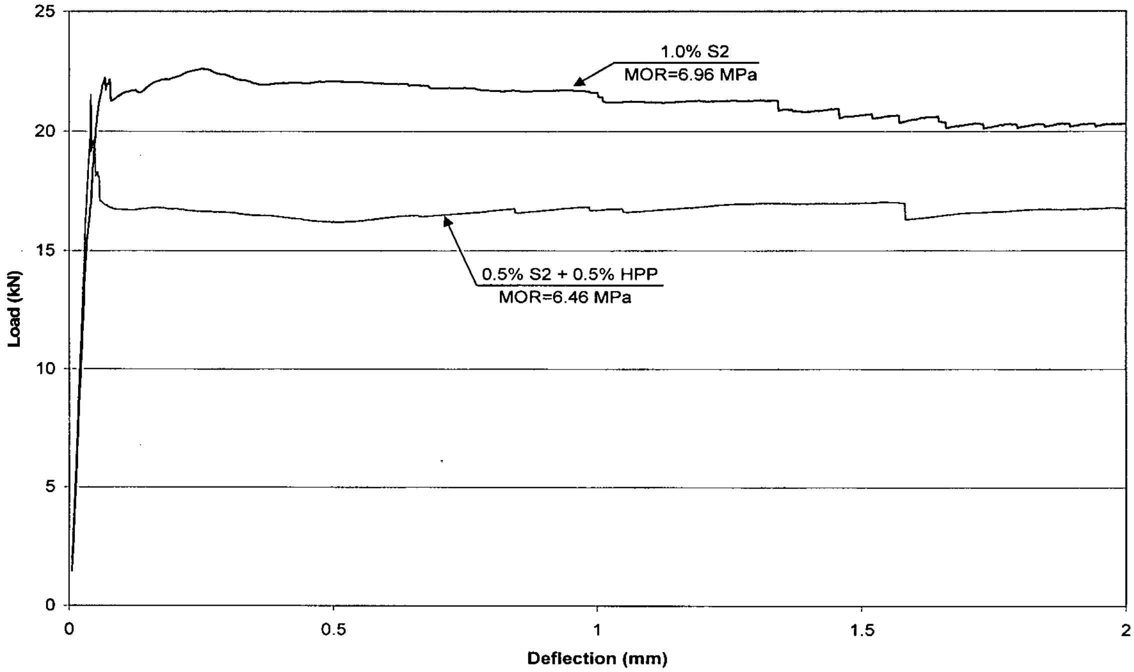

Figure 6.17 S_2 and HPP Fibers

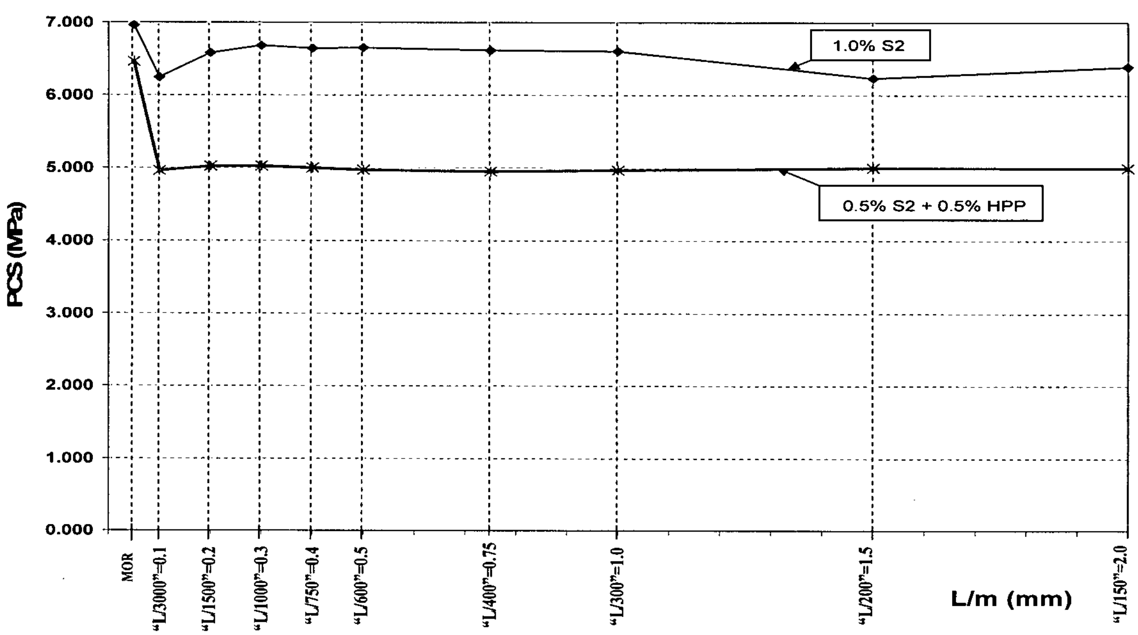

Figure 6.18 PCS – S_2 and HPP Fibers

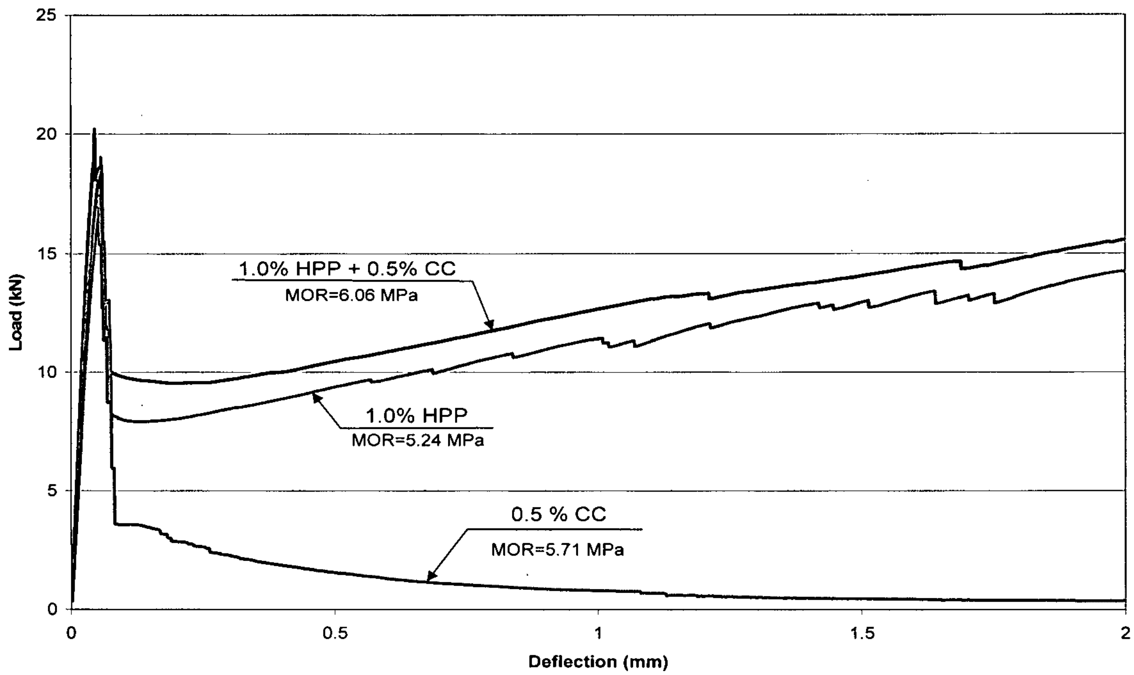

Figure 6.19 HPP and CC Fibers

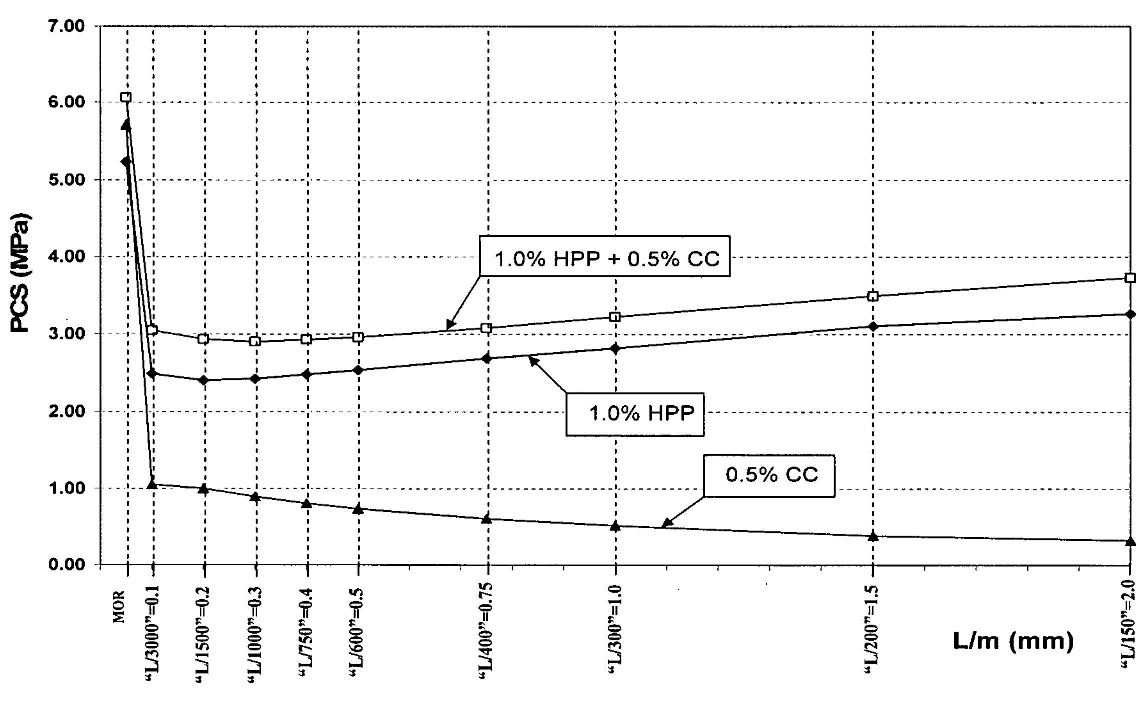

