FIBER REINFORCEMENT OF CONCRETE

Richard Brown, Arun Shukla and Sehaj P. Singh
University of Rhode Island

February 2004

URITC PROJECT NO. 536136

PREPARED FOR

UNIVERSITY OF RHODE ISLAND
TRANSPORTATION CENTER

1. Report No URITC FY 00-06	2. Government Accession No. N/A	3. Recipient's Catalog No. N/A
4. Title and Subtitle **FIBER REINFORCEMENT OF CONCRETE**		5. Report Date February 2004 6. Performing Organization Code N/A
7. Authors(s) Richard Brown, Arun Shukla and Sehaj P. Singh		8. Performing Organization Report No. N/A
9. Performing Organization Name and Address University of Rhode Island, Dept. of Chemical Engineering Crawford Hall, URI, Kingston, RI 02881 (401) 874- 2707 rbrown@egr.uri.edu		10. Work Unit No. (TRAIS) N/A 11. Contract or Grant No. URI 536136 13. Type of Report and Period Covered Final
12. Sponsoring Agency Name and Address University of Rhode Island Transportation Center 85 Briar Lane Kingston, RI 02881		14. Sponsoring Agency Code A study conducted in cooperation with U.S. DOT
15. Supplementary Notes N/A		

16. Abstract

A comprehensive experimental program on pullout behavior of polypropylene fibers from cementitious matrices is described. The parameters investigated include the effect of embedded length on the pullout characteristics, the development of the interfacial bond with age of curing of matrix and the effect of exposure to degrading environments like seawater and salt water on the interfacial bond between the fibers and cementitious matrix. The aim of these experiments was to understand the properties of fiber/matrix interface, which are of primary significance for the overall behavior of fiber reinforced cement based composites.

Polypropylene fibers have a weak bond with cementitious matrix because of smooth surface of fibers, which does not allow for sufficient friction to develop between the two. In this study a new method to improve the frictional bond by means of mechanical indentations of fibers was also proposed. The bonding performance was characterized by means of pullout tests of the plain and modified fibers from a cementitious matrix. An optimum level of fiber modification for maximization of bond efficiency was determined experimentally.

Also, recognizing the fact that fibers become most effective only in the post cracking phase of the matrix, a test method called Wedge splitting test was chosen for testing fracture characteristics. This test method allows stable crack propagation, providing valuable information about the post cracking behavior of concrete. Special molds were prepared for making the samples and appropriate fixtures for the experimental setup were fabricated. An experimental scheme to understand the effect of degrading environments on cracked concrete structures was initiated. Wedge splitting tests were used to initiate cracks in concrete samples in a controlled manner. The samples were exposed to salt water to simulate seawater environment. Testing of the control samples has been carried out. The samples exposed to salt water will be tested after one-year exposure.

17. Key Words Fiber Reinforced Concrete, Polypropylene Fibers, Fiber Pullout, Wedge Splitting Test, Fracture Toughness	18. Distribution Statement No restrictions. This document is available to the Public through the URI Transportation Center, 85 Briar Lane, Kingston, RI 02881

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 61	22. Price N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized (art. 5/94)

ABSTRACT

A comprehensive experimental program on pullout behavior of polypropylene fibers from cementitious matrices is described. The parameters investigated include the effect of embedded length on the pullout characteristics, the development of the interfacial bond with age of curing of matrix and the effect of exposure to degrading environments like seawater and salt water on the interfacial bond between the fibers and cementitious matrix. The aim of these experiments was to understand the properties of fiber/matrix interface, which are of primary significance for the overall behavior of fiber reinforced cement based composites.

Polypropylene fibers have a weak bond with cementitious matrix because of smooth surface of fibers, which does not allow for sufficient friction to develop between the two. In this study a new method to improve the frictional bond by means of mechanical indentations of fibers was also proposed. The bonding performance was characterized by means of pullout tests of the plain and modified fibers from a cementitious matrix. An optimum level of fiber modification for maximization of bond efficiency was determined experimentally.

Also, recognizing the fact that fibers become most effective only in the post cracking phase of the matrix, a test method called Wedge splitting test was chosen for testing fracture characteristics. This test method allows stable crack propagation, providing valuable information about the post cracking behavior of concrete. Special molds were prepared for making the samples and appropriate fixtures for the experimental setup were fabricated. An experimental scheme to understand the effect of degrading environments on cracked concrete structures was initiated. Wedge splitting tests were used to initiate cracks in concrete samples in a controlled manner. The samples were exposed to salt water to simulate seawater environment. Testing of the control samples has been carried out. The samples exposed to salt water will be tested after one-year exposure.

ACKNOWLEDGEMENTS

The financial support of University of Rhode Island Transportation Center under grant no. 536136 is gratefully appreciated

TABLE OF CONTENTS

CHAPTER1

CHAPTER2

CHAPTER3

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

PULLOUT BEHAVIOR OF POLYPROPYLENE FIBERS FROM CEMENTITIOUS MATRIX

1.1 INTRODUCTION

Fibers are increasingly being used for reinforcement of cementitious matrix, to enhance its toughness and energy absorption capacity and to reduce its cracking sensitivity. Cement based composites exhibit the general characteristics of brittle matrix composites i.e. the failure of the matrix precedes the fiber failure, thus allowing the fibers to bridge the propagating crack. The toughening effect is the result of several types of fiber/matrix interactions, which lead to energy absorption in the fiber-bridging zone of Fiber Reinforced Concrete (FRC). These processes include fiber bridging, fiber debonding, fiber pullout (sliding) and fiber rupture, as a transverse crack propagates through the matrix [1] shown in Figure 1.1. Although the amount of energy associated with each mechanism for individual fibers may not be significant, large amount of fibers bridging over an extended length can contribute an enormous toughening effect to the composite. Fiber bridging results in crack closure and a reduction in stress intensity factor at the crack tip. Fiber debonding and pullout (sliding) at the interface have a significant influence on total energy absorption during crack propagation. Thus the fiber-matrix bond strongly affects the ability of fibers to stabilize crack propagation in the matrix. Many researchers have investigated and modeled the effect of the interfacial bond on composite properties such as crack resistance [2,3] and durability [4]. Using different testing techniques, many researchers have conducted fiber pullout tests to characterize the fiber/matrix interfacial bond properties in fiber reinforced cementitious composites. In this study, the interfacial bond properties between polypropylene fibers and cementitious matrices were studied using pullout tests. The results obtained from this study are important for better understanding of the role of polypropylene fibers in improving the properties of brittle cement-based composites.

The second part of this study involved a new method for improvement of the fiber/matrix interfacial bond. While polymer fibers have certain advantages over other fiber types, they also have their limitations. One of these limitations is the poor adhesion and wettability to a cementitious matrix as a result of their chemical inertness and low surface energy [5], resulting in a weak bond with the cement matrix. Consequently it is necessary to develop special techniques to enhance the interfacial bond of polymer fibers in order to utilize the maximum possible strength of the fiber and to assure advantageous composite properties. The need for enhancing interface properties is especially important for higher modulus, higher strength polymeric fibers that are increasingly being introduced at attractive costs. A variety of interface strengthening mechanisms have been proposed and utilized. Some of these make use of macroscopic processes such as fiber deformation, others utilize microscopic changes such as fiber surface and/or transition zone modifications. Figure 1.2 shows the interface densification technique, achieved by addition of fine silica fume powder to the cement matrix. This technique provides bond strength enhancement up to several times, but is limited to metal and carbon fibers only. For low surface energy polymer fibers, fiber deformation and fiber surface modification have been shown to be more effective in improving the interface bond strength [6]. Most fiber deformation processes result in an increase in surface area of contact with the cement matrix per unit fiber length.

These processes include fibrillation, crimping and twisting of fibers shown in Figures 1.3(a), 1.3(b), 1.3(c). Another fiber deformation process, which results in an increase in mechanical anchorage of fibers in cementitious matrix, is the addition of buttons at the ends of the fibers [7] as shown in Figure 1.3(d). Finally surface treatment of fibers by means of plasma treatment [8] is also used to improve interfacial bond characteristics in polymeric fibers/cementitious systems. In the presence of a gas plasma, hydrogen atoms are removed from the polymer backbone and replaced by polar groups. The presence of polar functional chemical groups on the fiber surface enhances reactivity and thus improves the adhesion between fiber and cement. A review of the interface strengthening mechanisms in FRC is provided in [9]. In this study, a new fiber surface modification technique has been proposed and shown to be effective in improving the interfacial bond strength between polypropylene fibers and cement matrix.

1.2 EXPERIMENTAL INVESTIGATION AND RESULTS

1.2.1 *Pullout samples and experimental procedure*

Pullout of a fiber from a cement based matrix was used to characterize the interfacial bond between the matrix and the fiber. A schematic of the pullout sample used in this study is shown in Figure 1.4. These samples were cast in a 25 mm diameter, 50 mm long plastic cylindrical molds. The plastic cement matrix was poured in the mold and the fiber was introduced from the top and held there by a slot in the lid of the mold. Embedded fiber length of 25 mm was used for most of the tests. A bolt was cast in the samples on the side opposite to the fiber to hold the sample on the Instron testing machine through a threaded steel block. The samples were allowed to harden in air for 24 hours and then placed in a wet bath. Pullout tests were carried out after a period of 7 days. The sample was held on the Instron testing machine and the fiber was loaded in tension until the fiber debonded and was withdrawn. The rate of pullout used in this study was 0.02 mm/s. Pullout load and the end displacement of the fiber were continuously recorded and were used to develop pullout-load versus end displacement curves. These curves were used to obtain the peak pullout loads and pullout energies (toughness) by calculating the areas under the curves. The following materials were used in this experimental program: *Matrix* – Cement paste (w/c =0.35) and Mortar (cement/sand=0.5, w/c=0.35); *Fibers* – the fibers that were used for this study are called Strux 85/80 and were provided by Grace Construction Products, Massachusetts. These are thin strips of polypropylene, 50 mm long and having a rectangular cross-section of 1.25 x 0.2 mm. A picture of these fibers is shown in Figure 1.5.

1.2.2 *Pullout behavior of strux fibers*

A comprehensive experimental program on pullout tests of strux polypropylene fibers from cement matrix was carried out. The parameters investigated included the effect of embedded length on the pullout characteristics, the development of the interfacial bond with the age of curing of matrix and the effect of exposure to degrading environments like seawater and salt water on the interfacial bond. The bond strength was calculated from the peak load and the embedded area of the fiber. Also the area under the pullout curve up to 5 mm pullout displacement was calculated and termed as interfacial toughness. A typical Pullout curve of the fibers used in this study is shown in

Figure 1.6. It can be seen from this plot that the pullout load initially increases almost linearly with the slip. The non linear region indicates the start of debonding of the fiber from the matrix. The interfacial debonding can be considered as a mode II fracture. This interfacial crack stably propagates up to peak load; that is, the crack propagates only when the pullout load increases. After the peak load, unstable crack growth occurs, which means that the crack grows even though the pullout load decreases. Finally, the fiber starts slipping out of the matrix.

The average pullout strength of these fibers for an embedded length of 25 mm based on 17 samples was 24.5 ± 2.1 N. Interfacial toughness was defined as the area under the pullout curve up to a pullout displacement of 5 mm. This was decided based on the consideration that a crack opening of the order of 1 cm is not acceptable for normal serviceability in most practical structures. The average interfacial toughness for the 17 samples tested was found to be 122.6 ± 10.3 N-mm.

1.2.3 *Comparison of strux fibers with structural fibers*

Strux fibers were chosen for this study over two other fiber types also provided by Grace Construction Products. These fibers were also tested and compared with strux fibers in terms of their strength and pullout behavior. The results of this comparison revealed Strux fibers to be better than the other two as reinforcements for concrete and thus these fibers were chosen for further investigation.

(a) Fibrillated fibers

A picture of fibrillated twisted fibers is shown in Figure 1.7. The average pullout strength of these fibers was determined to be 48.1 ± 7.1 N. Although their pullout strength is almost twice the pullout strength of strux fibers they have other drawbacks. These fibers fibrillate extensively during mixing in concrete thus losing their effectiveness for bridging macro-cracks. Also, these fibers are about 50% more bulky than strux fibers. Thus, to obtain the same volume fraction of fibers in concrete, the number of strux fibers can be twice the number of fibrillated fibers resulting in the same efficiency in terms of pullout energy absorption in the composite.

