POLYPROPYLENE FIBER REINFORCED CONCRETE IN RAILWAY CROSSTIES

BY

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THESIS
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ABSTRACT

Cracking of concrete crossties is a performance problem that reduces service life and increases maintenance costs. While strong in compression, plain concrete is relatively weak and brittle under tensile stresses. Inclusion of synthetic polypropylene macro fibers in concrete is known to improve crack resistance and is a feasible solution for prolonging the life of crossties. The present study investigated the performance of synthetic polypropylene macro fiber reinforced concrete and their application in railway crossties.

The study involved a thorough review of the properties and testing of synthetic polypropylene fiber reinforced concrete (FRC). A standard test method for obtaining average residual strength of FRC was used to evaluate the performance of various concrete mixtures reinforced with synthetic polypropylene macro fibers. It was found out that the concrete with higher fiber proportions showed significantly higher residual load carrying capacity (post-cracking response). Moreover, the concrete mixtures had acceptable workability and showed only slight loss in compressive strength due to inclusion of fibers.

Self-consolidating concrete (SCC) is an emerging class of concrete which flows and consolidates on its own without vibration. Fiber reinforcement can be used in SCC to enhance the mechanical properties of concrete. The present study investigated the rheological and mechanical properties of SCC reinforced with different proportions of fibers. Fresh property tests included slump flow test and rheological tests using a concrete rheometer. The study underscored the potential for fibers to be accommodated by adjusting the mixture proportions of concrete. It was shown that inclusion of fibers in SCC is feasible for the purpose of manufacturing structural elements like railway crossties.
The present study also considered the current state of prestressed concrete crosstie design and the impact of FRC on mechanical performance of concrete crossties. The applicability of FRC in railway crossties was investigated by developing and testing prototype crossties. A comparative study was performed between a conventional crosstie and a fiber reinforced crosstie through tests at rail seat and center of crosstie. It was found out that the synthetic polypropylene fibers provided sustained capacity for deformation in the concrete crossties along with an improved crack resistance.

Lastly, this study developed a tensile stress-strain model for FRC behavior. Four point bending test results of FRC beams were used to determine tensile behavior of FRC using an inverse analysis approach and a back calculator tool. Preliminary tensile stress-strain models were established which can be used to define constitutive properties for concrete when using finite element analysis (FEA) to analyze experimental results. FEA has not been performed as a part of this thesis work, but will be pursued in subsequent research activities at the University of Illinois.
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CHAPTER 1
INTRODUCTION

1.1 Background and Motivation

Concrete crossties play a crucial role in the performance and safety of ballasted railway tracks (Taherinezhad et al. 2013). Consequently, there have been many analytical and experimental research projects around the world to investigate the progressive failure of crossties. Concrete crossties are exposed to repetitive and dynamic loading scenarios which can cause damage in the form of cracks (Ramezanianpour et al. 2013). Degradation mechanisms like cyclic freezing and thawing, delayed ettringite formation (DEF) and alkali silica reaction (ASR) are among the other potential factors responsible for cracking of crossties. Moreover, corrosion of reinforcement tendons has also been a contributing factor to crosstie failure. Reduced service life of crossties results in heavy maintenance and replacement costs. These concerns have evoked researchers’ interest in the area of durability of concrete crossties. With the support of the Federal Transit Administration (FTA), this thesis is a part of a larger effort within the Rail Transportation and Engineering Center (RailTEC) at the University of Illinois at Urbana-Champaign that aims to propose a resilient concrete crosstie design in order to have an increased service life.

1.2 Objectives

The objectives of this study are:

- To better understand the cracking issue in existing concrete crossties.
- To study the applications of synthetic polypropylene macro fiber reinforced concrete.
• To evaluate the performance of various fiber reinforced concrete mixtures through necessary tests and thus investigate the post failure mechanisms.

• To better understand the potential for synthetic polypropylene macro fibers to be accommodated by self-consolidating concrete mixtures for a possible application in the concrete crossties.

• To promote discussion of the potential benefits of concrete crossties reinforced with synthetic polypropylene fibers.

• To characterize the tensile behavior of fiber reinforced concrete.

1.3 Prestressed Concrete Crossties

1.3.1 Introduction

The important functions of the crossties are (Taherinezhad et al. 2013):

• To support the rail and maintain the track gauge.

• To withstand vertical and longitudinal movement of rails.

• To transfer and distribute loads from rail to ballast.

The first experimental use of concrete crossties in the United States was in 1893 (Hay 1982). These early crossties were reinforced with steel, and experienced cracking and deterioration failures, which resulted in their removal from track within the first few years of their service. The ties could have been improved by increasing the amount of reinforcing steel per tie. However, this made the concrete crosstie uneconomical and the additional reinforcement, although strengthening the ties, did not prevent the occurrence of cracks (Kerr 2003). During the early 1900’s, there were scattered trials of use of concrete crossties all over the world. However, the real escalation of their production and use coincided with the Second World War (FIP 1987).
The tendency of conventional reinforced concrete to crack gave rise to concept of prestressing in concrete crossties (Kerr 2003). The guiding principle has been to use prestressing forces that give rise to sufficiently large artificial compressive stresses in concrete and that do not drop below the level required for preventing the occurrence of tensile cracks during the service life of the structure. The development of prestressed concrete crossties intensified after Second World War. The longer life cycle and lower maintenance costs of prestressed concrete crossties brought many technical and economic advantages to the railway engineering (Taherinezhad et al. 2013). The prestressed concrete sleepers are more sustainable with lower life cycle emissions as compared to timber counterparts. Today, prestressed concrete crossties are one of the most commonly used types of crossties.

Figure 1.1 Concept of prestressing in concrete crossties (from Hay 1982)

1.3.2 Failure of Prestressed Concrete Crossties

Prestressed concrete crossties are expected to withstand high magnitude loading and harsh weather conditions (Taherinezhad et al. 2013). However, like any other concrete element, the prestressed concrete crossties are also subjected to deterioration. Multiple surveys have been conducted in order to investigate the most critical problems in concrete crossties (Zeman 2010). The results showed that cracking from center binding and dynamic loads are one of the
commonly faced problems in crossties. According to survey responses of various transit operators, the most critical concrete crosstie problem for North America transit agencies were ranked (Csenge et al. 2016). It was found out that the average criticality of cracking from dynamic loads and cracking from environmental degradation was ranked 2.42 and 2.29 respectively, with 5.00 being most critical.

The most likely locations for crossties to crack are at the top or at the bottom of the rail seat area, and on top of the crosstie at the center (FIP 1987). Center negative cracking in the top of the crosstie is caused by center binding of the track. The cracking of crosstie due to center binding has been identified as one of the critical problems that results in failure of the crosstie and fastening system (Chen et al. 2014). The cracks which appear on rail seat and mid-span decrease the structural stiffness and make the crossties susceptible to water and chloride ion penetration. Apart from these, splitting of concrete crossties has also been observed which is caused by too many prestressing tendons placed in one layer (FIP 1987).

Figure 1.2 Cracked concrete crosstie due to center binding (from Chen et al. 2014)
1.3.3 Modifications in Structural and Material Design of Crossties

The structural performance of prestressed concrete crossties is very important as reflected by the large volume of published literature (Taherinezhad 2013). However, concrete crossties also need to meet durability requirements. Extensive research has been conducted in order to fully understand the behavior of prestressed crossties. Various attempts have been made to improve the performance through modifications in structural and material design of the crossties. Using steel and polymer fibers for crack control, and utilizing ground granulated blast furnace slag for improving resistance against chloride ion ingestion are some measures which have been tried to improve the structural performance in a cost effective way (Shin et al. 2016). In order to improve the durability of the prestressed concrete crossties, the effects of additional materials, such as rubberized cement and fly ash, have been investigated. It is believed that further work needs to be done in order to understand the behavior of crossties and extend their service life.

1.4 Introduction to Synthetic Polypropylene Fiber Reinforced Concrete

1.4.1 Properties of Fiber Reinforced Concrete

Fiber reinforced concrete (FRC) is a composite material which is obtained by reinforcing conventional concrete with randomly distributed fibers. Fibers may be of steel, glass, polymeric materials, carbon, cellulose, and so forth, and their lengths vary from 0.1 to around 2.5 inches (Banthia et al. 2012). The diameter may vary from a few μm to about 1 mm (0.04 inches). Various sections like round, oval, square, etc. are available depending on the raw material and manufacturing process. Two major categories of fibers are micro and macro. Fibers having an equivalent diameter less than 0.012 inches are called micro and those having equivalent diameter
more than 0.012 inches are called macro fibers. The fibers may be used in concrete with proportions varying from 0.1% to 5.0% by volume of concrete.

Extensive research has been conducted to study the properties of polypropylene fiber reinforced concrete. It has been found out that the fibrillated polypropylene fibers start affecting the workability and increase the air content of concrete when used in proportions more than 0.5% by volume of concrete (Bayasi et al. 1993). Moreover, the concrete compressive strength starts reducing with the inclusion of fibers. However, the reduction is not significantly large. Polypropylene fibers have no effects on the flexural strength of concrete (Alhozaimy et al. 1996). However, these fiber affect the flexural toughness of concrete significantly. Studies have shown that an addition of 0.1%, 0.2%, and 0.3% volume fraction of fibers increases the flexural toughness by 44%, 271%, and 287% respectively. Studies also suggest an increase in impact resistance at failure of concrete with an increase in fiber dosage. Furthermore, researchers have mentioned that using polypropylene fibers can improve bond strength, spalling behavior, fire resistance, and post cracking behavior of concrete (Ramezanianpour et al. 2013). Polypropylene fibers are very effective in reducing the crack width (Banthia et al. 2012). Moreover, multiple crack development with smaller widths is promoted instead of an individual crack with larger width. Results have indicated that permeability depends largely on cracking in concrete. Due to higher crack resistance, it has been found out that the fiber reinforced concrete has lower permeability and thus higher durability.
Figure 1.3 Effect of fibers on crack width (left) and effect of crack width on permeability (right) (from Banthia et al. 2012)

A number of studies have also focused on hybrid reinforcement in concrete. It has been found out that a combination of steel and polypropylene fibers led to a considerable increase in fracture energy of concrete (Mindess et al. 1989). Such hybrid composites have also resulted in high fatigue endurance and impact resistance of concrete (Banthia & Nandakumar 2003). A possible explanation for this superior behavior is that under tensile forces, the fibers are able to bridge cracks and prolong fatigue life (Campione et al. 2004). There are other studies which suggest that concrete containing polypropylene fibers show fiber bridging action and fibers pullout dissipate energy in the wake of the crack tip, and thus show improved load-bearing capacity, and resistance to crack growth (Li et al. 2007). Additionally, the inclusion of polypropylene fibers produces a highly ductile behavior during fatigue loading. Damage initiates in concrete because of the repetitive cycle of loading, which leads to micro cracks and finally leading to failure of the structures (Banjara 2016). The fibers are useful in inhibiting the micro crack growth and thus have showed improved fatigue performance.
1.4.2 Development of Average Residual Strength Test

Crack propagation in concrete is a brittle process that occurs once the conditions of fracture are established at the tip of an existing critical flaw in concrete (Banthia & Dubey 1999). Fibers added to concrete suppress the crack growth by providing closing pressures around such cracked matrix and improving the capability of the material to carry stresses beyond matrix cracking. This results in an increased energy absorption and thus higher toughness which improves the long term durability of concrete by restricting the crack size in service.

There are number of available techniques to evaluate the flexural performance of fiber reinforced concrete. Researchers have extensively studied the concerns in the available test methods for characterization of flexural performance and also tried to propose alternate techniques of analyzing the same (Banthia & Trottier 1995). The most common test method is the ASTM C1609 (2012) technique where a fiber reinforced concrete beam is subjected to four point bending and the recorded load-displacement curve is analyzed for evaluating flexural performance. However, this test method and the related test techniques are problematic because of the sudden load drops that occur immediately after the peak load in an uncontrolled and unstable manner depending upon the stiffness of the machine (Banthia & Dubey 1999). For machines with lower stiffness, there is a high release of energy during the unstable part which results in an inferior post-peak load carrying response. In order to evaluate the performance of fiber reinforced concrete mixtures, it is essential to correctly capture the post-peak response. This can be achieved by using closed loop testing machines where the sudden release of energy and related damage are not allowed to occur. However, such techniques are expensive, difficult to run, and time consuming. Therefore, a simpler test is needed which can also provide reliable data. ASTM C1399 (2015) is a standard test method in which the fiber reinforced concrete beam
is subjected to four-point bending. The pre-cracking process requires loading the test beam to the point that a significant crack occurs by using a parallel loading arrangement with a ductile steel plate. The steel plate is used so that much of the energy of the loading system that is released at the time of cracking is dissipated to reduce its effect on cracking of beam specimen (Zollo et al. 1999). The steel plate is removed after the initial crack development so that the flexural performance of fiber reinforced concrete can be evaluated accurately by reloading the beam specimen.

1.4.3 Fibers in Concrete Crossties

Researchers have conducted a few studies to investigate the effect of fibers in concrete used in the manufacturing of crossties. The study conducted by Ramezanianpour et al. (2013) focused on the durability of concrete material used in crossties. Rapid chloride penetration test (RCPT), water penetration test, and sorptivity tests were performed in order to signify the effects of polypropylene fibers on durability. Additionally, Scanning Electron Microscope (SEM) and X-ray Diffraction (XRD) analysis techniques were used in order to study microstructure. It was found out that polypropylene fibers could reduce permeability and capillary porosity by pore blocking effect. Recently, studies have been conducted on prestressed concrete structural elements or crossties reinforced with fibers (Taherinezhad et al. 2013, Tehrani & Serrano 2014). It has been shown that concrete beams reinforced with fibers experienced a delay in crack growth in both length and width along with smaller initial crack length. These studies showed that the polypropylene fiber reinforcement showed a substantial increase in the ultimate displacement of specimens when tested under compression and flexure. It was found out that the addition of fibers could slow down the crack propagation of concrete crossties (Tehrani &
Serrano 2014). The bridging action of fibers enabled prestressed concrete crossties to sustain larger impact loads. The prestressed concrete crossties reinforced with fibers showed a residual load carrying capacity (Taherinezhad et al. 2013). Therefore, researchers have developed a penchant in the area of prestressed concrete crossties reinforced with fibers and this area needs to be explored further in order to extend the service life of crossties.

