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Fiber-Reinforced Concrete for Structure Components

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Fiber-Reinforced Concrete for Structure Components

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ABSTRACT

Concrete infrastructures in cold areas such as South Dakota tend to experience early deterioration that is mostly triggered by steel corrosion. The corrosion is initiated by chloride penetration through cracks in the concrete. Fiber reinforced concrete (FRC) is known to be a good alternative to conventional concrete in cold areas due to its enhanced durability and resistance to crack development. There is little guidance for SDDOT pertaining to the use and testing of FRC. There is also lack of information about new fiber products that have been introduced to the market in recent years. A comprehensive literature review, as well as interviews with SDDOT and other DOT personnel, were carried out in this study to evaluate past FRC experiences, effect of different factors on the properties of FRC, and existing FRC design and construction practices. The effect of fiber type and dosage on air content, slump, flexural strength, compressive strength, and impact resistance was examined by conducting laboratory experiments on FRC mixes incorporating five different fiber types and four different fiber dosages. While steel fibers had superior performance, the results showed that among the synthetic fibers the fiber type did not significantly affect any of the FRC properties. Fiber dosage, however, affected the slump and the flexural properties. While the slump decreased, the flexural strength properties increased with increased fiber dosage. The results were also in good agreement with provided manufacturers' claims. Of the four synthetic fibers tested in this study, the most cost-effective were the Fibermesh 650 and FORTA-FERRO fibers. Based on the experimental results and the literature, an FRC proportioning and selection guidelines were developed.

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EXECUTIVE SUMMARY

Reinforced concrete is widely used as a construction material across the entire world due to its low cost, suitability for various applications, and the availability of its constituent materials. However, concrete has some drawbacks such as low tensile strength and ductility. Consequently, micro cracks can easily develop on its surface under temperature changes and traffic loadings. These micro cracks, combined with structural loadings, evolve to become macro cracks, allowing moisture and chloride penetration. This, in turn, results in the corrosion of the reinforcing steel and, thus, the deterioration and loss of load-carrying capacity of the entire structure. Improving the tensile strength and ductility behavior of concrete is often achieved by utilizing fibers, creating what is called fiber reinforced concrete (FRC). FRC is known for its enhanced tensile strength and ductility among other things, which help control micro cracks and decrease potential risks of chemical intrusion that cause further deterioration of the concrete.

Currently, there is a wide variety of FRC products available for engineering applications, but the applicability and cost-effectiveness of different products have not been evaluated systematically for SDDOT in the past. Additionally, many of the fiber materials used in SDDOT projects have been phased out or discontinued, and more new products have been developed. Consequently, there is a lack of information about the new products that have been introduced to the market. There is also little guidance pertaining to the use and testing of FRC. There are many factors that play a role in the selection of FRC products. Depending on the application, different types and dosages of fibers will result in different performances. For the sake of improving durability and performance of infrastructures, research is needed to investigate recent product development, evaluate fiber products currently on the market, and generate guidance for use and testing of FRC. For lack of guidance, SDDOT may be sacrificing improved durability and performance as implementation lags technological developments in the area of fiber reinforced concrete structural components.

This research involved three main tasks aimed at describing best design and construction practices of FRC, assessing potential applications, performance, costs, benefits, and drawbacks of FRC, and developing guidance for the use and testing of FRC. These tasks were: conducting a comprehensive literature review, carrying out interviews with SDDOT and other DOT personnel, and conducting experiments involving several fiber types and dosages. The literature review and interviews looked at past FRC experiences and existing design and construction practices, in addition to the most recent studies about the effect of different factors on FRC properties.

A total of 21 concrete mixes were tested at the structures lab in the Civil Engineering Department of South Dakota State University. All mixes had the same basic design, with the only difference among them being the fiber type and dosage. One mix acted as a control, having no fibers added to it. The other 20 mixes incorporated five different fiber types and four different fiber dosages for each fiber type. Several fresh and hardened concrete tests were conducted to examine the effect of fiber type and dosage. These included measuring air content, slump, compressive strength, average residual strength, flexural strength, and impact resistance. Statistical analyses were also carried out to examine the significance of the effect of fiber type and dosage on each of the measured properties. The results from these experiments along with the findings from the literature review and interviews were used to write guidelines for FRC design, construction, and testing.

Following are the findings and conclusions, which are mainly based on the literature review and interviews.

- Fibers enhance the ductility, toughness, impact resistance, tensile strength, flexural strength, post-crack load-carrying capacity, fatigue life, abrasion resistance, scaling resistance, shrinkage

cracking resistance, durability, and cavitation resistance of the concrete (Ramakrishnan & Deo, 1998; Ostertag & Blunt, 2008).

- There is a lack of comprehensive guidance and specifications regarding design, material selection, construction, and testing of FRC.
- While SDDOT has no current specifications, there are some brief specifications available from DOTs in Georgia, Texas, Illinois, and Washington. SDDOT has some plan notes from previous FRC projects (Waters, 2014; Krstulovich, 2014; Grannes & Hodges, 2014).
- There is a lack of sufficient studies looking at the effect of fiber type and fiber dosage on the various fresh and hardened properties of FRC.
- Fibers can significantly decrease the consistency of fresh concrete (Dunn & Wolf, 2001).
- Increasing paste content can increase the slump of FRC while maintaining the required strength (Ramakrishnan, 1997).
- Mix design, preparation, mixing, testing, and finishing procedures of FRC are similar to that of PCC, except as detailed in Appendix G.
- Fiber balling can be minimized by increasing mixing time, increasing paste volume, and choosing fibers with low aspect ratios (Ramakrishnan & Deo, 1998; Ramakrishnan & Tolmare, 1998; Grannes & Hodges, 2014; Johnston, 2014; Strand et al., 2014).
- Fibers alter the compressive failure mode of concrete cylinders (Noushini et al., 2014).
- The effect of fibers on the compressive strength of FRC is inconsistent among the different studies found in the literature (Noushini et al., 2014; Saad et al., 2015; Li, 1992; Kim, et al., 2013).
- Fibers can increase the flexural strength by 25% to 55% compared with conventional PCC (Roesler et al., 2004).
- Fibers improve crack growth resistance, energy absorption capacity and compressive strength under impact loading conditions (Bindiganavile & Banthia, 2005; Pyo, 2016; Zhang and Mindess, 2010).
- Fibers can decrease exposed aggregates on the surface of concrete when subjected to freeze-thaw conditions by alleviating bond deterioration (Ostertag & Blunt, 2008).
- Fibers do not seem to significantly alter the permeability of concrete, except for the case of UHPC where it could reduce permeability (Ramakrishnan & Santhosh, 2000; Bierwagen, 2014).
- Macro fibers can increase the abrasion resistance by 14% compared with a 7% increase due to micro fibers, which could be because of the better bond that macro fibers have with the paste (Grdic et al., 2012).
- Fibers do not decrease the bond strength (Ramakrishnan & Santhosh, 2000).
- FRC develops many small shrinkage cracks compared with few large shrinkage cracks for conventional PCC (Lawler et al., 2005).
- FRC is commonly evaluated in the field through the bond strength test and surface inspection (Dunn & Wolf, 2001; Ramakrishnan & Santhosh, 2000).
- Crack widths of FRC can be further reduced by using higher mortar content (Ramakrishnan, 1997).

- The high cost of the fibers can sometimes result in doubling the cost of the overall structural component. UHPC is even more expensive, but could be justified for critical applications (Enbrecht, 2014; Gilsrud et al., 2014; Hedman, 2014; Letcher, 2014; Whitney, 2014; Abu-Hawash, 2014; Juntunen, 2014).
- Depending on the structural component, FRC demolition can sometimes be costly and tedious due to the tendency of the fibers to hold broken concrete pieces together (Maggenti et al., 2013).
- Early-age cracking could be better mitigated through the use of a combination of synthetic micro fibers and macro fibers (Maggenti et al., 2013).

Following are the findings and conclusions that are mainly based on experimental results.

- The difference in results between the specimen replicates for each test can be very significant for FRC due to possible difference in fiber distribution among the specimens.
- Regardless of fiber type or dosage, fibers have resulted in the reduction of compressive strength and modulus of elasticity of concrete by an average of 18% and 13%, respectively. These findings matched some studies in the literature, but other studies made opposite conclusions.
- The type of synthetic fibers used in the concrete has no significant effect on any of the fresh and hardened concrete properties that were measured in this study.
- Steel FRC has superior flexural properties compared with synthetic FRC, but it has the concern of being susceptible to corrosion (which was not examined in this study). Since it is not directly exposed to deicer salt, Jersey barrier is one application where steel fibers could be used.
- Steel fibers are twice the cost of synthetic fibers, but they can perform better or at least as good as synthetic fibers at half the dosage rate, giving an additional advantage of increased workability.
- The most cost-effective synthetic fibers among the tested ones are Fibermesh 650 and FORTA-FERRO fibers.
- Fiber dosage has no significant effect on the temperature, unit weight, or fresh air content of concrete.
- Slump decreases nonlinearly with the increase in fiber dosage. The average maximum slump drop was about 2.75 inches at the highest dosage rate of 0.69%.
- For the specific mix design adopted in this study and for synthetic FRC with fiber dosages between 0.21% and 0.69%, data showed that an increase of 0.1% in fiber dosage results in an increase of the following:
    - 74 lb. in toughness
    - 8% in equivalent flexural strength ratio
    - 37 psi in modulus of rupture
    - 81 psi in average residual strength
- Experimental results were in good agreement with available manufacturers' claims.
- The adopted impact test gave inconclusive results due to its qualitative nature and due to the lack of specimen replicates.
- Saw-cut surfaces of FRC cylinders showed uniform fiber distribution and no fiber balling, indicating the adequacy of five minutes of additional mixing.
- Based on the findings of this study, the research team offer the following recommendations.

- To minimize fiber balling, fibers with low aspect ratios should be used.
- Steel fibers should be avoided in components that would be exposed to chloride penetration.
- Among the tested synthetic fibers, FORTA-FERRO should be used due to its cost-effectiveness and low aspect ratio.
- Minimum fiber volume fraction should be 0.2%.
- The minimum fiber dosage that satisfies required properties should be chosen to ensure cost-effectiveness and higher slump values.
- Dosage recommendations for specific infrastructure applications are mentioned in Appendix G.
- Higher slump values, compared with PCC mixes, should be targeted for FRC mixes in order to compensate for the reduced workability of FRC mixes.
- Fine to coarse aggregate ratio should be increased in order to provide higher mortar content that is helpful to increase workability, minimize fiber balling, and reduce crack widths.
- Up to 20% and 15% reductions in compressive strength and modulus of elasticity, respectively, should be taken into consideration when designing FRC mixes.
- For FRC applications, a bridge deck paver, such as bridge deck overlays, instead of a low-slump paver should be used.
- Manual consolidation should be completely avoided.
- FRC tining should be modified by either reducing the tining angle, turning the tining rake over, or grinding the tining grooves after hardening.
- A burlap drag or a broom should be used instead of a carpet drag in order to avoid pulling out fibers from the surface of the FRC.
- For laboratory testing, five minutes of additional mixing time should be provided for FRC mixes in order to ensure uniform fiber distribution and minimize fiber balling.
- Flexural laboratory tests should be given emphasis because flexural properties are the ones affected most by the introduction of fibers. The average residual strength test is especially the most important.
- FRC mixes should be at least duplicated to ensure reliable testing results.
- For each hardened test, at least five specimens should be tested to ensure reliable testing results.
- Field surface inspections should be carried out on FRC structures periodically to monitor their long-term performance.
- Bond strength testing of extracted cores from the field should be conducted to ensure adequate bond between FRC components and other components.
- Instead of the empirical correlations that are usually obtained from experimental results, which cannot be guaranteed to work under all circumstances due to limitations in the testing matrix, it is better to come up with theoretical correlations and then verify them against comprehensive experimental results obtained from very different mixes.
- For future studies, mixes should be at least duplicated to attain better statistical confidence in the correlations.

- The effect of other aspects of the mix design, such as mortar content, water to cementitious materials ratio (w/c), coarse aggregate, and cementitious materials, should be studied.
- Other, more informative, workability measurements such as rheology should be explored in order to better correlate fiber dosage to workability of FRC mixes.
- Effect of fiber type and dosage on impact performance of FRC structures should be studied using more reliable instrumental impact tests incorporating compressive and tension loading with variable strain rates.
- Effect of fiber type and dosage on fatigue resistance, abrasion resistance, and durability of FRC structures should be studied since they are very important for transportation applications.

An FRC guideline based on the aforementioned conclusions and recommendations is found in Appendix G of this report. The guideline puts emphasis on the synthetic fibers that were tested in this study.

1. INTRODUCTION

1.1 Project Description

Concrete deterioration is one of the major causes of poor performance and shortened life expectancy of concrete roadway infrastructure nationwide. Due to the low tensile strength of traditional concrete, reinforced concrete structures often experience cracking and spalling, leading to accelerated corrosion of imbedded reinforcement, failure under severe loading, and lack of durability. Fiber-reinforced concrete (FRC) has a solid reputation for superior resistance to crack development and abrasion, along with improvements in strength, ductility, resistance to dynamic loading, and resistance to freeze-thaw effects. Because of these properties, FRC has been used in many applications such as bridge decks, repairs, and building beam-column connections.

Currently, there is a wide variety of FRC products available for engineering applications, but the applicability and cost-effectiveness of different products have not been evaluated systematically for SDDOT in the past. There are many factors that play a role in the selection of FRC products. Depending on the application, different types and dosages of fibers will result in different performances. Guidelines are needed in order to facilitate selection of fiber type and dosage required to achieve optimal performance at a reasonable cost. Engineers find it challenging to interpret performance claims by manufacturers based on unstandardized testing procedures and what seem to be high fiber dosage recommendations.

It has been nearly 20 years since SDDOT delved into the topic. Many of the fiber materials used in SDDOT projects have been phased out or discontinued, and many new products have been developed. What little guidance available on the proper specifications and use of FRC comes from the American Concrete Institute (ACI), and is generic in nature. Research is needed to investigate recent product development, evaluate fiber products currently on the market, and generate guidance for use, testing, and potential application of FRC. For lack of guidance, SDDOT may be sacrificing improved durability and performance as implementation lags technological developments in the area of fiber reinforced concrete structural components.

1.2 Objectives

The three main objectives of this study are listed below.

- Identify and describe best practices for design and construction of fiber reinforced concrete structural components. This objective was accomplished through an extensive literature search in addition to interviews with various state DOTs and fiber manufacturers. The effort was focused on FRC products related to structural applications that are relevant to DOT projects. Moreover, the most commonly used products were identified and the most relevant SDDOT applications were looked at in more detail.
- Assess potential application, performance, costs, benefits, and drawbacks of fiber reinforced concrete structural components. After identifying the structural applications of FRC in common SDDOT projects through interviews, the FRC materials were evaluated experimentally at SDSU's structures lab. The testing results, together with literature review and interview findings, were combined to provide a realistic assessment of performance, costs, benefits, drawbacks, and constructability of these structural applications.

- Develop guidance for design, material selection, construction, testing, and application of fiber reinforced concrete structures in South Dakota. A South Dakota specific guideline for using FRC in structural applications was developed with consideration to the availability, experience, and economic aspect of FRC application in South Dakota. The guideline is very concise and incorporates the findings that were obtained from the literature review, DOT interviews, and experimental testing.

2. LITERATURE REVIEW

This section provides a summary of existing literature pertaining to best practices in structural applications of FRC regionally and nationally. The literature review focused on structural performance of FRC materials, successful implementation practices, and potential applications. Emphasis was placed on design, material selection, construction, and laboratory and field testing of FRC. An FRC catalog was created to summarize literature review findings. The catalog contains detailed information, experiences, fiber properties, and required tests for the different types of FRC products currently available.

2.1 Introduction

Concrete is a widely used construction material throughout the entire world. It is relatively inexpensive, comprised of materials that are often readily available, and can be implemented in numerous applications. Yet, concrete has some drawbacks such as low ductility and tensile strength. Repeated loadings because of traffic and temperature variations due to seasonal changes can often develop micro-cracking within the concrete. This can then result in development of macro-cracks under additional applied stresses, leading to imminent failure of the concrete structure. To control this behavior, steel reinforcing bars (rebar) are placed within concrete elements. This increases the effective tensile strength of the structure and also intersects potential crack planes that form throughout the concrete. However, since cracking generally initiates at the surface of the concrete, by the time a crack reaches to the level of the rebar, it would have expanded and developed into a macro-crack. Therefore, additional reinforcement methods are desired to control the cracking while it is still at the micro-crack level and to decrease potential risks of chemical intrusion that cause further deterioration of the concrete.

To reinforce the concrete matrix and enhance the durability of a concrete structure, fibers have occasionally been incorporated into concrete mixes. This concept has been used for almost a century, with some of the first methods being the use of horsehair in mortar and straw in mud bricks. Over the past five decades, the use of fibers in concrete has advanced further and been studied with great interest. Various classes of fibers, such as steel, glass, synthetic, and natural fibers, have been utilized as a method of concrete reinforcement to prevent micro-cracks from evolving to macro-cracks. When a normal Portland Cement Concrete (PCC) structure reaches its ultimate flexural strength, it cracks without any components available to transfer the stresses. On the other hand, when an FRC structure cracks, the applied stresses are transferred from the matrix to the fiber components. This in turn enhances the ductility, toughness, impact resistance, tensile strength, flexural strength, fatigue life, abrasion resistance, shrinkage, durability, and cavitation resistance of the concrete (Ramakrishnan and Deo, 1998). These enhanced concrete properties have made FRC a highly attractive material for structural bridge components since they are subjected to repeated traffic loadings, which require a material with high durability.

2.2 Fiber Types

The American Society for Testing and Materials (ASTM), the American Concrete Institute (ACI) Committee 544, and the Fiber-Reinforced Concrete Association (FRCA) are all organizations that provide information regarding FRC.

ASTM C1116 addresses the classification of all forms of FRC, but does not address the placement, consolidation, curing, or protection of the FRC.

ACI Committee 544 develops and provides information on concrete reinforced with short, discontinuous, randomly dispersed fibers. ACI provides various documents that discuss methods for measuring properties of FRC. ACI also provides guidance for the specification, proportioning, production, physical properties, and durability of FRC.

The FRCA serves to further FRC knowledge development as defined by ACI Committee 544 and expand the FRC market. It also discusses various fiber types, common applications, and past projects using FRC.

According to ASTM C1116, fibers for FRC are categorized into four main types: (1) steel, (2) glass, (3) synthetic, and (4) natural. To illustrate the visual differences among the fiber categories, an example for each fiber category is shown in Figure 2.1.

Figure 2.1 An example of each of the four fiber categories, as specified by ASTM C1116

(1) Steel fibers are generally used to provide concrete with enhanced toughness and post-crack load-carrying capacity (FRCA, 2007). They are typically made from carbon steel or stainless steel and are shaped into varying geometries (e.g., crimped, hooked-end) in order to provide adequate anchorage with the concrete. Steel fibers range in length from 1.5 inches to 3 inches and are dosed at 25 to 100 pounds of fiber per cubic yard of concrete (lb/yd^3). Steel fibers are often used in conjunction with rebar or one of the other fiber types listed below, but are also able to be used on their own to reinforce concrete.

(2) Glass fibers are predominantly implemented in architectural applications and modified cement-based panel structures. Fiberglass is used to reinforce and insulate the concrete. These fibers help prevent the concrete from cracking over time due to mechanical or thermal stresses (FRCA, 2007).

Glass fibers can significantly improve concrete hardness and, therefore, are often used in concrete countertops and facades (Suksawang et al., 2014). They are not commonly used for structure components in bridges.

(3) Synthetic fibers are generally made from polypropylene, polyethylene, and other polymer blends. This type of material has low coefficient of thermal expansion, which helps prevent cracking due to thermal effects. Synthetic fibers are typically split into two subcategories called micro-synthetic and macro-synthetic fibers. Micro-synthetic fibers are generally used for protection and mitigation of plastic shrinkage cracking in concrete. They typically range in length from 0.5 inches to 0.75 inches and are dosed at rates ranging from 0.5 to 3 lb/yd^3 (FRCA, 2007). Short polyethylene fibers display the best ability in preventing early-age cracking in a mix of high-early strength concrete when compared with various other fibers such as steel, glass, nylon, and long polyethylene fibers (Suksawang et al., 2014). Macro-synthetic fibers are commonly used as a non-corrosive alternative to steel fibers since they provide similar characteristics. They typically range in length from 1.5 inches to 2.5 inches and are dosed at rates ranging from 3 to 20 lb/yd^3 (FRCA, 2007). A study found that polyethylene fibers provide good flexural strength, but do not perform well in preventing restrained shrinkage cracking, when compared with other fiber types (Suksawang et al., 2014).

(4) Natural fibers such as hay and hair were traditionally used in FRC. Nowadays, they are no longer used in commercial applications (FRCA, 2007). They are made from natural materials such as coconut, sisal, jute, and sugarcane. These materials are more susceptible to rotting and can cause harm to the concrete strength. Each of these materials comes in varying lengths, geometries, and material characteristics.

ASTM C1116 and FRCA (2007) provide detailed descriptions of the properties of each fiber type. Table 2.1 shows an abbreviated FRC catalog detailing fiber properties, manufacturers/suppliers, applications, and typical dosage rate. A more detailed discussion of various fibers is provided in the FRC Catalog in Appendix A. Dosage rates for the glass fibers and the natural fibers were not investigated in this work as they are not typically used for structural applications and, therefore, do not fit within the scope of this research. Common FRC applications, along with some names of various manufacturers and suppliers, were obtained from the literature review. The applications listed in this catalog are general examples.