Figure 6.20 PCS - HPP and CC Fibers

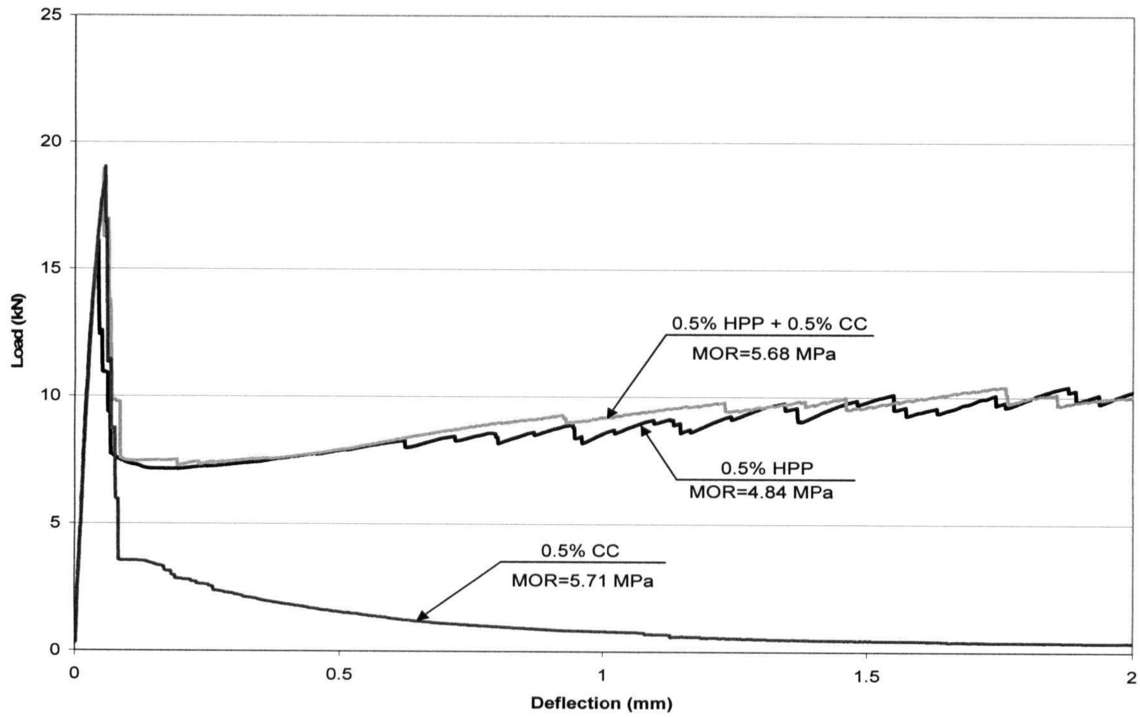

Figure 6.21 HPP and CC Fibers

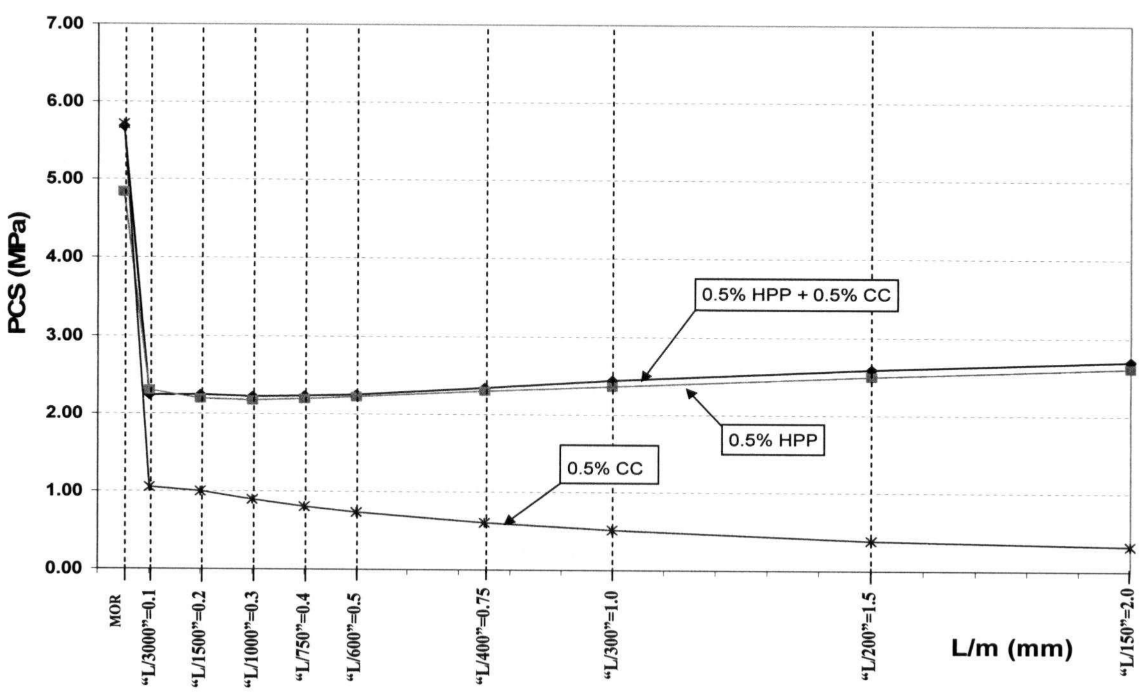

Figure 6.22 PCS - HPP and CC Fibers

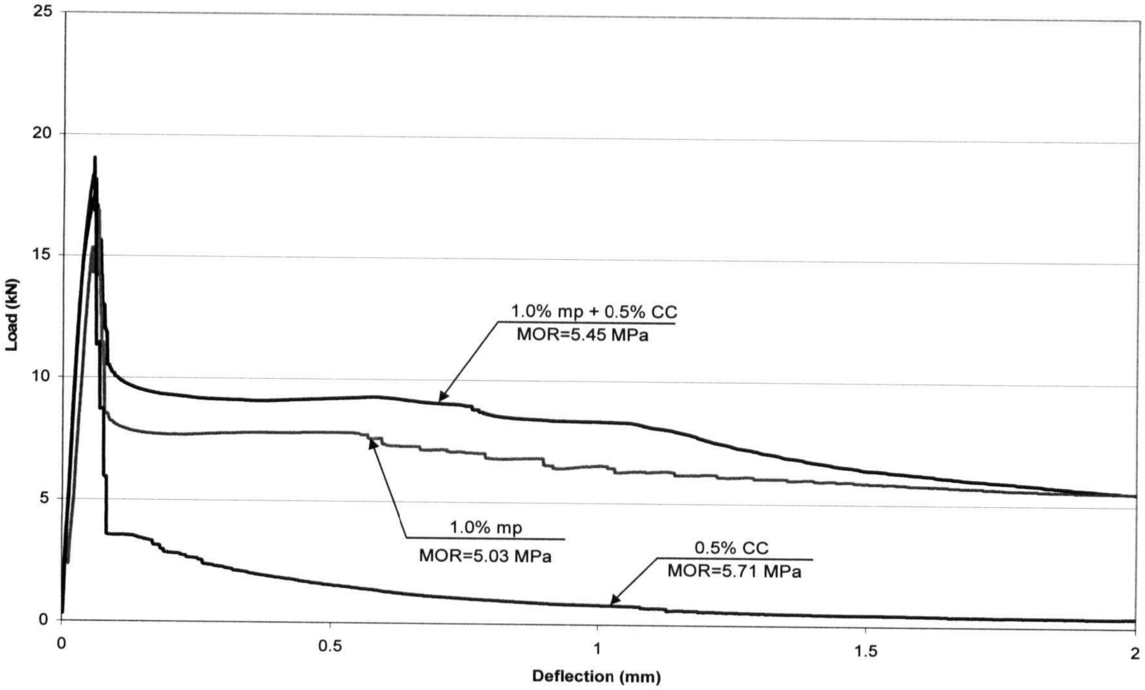

Figure 6.23 mp and CC Fibers

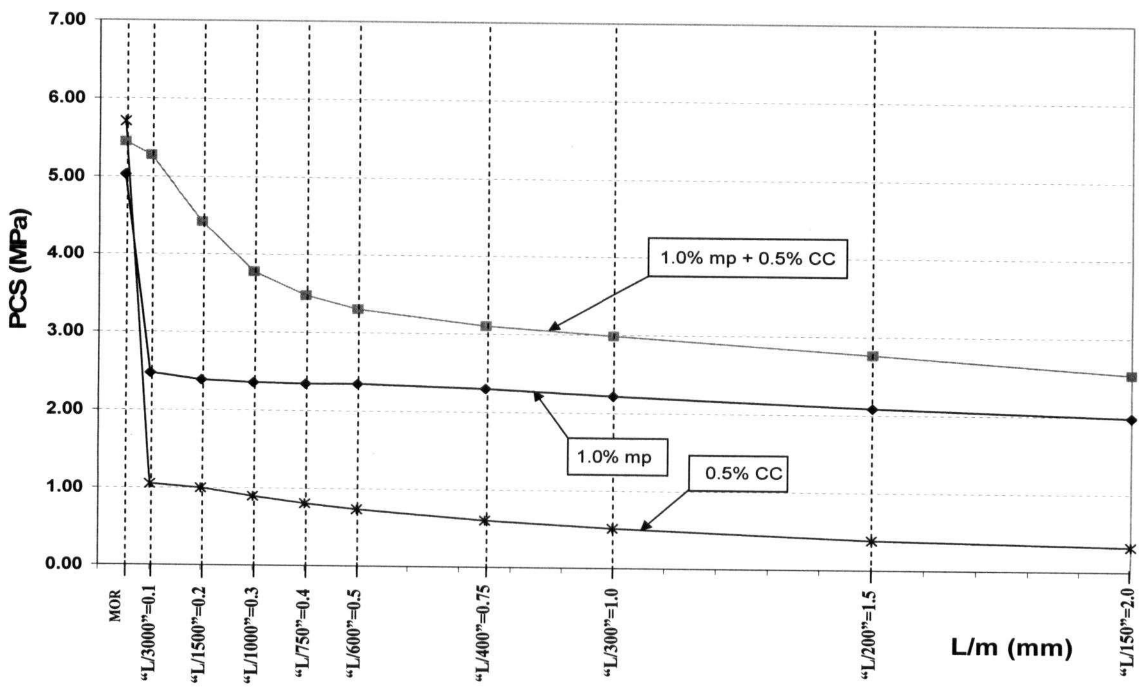