1.5 Introduction to Self-Consolidating Concrete Reinforced with Fibers

1.5.1 Properties of Self-Consolidating Concrete

Self-consolidating concrete (SCC) is a highly flowable concrete that can spread under its own weight and achieve good consolidation in the absence of vibration methods (Khayat 1999). Moreover, this self flowable concrete is devoid of segregation and bleeding. SCC is prepared by addition of high amount of high range water reducing admixture, accompanied by addition of viscosity modifying admixture. An appropriate combination of these two admixtures make a highly flowable concrete without any signs of segregation. SCC is finding widespread application in modern day infrastructure because of its numerous advantages. It eliminates the need for compaction and also improves filling capacity of highly congested structural members. Furthermore, it decreases construction time, noise, and labor cost. SCC can also be used in the construction industry in order to accelerate the progress of construction without affecting the mechanical properties and durability of the structure. This particular application makes it very interesting to study its behavior in the field of railway industry where the manufacturing of multiple concrete crossties needs to be achieved quickly.
The most fundamental relationship that can be used to characterize the flow of concrete is the Bingham model (Koehler et al. 2005). This model requires the determination of yield stress ($\tau_0$) and plastic viscosity ($\mu$). The Bingham model is given by equation 1.1.

$$\tau = \tau_0 + \mu \dot{\gamma}$$  \hspace{1cm} (1.1)

In the above model, shear stress ($\tau$) is related to the shear rate ($\dot{\gamma}$) in order to describe fundamental flow properties. The yield stress provides a measure of the shear stress required to initiate the flow and the viscosity provides a measure of the resistance of the flow of materials once the yield stress has been exceeded (Benaicha et al. 2013). These two rheological properties can be used to characterize quantitatively the flow of fresh concrete. In case of SCC, the yield stress has a very low value while the plastic viscosity can vary significantly (Zerbino et al. 2009). An appropriate SCC with adequate mobility and stability involves a balance between the two necessary rheological parameters. High viscosity SCC requires a very low yield stress, whereas a low viscosity SCC requires a greater yield stress. If both parameters are very low, it creates possibilities of segregation. On the other hand, if both parameters are very high, a very stiff concrete is made.

1.5.2 Testing Self-Consolidating Concrete

There are numerous tests available to characterize the adequacy of fresh properties of SCC. The most conventional test to characterize SCC is the slump flow test (ASTM C1611 2014). Over the years, researchers have used slump flow test result as a standard parameter to qualify a concrete mixture as SCC. Studies suggest that SCC has a slump flow value of 24 to 30 inches (Hwang et al. 2006, Khayat 1999). The slump flow test provides a measure of yield stress...
of SCC. A higher slump flow corresponds to lower yield stress. Under the same test set up, ‘flow
time’ can also be evaluated. A higher flow time corresponds to higher viscosity of SCC.

Extensive research has been conducted in order to characterize the self-consolidating
cement through various other fresh property tests as well (Hwang et al. 2006). Various tests in
order to characterize passing ability of SCC include V-funnel, L-box, U-box, and J-ring test. L-
box, U-box, and J-ring test along with filling vessel test can be used to characterize the filling
capacity of SCC. The static stability of SCC can be interpreted by surface settlement test, visual
stability index test, and penetration test. The relevant details of these test methods and
recommended values for different types of concrete mixtures for a performance based
specification have been summarized by Hwang et al. (2006). It was found that a combination of
different tests was needed depending on the structural applications in order to characterize the
behavior of SCC in a better way. Additional studies in this area suggest that the composition of
the concrete mixture, water to cement ratio, the type of cement, and superplasticizer affect the
rheological behavior of concrete (Benaicha et al. 2013). Using pozzolanic fillers, like limestone
powder, and fly ash as a partial replacement of cement content can result in SCC mixtures with
higher flow (Khayat 1999).

Over the years, researchers have also developed various rheometers in order to
characterize the rheological properties of SCC. Some of these concrete rheometers are BML
rheometer, BTRHEOM rheometer, IBB rheometer, and ICAR rheometer (Beaupré et al. 2004).
The different rheometers have been tested and compared, and it was found out that they were
reasonably successful in characterizing the rheological properties of concrete. The ICAR
rheometer was developed at the International Center for Aggregate Research (ICAR) at the
University of Texas at Austin in order to overcome the limitations of the existing rheometers
(Koehler et al. 2005). The ICAR rheometer can be used in two modes: stress growth test and flow curve test. The stress growth test provides static yield stress, whereas the flow curve test provides the dynamic yield stress, and plastic viscosity. The dynamic yield stress is defined as the minimum stress required for maintaining flow, while the static yield stress is defined as the minimum stress required for initiating the flow (Malvern Instruments Limited 2012).

Figure 1.4 BTRHEOM rheometer (left) and first generation prototype of ICAR rheometer (right) (from Koehler et al. 2005)

1.5.3 Fibers in Self-Consolidating Concrete

Fiber reinforcement in concrete leads to enhanced hardened concrete properties like higher ductility and improved post-cracking response. However, the addition of fibers to fresh concrete results in loss of workability (Gencel et al. 2011). Various studies have been conducted to see the effects of adding fibers in self-consolidating concrete (Gencel et al. 2011, Grünewald et al. 2012, Liao et al. 2006, Khayat et al. 2014, and Ferrara et al. 2007). According to Ferrara et al. (2007), “the addition of fibers to self-compacting concrete (SCC) may take advantage of its
superior performance in the fresh state to achieve a more uniform dispersion of fibers, which is critical for wider structural use of fiber-reinforced concrete”. The inclusion of fibers would lead to an increase in internal friction and resistance to flow or viscosity (Khayat et al. 2014). Therefore, the fresh properties of SCC might get affected and the mixture design has to be tailor made in order to meet the requirements of SCC. As a result, rheological studies of fiber reinforced SCC are important.

Studies suggest that when the polypropylene fibers are mixed, there are insignificant problems in mixing while the fiber distribution is uniform (Gencel et al. 2011). However, with an increase in fiber content, the air content increases and the unit weight decreases. Other studies have found that the flowability (through slump flow) of fiber reinforced SCC was not as high as for conventional SCC without fibers (Liao et al. 2006). However, the flow characteristics were sufficient for practical implementation with slight vibration. An extensive testing program was undertaken by Khayat et al. (2014) to evaluate the applicability of adjusting mixture proportions in order to accommodate fibers. The benefits of fiber reinforced concrete in terms of improvement in the mechanical properties of concrete have created a penchant among the research community to further explore the area of fiber reinforced SCC.

Fresh properties are routinely of interest when using fiber reinforced SCC. However, there are limited studies which use rheometers in order to carefully study fiber reinforced SCC. A rheometer is a useful tool for investigating rheological properties of fiber reinforced SCC by developing relationships between the Bingham model parameters and conventional test results for SCC. Rheometers have great potential to provide knowledge about the rheological characteristics of fiber reinforced SCC.
1.6 Tensile Stress-Strain Response of Fiber Reinforced Concrete

Fiber reinforced concrete has seen increasing field applications in recent years (Qian & Li 2008). The tensile stress-strain response of fiber reinforced concrete is a fundamental constitutive material property and reliable knowledge of this response is necessary for appropriate application of the tensile carrying capacity of such advanced materials (Baby et al. 2013). Many researchers have attempted to use uniaxial tensile tests to characterize the tensile behavior of fiber reinforced concrete. However, such methods are complicated, time consuming, and require advanced experimentation skills. As an alternative to the uniaxial tension test, a four point bending test has been proposed for quality control (Qian & Li 2008). The results of a four point bending test can be analyzed by an appropriate inverse analysis procedure to derive fundamental constitutive behavior of the material. This type of test is simpler in terms of experimentation skills and has been widely practiced by various people in the research community (Baby et al. 2013, Qian & Li 2008, and Rigaud et al. 2012).

The inverse analysis technique involves determination of mid-span deflection and corresponding load in the four point bending of fiber reinforced concrete beam. The curvature in the constant bending moment zone can be derived from the preliminary inverse analysis from the “bending moment versus mid-span deflection experimental response” (Baby et al. 2013). This is followed by a second point-by-point inverse analysis which is used to derive the tensile stress-strain relationships from the “Bending moment – Curvature” curve without assuming the profile of the tensile stress-strain curve. These inverse analysis techniques have provided results which are comparable to the tensile stress-strain response from uniaxial tension test of concrete. Thus, the inverse analysis approach has been found reasonably reliable and successful in characterizing the tensile behavior of fiber reinforced concrete.
A similar approach has been used to develop a “back calculator tool” and is available from the American Concrete Institute (ACI 544.8R-16 2016). These tools have been considered by leading experts and validated by finite element methods, and shown to provide equivalent tensile stress-strain relationships for a variety of fiber reinforced concrete materials. This tool is very useful for evaluating the performance of fiber reinforced concrete by estimating parameters like residual strength at various deflections, average residual strength, ultimate tensile strength, compressive stress-strain model, etc.

The available approaches for development of tensile stress-strain model can be used appropriately in order to better understand the behavior of fiber reinforced concrete. A better understanding of this behavior would be useful in implementing finite element analysis on fiber reinforced concrete specimens. Furthermore, the existing finite element models of concrete crossties can incorporate this behavior to predict their response under various loading conditions.
CHAPTER 2

PERFORMANCE OF FIBER REINFORCED CONCRETE

2.1 Introduction

A testing program was undertaken in order to evaluate the performance of fiber reinforced concrete (FRC) by using different fiber samples and variable proportions in the concrete mixtures. ASTM C1399, “Standard Test Method for Obtaining Average Residual Strength of Fiber-Reinforced Concrete”, was used as the principal test method for providing a measure of post-cracking response of the various FRC mixtures (ASTM C1399 2015).

2.2 Testing Methodology

Fiber Reinforced Concrete beams were cast for ASTM C1399 tests. The molds used for casting the prisms had dimensions of 4” x 4” x 14”. Multiple concrete beams were tested corresponding to each mixture design in order to gain higher confidence in the test results. The beams were cured in a moist curing room for 28 days before testing. The test was conducted as per the recommendations of ASTM C1399 (2015). This test method can be used to compute the average residual strength of a fiber reinforced concrete mixture using specific deflections obtained from a beam cracked in a certain manner. The results can be used as a measure of post-cracking strength of FRC.
In this test method, the FRC beams of 4” x 4” x 14” are initially loaded under a four point bending test set up which is modified by inclusion of a stainless steel plate at the bottom of the beam. The steel plate is used to control the rate of deflection when the beam develops the first crack. The dimensions of the steel plate are 4” x 0.5” x 14”. In order to obtain the net deflection at the mid span of the beam, a linear variable displacement transducer (LVDT) is placed at the bottom and the test is run in displacement control at a rate of 0.025 inches/min. In order to safely capture the load-displacement data out of the test, a hydraulic testing machine with a load capacity of 25000 lbf was used. As seen in Figure 2.1, the effective span length under loading is 12 inches long with the supports placed approximately 1 inches from the sides. The description of the various test apparatus and the schematics can also be seen in Figure 2.1. The actual test set up used in the laboratory is as given in Figure 2.2.
The bending test is conducted on the FRC beam with the steel plate until the occurrence of first crack. This initial cracking is usually accompanied by a sound and/or a drop in the load value in the load-displacement response obtained while conducting the test. After the occurrence of first crack, the steel plate is removed carefully and the cracked beam is reloaded with the same displacement rate as in the initial loading to obtain a load-displacement curve through which the average residual strength of FRC can be determined. The test is continued until we reach a minimum deflection of 0.05 inches. The test set up is as given in Figure 2.2 (right).

A typical set of load-displacement curve obtained from the ASTM C1399 testing looks like the one given in Figure 2.3. From the reloading curve obtained from the experiment, the load values corresponding to net deflections of 0.02 inches, 0.03 inches, 0.04 inches, and 0.05 inches are recorded. These load values, along with the dimensional details, can be used to calculate the average residual strength with the help of the equation 2.1.
\[ ARS = \left( \frac{P_a + P_b + P_c + P_d}{4} \right) \times k \]  

(2.1)

where:

\[ k = \frac{L}{bd^2} \]  

(2.2)

In the above equation, ARS denotes Average Residual Strength. \( P_a, P_b, P_c, \) and \( P_d \) correspond to the recorded loads (lb) at specified deflections. \( L, b, \) and \( d \) signify the span length (inches), breadth (inches) and depth (inches) of the beam respectively. The results obtained from the testing can be used to evaluate the performance of fiber reinforced concrete mixtures. These results can be utilized to optimize the proportions of fiber in the concrete mixtures for specific applications.

Figure 2.3 Typical load-deflection response obtained from ASTM C1399 testing (from ASTM C1399 2015)
2.3 **Performance of Synthetic Polypropylene Macro Fibers: Strux 90/40**

The purpose of this test program was to evaluate the performance of FRC produced with commercially available synthetic polypropylene macro fibers: Strux 90/40.