(b) Welded fibers

To improve the performance of fibrillated fibers, welds were created at the edges of these fibers. A picture of these fibers is shown in Figure 1.8. The aim of putting welds at the edges was twofold. Firstly, the welds would prevent the complete fibrillation of the fibers. Secondly, the fibrils at the edges would flare up during vigorous mixing in concrete and thus provide excellent mechanical anchorage. A schematic illustration of this concept is shown in Figure 1.9. In this study, the strength of the fibers with and without welds was determined using tension grips on the Instron testing machine. The strength of the fibers with welds was found to be 50% less than that of fibers without welds. Thus it was concluded that the fibers lose much of their effectiveness due to loss of strength as result of welding.

Based on the above analysis it was decided to choose strux fibers for this study. The following sections deal with the pullout behavior of strux fibers under different conditions.

1.2.4 *Effect of embedded length on the pullout characteristics*

Pullout tests were carried out for three different embedded lengths (19 mm, 25 mm, 38 mm) of strux fibers in cement mortar. It was found that the peak pullout load increases with the increase in embedded length. With an increase in the embedded length, the pullout characteristics of the fibers also change. The pullout curves for the three embedded lengths are shown in Figure 1.10 where A, B and C correspond to the three embedded lengths of 19, 25 and 38 mm. With an increase in embedded length, the part of the curve corresponding to frictional sliding shows an increase in the pullout load. This increase can be attributed to the increase in friction between the fiber and matrix due to abrasion of the fiber as it slides out of the matrix. The abrasion effect tends to increase with the increase in embedded fiber length. The plot of the Peak Pullout loads is shown in Figure 1.11. The error bars shown on the graph are 95% confidence intervals, calculated using student’s t-distribution. The shear strength of the bond based on peak loads was calculated for the three embedded lengths and it was found that it is almost constant, as shown in Figure 1.12.

1.2.5 *Effect of curing age of matrix on the pullout characteristics*

Mechanical properties of cement-based materials are time dependent due to prolonged cement hydration process. In fiber reinforced concrete, mechanical behavior may also be time dependent due to the aging effect not only on the matrix properties but also on the fiber/matrix bond property. The contrast in the rate of development between interfacial bond and various properties could result in a complicated composite age-dependent behavior compared with ordinary cement materials especially at the early age. Thus, it is important to understand the development of interfacial bond with the curing age of matrix.

A batch of pullout samples was prepared and tests were carried out after first 8 hours, 24 hours and each day after that for a period of 7 days. The peak pullout loads from this test scheme are plotted in Figure 1.13. It was found from these tests that the interfacial bond achieves its maximum strength within the first two days of curing and further curing of matrix has no effect on the interfacial bond. This is in contrast to the development of the properties of matrix, which is a long process.

1.2.6 *Effect of degrading environments on pullout characteristics*

Although, polypropylene is fairly resistant to chemical agents such as acids, alkalis, and salts [10], concrete is known to degrade under the attack of seawater [11]. Diffusion of aggressive ions present in seawater results in a series of chemical reactions leading to degradation of concrete and also alteration of its microstructure. Changes in the microstructure at the interfacial zone may also affect the fiber/matrix interfacial bond which is mainly mechanical in nature. To study the effect of seawater and salt water on the interfacial bond properties, a batch of 24 pullout samples was prepared. After curing for a period of 28 days, 6 samples were tested to obtain baseline data and 6 samples each were placed in plain water (control), salt water (5% weight fraction) and seawater. These samples were tested after a period of 6 months. The 28 day average pullout strength was 24.0 ± 1.0 N and the average pullout strength of samples exposed to plain water, salt water and seawater for 6 months was respectively 24.5 ± 1.6 N, 27 ± 1.0 N and 30.3 ± 1.3 N. A comparison of the pullout curves for the samples exposed to plain water, salt water and seawater is shown in Figure 1.14. The pullout curves shown are the average of 6 samples for each of the environments. It can be observed from these results that the pullout strength of samples exposed to salt water and seawater is more than those kept in plain water, with the pullout strength of samples exposed to seawater being maximum. The change in microstructure of concrete at the interfacial region with exposure to seawater could be the reason behind this phenomenon.

1.3 A METHOD FOR IMPROVEMENT OF INTERFACIAL BOND

A new method for improving the interfacial bond between Polypropylene fibers and cement mortar matrix is proposed. In this method, mechanical indentations were created on the fiber surface by pressing the fibers between two hardened steel surfaces having projections. A picture of the indenting surfaces is shown in Figure 1.15. Fibers were placed one at a time between the two surfaces and the surfaces were pressed together on an Instron machine at known loads. Three different levels (pressures) of indentation were used and pullout tests were carried out with the fibers thus modified. A schematic of the indenting procedure is shown in Figure 1.16.

Pullout of indented fibers

A picture of a plain fiber (A) along with fibers having three different levels of indentations is shown in Figure 1.17. Three levels of indentation were obtained by pressing the fiber between the two surfaces at three different pressures of 200 kPa, 500 kPa and 700 kPa (B, C, D). Figure 1.18 shows the comparison of the pullout curves of these four fibers. The average pullout strengths of the fibers A, B, C, D are 25.8 ± 0.5, 61.0 ± 2.9, 73.9 ± 1.4, and 101.6 ± 5.3 N. The pullout strength of fibers with the indentation level of 700 kPa is 3 times the pullout strength of plain fibers. The peak pullout loads of these fibers are plotted in Figure 1.19. The figure also shows the decrease in the fiber strength with increasing indentation. This plot shows that using this indentation procedure, an indentation level of 700 kPa would be the optimum for the maximum utilization of the fiber strength. At this indentation level, the fiber would just pullout of the matrix without breaking and thus resulting in maximum energy absorption. These deformations can be easily created on the fibers on a large scale in the following way. Extruded sheets of polypropylene can be passed through rollers having projections, and pressed together at the required load using a mechanism capable of adjusting the pressure between the two rolls. A schematic of this process is shown in Figure 1.20. The sheets thus produced with indentations can be slit longitudinally into tapes which can be cut to the required length to obtain the fibers.

1.4 CONCLUSIONS

A comprehensive experimental program was carried out to evaluate the pullout behavior of polypropylene fibers from cementitious matrix. This data would be helpful in better understanding the behavior of the fibers in the cementitious matrix and also the overall behavior of the composite. Based on these experiments, the following conclusions can be drawn. With the increase in embedded length, fiber abrasion effect becomes prominent and results in an increase in pullout load. The fiber/matrix interfacial bond attains its maximum strength within the first two days of curing of the matrix unlike the strength development of the matrix, which is a long process. The effect of degrading environments like salt water and seawater on the interfacial bond strength was also evaluated. Based on the pullout tests, the fiber/matrix bond strength was found to increase with exposure to salt water and more so with exposure to seawater. The reason behind this observation could be a change in the microstructure of concrete with exposure to such environments, leading to an increase in friction between the fibers and matrix. Finally, a fiber surface modification methodology for improving the interfacial bond properties between fiber/cement using mechanical indentations of fibers was proposed. Maximization of bond strength and interface toughness can be achieved with optimum level of indentations, as illustrated for polypropylene fibers. The bond strength between polypropylene fibers and cement matrix was shown to increase by a factor of 3 with optimum level of modification. This result may have important implications in optimal design of fiber reinforced concrete. This method can be used for other high strength, high modulus polymer fibers. By improving the fiber matrix bond, it is possible to use lower fiber aspect ratio or volume fraction in FRC while retaining essentially the same crack resistance.