Figure 6.24 PCS – mp and CC Fibers

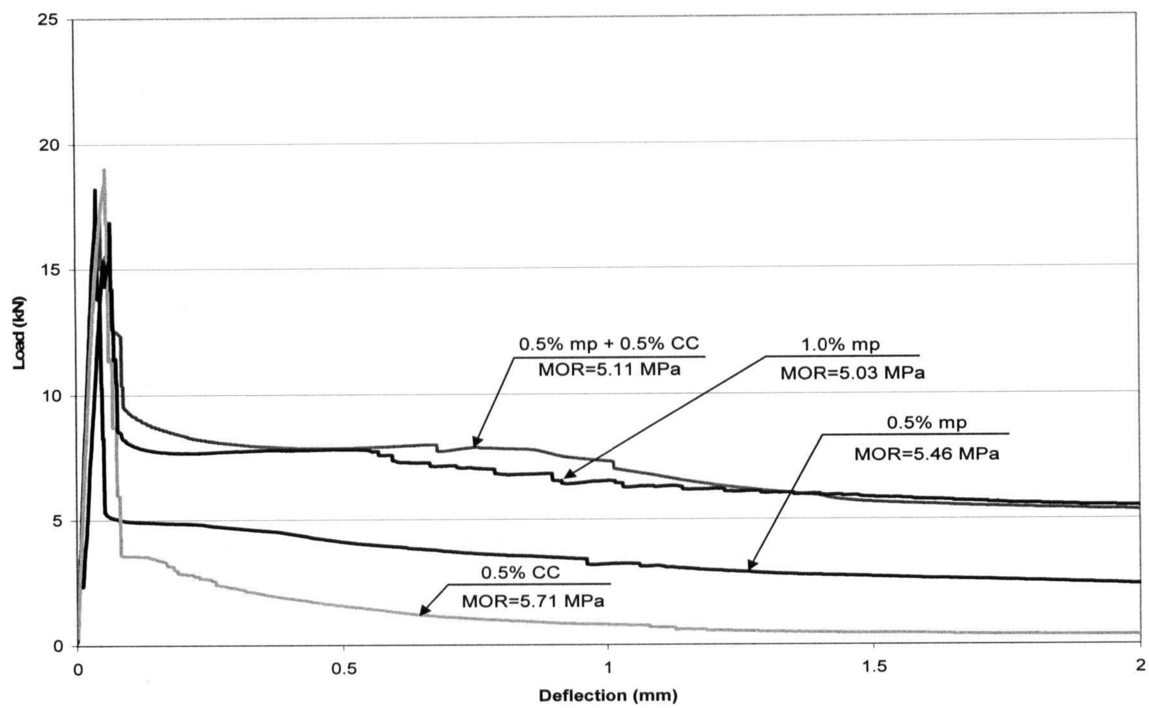

Figure 6.25 mp and CC Fibers

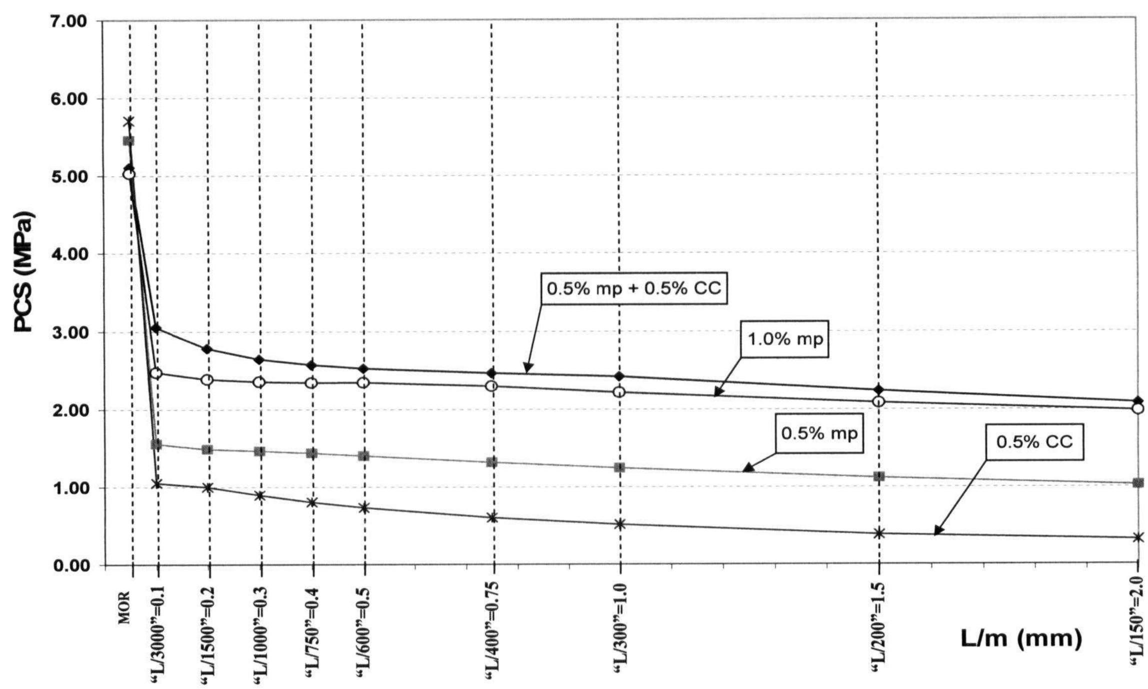

Figure 6.26 PCS - mp and CC Fibers

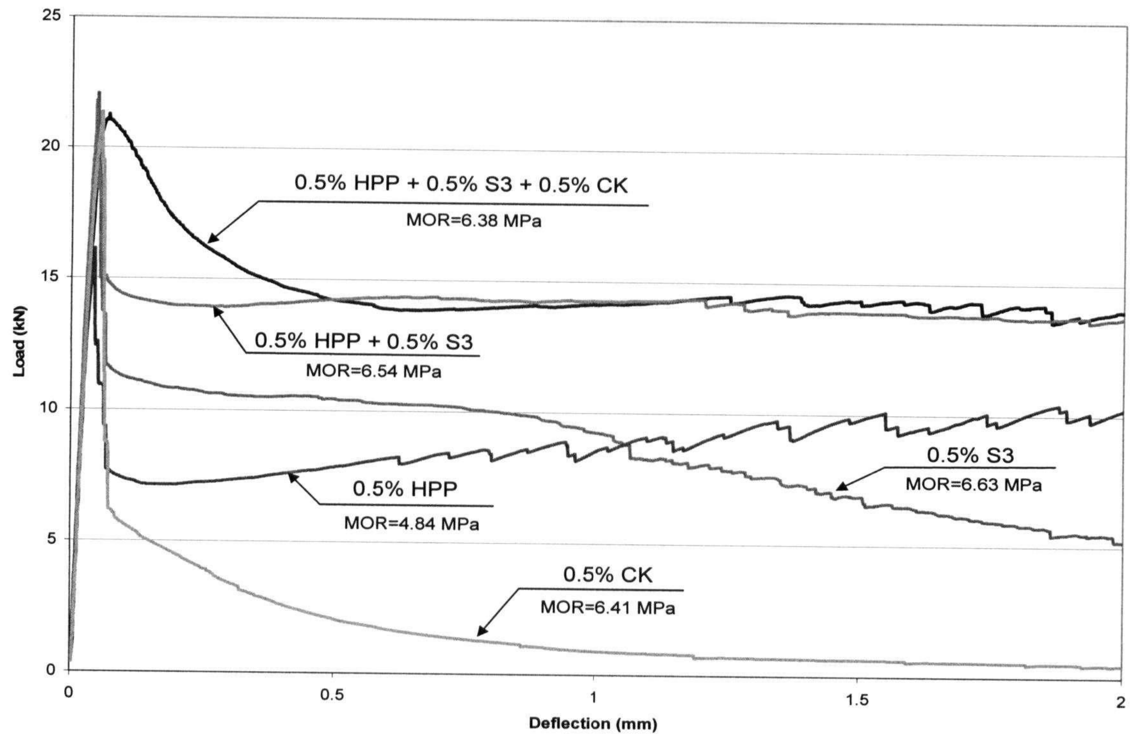

Figure 6.27 S_3, HPP and CK Fibers