2.3.1 *Materials*

In order to meet the strength requirements of a railway concrete crosstie, a typical high strength concrete mixture design was prepared which served as the base mixture design for the different fiber reinforced concrete samples. The target 28 day minimum compressive strength of this mixture design was 7000 psi. A low water to cement ratio of 0.30 was used in order to meet the strength requirements of concrete crosstie. A high amount of high-range water reducer (superplasticizer) was used to obtain good workability of the concrete mixture, keeping in mind that the inclusion of fibers could reduce the workability of the concrete mixture and could also cause reduction in the concrete compressive strength. This concrete mixture design was named as FRC-1 and its details are given in Table 2.1.

In order to attain rapid gain in the compressive strength as practiced in the field for the production of railway concrete crossties, another concrete mixture design was prepared with type III Portland cement. The amount of cement content was kept the same as in the case of FRC-1 and the rest of the mixture design parameters also remained the same. This concrete mixture design was named FRC-2.
### Table 2.1 Mixture design for high strength FRC

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I Portland cement (^a)</td>
<td>683.40 lb/yd(^3)</td>
</tr>
<tr>
<td>Type C fly ash</td>
<td>292.90 lb/yd(^3)</td>
</tr>
<tr>
<td>Limestone chip</td>
<td>1739.21 lb/yd(^3)</td>
</tr>
<tr>
<td>Natural sand</td>
<td>819.00 lb/yd(^3)</td>
</tr>
<tr>
<td>w/c</td>
<td>0.30 lb/yd(^3)</td>
</tr>
<tr>
<td>Sika Viscocrete admixture</td>
<td>1733.40 ml/yd(^3)</td>
</tr>
<tr>
<td>Fibers</td>
<td>variable</td>
</tr>
</tbody>
</table>

Notes: \(^a\)—Type I Portland cement was replaced by Type III Portland cement for FRC-2

The synthetic fibers used in this testing program were polypropylene macro fibers and can be seen in Figure 2. Vernier caliper was used for taking geometric details of the individual fiber samples. These fibers were approximately 2 inches in length. Their average breadth and average thickness was 0.055500 inches and 0.003000 inches respectively. These dimensions were equivalent to an area of cross section of 0.000167 in\(^2\).

![Synthetic polypropylene macro fibers: Strux 90/40](image)
2.3.2 Testing Plan

For the purpose of this research, four different proportions of fibers were considered. The fiber dosages were 3 lb/yd$^3$, 5 lb/yd$^3$, 8 lb/yd$^3$, and 11 lb/yd$^3$ which correspond to 0.19%, 0.32%, 0.51%, and 0.71% by volume of concrete. The fiber reinforced concrete beam samples were cast and then cured for 28 days before testing them to determine their average residual strength as per the recommendations of ASTM C1399 (2015). The test matrix is given in Table 2.2. Moreover, fiber reinforced concrete cylinders of 4 inches diameter and 8 inches height in size were cast according to ASTM C31 (2017). This was done for the purpose of compression strength determination as per the recommendations of ASTM C39 (2017). For compression strength testing, the cylindrical concrete samples were tested after 28 days of curing in the case of FRC-1. Whereas in the case of FRC-2, the samples were tested after 7 days of curing in order to verify the rapid gain in compressive strength.

Table 2.2 Test matrix for ASTM C1399 testing

<table>
<thead>
<tr>
<th>FRC ID</th>
<th>Fiber proportions tested</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 lb/yd$^3$</td>
</tr>
<tr>
<td>FRC-1</td>
<td>●</td>
</tr>
<tr>
<td>FRC-2</td>
<td>●</td>
</tr>
</tbody>
</table>

2.3.3 Results and Discussion of Hardened Concrete Property Tests

The results obtained from the ASTM C1399 testing were analyzed for evaluating the post-cracking performance of the fiber reinforced concrete beam samples. Table 2.3 provides the mean of the Average Residual Strength (ARS) for the various fiber reinforced concrete mixture designs that were tested for the purpose of this research. The test results of individual beams samples are given in Appendix A.1.
Table 2.3 Average of ARS of different fiber reinforced concrete samples

<table>
<thead>
<tr>
<th>FRC type</th>
<th>ARS (psi) for various fiber dosages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 lb/yd³ (0.19% by volume of concrete)</td>
</tr>
<tr>
<td>FRC-1</td>
<td>169.7</td>
</tr>
<tr>
<td>FRC-2</td>
<td>188.6</td>
</tr>
</tbody>
</table>

From Figure 2.5, it is observed that with an increase in fiber dosage the average ARS of the concrete also increases. The above results also indicate that changing the type of cement from type I to type III did not have significant effect on the average residual strength of fiber reinforced concrete. One anomaly in the obtained results is that FRC-2 showed a lower ARS
value average corresponding to a fiber dosage of 8 lb/yd$^3$. This could be a result of inadequate compaction of the beam samples when the concrete was being cast.

The 28 day average compressive strengths for FRC-1 type samples were 8877 psi, 10800 psi, 9330 psi, and 10080 psi corresponding to fiber dosages of 3 lb/yd$^3$, 5 lb/yd$^3$, 8 lb/yd$^3$, and 11 lb/yd$^3$ respectively. The 7 day average compressive strengths for FRC-2 type samples were 8923 psi, 8923 psi, 8136 psi, and 7771 psi corresponding to fiber dosages of 3 lb/yd$^3$, 5 lb/yd$^3$, 8 lb/yd$^3$, and 11 lb/yd$^3$ respectively. These results indicated that the inclusion of synthetic fibers did not severely affect the compressive strength of the concrete mixtures. Moreover, the 7 day average compressive strength results for FRC-2 samples showed the effectiveness of type III cement in rapidly gaining required compressive strength. Furthermore, these synthetic fibers were easy to work with from workability point of view and there was no significant clumping of fibers during mixing. This suggests that the range of dosage of fibers chosen for the purpose of this research was adequate.

Another interesting observation was that some of the concrete beams reinforced with higher amount of fiber proportions showed a multiple cracking behavior. This behavior is also shown in Figure 2.6 in the FRC beam with fiber dosage of 8 lb/yd$^3$. This behavior reinforces the concept of having multiple cracks of lesser widths instead of having a single crack and a larger crack width. This behavior is also direct indication of the ability of fiber reinforced concrete beams to carry loads even after cracking and thus reflects a good post-cracking response. Moreover, it was observed that an increase in the fiber dosage was accompanied by a decrease in the crack width.
2.4 Performance of Macro Fibers with Unique Shapes

Various experimental fiber samples were included in this study because they had unique shape, length and the crimp patterns. A study was undertaken to learn more about how fiber shape can influence fresh mixing and hardened mechanical properties. The series of Experimental Crimped (EC) fibers encompassed a variety of novel crimped shapes.

2.4.1 Materials

A typical moderate strength concrete mixture design was prepared as the base mixture of different FRC samples. The target 28 day minimum compressive strength of this mixture was 4500 psi. This mixture design served as a reference mixture for the basis of comparison of different fiber samples. The details of the concrete mixture design are given in Table 2.4.

Six different types of EC fibers samples were tested: Crimped fibers, sample 1, sample 2, sample 3, sample 6, and sample 7. They can be seen in Figure 2.7 and Figure 2.8. The geometric details of these fibers are given in Table 2.5. A Vernier caliper was used for taking geometric details of the individual fiber samples.
Table 2.4 Mixture design for moderate strength FRC

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1 Portland cement</td>
<td>580.00 (lb/yd^3)</td>
</tr>
<tr>
<td>Coarse limestone (#57) aggregate</td>
<td>1760.00 (lb/yd^3)</td>
</tr>
<tr>
<td>Natural sand</td>
<td>1290.00 (lb/yd^3)</td>
</tr>
<tr>
<td>w/c</td>
<td>0.53</td>
</tr>
<tr>
<td>EC fibers</td>
<td>variable</td>
</tr>
</tbody>
</table>

Figure 2.7 Crimped fibers

Figure 2.8 Profiles of other fibers (sample 1, sample 2, sample 3, sample 6, and sample 7)
Table 2.5 Cross section details of EC fibers

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Breadth (in)</th>
<th>Thickness (in)</th>
<th>Area of cross section (in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crimped fibers</td>
<td>0.06350</td>
<td>0.01690</td>
<td>0.00108</td>
</tr>
<tr>
<td>Sample 1</td>
<td>0.06300</td>
<td>0.01850</td>
<td>0.00117</td>
</tr>
<tr>
<td>Sample 2</td>
<td>0.05965</td>
<td>0.01720</td>
<td>0.00103</td>
</tr>
<tr>
<td>Sample 3</td>
<td>0.06110</td>
<td>0.01840</td>
<td>0.00112</td>
</tr>
<tr>
<td>Sample 6</td>
<td>0.02115</td>
<td>0.01485</td>
<td>0.00031</td>
</tr>
<tr>
<td>Sample 7</td>
<td>0.06160</td>
<td>0.02000</td>
<td>0.00123</td>
</tr>
</tbody>
</table>

2.4.2 *Testing Plan*

Table 2.6 provides the details of the different fiber proportions that were tried for the purpose of this research. The fiber proportions varied from 3 lb/yd³ to 11 lb/yd³ which correspond to 0.19% to 0.71% by volume of concrete. The fiber reinforced concrete beam samples were created for average residual strength testing as per the recommendations of ASTM C1399 (2015). Moreover, fiber reinforced concrete cylinders of 4 inches diameter and 8 inches height in size were cast according to ASTM C31 (2017). This was done for the purpose of compression strength determination as per the recommendations of ASTM C39 (2017).

Table 2.6 Test matrix for ASTM C1399 testing

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Fiber proportions tested</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 lb/yd³</td>
</tr>
<tr>
<td>Crimped Fibers</td>
<td>●</td>
</tr>
<tr>
<td>Sample 1</td>
<td>●</td>
</tr>
<tr>
<td>Sample 2</td>
<td>●</td>
</tr>
<tr>
<td>Sample 3</td>
<td>●</td>
</tr>
<tr>
<td>Sample 6</td>
<td>●</td>
</tr>
<tr>
<td>Sample 7</td>
<td>●</td>
</tr>
</tbody>
</table>
2.4.3 Workability of Various Fiber Reinforced Concrete Mixture Samples

It was observed that many of the fibers with unique geometry showed poor workability in a concrete mixture. Sample 1 fibers were circular shaped and got entangled in the blades of concrete mixer. Moreover, these fibers clumped to each other because of their circularity. Furthermore, fibers emerged out of the beams during vibration and tamping, making it difficult to achieve a finished surface. Sample 2 fibers were very long and did not disperse well in the concrete mixture, creating finishing issues in the beam specimens. Sample 3 and the crimped fibers with radical waves exhibited clumping and entangling issues in the mixing process. Moreover, these fibers generally did not disperse well and produced poor surface finish. Sample 6 fibers had a high aspect ratio and stiffness which made these needlelike fibers difficult to work with. Sample 7 fibers had less clumping and better dispersion compared to the rest of the fiber samples. Some of the workability issues with these EC fibers can be seen in Figure 2.9 and Figure 2.10.

Figure 2.9 Clumping and levelling issue with sample 3 fibers
2.4.4 Results of Hardened Concrete Property Tests

The results obtained from the ASTM C1399 testing were analyzed for evaluating the post-cracking performance of the fiber reinforced concrete samples. Table 2.7 provides the mean of the Average Residual Strength (ARS) for the mixture designs corresponding to various fiber types and proportions. The individual test results are given in the Appendix A.2.

From Figure 2.11, it can be observed that the average residual strength of all the fiber reinforced concrete samples increases with an increase in fiber dosage except for sample 6 fibers. This anomaly could be a result of the non-uniform dispersion of fibers in the concrete mixture. Another interesting observation was that the concrete mixtures reinforced with sample 2 fibers showed very high average residual strength values as compared to the rest of the fiber samples. It can also be observed that sample 3 fibers had steeper crimps and this resulted in relatively higher average residual strength values as compared to concrete mixtures reinforced with ‘crimped fibers’.

Figure 2.10 Clumping issues with sample 6 fibers
Table 2.7 Average of ARS of different fiber reinforced concrete samples

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>ARS (psi) for various fiber dosages</th>
<th>3 lb/yd³ (0.19% by volume of concrete)</th>
<th>5 lb/yd³ (0.32% by volume of concrete)</th>
<th>8 lb/yd³ (0.52% by volume of concrete)</th>
<th>11 lb/yd³ (0.71% by volume of concrete)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crimped fibers</td>
<td>96.9</td>
<td>132.6</td>
<td>238.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Sample 1</td>
<td>-</td>
<td>213.1</td>
<td>302.9</td>
<td>422.4</td>
<td></td>
</tr>
<tr>
<td>Sample 2</td>
<td>-</td>
<td>404.9</td>
<td>513.4</td>
<td>649.4</td>
<td></td>
</tr>
<tr>
<td>Sample 3</td>
<td>-</td>
<td>213.1</td>
<td>350.1</td>
<td>395.3</td>
<td></td>
</tr>
<tr>
<td>Sample 6</td>
<td>-</td>
<td>172.9</td>
<td>221.5</td>
<td>158.8</td>
<td></td>
</tr>
<tr>
<td>Sample 7</td>
<td>-</td>
<td>125.6</td>
<td>133.1</td>
<td>244.0</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.11 Plot of ARS vs. fiber dosage for various FRC mixtures
Table 2.8 provides the results of 28 day average compressive strength of various fiber reinforced concrete samples. The 28 day average compressive strength for the base mixture without the inclusion of fibers was 5137 psi. It can be observed that the compressive strength results were not severely affected by the addition of fibers. This indicated that the dosage of fibers that were used for the purpose of this research program were adequate to work with.