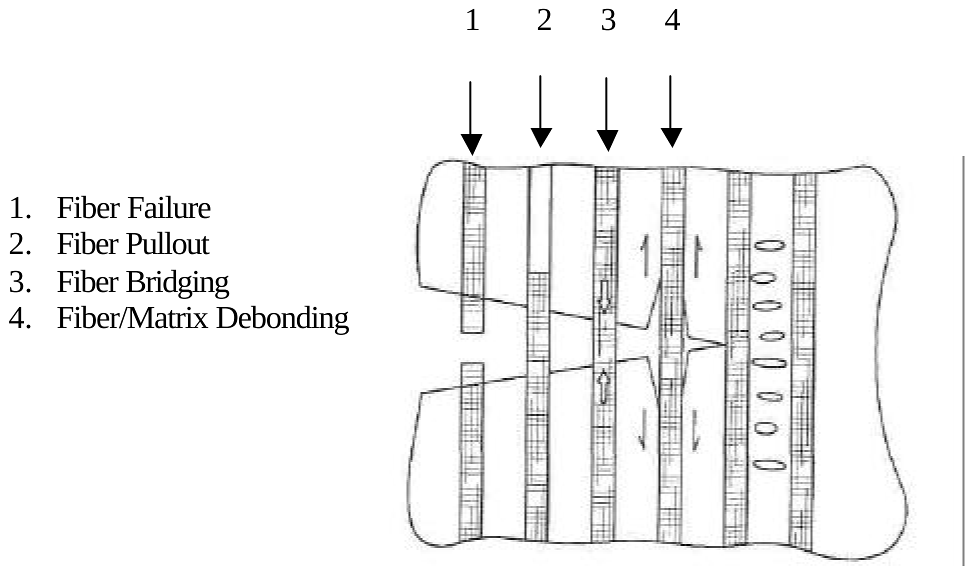


Figure 1.1. Energy absorption mechanisms in FRC

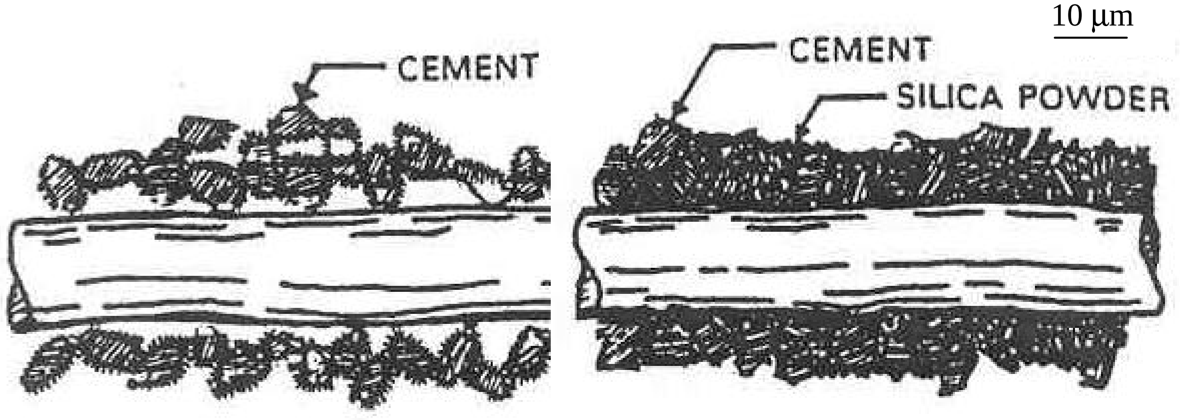


Figure 1.2. Interface densification for fiber-matrix bond strengthening

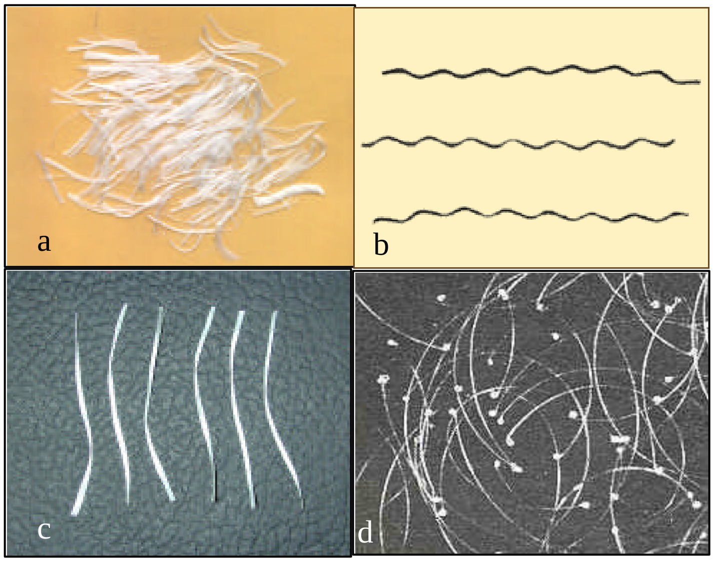


Figure 1.3. Fiber deformation processes for bond improvement

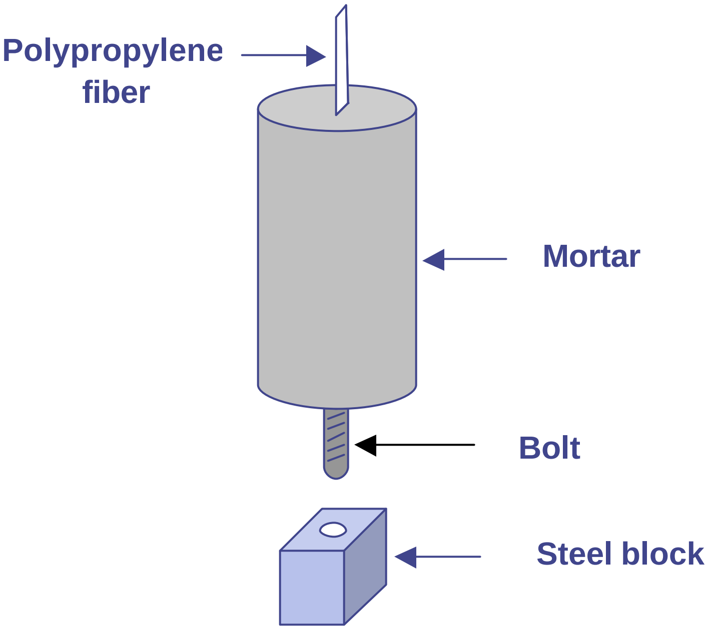


Figure 1.4. Schematic of the pullout test sample

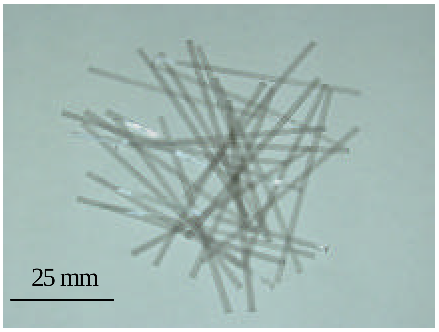


Figure 1.5. A picture of the fibers used in this study

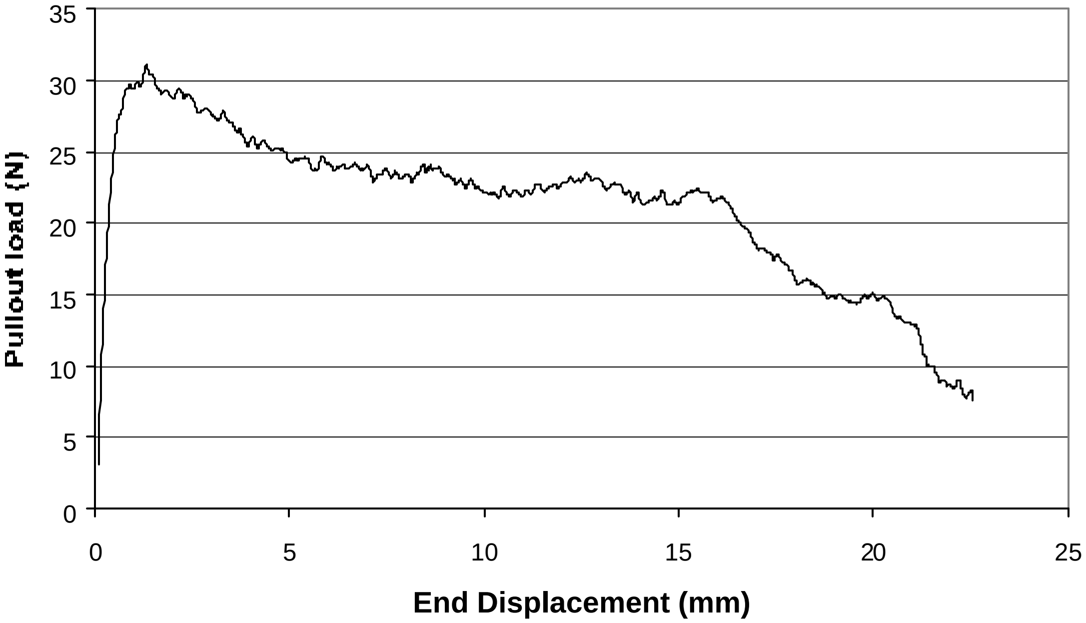


Figure 1.6. A typical Pullout of curve of Strux 85/80 fiber

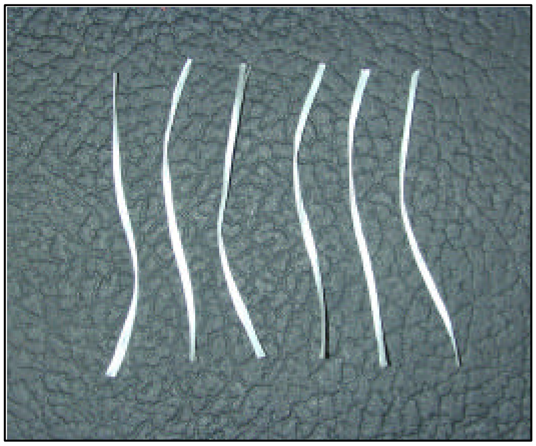


Figure 1.7. A picture of fibrillated twisted polypropylene fibers

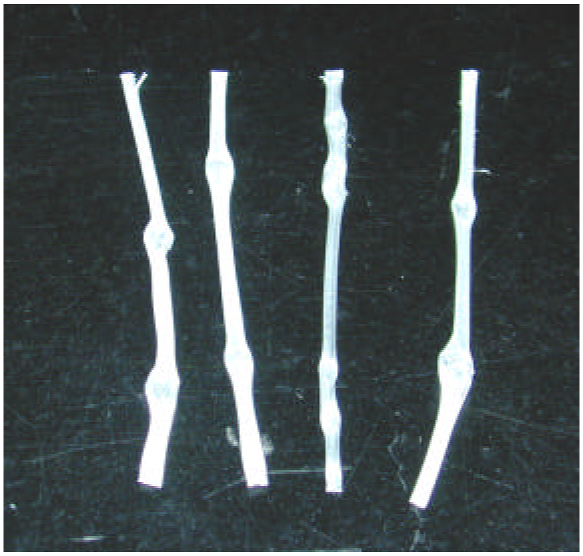


Figure 1.8. Picture of Welded Fibers

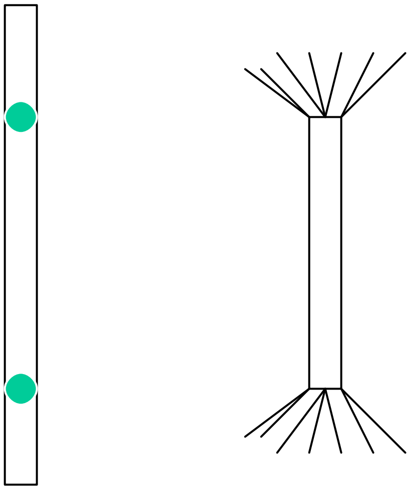


Figure 1.9. A schematic of welded fibers

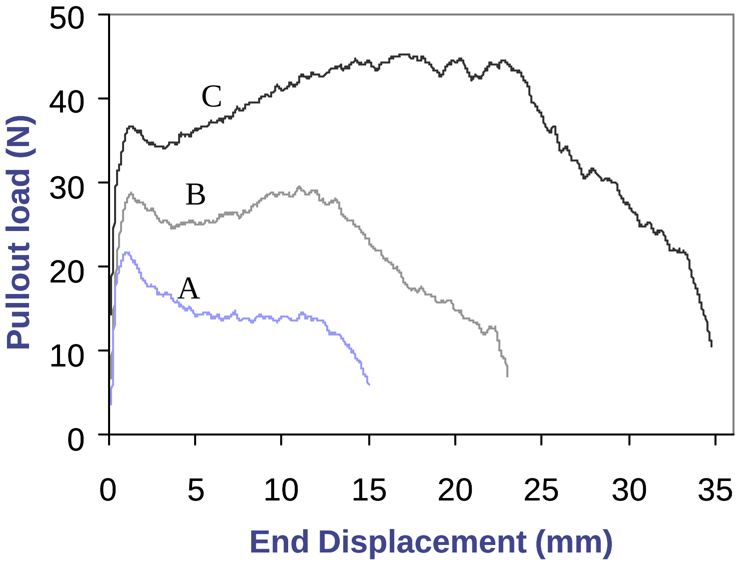


Figure 1.10. Pullout plots for three different embedded lengths
(A) 19 mm (B) 25 mm (C) 38 mm

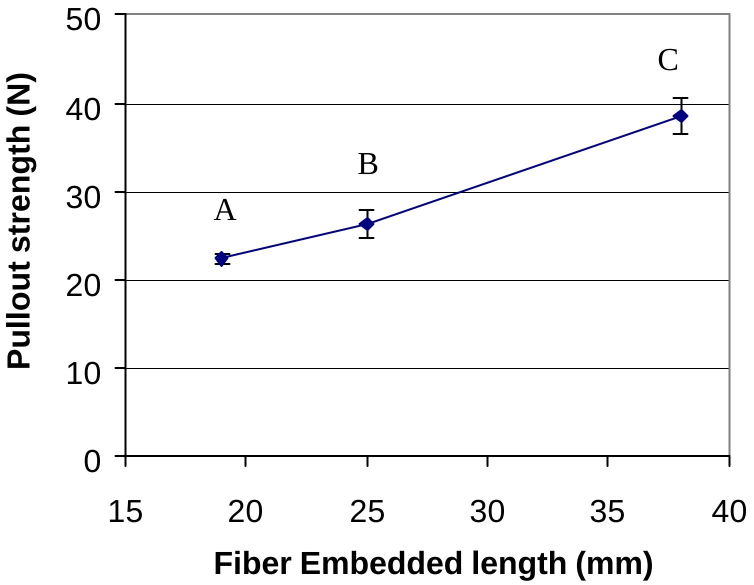


Figure 1.11. Peak Pullout loads for three different embedded lengths
(A) 19 mm (B) 25 mm (C) 38 mm

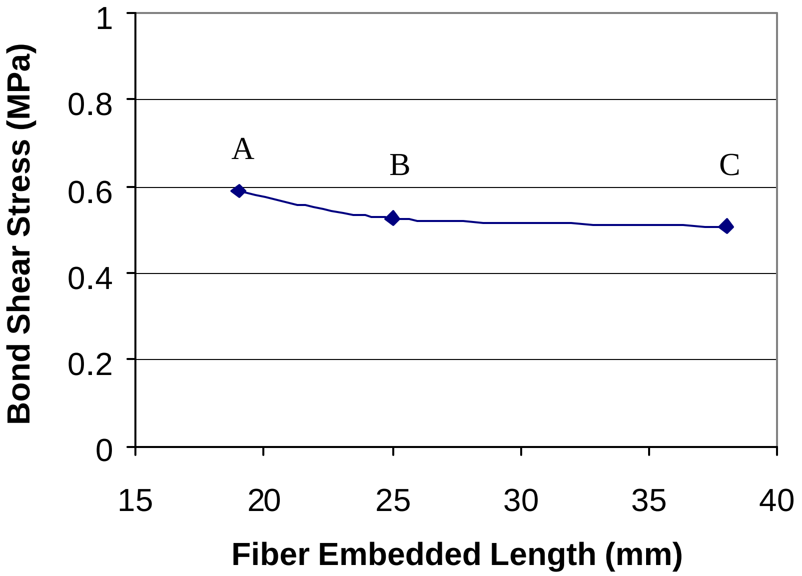


Figure 1.12. Bond Shear stress for three different embedded lengths
(A) 19 mm (B) 25 mm (C) 38 mm