Table 2.1 Abbreviated FRC Catalog

Fiber Type	Properties	Manufacturers and Suppliers	Applications	Typical Dosage Rate
1) Steel	Length: 1.5″ to 3″ Generally made from carbon, alloy, or stainless steel Provide enhanced toughness and post-crack load carrying capacity Available in various geometries (such as crimped or hooked-end) for anchorage	Bekaert Fibercon International Inc. BASF Construction Chemical	Slabs-on-grade Overlays Whitetoppings Bridge decks Jersey barriers Bridge girders Approach slabs Bridge columns	25-100 lbs/yd^3
2) Glass	Alkali-resistant	BASF Construction Chemicals	Architectural applications Modified cement-based panel structures	N/A
3.1) Micro-Synthetic	Length: 0.5″ to 0.75″ Diameter: < 0.004″ Generally made from polypropylene, cellulose, and nylon Controls/reduces plastic shrinkage cracks within the first 24 hours Non-corrosive Non-magnetic	W.R. Grace and Co. Propex Concrete Systems Corp. Euclid Chemical Company FORTA Corp. BASF Construction Chemicals	Generally the same applications as steel and macro synthetic fibers, if used in a hybrid-FRC mix (use of two sizes and/or types of fibers in one concrete mix)	0.5-3.0 lbs/yd^3 W.R. Grace Micro-Fibers: 0.5-1.5 lbs/yd^3
3.2) Macro-Synthetic	Length: 1.5″ to 2.5″ Diameter: 0.012″ to 0.05″ Generally made from polyolefin, polypropylene, and poly-vinyl alcohol Provide enhanced toughness and post-crack load carrying capacity Meets temp/shrinkage reinforcement similar to welded wire fabric Non-corrosive Non-magnetic	W.R. Grace and Co. Propex Concrete Systems Corp. Euclid Chemical Company FORTA Corp. BASF Construction Chemicals Nycon, Inc.	Slabs-on-grade Overlays Whitetoppings Shotcrete Bridge decks Jersey barriers Bridge girders Approach slabs Bridge columns	3-20 lbs/yd^3 W.R. Grace Strux 90/40: 3-12 lbs/yd^3 Euclid TUF-STRAND SF: 3-20 lbs/yd^3 FORTA-FERRO: 3-30 lbs/yd^3
4) Natural	Non-corrosive Material such as coconut, sisal, and sugarcane	N/A	Generally not in commercial applications of FRC Commonly to reinforce cement-based products	N/A

Some of the recommended dosage rates provided in Table 2.1 are broad. Therefore, a method for narrowing the desired dosage rate for a certain fiber in any particular application is needed. No information was discovered from the literature review regarding processes used in determining the required fiber dosage rate. Fiber manufacturers and suppliers commonly provide a recommended dosage rate. These recommended rates often seem to be independent of the application. For instance, SDDOT and NDDOT have used 3M's polyolefin macro fiber in multiple FRC applications with almost identical fiber dosages. These projects involved bridge decks (Ramakrishnan and Deo, 1998), deck overlays (Ramakrishnan, 1997; Ramakrishnan and Deo, 1998; Ramakrishnan and Santhosh, 2000) Jersey barriers (Ramakrishnan, 1997), whitetopping (Dunn and Wolf, 2001), and full-depth pavement (Ramakrishnan, 1997; Ramakrishnan and Tolmare, 1998). Each of these applications called for a fiber dosage rate of 20 lbs/yd^3 or 25 lbs/yd^3. Considering each application has its own performance requirements, a universal dosage rate may not be the most cost-effective process. This potentially calls for some additional investigations and experimental testing to determine a more exact dosage rate for each specific application depending on the desired concrete properties. Using results from various experimental tests, one can come up with the minimum and most cost-effective fiber dosage rate depending on the desired property level. For example, if an average residual strength for an FRC bridge deck overlay is specified to be a minimum of 200 psi, results obtained using ASTM C1399 can be utilized to select the lowest possible fiber dosage rate that will satisfy the specified requirement. This experimental testing approach will be used during this research. Specific material tests will be discussed in more detail in Section 5.

2.3 Fresh Concrete Properties

2.3.1 Slump

The slump of FRC is measured using ASTM C143. This is the same testing method that is typically used to measure the slump of PCC. When 3M polyolefin fibers were used in a thin whitetopping, an average decrease in slump of 2.8 inches was measured (Dunn and Wolf, 2001). Such decreased concrete consistency is often adjusted through the addition of admixtures such as a superplasticizer or a water-reducing agent (Ramakrishnan, 1997). Another way to achieve a more workable concrete mix is to increase the paste and/or mortar content. Addition of fly ash increases the paste content and thereby improves the uniform and proper mixing of the fibers without a need for a higher initial slump (Ramakrishnan, 1997). It is, however, important to note that the addition of these materials might alter the other properties of the concrete.

2.3.2 Air Content

The air content of FRC is measured using ASTM C231 (Ramakrishnan, 1997). This is the same testing method that is typically used to measure the air content of PCC. No information regarding the relationship between air content and fiber type or fiber dosage was discovered in the literature review.

2.3.3 Fresh Unit Weight

The fresh unit weight of FRC is measured using ASTM C138 (Ramakrishnan, 1997). This is the same testing method that is typically used to measure the fresh unit weight of PCC. No information regarding the relationship between fresh unit weight and fiber type or fiber dosage was discovered in the literature review.

2.3.4 Concrete Temperature

The concrete temperature of FRC is measured using ASTM C1064 (Ramakrishnan, 1997). This is the same testing method that is typically used to measure the concrete temperature of PCC. No information regarding the relationship between concrete temperature and fiber type or fiber dosage was discovered in the literature review.

2.3.5 Fiber Distribution

Determining the actual fiber content per cubic yard of FRC is a method for evaluating the degree of distribution of fibers throughout the entire batch of concrete. Using a nonstandard test method (Ramakrishnan, 1997), the actual fiber content can be determined by washing out the concrete, separating the fibers, and determining the weight of the washed fibers per cubic yard of concrete. Additionally, it is possible to have the fibers clump during FPC mixing, which is known as “balling.” This is dependent on whether the amount of cementitious paste within the concrete is adequate to fully cover the entire surface area of the fibers that are introduced into the concrete mix (Ramakrishnan and Deo, 1998). Also, fiber balling often occurs if the fiber’s aspect ratio is too large (Ramakrishnan and

Tolmare, 1998). The aspect ratio is the fiber length divided by the fiber diameter. It is important to note that in order to properly consolidate FRC testing specimens, a form of vibration (internal or external) must be performed instead of rodding. This is because rodding may result in non-uniform distribution of fibers (ACI Committee 544, 1988).

2.4 Hardened Concrete Properties

2.4.1 Laboratory Testing

2.4.1.1 Compressive Strength

The compressive strength of FRC is evaluated using the common ASTM standard procedure (ASTM C39) for PCC specimens. Fibers within the concrete specimen may alter the failure mode for this test by making the concrete less brittle. They hold any pieces of concrete, which have split from the specimen, tightly to the specimen body and preventing them from completely detaching from the specimen. Even though fibers can significantly increase the post-peak strength and the deformation beyond the maximum load (ACI, 1988), results from previous studies seem to be contradictory in regard to the effect of fibers on the compressive strength of concrete. A study conducted by Noushini and his colleagues on FRC reinforced with polyvinyl alcohol fibers showed an increase of 12% in the compressive strength at a fiber dosage rate of 0.25% (Noushini et al., 2014). Another study conducted by Saad and his colleagues showed an increase of up to 90% in the compressive strength of high performance fiber reinforced concrete containing 5% of fibers (Saad et al., 2015). On the other hand, Li constructed a micromechanical model that showed a reduction in compressive strength with an increasing fiber volume fraction of fiber reinforced cementitious composites (Li, 1992). A similar result was obtained for high strength steel fiber reinforced concrete (Kim, et al., 2013). These contradictory conclusions could be attributed to the different fiber types, concrete designs, and concrete constituents used in each of these studies.

2.4.1.2 Tensile Strength

Currently there is no standardized test method for determining the direct tensile strength of a concrete specimen. One test method commonly used to determine the tensile strength is the uniaxial direct tensile test, which identifies key properties of FRC such as stress-strain relationships under tension, elastic modulus, and strain-hardening or strain-softening. Complications with this test method commonly involve the high variation in post-crack performance due to inconsistent crack location and propagation. Chao et al. (2011) attempted to localize the crack location by utilizing double dog-bone geometry (Figure 2.2) and steel meshes to strengthen the end portions of the specimen.

Figure 2.2 Double dog-bone geometry of a uniaxial direct tensile test specimen (Chao et al., 2011)

The double dog-bone geometry and the steel mesh were both utilized to ensure cracking occurs only at the central portion within the gauge length. The first cracking stresses were similar among specimens, but the post-cracking response and the residual strength showed variability. Chao et al. (2011) concluded that this inconsistency is the result of difficulties associated with controlling the location and propagation of cracks during the uniaxial direct tensile test.

2.4.1.2 Flexural Strength

According to ACI Committee 544 (1988), the preferred method for determining the flexural strength of an FRC beam specimen is the third-point loading test (ASTM C1609). The Midpoint loading test is also acceptable. It has been shown that fiber enhances the post-crack flexural stiffness of concrete and provides a controlled deflection hardening behavior (Lawler et al., 2005; Ostertag and Blunt, 2008; Ramakrishnan and Deo, 1998; Ramakrishnan and Santhosh, 2000; Ramakrishnan and Tolmare, 1998). It has been shown that the flexural cracking load of plain concrete can potentially be increased by 25% to 55% through the utilization of reinforcing fibers (Roesler et al., 2004). Occasionally, the results from a flexural test can vary among specimen replicates of an FRC mix due to non-uniform fiber distribution that affects the amount of reinforcement along a certain cracking plane (Chao et al., 2011). This shows the importance of performing proper sample preparation techniques to provide FRC specimens with minimized preferential fiber alignment and non-uniform distribution.

Certain types of FRC, such as engineered cementitious composites (ECCs), are considered to be high performance FRC due to their enhanced ductility and flexural load-carrying capacity. ECCs contain water, cement, sand, fibers, and some common chemical additives, but does not use coarse aggregates, as they tend to adversely affect the unique ductile behavior of the composite. Due to its strain-hardening response following the first flexural crack, the stress-strain curve of ECC has a shape similar to that of a ductile metal. Under bending stresses, ECC produces multiple micro-cracks at the base of a flexural beam, which allows the beam to develop a large curvature prior to failure (Li and Kanda, 1998; Li, 2007). Therefore, this type of FRC is also known as bendable concrete. The fibers do not rupture at the crack location during flexural loading and are able to maintain the structural integrity of the ECC beam (Akkari, 2011).

2.4.1.4 Average Residual Strength

The average residual strength is a measurement of post-crack load-carrying capacity of fiber reinforced concrete. It is carried out according to ASTM C1399. It provides the ability to evaluate the flexural performance of a specimen in its post-cracking state. The cracked concrete does not provide any flexural strength to the specimen while only the fibers prevent the specimen from failure. This provides a method for evaluating the strength of the fibers in the concrete to allow for comparative analysis among beams containing different fiber types, fiber dimensions, and/or fiber dosage rates. Research studies showed that the average residual strength of FRC increases with increasing fiber dosage. For instance, Lee found an increase in the average residual strength of 0.65 MPa per 0.1% volume fraction of steel fibers. He tested volume fractions ranged from 0.25% to 0.5% (Lee, 2017).

2.4.1.5 Toughness

Toughness, which is the energy absorption capacity of a material, is determined using a flexural test (ASTM C1609) according to the recommendation of the ACI Committee 544 (1988). This method is simpler than other potential methods and also simulates the loading conditions of many FRC applications. The energy absorbed by a specimen is represented by the area under the entire load-deflection curve obtained from the flexural test (ACI, 1988). One alternative testing method to determine the toughness is the round panel test (ASTM C1550), which occasionally provides more consistent data than the normal flexural test. However, it is more tedious to conduct due to the need of handling and moving larger concrete specimens and testing equipment. Also, ASTM C1550 only provides the toughness of the specimen, whereas ASTM C1609 provides the toughness along with the flexural strength, the residual strength, and the post-crack performance of the specimen (Chao et al., 2011). Considering that FRC commonly increases the post-crack load carrying capacity, the toughness will also be increased due to the prolonged behavior of the load-deflection curve. The fibers continue to carry additional load even after the concrete has cracked and is no longer contributing to the tensile strength of the matrix (Lawler et al., 2005; Ostertag and Blunt, 2008; Ramakrishnan and Deo, 1998; Ramakrishnan and Tolmare, 1998).

2.4.1.6 Impact Strength

Impact resistance, which is one of the most important attributes of FRC, is often significantly increased with the addition of fibers into a concrete mix (Ramakrishnan and Deo, 1998; Ramakrishnan and Tolmare, 1998). Several types of tests have been used to determine the impact resistance of FRC, but the most common is the drop-weight test (ACI, 1988), which yields the number of repeated blows necessary to cause specified levels of distress to the specimen. This value acts as an estimate of the energy absorbed by the specimen at the specified levels of distress. Fibers significantly enhance the crack growth resistance under impact loading conditions (Bindiganavile and Banthia, 2005). A study conducted on high strength FRC showed better improvements in compressive strength under dynamic loading compared with static loading (Zhang and Mindess, 2010). Another study on ultra-high performance FRC showed exceptional energy absorption capacity under dynamic tensile loading (Pyo, 2016).

2.4.1.7 Fatigue Strength

Another important property of FRC is its endurance under dynamic cyclic flexural loading. Currently there is no testing standard for fatigue strength, but testing methods similar to those performed for conventional PCC have been used and are considered to be acceptable. A procedure recommended by ACI Committee 544 (1988) is conducted using reversing and non-reversing loading of a flexural concrete beam. The applied loading in this test generally corresponds to 10% to 90% of the static flexural strength. Under this loading, a passing specimen must exceed at least two million cycles, as this value is equivalent to a typical lifespan of a pavement structure. Ramakrishnan (1997) has used the following testing procedure in his research:

- Third point loading with a span of 12 inches on 4x4x14-inch beams
- Frequency of loading of 20 cycles per second (Hz)

- Lower limit for the dynamic loading set at 10% of the average maximum loads from the static flexural test
- Upper limit varying from 85% to 50% of the maximum static flexural load
    - If the beam failed before reaching two million cycles, the upper limit for the next beam was set at a lower percentage
    - If the beam survived two million cycles, two more beams were tested at the same percentage
- Fatigue strength defined as the maximum stress at which the specimen withstood more than 2 million cycles of non-reversed fatigue loading

The addition of fibers has been shown to provide a noticeable increase in the flexural fatigue strength and endurance limit of concrete (Ramakrishnan and Deo, 1998; Ramakrishnan and Tolmare, 1998).

2.4.1.8 Freeze-Thaw Resistance

To evaluate the resistance of an FRC specimen to freeze-thaw conditions, the same procedure as that used for conventional concrete (ASTM C666) may be utilized. Because the fibers tend to remain bonded to any dislodged pieces of concrete in an FRC specimen, the degree of weight loss is not a recommended method for determining the freeze-thaw resistance of FRC. However, the relative dynamic modulus of elasticity method (ASTM C215) is still considered to be an appropriate method for FRC and should be utilized for determining the freeze-thaw resistance of FRC (ACI, 1988). Fibers will generally alleviate the bond deteriorations that are caused by extreme environmental conditions, such as freeze-thaw cycles. Ostertag and Blunt (2008) found a decrease in exposed aggregate on the surface of FRC, compared with conventional concrete, when subjected to repeated freeze-thaw cycles. This decrease in exposed aggregate is shown in Figure 2.3, which displays (a) a concrete specimen prior to freeze-thaw cycles, (b) a plain concrete specimen after being introduced to freeze-thaw cycles, and (c) a hybrid FRC (HyFRC) specimen after being introduced to freeze-thaw cycles. HyFRC is a mix of concrete that contains more than one size of fiber and/or more than one fiber material (e.g., steel and polyolefin) (Ostertag and Blunt, 2008). This figure clearly shows the HyFRC's enhanced resistance to deterioration under freeze-thaw cycles when compared with conventional concrete.

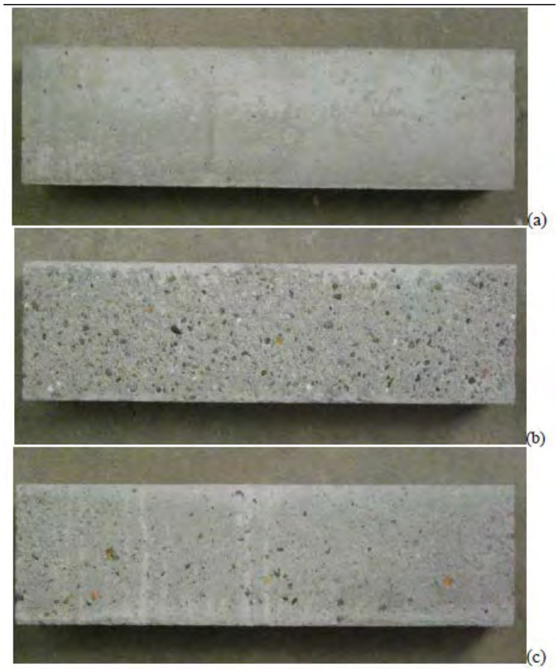

Figure 2.3 Surfaces of freeze-thaw specimens (a) before, (b) plain concrete after, and (c) HyFRC after freeze-thaw cycling (Ostertag and Blunt, 2008)

2.4.1.9 Scaling Resistance

The resistance to scaling of an FRC surface may be evaluated in the laboratory by exposing the concrete to freezing-and-thawing cycles in the presence of deicing chemicals (ASTM C672). Concrete's resistance to scaling under these conditions is a pivotal characteristic for the pavement surface in certain regions of the world. Concrete pavement in regions that experience freezing temperatures is commonly exposed to deicing chemicals, such as salt, and must be able to resist corrosion in order to enhance the concrete's durability and increase the pavement's lifespan. Hybrid-FRC consisting of a combination of polyvinyl alcohol microfibers and steel macro fibers was compared against conventional concrete by Ostertag and Blunt (2008). Multiple concrete specimens of each mix were assessed at increments of at least five complete freeze-thaw cycles and rated based on the scale in Table 2.2.

Table 2.2 Rating scale for concrete scaling (Ostertag and Blunt, 2008)

Rating	Description
0	No scaling
1	Very light scaling (1/8″ max depth and no coarse aggregate visible)
2	Slight to moderate scaling
3	Moderate scaling (some coarse aggregate visible)
4	Moderate to severe scaling
5	Severe scaling (coarse aggregate visible over the entire surface)

After a total of 50 cycles and seven different predetermined surface analysis periods, the conventional concrete had an average rating of 1.69 while the hybrid-FRC had an average rating of only 0.63. The lower rating value for the hybrid-FRC demonstrated the enhanced performance that FRC can provide over conventional concrete when exposed to freezing-and-thawing cycles in the presence of deicing chemicals.

2.4.1.10 Chloride Permeability

To determine a concrete specimen's resistance to chloride ion penetration, the electrical indication method (ASTM C1202) may be used. This method is used to evaluate the electrical conductance of concrete samples in order to provide a rapid indication of their resistance to chloride ion penetration. Ramakrishnan and Santhosh (2000) tested specimens that were obtained from cores drilled in the field and specimens that were cast in a laboratory. The specimens that were cast in the lab consisted of five different mix designs with varying fiber dosage rates of 3M polyolefin macro-fibers. Each selected dosage rate was previously implemented in SDDOT projects (see Ramakrishnan, 1997, and Ramakrishnan and Deo, 1998). The specimens were also cast using varying consolidation efforts such as: (1) no rodding/vibration, (2) two lifts with 25 rods per lift, (3) two lifts with 10 seconds of vibration per lift, (4) two lifts with 20 seconds of vibration per lift, and (5) two lifts with 30 seconds of vibration per lift. Ramakrishnan and Santhosh found it was difficult to conclude that the addition of fibers into the concrete altered the permeability of the concrete. However, it was concluded that the consolidation effort largely affected the permeability of the concrete. The specimens that were introduced to 30 seconds of vibration per lift displayed a much lower permeability than the other specimens that were subjected to lower consolidation efforts.

2.4.1.11 Abrasion Resistance

The abrasion resistance of concrete may be determined using the rotating-cutter method (ASTM C944). Results from this testing method could be important for certain applications such as bridge decks and pavements, as the rotating-cutter bit simulates the wearing action exerted by the traffic loading. Grdic et al. (2012) investigated the abrasion resistance of concrete reinforced by either a polyolefin microfiber named FIBRILs S120 or a polyolefin macro fiber named FIBRILs F120. They determined that, compared with plain concrete, the microfiber increased the abrasion resistance by approximately 7%, while the macro fiber increased the abrasion resistance by approximately 14%. Deterioration due to abrasion occurs from the cementitious material getting worn away by the abrasive force. Due to their larger dimensions, the macro fibers have better bond to the cementitious material than the microfibers, which decreases the amount of deterioration due to abrasive forces. The ability to resist deterioration due to abrasion helps the surface of concrete remain fully intact and, therefore, decreases the risk of water and chemical intrusion, thus increasing the durability and lifespan of a certain structure.

2.4.1.12 Bond Strength

FRC is commonly used as a concrete overlay or an asphalt whitetopping. An effective overlay or whitetopping must provide adequate bonding to the underlying material. This creates a stronger section that works as one composite piece rather than two separate pieces. The slant shear test (ASTM C882) was developed to determine the quality of a bonding agent and not necessarily the bond strength of an overlay in the field. However, a modified slant shear test would be adequate for evaluating the bond strength of an overlay (Ramakrishnan and Santhosh, 2000). In this modified method, the upper half of the specimen was made of repair material directly bonded on the lower half, which was base concrete. Figure 2.4 shows this specimen setup for the modified slant shear test.

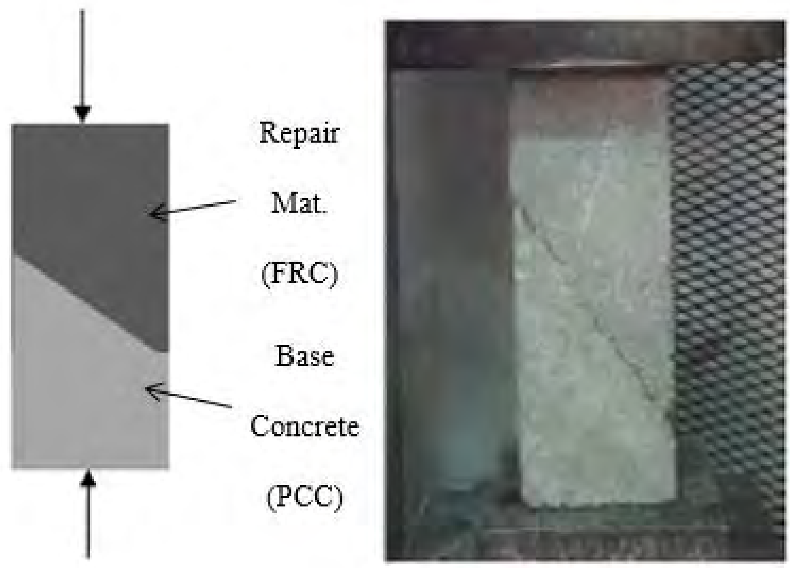

Figure 2.4 A specimen for the modified slant shear test consisting of one-half base concrete and one-half repair material (Momayez et al., 2005)

A mix of ECC that utilized poly-vinyl alcohol fibers was placed over the top of conventional concrete and provided bond strength of 1,200 psi (Akkari, 2011). This was considered to be a reasonably high bond strength for a concrete to concrete bond.