Table 2.8 28 day average compressive strength of different fiber samples

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>28 Day compressive strength (psi) for different fiber dosage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 lb/yd³ (0.19% by volume of concrete)</td>
</tr>
<tr>
<td>Crimped fibers</td>
<td>5263</td>
</tr>
<tr>
<td>Sample 1</td>
<td>4865</td>
</tr>
<tr>
<td>Sample 2</td>
<td>4992</td>
</tr>
<tr>
<td>Sample 3</td>
<td>4460</td>
</tr>
<tr>
<td>Sample 6</td>
<td>4705</td>
</tr>
<tr>
<td>Sample 7</td>
<td>4744</td>
</tr>
</tbody>
</table>

2.4.5 Discussion

The aim of the test program was to evaluate the performance of EC fibers with unique geometry by measuring average residual strength of the concrete beams mixed with different proportion of fibers. The EC fibers with unique geometry generally did not disperse well in the concrete mixture. The variability in the average residual strength and compressive strength results also suggests that the distribution of fibers was not uniform. Most of the fibers exhibited levelling and clumping issues. Among all the fibers, sample 7 fiber was the one which had least workability issues.
It was observed that the sample 2 fibers showed relatively high ARS values greater than the rest of the EC fibers. It was observed that the beam samples could retain very high amount of load for a long range of displacements indicating that the post cracking strength provided by sample 2 fibers is very good. Moreover, multiple cracks were developed in ARS testing and the crack widths were smaller as compared to those in beams made from other fiber samples. The higher performance of sample 2 fibers could be possible due to their larger lengths as compared to rest of the fiber samples. A possible solution to encounter the issues in this test program could be the manufacturing of lower thickness fibers which would result in a higher fiber count per pound dosage and possibly a better dispersion as well.

### 2.5 A Comparative Study between Crimped Fibers and Strux 90/40 Fibers

A comparative study between the ‘crimped fibers’ and Strux 90/40 fibers was done in order to evaluate the relative effectiveness of each.

#### 2.5.1 Materials

A typical high strength concrete mixture design was used to prepare the base mixtures of different FRC samples. The target 28 day minimum compressive strength of this mixture was 7000 psi. The high strength concrete mixture was selected in order to meet the strength requirement of a concrete crosstie and checking the usefulness of fiber samples for high strength concrete mixtures. The details of the concrete mixture design are given in Table 2.9.
Table 2.9 Mixture design for high strength FRC

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 3 Portland cement</td>
<td>683.40 (lb/yd³)</td>
</tr>
<tr>
<td>Type C fly ash</td>
<td>292.90 (lb/yd³)</td>
</tr>
<tr>
<td>Limestone chip</td>
<td>1739.21 (lb/yd³)</td>
</tr>
<tr>
<td>Natural sand</td>
<td>819.00 (lb/yd³)</td>
</tr>
<tr>
<td>w/c</td>
<td>0.30</td>
</tr>
<tr>
<td>Sika Viscocrete admixture</td>
<td>1733.40 ml/yd³</td>
</tr>
<tr>
<td>Fibers</td>
<td>variable</td>
</tr>
</tbody>
</table>

2.5.2 Testing Plan

Table 2.10 provides the details of the different fiber proportions that were tried for the purpose of the comparison. The fiber proportions varied from 3 lb/yd³ to 11 lb/yd³ which correspond to 0.19% to 0.71% by volume of concrete. The fiber reinforced concrete beam samples were created for average residual strength testing as per the recommendations of ASTM C1399 (2015). Moreover, fiber reinforced concrete cylinders of 4 inches diameter and 8 inches height in size were cast according to ASTM C31 (2017). This was done for the purpose of compression strength determination as per the recommendations of ASTM C39 (2017).

Table 2.10 Test matrix for ASTM C1399 testing

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Fiber proportions tested</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 lb/yd³</td>
</tr>
<tr>
<td>Crimped fibers</td>
<td>●</td>
</tr>
<tr>
<td>Strux 90/40</td>
<td>●</td>
</tr>
</tbody>
</table>
2.5.3 Results and Discussion of Hardened Concrete Property Tests

The results obtained from the ASTM C1399 testing were analyzed for evaluating the post-cracking performance of the fiber reinforced concrete samples. Table 2.11 provides the mean of the average residual strength (ARS) for the mixture designs corresponding to various fiber proportions. The individual test results are given in the Appendix A.3.

From Figure 2.12, it can be observed that the ARS of all the concrete samples reinforced with crimped fibers increases with an increase in fiber dosage. Another observation was that high strength concrete mixtures provided a higher average residual strengths for the FRC samples as compared to the samples made from lower strength concrete mixtures. This indicates that the average residual strength is dependent on the strength of the base concrete mixture itself.

Through Figure 2.13, a comparison can be drawn between the performance of Strux 90/40 fibers and crimped fibers. It is seen that the Strux 90/40 fibers consistently showed a better performance in terms post-cracking behavior. A probable reason for such an observation could be the lesser thickness (and cross section) of the Strux 90/40 fibers, which results in higher fiber count per dosage. This could also result in better dispersion of fibers. It was determined that the thickness and area of cross section of Strux 90/40 fibers was smaller by 17.75% and 15.48% respectively as compared to the crimped fibers. The 28 day average compressive strength for the base mixture without the inclusion of crimped fibers was 13538 psi. It was observed that the concrete reinforced with crimped fibers had compressive strengths of 12935 psi, 13057 psi, 11932 psi, and 12117 psi corresponding to fiber proportions of 3 lb/yd³, 5 lb/yd³, 8 lb/yd³, and 11 lb/yd³ respectively. These results suggests that the given fiber dosages did not severely affect the gain in compressive strength.
Table 2.11 Average of ARS of different fiber reinforced concrete samples

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>ARS (psi) for various fiber dosages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 lb/yd(^3) (0.19% by volume of concrete)</td>
</tr>
<tr>
<td>Crimped fibers</td>
<td>149.4 291.1 326.5 517.6</td>
</tr>
<tr>
<td>Strux 90/40</td>
<td>188.6 333.3 423.8 687.1</td>
</tr>
<tr>
<td></td>
<td>5 lb/yd(^3) (0.32% by volume of concrete)</td>
</tr>
<tr>
<td></td>
<td>8 lb/yd(^3) (0.52% by volume of concrete)</td>
</tr>
<tr>
<td></td>
<td>11 lb/yd(^3) (0.71% by volume of concrete)</td>
</tr>
</tbody>
</table>

Figure 2.12 ARS Performance for crimped fibers for different base concrete mixture designs
Conclusions

From this work, several conclusions relating to the performance of fiber reinforced concrete mixtures were drawn:

- Use of concrete reinforced with synthetic polypropylene fibers could be a useful technique to increase the service life of railway concrete crossties because of the significant residual strength observed after cracking in fiber reinforced concrete mixtures.

- Average residual strength (ARS) measured with the help of ASTM C1399 is a useful parameter which reflects a concrete material’s post-cracking response. Moreover, this behavior remains unchanged with the replacement of type I cement by type III cement.

- Increasing the amount of fibers results in an increase in the value of average residual strength of fiber reinforced concrete. Moreover, multiple cracking behavior was observed.
in some of the concrete mixtures reinforced with higher dosages of fibers. Furthermore, higher dosages of fibers resulted in tighter cracks or lesser crack width.

- The performance of Strux 90/40 fibers is superior to that of the EC fibers because of the better workability observed while working with Strux 90/40 fibers. Moreover, it was observed that average residual strength was relatively higher in concrete mixtures reinforced with Strux 90/40 fibers. The superior performance could be attributed to the lesser area of cross section of individual fibers which subsequently results in higher fiber count per dosage. However, it was also observed that the experimental crimped fiber sample 2 had relatively higher load carrying capacity suggesting that crimping can sometimes improve ARS significantly.

- For the Strux 90/40 fibers, a fiber dosage as high as 11 lb/yd³ can be used in the concrete as increasing the amount of polypropylene fibers does not affect the workability very much as long as adequate amount of superplasticizer is added. Moreover, the compressive strength of the concrete mixtures was also not severely affected by the addition of fibers.
CHAPTER 3
FIBER REINFORCED SELF-CONSOLIDATING CONCRETE

3.1 Introduction

The present study underscores potential for synthetic polypropylene macro fibers to be accommodated in self-consolidating concrete (SCC) mixtures by adjusting material mixture design properties of concrete. A rheometer could be a useful tool in investigating rheological properties of fiber reinforced SCC by developing relationships between slump flow, yield stress, and viscosity. The study investigated the rheological and mechanical properties of self-consolidating concrete reinforced with different proportions of synthetic polypropylene macro fibers. Fresh property tests include the slump flow test and rheological tests using an ICAR rheometer. The results include relationships between slump flow, yield stress, and plastic viscosity. Mechanical property tests include the average residual strength test using the four point bending set up as per the recommendations of ASTM C1399 (2015). The adjustments in concrete mixture design include changes in aggregate proportions, modifying the cement paste content, adopting different dosages of fiber, and proportioning the amount of chemical admixtures.

3.2 Testing Methodologies

The testing methodologies included fresh property tests and hardened property tests of the various concrete mixtures. Figure 3.1 provides an overview of the various tests that were performed for the purpose of this research program.
3.2.1 **Slump Flow Test**

The slump flow test was performed as per the recommendations of ASTM C1611 (2014). This test is performed on a freshly prepared self-consolidating concrete. In this test, a slump cone mold is placed in an inverted position on a base plate or a mat. The concrete is poured in one lift after which the mold is raised and the concrete is allowed to spread. Once the maximum spreading is achieved, diameter of the concrete mass is measured in approximately two orthogonal directions. The average of the two diameters is considered as the slump flow value. The slump flow value gives a measure of the yield stress of the concrete. A higher slump flow is an indication of a lower yield stress and thus the concrete can flow with a higher ease. Through the slump flow test, visual inspection of the segregation of concrete can also be done.
3.2.2 ICAR Rheometer Test

The ICAR rheometer is a portable rheometer used to evaluate rheological performance of concrete with slump greater than 3 inches (Germann Instruments, Inc. 2012). The whole set up includes the rheometer itself with the base plate, utilizing a four bladed vane that is immersed into concrete and rotated at a range of fixed angular velocities (Koehler et al. 2005). The vane radius is 2.5 inches and the vane height is 5 inches. The vane can be attached to the rheometer and the rheometer can be mounted in a frame, positioned over a standard container. The container has a diameter of 12 inches and it is 12 inches high. A standard alternating current source is needed to supply the required power to run the rheometer. The operation of the device and the complete testing is facilitated by a computer software. As a matter of fact, the software is capable of computing the results as well which makes its use easier. The complete rheometer set up with its components is as shown in Figure 3.3.
The installation of ICAR rheometer involves the following steps.

- Connecting the USB wire from the rheometer to the computer.
- The vane is inserted into a keyless chuck in the rheometer and the chuck is tightened by hand. It is ensured that the vane remains in proper vertical position.
- The bottom plate of the rheometer is inserted into the red colored frame (shown in rightmost picture in Figure 3.3).
- Finally the latches are slid over the rheometer plate.

The ICAR rheometer is capable of performing two types of rheological tests: stress growth test and flow curve test. The stress growth test is used to determine the static yield stress. It involves rotating the vane at a low, constant speed of 0.025 revolutions per second (rps) while monitoring the build-up in torque. The maximum torque corresponds to the static yield stress which is computed by the rheometer software. A typical stress growth plot is shown in Figure
3.4. A flow curve test is used to measure the Bingham parameters of yield stress and plastic viscosity. The yield stress measured with the flow curve test is dynamic yield stress. This test consists of a breakdown of the effects of thixotropy, followed by a series of flow curve points. In a flow curve test, the vane is rotated at seven fixed angular velocities in the range of 0.50 to 0.05 rps (in the descending order) while the torque acting on the vane is recorded. The rheometer software computes the dynamic yield stress and plastic viscosity by itself, based on results. A typical flow curve test is shown in Figure 3.4.

![Sample Stress Growth Test](image1)

![Sample Flow Curve Test](image2)

**Figure 3.4 Typical stress growth test (left) and flow curve test (right)**

For the purpose of this research, both stress growth test and flow curve test are performed as per the recommendations given in the ICAR manual (Germann Instruments, Inc. 2012). Immediately after mixing, the concrete is filled inside the container, after which the whole rheometer set up is inserted into the container filled with concrete. First, the stress growth test is performed which is used to evaluate the static yield stress (Pa). After the stress growth test terminates, the flow curve test is performed which is used to evaluate the dynamic yield stress (Pa), and plastic viscosity (Pa.sec) for the given concrete mixture.
3.2.3 *Hardened Property Tests*

In order to evaluate the performance of self-consolidating concrete reinforced with fibers, standard test for determining the average residual strength was conducted as per the recommendations of ASTM C1399 (2015). The relevant details about the test methodology have been provided in section 2.2 of Chapter 2. Multiple concrete beams were cast corresponding to each mixture design in order to gain higher confidence and they were cured for 28 days before testing.

Apart from casting beams for ASTM C1399 tests, multiple concrete cylinders were cast for the purpose of compression strength testing as per the recommendations of ASTM C39 (2017). These cylinders had a height of 8 inches and a diameter of 4 inches.

3.3 *Test Program*

The goal of the test program was to determine if the self-consolidating concrete mixtures can comfortably accommodate the synthetic polypropylene fibers.