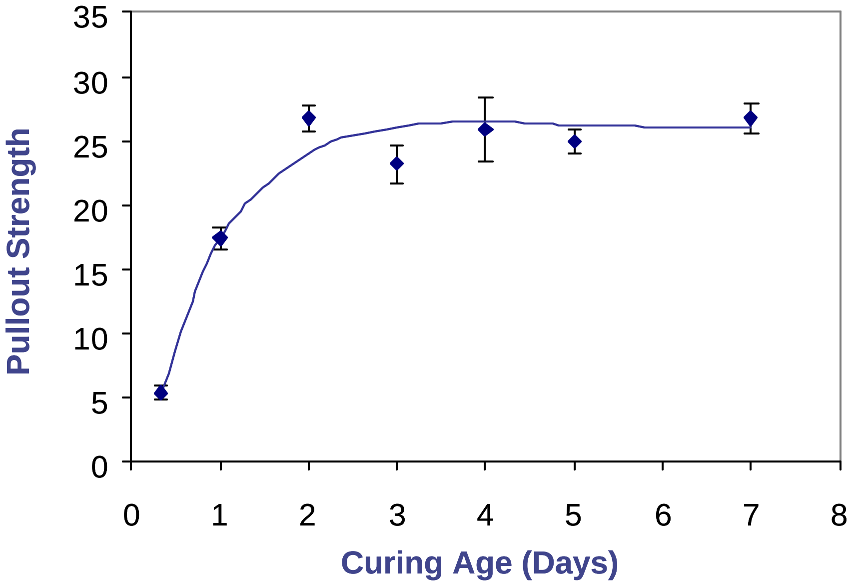


Figure 1.13. Development of Bond strength with curing age of matrix

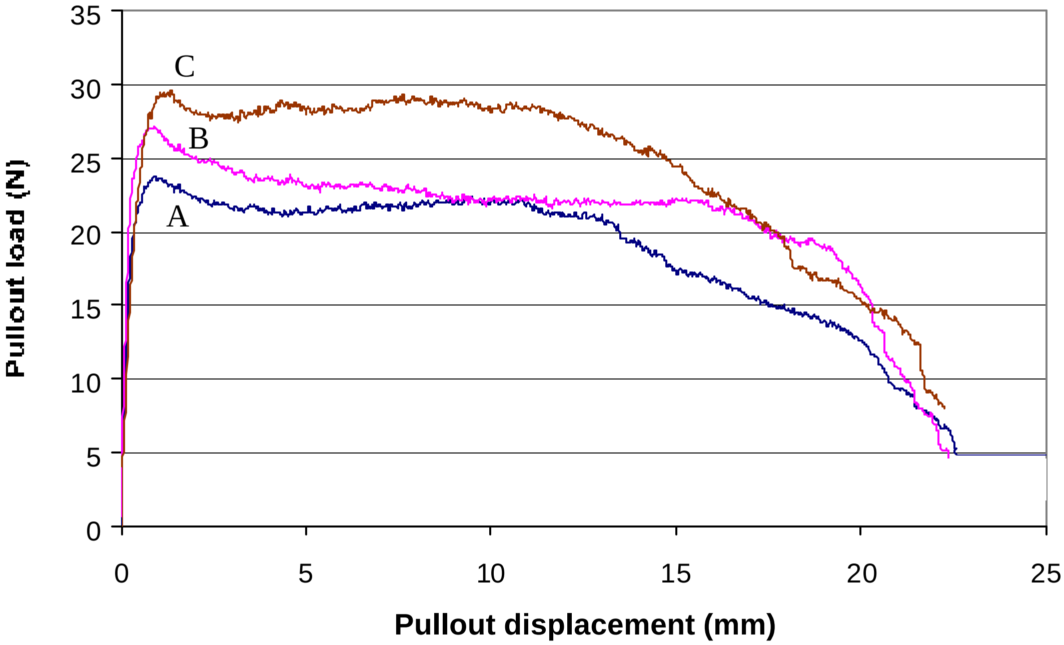


Figure 1.14. Average pullout curves for (A) samples exposed to plain water (B) samples exposed to salt water (C) samples exposed to seawater

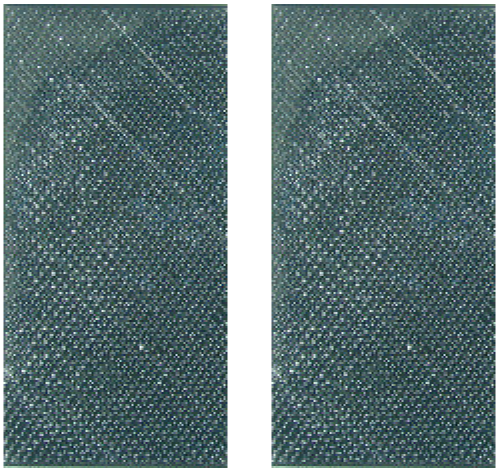


Figure 1.15. Picture of indenting surfaces

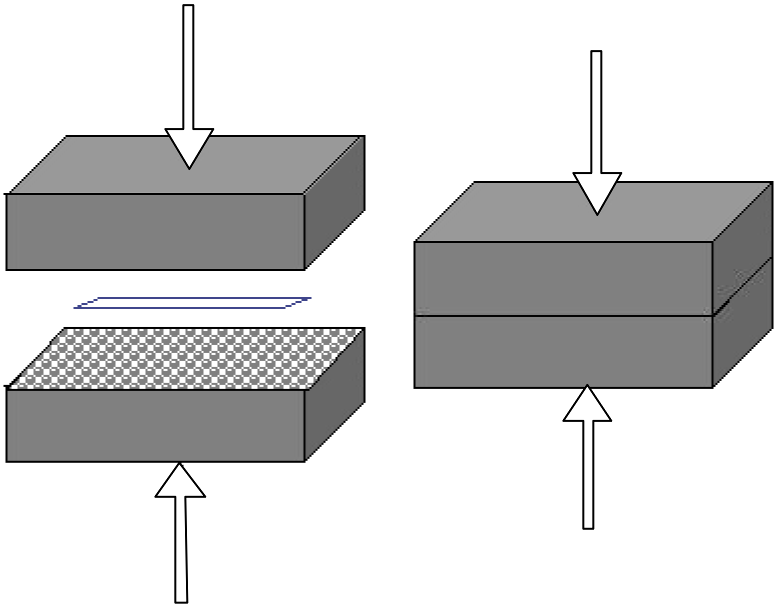


Figure 1.16. Schematic of the indenting procedure

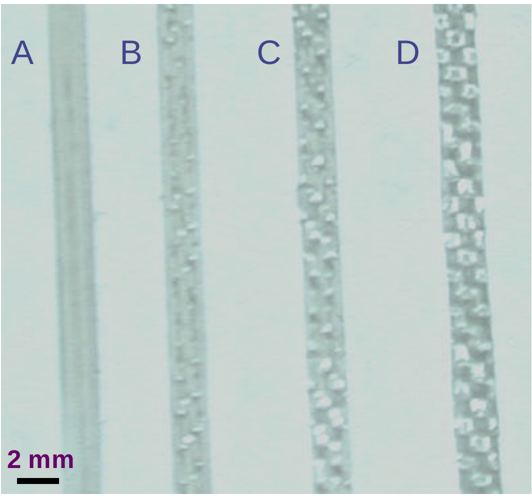


Figure 1.17. A picture of plain and indented fibers

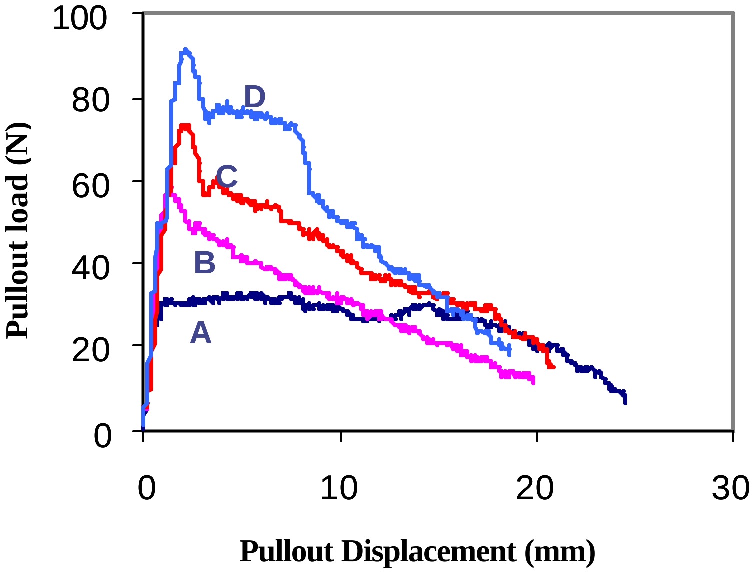


Figure 1.18. Pullout curves of plain and indented fibers

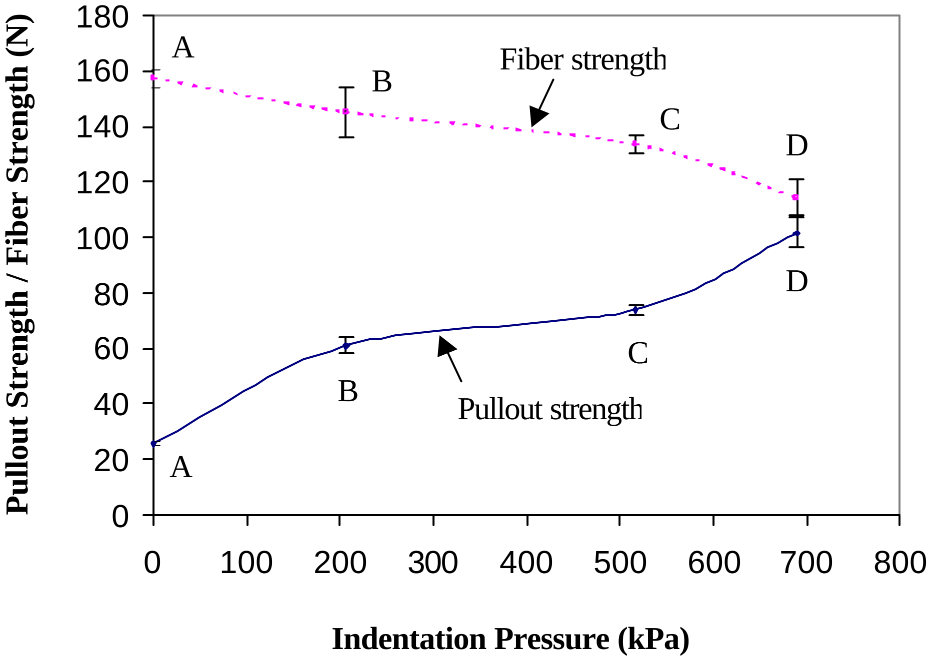


Figure 1.19 Peak pullout loads and strengths of fibers with different levels of indentation (A) Plain fiber (B) Indentation pressure= 200 kPa (C) Indentation pressure= 500 kPa (D) Indentation pressure= 200 kPa

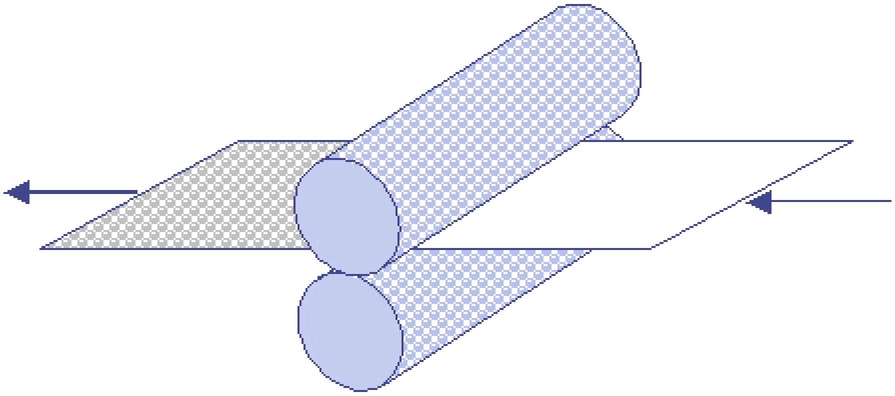


Figure 1.20 Schematic of the suggested indenting procedure on a large scale

CHAPTER 2

FRACTURE CHARACTERIZATION OF POLYPROPYLENE FIBER REINFORCED CONCRETE

2.1 INTRODUCTION

In recent years, the importance of fracture mechanical characterization of cementitious composites has been recognized not only by researchers but also by the industry. It was found that parameters such as the compressive strength and the elastic modulus do not adequately describe the behavior of cementitious materials under different loading conditions. This is truer for the case of fiber reinforced concrete, especially polymeric fiber reinforced concrete, where the fibers become most effective only after the matrix cracks. The use of fibers in cement based composites leads to a significant toughening effect, much more so than improvements in strength properties. Thus, it is of utmost importance to study the fracture behavior of fiber reinforced concrete to understand the role of fibers in concrete. Several fracture test methods for concrete have been proposed to RILEM and ASTM [12]. A wedge splitting test method proposed by Tschegg and Linsbauer [13] and later refined by Bruhwiler and Whittman [14] was used for this study. This test method is most suitable for fiber reinforced concrete because it provides a large fracture surface area and provides stable crack propagation until complete separation of the specimen thus providing valuable information about the post cracking region where the fibers are most effective. Special molds were prepared for making the samples and appropriate fixtures for the experimental setup were fabricated. After establishing the experimental setup and procedure, an experimental program for determining the effect of degrading environments on the fracture properties of polypropylene fiber reinforced concrete was started. The aim of this program is to determine the effect of seawater on cracked concrete marine structures.