2.4.1.13 Shrinkage Cracking

Several testing methods for evaluating shrinkage cracking resistance of concrete at an early age have been proposed due to the lack of a standard test method. Ring, rectangular, and square are some specimen shapes that have been commonly used to compare the crack resistance characteristics of FRC to plain concrete.

These methods involve measurement of the length and width of the cracks in the concrete (ACI, 1988). Measurements of cracking resistance are quantified by summing the product of the lengths and widths of the cracks and expressing the resultant as a percent difference from plain concrete. A different method was performed by Lawler et al. (2005) with the use of a ring-shaped specimen. The specimen was cast in the ring-shaped form and cured for a predetermined period. The outside part of the specimen's mold was then removed and the top surface of the concrete ring was sealed with silicone caulking. This allowed drying to occur only from the outer surface. Lawler recorded the age at which cracks were first observed on the outer surface of the ring in addition to the crack widths after a specified amount of days. A total of four concrete mix designs were evaluated during this study. One concrete mix contained no reinforcing fibers, another contained steel macro fibers, and two hybrid FRC mixes were created using a combination of steel macro fibers and either steel microfibers or polyvinyl alcohol microfibers. Cracking was first observed after nine days for all four of the design mixes investigated. The mixes that contained fibers developed two cracks, while the mixes without fibers developed only one crack. With only one crack developing throughout the plain concrete specimens, the width of that crack was much larger than that of the cracks in the FRC specimens.

2.4.2 Field Testing

2.4.2.1 Surface Inspections

An effective method for evaluating the performance of any structural application is by performing periodic inspections. Such inspections are a helpful method to investigate whether cracks are forming and propagating on the surface of the structure. This provides a simple, non-destructive method for comparing the surface conditions of different mixes of concrete. A bridge deck overlay consisting of concrete reinforced with 3M polyolefin fibers was periodically inspected (Ramakrishnan, 1997). This inspection showed that the FRC displayed a greater crack density than the plain concrete, but with significantly thinner cracks. Similarly, an FRC whitetopping with various transverse joint spacing was inspected (Dunn and Wolf, 2001). This whitetopping was approximately 3.5 inches to 4 inches thick with joints spaced anywhere between 6 feet and 25 feet. These inspections concluded that as the joint spacing increased, the concrete cracking also increased. It was determined that joint spacing under 15 feet provided satisfactory resistance to cracking while joint spacing greater than 15 feet showed significant signs of cracking, faulting, and spalling. Also, the riding quality of an FRC pavement with 3M polyolefin macro fibers did not present any significant difference compared with the riding quality of a plain concrete pavement (Ramakrishnan and Tolmare, 1998).

2.4.2.2 Bond Strength

Determination of the bond strength between an underlying concrete and its overlay may be determined either in the laboratory or in the field. The process that has been used in the field differs from the method that has been used in the laboratory. Two-inch cores were cut from various locations on two different South Dakota bridges (Ramakrishnan and Santhosh, 2000). A steel grip was then epoxied to the top surface of these cores. Finally, a tensile force was applied to the steel grip until the core separated into two sections. This field test method provided relatively similar results to those that were obtained from the slant shear laboratory test performed by Ramakrishnan and Santhosh.

2.5 Structural Applications

2.5.1 Mix Design

A standardized FRC mix design procedure does not currently exist for most DOTs in the country. A specific procedure explaining how to design an FRC mix was not discovered in the literature review as well. Designing FRC mixes is usually carried out using the same procedure for designing plain concrete. Ramakrishnan and Santhosh (2000) recommend that an FRC deck overlay (in South Dakota) should have the same specifications and mixture proportions as that of SDDOT’s plain low-slump dense concrete (LSDC), with the exception of the inclusion of fibers. LSDC is the type of concrete design currently used for most deck overlays in South Dakota. For the construction of Jersey barriers, which are typically heavily reinforced, Ramakrishnan (1997) recommends that the mix design proportions should be adjusted to provide the same strength but at a higher slump of 4 inches to 6 inches. He recommends that increased paste content could possibly achieve higher slump concrete at the same strength. Chojnacki (2000) designed an FRC mix that was based on Missouri’s standard PCC mix, with some modifications based on the fiber manufacturer’s recommendations. The stated modifications consisted of regulations such as (1) “Type 1 cement shall be used,” (2) “Type C fly ash may be used to replace a maximum of 15 percent of Type 1 cement,” (3) “any admixtures used will require certification from the fiber manufacturer for compatibility,” and (4) “ratio of fine to coarse aggregate for the fiber-reinforced concrete mix shall be 45/55 by volume content.”

Considering these recommendations, the design procedure for FRC would be very similar to the design procedure for PCC. This provides a possible method for determining the required mixture proportions for FRC. At this time, there does not seem to be a reliable method for determining a required or recommended fiber dosage rate for specific structural applications. Currently, fiber manufacturers and suppliers seem to provide a recommended dosage rate regardless of the application. As previously mentioned, the required dosage may be more easily determined through additional material testing. The testing could include multiple fiber types at various dosage rates since each might perform differently compared with the others. This form of testing may provide a method for determining the optimum fiber dosage rate for any specific application. Using the optimum fiber dosage rate for each FRC application will provide the most cost-effective concrete design and should noticeably decrease the initial cost of FRC.

2.5.2 Construction

Due to the enhanced concrete properties of FRC, it has previously been used for various structure components. Such components consist of bridge decks, bridge deck overlays, Jersey barriers, and approach slabs (Eggers and Rupnow, 2008; ODOT, 2012; Ostertag and Blunt, 2008; Ozyildirim, 2011; Ramakrishnan, 1997; Ramakrishnan and Deo, 1998; Ramakrishnan and Santhosh, 2000; Ramakrishnan and Tolmare, 1998; Wipf et al., 2009; Yazdani et al., 2002). Construction methods and equipment required for FRC have generally been similar to that of conventional concrete (Ramakrishnan and Deo, 1998; Ramakrishnan and Santhosh, 2000; Ramakrishnan and Tolmare, 1998; Suksawang et al., 2014). Mixing of FRC is similar to that of normal concrete, except that additional mixing time/revolutions are often required for the fibers to be properly dispersed throughout the concrete mix (Chojnacki, 2000; Li and Kanda, 1998; Ozyildirim, 2011). Adding 3M polyolefin fibers to a PCC mix required at least two additional minutes of mixing to provide adequate fiber dispersion throughout the concrete (Dunn and Wolf, 2001). Also, the mixing period of FRC occasionally requires an additional laborer(s) to add the fibers into the mixer during the mixing process (Chojnacki, 2000; Ramakrishnan and Tolmare, 1998). Two different techniques of adding fibers to the concrete were investigated, and the distribution of the fibers in each case was evaluated (Suksawang et al., 2014). In the first technique, the fibers were added in the dry state along with the coarse and fine aggregates, prior to the addition of water to the mixer. In the second technique, the fibers were added in the wet state after the water was added to the mix. After observing the concrete in both the plastic and the hardened states, the observers determined that both techniques provided good fiber distribution throughout the concrete.

FRC occasionally creates additional complications when it comes to finishing due to its decreased workability, although the same techniques and equipment that are typically used for plain concrete can still be used for FRC. The low slump of a polyolefin FRC mix is shown in Figure 2.5.

Figure 2.5 Consistency of a polyolefin FRC mix as it is discharged from the mixing truck (Dunn and Wolf, 2001)

To prevent catching on fibers at the surface of the concrete during tining, the tining fork can be used at a reduced angle (Ramakrishnan and Tolmare, 1998). Another successful technique is to turn the tining rake over so that the tines are no longer vertical, which creates more of a downward force than a pulling force (Ramakrishnan and Deo, 1998). This latter technique has shown very promising results, but it often requires a more experienced laborer to properly perform the desired tining. Another method that has been used is to grind the tining grooves into the concrete after hardening. This method does not require a laborer with the experience required for the previous method, but it does commonly take more time than the other methods. Ramakrishnan and Santhosh (2000) recommended that FRC should be tined using the first method of reduced tining angle.

2.5.2.1 Bridge Decks

As previously discussed, the use of FRC commonly enhances the wearing resistance and the durability of a structure. This makes FRC a very desirable material for use as a wearing surface such as a bridge deck. SDDOT used FRC with 3M polyolefin fibers for a full-depth bridge deck replacement (Ramakrishnan and Deo, 1998). During this implementation, it was determined that the addition of fibers did not cause any construction problems during mixing, pumping, placing, consolidating, finishing, and tining. The only modification was the additional mixing time required. An additional five minutes of mixing was needed to achieve uniform distribution of the fibers. The only major complication was the discovery of a few unopened bundles of fibers in two of the concrete trucks. It was concluded that these unopened fiber bundles were due to the concrete’s higher slump. The higher slump resulted in less shearing action during mixing, preventing the bundles from breaking open. This suggests that, although a higher slump enhances the workability of an FRC mix, it also may result in some fiber balling and decreased performance of the FRC structure.

The Oregon Department of Transportation (ODOT) has also previously utilized synthetic fibers to reinforce concrete used in bridge decks. In 2012, ODOT used Novomesh 950 synthetic fibers. The fibers dispersed evenly throughout the concrete to create a secondary reinforcement. This FRC mix significantly reduced the risk of cracking throughout the bridge deck and increased the durability of the deck (ODOT, 2012).

Previously, steel fibers have also been added to concrete for bridge deck applications. Eggers and Rupnow (2008) used steel FRC for a thin concrete layer as the top of a composite bridge deck. However, no conclusive results pertaining to the performance of steel FRC for a bridge deck were obtained from this research. This was because the failure mechanism for all of the testing specimens was shear developed at the epoxy/steel interface.

2.5.2.2 Deck Overlays

Bridge deck overlays are other components for which FRC provides many potential benefits. In the past, polyolefin fibers have been used for deck overlay applications (Ramakrishnan, 1997; Ramakrishnan and Deo, 1998). During the construction of the deck overlays, standard practice was followed for placing, consolidating, finishing, and tining the concrete. Wet burlap and polyethylene sheets were placed over the top of the finished concrete to allow it to cure. This is the same procedure that has been proven adequate for curing a low-slump concrete deck overlay. From the periodic inspections that were performed on these deck overlays, it was observed that the FRC provided enhanced resistance to crack widening and crack propagation. As discussed in Section 2.4.2.1, this property is expected for FRC applications. Many other benefits from the FRC were observed, such as increased flexural strength, toughness, impact strength, and post-crack load carrying capacity (Ramakrishnan and Deo, 1998).

2.5.2.3 Jersey Barriers

Desired properties of Jersey barriers include the ability to absorb energy due to impact forces and the ability to resist common wearing due to environmental changes. Concrete surfaces with thinner crack widths are less permeable to water and deicing chemicals that commonly harm concrete surfaces. FRC is a desirable material to be used for Jersey barriers due to its ability to resist crack widening and propagation. Jersey barriers containing 3M polyolefin fibers were constructed using the same mix design and construction methods used for the bridge deck and deck overlay that were also constructed in the same project (Ramakrishnan, 1997; Ramakrishnan and Deo, 1998). Therefore, there were no complications with mixing, pumping, placing, consolidating, or finishing. Moreover, from inspections performed, a majority of the cracks observed on the Jersey barriers did not exceed the allowable width of 0.007 inches, as specified by ACI Committee 224. Ramakrishnan (1997) recommended that in order to optimize the concrete design and decrease the observed crack widths, a higher paste and mortar content should be used. He also recommended that the FRC mix used for Jersey barriers should have a higher slump than generally specified, ranging from 4 to 6 inches, so that the concrete can adequately consolidate around the steel reinforcing bars.

2.5.2.4 Approach Slabs

For approach slabs to perform as desired, they need to comply with certain performance criteria. The criteria often include crack resistance due to mechanical and environmental conditions and post-crack flexural stiffness. FRC is a very favorable material for this type of application, as it often meets all these criteria. A hybrid FRC (HyFRC) mix was previously used in approach slabs (Ostertag and Blunt, 2008). This HyFRC mix consisted of steel macro fibers and poly-vinyl alcohol synthetic microfibers. They found that HyFRC can outperform relatively low reinforcing ratios (less than 0.31%) under flexure, and may be a suitable replacement when minimum reinforcement is required. They recommended that the existing reinforcing ratios or the thickness could be reduced to optimize the design. However, they also recommended that full-scale tests should be performed first to verify the performance of the proposed design changes.

2.5.3 Specifications

2.5.3.1 South Dakota

There were no SDDOT FRC specifications discovered during the literature review. However, during interviews, input on plan notes for past FRC pavement and FRC bridge-overlay applications was provided (Grannes and Hodges, 2014). These plan notes are discussed in detail in Section 3.5.

2.5.3.2 Georgia

The Georgia DOT has specifications regarding the use of macro synthetic fibers for concrete reinforcement. Specific requirements and acceptance guidelines are shown below. These were obtained from a Georgia DOT employee (Jason C. Waters, Office of Materials and Testing) via email.

A. Requirements

1. Ensure that macro-synthetic fibers are manufactured from virgin polyolefins (polypropylene and polyethylene) and comply with ASTM C 1116.4.1.3. Fibers manufactured from materials other than polyolefins must show documented evidence confirming their long-term resistance to deterioration when in contact with the moisture and alkalis present in cement paste and/or the substances present in air-entraining and chemical admixtures.
2. The minimum fiber length required is 1.50 inches (38 mm).
3. Ensure that macro-synthetic fibers have an aspect ratio (length divided by the equivalent diameter of the fiber) between 45 and 150.

B. Acceptance

1. Ensure that macro-synthetic fibers have a minimum tensile strength of 40 ksi (276 MPa) when tested in accordance with ASTM D 3822.
2. Minimum dosage rate in pounds of fibers per cubic yard is established by determining a minimum average residual strength of no less than 150 psi (1034 kPa) when tested in accordance with ASTM C 1399. In all cases, ensure a minimum fiber dosage rate of 5 lbs/yd^3 (2.9 kg/m^3) and a maximum fiber dosage rate of 10 lbs/yd^3 (5.9 kg/m^3).
3. Ensure that macro-synthetic fibers have a minimum modulus of elasticity of 400 ksi (2758 MPa) when tested in accordance with ASTM D 3822.
4. The fiber manufacturer is required to obtain independently performed test results that confirm the requirements listed herein and submit those for approval by the engineer.
5. Approved fibers are listed on the department's Qualified Products List 86 (QPL-86), "Macro-Synthetic Fibers for Concrete Reinforcement."

A qualified products list identified by the Georgia DOT was also provided by the same employee mentioned above and is shown in Table 2.3. Note that each of the fibers listed in this table are synthetic fibers.

Table 2.3 Georgia DOT's qualified products list

Fiber Name	Manufacturer/Supplier
TUF-MAX DOT Performance Plus DOT	ABC Polymer Industries, LLC
Masterfiber MAC 100	BASF Corporation
Bar Chip 48 (BC48)	Elasto Plastic Concrete
TUF-STRAND SF	Euclid Chemical Company
Forta Ferro Fiber	Forta Corporation
Novomesh 950 Fibermesh 650	Propex Operating Co., LLC
Strux 90/40	W.R. Grace and Co. - Conn.

2.5.3.3 New York

The New York DOT provided a list of its approved fibers for concrete reinforcement. An approved list, provided by William Cuerdon from NY DOT, is shown in Table 2.4. These fibers are also synthetic fibers.

Table 2.4 New York DOT's acceptable list of fibers for concrete reinforcement

Fiber Name	Manufacturer/Supplier
Fibermesh 300	Propex Concrete Systems
Fiberstrand F	Euclid Chemical Company
Fibrillated Polypropylene	The Fiber Depot
FIBRIL-TUF	ABC Polymer Industries, LLC Advanced Fiber Solutions, Inc.
FORTA Econo-Net FORTA Super-Net	FORTA Corporation
FRC FIB-300	FRC Industries
Genesis Fiber	Fabpro Performance Fibers
MasterFiber F70 MasterFiber F100	BASF Corporation
MATRIX Fibrillated Bi-Blend	FRC Industries
PolyMesh	O'Dea Concrete Products, Inc.
ProConF	Nycon, Inc.
Sika Fiber PPF	Sika Corporation
Strux 90/40 Grace Fibers	W.R. Grace and Company

2.5.3.4 Texas

The Texas DOT also provided specifications for the use of fibers in concrete, and which are available in Section 4550 of its Department Materials Specification. According to the Texas DOT, each of the four fiber classifications must conform to the following ASTM specifications:

- Synthetic fiber: ASTM C1116
- Steel fiber: ASTM A820
- Glass fiber: ASTM C1666
- Cellulose fiber: ASTM D7357

Also, Section 4550 sets a minimum average residual strength of 115 psi for any fiber dosage being used in curb, gutter, sidewalks, and/or riprap. The Materials and Pavements Section of the Construction Division of the Texas DOT must also test all fibers submitted to determine if they meet the average residual strength requirement mentioned above.

2.5.3.5 Washington

The Washington State DOT has some specifications pertaining to the use of synthetic structural fibers for precast units. These specifications can be found in Section 9-05.50(10) of the Standard Specifications for Road, Bridge, and Municipal Construction for the Washington State DOT. The current specifications for the use of synthetic structural fibers are as follows:

> Synthetic fibers shall be monofilament or monofilament/fibrillated blend made of polyolefin, polypropylene, or polypropylene/polyethylene blend, meeting the requirements of ASTM C 1116, Section 4.1.3, and ICC ES Acceptance Criteria 32, Sections 4.1.3 and 4.1.2. Additionally, the vendor or manufacturer must furnish an engineering report that provides test data in accordance with ASTM C 1018 and/or ASTM C 1399 from an ICC-qualified commercial laboratory relating to the specification requirements.
>
> The vendor or manufacturer shall provide a letter of certification stating compliance with specifications and/or standard codes.
>
> The fibers shall be a minimum of 2 inches in length and have an aspect ratio (length divided by the equivalent diameter of the fiber) between 70 and 100 when the fibers are in their final phase.
>
> The fibers shall have a minimum tensile strength of 50 ksi and a minimum modulus of elasticity of 600 ksi, when tested in accordance with ASTM D 3822.
>
> Precast drainage units shall have a minimum dosage rate of 3.75-lbs/cu yd. or more in order to obtain an Average Residual Strength (ARS) of 175 psi when tested in accordance with ASTM C 1018 and/or ASTM C 1399. The fiber supplier shall submit independent laboratory data to support ARS results.

2.5.3.6 Summary

Table 2.5 displays a summarized list of the material requirements that are set forth by the state DOT specifications discussed in the previous sections.

Table 2.5 Summary of material requirements specified by other state DOTs

	Georgia	Texas	Washington
Min. fiber Length	1.5 in.	-	2 in.
Aspect Ratio	45-150	-	70-100
Min. fiber Tensile Strength	40 ksi	-	50 ksi
Min. fiber Modulus of Elasticity	400 ksi	-	600 ksi
Min. Average Residual Strength	150 psi	115 psi	175 psi
Min. fiber Dosage	5 lb/yd^3	-	3.75 lb/yd^3
Max. fiber Dosage	10 lb/yd^3	-	-

3. SOUTH DAKOTA DOT INTERVIEWS

This section provides a summary of findings from personal interviews with SDDOT personnel who have past experience with FRC implementation. The main purpose of the interviews was to obtain information regarding current FRC specifications and applications, past experiences, performance enhancements or problems, and comments on potential adjustments in the use of FRC in SDDOT projects.

3.1 Introduction

In order to gain further knowledge on the use of FRC for structure components in South Dakota, interviews of select personnel within SDDOT were performed. Additionally, one employee from each of the Federal Highway Administration (FHWA) and the American Concrete Pavement Association (ACPA) were interviewed. A list of the selected interviewees is provided in Appendix B, along with a brief description of each person's job title/office. In addition to information on current SDDOT FRC practices, specifications, and applications, the interview questions (see Appendix B) covered topics such as the selection of fibers for an FRC mix design, the performance of previous structural FRC projects, the construction/demolition methods and complications for FRC applications, SDDOT's current FRC interests, and contact information for personnel outside of South Dakota with FRC experience. A summary of the results from the interviews is discussed throughout the following sections.

3.2 Previous Experience

FRC has been used for multiple applications within South Dakota, as discovered during the literature review and discussed during all the SDDOT interviews (Engbrecht, 2014; Flesner, 2014; Flottmeyer, 2014; Gilsrud et al., 2014; Grannes and Hodges, 2014; Hedman, 2014; Hrabanek, 2014; Johnston, 2014; Letcher, 2014; McMahon, 2014; Sauter, 2014; Strand et al., 2014; Whitney, 2014). Such FRC applications include bridge deck overlays, full-depth bridge decks, Jersey barriers, whitetopping, approach slabs, full-depth pavement, and pavement overlays. Table 3.1 is a summary of the various FRC applications that have previously been incorporated by SDDOT. Note that the percentages in this table add up to more than 100%. This is because some interviewees had experience with several applications. Therefore, there are more total answers than there are interviewees. This is also the case for both Table 3.2 and Table 3.4, discussed later.

Table 3.1 Percent of interviewees with previous experience with certain FRC applications

Application	Percent of Interviewed Personnel with Experience with the Application
Deck Overlay	69% (9/13)
Bridge Deck	23% (3/13)
Jersey Barrier	23% (3/13)
Approach Slab	15% (2/13)
Whitetopping	23% (3/13)
Full-depth Pavement	15% (2/13)
Pavement Overlay	7.7% (1/13)

FRC was used for these applications in order to enhance the structural performance and durability of the concrete, and to increase the life expectancy of the concrete. In some instances, FRC was utilized to evaluate the performance of 3M Polyolefin fiber, which was a new product at the time. The 3M Polyolefin fibers were used for all SDDOT projects in the 1990s while other fibers, such as WR

Grace's Strux 90/40 and Propex's Fibermesh 650, were introduced into bridge components in South Dakota in the early-to-mid 2000s (Gilsrud et al., 2014; Johnston, 2014; Sauter, 2014). Table 3.2 is a summary of the various fiber types that have previously been incorporated into applications within South Dakota. This table lists the percent of interviewed personnel with personal experience with each of the listed fibers.