3.3.1 *Materials*

In order to prepare self-consolidating concrete, different base mixture designs were experimented for the purpose of this research. There were three different concrete mixture designs which served as the base mixture for the different fiber reinforced self-consolidating concrete samples. These base mixture designs were identified as M1, M2, and M3. The details of material mixture design can be found in Table 3.1.
Table 3.1 Base mixture designs for self-consolidating concrete

<table>
<thead>
<tr>
<th>Material</th>
<th>Mixture proportions for different mixture designs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M1</td>
</tr>
<tr>
<td>Type I Portland cement</td>
<td>610 (lb/yd^3)</td>
</tr>
<tr>
<td>Type C fly ash</td>
<td>185 (lb/yd^3)</td>
</tr>
<tr>
<td>w/c</td>
<td>0.35</td>
</tr>
<tr>
<td>Natural sand</td>
<td>1350 (lb/yd^3)</td>
</tr>
<tr>
<td>Coarse limestone</td>
<td>1300 (lb/yd^3)</td>
</tr>
<tr>
<td>Crushed limestone chip</td>
<td>-</td>
</tr>
<tr>
<td><strong>Chemical admixtures (ml/yd^3)</strong></td>
<td></td>
</tr>
<tr>
<td>Sika Viscocrete admixture</td>
<td>1170</td>
</tr>
<tr>
<td>Viscosity Modifying Admixture (VMA)</td>
<td>2200</td>
</tr>
</tbody>
</table>

Notes: a—Coarse limestone < 19 mm were used by sieving them

The synthetic fibers used in this testing program were Strux 90/40, polypropylene macro fibers. The geometric information and other details have been provided in section 2.3.1 of Chapter 2.

3.3.2 Testing Plan

All three base mixtures were tested for the fresh property tests. Cylinders were cast for compression strength determination after 28 days of curing. To evaluate the effects of fibers in these base concrete mixtures, different fiber proportions were considered. These fiber dosages were 3 lb/yd^3, 5 lb/yd^3, and 8 lb/yd^3, which correspond to 0.19%, 0.32%, and 0.51% by volume of concrete. The test matrix is given in Table 3.2. For the concrete mixtures reinforced with fibers, concrete beams were also cast for average residual strength determination according to ASTM C1399.
Table 3.2 Test matrix for self-consolidating concrete testing

<table>
<thead>
<tr>
<th>Mixture ID</th>
<th>Fiber proportions tested</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No fibers</td>
</tr>
<tr>
<td>M1</td>
<td>●</td>
</tr>
<tr>
<td>M2</td>
<td>●</td>
</tr>
<tr>
<td>M3</td>
<td>●</td>
</tr>
</tbody>
</table>

3.4 Results

The fresh property and hardened property test results for the various SCC samples have been summarized in this section. The individual test results can be found in Appendix B.

3.4.1 Slump Flow Testing

The slump flow test results of various self-consolidating concrete samples were used for preliminary evaluation of their flowability. The results are plotted in Figure 3.5. It was found out that usually the slump flow value decreased with the increase in fiber amount in concrete. The slump flow values for mixture proportions M1 and M3 indicated that even higher proportions of fiber can be accommodated in self-consolidating concrete with a marginal loss in the slump flow. However, for higher proportions like 8 lb/yd³, the slump flow values were not large enough to characterize them as highly flowable concrete. It was also found out that the self-consolidating concrete samples corresponding to M3 showed no segregation as compared to M1 and M2, where the concrete was slightly segregated. From these results, it can be interpreted that a better control in terms of smaller coarse aggregate size in M3 must have resulted in higher absorption of the paste around aggregates, which could have resulted in a cohesive and non-segregating concrete mixture.
Figure 3.5 Slump flow test results for various self-consolidating concrete samples

3.4.2 ICAR Rheometer Testing

Static yield stress results for the various self-consolidating concrete samples that were obtained from the ICAR rheometer are plotted in Figure 3.6. It was found out that the static yield stress increased with an increase in amount of fibers in concrete. Additionally, it was seen that the M1 mixture consistently showed higher static yield stress values as compared to M2 and M3 mixture. The static yield stress values for M1 mixture were in a higher range of 360 to 640 Pa in comparison to that for M2 and M3 mixture where the values were in the range of 60 to 265 Pa. This could have been a result of lower water to cement ratio of 0.35 in case of M1 as compared to 0.40 in case of M2 and M3. Moreover, within a single mixture type, the higher static yield stress values corresponded to lower slump flow values obtained from slump flow testing.

Dynamic yield stress results for the various self-consolidating concrete samples that were obtained from the ICAR rheometer are plotted in Figure 3.7. The dynamic yield stress results followed a similar trend to the one that was observed in static yield stress results. These results
indicated that the ICAR rheometer was able to follow the change in behavior of SCC with the additional amount of fibers and change in mixture proportions of concrete.

Figure 3.6 Static yield stress results for various self-consolidating concrete samples

Figure 3.7 Dynamic yield stress results for various self-consolidating concrete samples
Plastic viscosity results for the various self-consolidating concrete samples that were obtained from the ICAR rheometer are plotted in Figure 3.8. It was found out that the plastic viscosity values for M2 and M3 mixtures were very similar and consistently lower than that for M1 mixture. It was seen that the plastic viscosity increased with an increase in fiber amount. However, the increase was not significantly large and thus fibers did not affect the plastic viscosity as much as they affected the yield stress values.

![Plastic viscosity vs. fiber amount graph](image)

**Figure 3.8** Plastic viscosity results for various self-consolidating concrete samples

### 3.4.3 Compression Strength Testing

The results of compression strength testing for various self-consolidating concrete samples are plotted in Figure 3.9. It was found out that the compression strength of the concrete decreased with an increase in the amount of fibers. It was seen that the concrete sample corresponding to M1 type mixture showed relatively higher compressive strength as compared to other mixture types. This could be a direct result of the lower water to cement ratio in case of M1.
mixture. However, as a result, the losses in the slump flow values and yield stress values were higher in case of M1 mixture. It can also be seen that the change in concrete mixture design in terms of coarse aggregate size from M2 to M3 mixture resulted in a marginal increase in the compressive strength values.

![Compressive strength vs. fiber amount](image)

**Figure 3.9 Compressive strength results for various self-consolidating concrete samples**

### 3.4.4 Average Residual Strength Testing

The results of average residual strength (ARS) testing for various self-consolidating concrete samples are summarized in Table 3.3. It can be seen in Figure 3.10 that the SCC samples corresponding to 8 lb/yd$^3$ showed a significantly high residual load carrying capacity resulting in higher average residual strength values. It was found out that the average residual strength of the concrete increased with an increase in the amount of fiber dosage, as shown in Figure 3.11. It can also be seen that the average residual strength values were very similar for the various concrete mixtures corresponding to same fiber dosage.
Table 3.3 Average of ARS of different self-consolidating concrete samples

<table>
<thead>
<tr>
<th>Mixture ID</th>
<th>ARS (psi) for various fiber dosages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 lb/yd³</td>
</tr>
<tr>
<td>M1</td>
<td>-</td>
</tr>
<tr>
<td>M2</td>
<td>-</td>
</tr>
<tr>
<td>M3</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 3.10 Reloading curves obtained from ASTM C1399 tests for M1, M2, and M3
3.5 Conclusions

From this work, several conclusions relating to fiber reinforced self-consolidating concrete were drawn:

- Rheometers are useful in characterizing the rheological properties of SCC mixtures reinforced with synthetic polypropylene macro fibers.
- Static yield stress, dynamic yield stress, and plastic viscosity of the SCC mixtures increased with the increasing amount of fibers. This was also accompanied by a decrease in slump flow values.
- The fresh property test results including slump flow and ICAR rheometer results showed that through careful adjustment in the mixture design, it was possible to accommodate fibers in SCC without significantly affecting the rheological characteristics of SCC. Some of the possible adjustments were better control over coarse aggregate size (using a higher
proportion of smaller size coarse aggregates), and a balanced addition of chemical admixtures like viscosity modifying admixtures and superplasticizers.

- Addition of synthetic polypropylene fibers enhanced the post cracking performance of SCC. Moreover, there was an increase in the value of average residual strength with an increase in amount of fibers in concrete.

- Addition of synthetic polypropylene fibers resulted in a decrease in compression strength of self-consolidating concrete. However, appropriate adjustments in the mixture design could provide a self-consolidating concrete with higher compressive strength, without sacrificing the rheological characteristics of a conventional self-consolidating concrete.

- A possible accommodation of fibers in self-consolidating concrete mixtures could be useful keeping in mind their application in the railway industry for manufacturing of concrete crossties.
CHAPTER 4

PROTOTYPE CONCRETE CROSSTIES WITH FIBERS

4.1 Introduction

The objective of developing prototype crossties was to demonstrate the performance of crosstie designs that were based on the basis of data collected in field experiments. The work is part of collaborative research performed by students and faculty members from the different disciplines at the University of Illinois at Urbana-Champaign. As a part of this research program, a large amount of data collected from the field was analyzed for the crossties under light rail transit loading conditions. Moreover, a review of the current industry practices was performed. Consequently, potential areas of further study were identified for the improvement in the current crosstie design. The purpose of this research was to investigate the benefits of adding synthetic polypropylene fibers in concrete crossties in order to propose a resilient concrete crosstie design and thus increase their service life.

4.2 Testing Methodologies

Various material property tests were conducted in order to characterize the quality of concrete used in the crossties. Moreover, standard railway tests were performed on the concrete crossties so as to evaluate and compare the performance of crossties with and without fibers.

4.2.1 Slump Test

The slump test was performed on the concrete as per the recommendations of ASTM C143 (2015). The slump value gives a measure of the workability of the concrete. This test is
especially useful when a high dosage of fibers is used in concrete, which might reduce the workability of concrete.

4.2.2 Unit Weight Test

The unit weight test was performed on the concrete as per the recommendations of ASTM C138 (2017). This test is conducted on fresh concrete in which the concrete is poured in a cylindrical container in three lifts, after which the density or the unit weight of the concrete is determined.

4.2.3 Compression Strength Test

The compression strength test was performed on the hardened concrete samples as per the recommendations of ASTM C39 (2017). This test was performed in order to ensure that the base concrete mixture used in the development of crossties passes the minimum strength requirements. This test also indicates that a concrete has reached the transfer strength required for release of prestress.

4.2.4 Average Residual Strength Test

The average residual strength test was performed on the fiber reinforced concrete beam samples as per the recommendations of ASTM C1399 (2015). The relevant details about the test methodologies have been provided in section 2.2 of Chapter 2. The concrete beams were cured for 28 days before testing was undertaken. This test was used as a measure to evaluate the performance of fiber reinforced concrete.
4.2.5 Center Negative Bending Moment Test

The crossties were placed upside down where both rail seats were simply supported by half-moon steel bars spaced 60 inches apart (Bastos et al. 2017). A vertical load was applied at two locations 6 inches apart. This configuration can be seen in Figure 4.1 and is similar to the center negative bending moment test set up given in article 4.9.1.6 of AREMA Chapter 30 (American Railway Engineering and Maintenance-of-Way Association 2014). The test was performed as per the recommendations given in the work done by Bastos et al. (2017). However, for the purpose of this research, the crossties were loaded even beyond peak load in order to capture and compare the post-peak response of crossties with and without fibers.

![Figure 4.1 Concrete crosstie under center negative bending moment test set up](image)

4.2.6 Rail Seat Positive Bending Moment Test

The crossties were subjected to a rail seat bending moment test in a four-point bending configuration. The two half-moon steel bars were placed under the crosstie, each spaced 14 inches away from the rail seat vertical center line (Bastos et al. 2017). Two additional half-moon steel bars were placed 2.25 inches away from the rail seat vertical center line in order to apply the load. This configuration can be seen in Figure 4.2 and is similar to the recommendations given in article 4.9.1.8 of AREMA Chapter 30 (American Railway Engineering and
Maintenance-of-Way Association 2014), with the difference that steel bars were used in place of the rubber pads. The test was performed as per the recommendations given in the work done by Bastos et al. (2017). For the purpose of this research, this test was performed in displacement control mode even after the peak load had been achieved. This was done in order to capture the potential benefits of the reinforcement of fibers in concrete.

![Concrete crosstie under rail seat positive bending test set up](image)

**Figure 4.2** Concrete crosstie under rail seat positive bending test set up

4.3 Experimental Plan

The goal of the test program was to cast prototype concrete crossties with and without fibers, and also compare their performance through various tests mentioned in the section 4.2.

4.3.1 Materials

The steel formwork had a capacity of development of six crossties at a time. The prestressing wire material was made up of high strength steel. It had a diameter of 5.32 mm (0.21 inches) with an ultimate strength of 9200 lbf. The target 28 day minimum compressive strength of the base concrete mixture design was 8000 psi. This was more than the minimum required compressive strength of 7000 psi for a standard concrete crosstie because of the possibility of
loss in compressive strength of concrete after addition of fibers. Use of superplasticizers (high range water reducers) was required so as to achieve sufficient workability. Synthetic polypropylene macro fibers (Strux 90/40) were used for the development of fiber reinforced concrete crossties. The geometric details of these fibers are given in section 2.3.1 of Chapter 2.

4.3.2 Testing Plan

For the purpose of this research, after the arrival of the batch of fresh concrete, the slump test was performed on the base concrete mixture to ensure good workability. For quality control, unit weight test was also performed on the base concrete mixture. For the purpose of determination of gain in concrete compressive strength, multiple concrete cylinders of diameter 6 inches and height 12 inches were cast. This was followed by the casting of three full scale concrete crossties which were to be used for rail seat positive bending moment test and center negative bending moment test after sufficient gain in compressive strength. The remaining amount of concrete in the truck was calculated and accordingly synthetic polypropylene fibers were added to the fresh concrete. The fiber dosage was 11 lb/yd³ which was equivalent to 0.71% by volume of concrete. Additional superplasticizer was added to the concrete mixture in order to achieve good workability and slump test was performed to ensure the same. For the purpose of determination of gain in compressive strength of fiber reinforced concrete, multiple concrete cylinders of diameter 6 inches and height 12 inches were cast. This was accompanied by casting of fiber reinforced concrete beam samples of size 4” x 4” x 14”, which were then cured for 28 days before testing them to determine average residual strength as per the recommendations of ASTM C1399 (2015). Casting of beam samples was followed by the casting of three full scale
crossties (with fibers) which were to be used for rail seat positive bending moment and center negative bending moment testing after sufficient gain in compressive strength.