2.2 WEDGE SPLITTING TEST

2.2.1 Wedge splitting test sample preparation

Samples were prepared using special molds made of plyform. A picture of a wedge splitting test sample is shown in Figure 2.1. The groove and the starter notch were prepared by attaching a 41 mm x 20 mm x 200 mm PVC bar to the bottom of the mold. Specimens were taken out of the molds 24 hours after the final set and PVC bars were removed. The starter notch and the side notches were cut into the specimens with a diamond bladed rock cutting saw one day prior to testing. The initial depth of the starter notch after removing the PVC bar is approximately 5 mm. The depth of the starter notch is increased to 25 mm using a diamond blade saw.

2.2.2 Experimental setup and procedure

Wedge splitting testing needs special experimental fixture since it is not a standard test method. A picture of the test setup is shown in Figure 2.2. The aluminum fixtures and the steel wedges were fabricated in the mechanical engineering workshop. The hardened steel wedge was used to load the specimen through a line of rollers placed on the groove in the specimen. Grace Construction Products provided the special rollers. The tests were carried out on Instron Testing Machine. Testing is performed in the vertical position and the sample is supported linearly along its base directly below the line of loading. To maintain an approximately constant rate of crack opening, the tests were carried out at a constant crosshead speed of 1.0 mm/min. The crack mouth opening displacement was recorded using a clip gage attached to the aluminum fixture screwed on the sample. The vertical load provided by the wedge translates into horizontal splitting load. The vertical load is recorded by the machine and can be converted into horizontal splitting load using the geometry of the wedge. Thus a plot of the horizontal splitting load v/s CMOD (Crack Mouth Opening Displacement) can be obtained.

Initial tests were carried out on a batch of 4 samples (batch 1), prepared using fibrillated fibers. A picture of fibrillated fibers is shown in Figure 1.7. The mix design of this concrete is shown in Table 2.1. The horizontal splitting load v/s CMOD for one of these samples is shown in Figure 2.3. This curve shows three distinct regions, a linear elastic region up to the peak load, initiation of the crack and unstable crack propagation i.e., the crack requires lesser and lesser load to propagate, and finally a region of stable crack propagation where the crack propagates at constant load.

A picture of the fractured surfaces is shown in Figure 2.4. The fibers can be seen to have fibrillated and broken. The critical stress intensity factor for this geometry has been calculated using finite element method [15] and is given by

$$K_{IC} = k.F_{H,max} \qquad (1)$$

where k for this geometry has the value of 62.37 $m^{-1.5}$ and $F_{H,max}$ is the maximum horizontal splitting load. Average fracture toughness of the four samples based on the peak horizontal splitting load was 0.86 ± 0.02 MPa√m. Normally accepted value of fracture toughness for concrete is approximately 1 MPa√m. The fracture toughness of this concrete was low because of high water/cement ratio of 44%.

2.3 EFFECT OF SALT WATER ON SAMPLES WITH INITIATED CRACKS

2.3.1 Test Program

The motivation behind these experiments was to determine the effect of seawater on cracked concrete structures. Exposure to salt water was used as a simulation for seawater. For this purpose a batch of 54 wedge splitting samples was prepared. The mix design of this concrete is shown in Table 2.2. After a period of 28 days of curing, three different crack lengths were initiated in the samples. The three crack lengths were corresponding to three CMOD (crack mouth opening displacements) of 0.25 mm, 0.5 mm and 1.5 mm. Three samples each with these crack lengths and three samples each without cracks have been placed in two environments (a total of 48 samples), plain water and salt water. Another six samples were tested immediately after the curing period of 28 days, to obtain baseline data. Fracture energy (G) for extending the crack from 0 to 0.25 mm ($G_{0-0.25}$) , 0.25 mm to 0.5 mm($G_{0.25-0.5}$), 0.5 mm to 1.5 mm ($G_{0.5-1.5}$) and 1.5 mm to 2.5 mm ($G_{1.5-2.5}$) was obtained experimentally for these samples. The fracture energy was calculated using

$$G_F = \frac{1}{B.W} \int_{a_0}^{a_f} F_H\,(CMOD).d(CMOD) \qquad (2)$$

where W= width of crack area, B=Height of crack area, F_H =Horizontal splitting load, a_0=initial crack length, a_f= final crack length.

The samples placed in the two environments will be tested after a period of one year and the fracture energies ($G_{0\text{-}0.25}$, $G_{0.25\text{-}0.5}$, $G_{0.5\text{-}1.5}$, $G_{1.5\text{-}2.5}$) for the samples placed in plain water and salt water will be compared with the baseline data.

2.3.2 Baseline Data

Six samples were tested immediately after 28 days of curing to obtain baseline data. For three of these samples the test was run continuously up to a CMOD of 2.5 mm. The horizontal splitting load v/s CMOD for one of these samples is shown in Figure 2.5. For the other three, a repeated loading-unloading procedure was followed where the sample was loaded up to a CMOD of 0.25 mm, unloaded and loaded again up to a CMOD of 0.5 mm and so on up to a CMOD of 2.5 mm. The horizontal splitting load v/s CMOD for one of these samples is shown in Figure 2.6. The fracture energy for extending the crack from 0 to 2.5 mm CMOD was calculated from all the six specimens. The fracture energies ($G_{0\text{-}0.25}$, $G_{0.25\text{-}0.5}$, $G_{0.5\text{-}1.5}$, $G_{1.5\text{-}2.5}$) were calculated from the three samples that were subjected to repeated loading and unloading. This data is shown in Table 2.3. Average fracture toughness for this batch was 1.28 ± 0.07 MPa√m.

2.4 FRACTURE SURFACES

The wedge splitting tests provide a large fracture surface that can be used to understand the behavior of fibers in the concrete matrix. A side view of one of the fractured surfaces is shown in Figure 2.7. Most of the fibers in this sample can be seen to have pulled out rather than broken. The interaction of the fibers with a crack can be observed from the fracture surface. Figure 2.8 shows a propagating crack in a wedge splitting test. In this figure, the fibers can be seen being pulled out of the matrix and bridging the crack. This observation further stresses the need of understanding the pullout behavior of fibers from matrix.

2.5 CONCLUSIONS

A setup for conducting wedge splitting tests was successfully fabricated and the procedure established. The values of fracture toughness obtained from these tests are fairly close to the reported values for concrete. The wedge splitting tests provide stable crack propagation until complete separation of the specimen. This feature was utilized in this study to initiate cracks in samples in a controlled manner and then exposing them to degrading environments. This would be helpful in understanding the impact of environment on cracked concrete structures. The tests of the control batch (28 days curing) have been carried out and samples with initiated cracks have been placed in plain water and salt water. The tests will be carried out after one year and will be compared with the baseline data.

CEMENT (PORTLAND TYPE II)	984 lbs (447 kg)
FINE AGGREGATE (SAND)	1730 lbs (786 kg)
COARSE AGGREGATE (19 MM)	3900 lbs (1772 kg)
FINE AGGREGATE (3.2)	461 lbs (209 kg)
WATER (W/C =0.43)	425 lbs (193 kg)

Table 2.1 Concrete mix design for batch 1

CEMENT (PORTLAND TYPE II)	725 lbs (329 kg)
FINE AGGREGATE (SAND)	1433 lbs (651 kg)
COARSE AGGREGATE (19 MM)	1162 lbs (528 kg)
FINE AGGREGATE (3.2)	387 lbs (175 kg)
WATER (W/C =0.40)	290 lbs (131 kg)

Table 2.2 Concrete mix design for environmental testing

Fracture Energies	$G_{0-2.5}$	$G_{0-0.25}$	$G_{0.25-0.5}$	$G_{0.5-1.5}$	$G_{1.5-2.5}$
Values in N-mm	1133.6±30.3	246.4±11.1	105.9±8.5	351.3±15.4	368.6±17.2