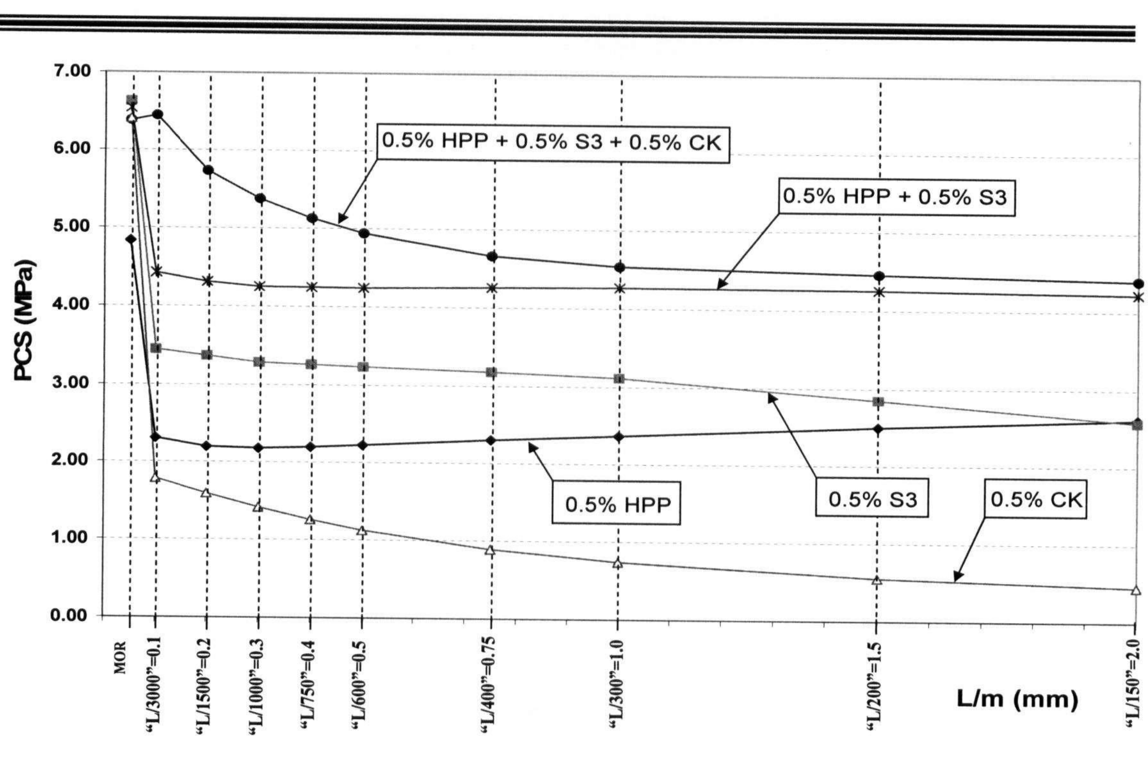

Figure 6.28 PCS - S_3, HPP and CK Fibers

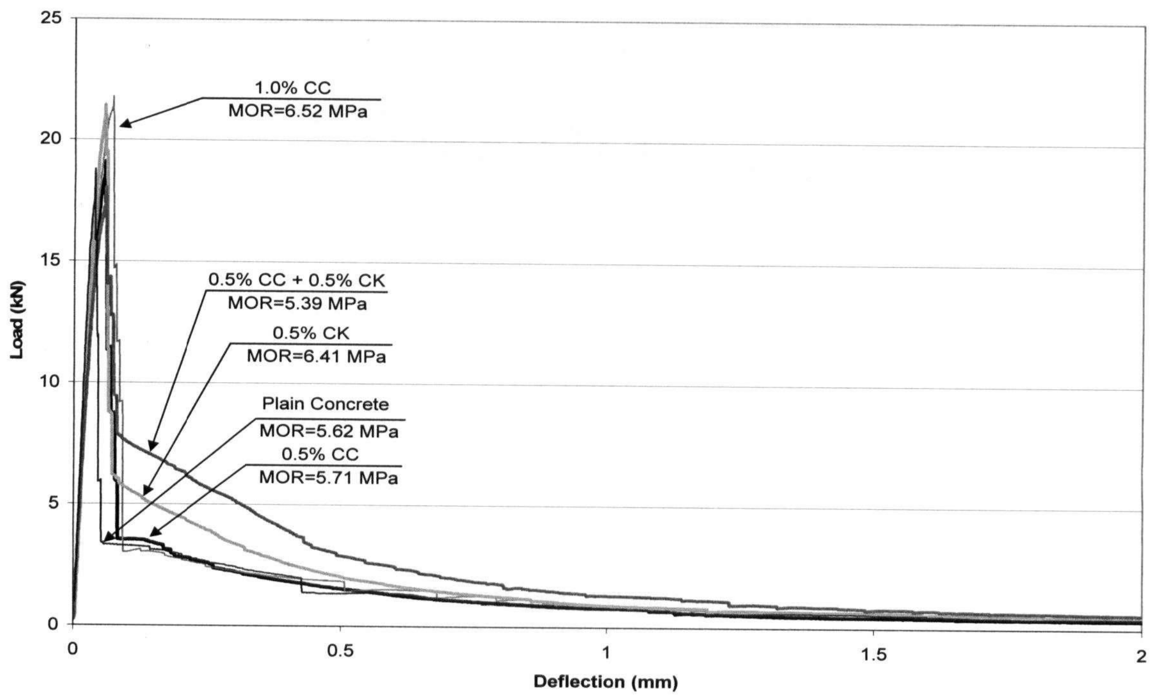

Figure 6.29 CC and CK Fibers

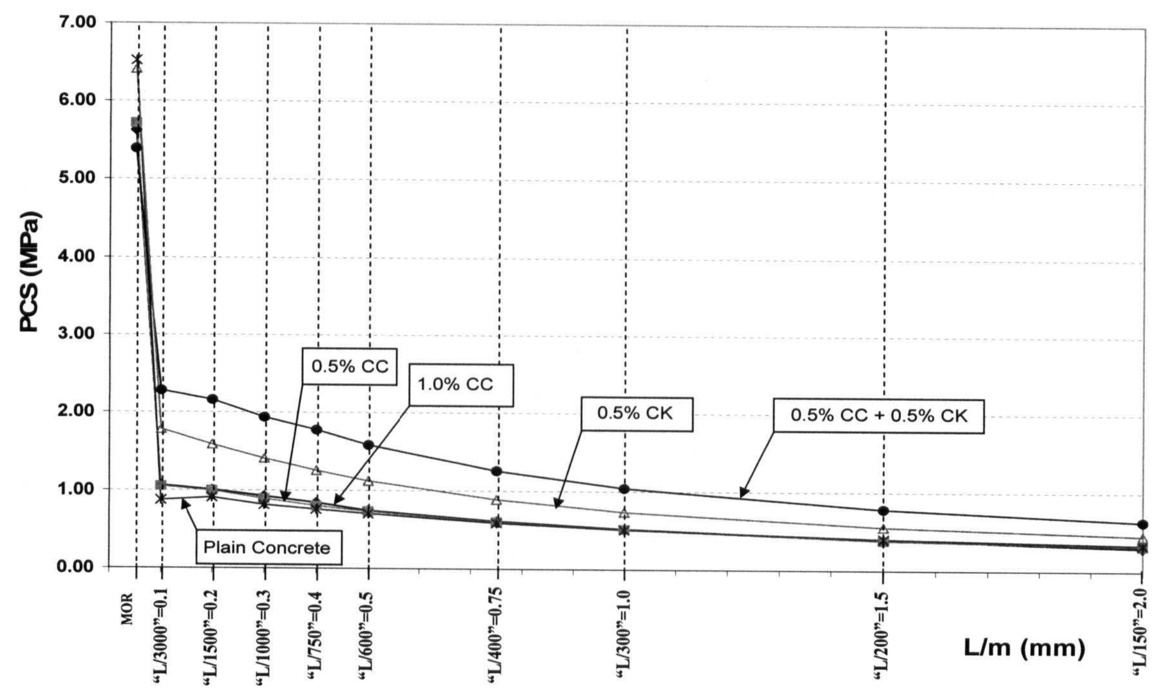

Figure 6.30 PCS - CC and CK Fibers

6.2.3.1 Hybridization of Macro Steel (S_1 and S_2) with Micro Polypropylene (mp) and Micro Conoco Carbon (CC) Fibers:

The results of this hybridization are indicated in Figures 6.3 to 6.10. Adding Conoco carbon fiber and micro polypropylene fiber did not show a noticeable improvement in flexural behavior of the FRC containing flat-ended steel fibers (S_1). On the other hand, adding 0.5% by volume of Conoco carbon fiber, which on its own did not improve the toughness values of plain concrete significantly, increased the PCS_m values for FRC containing 0.5% by volume of the crimped steel fibers (S_2).