4.4 Manufacturing of Prototype Crossties

The prototype crossties were developed based on the industrial standard design requirements. For the purpose of casting prestressed crossties, the steel wires were installed in the formwork throughout its length. The formwork followed the cross-section details according to CXT crosstie design, CXT 100, manufactured by L.B. Foster. These are the same concrete cross ties which have been placed in the St. Louis area in the United States. In order to replicate the wire arrangement of the CXT 100 design, twelve wires were installed as per the drawing details of CXT 100. A rough sketch of the wire arrangement at the end cross-section is shown in Figure 4.3.

![Figure 4.3 Rough sketch for the wire arrangement of prototype crossties](image)

After installing the steel wires in the formwork, a prestressing level of approximately 6 kips per wire was applied. The same wire arrangement and prestressing level was applied for both types of concrete crosstie designs, with and without fibers. The prototype concrete crosstie without polypropylene fibers was named ‘Baseline’ and the one reinforced with polypropylene
fibers was named ‘Baseline with fibers’. The formwork with prestressed wires can be seen in Figure 4.4. The leftmost tie was numbered as tie 0, followed by tie 1, tie 2, tie 3, tie 4, and the rightmost tie numbered as tie 5. The prestressing force details for individual ties are given in Appendix C.1.

![Formwork with prestressed wires](image)

**Figure 4.4 Formwork with prestressed wires installed in it**

On the day of casting, the steps given in section 4.3.2 were followed for the required testing. The slump test and unit weight test were performed on the fresh concrete batch. The concrete cylinder samples and beam samples were cast and then demolded after one day, after which they were kept in the curing room. The average compressive strength of the concrete samples was determined at different ages: 5 days, 7 days, 14 days, and 28 days. The average residual strength of the fiber reinforced concrete samples was determined after 28 days of curing.
For the purpose of casting concrete crossties, needle vibrators were used which ensured good compaction effort. After casting of crossties, they were covered properly so as to cure them. The compressive strength testing of cylindrical concrete samples aided in determining if the concrete in crossties had reached the transfer strength or not. Once the concrete had reached a minimum transfer strength of 5000 psi, the prestress wires were released. The transfer of prestress (cutting of wires) was followed by demolding the crossties from the formwork. The full scale crossties were utilized for center negative and rail seat positive bending moment test.
Figure 4.7 Casting and finishing of prototype crossties

Figure 4.8 Curing of crossties (left) and the finished product (right)

4.5 Laboratory Testing Results

4.5.1 Results of Fresh Concrete Property Tests

The results of fresh concrete property tests conducted on the plain cement concrete and fiber reinforced concrete are summarized in Table 4.1. A slump value of 7.5 inches indicated that the plain concrete was highly workable. It was observed that the workability of concrete reduced due to the addition of fibers. However, the fiber reinforced concrete with a slump value of 3.0 inches indicated an acceptable workability. It was observed that the unit weight of plain cement concrete was 151.2 lb/ft³, which indicated a fairly dense concrete.
Table 4.1 Results of fresh concrete property tests

<table>
<thead>
<tr>
<th>Concrete type for crosstie</th>
<th>Slump (in)</th>
<th>Unit weight (lb/ft$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain cement concrete (PCC)</td>
<td>7.5</td>
<td>151.2</td>
</tr>
<tr>
<td>Fiber reinforced concrete (FRC)</td>
<td>3.0</td>
<td>-</td>
</tr>
</tbody>
</table>

4.5.2 Results of Compression Strength Tests

The results of compression strength testing are summarized in Table 4.2. These results indicated that both plain cement concrete and fiber reinforced concrete had reached the transfer strength of 5000 psi within 5 days. This allowed the transfer of prestress by releasing the wires.

Table 4.2 Results of compression strength testing

<table>
<thead>
<tr>
<th>Age (days)</th>
<th>28 day average compressive strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Plain cement concrete</td>
</tr>
<tr>
<td>5</td>
<td>7559</td>
</tr>
<tr>
<td>7</td>
<td>7635</td>
</tr>
<tr>
<td>14</td>
<td>9173</td>
</tr>
<tr>
<td>28</td>
<td>9427</td>
</tr>
</tbody>
</table>

The plot for compressive strength development for both plain cement concrete (PCC) and fiber reinforced concrete (FRC) is given in Figure 4.9. It indicates that both the types of concrete used in the development of crossties passed the minimum compressive strength requirement of 7000 psi at the age of 28 days. It can also be seen that the average compressive strength of fiber reinforced concrete was slightly lesser than that of plain cement concrete at every stage. However, the difference in compressive strength was not very significant.
Results of Average Residual Strength Tests

The results of average residual strength testing are summarized in Table 4.3. Multiple beams were cast in order to gain higher confidence in the results obtained. The mean of average residual strength was 308 psi which reflected a reasonable post-cracking behavior. The reloading curves obtained from bending of the cracked beams can be seen in Figure 4.10. It can be seen that the post-cracking response of the fiber reinforced concrete beams varies from one another. This kind of variation has been known to occur if consolidation of concrete is imperfect.

![Concrete Compressive Strength](image)

**Figure 4.9 Compressive strength development for two types of concrete**
Table 4.3 Results of average residual strength testing of fiber reinforced concrete

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Average residual strength (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam 1</td>
<td>296</td>
</tr>
<tr>
<td>Beam 2</td>
<td>311</td>
</tr>
<tr>
<td>Beam 3</td>
<td>353</td>
</tr>
<tr>
<td>Beam 4</td>
<td>271</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>308</strong></td>
</tr>
</tbody>
</table>

Figure 4.10 Reloading curves obtained from ASTM C1399 testing

4.5.4 Center Negative Bending Moment Test on Crossties

When the crossties were tested under center flexure test in displacement control mode, it was observed that the ultimate load carrying capacity for both ‘baseline’ and ‘baseline with fibers’ crossties remains identical. This behavior can be seen in Figure 4.11, where a comparison can be drawn between the two types of crossties. However, an important observation in these
tests was the post-peak behavior of the prototype crossties. ‘Baseline’ crosstie showed an immediate drop in the load (seen in Figure 4.11) and the crosstie failed in shear (seen in Figure 4.12). This failure was sudden and was representative of a typical crosstie where the crosstie would not be functional in such a situation. Whereas, the ‘baseline with fibers’ crosstie showed an atypical failure. The post-peak behavior of ‘baseline with fibers’ crosstie can be seen in Figure 4.11. It was observed that the drop in the load was not immediate. Due to the presence of fibers, the crosstie was able to carry significant loading for larger displacements. This behavior illustrates the benefits of fibers in terms of increased strain and thus sustained capacity for deformation in concrete crossties. Moreover, it can be observed in Figure 4.12 that the ‘baseline with fibers’ crosstie shows a flexural failure with reduced crack width. This behavior suggests the confinement and improved crack resistance provided by fibers. Therefore, the presence of fibers renders the crossties functional even after the occurrence of cracking.

![Figure 4.11 Loading behavior of prototype crossties under center flexure test](image-url)
Figure 4.12: Behavior of prototype crossties under center flexure test: baseline (top) and baseline with fibers (bottom)

4.5.5 Rail Seat Positive Bending Moment Test on Crossties

The behavior of the prototype crossties under rail seat positive bending moment test is plotted in Figure 4.13. It was observed that the ultimate load carrying capacity for both ‘baseline’ and ‘baseline with fibers’ crossties remains identical. However, it was observed that the post-peak behavior of the two types of crossties was different. It can be observed through Figure 4.13 that the ‘baseline’ crosstie showed an immediate drop in the load value after reaching the peak load. At this juncture, the crosstie has failed and retained a marginal residual strength for a very small displacement. On the other hand, the ‘baseline with fiber’ crosstie did not show an immediate drop in the load value and showed a significant amount of residual strength after the peak load. This type of crosstie carries a residual load for a substantial amount of displacement. Therefore, the rail seat positive bending moment test illustrates the benefits of fibers in terms of residual strength after ultimate load.
Figure 4.13 Loading behavior of prototype crossties under rail seat flexure test

Figure 4.14 Behavior of prototype crossties under rail seat flexure test: baseline (left) and baseline with fibers (right)
4.6 Conclusions

Conclusions relating to the performance of fiber reinforced concrete crossties can be drawn from this study:

- The workability of concrete is affected by the inclusion of synthetic polypropylene fibers. However, addition of adequate amount of high-range water reducers and use of needle vibrators allow for efficient compaction of fiber reinforced concrete.
- The compressive strength of concrete is not significantly affected by the inclusion of fibers at the volume fraction considered in this test program.
- Synthetic polypropylene fibers provide sustained capacity for deformation in the concrete crossties. Therefore, polypropylene fiber reinforced concrete could be a useful way to increase the service life of concrete crossties as the crossties would remain functional even if the ultimate loading scenario has been achieved.
- Relevant tests at the rail seat and center of the crosstie indicate that the ultimate load carrying capacity of the crossties is not affected by the inclusion of fibers. Therefore, the concrete crosstie design can be optimized by changing the prestress level, quantity of prestress, and addition of adequate amount of fibers.
5.1 Introduction

The tensile stress-strain response of fiber reinforced concrete is a fundamental material property and it is necessary to have a reliable knowledge of this response for appropriate applications where the tensile carrying capacity of fiber reinforced concrete needs to be utilized. Due to the absence of a direct tension test for concrete, obtaining a tensile stress-strain response for fiber reinforced concrete is a difficult task. A four point bending test is the fundamental test for obtaining flexural response of fiber reinforced concrete in terms of a load-displacement relationship. The present study focuses on developing an appropriate tensile stress-strain model for the synthetic polypropylene fiber reinforced concrete from an indirect tension test like four point bending. A better knowledge of the tensile behavior of fiber reinforced concrete would be useful in inputting an appropriate tensile stress strain model for Finite Element Method (FEM). Utilizing FEM for quantifying the performance of various fiber reinforced concrete mixtures could be a very useful and time efficient approach.

5.2 Experimental Plan

In order to characterize the stress-strain behavior of fiber reinforced concrete, various material property tests were required. The goal of the test program was to cast multiple fiber reinforced concrete specimens for the necessary material property tests.
5.2.1 Materials

A typical normal strength concrete mixture was prepared which served as the base mixture design for the various fiber reinforced concrete samples. In order to prepare a fiber reinforced concrete mixture, Strux 90/40 fibers were used. These are synthetic polypropylene macro fibers and the relevant geometric information about the fibers has been provided in section 2.3.1 of Chapter 2. A fiber dosage of 11 lb/yd$^3$ was used which corresponds to 0.71% by volume of concrete. The details of the concrete mixture design can be found in Table 5.1.

**Table 5.1 Mixture design for material property tests**

<table>
<thead>
<tr>
<th>Material</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I Portland cement$^a$</td>
<td>677.78 (lb/yd$^3$)</td>
</tr>
<tr>
<td>Type C fly ash</td>
<td>169.44 (lb/yd$^3$)</td>
</tr>
<tr>
<td>Coarse limestone</td>
<td>1755.00 (lb/yd$^3$)</td>
</tr>
<tr>
<td>Natural sand</td>
<td>891.00 (lb/yd$^3$)</td>
</tr>
<tr>
<td>w/c</td>
<td>0.36</td>
</tr>
<tr>
<td>Sika Viscocrete admixture</td>
<td>770.20 ml/yd$^3$</td>
</tr>
<tr>
<td>Strux 90/40 fibers</td>
<td>11.00 (lb/yd$^3$)</td>
</tr>
</tbody>
</table>

5.2.2 Testing Plan

For the purpose of this research, multiple fiber reinforced concrete samples were cast. Beam samples of dimensions 4” x 4” x 14” were cast and then cured for 28 days before performing the required bending tests. Two types of four point bending tests were performed for the purpose of this research. First, the standard test to determine average residual strength was conducted as per the recommendations of ASTM C1399 (2015). The relevant details about the test set up have been discussed in section 2.2 of Chapter 2. Secondly, the standard test for flexural performance of fiber-reinforced concrete was conducted as per the recommendations of
ASTM C1609 (2012). This test method was necessary to obtain a continuous load-displacement response for fiber-reinforced concrete, unlike the ASTM C1399 (2015) test method where the initial loading is performed with the supporting steel plate. The bending test results were necessary to apply the ‘inverse analysis’ and ‘back calculator tool’ approaches in order to obtain the tensile stress strain model for fiber reinforced concrete. These modeling approaches have been described in detail in the later sections.

Apart from the necessary bending tests, compression strength testing was performed on fiber reinforced concrete cylinders as per the recommendations of ASTM C39 (2017). Furthermore, standard test method for determining the static modulus of elasticity of fiber reinforced concrete was performed according to ASTM C469 (2014). These tests were performed after 28 days of curing of cylindrical specimens of diameter 4 inches and height 8 inches.

5.3 Laboratory Test Results

5.3.1 Material Property Test Results

The results of all the material property tests are summarized in Table 5.2. The compression strength and modulus of elasticity results were useful for applying the inverse analysis approach. The average residual strength results were useful to appropriately fit the data while using back calculator tool.