Table 2.3. Baseline data for fracture energy comparison

Figure 2.1 Picture of a wedge splitting test specimen

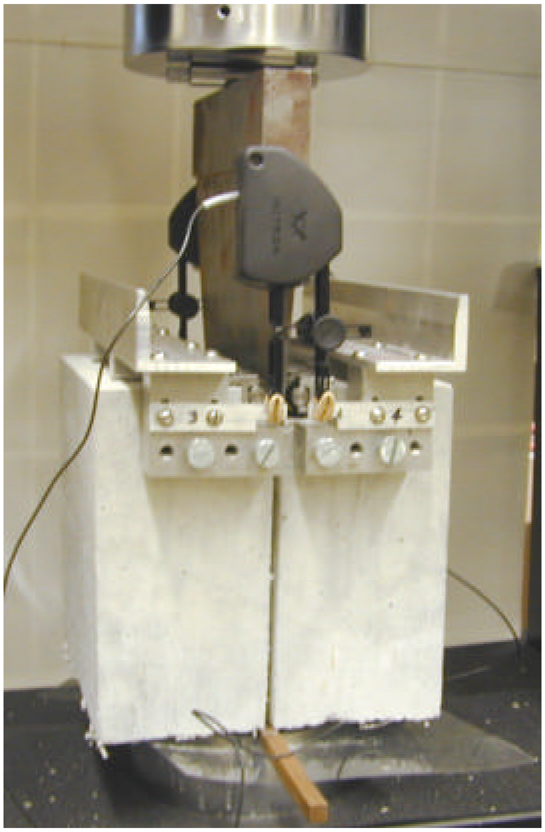


Figure 2.2 Experimental setup for conducting wedge splitting test

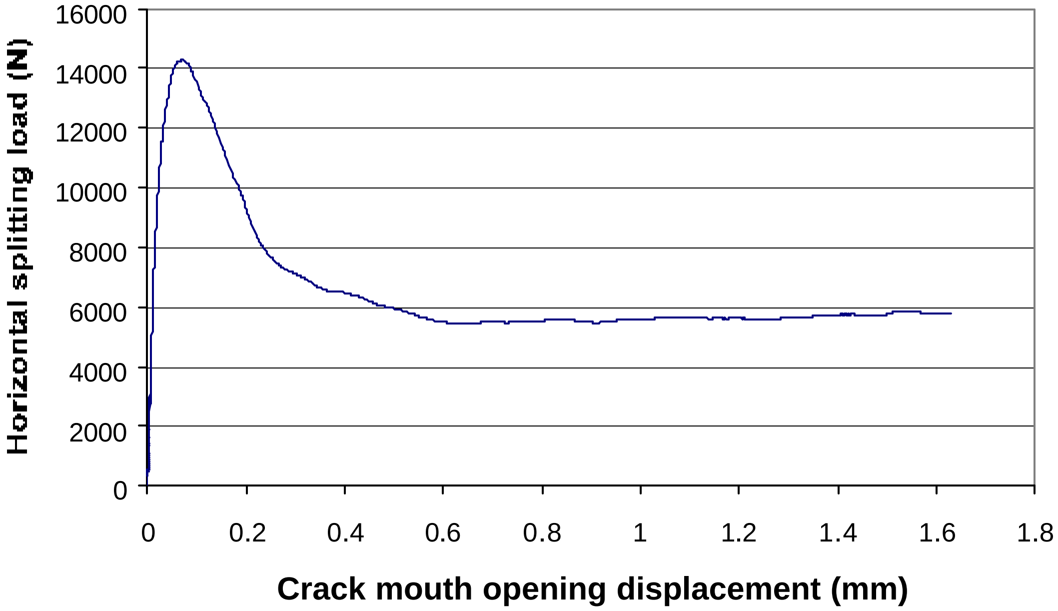


Figure 2.3 Horizontal splitting load v/s CMOD for a wedge splitting sample

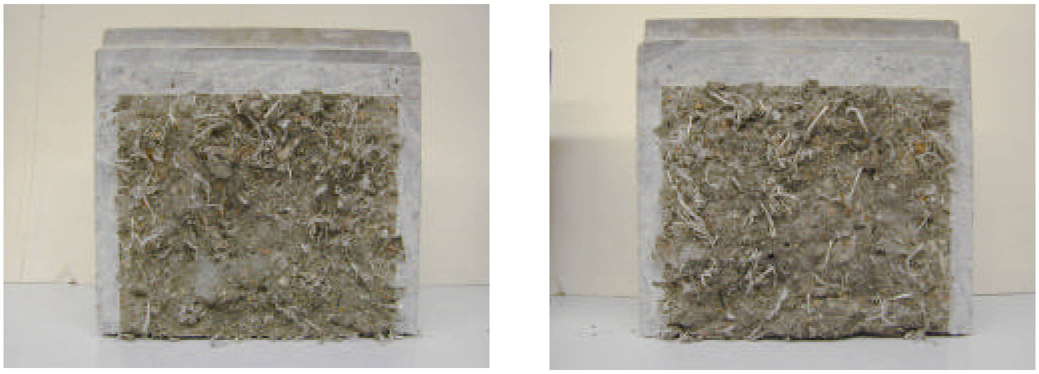


Figure 2.4. Fracture surfaces of Wedge

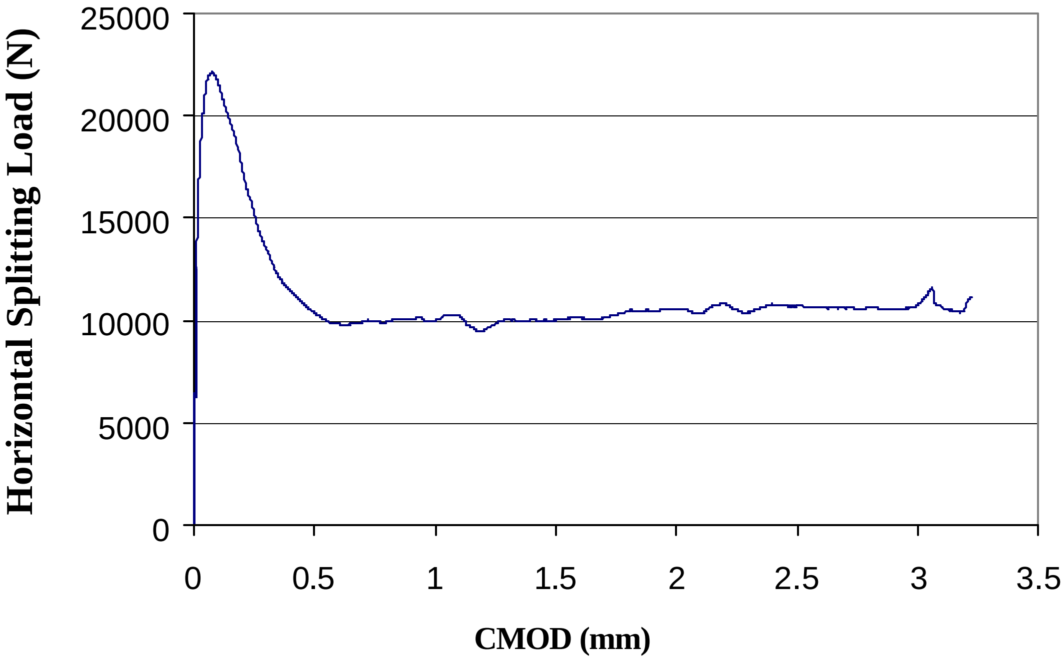


Figure 2.5 Horizontal splitting load v/s CMOD for a control batch sample

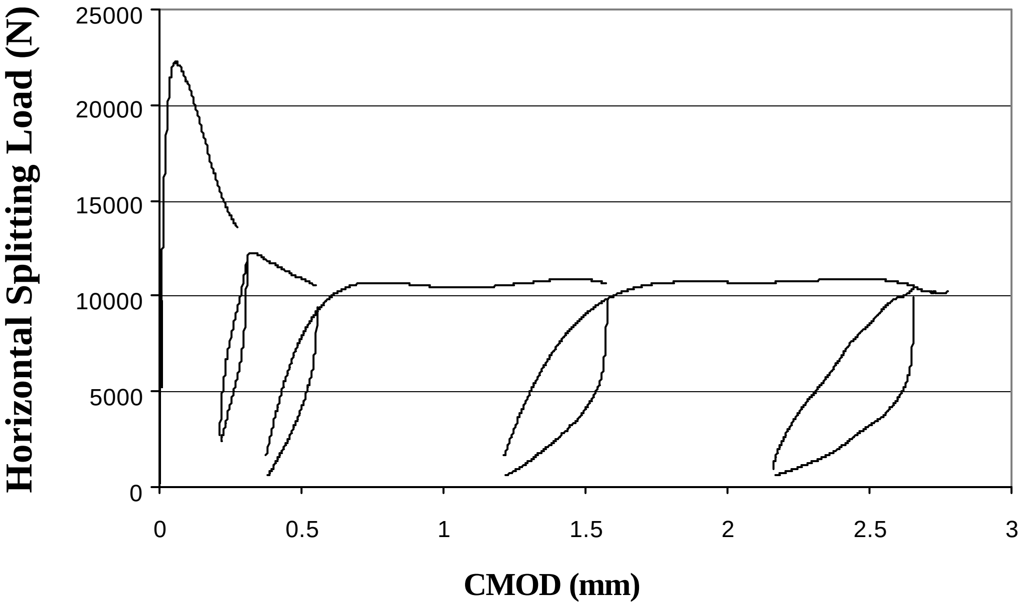


Figure 2.6 Loading-Unloading curve for a control batch sample

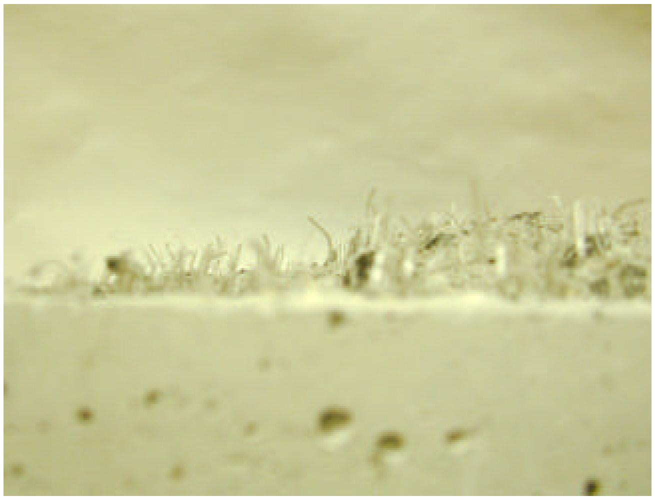
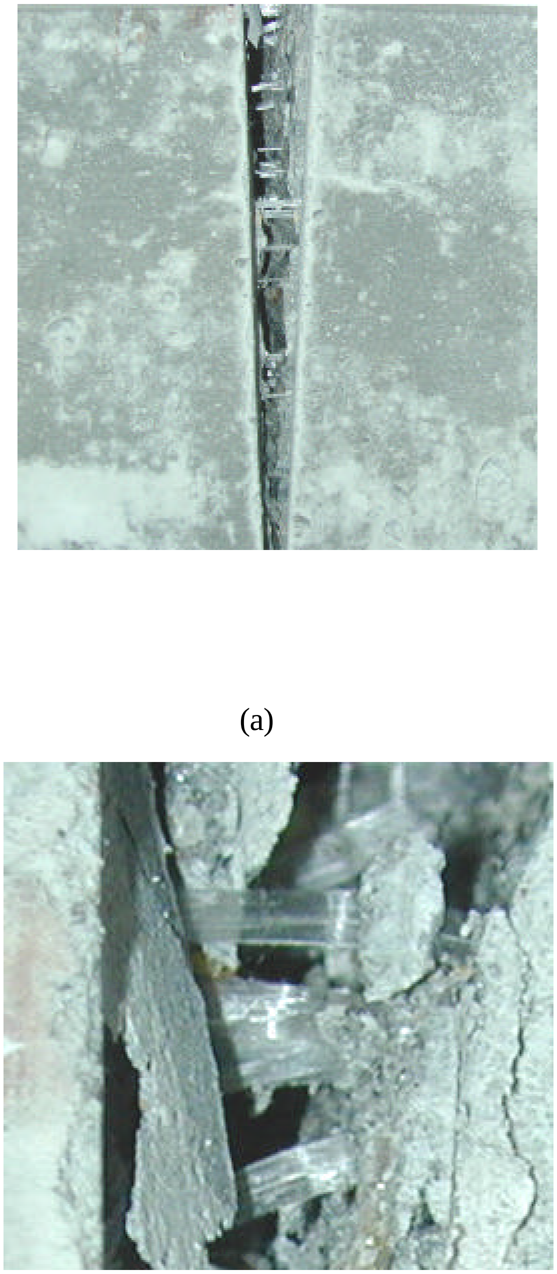


Figure 2.7. A picture of the fractured surface showing fiber pullouts



(a)

(b)

Figure 2.8. (a) Photograph of a crack in wedge splitting test sample
(b) A close-up view of fibers bridging the crack

CHAPTER 3

RECOMMENDATIONS FOR FUTURE WORK

The interfacial bond between polypropylene fibers and cement matrix were studied using pullout tests. The data from the pullout tests can be used in modeling the composite properties. Improvements in the properties of interfacial bond translate directly into improvements of the composite properties. In this study, a new method for improvement of the interfacial bond between polypropylene fibers and cement matrix is proposed and its effectiveness demonstrated through pullout tests. This method was based on the observation that the fiber/matrix interfacial bond is mainly frictional in nature. Another means of increasing the friction between fiber and matrix and thus enhancing the bond could be to deliberately introduce residual shrinkage stress, and therefore, clamping pressure on the fiber by the surrounding matrix. For example, using special additives for increasing the shrinkage of concrete. The fibers can be coated with such materials before mixing them in concrete.

The method for improvement of interfacial bond described in this study for polypropylene fibers can also be used with steel fibers. Steel fibers are stronger than concrete, so the optimum level of surface modification would be the point where the fibers pull out of the matrix without breaking the matrix. This would result in the maximum possible utilization of the strength of the fiber.

Wedge splitting test is a relatively new type of test for measuring the fracture properties of concrete. A facility for performing these tests and for preparing the samples has been established. These tests provide stable crack propagation until complete separation of the specimen. This feature was utilized in this study to initiate cracks in samples in a controlled manner and then exposing them to degrading environments. This would be helpful in understanding the impact of environment on cracked concrete structures. Wedge splitting tests can be used to understand the contribution of fibers towards improvement of fracture properties of concrete. The energy absorbed during the pullout of fiber can be obtained from the pullout tests and can be compared with the difference in energy absorption between plain concrete and fiber reinforced concrete. The effectiveness of the fiber modification proposed in this study has been shown using pullout tests. The effectiveness of this modification can be verified by using the wedge splitting tests.

REFERENCES

[1] Zollo, Ronald F., “Fiber-reinforced Concrete: an Overviewafter 30 Years of Development”, *Cement and Concrete Composites* 19 (1997), pp 115.

[2] Mobasher, B., Li, C. Y., “Effect of interfacial properties on the crack propagation in cementitious composites”, *Advanced cement based materials* 1996, 4, pp 93-105.