As shown in Figures 6.3 and 6.4 HyFRC containing equal volumetric amount of S_1, CC and mp fibers (0.5% by volume of each) showed an improvement in modulus of rupture and the PCS_m values. Figures 6.5 and 6.6, surprisingly, show that adding of mp fibers to HyFRC containing 0.5% by volume S_2 and 0.5% by volume CC decreased its toughness values. Therefore, one can say that among all these mixes, HyFRC containing 0.5% by volume CC and 0.5% by volume S_2 fibers has shown a significant synergy effect at any deflection higher than 0.5mm.

Figures 6.7 to 6.10 show that adding only 0.15% by volume of CC fibers to FRC containing 0.35% macro steel fibers increased toughness values (i.e. PCS_m values) significantly and in the case of having crimped steel fibers in the HyFRC mixture, modulus of rupture increased as well.

In general, one can say that crimped macro steel fiber showed a better compatibility with Conoco carbon fiber than did the flat-ended steel fiber.

6.2.3.2 Hybridization of Macro Steel (S_1 and S_2) with Macro Polypropylene (HPP) and Micro Conoco Carbon (CC) Fibers:

Results of this hybridization are shown in Figures 6.11 to 6.18. Both mixes, one containing 0.5% HPP and the other one containing 0.5% S_1, showed strength gains (i.e. load carrying capacity increased while the mid-span deflection of beams increased). This behavior can also be seen in both HyFRCs in Figure 6.11. Conoco carbon fiber increased the initial toughness values as shown in PCS graph in Figure 6.12. Modulus of rupture of HyFRC containing 0.5% S_1 and 0.5% HPP showed an increase compared to that of FRCs containing one fiber with a fraction of 0.5% by volume. This hybrid also achieved a modulus of rupture even higher than that of FRC containing 1.0% S_1 (see Figures 6.15 and 6.16). Also PCS_m values for this HyFRC became closer to that of FRC containing 1.0% S_1 as deflection increased (see Figure 6.16). As a matter of fact, FRC beams with 1.0% macro steel fibers showed a perfectly elasto-plastic response and can not be compared with other mixes (see Figures 6.15 and 6.17). Unlike FRC with 0.5% S_1, FRC containing 0.5% S_2 (crimped steel fiber) showed a softening curve as shown in Figure 6.13. Therefore, HyFRC containing 0.5% S_2 and 0.5% HPP showed a constant load carrying capacity for deflection of up to 2 mm which can be compared with FRC containing 1.0% steel fibers (see Figures 6.13, 6.15 and 6.17). Adding Conoco carbon fiber to HyFRC of 0.5% HPP and 0.5% S_2 decreased MOR, but overall toughness (i.e. PCS_m values) increased with an increasing deflection up to 2 mm. Hybridization of S_2 with HPP, also, improved MOR as shown in Figures 6.13 and 6.14.

6.2.3.3 Hybridization of Macro Polypropylene (HPP) with Micro Conoco Carbon (CC) Fibers:

Adding 0.5% by volume of Conoco carbon fiber to FRC containing 1.0% HPP increased MOR and PCS_m values at all deflections up to 2 mm. Increases in the PCS_m values were almost constant at all different L/m ratios as shown in Figure 6.20. On the other hand, adding the same amount of Conoco carbon fiber to 0.5% by volume HPP fiber as indicated in Figures (6.21) and 6.22 did not change beams' flexural behavior as well as their PCS_m values significantly. Therefore, one can say that adding Conoco carbon fiber to FRC containing less than 1.0% by volume of HPP fiber is not useful.

6.2.3.4 Hybridization of Micro Polypropylene (mp) with Micro Conoco Carbon (CC) Fibers:

A real synergy was observed in this hybridization. Figures 6.23 and 6.24 show the flexural test results of HyFRC containing 1.0% mp and 0.5% CC as compared to those of FRCs containing each of these fibers individually. PCS_m values, especially in lower end of beam deflections, significantly increased by introducing carbon fibers into the mix. Interesting results are also shown in Figures 6.25 and 6.26. HyFRC containing 0.5% of mp and 0.5% of CC by volume showed higher PCS_m values than FRC containing 1.0%

by volume of mp fiber. Therefore, hybridization of micro polypropylene with Conoco carbon fiber is one of the most promising combinations of micro fibers, even if total fiber volume fractions are compared.

6.2.3.5 Hybridization of Macro Polypropylene (HPP) with Micro Steel (S_3) and Micro Kureha Carbon (CK) Fibers:

Similar to hybridization of HPP with S_2 as shown in Figures 6.13 and 6.14, adding 0.5% by volume of micro steel fiber (S_3) to FRC containing 0.5% HPP by volume allowed the beams to carry a constant load in post peak region up to 2 mm deflection as shown in Figure 6.27. Adding 0.5% by volume of Kureha carbon fiber to HyFRC containing both HPP and S_3 fibers, significantly improved the flexural respond of beams in initial part of the curve (i.e. up to L/m=0.5 mm deflection). MOR of HyFRC in this category did not show a big difference compared to FRC containing 0.5% by volume of micro steel fiber.

6.2.3.6 Hybridization of Micro Conoco Carbon (CC) with Micro Kureha Carbon (CK) Fibers:

FRC containing 1.0% Conoco carbon fiber in flexure showed no improvements compared to that of 0.5% Conoco carbon fiber by volume as indicated in Figures 6.29 and 6.30. On the other hand, HyFRC made of 0.5% Kureha and 0.5% Conoco carbon fibers showed a very good response which can be compared to FRC of 0.5% by volume micro polypropylene fiber. The first two PCS values of this HyFRC can even be compared with FRC containing 1.0% micro polypropylene fiber which is remarkable. Adding of 0.5% by volume of Conoco carbon fiber to FRC containing 0.5% by volume of the same fiber (i.e. FRC containing 1.0% Conoco carbon fiber) did not change the behavior of concrete under flexure at all. On the other hand, when the same amount of this fiber (0.5% by volume Conoco carbon fiber) was added to FRC containing 0.5% by volume of Kureha carbon fiber, it improved the flexural toughness of concrete beams significantly as shown in Figures 6.29 and 6.30. Elongation to break for Kureha carbon fiber is 2.0% whereas for Conoco carbon fiber it is only 1.0% and this can be considered as the main reason why Kureha carbon fiber performs better in hybrid fiber reinforced concretes.