Table 3.2 Percent of interviewees with previous experience with certain fibers

Fiber	Percent of Interviewed Personnel with Experience with the Fiber
3M Polyolefin	62% (8/13)
Strux 90/40	15% (2/13)
Fibermesh 650	31% (4/13)
Dramix RC-80/60	15% (2/13)

As shown in Table 3.2, SDDOT has predominantly used synthetic fibers (3M Polyolefin, Strux 90/40, Fibermesh 650) in its FRC applications. Some believe that this is due to concern over the susceptibility of steel fibers to corrosion. Additionally, they could cause a hazardous pavement surface to bike tires and bare feet (Hedman, 2014; Strand et al., 2014; Whitney, 2014). The main concern for the application of synthetic fibers was the fibers' high cost, which doubled the unit cost of the concrete at times (Engbrecht, 2014; Gilsrud et al., 2014; Hedman, 2014; Letcher, 2014; Whitney, 2014). For both synthetic fibers and steel fibers, the concrete mix was designed using the same procedure as conventional PCC, while at times the fine-to-coarse aggregate ratio would be increased to provide complete coating of cement on all the materials inside the concrete mix (Engbrecht, 2014; Strand et al., 2014). FRC applications have performed favorably within South Dakota so far, increasing the post-crack performance and decreasing the crack widths, when compared with PCC in similar applications (Engbrecht, 2014; Gilsrud et al., 2014; McMahon, 2014; Strand et al., 2014). Despite the increased performance, the drastic cost increase is a large concern commonly deterring more frequent use of FRC. Various suggestions regarding the cause of such cost increases were provided by six of the SDDOT employees (Gilsrud et al., McMahon, Flottmeyer, Sauter, Engbrecht, and Whitney [2014]), although they claimed to have limited previous experience with project costs. A summary of their responses is shown in Table 3.3.

Table 3.3 Proposed reasons for any increased cost during FRC applications

Personal Reasoning for Cost Increase	Percentage of Responses
Material costs	33% (2/6)
Labor costs	17% (1/6)
Bidding process (unfamiliarity with FRC)	33% (2/6)
Does not believe cost was increased	17% (1/6)

As shown in Table 3.3, the cost of the fibers themselves is believed to be one of the main reasons for the increase in construction costs of FRC applications. Therefore, it may be worthwhile to further investigate optimal fiber dosage to reduce the unit cost of FRC, which would increase the benefit-to-cost ratio and make FRC more efficient for use in structural components. A cost increase during the project bidding process was another common response by interviewees. However, this cost increase was believed to be due to unfamiliarity with FRC. This product unfamiliarity should diminish through time as FRC applications become more familiar to contractors.

3.3 Construction/Demolition

3.3.1 Mixing and Placement

To obtain the optimum performance of an FRC mix, the fibers need to be dispersed evenly with random orientation throughout the concrete matrix so as to create a three-dimensional reinforcement system for the concrete. In recent years in South Dakota, in order to allow adequate time for the bundles of fibers to disperse uniformly throughout the concrete, ready-mix trucks were used to mix and place the FRC. This mixing procedure is different than the normal method typically used for PCC, which uses a mobile-mixer (Grannes and Hodges, 2014; Johnston, 2014; Strand et al., 2014). Allowing longer mixing times did limit the occurrence of fiber balling, but did not always completely eliminate the problem. When FRC was utilized for a bridge deck overlay in South Dakota, a bridge deck paver was used rather than the commonly used low-slump paver (Flottmeyer, 2014; Gilsrud et al., 2014; Grannes and Hodges, 2014; Johnston, 2014).

3.3.2 Consolidation

Spud vibrators that are attached to the bridge deck pavers help to provide proper consolidation of FRC in bridge decks and also simplify the finishing process (Grannes and Hodges, 2014; Hrabanek, 2014; McMahon, 2014; Strand et al., 2014; Whitney, 2014). This is a common form of consolidation that is used for similar PCC applications. A fluid mix of FRC does not act the same as a fluid mix of PCC due to the fibers holding the fresh concrete together. Therefore, additional vibration is occasionally required for FRC (Gilsrud et al., 2014). Common concrete liquid admixtures, such as air entraining agents and water reducers, are often used in FRC mixes to enhance their workability (Flesner, 2014; Flottmeyer, 2014; Hrabanek, 2014; Johnston, 2014; Letcher, 2014).

3.3.3 Finishing

FRC components have often caused more complications than normal PCC components during finishing, tining, and dragging of the concrete. Fibers sticking out of the surface make it more difficult to provide a smooth finish to the concrete. Additionally, the decrease in workability makes it harder to move the concrete during finishing or while cutting down any bumps in the fresh pavement (Engbrecht, 2014; Hedman, 2014; Hrabanek, 2014; McMahon, 2014; Whitney, 2014). Common hand-tining techniques, where the tining rod is used with a “horizontal pulling motion,” often catch on fibers located on the surface (Engbrecht, 2014; Strand et al., 2014). Two other methods that have been utilized for tining are: (1) flipping the tining rod over and pushing down on any fibers at the top surface of the concrete so that the tines are created with more of a downward force rather than a pulling force (Johnston, 2014; Strand et al., 2014) and (2) machine grinding the tines into the concrete after hardening (Flesner, 2014; Flottmeyer, 2014; Grannes and Hodges, 2014). Both of these methods have been successful in recent years, although the method where the tines are ground into the hardened concrete requires much less experienced laborers than the method where the tines are hand tined with the tining rod flipped over (Strand et al., 2014). Lastly, a carpet drag does not work for FRC, as the carpet catches and pulls out the fibers that are at the surface of the concrete. As an alternative, contractors have used either a burlap drag or a broom to provide the required texture to the pavement without catching on the fibers (Flottmeyer, 2014; Johnston, 2014; Letcher, 2014; Strand et al., 2014).

3.3.4 Curing

Although fibers themselves assist in controlling cracking due to shrinkage, a curing procedure should also be performed for FRC components to retain moisture within the concrete and to limit the shrinkage cracking. Common curing techniques, such as covering a bridge deck overlay with wet burlap and plastic and using curing compound for pavement, are acceptable methods and have been deemed successful in past FRC applications in South Dakota (Engbrecht, 2014; Flesner, 2014; Flottmeyer, 2014; Grannes and Hodges, 2014; Hrabanek, 2014; Johnston, 2014; Letcher, 2014; Whitney, 2014).

3.3.5 Demolition

For demolition of FRC structures, disassembling the concrete can sometimes be difficult for contractors. SDDOT has previously used a hydraulic stinger on the end of an excavator to break apart an FRC overlay (Flesner, 2014). The fibers held the concrete together even when the concrete was being crushed, creating much larger pieces of concrete that needed to be cleaned up from the job site (Flesner, 2014; Grannes and Hodges, 2014; Johnston, 2014). This can cause delays in a project schedule and cost contractors additional time and money. However, demolition of an FRC whitetopping was performed by SDDOT with fewer difficulties, resulting in no additional cost or time (Strand et al., 2014). The teeth on an excavator bucket were used to get underneath the concrete and lift up the whitetopping. Personnel stated that the whitetopping came off the underlying asphalt relatively easily once they successfully got underneath the concrete layer. This shows that, depending on the procedure used, demolition of FRC overlays might not create any additional cost or time.

3.4 Current/Future Practice

As previously discussed, microfibers provide resistance to shrinkage cracking, while macro-fibers commonly enhance the structural performance. The majority of the interviewees believed that shrinkage cracking control is of more interest for SDDOT (Engbrecht, 2014; Flesner, 2014; Flottmeyer, 2014; Grannes and Hodges, 2014; Johnston, 2014; McMahon, 2014; Sauter, 2014; Strand et al., 2014), while Hrabanek (2014) believed that structural cracking control is of more interest since “shrinkage cracking should be able to be controlled by curing of the concrete.” Some potential FRC bridge components of interest to SDDOT commonly mentioned during the interviews are bridge deck overlays, bridge decks, and Jersey barriers (Engbrecht, 2014; Flesner, 2014; Gilsrud et al., 2014; Hrabanek, 2014; Johnston, 2014; Letcher, 2014; McMahon, 2014; Sauter, 2014; Strand et al., 2014). A summary of all the FRC applications mentioned as possible applications of interest in South Dakota is shown in Table 3.4.

Table 3.4 FRC applications recommended by the SDDOT interviewees

Bridge Component	Number of Times Mentioned
Deck Overlay	46% (6/13)
Bridge Deck	38% (5/13)
Jersey Barrier	23% (3/13)
Approach Slab	7.7% (1/13)
Column	7.7% (1/13)
Bent Cap	7.7% (1/13)
Abutment	7.7% (1/13)

Controlling cracking in components such as bridge decks, deck overlays, and Jersey barriers would help to reduce possible intrusion of water or de-icing chemicals that could cause harm to the pavement and reduce its durability and lifespan. FRC’s ability to control shrinkage cracking makes it a beneficial material for these applications.

3.5 Specifications

SDDOT currently does not have any FRC specifications. However, plan notes from previous SDDOT projects for FRC deck overlay and FRC pavement repair were provided (Grannes and Hodges, 2014). The FRC deck overlay plan notes were from a project constructed in 2013, while the plan notes for FRC pavement repair were from a project constructed in 2010. Also, interviewees provided personal recommendations on specifications that should be implemented by SDDOT.

3.5.1 Deck Overlay

The SDDOT plan notes for FRC deck overlay indicate the following:

> The FRC shall be Class A45 (f′c = 4500psi) and conform to Section 460 of the SDDOT Standard Specifications for Roads and Bridges document (SDDOT, 2015), except as modified by the plan notes. The FRC shall have a minimum thickness of 2 inches, be placed by a bridge deck finishing machine, contain 6.5 percent plus or minus 1.0 percent entrained air, and have a slump between 2.75 and 5.25 inches. The synthetic fiber-reinforcement shall be approximately 1.5 inches or longer (W.R. Grace - Strux 90/40 or approved equal) at an addition rate of 8 lb/yd^3. Also, the minimum coarse aggregate content shall be 48 percent of the total aggregate. The coarse aggregate shall conform to Size Number 3 gradation requirements of section 820 of the SDDOT Standard Specifications for Roads and Bridges document (SDDOT, 2015).

3.5.2 Pavement Repair

The SDDOT plan notes for pavement repair indicate the following:

> The FRC shall follow Section 380 of the SDDOT Standard Specifications for Roads and Bridges document (SDDOT, 2015) and the following requirements from the plan notes. The synthetic fiber-reinforcement shall be approximately 1.5 inches or longer (W.R. Grace - Strux 90/40 or approved equal) at an addition rate of 8 lb/yd^3. Also, the FRC shall contain 6.5 percent plus 1.0 percent or minus 1.5 percent entrained air and have a slump between 1.0 and 3.5 inches. Finishing machines equipped with surface vibrators shall be used to consolidate and finish the concrete surface. A rough broom finish or a rough burlap drag shall be applied as soon as the surface permits. The entire surface of the FRC shall be uniformly sprayed with a curing compound and then covered with wet burlap and plastic for a duration of 72 hours. The wet burlap and plastic cover shall be applied after the concrete has cured to the point of no indentation from burlap.

3.5.3 Future Specifications

Interviewees provided personal recommendations on FRC specifications that they believed SDDOT should implement. For material testing requirements, the main concern of those interviewed is to determine an acceptable slump for an FRC mix as it requires a larger slump than normal PCC due to its decrease in workability (Engbrecht, 2014; Gilsrud, 2014). For construction, concerns included the successful incorporation and distribution of fibers into the concrete during mixing (Engbrecht, 2014), acceptable pavement finishing and texturing techniques (Engbrecht, 2014; Letcher, 2014), and acceptable tining methods (Flesner, 2014; Johnston, 2014). Lastly, concerns about the FRC mix design included the selection procedure of fibers and the determination of an appropriate dosage rate (Gilsrud et al., 2014; Grannes and Hodges, 2014).

3.6 Fiber Suppliers and Types

Fiber manufacturers and/or suppliers in this region of the country were discussed during the interviews. Strux 90/40 from WR Grace and Fibermesh 650 from Propex are the only synthetic fibers that have been used in SDDOT FRC projects over the past decade (Engbrecht, 2014; Flottmeyer, 2014; Gilsrud et al., 2014; Grannes and Hodges, 2014; Johnston, 2014). Forta in Minneapolis, MN, is another fiber manufacturer that supplies concrete reinforcing fibers for this region (Gilsrud, 2014; Grannes and Hodges, 2014). For all of South Dakota's previous projects that incorporated fibers into the mix design, no interviewees were aware whether or not any of the claims regarding material performance made by the fiber manufacturers were assessed or verified by SDDOT (Engbrecht, 2014; Flesner, 2014; Flottmeyer, 2014; Grannes and Hodges, 2014; Johnston, 2014). The performance of a concrete mix containing a particular fiber is often provided on the fiber's data sheet. Therefore, a possible method for assessing these manufacturer claims would be to perform the test method specified on the data sheet and compare the two results (Grannes and Hodges, 2014).

Very limited knowledge on any new fiber technology introduced to structural applications within the past five to10 years was provided during the interviews. The only exception is the institution of some new shapes of steel fibers (Flesner, 2014). The different types of FRC discussed during the interviews were ECC, hybrid FRC, and ultra-high-performance concrete (UHPC). No interviewees had any personal experience or knowledge about any of these types of FRC since they were never implemented within South Dakota (Engbrecht, 2014; Flesner, 2014; Flottmeyer, 2014; Gilsrud et al., 2014; Grannes and Hodges, 2014; Hrabanek, 2014; Johnston, 2014; Letcher, 2014; Sauter, 2014; Whitney, 2014).

4. OTHER STATE DOT INTERVIEWS

This section provides a summary of findings from personal interviews with DOT personnel outside of South Dakota who have experience with FRC implementation. The interviews provided information on FRC specifications, current and past FRC applications, and performance of existing FRC components.

4.1 Introduction

In order to further investigate the use of FRC for structural components around the country, interviews were conducted with selected personnel throughout the country. Employees from various state DOT agencies outside of South Dakota were contacted. Additionally, fiber manufacturer employees were also interviewed for additional information about FRC. The focus was placed on DOTs from states in the region surrounding South Dakota that had previous experience with FRC. Appendix C lists the selected interviewees, along with their respective agencies. The interview questions for these state DOT employees were very similar to those directed to the SDDOT employees. The questionnaire is presented in Appendix C. Each interview covered the following topics: the process of selection of fibers and dosage rates for an FRC mix design, the performance of previous structural FRC projects, the construction/demolition methods and complications for FRC applications, current specifications for FRC within each state, and contact information for additional personnel with FRC experience. Select questions related to the selection of fibers and design of FRC were used for the fiber manufacturer employee interviews. A summary of the results from the interviews is discussed throughout the following sections.

4.2 Previous Experiences with FRC

During the state DOT interviews, the various applications for FRC throughout the country were discussed. These FRC applications are listed in Table 4.1.

Table 4.1 FRC applications discussed with interviewees from other DOTs

Application	State
Bridge Deck Overlays	Illinois (Krstulovich, 2014) California (Maggenti et al., 2013)
Whitetoppings	North Dakota (Schumaker, 2014)
Approach Slabs	California (Maggenti et al., 2013)
Pre-stressed Girders	Iowa (Abu-Hawash, 2014; Bierwagen, 2014)
Girder Connections	Michigan (Juntunen, 2014)
PCC Pavement Overlays	Iowa (Hanson, 2014) Illinois (Krstulovich, 2014) Minnesota (Izevbekhai, 2014)

The following is a list of specific benefits that can be provided by fibers according to interviewees.

- FRC was used in pre-stressed girders and girder connections to decrease the permeability and improve the durability of the concrete (Abu-Hawash, 2014).
- FRC was implemented to investigate the possibility of decreasing the concrete thickness of overlays without compromising performance and durability (Izevbekhai, 2014; Schumaker, 2014).
- Fibers in concrete tend to hold smaller pieces of loose concrete together, while traditional steel reinforcement bars present more “gaps” in the concrete, thereby providing more areas where

loosened concrete can completely detach from the rest of the concrete matrix (MacDonald, 2014).

- FRC was used in deck overlays and full-depth bridge decks to mitigate early age cracking due to shrinkage of the concrete (Maggenti et al., 2013).

These benefits present a material that could be extremely beneficial for any type of pavement surface (such as deck overlays and approach slabs) where resistance to concrete deterioration is an important factor in the performance of the concrete element.

Various types of FRC were used in the applications. Conventional FRC was most commonly used throughout all the interviewees' experiences. Ultra-high-performance concrete (UHPC) was occasionally used, while steel FRC was utilized in some approach slabs. When the term "conventional FRC" is used in the following sections, it refers to an FRC mix containing common concrete materials (i.e., cement, coarse aggregate, fine aggregate, water, air entraining agent, and water-reducer) along with synthetic concrete reinforcing fibers. UHPC is used to refer to an FRC mix that does not contain any coarse aggregate and uses steel fibers rather than synthetic fibers. This mix is designed to provide enhanced properties such as compressive strength, permeability, and durability.
For conventional FRC:

- Structural macro-synthetic fibers seemed to work better than the microfibers when used for a pavement overlay (Hanson, 2014).
- The structural macro-fiber is a better fiber selection than the smaller microfiber for transportation applications (Mahoney, 2014).
- The polyvinyl alcohol (PVA) fibers used by the Minnesota DOT in an overlay application were found to be inadequate for reducing the thickness of an overlay (Izevbekhai, 2014).

For UHPC:

- The cost was estimated to be at least two to three times more expensive than PCC (Abu-Hawash, 2014; Juntunen, 2014).
- The use of UHPC in smaller, critical applications, such as girder connections/joints and concrete repairs, seemed to justify the increased cost (Abu-Hawash, 2014; Juntunen, 2014).
- The use of UHPC in pre-stressed girders enhanced concrete durability and decreased permeability (Bierwagen, 2014).

For steel FRC:

- The use of steel fibers in concrete for approach slabs provided some complications. The fibers did not disperse well during mixing, and the sharp fibers presented dangerous conditions during finishing and on the surface of the hardened pavement (Maggenti et al., 2013).

4.3 Preparation and Placement of FRC

4.3.1 Mixing

Consistent with the findings of the literature review and SDDOT interviews, mixing is a crucial process that must be performed adequately to obtain a fully functional FRC mix. Occasional balling of fibers occurs during the mixing process (Maggenti et al., 2013). Additional mixing is often required to allow for the fiber packaging to completely break open and to prevent fiber balling (Hanson, 2014; Schumaker, 2014). Krstulovich (2014) mentioned one method he had previously witnessed that would eliminate the concern over whether the fiber packaging would open or not. In this method, a worker would take handfuls of fibers out of the packaging and manually add them to the mixer rather than adding the entire packaging at once. For UHPC, mixing differs from that of conventional FRC. UHPC must be mixed in smaller batches than conventional FRC, which generally slows the construction time (Abu-Hawash, 2014; Juntunen, 2014). There is, therefore, a need for a method to mix UHPC in larger batches to reduce construction time and cost (Juntunen, 2014).

4.3.2 Placement

Placement of conventional FRC for pavements and overlays does not generally differ from placement of PCC for similar applications (Izevbekhai, 2014; Krstulovich, 2014). However, conventional FRC and UHPC seemed to require completely different efforts during placement. UHPC must be treated like self-consolidating concrete (SCC), since it is a very easy flowing concrete (Abu-Hawash, 2014; Bierwagen, 2014). The concrete forms must be very tight to prevent any leakage during placement. While a UHPC mix is generally an easy flowing mix, conventional FRC occasionally sticks together to the point that pitchforks are used to move the concrete instead of shovels (Schumaker, 2014). Caltrans occasionally has concrete contractors perform a trial batch of FRC placement in order to become familiar with the concrete workability. The trial batch is placed in a small section off to the side of the construction site. This allows the contractors to practice their placement, consolidation, and finishing methods with FRC prior to constructing the deck overlay or any other components. Also, there are no differences in placement methods between FRC and PCC for deck overlays, full-depth bridge decks, or approach slabs (Maggenti et al., 2013).

4.3.3 Consolidation

As previously mentioned, UHPC must be treated similarly to SCC; therefore, consolidation is not required (Abu-Hawash, 2014; Bierwagen, 2014; Juntunen, 2014). On the other hand, conventional FRC requires some form of consolidation. Internal vibration has previously been successful using hand-held spud vibrators (Krstulovich, 2014; Schumaker, 2014). The consolidation methods performed for PCC components should be the same for similar components of FRC (Maggenti et al., 2013).

4.3.4 Finishing

Although conventional FRC and UHPC require different placement and consolidation techniques, they typically require the same amount of effort for finishing. Finishing FRC is performed using the same equipment and techniques for PCC, but requires more energy to move the concrete and to get the desired smooth surface. A turf drag cannot be used with FRC, as the fibers tend to catch and ball up on the turf (Hanson, 2014; Krstulovich, 2014). Alternatively, a rough broom finish should be utilized, in one direction only, instead of the turf drag (Krstulovich, 2014; Najjar, 2014). Macro synthetic fibers commonly protrude from the surface of the hardened concrete, but they eventually break off by the daily traffic driving over the top of the fibers (Maggenti et al., 2013).

4.3.5 Curing

Similar to the information obtained during the literature review and SDDOT interviews, curing techniques for FRC do not differ from those of PCC (Izevbekhai, 2014; Maggenti et al., 2013). Also, the admixtures used in the conventional FRC mix for the various applications did not differ from those of PCC (Hanson, 2014; Izevbekhai, 2014; Schumaker, 2014). Caltrans were able to reduce early-age cracking in FRC deck overlays and full-depth decks through the utilization of shrinkage-reducing admixture (SRA) and water-reducing admixture (WRA) along with both synthetic microfibers and synthetic macro fibers (Maggenti et al., 2013). The hybrid FRC mix contained 0.5 lb/yd^3 of synthetic microfibers and 3 lb/yd^3 of synthetic macrofibers. Caltrans believes that the combination of fibers, SRA, and WRA results in a very good concrete mix that can successfully mitigate early-age cracking.