[3] Li, V. C., Wang, Y., Backer, S., “Effect of fiber-matrix bond strength on the crack resistance of synthetic fiber reinforced cementitious composites”, Mat. Res. Soc. Symp. Proc. Vol. 114, pp167-173, 1988 Materials research society.

[4] Bentur, A.,“Role of interfaces in controlling the durability of fiber-reinforced cements”, Journal of materials in civil engineering, Vol. 1, No. 1, February, 2000, pp 2-7.

[5] Wu, S., Polymer interface and adhesion, Marcel Dekker, New York, 1982.

[6] Li, V. C., Stang, H., “Interface property characterization and strengthening mechanisms in fiber reinforced cement based composites”, *Advanced Cement Based Materials* 1997, 6, 1-20.

[7] Naaman, A. E., Shah. S. P., “Some developments in polypropylene fibers for concrete”, SP 81-18, pp 390.

[8] Wu, H. C., Li, V. C., “Fiber cement interface tailoring with plasma treatment”, Cement and Concrete Composites 21 (1999) 205-212.

[9] Li, V. C., Chan, Y. W., Wu, H. C., “Interface strengthening mechanisms in polymeric fiber reinforced cementitious composites”,Proc. Int. Symp., Brittle

Matrix Composites , Warsaw, September 13-15, 1994, IKE and Woodhead Publ., Warsaw 1994, pp 7-16.

[10] Segre, N., Tonella, E., Joekes, I., “Evaluation of the stability of polypropylene fibers in environments aggressive to cement-based materials”, Cement and Concrete research, Vol. 28, No. 1, pp. 75-81, 1998.

[11] Regourd, M., “Physico-Chemical studies of cement pastes, mortars, and concretes exposed to seawater”, SP 65-4, American Concrete Institute, 1980, pp 63-82.

[12] Shah, S. P., Swartz, S. E., *Fracture Mechanics of Concrete*, John Wiley and Sons, Inc., 1995.

[13] Linsbauer, H. N., and Tschegg, E. K., “Fracture energy determination of concrete with cube-shaped specimens”, *Zement und Beton* 31 (1986) 38-40.

[14] Bruhwiler, E., and Whittmann, F. H., “The wedge splitting test: A method of performing stable fracture mechanics tests”, *Engineering Fracture Mechanics* 35 (1990) 117-125.

[15] Guinea, G. V., Elices, M. and Planas, J., “Stress intensity factors for wedge splitting geometry”, International journal of fracture 81:113-124,1996.

APPENDIX A

POLYPROPYLENE FIBER REINFORCED CONCRETE

POLYPROPYLENE FIBER

Polypropylene is the most commonly used polymeric fiber for reinforcement of concrete. Polypropylene is a man made hydrocarbon polymer. Polypropylene fiber is made using an extrusion process in which the material is hot drawn through a die. The draw ratio, which is a measure of the extension that is applied to the fiber during fabrication, is responsible for the molecular orientation and crystallization that determines the physical material properties of the fiber. Draw ratios are generally around eight for polypropylene fiber.

Polypropylene fibers are produced as continuous cylindrical monofilaments that can be chopped to specific lengths or as films and tapes that can be fibrillated to form the fibrils of rectangular cross-section. Fibrillated means the polypropylene film is slit so it can be expanded into an open network of fibers. Monofilament polypropylene fibers are more expensive than the fibrillated film or tape fibers and have inherent weak bond with the cement matrix because of their relatively small surface area.

Polypropylene fibers have some unique properties that make them suitable for incorporation into concrete matrices. They are chemically inert and very stable in the alkaline environment of concrete. They have a relatively high melting point with low cost raw materials. The polymer has a hydrophobic surface so that it does not absorb water. Disadvantages include poor fire resistance, sensitivity to sunlight and oxygen, a low modulus of elasticity, and a poor bond with the concrete matrix.

FABRICATION AND PROPERTIES OF POLYPROPYLENE FIBER REINFORCED CONCRETE

Polypropylene fibers can be incorporated into concrete in several different forms and using several different methods. In this study short discrete chopped fibers were used as reinforcement. Because polypropylene fibers are hydrophobic, they need only be mixed long enough to ensure even dispersion in the concrete mix. These fibers are added when all the constituents have been mixed and further mixing is carried out for five minutes. The addition of relatively low-modulus polypropylene fibers to concrete does not yield substantially improved strength properties. However these fibers help in controlling temperature and shrinkage cracking and also in improving the post crack behavior of concrete. Typical applications of concrete reinforced with polypropylene fibers include: overlays and pavements, slabs, flooring systems, crash barriers, recast pile shells, and shotcrete for tunnel linings, canals, and reservoirs.

FAILURE MODES OF POLYPROPYLENE FIBER REINFORCED CONCRETE

Standard tests were carried out on polypropylene fiber reinforced concrete with 1% volume fraction of fibers. Tension, compression and flexure tests were carried out using ASTM standards. Fracture test was carried out using the wedge splitting test method. The main aim of these experiments was to determine the failure modes of the polypropylene fiber reinforced concrete under the modes of tension, compression, flexure and fracture.

Compression tests

Compression tests were carried out on cylinders (4”diameter and 8”length) according to ASTM standard C 39. A picture of a failed specimen is shown in Figure 1. The specimen failed in shear mode. The failure was not catastrophic as is the case with regular concrete. The fibers held the specimen together even after peak load. The average compressive strength was 26 Mpa. The accepted benchmark for compressive strength is 21 Mpa.

Tensile tests

Splitting tensile tests were carried out on Cylinders (4” diameter and 8” length) according to ASTM standard C 496. A picture of a failed specimen is shown in Figure 2. Regular concrete cylinders break apart into two halves under tensile splitting load. For the samples with fibers, the two halves were held together by the fibers. The fibers can be seen bridging the two halves in Figure 2. The average tensile strength was 2.7 MPa. The accepted benchmark for tensile strength of concrete is 2.0 MPa.

Flexure tests

The flexural toughness was measured using ASTM C 293-94. These tests were performed on a MTS™ testing system Model 810. The specimen had a 152.4 mm (6”) thickness and height and a 508 mm (20”) length, which gave a 457.2 mm (18”) test span. The test setup and a failed specimen is shown in Figure 3. The fibers can be seen bridging the cracked surfaces. The average flexural toughness was 3.9 MPa.

Figure 1. Failure mode in compression

Figure 2. Failure mode under tensile splitting load

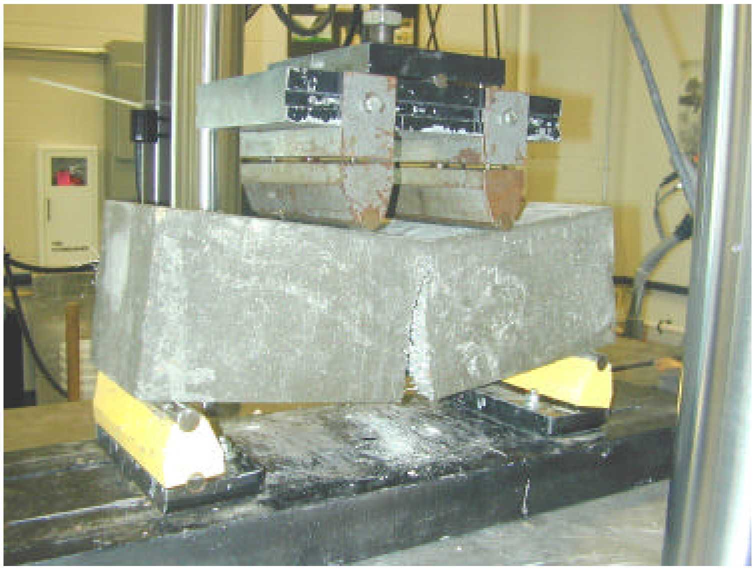
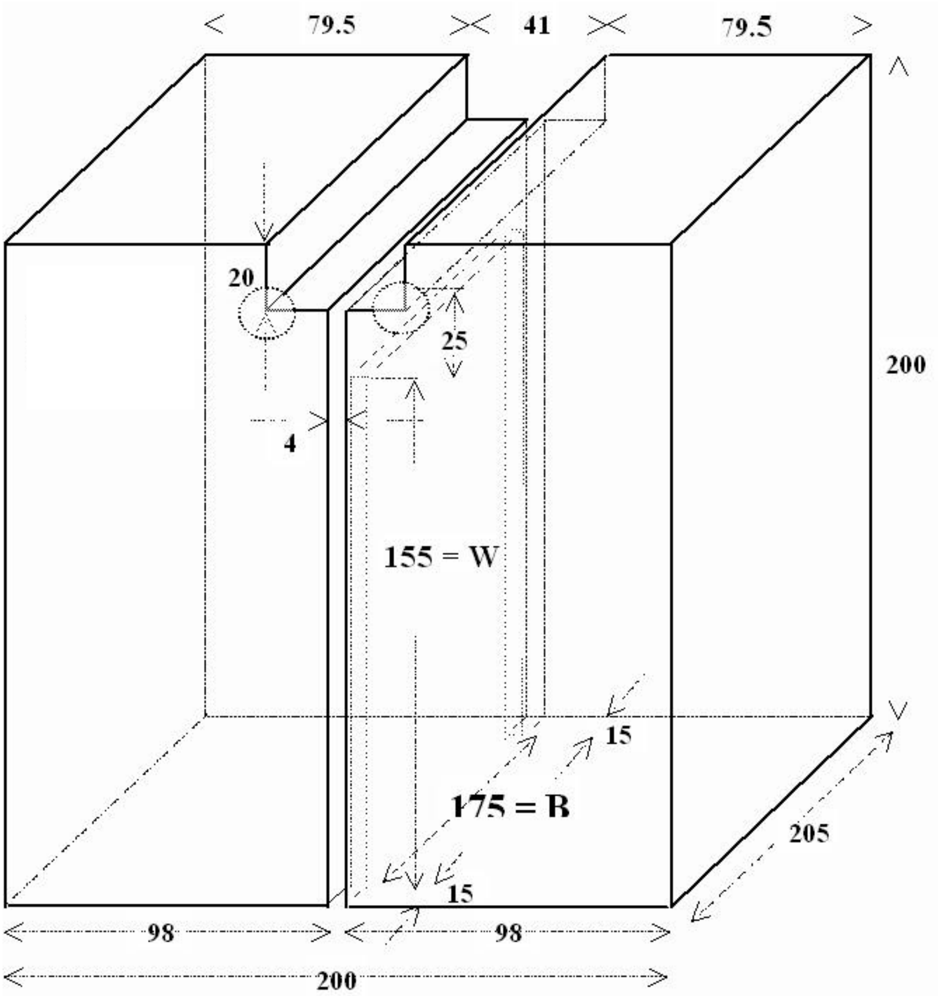