<table>
<thead>
<tr>
<th>Property test</th>
<th>Test result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression strength</td>
<td>6822 psi</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>$4.24 \times 10^6$ psi</td>
</tr>
<tr>
<td>Average residual strength</td>
<td>363 psi</td>
</tr>
</tbody>
</table>
Apart from the average residual strength testing, the fiber reinforced concrete beams were also tested for flexural performance according to ASTM C1609 (2012). The test results obtained from the different methodologies of four point bending are compared in Figure 5.1. It can be seen that both the types of bending test provided similar results in terms of flexural performance of fiber reinforced concrete beams. The reloading curves obtained from ASTM C1399 showed a similar residual load response to that obtained from ASTM C1609. These results allowed for selecting a sample test result from ASTM C1609 to be used for modeling approaches. The four point bending test conducted on beam 2 according to ASTM C1609 was chosen as a sample experimental test result for modeling purposes and it can be seen in Figure 5.2.

![Comparison of Bending Results](image_url)

**Figure 5.1 Comparison of bending test results**
5.4 Modeling Approaches

5.4.1 Inverse Analysis Approach

An inverse analysis approach proposed by Rigaud et al. (2012) was adopted in order to obtain the tensile behavior of fiber reinforced concrete from bending test results. In this approach, the calculations are done for a rectangular cracked section of height 4 inches and width 4 inches, loaded in flexure. The cross section is divided into two parts. First, the material has an elastic behavior in the compressive zone and at the beginning of the tensile zone. Second, the material is in tension and damaged by the flexural crack development. The objective of this technique is to determine the tensile post-cracking behavior of fiber reinforced concrete. The experimental load and deflection at the mid-span of the beam are the primary parameters used to perform the required calculations. The mechanical equilibrium of the section led to two main

![Load-displacement curve from ASTM C1609](image)

**Figure 5.2 Sample test result used for tensile stress-strain modeling**
equations, equation 5.1 and equation 5.2, which are used to simulate the behavior of cracked section. Equation 5.1 corresponds to load equilibrium where the sum of axial loads in the section is equal to zero. Equation 5.2 corresponds to moment equilibrium where the sum of moments is equal to the applied external bending moment.

\[ N = N_e + N_d = 0 \]  \hspace{1cm} (5.1)

\[ M_{\text{ext}} = M_e + M_d \]  \hspace{1cm} (5.2)

In the above equations, \( N_e \) and \( N_d \) are the axial loads in elastic and damaged zone respectively. \( M_{\text{ext}} \), \( M_e \), and \( M_d \) correspond to external bending moment, bending moment in elastic zone and bending moment in damaged zone respectively. The inverse analysis consists of determining two parameters, relative height of neutral axis and tensile stress, in order to ensure the mechanical equilibrium of the section at every iteration. The simulation is started from the point corresponding to the peak tensile stress and the inverse analysis is performed step-by-step to obtain the tensile behavior of fiber reinforced concrete. A comprehensive explanation of the inverse analysis approach and the relevant details of the technique can be found in the reference paper written by Riguad et al. (2012).

The inverse analysis approach was modeled using MATLAB (MATLAB 2015) and the script is given in Appendix D. The sample four-point bending test result as given in Figure 5.2 was used to input the load and deflection of mid-span values. The peak tensile stress was assumed to be 0.08 times of the concrete’s compression strength (Mindess et al. 2003). The concrete compression strength results are given in section 5.3.1 corresponding to material property test results. Furthermore, the modulus of elasticity test result value was used for modeling the tensile behavior of fiber reinforced concrete. The tensile stress-strain model was obtained from the inverse analysis approach after a reasonable smoothening process to avoid
numerical instabilities and is given in Figure 5.3. The figure suggests that the proposed tensile stress-strain model for fiber reinforced concrete has a peak tensile stress of 545.8 psi and maintains a residual (post-peak) stress of approximately 80.0 psi.

Figure 5.3 Tensile stress-strain model for FRC using inverse analysis

5.4.2 Back Calculator Tool

The ACI 544 document provides a report on an indirect method to obtain stress-strain response of fiber-reinforced concrete (ACI 544.8R-16 2016). The back calculator tool available with this report was used to present the flexural test results in terms of equivalent tensile stress-strain response of fiber reinforced concrete. The back calculator tool is based on the finite element method and analytical closed-form solutions. In this approach, closed form moment curvature relationships are used to obtain load-deflection response for a beam under four-point bending. The back calculator is also capable of incorporating three-point bending experimental results and different geometry of fiber reinforced concrete beams.
For the flexural modeling, the experimental load-displacement data is inputted into the back calculator tool. This experimental load-displacement data corresponds to the sample four point bending test result as given in Figure 5.2. The next step is to input sample dimensions and test method. The next step in using the back calculator is to simulate a load-deflection response which is a best fit for the experimental load-deflection response. This is done by modifying the model parameters given in the back calculator tool. A detailed guideline on how to modify the simulated response as per the needs of the user is provided along with the back calculator tool. The first step for fitting of the simulated data involves determining the best fit for the Young’s modulus for the linear elastic phase which can be done by modifying the value of the Young’s modulus. The next steps for fitting of the simulated data can be found in the guideline document provided with the ACI 544 report (ACI 544.8R-16 2016).

It is essential to understand that it was not possible to perfectly fit the simulated curve to the experimental result. Thus, the average residual strength values obtained from different simulated curves were compared with the average residual strength value of 363 psi which was obtained experimentally. This process led to the selection of a simulated curve which yielded an average residual strength value closest to the one obtained experimentally. The simulated plot obtained from the experimental data using the back calculator tool is given in Figure 5.4. The corresponding tensile stress-strain behavior obtained from the back-calculator tool is given in Figure 5.5. The figure suggests that the proposed tensile stress-strain model for fiber reinforced concrete has a peak tensile stress of 546.0 psi and maintains a residual (post-peak) stress of 120.1 psi.
Figure 5.4 Simulation of load-deflection response using back calculator tool

Figure 5.5 Tensile stress-strain model for FRC using back calculator tool
The tensile stress-strain model obtained from the back-calculator tool was compared with the one obtained from the inverse analysis approach. The comparison can be seen in Figure 5.6. It was found out that both the modeling approaches provided similar results. The peak tensile stress value for the fiber reinforced concrete had a negligible difference. However, the post-peak response obtained from the back calculator approach showed higher residual stress values as compared to the residual stress obtained from the inverse analysis approach. The similarity in results from the two model approaches reinforced the confidence in using such tensile stress-strain models for fiber reinforced concrete in the absence of a direct tensile test result. These preliminary model results can be used to input in finite element analysis in order to refine the tensile stress strain model of fiber reinforced concrete.

Figure 5.6 Comparison of tensile stress-strain models obtained from available approaches
5.5 Conclusions

From this work, several conclusions relating to the tensile stress strain model of fiber reinforced concrete were drawn:

- Direct tension test methods for concrete are experimentally difficult and prone to error. Thus, indirect methods for determination of tensile behavior of fiber reinforced concrete are useful in developing a comprehensive material model.

- Four point bending test results can be useful in applying the indirect methods to determine the tensile behavior of concrete. However, it has to be ensured that the load-deflection response obtained from test methods like ASTM C1609 (2012) do not have any instability and match the post-peak response obtained from more controlled methods like ASTM C1399 (2015).

- Both the inverse analysis approach and the back calculator tool are useful for characterizing the tensile stress-strain behavior of fiber reinforced concrete. It was shown that the back calculator tool available from ACI 544 (2016) produces a higher residual load carrying capacity than that obtained from inverse analysis.

- The techniques provide a constitutive model which can be used to input in finite element analysis for a fiber reinforced concrete beam model and thereby refining the existing model to interpret laboratory experimental results.
CHAPTER 6
CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The objective of this research was to better understand the performance of polypropylene fiber reinforced concrete and consider their applicability in railway concrete crossties. Currently, cracking in concrete crossties is one of the most critical issues faced by the railway industry. Therefore, there is a demand for resilient concrete crosstie designs in order to extend their service life. The study focused on reviewing the current design of crossties. Additionally, a thorough review of the properties and testing of polypropylene fiber reinforced concrete was performed. Moreover, a study was undertaken with the aim of extending benefits of self-consolidating concrete by incorporating polypropylene fibers. Lastly, an attempt was made to develop a tensile stress-strain model of polypropylene fiber reinforced concrete so as to have a better understanding of the tensile behavior of fiber reinforced concrete.

The testing of various polypropylene fiber reinforced concrete mixtures showed that inclusion of fibers may be a useful technique to increase the service life of railway crossties because of the substantial residual strength observed after cracking. It was found that the average residual strength measured with the help of ASTM C1399 (2015) is a useful parameter which reflects the performance of a particular type of fiber reinforced concrete. There is a need to improve the current state of the standard requirements for a concrete crosstie, which could possibly be achieved by incorporating a minimum average residual strength requirement.

The testing of self-consolidating concrete (SCC) reinforced with polypropylene fibers indicated that it was possible to accommodate fibers in SCC through careful adjustments in the
mixture design. This can be achieved without significantly affecting the rheological properties, yield stress and plastic viscosity of SCC. Moreover, addition of polypropylene fibers enhanced the post-cracking performance of SCC along with higher crack resistance.

The development and testing of prototype crossties showed that the polypropylene fibers provided sustained capacity for deformation in the concrete crossties, when crosstie tests are conducted at rail seat and center. The crossties with fibers showed a significant residual load carrying capacity for larger displacements unlike the conventional crossties where there was a sudden drop in the load after reaching the peak. The post-peak behavior of fiber reinforced concrete crossties was also accompanied by tighter cracks (higher crack resistance).

The attempt made to develop tensile stress-strain model for polypropylene fiber-reinforced concrete showed that four-point bending test results can be used appropriately to apply modeling approaches like inverse analysis and ACI 544 back calculator tool. It was concluded that both the indirect methods gave similar results and can be used as reasonable constitutive models for the tensile behavior of polypropylene fiber reinforced concrete.

6.2 Future Work

This study has reviewed the performance of polypropylene fiber reinforced concrete. Moreover, a better understanding of their application in concrete crossties was achieved. Additional research is needed in order to improve upon these findings. Some of the key topics which could be studied in future are as follows.

- It is essential to evaluate performance of other types of polypropylene fibers. These include fibers of different pattern, crimp sizes, shapes, cross-section, etc. Moreover, a higher range of fiber dosage could be experimented by adjusting the material mixture
design of concrete, ensuring the workability of the concrete is not compromised. These studies could result in achieving a higher residual load-carrying capacity for fiber reinforced concrete and greater crack resistance.

- The potential for self-consolidating concrete to accommodate higher fiber proportions than the ones studied in this research work needs to be investigated. Additionally, the self-consolidating concrete mixtures could be modified to achieve compressive strength requirements of a railway crosstie. The various fiber proportions need to be tested for this modified mixture design. Moreover, different types of fibers could be investigated for their influence on rheology.

- The prototype crossties could be investigated for different prestress level and quantity for prestressing. These studies could be performed to propose an optimized crosstie design based on the specific requirements in the field. Moreover, higher proportions of fibers could be studied in order to achieve better post-peak behavior in crossties.

- The preliminary tensile stress-strain models for fiber reinforced concrete obtained from various approaches should be utilized for finite element analysis (FEA) of fiber reinforced concrete specimens. The FEA modelling should be done to replicate the four-point bending of fiber reinforced concrete beam specimens. The load-displacement response obtained from the FEA models can be compared with the experimental results and thus the preliminary tensile stress-strain models can be further refined to reduce the dissimilarity, if any, between the FEA results and experimental results. Eventually, the advanced tensile stress-strain model of fiber reinforced concrete can be incorporated in FEA models of crossties in order to interpret the experimental results.
REFERENCES


APPENDIX A

AVERAGE RESIDUAL STRENGTH FOR FIBER REINFORCED CONCRETE SAMPLES

This appendix includes the average residual strength (ARS) test results for the concrete beam samples reinforced with Strux 90/40 fibers and Experimental Crimped (EC) fibers.

A.1 ARS for Strux 90/40 Fibers

The average residual strength for the individual fiber reinforced concrete beam samples made from Strux 90/40 fibers is provided here in Table A.1 and Table A.2.

Table A.1 ARS for individual fiber reinforced concrete beam samples for FRC-1

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>ARS (psi) for various fiber dosages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 lb/yd³</td>
</tr>
<tr>
<td>Beam 1</td>
<td>155.0</td>
</tr>
<tr>
<td>Beam 2</td>
<td>214.5</td>
</tr>
<tr>
<td>Beam 3</td>
<td>139.6</td>
</tr>
<tr>
<td>Average</td>
<td>169.7</td>
</tr>
</tbody>
</table>

Table A.2 ARS for individual fiber reinforced concrete beam samples for FRC-2

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>ARS (psi) for various fiber dosages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 lb/yd³</td>
</tr>
<tr>
<td>Beam 1</td>
<td>123.6</td>
</tr>
<tr>
<td>Beam 2</td>
<td>211.8</td>
</tr>
<tr>
<td>Beam 3</td>
<td>230.5</td>
</tr>
<tr>
<td>Average</td>
<td>188.6</td>
</tr>
</tbody>
</table>
A.2 ARS for Experimental Crimped Fibers

The average residual strength for the individual fiber reinforced concrete beam samples made from various EC fibers is provided here in Table A.3 and Table A.4.