7. CONCLUSIONS

An experimental study was conducted to investigate the flexural response of hybrid fiber reinforced concrete (HyFRC) with a compressive strength of around 55 MPa. This study also investigated the influence of various fiber combinations on fresh properties (i.e. workability) and compressive strength of concrete.

7.1. Effects on the Fresh Mix:

In a fresh mix, as indicated in section 5.1, presence of macro fibers such as flat-ended steel (S_1), crimped steel (S_2) and polypropylene (HPP) fibers and micro steel fiber (S_3) did not affect the workability (i.e. VeBe time in seconds) of concrete significantly. The w/c ratio of 0.45 can be considered as the main reason for that. On the other hand, micro fibers, especially micro polypropylene fiber (mp) because of its hydrophobic nature and high specific area, decreased the available water for maintaining a reasonable workability in the fresh mix. Therefore, use of a superplasticizer is recommended when the volume fraction of micro fiber, especially mp fiber, is 1.0% by volume or more. This recommendation can be applied to any HyFRC with total fiber volume fractions of more than 1.0% containing at least 0.5% by volume of micro fibers in the mix.

7.2. Effects on the Compressive Strength:

This experimental study leads to the following conclusions:

1. FRC or HyFRC with a lower density than the control, which was a result of improper workability, showed a lower compressive strength than that of plain concrete.
2. Usage of micro fibers, except micro steel fibers, decreased the workability and as a result the compressive strength also decreased.
3. Proper compaction (i.e. vibration) of FRC or HyFRC played an important role in achieving a reliable compressive strength (i.e. low value of standard deviation for a given group of tests).

4. Micro polypropylene changed the failure mode of concrete cylinders from a brittle mode to a ductile mode. Micro carbon fibers did not affect the failure mode of concrete cylinders as compared to that of plain concrete. FRC or HyFRC cylinders containing other types of fibers (S_1, S_2, S_3 and HPP) failed in a brittle manner but did not split.

7.3. Effects on the Flexural Toughness:

FRC and especially HyFRC showed a higher first crack strength (i.e. MOR) than that of plain concrete in general. Even HyFRC with low compressive strength (mix number 10 with f'_c=43.7 MPa) showed a higher first crack strength (MOR=6.05 MPa) than plain concrete with an MOR of 5.62 MPa. The weaknesses of ASTM C 1018 and JSCE standard SF-4 methods were also shown and as a result, the PCS method was chosen to calculate and compare the toughness values of different mixes. In this method a wide range of deflections for different serviceability conditions was considered and results can be summarized as follows:

1. Conoco carbon fiber had better synergy with crimped macro steel fibers than with flat-ended fibers. Different cross-sectional and longitudinal shapes of these two types of steel fibers can be considered as the main reason.
2. Different combinations of macro steel fibers with HPP and Conoco carbon fibers were investigated. Although FRCs containing 1.0% macro steel fibers were the best composites for flexural toughness, partial replacement of macro steel fibers with HPP produced HyFRCs with reasonable PCS_m values. Adding Conoco carbon fiber to these HyFRCs also increased the PCS_m values. Conoco carbon fiber in HyFRC containing flat-ended steel fibers increased the initial PCS_m values (i.e. $L/m \leq 0.5$ mm). On the other hand, in HyFRC containing crimped steel fibers, addition of Conoco carbon fiber increased the PCS_m values beyond the initial part ($L/m > 0.5$ mm).
3. Adding of Conoco carbon fiber to FRC containing less than 1.0% HPP is not useful.

4. Hybridization of micro polypropylene with Conoco carbon fiber is one of the most promising combinations of micro fibers. Synergy can be easily seen even if total fiber volume fractions are compared.
5. Kureha carbon fiber showed a better synergy than Conoco carbon fiber. This can be seen in HyFRC containing micro steel fiber, HPP and Kureha carbon fiber, especially at small deflections. Elongation to break for Kureha carbon fiber was 2.0% whereas for Conoco carbon fiber it is only 1.0%. This can be cited as the primary cause.
6. Kureha carbon fiber in combination with Conoco carbon fiber showed a very good synergy and can be considered as one of the best micro fiber combinations.

8. RECOMMENDATIONS FOR FUTURE RESEARCH

Although Fiber Reinforced Concrete (FRC) is extensively used in Canada and elsewhere in the world, Hybrid Fiber Reinforced Concrete (HyFRC) is a relatively new concept. The small number of published papers in this area to date indicates that significant further research is necessary. Following is a list of suggestions for future work in this area.

1. Although numerous combinations of fibers were investigated in this study, there are still a lot of other combinations of macro and micro fibers which should be studied including: various combinations of micro steel fibers with macro steel fibers, various combinations of macro polypropylene fibers with micro polypropylene fibers, various combinations of micro polypropylene fibers with micro and/or macro steel fibers, and so on.
2. Extensive microscopic examination should be carried out to understand the micro-structural development at the fiber-matrix interface in HyFRC. In this regard, fiber pull-out tests should be done on macro fibers to understand the influence of the presence of a secondary fiber on bond and energy absorption capacity.
3. Selected hybrid composites should also be tested for dynamic properties such as impact resistance and fatigue endurance. A high-speed camera can be employed for interpreting the data and studying crack patterns for impact modeling.
4. One of the main and primary advantages of fiber reinforcement is in an enhanced shear resistance. Therefore, shear tests should be carried out as per JSCE SF-6. Shear under impact and fatigue loads should also be studied.
5. The influence of a second fiber on the crack growth resistance needs to be studied by conducting controlled crack growth studies on selected hybrid composites using contoured double cantilever beam specimens or a similar device.

6. Plastic shrinkage cracking should also be studied. A drying chamber with controlled humidity and temperature for crack observations should be used to determine the effectiveness of various hybrid combinations of fibers towards controlling plastic shrinkage cracking.
7. It is known that some macro-micro hybrid combinations (carbon-steel hybrids, for example) can significantly improve the electrical conductivity of concrete. Selected composites should be investigated for electrical conductivity. Conducting composites have numerous applications including conducting floor panels for computers and other instrumentation rooms, lightening arresters, etc.
8. Selected hybrid combinations should be investigated in dry and wet process shotcretes. In this case, dynamic properties will be of particular interest given the required resistance to rock burst and sudden ground movements.

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