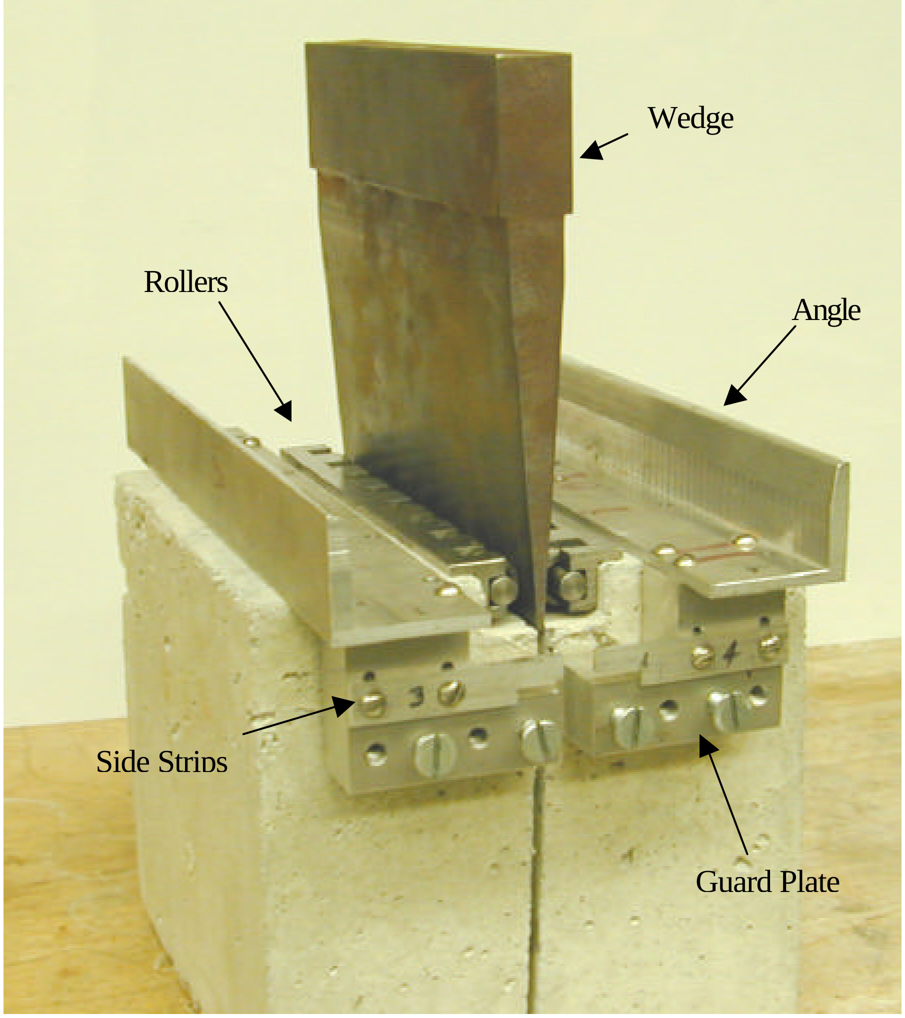
Figure 3. Failure of a beam in flexure

APPENDIX B

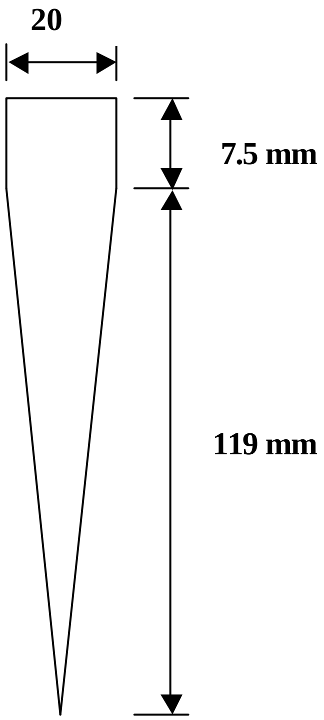
DRAWINGS OF THE WEDGE SPLITTING TEST SAMPLE AND FIXTURE



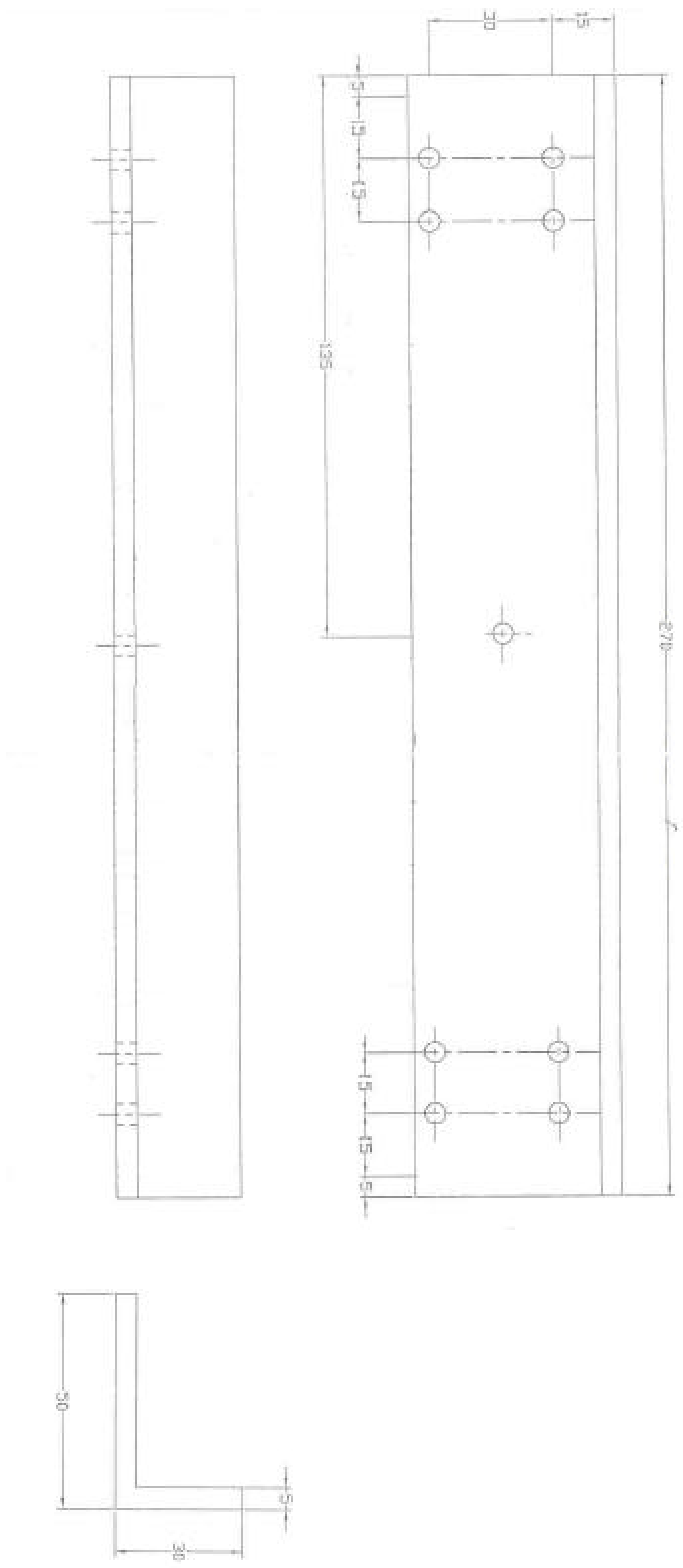
Geometry of the wedge splitting test sample



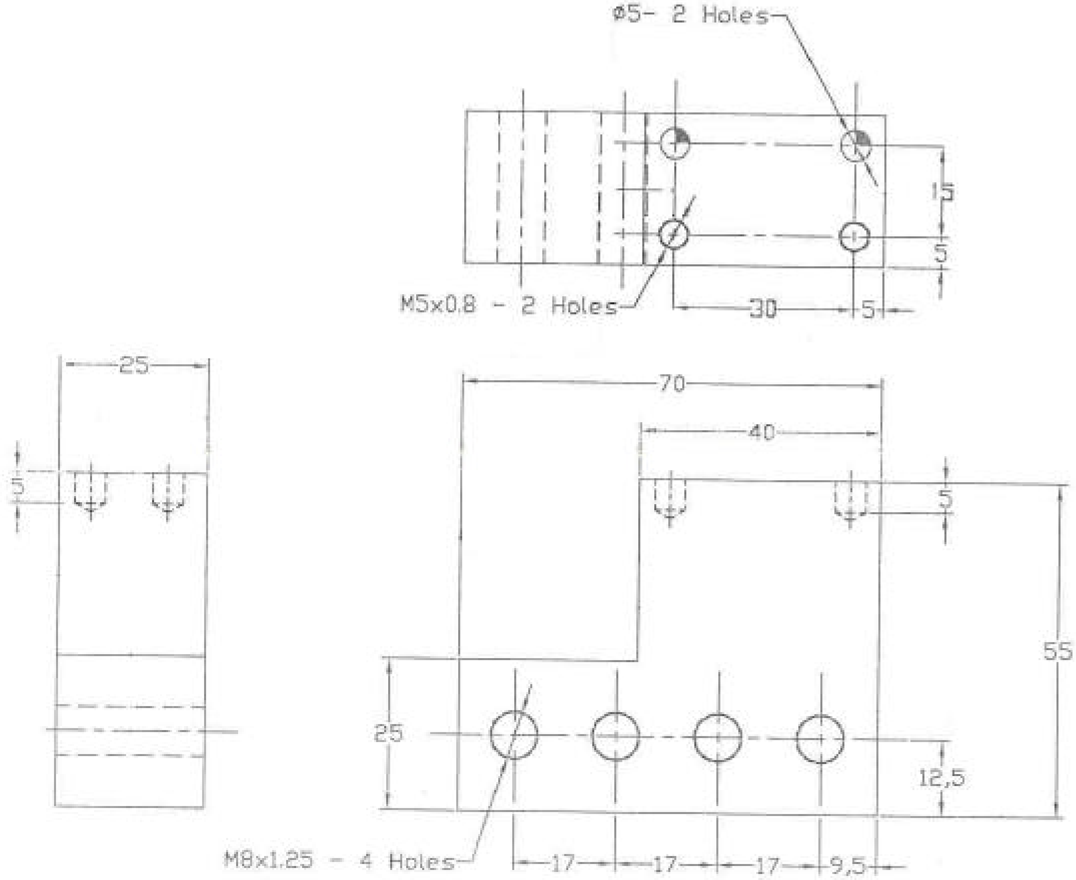
Picture of the wedge splitting test fixture and the wedge



Drawing of the wedge used for splitting



Aluminum Angle



Guard Plates (four)

BIBLIOGRAPHY

Bentur, A.,"Role of interfaces in controlling the durability of fiber-reinforced cements", *Journal of materials in civil engineering*, Vol. 1, No. 1, February, 2000, pp 2-7.

Bentur, A., "Interfaces in fiber reinforced cements", *Materials Research Society Symposium Proceedings* Vol. 114, pp 133-144.

Bruhwiler, E., Whittmann, F. H., "The wedge splitting test: A method of performing stable fracture mechanics tests", *Engineering Fracture Mechanics* 35 (1990) 117-125.

Conjeaud, M. L., "Mechanism of seawater attack on cement mortar", Publication SP 65-3, *American Concrete Institute*, 1980, pp 39-61.

Guinea, G. V.,, Elices. M., Planas, J., "Stress intensity factors for wedge-splitting geometry", *International Journal of Fracture* **81:** 113-124, 1996.

Linsbauer, H. N., and Tschegg, E. K., "Fracture energy determination of concrete with cube-shaped specimens", *Zement und Beton* 31 (1986) 38-40.

Jan G. M van Mier., *Fracture Processes of Concrete*, CRC Press, Inc., 1997.

Li, V. C., Chan, Y. W., Wu, H. C., "Interface strengthening mechanisms in polymeric fiber reinforced cementitious composites", *Proceedings of the International Symposium on Brittle Matrix Composites*, Warsaw, September 13-15, 1994, IKE and Woodhead Publ., Warsaw 1994, pp 7-16.

Li, V. C., Maalej, M., "Toughening in cement based composites. Part II: Fiber reinforced cementitious composites", *Cement and Concrete Composites* 18 (1996) 239-249.

Li, V. C., Stang, H., "Interface property characterization and strengthening mechanisms in fiber reinforced cement based composites", *Advanced Cement Based Materials* 1997, 6, 1-20.

Li, V. C., Wang, Y., Backer, S., "Effect of fiber-matrix bond strength on the crack resistance of synthetic fiber reinforced cementitious composites", *Materials Research Society Symposium Proceedings* Vol. 114, pp167-173, 1988 Materials research society.

Mobasher, B., Li, C. Y., "Effect of interfacial properties on the crack propagation in cementitious composites", *Advanced cement based materials* 1996, 4, pp 93-105.

Naaman, A. E., Shah. S. P., "Some developments in polypropylene fibers for concrete", Publication SP 81-18, *American Concrete Institute*, pp 390.

Regourd, M., "Physico-Chemical studies of cement pastes, mortars, and concretes exposed to seawater", SP 65-4, *American Concrete Institute*, 1980, pp 63-82.

Segre, N., Tonella, E., Joekes, I., "Evaluation of the stability of polypropylene fibers in environments aggressive to cement-based materials", *Cement and Concrete research*, Vol. 28, No. 1, pp. 75-81, 1998.

Shah, S. P., Swartz, S. E., *Fracture Mechanics of Concrete*, John Wiley and Sons, Inc., 1995.

Wu, S., *Polymer interface and adhesion*, Marcel Dekker, New York, 1982.

Zollo, Ronald F., "Fiber-reinforced Concrete: an Over view after 30 Years of Development", *Cement and Concrete Composites* 19 (1997), pp 115.