Table A.3 ARS of individual beam samples for crimped fibers

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>ARS (psi) for various fiber dosages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 lb/yd$^3$</td>
</tr>
<tr>
<td>Beam 1</td>
<td>133.8</td>
</tr>
<tr>
<td>Beam 2</td>
<td>107.3</td>
</tr>
<tr>
<td>Beam 3</td>
<td>77.3</td>
</tr>
<tr>
<td>Beam 4</td>
<td>89.3</td>
</tr>
<tr>
<td>Average</td>
<td>96.9</td>
</tr>
</tbody>
</table>
Table A.4 ARS of individual beam samples for other EC fibers

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Beam sample</th>
<th>ARS (psi) for various fiber dosages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>5 lb/yd³</td>
</tr>
<tr>
<td>Sample 1</td>
<td>Beam 1</td>
<td>275.9</td>
</tr>
<tr>
<td></td>
<td>Beam 2</td>
<td>245.9</td>
</tr>
<tr>
<td></td>
<td>Beam 3</td>
<td>117.6</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>213.1</td>
</tr>
<tr>
<td>Sample 2</td>
<td>Beam 1</td>
<td>409.0</td>
</tr>
<tr>
<td></td>
<td>Beam 2</td>
<td>282.3</td>
</tr>
<tr>
<td></td>
<td>Beam 3</td>
<td>369.2</td>
</tr>
<tr>
<td></td>
<td>Beam 4</td>
<td>559.0</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>404.9</td>
</tr>
<tr>
<td>Sample 3</td>
<td>Beam 1</td>
<td>215.0</td>
</tr>
<tr>
<td></td>
<td>Beam 2</td>
<td>250.9</td>
</tr>
<tr>
<td></td>
<td>Beam 3</td>
<td>233.5</td>
</tr>
<tr>
<td></td>
<td>Beam 4</td>
<td>153.1</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>213.1</td>
</tr>
<tr>
<td>Sample 6</td>
<td>Beam 1</td>
<td>262.4</td>
</tr>
<tr>
<td></td>
<td>Beam 2</td>
<td>155.4</td>
</tr>
<tr>
<td></td>
<td>Beam 3</td>
<td>111.2</td>
</tr>
<tr>
<td></td>
<td>Beam 4</td>
<td>162.7</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>172.9</td>
</tr>
<tr>
<td>Sample 7</td>
<td>Beam 1</td>
<td>97.8</td>
</tr>
<tr>
<td></td>
<td>Beam 2</td>
<td>121.2</td>
</tr>
<tr>
<td></td>
<td>Beam 3</td>
<td>115.8</td>
</tr>
<tr>
<td></td>
<td>Beam 4</td>
<td>167.6</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>125.6</td>
</tr>
</tbody>
</table>
A.3 ARS for Comparative Study between Strux 90/40 and Crimped Fibers

The average residual strength for the individual concrete beam samples made from Strux 90/40 fibers and Crimped fibers is provided in Table A.5. These results correspond to the high strength concrete mixture used for a comparative study in section 2.5 of Chapter 2.

Table A.5 ARS of individual samples for the comparative study of fibers

<table>
<thead>
<tr>
<th>Fiber type</th>
<th>Beam sample</th>
<th>ARS (psi) for various fiber dosages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3 lb/yd³</td>
</tr>
<tr>
<td>Crimped fibers</td>
<td>Beam 1</td>
<td>92.7</td>
</tr>
<tr>
<td></td>
<td>Beam 2</td>
<td>158.6</td>
</tr>
<tr>
<td></td>
<td>Beam 3</td>
<td>149.6</td>
</tr>
<tr>
<td></td>
<td>Beam 4</td>
<td>196.5</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>149.4</td>
</tr>
<tr>
<td>Strux 90/40</td>
<td>Beam 1</td>
<td>123.6</td>
</tr>
<tr>
<td></td>
<td>Beam 2</td>
<td>211.8</td>
</tr>
<tr>
<td></td>
<td>Beam 3</td>
<td>230.5</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>188.6</td>
</tr>
</tbody>
</table>
APPENDIX B

TEST RESULTS FOR FIBER REINFORCED SELF-CONSOLIDATING CONCRETE

This appendix includes all the results obtained from testing of various self-consolidating concrete mixtures with and without fibers.

B.1 Summary of Fresh State Property Test Results

Table B.1 Fresh state property test results for M1 mixture

<table>
<thead>
<tr>
<th>Test parameter</th>
<th>Test result for various fiber dosage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 lb/yd³</td>
</tr>
<tr>
<td>Slump flow (in)</td>
<td>27.0</td>
</tr>
<tr>
<td>Static yield stress (Pa)</td>
<td>360.8</td>
</tr>
<tr>
<td>Dynamic yield stress (Pa)</td>
<td>65.3</td>
</tr>
<tr>
<td>Plastic viscosity (Pa.sec)</td>
<td>35.2</td>
</tr>
</tbody>
</table>

Table B.2 Fresh state property test results for M2 mixture

<table>
<thead>
<tr>
<th>Test parameter</th>
<th>Test result for various fiber dosage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 lb/yd³</td>
</tr>
<tr>
<td>Slump flow (in)</td>
<td>25.0</td>
</tr>
<tr>
<td>Static yield stress (Pa)</td>
<td>84.6</td>
</tr>
<tr>
<td>Dynamic yield stress (Pa)</td>
<td>17.2</td>
</tr>
<tr>
<td>Plastic viscosity (Pa.sec)</td>
<td>13.8</td>
</tr>
</tbody>
</table>
Table B.3 Fresh state property test results for M3 mixture

<table>
<thead>
<tr>
<th>Test parameter</th>
<th>Test result for various fiber dosage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 lb/yd³</td>
</tr>
<tr>
<td>Slump flow (in)</td>
<td>27.0</td>
</tr>
<tr>
<td>Static yield stress (Pa)</td>
<td>62.0</td>
</tr>
<tr>
<td>Dynamic yield stress (Pa)</td>
<td>28.0</td>
</tr>
<tr>
<td>Plastic viscosity (Pa.sec)</td>
<td>12.1</td>
</tr>
</tbody>
</table>

B.2 Summary of Hardened State Property Test Results

Table B.4 Concrete compressive strength test results for various concrete mixtures

<table>
<thead>
<tr>
<th>Mixture type</th>
<th>Average compressive strength (psi) for various fiber dosages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 lb/yd³</td>
</tr>
<tr>
<td>M1</td>
<td>9853</td>
</tr>
<tr>
<td>M2</td>
<td>7539</td>
</tr>
<tr>
<td>M3</td>
<td>8046</td>
</tr>
</tbody>
</table>
Table B.5 Average residual strength test results for various concrete mixtures

<table>
<thead>
<tr>
<th>Mixture type</th>
<th>Beam sample</th>
<th>ARS (psi) for various fiber dosages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3 lb/yd³</td>
</tr>
<tr>
<td>M1</td>
<td>Beam 1</td>
<td>150.7</td>
</tr>
<tr>
<td></td>
<td>Beam 2</td>
<td>121.6</td>
</tr>
<tr>
<td></td>
<td>Beam 3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>136.1</td>
</tr>
<tr>
<td>M2</td>
<td>Beam 1</td>
<td>187.0</td>
</tr>
<tr>
<td></td>
<td>Beam 2</td>
<td>177.5</td>
</tr>
<tr>
<td></td>
<td>Beam 3</td>
<td>169.0</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>177.8</td>
</tr>
<tr>
<td>M3</td>
<td>Beam 1</td>
<td>174.9</td>
</tr>
<tr>
<td></td>
<td>Beam 2</td>
<td>157.0</td>
</tr>
<tr>
<td></td>
<td>Beam 3</td>
<td>180.1</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>170.7</td>
</tr>
</tbody>
</table>
APPENDIX C  

PROTOTYPE CROSSTIES WITH AND WITHOUT FIBERS

This appendix includes some additional information on the development of prototype crossties with and without fibers.

C.1 Prestressing Forces in Wires

The exact prestressing force per wire in the different crossties is given in Table C.1.

<table>
<thead>
<tr>
<th>Formwork Tie No.</th>
<th>Prestressing force per wire (kips)</th>
<th>Type of crosstie</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6.28</td>
<td>Baseline</td>
</tr>
<tr>
<td>1</td>
<td>6.02</td>
<td>Baseline</td>
</tr>
<tr>
<td>2</td>
<td>5.50</td>
<td>Baseline</td>
</tr>
<tr>
<td>3</td>
<td>5.37</td>
<td>Baseline with fibers</td>
</tr>
<tr>
<td>4</td>
<td>5.51</td>
<td>Baseline with fibers</td>
</tr>
<tr>
<td>5</td>
<td>6.04</td>
<td>Baseline with fibers</td>
</tr>
</tbody>
</table>
C.2 Additional Images Related to Development of Prototype Crossties

Figure C.1 Release of prestress (left) and demolding of crossties (right)

Figure C.2 Fiber reinforced concrete (left) and plain cement concrete (right) specimens after compression strength testing, showing confinement due to fibers
APPENDIX D
MATLAB CODE FOR INVERSE ANALYSIS APPROACH

This appendix includes the MATLAB code which was written to apply the inverse analysis approach on the four point bending test results. This code can be edited for modifying the input parameters and thus obtain the tensile stress-strain model accordingly.

D.1 MATLAB Code for Inverse Analysis

```matlab
% Sample run for stress-Strain determination of FRC with 1609 testing data
% FRC_25 (11 lb/yd^3)_Beam4 (2nd beam of 1609)
% This code is based on work of Riguad et al.
clc;
clear all;

% Getting Load-Displacement data characteristics by importing the file
Data = xlsread('Data_Minsoo_11lbperyd3.xlsx','I10:J111033');

% Defining load (Load) and displacement (Disp) separately
Load = smooth(Data(:,1)); % load is in kips
Disp = smooth(Data(:,2)); % Displacement is in inches

figure(1);
plot(Disp,Load);

Peakload = max(Load); % finding peak load
k = find(Load==Peakload,1);

Postload = Load(k:end);
Postdisp = Disp(k:end); % Postdisp is the displacement data for just post peak including peak

% n is the interval after which every data point is selected.
n=80;
for i=1:((length(Postload))/n)+1
    Postload1(i,1) = Postload((i-1)*n+1);
    Postdisp1(i,1) = Postdisp((i-1)*n+1);
end

% Parameters
b = 4; % breadth of cross-section in inches
h = 4; % height of cross section in inches
L = 12; % span length of FRC beam in inches
```
Compst = 6822; \% Compressive strength in psi
MOR = Peakload*L*1000/(b*h^2); \% Modulus of rupture in psi
E = 4240000; \% Modulus of elasticity in psi

Stress(1) = -0.08*Compst; \%Peak tensile stress assumption

\%Initial Stress and strain values
Stressinitial = Load(1:k-1,1)*L*1000/(b*h^2);
Straininitial = 0.5*h*216*Disp(1:k-1,1)/(23*L^2);

\%Curvature
Curv= 216*Postdisp1/(23*L^2);

\%Ne is elastic load, Me is elastic moment
\%Nd is damaged moment, Md is damaged moment
Ne(1) = 0;
Me(1) = -b*h^2*Stress(1)/6;
Nd(1) = 0;
Md(1) = 0;

\%Alpha is height of neutral axis relative to beam height
Alpha(1) = 0.5;

\%Strain is tensile strain, starting from the strain value corresponding to
\%the peak tensile stress
Strain(1) = -1*Curv(1)*0.5*h;

\%Mext is external bending moment
Mext = ((Postload1(2:end))*1000*L/6);

\%Iterative process to compute tensile stress-strain for the data points
\%corresponding to the post-peak response of FRC

for i = 1:(size(Postdisp1,1)-1)
    for j = 1:50000
        Alphaj(j) = 0.5 + (j*0.00001);
        Strain1 = -h*Curv(i)*Alpha(i);
        Strain2 = -h*Curv(i+1)*Alphaj(j);
        zc2 = h - (h*Alphaj(j));
        zt2 = -6*Me(1)/(E*b*(h^2)*Curv(i+1));
        Ne2 = E*b*Curv(i+1)*(((zc2)^2)-((zt2)^2))/2;
        %Computing the unknown stress at i+1
        Stressj(j) = (2*Curv(i+1)*((-1*Ne2)-((Curv(i)/Curv(i+1))*Nd(i)))/(b*(Strain1-Strain2)))-Stress(i);
        Me2 = E*b*Curv(i+1)*(((zc2)^3)-((zt2)^3))/3;
    end
end
Md2 = 
((Curv(i)/Curv(i+1))*Md(i))+(b*((Stress(i)*Strain1)+(Stress(j)*Strain2))*(Strain1-Strain2)/(2*(Curv(i+1))^2));

%Defining Eqn 2
Eqn2 = Me2+ Md2- Mext(i);

Diffj(j) = abs(Eqn2);

end

factor = find(Diffj == min(Diffj),1);
Stress(i+1) = Stressj(factor);
Alpha(i+1) = Alphaj(factor);
Strain(i+1)= -1*h*Curv(i+1)*Alpha(i+1);

Nd(i+1)=
((Curv(i)/Curv(i+1))*Nd(i))+(b*(Stress(i)+Stress(i+1))*(Strain(i)-Strain(i+1))/(2*Curv(i+1)));
Md(i+1)=
((Curv(i)/Curv(i+1))*Md(i))+(b*((Stress(i)*Strain(i))+(Stress(i+1)*Strain(i+1)))*(Strain(i)-Strain(i+1))/(2*(Curv(i+1))^2));

end

% Defining continuos arrays for tensile stress and strain starting from
% initial loading point of zero displacement.
% Totalstress is the continuous array for tensile stress in FRC.
% Totalstrain is the continuous array for corresponding tensile strain in
% FRC.

A = 0;
B = 0;
C = -1*smooth(Stress);
D = -1*smooth(Strain);
Totalstress = [A;C];
Totalstrain = [B;D];
figure(2);

% Plot tensile stress-strain reponse
plot(Totalstrain, Totalstress);
hold on;
xlabel('Strain (in/in)');
ylabel('Stress (psi)');
title('Tensile Stress Strain curve');
xlim([0 0.025]);
ylim([0 600]);

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