4.3.6 Demolition

It is sometimes significantly more difficult to break apart and remove FRC structures due to the fibers holding the concrete together (Maggenti et al., 2013). However, Caltrans did not mention any specific changes in methods or equipment that must be used to demolish FRC structures. All other interviewees stated they had no previous experience or knowledge of demolition of any FRC application. This is most likely because most of the applications discussed during the interviews were constructed within the past decade and have not yet reached the end of their lifetime.

4.4 Specifications

Since FRC is not yet used as commonly as PCC for structural bridge components throughout the country, specifications are not as well established. Minnesota, Iowa, and North Dakota DOTs do not currently have specifications regarding FRC for structural bridge components (Izevbekhai, 2014; Hanson, 2014; Schumaker, 2014). However, the Illinois DOT provided some special provisions currently in use for various bridge deck overlays (Krstulovich, 2014). These special provisions are as follows:

> For fly ash or ground granulated blast-furnace (GGBF) slag bridge deck overlays, fibers could be included as follows:
>
> When specified on the plans, synthetic fibers shall be added to the concrete and mixed per the manufacturer's recommendation. The fibers shall be from the 'Approved List of Synthetic Fibers' except the maximum length of the fiber shall be 1.75 inches (45 mm). Synthetic fibers shall be added at a rate of 3.0 lbs/cu yd (1.8 kg/cu m). A 2 cu yd (1.5 cu m) trial batch shall be performed to evaluate the mixture for strengths and other properties. Samples for testing will be done by the Department. The trial batch shall be placed in a 12 ft. x 12 ft. (3.6 m x 3.6 m) slab or other configuration approved by the Engineer to evaluate the mixture for fiber clumping, ease of placement, and finishing. Based on the trial batch, the Department has the option to reduce the weight (mass) of fibers to be added to the concrete mixture.
>
> For latex concrete bridge deck overlays, fibers could be included as follows:
>
> Synthetic fibers shall be Type III according to ASTM C 1116. The synthetic fiber shall be a monofilament with a minimum length of 0.5 in. (13 mm) and a maximum length of 2.5 in. (63 mm), and shall have an aspect ratio (length divided by the equivalent diameter of the fiber) between 70 and 100. The synthetic fiber shall have a minimum toughness index I20 of 4.5 according to Illinois Modified ASTM C 1018.
>
> The synthetic fibers shall be added to the concrete and mixed per the manufacturer's recommendation. The dosage rate shall be 2.0 lb/cu yd (1.2 kg/cu m).
>
> The department will maintain an 'Approved List of Synthetic Fibers.'
>
> For microsilica (i.e., silica fume) bridge deck overlays, fibers could be included as follows:
>
> Synthetic fibers shall be Type III according to ASTM C 1116. The synthetic fiber shall be a monofilament with a minimum length of 0.5 in. (13 mm) and a maximum length of 2.5 in. (63 mm), and shall have an aspect ratio (length divided by the equivalent diameter of the fiber) between 70 and 100. The synthetic fiber shall have a minimum toughness index I20 of 4.5 according to Illinois Modified ASTM C 1018.

> The synthetic fibers shall be added to the concrete and mixed per the manufacturer's recommendation. The dosage rate shall be 2.4 lb/cu yd (1.2 kg/cu m).
>
> The department will maintain an 'Approved List of Synthetic Fibers.'

Illinois is currently attempting to standardize the above special provisions. The guidelines for the selection of a fiber in these provisions are based on the fiber length, the aspect ratio, and the toughness index (I20). These are helpful guidelines since the length and aspect ratio of a fiber can easily be determined, while the toughness index may be calculated using ASTM C1609, which is an accepted material testing standard for FRC. MacDonald (2014) agreed that a fiber's dimensions should be specified by the length and aspect ratio without including the equivalent diameter. He also discussed how the risk of fiber distribution problems is generally introduced when the aspect ratio of a fiber reaches a value greater than 100.

Caltrans commonly specifies a desired fiber material (e.g., synthetic or steel), size range, and other properties instead of specifying a specific fiber or manufacturer to be used (Maggenti et al., 2013). Caltrans believes this is the best practice for specification of fiber type because it provides contractors with the option to choose a fiber they may be more familiar with, as long as the fiber fits the specified requirements (e.g., material and size).

4.5 Fiber Suppliers and Types

Fibers that have previously been used to reinforce concrete in the region surrounding South Dakota are of interest for the experimental testing portion of this research. Therefore, the fiber manufacturers and fiber types that were used in the previous applications were also discussed during these interviews.

- For UHPC, the fiber manufacturer used by Iowa and Michigan was Lafarge, which is the company that provides the Ductal concrete mix that formulates UHPC (Abu-Hawash, 2014; Juntunen, 2014).
- Minnesota DOT (MNDOT) used synthetic fibers from Propex in a successful 2013 project investigating advantages in load transfer and slab capacity. They also used polyvinyl alcohol fibers in an unsuccessful 2011 pavement overlay project. The experience with the polyvinyl alcohol fibers in MNDOT's study was not very encouraging because the material did not demonstrate high flexural strength and ductile behavior as desired (Izevbekhai, 2014).
- Three types of fibers from W.R. Grace were used in pavement overlay applications in Iowa. They were polypropylene fibrillated fibers, polypropylene monofilament fibers, and structural synthetic fibers. The structural fibers performed the best out of the three fibers (Hanson, 2014).
- A link to Illinois DOT's "Approved Product List" for synthetic fibers was provided (Krstulovich, 2014). The fibers listed in this document for pavement overlays are shown in Table 4.2.

Table 4.2 Illinois DOT's Approved Product List for synthetic fibers for PCC pavement inlays or overlays

Manufacturer	Fiber	Dosage Rate
ABC Polymer Industries	TUF-MAX DOT	4.5 lb/yd^3
BASF Corporation	Masterfiber Mac Matrix	4 lb/yd^3
The Euclid Chemical Company	TUF-STRAND SF	5 lb/yd^3
General Resource Technology	Advantage Structural Fiber	4 lb/yd^3
W.R. Grace and Company	Strux 90/40	4 lb/yd^3
Propex	Fibermesh 650	5 lb/yd^3

Some of the interviewees from the fiber manufacturers also provided their input on fiber candidates. The following advice for fiber selection was provided:

- The FORTA-FERRO fiber provided by Forta Corporation is generally its recommended fiber for deck overlay applications (MacDonald, 2014).
- The Euclid Chemical Company has multiple fiber options, depending on the desired application. For shrinkage control, a synthetic fibrillated fiber at approximately 1 to 1.5 lb/yd^3 is recommended. If a structural macro-fiber is desired, the TUF-STRAND SF fiber is recommended. The following dosage rates for the TUF-STRAND SF fiber were also recommended (Mahoney, 2014):
    - For non-structural use (temp/shrinkage only): 3 - 5 lb/yd^3
    - For full-depth pavement: 8 - 9 lb/yd^3
- There are various fiber selections provided by W.R. Grace. The most commonly recommended and used structural fiber produced by W.R. Grace is the Strux 90/40 fiber. A newer fiber, which is similar in cost and performance to Strux 90/40, named Strux BT50, is another option from W.R. Grace. Strux BT50 is 2 inches long, which is longer than the 1.55-inch long Strux 90/40. The new fiber also has an aspect ratio of 75, which is less than the aspect ratio of 90 for Strux 90/40. Strux 90/40 should be used for a lower dosage rate, while Strux BT50 should be used for a higher dosage rate. Dosage rates higher than 8 lb/yd^3 of Strux 90/40 may potentially cause trouble with fiber distribution (Durning, 2014).

The information gained regarding common fibers utilized by states in the surrounding region was used in selecting the fibers evaluated during the experimental testing task of this research. Only fibers that have shown potential for use in structural components in the surrounding region were selected. The selection of the fibers is discussed in more detail in Section 5.

5. METHODOLOGY

This section discusses the experimental laboratory testing plan for this study. The testing plan implemented standard ASTM and ACI testing procedures. A select list of candidate fibers with potential suitability for use in structural applications in South Dakota was investigated. The purpose of the experimental work was to perform material testing of multiple FRC mix designs to identify the optimal fiber dosage necessary to achieve required strength with minimal cost, assess material properties and protocols for performance testing, and verify the manufacturers' reported performance of their products. Candidate fibers were selected based on the results obtained from the literature review and DOT interviews. Various standard material tests were selected based on the intended use of FRC in South Dakota bridges.

5.1 Selection of Fibers

Fibers were selected based on their usage in structural bridge components. To provide a variety of FRC designs, five different fibers were selected. Considering their non-corrosive behavior, synthetic fibers are of more interest to states such as South Dakota that experience extreme weathering conditions from freezing winter climates. Therefore, it was determined that four of the five selected fibers would be synthetic fibers and the final fiber would be steel. Table 5.1 shows the five fibers that were selected, along with the fiber manufacturer and certain properties for each. Figure 5.1 through Figure 5.5 illustrate images of each of the selected fibers.

Table 5.1 List of selected fibers for experimental evaluation

Fiber	Strux 90/40	Fibermesh 650	TUF-STRAND SF	FORTA-FERRO	Dramix 5D
Manufacturer	W.R. Grace	Propex Fibermesh	Euclid Chemical Company	Forta Corporation	Bekaert
Fiber Class	Synthetic	Synthetic	Synthetic	Synthetic	Steel
Length (in)	1.55	1.5 - 1.75 blend	2.0	2.25 - 1.5 blend	2.4
Equivalent Diameter (in)	0.017	0.016 - 0.018	0.027	0.028, 0.019	0.04
Aspect Ratio*	90	96.5	74	79.5	65
Specific Gravity	0.92	0.91	0.92	0.91	7.85
Tensile Strength (ksi)	90	89	87 - 94	83 - 96	333.5
Modulus of Elasticity (ksi)	1,378	1,088	1,380	690	30,000
Recommended Dosage Rate (lb/yd^3)	3 - 12	3 minimum	3 - 20	3 - 30	25 minimum
Manufacturer Recommended Applications	Overlays, Slab-on-grade, Pavements, Composite steel floor decks	Overlays, Slab-on-grade, Pavements, Composite metal decks	Toppings, Slab-on-grade, Pavements, Thin walled pre-cast	Bridge decks, Industrial floors, Pre-cast products, Shotcrete	Bridges, Structural floors, Foundation slabs
Cost ($/lb)	6.00 **	5.00 **	6.00 **	5.00 **	1.19

* Aspect Ratio = fiber length divided by equivalent fiber diameter

** Cost was estimated by fiber manufacturers based on typical material and labor costs

Figure 5.1 Strux 90/40 fibers, manufactured by W.R. Grace

Figure 5.2 Fibermesh 650 fibers, manufactured by Propex

Figure 5.3 TUF-STRAND SF fibers, manufactured by The Euclid Chemical Company

Figure 5.4 FORTA-FERRO fibers, manufactured by Forta Corporation

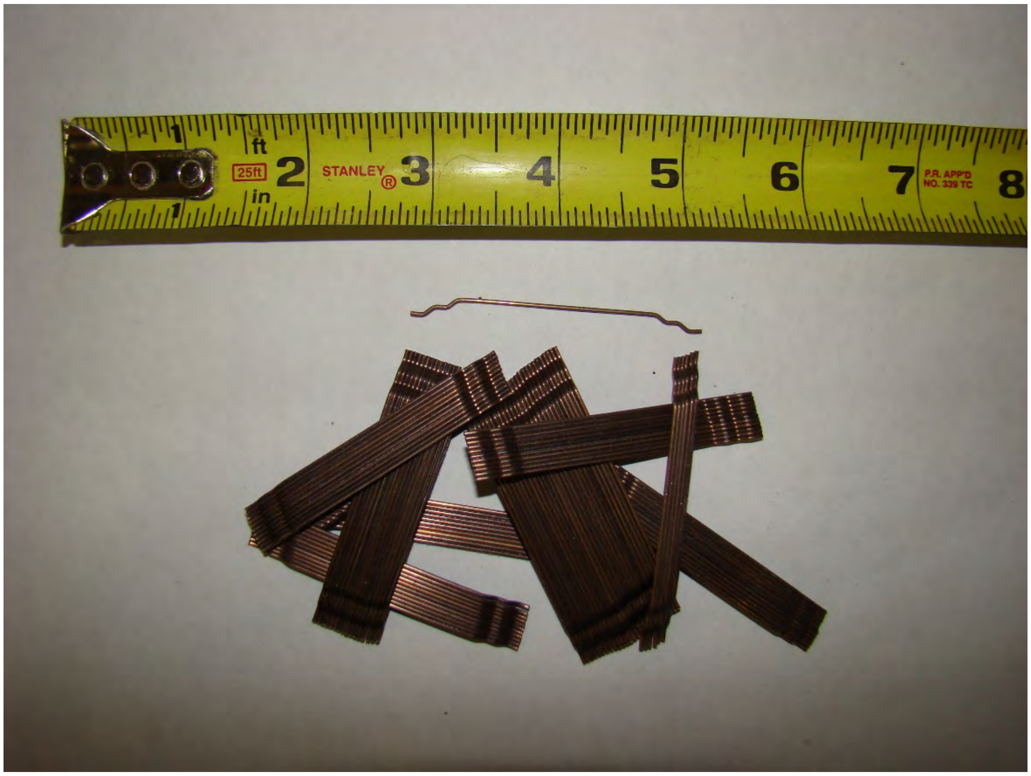

Figure 5.5 Dramix 5D fibers, manufactured by Bekaert

Both Strux 90/40 and Fibermesh 650 have been recently used by SDDOT in applications, such as deck overlay and full-depth pavement, within South Dakota, as discussed during the SDDOT interviews. In addition, Strux 90/40 was the most commonly used fiber throughout the United States, based on the DOT interviews.

TUF-STRAND TF, manufactured by the Euclid Chemical Company, provides a fiber with a tensile strength and modulus of elasticity similar to that of Strux 90/40. However, TUF-STRAND SF is 2 inches long, which is longer than the 1.55-inch-long Strux 90/40. The longer length presents a larger surface area per fiber. A greater surface area is expected to potentially increase the fiber's post-crack load-carrying capacity by increasing the fiber's pull-out strength. This can be investigated by comparing test results for the different fibers using tests such as ASTM C1399 and ASTM C1609, which evaluate the post-crack load-carrying capacity of an FRC specimen in flexure. Post-crack load-carrying capacity of FRC is important in applications such as bridge decks, deck overlays, and approach slabs where the size of cracks in the concrete should be minimized to decrease the possibility of intrusions.

Forta Corporation provides the FORTA-FERRO fiber. Similar to Strux 90/40, FORTA-FERRO is a synthetic fiber, but consists of a blend of two different fiber geometries: (1) a twisted bundle fiber where multiple macro synthetic fibers are twisted together to act as one larger fiber, and (2) a network fiber that is a mesh of thinner fiber sections. The two different fiber geometries result in a type of hybrid FRC mix, where more than one size of fiber is used in a concrete mix. A HyFRC mix containing polyvinyl alcohol microfibers, steel microfibers, and steel macro fibers was previously investigated (Ostertag and Blunt, 2008). When compared with plain concrete approach slabs, they found that this HyFRC mix provided enhanced post-crack flexural stiffness and spalling resistance in bridge approach slabs. Since SDDOT has never previously implemented a HyFRC design, FORTA-FERRO is a potential future alternative for use in structural bridge components. Therefore, investigation of this fiber was deemed beneficial by the research team.

Finally, the Dramix 5D steel fiber from Bekaert was selected based on the results from the literature review. Bekaert steel fibers were previously used by SDDOT in concrete pavement (Ramakrishnan, 1997) and by the Missouri DOT (MoDOT) in an unbonded pavement overlay (Chojnacki, 2000). The Dramix ZC 60/80 steel fibers used in both cases provided enhanced properties such as toughness, impact, fatigue, and post-crack load-carrying capacity. However, Dramix ZC 60/80 fiber is an old product that Bekaert no longer produces. This fiber was recently replaced with a group of three different fibers: Dramix 3D, Dramix 4D, and Dramix 5D. The differences among these three fibers, shown in Figure 5.6, are the number of bends at the end of each fiber, which results in varying anchorage actions. Dramix 3D has two bends at each end of the fiber, Dramix 4D has three bends at each end, and Dramix 5D has four bends at each end. The anchorage efficiency increases with an increase in the number of bends. Therefore, Dramix 5D provides the largest amount of anchorage among the three Dramix steel fibers.

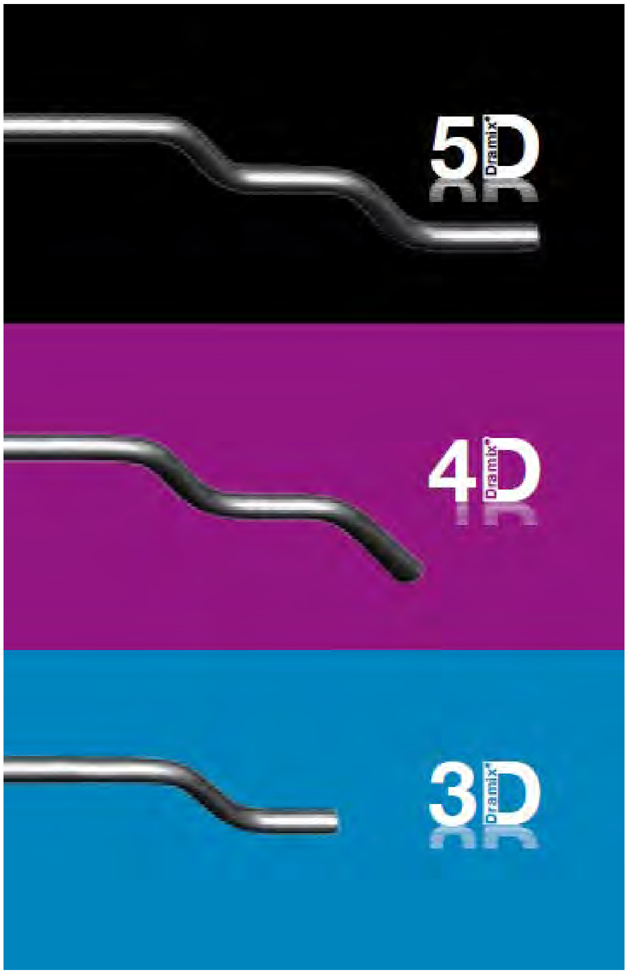

Figure 5.6 Three types of Dramix steel fibers available from Bekaert

The varying amount of anchorage provided by these three fibers results in different properties and, therefore, different applications for each fiber. Based on Bekaert's recommendation regarding usage of Dramix 5D for bridge components, this fiber was selected to be evaluated during the experimental testing.

Fiber data sheets for each of the selected fibers are provided in Appendix D. These data sheets provide additional information, including properties for the fibers, common applications, and results from various ASTM standard tests.

5.2 Materials and Mix Design

All mixes in this study utilized Type I/II cement, which was supplied by the Dacotah Cement plant in Rapid City, SD. Headwaters supplied Class F fly ash, which was used in all mixes. Quartzite coarse aggregate was obtained from the West Quarry in Dell Rapids, SD. It had a specific gravity of 2.639 and an absorption of 0.27%. The natural sand was supplied by L.G. Everist, Inc., located in Brookings, SD. It had a specific gravity of 2.645 and an absorption of 1.2%. Chemical admixtures were supplied by Grace Construction Products. The air entraining agent was Daravair M while the water reducer was WRDA 82. The data sheets for these admixtures can be found in Appendix E.

The FRC mixes for all the testing samples were designed according to Section 460 of the SDDOT Standard Specifications for Roads and Bridges document (SDDOT, 2015). Additionally, SDDOT provided a mix design for structural concrete that was previously used and met all of the requirements specified by Section 460. The w/c was 0.38. The water proportion was adjusted based on the coarse and fine aggregates moisture contents, which were determined according to ASTM C566. The mix design is shown in Table 5.2.

Table 5.2 FRC mix design for all mixes

Material	Proportion
Type I/II Cement	524 lb/yd^3
Class F Fly Ash	131 lb/yd^3
Coarse Aggregate	1620 lb/yd^3
Fine Aggregate	1300 lb/yd^3
Water	250 lb/yd^3
Air Entraining Agent	0.62 oz/cwt
Water-Reducer	3.6 oz/cwt

The specified concrete material proportions were used for a control mix and for mixes containing each of the fibers discussed in Section 5.1. The control mix consisted of the same material proportions shown in Table 5.2, but without reinforcing fibers. During experimental testing, the proportions were kept the same for each concrete mix. Therefore, the only difference from one batch to the other was the fiber type and the fiber dosage rate, which allowed the research team to compare the performance of different fibers at varying dosage rates. Four dosage rates were selected for each fiber. To evaluate the performance of the least expensive alternative, the minimum recommended dosage rate by manufacturer was used for each fiber. The remaining dosage rates were then selected based on previous successful dosages, as discovered from the literature review, agency interviews, and fiber manufacturer recommendations. The selected dosage rates for each of the fibers are shown in Table 5.3.

Table 5.3 Proposed dosage rates for each fiber

Fiber	Dosage 1	Dosage 2	Dosage 3	Dosage 4
Strux 90/40	3 lb/yd^3 (0.21%)	5 lb/yd^3 (0.34%)	8 lb/yd^3 (0.55%)	10 lb/yd^3 (0.69%)
Fibermesh 650	3 lb/yd^3 (0.21%)	5 lb/yd^3 (0.35%)	8 lb/yd^3 (0.56%)	10 lb/yd^3 (0.69%)
TUF-STRAND SF	3 lb/yd^3 (0.21%)	5 lb/yd^3 (0.34%)	8 lb/yd^3 (0.55%)	10 lb/yd^3 (0.69%)
FORTA-FERRO	3 lb/yd^3 (0.21%)	5 lb/yd^3 (0.35%)	8 lb/yd^3 (0.56%)	10 lb/yd^3 (0.69%)
Dramix 5D	25 lb/yd^3 (0.20%)	45 lb/yd^3 (0.36%)	65 lb/yd^3 (0.53%)	85 lb/yd^3 (0.69%)

The percentage shown for each dosage rate in Table 5.3 is the volume fraction of fibers incorporated into the concrete mix. Note that this volume fraction is relatively consistent for each of the various fibers, which allowed for comparison between the mixes containing different fibers. This percentage is defined as the ratio of the volume of fibers to the total volume of the composite concrete mix (Abdalla, et al., 2008). Therefore, the equation (Equation 1) to determine the volume fraction of fibers can be written as follows:

$$V_f = \frac{V_{fib}}{V_{total}} = \frac{V_{fib}}{V_{mat} + V_{fib}} = \frac{(m_{fib}/\rho_{fib})}{(m_{mat}/\rho_{mat}) + (m_{fib}/\rho_{fib})} = \frac{(m_{fib})(\rho_{mat} * \rho_{fib})}{\rho_{fib}(m_{mat} * \rho_{fib} + m_{fib} * \rho_{mat})}$$

$$\therefore V_f = \frac{(m_{fib})(\rho_{mat})}{(m_{mat})(\rho_{fib}) + (m_{fib})(\rho_{mat})} \qquad \text{Equation 1}$$

Where:

$V_f = volume\ fraction\ of\ fibers$

$V_{fib} = volume\ of\ fibers$

$m_{fib} = mass\ of\ fibers\ [lb]$

$\rho_{fib} = density\ of\ fibers\ \left[{}^{lb}/_{yd^3}\right]$

$V_{mat} = volume\ of\ concrete\ materials\ (excluding\ fibers)$

$m_{mat} = mass\ of\ concrete\ materials\ [lb]$

$\rho_{mat} = density\ of\ concrete\ materials\ \left[{}^{lb}/_{yd^3}\right]$

The volume fraction of fibers is a measurement that is widely used for specifying the fiber dosage rate.

5.2 Laboratory Tests

The tests that were selected in this study are shown in Table 5.4.

Table 5.4 Selected material tests

Type of Test	Test Name	Standard/Source
Fresh Concrete	Density (Unit Weight)	ASTM C138
	Slump of Hydraulic-Cement Concrete	ASTM C143
	Air Content of Freshly Mixed Concrete by the Pressure Method	ASTM C231
	Temperature of Freshly Mixed Hydraulic-Cement Concrete	ASTM C1064
Hardened Concrete	Compressive Strength of Cylindrical Concrete Specimens	ASTM C39
	Average Residual-Strength of Fiber-Reinforced Concrete	ASTM C1399
	Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)	ASTM C1609
	Drop-Weight Impact Test	ACI Comm. 544
	Fiber Distribution Verification	N/A

The testing procedures for each fresh concrete and hardened concrete specimen are discussed in Section 5.3.2 and Section 5.3.3, respectively.

5.3.1 Sample Preparation

Each specimen was prepared according to ASTM C192 and ACI Committee 544 (1988). ASTM C192 provided basic concrete sample preparation while ACI Committee 544 provided various alterations that should be followed when working with FRC. The following sections discuss the standard methods that were used for mixing, placing, consolidating, and curing each specimen, along with any alterations in procedures that are specified by ACI Committee 544.

5.3.1.1 Mixing

Concrete mixing was performed in the concrete laboratory in Crothers Engineering Hall on the campus of SDSU. A ½-cubic yard electric concrete drum mixer was used and is shown in Figure 5.7.

Figure 5.7 1/2-cubic yard capacity concrete drum mixer

As determined from the literature review and SDDOT interviews, there are limited differences between mixing Portland Cement Concrete (PCC) and FRC. Currently, there is no specific method for mixing FRC. Therefore, the method specified by ASTM C192 for mixing PCC was used for mixing the FRC batches and the fibers were added to the mix at the end of the procedure, as recommended by fiber manufacturers. Once all the other concrete materials were mixed together as specified by ASTM C192, the fibers were added to the mixer and allowed additional mixing time. The mixing procedures adopted are as follows:

1) Allow for 10% excess of concrete after molding the test specimens.
2) Add air entrainment to the mixing water.
3) Prior to starting rotation of the mixer, add the coarse aggregate and approximately one-third of the mixing water.
4) Start the mixer, then add the fine aggregate, cement, fly ash, and remaining water with the mixer running.
5) After all of the ingredients are in the mixer, mix for three minutes.
6) Stop the mixer and allow the concrete to rest for three minutes.
7) Prior to starting the mixer, add the fibers (if applicable) by evenly distributing them above the surface of the resting concrete (shown in Figure 5.8).
8) Start the mixer, then add the water reducer with the mixer running, and mix for 5 minutes.

Figure 5.8 Distribution of fibers on the surface of the resting concrete, prior to the final five minutes of mixing

The specified mixing time following the addition of fibers was determined based on manufacturer recommendations. The recommended additional mixing times were obtained from data sheets for the selected fibers on the manufacturers' webpages, and are as follows.

- Strux 90/40: Minimum of 70 revolutions
- Fibermesh 650: At least 5 minutes
- TUF-STRAND SF: Minimum of 3-5 minutes
- FORTA-FERRO: 4-5 minutes

The maximum required mixing time specified among all the manufacturers was selected in order to satisfy each recommendation. Therefore, a required additional mixing time of five minutes was adopted, as previously stated.

5.3.1.2 Placement

According to ACI Committee 544, internal or external vibration must be used for consolidating FRC specimens to avoid preferential fiber alignment and non-uniform distribution of fibers. However, rodding was used for the fresh concrete tests, as per ASTM Standards (Figure 5.9).

Figure 5.9 Rodding during a concrete slump test

ACI Committee 544 adopts the ASTM C143 (2012) procedure for determining the concrete slump. For the rest of the experimental tests, which are listed in Table 5.4, ASTM C192 specifies the amount of lifts that should be used for filling specimen forms of different shapes and dimensions. Table 5.5 displays the number of lifts used for each test.

Table 5.5 Number of lifts required for each experimental test

	Specimen Shape and Dimensions	Number of Lifts Required
Slump	Standard slump cone	3
Air Content	Standard air content measure	3
Compressive Strength	6″ x 12″ cylinder	2
Impact Strength	6″ x 12″ cylinder	2
Flexural Performance	6″ x 6″ x 22″ beam	1
Average Residual Strength	4″ x 4″ x 14″ beam	1

5.3.1.3 Consolidation

As previously discussed, internal or external vibration must be used when consolidating a specimen for hardened concrete testing. ASTM C143 and ASTM C231 were used for determining the amount of consolidation required for each of the respective material tests. Internal vibration was selected since it was a common method based on the literature review and DOT interviews. Table 5.6 shows the required number of rod or vibrator insertions performed for each lift, as specified by ASTM C143 and ASTM C231.

Table 5.6 Number of vibrator insertions required per lift for each experimental test

	Specimen Shape and Dimensions	Number of Insertions Required Per Lift
Slump	Standard slump cone	Rodding: 25
Air Content	Standard air content measure	Rodding: 25
Compressive Strength	6″ x 12″ cylinder	Vibration: 2
Impact Strength		
Flexural Performance	6″ x 6″ x 22″ beam	Vibration: 5
Average Residual Strength	4″ x 4″ x 14″ beam	Vibration: 3

According to ASTM C192, the rod/vibrator head should penetrate into the lower layer of concrete by approximately 1 inch. Sufficient vibration was usually considered to have been achieved as soon as the surface of the concrete became relatively smooth and large air bubbles ceased to break through the top surface, as can be seen in Figure 5.10. For consistency, the vibrator was inserted for a period of three to five seconds for each insertion. After each lift was rodded or vibrated, the outsides of the mold were tapped at least 10 times by a rubber mallet. The use of a rubber mallet is shown in Figure 5.11. ASTM C192 also states that for any beam molds, the vibrator should be inserted at intervals not exceeding 6 inches along the center line of the specimen's long dimension. This requirement was also followed during the consolidation.

Figure 5.10 Hand-held spud vibrator in use

Figure 5.11 Use of rubber mallet to obtain final consolidation efforts of the concrete

5.3.1.4 Curing

As revealed from the literature review and SDDOT interviews, curing techniques for FRC do not differ from that of PCC. Therefore, the curing method specified by ASTM C192 was used for all the hardened concrete material test specimens. Most of the specimens were moist-cured in a moist curing room, shown in Figure 5.12, at 73.5 ± 3.5°F from the time of molding until the time of testing. Due to space constraints in the cure room, the research team also created a curing chamber that was used for curing the large 6" x 6" x 22" flexural beams. The curing chamber was made of wet burlap and plastic sheets that were placed over the top of the specimens. The burlap was placed directly on top of the specimens and was monitored daily and watered, if necessary. The plastic sheets were then placed over the top of the wet burlap and used to seal the moisture inside of the curing chamber. Therefore, the concrete specimens stayed moist continuously while curing, similar to being in an actual curing room. Figure 5.13 and Figure 5.14 show the curing chamber used to cure the large flexural beams. The specimen molds were removed 24 ± 8 hours after casting.

Figure 5.12 Moist cure room used to cure a majority of the testing specimens

Figure 5.13 Wet burlap placed over the top of the concrete specimens in the curing chamber

Figure 5.14 Plastic sheet placed over the top of the wet burlap to seal in the moisture

5.3.2 Fresh Concrete Testing

The fresh concrete tests, including slump, air content, unit weight, and concrete temperature, were performed according to the respective ASTM standards, and are discussed in the following sections. Acceptable slump and air content ranges for FRC are specified in Section 460 of the SDDOT Standard Specifications for Roads and Bridges document (SDDOT, 2015).

5.3.2.1 Slump

The slump of each concrete mix was measured according to ASTM C143. There were no alterations made to this procedure. A typical slump test that was performed by the research team is shown in Figure 5.15.

Figure 5.15 Measurement of the concrete slump, according to ASTM C143

Section 460 of the SDDOT Standard Specifications for Roads and Bridges document (SDDOT, 2015) specifies an acceptable slump range of 1 inch to 4 ½ inches.

5.3.2.2 Air Content

The air content of each concrete mix was evaluated according to ASTM C231. No alterations to the specified test method were made. According to Section 460 of the SDDOT Standard Specifications for Roads and Bridges document (SDDOT, 2015), an acceptable range for air content for an A45 mix of concrete is 5% to 7.5%. The air meter that was used is shown in Figure 5.16.

Figure 5.16 Air meter used to determine the concrete’s air content, according to ASTM C231

5.3.2.3 Fresh Unit Weight

The fresh unit weight of each concrete mix was evaluated according to ASTM C138 (2013). No alterations to the specified test method were made. The weight measurement of a known volume of concrete was used to determine the unit weight, and is shown in Figure 5.17.

Figure 5.17 Determination of the fresh concrete unit weight, according to ASTM C138

5.3.2.4 Concrete Temperature

The concrete temperature of each concrete mix was evaluated according to ASTM C1064 (2012). No alterations to the specified test method were made.

5.3.3 Hardened Concrete Testing

5.3.3.1 Compressive Strength

Three Standard 6” x 12” cylinders were used for each concrete mix to determine the compressive strength at 28 days according to ASTM C39 (2012). The ends of the cylinders were capped with high-strength sulfur capping compound according to ASTM C617 (2012). Capping the cylinders provided a level surface for uniform loading of the specimen.

The tests were performed under load-control settings at a rate of 35 ± 7 psi/sec, as specified by ASTM C39. The modulus of elasticity of the cylinders was also determined during compression testing. An 8 inch extensometer from Instron was used to accurately measure the axial strain, as shown in Figure 5.18, clamped onto a concrete cylinder at four points. Two clamping points were 2 inches above the bottom of the cylinder, while the other two points were 2 inches below the top of the cylinder. The entire compressive strength testing setup is shown in Figure 5.19.

Figure 5.18 8” Extensometer used to measure the compressive strain of a concrete cylinder during testing, according to ASTM C39

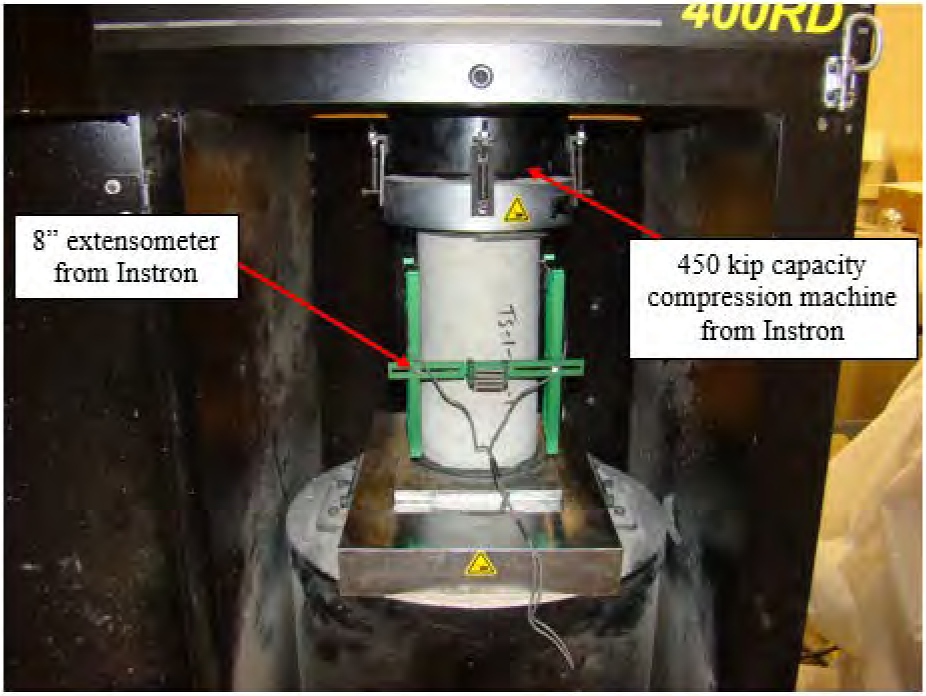

Figure 5.19 Compressive strength testing setup

The theoretical modulus of elasticity was also calculated in accordance with Equation 2 in order to verify the experimental results.

$$E_c = 33{w_c}^{1.5}\sqrt{f'_c} \qquad \text{Equation 2}$$

Where:

$E_c = Modulus\ of\ elasticity\ [psi]$
$w_c = Concrete\ unit\ weight\ [lb/ft^3]$
$f'_c = Compressive\ strength\ [psi]$

5.3.3.2 Flexural Performance

Three Beams with dimensions of 6" x 6" x 22" were evaluated for each concrete mix to determine the flexural strength at 28 days according to ASTM C1609 (2012). The specimens were simply supported with a clear span of 18 inches. Third-point loading was used under a displacement-control setting. The rate of mid-span deflection used is shown in Table 5.7, as specified by ASTM C1609.

Table 5.7 Rate of net mid-span deflection to be used for flexural strength testing

Deflection Rate (in/min)	Beginning Deflection	Ending Deflection
0.004	0″	0.02″ (= L/900)
0.006	0.02	0.023″
0.008	0.023	0.027″
0.010	0.027	0.032″
0.012	0.032	0.12″ (= L/150)

The deflection of the beam was measured using two deflectometers from Instron. These deflectometers were accurate to 1 x 10^{-6} inches and had a range of 0.6 inches. A yoke was secured to the specimen directly above the supports and was used to hold the deflectometers in place. This setup helped ensure accurate measurement of the net mid-span deflection regardless of any concrete crushing or specimen seating or twisting on its supports. There was one deflectometer mounted on each side of the specimen at mid-span. The values recorded from each gage were averaged to determine the net mid-span deflection. Figure 5.20 and Figure 5.21 show the test setup, along with the yoke and LVDT locations, respectively.

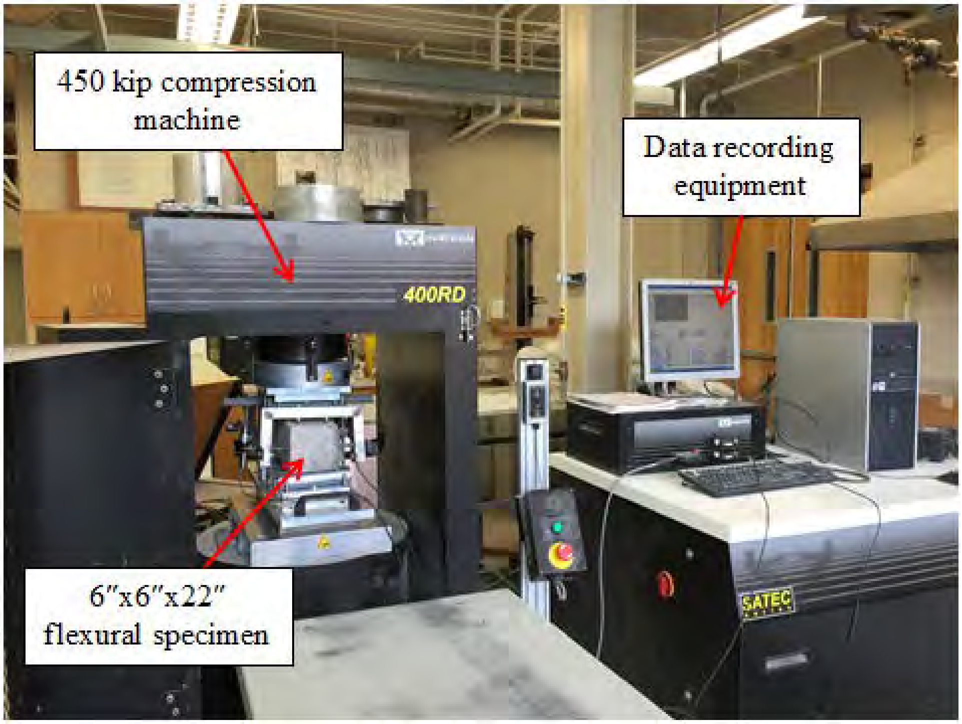

Figure 5.20 Flexural Performance (ASTM C1609) testing setup

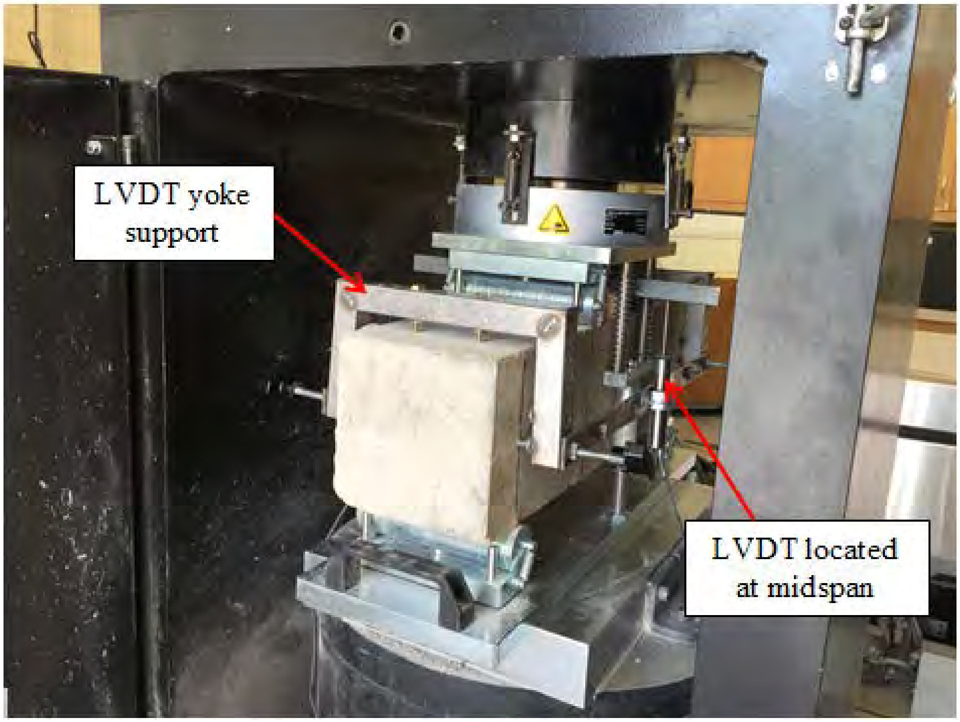

Figure 5.21 Location of the LVDTs and the LVDT yoke for ASTM C1609

A data recording system was used to plot a load-deflection curve from the flexural testing. The load and deflection corresponding to the first-peak and the peak load were determined from the data. As defined by ASTM C1609, the first-peak load is the load value at the first point on the load-deflection curve where the slope is zero. Also, the peak load is the maximum load on the load-deflection curve. These values were used in determining the corresponding first-peak and peak strengths, respectively. The area under the entire load-deflection curve was also calculated in order to determine the toughness. Moreover, the equivalent flexural strength ratio was calculated according to ASTM C1609 using Equation 3:

$$R^D{}_{T,150} = \frac{150 * T^D_{150}}{f_1 * b * d^2} * 100\% \qquad \text{Equation 3}$$

Where:

$T^D_{150} = Specimen\ toughness\ at\ a\ net\ deflection\ of\ \frac{L}{150}\ [lb.in]$

$f_1 = First - peak\ strength\ [\frac{lb}{in^2}]$

$b = Specimen\ width\ [in]$

$d = Specimen\ depth\ [in]$

The equivalent flexural strength ratio was then used to determine an effective modulus of rupture for FRC specimens. The effective modulus of rupture provided a method for quantifying the contribution of the fiber reinforcement to the concrete's flexural strength. It was calculated using Equation 4 (Roesler and Gaedicke, 2004):

$$MOR' = MOR * \left(1 + \frac{R^D_{T,150}}{100}\right) \qquad \text{Equation 4}$$

Where:

$MOR' = Effective\ modulus\ of\ rupture\ [psi]$

$MOR = f_r = Modulus\ of\ rupture\ [psi]$

$R^D{}_{T,150} = Equivalent\ flexural\ strength\ ratio\ [\%]$

In order to provide a more accurate comparison between flexural strength values, the effective modulus of rupture was also normalized to a compressive strength of 4500 psi, which is the design strength of A45 concrete according to Section 460 of the SDDOT Standard Specifications for Roads and Bridges document (SDDOT, 2015). The normalization was carried out using Equation 5, which was proposed by the research team:

$$MOR'_{4500} = MOR' * \left(\frac{\sqrt{4500\ psi}}{\sqrt{f'_c}}\right) \qquad \text{Equation 5}$$

Where:

$MOR'_{4500} = Effective\ modulus\ of\ rupture\ normalized\ to\ f'_c = 4500psi$

$f'_c = Measured\ compressive\ strength\ [psi]$

5.3.3.3 Average Residual Strength

Five Beams with dimensions of 4” x 4” x 14” were used for each concrete mix to measure the average residual strength at 28 days according to ASTM C1399. The specimens were simply supported with a clear span of 12 inches. Third-point loading was used under a displacement-control setting. A set of five specimens was tested for each mix design. The deflection measuring equipment and data recording system was the same as the flexural performance test (ASTM C1609). Initially, the specimen was placed on top of a 4” x ½” x 14” steel plate and centered onto the flexural support apparatus.

An initial loading rate of 0.025 ± 0.005 in/min was used until reaching a deflection of 0.008 inches. After that, the specimen was unloaded and the steel plate was removed from beneath the concrete. Once the steel plate was removed, the concrete specimen was placed back on the support apparatus. Using the same loading rate as before, the specimen was loaded to a deflection of 0.05 inches. During the second stage of loading, the strength of the beam at 0.02, 0.03, 0.04, and 0.05 inches was recorded, as specified by ASTM C1399 and shown in Figure 5.22. The average residual strength for each beam was calculated using Equation 6, and then a mean average residual strength for each set of beams was calculated.

$$ARS = \frac{(P_A + P_B + P_C + P_D)L}{4bd^2} \qquad \text{Equation 6}$$

Where:

$ARS = Average\ residual\ strength\ [psi]$

$P_A + P_B + P_C + P_D = Sum\ of\ recorded\ loads\ at\ specified\ deflections\ [lb]$

$L = Span\ length\ [in]$

$b = Specimen\ width\ [in]$

$d = Specimen\ depth\ [in]$

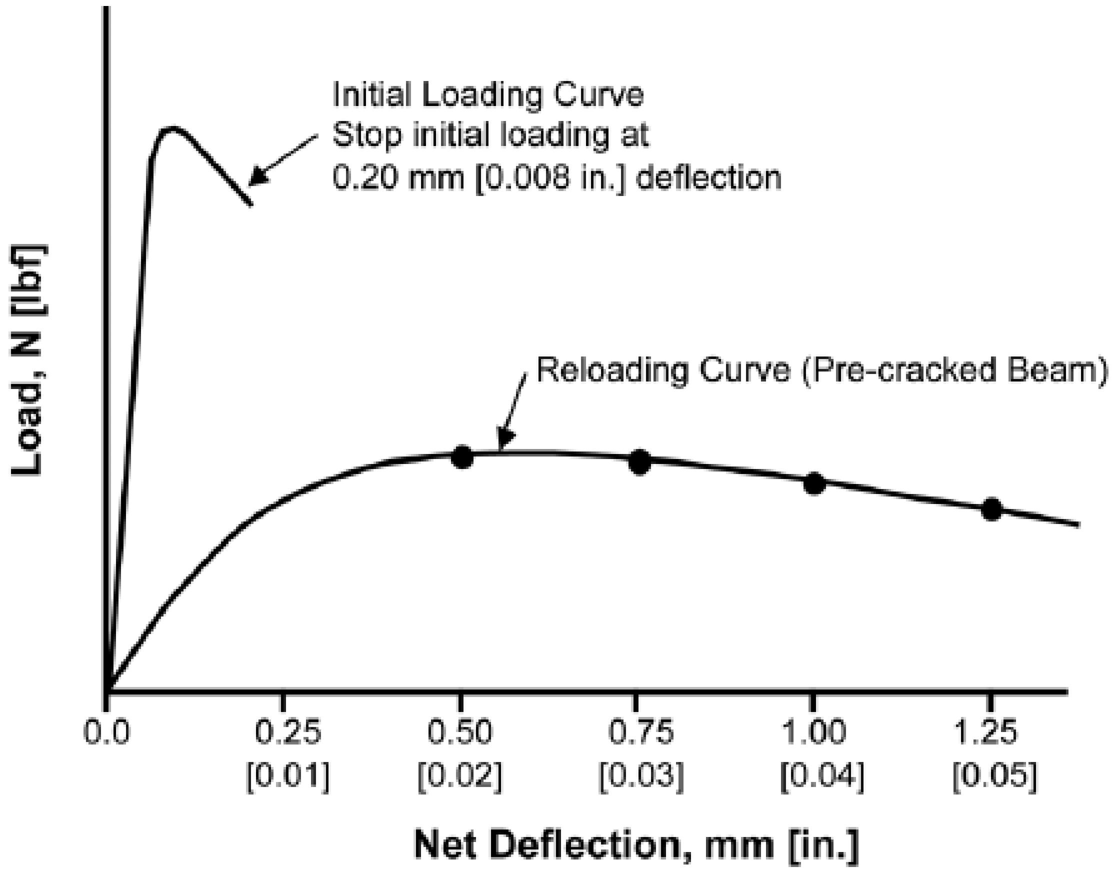

Figure 5.22 Typical load-deflection curves for the average residual strength test (ASTM C1399, 2010)

5.3.3.4 Impact Strength

The impact strength was qualitatively evaluated using the drop-weight impact test in accordance with ACI Committee 544.

Only one specimen for each concrete mix was tested for impact strength. Specimens were 6 inches in diameter and 2-1/2 inches thick. The specimens were obtained by sawing off the top 2-1/2 inches of full-size (6" x 12") cylinders. The specified testing apparatus held a 2-1/2 inch diameter steel ball centered on top of the specimen. A 10-pound manually operated compaction hammer was held on top of the steel ball to apply the impact loads. The testing setup is shown in Figure 5.23 and Figure 5.24.

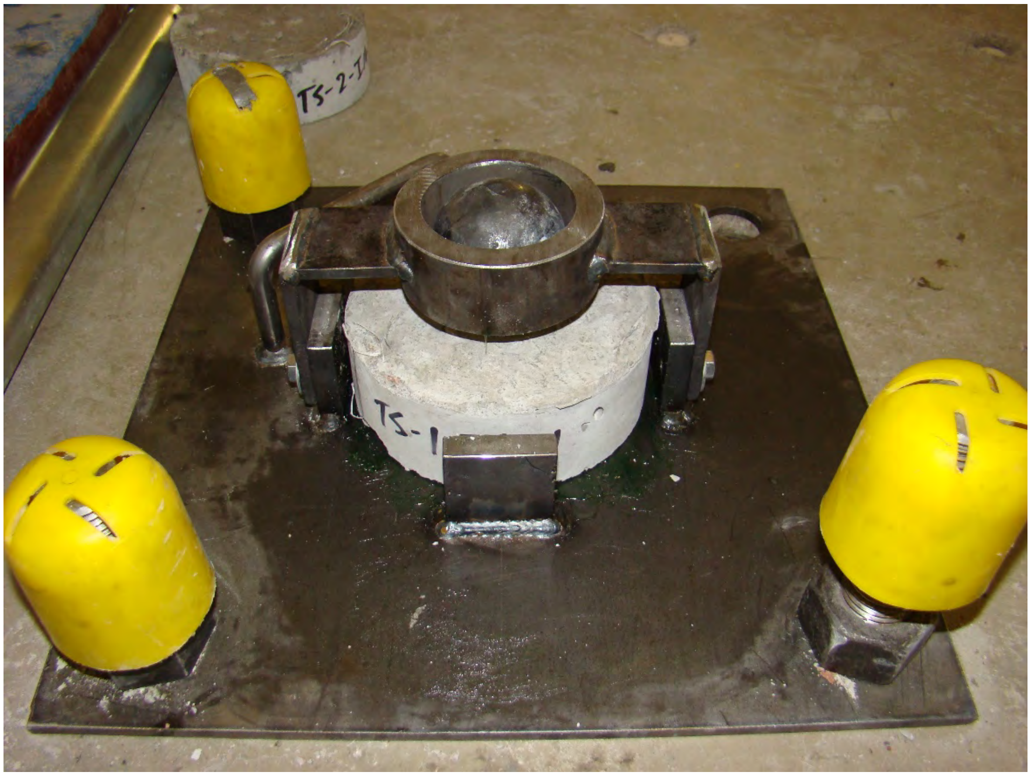

Figure 5.23 Testing setup for the impact strength test, according to ACI Committee 544

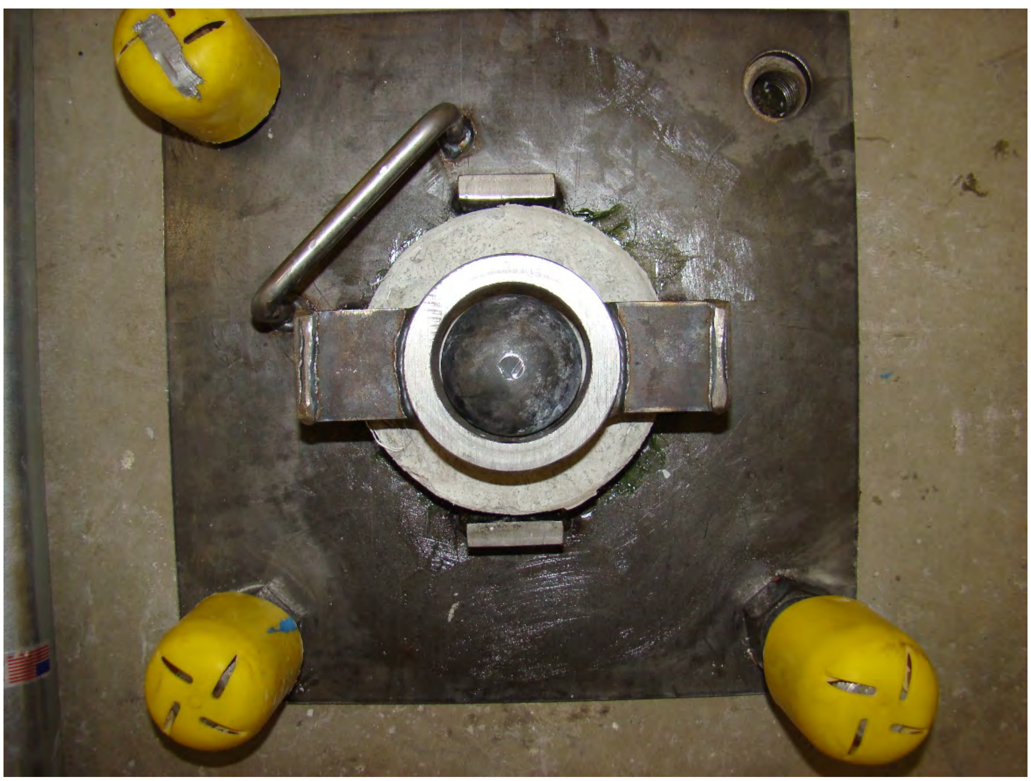

Figure 5.24 Top view of the impact strength testing setup

The hammer was repetitively dropped on the steel ball from a height of 18 inches. The number of blows required to cause the first visible crack on the surface and to cause ultimate failure were both recorded. Ultimate failure is defined as the sufficient opening of cracks in the specimen such that the pieces of concrete are touching three of the four positioning lugs on the baseplate (ACI, 1988), as shown in Figure 5.25.

Figure 5.25 Failed impact specimen

5.3.3.5 Fiber Distribution

The method used to investigate the fiber distribution within the concrete is a non-standard procedure devised by the research team. In order to evaluate the distribution of the fibers in each concrete mix, the inside of hardened concrete specimens was inspected. As previously discussed, the specimens used for the ACI Committee 544 (impact strength) tests were cut from larger specimens. These cut specimens provided an opportunity to inspect the inside of concrete and determine the orientation and the degree of distribution of the fibers. This allowed for comparison among the varying dosage rates for each fiber. It also provided an additional opportunity to observe any fiber balling that may have occurred during concrete mixing.

5.3.3.6 Statistical Analysis

A statistical test called the F-test was performed on the obtained data using software called SAS in order to see the significance of the effect of fiber type and fiber dosage on the values obtained from the aforementioned experimental measurements. This test works by calculating an F parameter, which is the ratio of variation in data among different groups to the variation in data within a certain group. For instance, considering the fiber type, the F value would be the ratio of variation between data obtained from all FRC mixes to the variation between data obtained from FRC mixes that have the same fiber type. If the F value is too small, then the variation due to the studied factor is deemed to be statistically insignificant and, therefore, it is concluded that the factor does not have an impact on the output.

Another important value looked at in this test is the p-value, which is the probability that random sampling will result in means as far apart as observed in this particular data set assuming the effect of the factor is indeed insignificant. A high p-value confirms the statistical insignificance of the effect of the factor on the output while a low p-value negates that argument. A p-value below 0.05 is commonly used to argue statistical significance of a treatment.

6. EXPERIMENTAL RESULTS AND ANALYSIS

This section discusses the results obtained from fresh and hardened concrete experiments conducted on both the conventional mix and the FRC mixes. It mainly discusses the effects of fiber dosage and fiber type on the various fresh and hardened concrete properties. The results are also compared, wherever applicable, to the information found in the literature. Moreover, the results for the FRC mixes are generally expressed as ratios to those of the conventional mix in order to facilitate comparison with the conventional mix and the other FRC mixes at the same time. However, there are some exceptions for the experiments that were not carried out on the conventional mix, such as the average residual strength test. Also, the presented data are the averages obtained for each experiment from all specimens.

6.1 Fresh and Hardened Properties

The specimens were labeled using an A-B-C format, where A, B, and C correspond to the following:

A: Fiber Name
- NA: Control Mix (no fibers)
- ST (or 1): Strux 90/40 (W.R. Grace)
- FM (or 2): Fibermesh 650 (Propex)
- TS (or 3): TUF-STRAND SF (Euclid Chemical Company)
- FF (or 4): FORTA-FERRO (Forta Corporation)
- DR (or 5): Dramix 5D (Bekaert)

B: Dosage Rate Level
- 0: No fibers (i.e., Control mix)
- 1: approximately 0.21% Volume fraction (Synthetic: 3 lb/yd^3, Steel: 25 lb/yd^3)
- 2: approximately 0.35% Volume fraction (Synthetic: 5 lb/yd^3, Steel: 45 lb/yd^3)
- 3: approximately 0.55% Volume fraction (Synthetic: 8 lb/yd^3, Steel: 65 lb/yd^3)
- 4: approximately 0.69% Volume fraction (Synthetic: 10 lb/yd^3, Steel: 85 lb/yd^3)

C: Specimen Number (for each respective material test): e.g., 1, 2, 3, etc.

For example, FM-4-2 corresponded to the second FRC specimen that incorporated Fibermesh 650 fibers at 0.69% (10 lb/yd^3). The labeling system was adopted for specimens used in each of the hardened concrete tests.

Table 6.1 and Table 6.2 summarize fresh and hardened properties of all concrete mixes.

Table 6.1 Summary of fresh concrete properties

Mixture ID	Fresh Air Content (%)	Unit Weight (lb/ft^3)	Slump (in)	Temperature (^{o}F)
NA-0	5	146.6	4.5	75
ST-1	4.8	147.0	4.5	73
ST-2	6	144.3	4.5	72
ST-3	6.3	143.2	3.5	70
ST-4	5.5	144.9	2	72
FM-1	6.2	144.6	4.25	72
FM-2	7.1	142.3	4.5	72
FM-3	5.6	144.1	2.75	71
FM-4	5.2	145.4	1.75	80
TS-1	7.4	141.0	4.5	79
TS-2	5.1	146.2	3	79
TS-3	5.1	146.2	2	78
TS-4	5.2	145.8	1.75	79
FF-1	7	142.6	4	80
FF-2	6.6	142.7	4	79
FF-3	5.4	144.2	3.5	81
FF-4	5.1	146.2	1.5	81
DR-1	7.4	141.0	4.5	81
DR-2	6.8	145.4	3.5	79
DR-3	7.5	140.7	4	79
DR-4	7.1	143.5	2	80

Table 6.2 Summary of hardened concrete properties

Mixture ID	Compressive Strength (psi)	Modulus of Elasticity	Toughness (lb.in)	Equivalent Flexural Strength Ratio (%)	Normalized Effective Modulus of Rupture (psi)	Average Residual Strength (psi)	First Crack	Failure
NA-0	7708.0	5190.0			606.4		6	20
ST-1	6970.3	4830.0	221.3	22.1	683.4	176.1	10	14
ST-2	6171.7	4733.3	236.2	29.8	609.9	378.8	6	14
ST-3	6913.7	4646.7	442.5	46.0	786.7	465.7	6	13
ST-4	6364.3	4576.7	410.4	46.2	760.3	418.2	10	32
FM-1	6549.3	4850.0	188.5	22.1	612.1	197.4	9	16
FM-2	6511.0	4980.0	279.0	28.5	719.2	385.7	6	16
FM-3	6520.3	4730.0	402.3	42.7	770.0	457.1	12	29
FM-4	6662.3	4536.7	528.9	59.2	818.3	565.1	9	57
TS-1	6203.3	4536.7	113.4	14.0	546.9	161.4	13	29
TS-2	6623.7	4550.0	280.6	32.2	654.2	267.6	9	25
TS-3	6062.7	4473.3	380.8	44.2	743.3	385.5	7	27
TS-4	5734.0	4366.7	563.1	60.4	923.2	438.9	9	76
FF-1	6669.7	4506.7	202.6	22.9	619.6	185.9	6	14
FF-2	6002.3	4386.7	172.8	22.6	565.5	285.7	5	22
FF-3	5414.3	4116.7	463.7	48.3	908.9	643.6	5	28
FF-4	6671.7	4600.0	480.0	50.7	812.4	560.5	12	48
DR-1	6345.0	4500.0	496.0	53.9	832.3	443.6	4	19
DR-2	6690.7	4593.3	658.9	77.2	859.3	604.2	8	23
DR-3	5219.0	3980.0	601.0	80.2	880.5	473.4	10	23
DR-4	5676.0	4183.3	643.1	89.9	844.8	673.5	11	33

6.2 Statistical Results

Table 6.3summarizes the results of the F-test, examining the statistical significance of the effect of fiber type and fiber dosage on each of the fresh and hardened concrete properties. It can be observed from the p-values that, overall, the statistical significance of the effect of the fiber dosage was more apparent than that of the fiber type. In fact, the fiber type had significant effect only on the temperature, modulus of elasticity, equivalent flexural strength ratio, and impact test failure point. The insignificant effect of fiber type on air content, unit weight, and slump was intuitive since the introduction of fibers to the concrete was not believed to cause any chemical alteration. Therefore, for the same fiber dosage, different fiber types should not cause any significant alteration to the fresh concrete properties. However, the results still showed a statistically significant effect on the temperature of the concrete. Looking at the data shown in Table 6.1, this observation was believed to be because some mixes might have been poured during days in which the surrounding temperature was lower compared with other mixes. Despite the differences in temperature among the various mixes, they were all still within a reasonable range of ±5^{o} F compared with the conventional mix. For general structural concrete applications, SDDOT requires the concrete temperature at the time of casting to be between 50°F and 90°F (SDDOT, 2015). For bridge decks, SDDOT requires concrete temperature values to be a maximum of 80°F (SDDOT, 2015). For pavement repair, relatively recent SDDOT construction plans specified an FRC mix with 8 lb/yd^3 synthetic fiber content (0.55% volumetric ratio) and a minimum concrete temperature of 45°F (Grannes and Hodges, 2014). The measured concrete temperature values for the mixes considered in this study were within or marginally outside the SDDOT acceptable concrete temperature range for the various applications. However, it should be noted that these temperature values were obtained in laboratory experiments and they might vary drastically in the field depending on the season. The effect of the fiber type on the hardened concrete properties will be discussed in details in the subsequent sections.

Table 6.3 F-test results

	Fiber Type		Volume Fraction of Fibers	
	F-value	p-value	F-value	p-value
Fresh Air Content	0.93	0.4994	0.79	0.6271
Unit Weight	0.22	0.9195	0.89	0.5676
Slump	1.93	0.211	12.38	0.0017
Temperature	9.65	0.0056	0.68	0.704
Compressive Strength	1.83	0.2283	1.53	0.2948
Modulus of Elasticity	5.12	0.0301	2.09	0.1738
Toughness	1.19	0.3919	8.67	0.005
Equivalent Flexural Strength Ratio	9.3	0.0062	15.98	0.0008
Normalized Effective Modulus of Rupture	0.02	0.9985	2.87	0.0916
Average Residual Strength	2.22	0.1676	8.13	0.0061
Impact Test First Crack	0.71	0.6115	1.43	0.3263
Impact Test Failure	5.12	0.0301	7.18	0.0087

Table 6.3 also shows that the fiber dosage had a statistically significant effect on slump, toughness, equivalent flexural strength ratio, average residual strength, and impact test failure point. It was intuitive that the effect of fiber dosage would be insignificant on the air content, unit weight, and temperature since the volume of these fibers is very low even at the highest dosage rate. It should be noted that the air content values (Table 6.1) did experience some fluctuation within an acceptable range considering the erratic nature of any air content dataset. SDDOT requires the concrete air content at the time of casting to be between 5.0% and 7.5% for general structural concrete applications, and between 5.5% and 7.5% for bridge decks (SDDOT, 2015). Relatively recent SDDOT construction plans specified synthetic FRC mixes with an air content range of 5.5% to 7.5% for bridge deck non-latex overlays and 5.0% to 7.5% for pavement repair with 8 lb/yd^3 synthetic fiber content mixes (0.55% volumetric ratio) (Grannes and Hodges, 2014). The results indicate that the measured air content values for all mixes considered in this study were within or marginally outside the acceptable air content range for the various applications. For mixes with air contents outside the specified range, it is possible to adjust that by changing the air entraining agent dosage. However, it should be kept in mind that this might affect the workability and the compressive strength of the mix. The effect of fiber dosage on the other properties will be discussed in detail in the subsequent sections.

6.3 Effect of Fiber Type

6.3.1 Compressive Strength

Even though statistical data suggested that fiber type seemed to have an apparent effect only on the modulus of elasticity, equivalent flexural strength ratio, and impact test failure point, some figures in this section might indicate that other properties were also affected. For instance, Figure 6.1 illustrates that the Fibermesh 650 and the Strux 90/40 mixes experienced lower reductions in the compressive strength compared with the Dramix 5D mix. Nonetheless, the difference was extremely small, hence the p-value of 0.2283. It is important to note, however, that, regardless of fiber type, the compressive strength dropped significantly due to the introduction of fibers into the mix. The average drop was about 18%. This reduction could be attributed to the lack of good interlock between the cement paste and the aggregates that could have been caused by the presence of fibers. However, this cannot be asserted until further studies on the microstructure of FRC is conducted. Another reason why further studies are needed before concluding that fibers reduce the compressive strength of concrete is that previous studies have shown contradictory conclusions. Some studies found that fibers increase the compressive strength (Noushini et al., 2014; Saad et al., 2015), while others concluded that they decrease it (Li, 1992; Kim, et al., 2013).

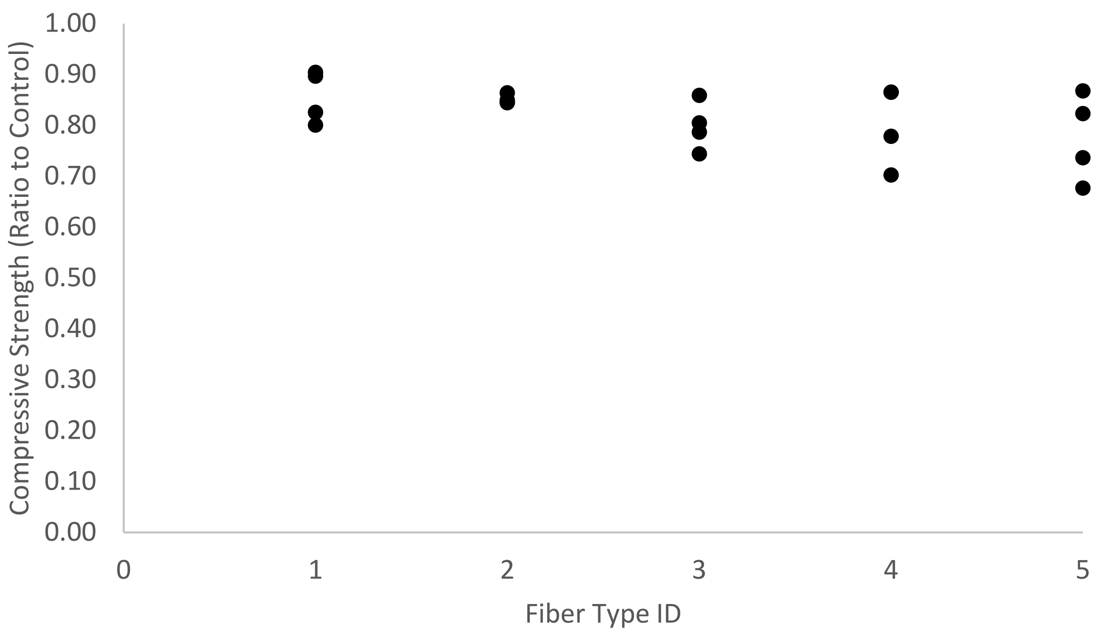

Figure 6.1 Effect of fiber type on compressive strength

Even though the p-value for the effect on the modulus of elasticity came out to be 0.0301, Figure 6.2 does not show large differences among the different mixes. However, the superiority of the Fibermesh 650 and the Strux 90/40 mixes over the Dramix 5D mix was more apparent here than in Figure 6.1. The average reduction in the modulus of elasticity due to the introduction of fibers, regardless of their type, was about 13%. As a way of validating the experimental results, theoretical modulus of elasticity values was calculated and compared with the experimental modulus of elasticity values. Figure 6.3 shows a high agreement between the theoretical modulus of elasticity and the measured modulus of elasticity. The average ratio of the theoretical modulus of elasticity to the measured modulus of elasticity was found to be 0.999 with a standard deviation of 0.035.

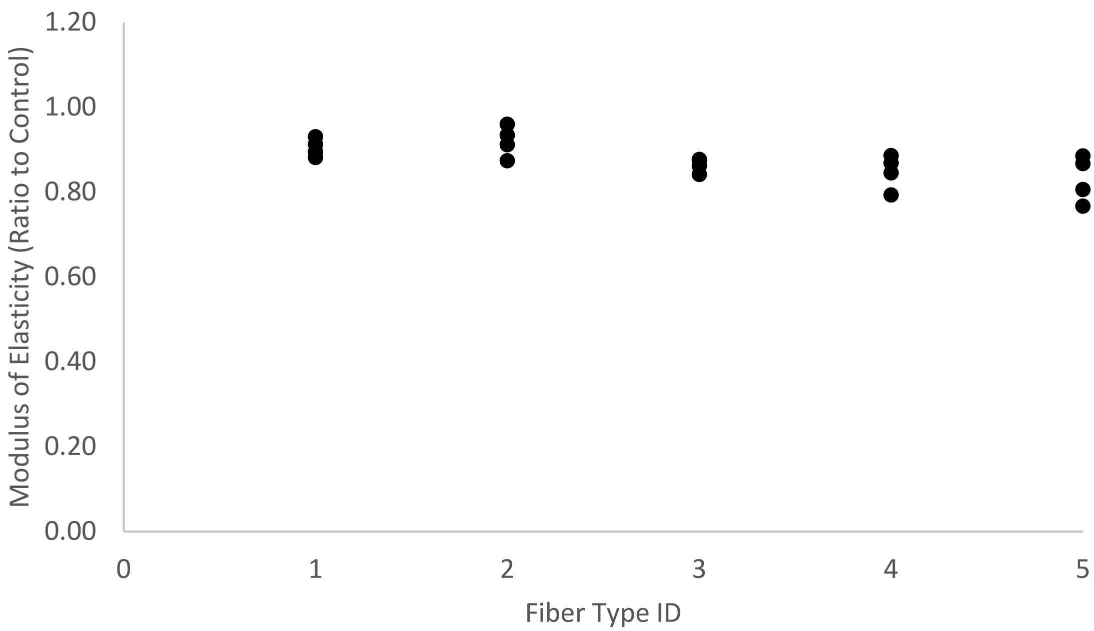

Figure 6.2 Effect of fiber type on modulus of elasticity

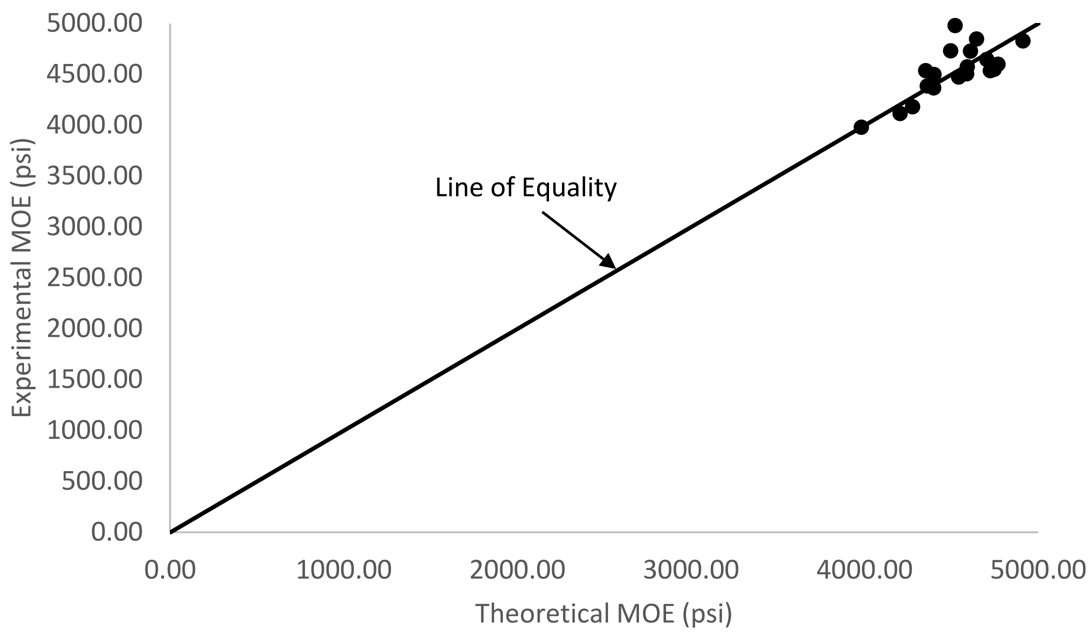

Figure 6.3 Experimental vs. theoretical modulus of elasticity values

Currently, SDDOT Standard Specifications for Roads and Bridges (SDDOT, 2015) does not specify acceptable compressive strength or modulus of elasticity limits for FRC mixes. However, recent SDDOT construction plans for bridge deck non-latex overlays specified synthetic Class A45 FRC mix with a minimum compressive strength of 4,500 psi (Grannes and Hodges, 2014). While the compressive strength for all the mixes considered in this study were well above this limit, it is important to keep in mind the significant reduction in compressive strength that could be caused by the introduction of fibers into the mix. Thus, it is a good practice to always choose a mix with a much higher compressive strength than required.

The failure shape for the FRC specimens was different than that of the control mix specimens. Contrary to the control mix specimens, which crumbled at failure, the FRC specimens stayed intact after reaching their compressive strength as shown in Figure 6.4. This type of failure indicated that the fibers were still holding the broken concrete pieces tight to the specimen. It is possible that the fibers could potentially support additional load after the compressive strength has been reached.

Figure 6.4 FRC compressive strength cylinder at failure

6.3.2 Flexural Performance

The effect of fiber type on the post-crack load-carrying capacity was examined by looking at the equivalent flexural strength ratio, toughness, modulus of rupture, and average residual strength. While the statistical results indicated that the fiber type had an effect only on the equivalent flexural strength ratio with a p-value of 0.0062, Figure 6.5 through Figure 6.8 clearly illustrate that the FRC mix with Dramix 5D fiber had superior flexural performance with respect to all flexural properties. All of the other FRC mixes with synthetic fibers, on the other hand, seem to have had comparable flexural performances. This could be due to the similarity in tensile strength between all synthetic fibers. The dramatic increase in the flexural performance of FRC mixes with steel fibers compared with those with synthetic fibers was attributed to the high tensile strength and modulus of elasticity of the steel fibers (333.5 ksi and 30,000 ksi, respectively). Even though these mixes seem to provide superior flexural performance, durability issues such as corrosion might be of concern, especially in transportation applications in cold areas where deicing salt is regularly applied during the winter. These mixes, however, could be a good option for Jersey barriers since they are not directly subjected to the application of deicing salt. It is important to note that the cost of steel fibers is twice as much as that of synthetic fibers. However, results showed that steel FRC mixes, with even half the dosage of fibers compared with that of synthetic FRC mixes, could still perform better or at least as good.

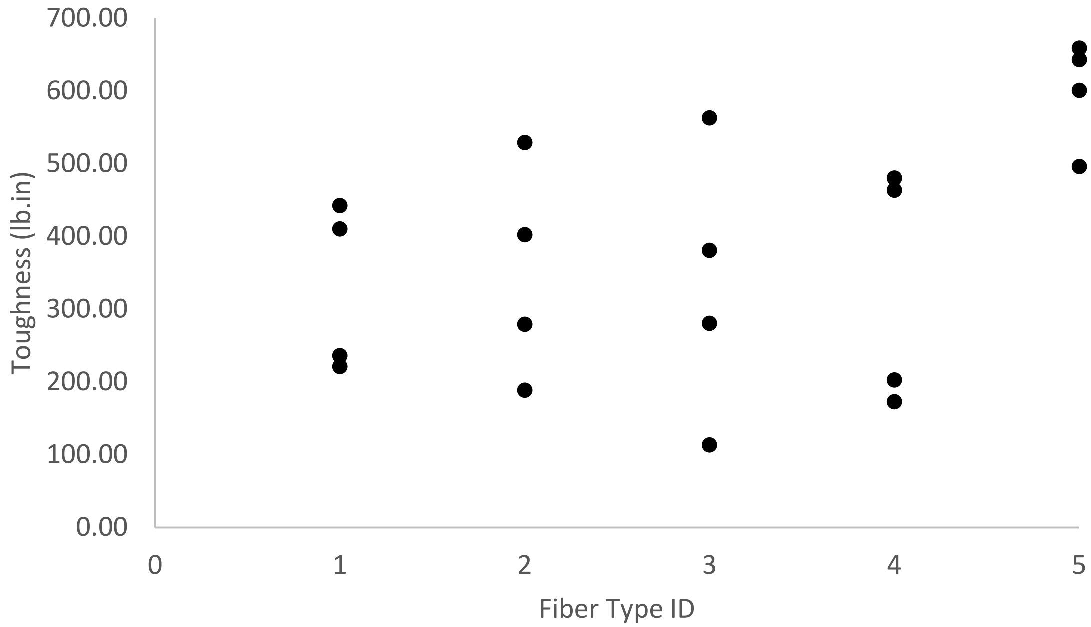

Figure 6.5 Effect of fiber type on toughness

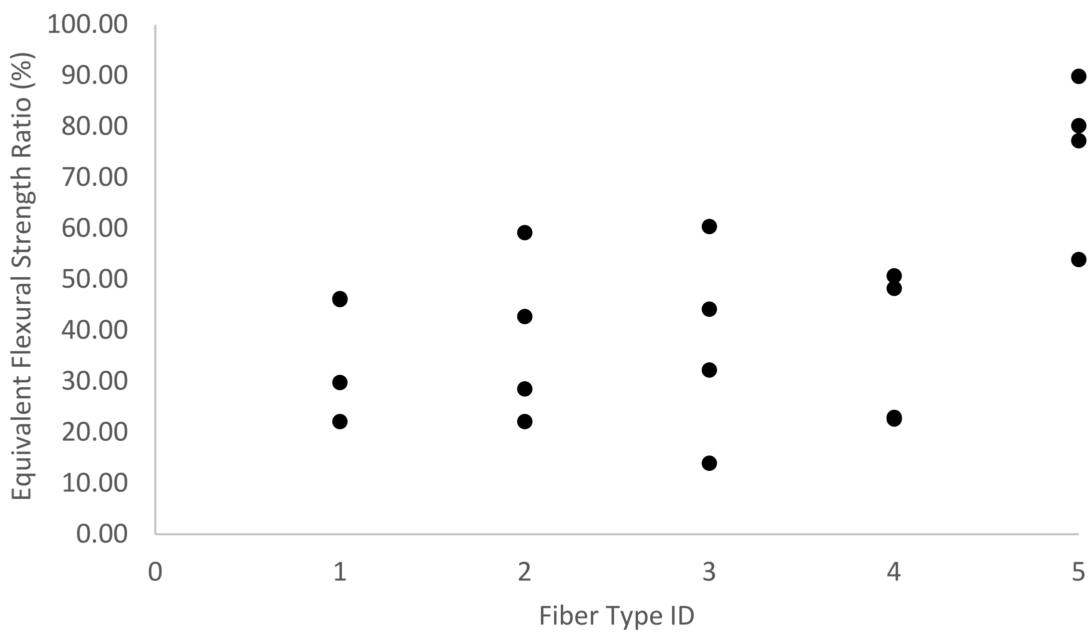

Figure 6.6 Effect of fiber type on equivalent flexural strength ratio

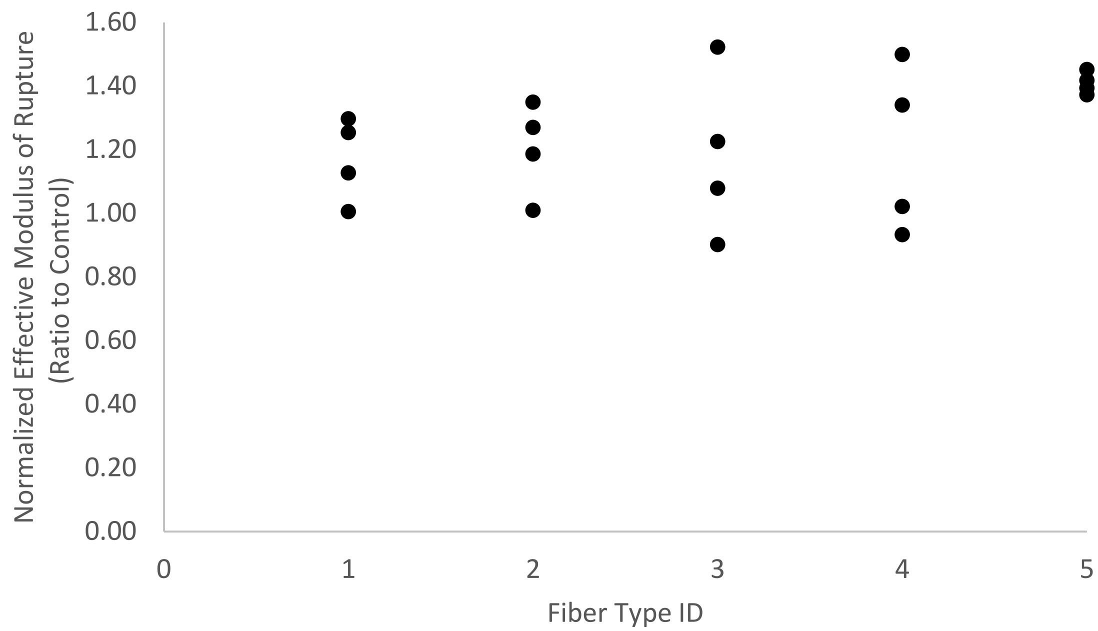

Figure 6.7 Effect of fiber type on normalized effective modulus of rupture

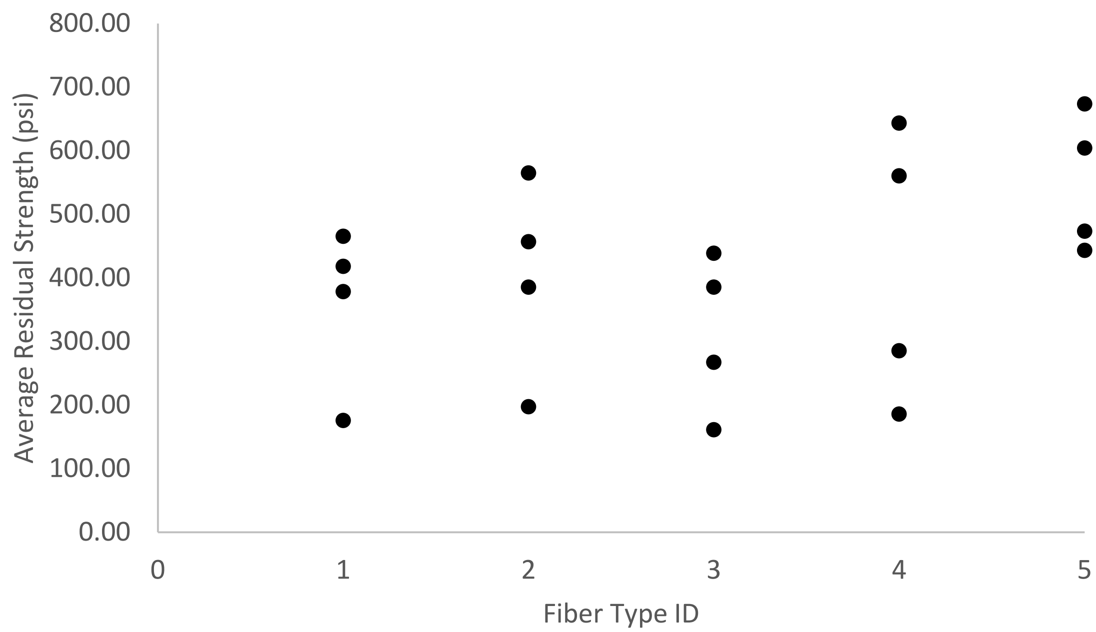

Figure 6.8 Effect of fiber type on average residual strength

There are no specifications for acceptable flexural performance limits for FRC mixes in the SDDOT Standard Specifications for Roads and Bridges (SDDOT, 2015). Also, no specifications regarding flexural performance were discovered during the literature review and the interviews except for the average residual strength, which will be discussed in Section 6.4.2. As a way of examining the validity of the presented results, theoretical modulus of rupture was calculated and compared with experimental modulus of rupture. Figure 6.9 shows a good agreement with an average theoretical to experimental modulus of rupture ratio of 0.977 and a standard deviation of 0.077.

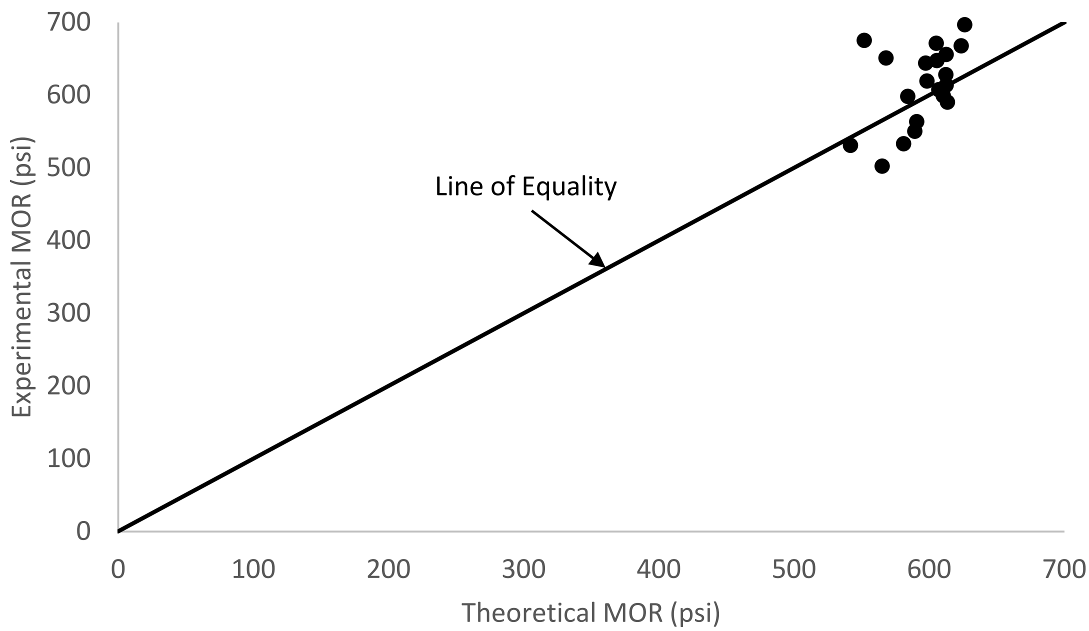

Figure 6.9 Experimental vs. theoretical modulus of rupture values

6.3.3 Impact Strength

For the impact performance, Figure 6.10 and Figure 6.11 do not indicate any significant effect of fiber type except for the failure point of the FRC mix with the highest dosage of TUF-Strand SF fiber, which is believed to be the one causing the low p-value of 0.0301. While it might be tempting to conclude that the TUF-Strand SF FRC mix is superior in terms of impact resistance, the authors believe it would be an immature conclusion in light of the fact that only one specimen was tested for impact resistance for each mix. In fact, the failure point for the other three TUF-Strand SF FRC mixes (Figure 6.11) hints that it is highly likely the result from the fourth mix might be an outlier. There was nothing found in the literature review or agency interviews regarding FRC impact strength specifications.

Since it was found that fiber type, excluding steel fibers, had no significant effect on flexural and impact performance, one could conclude it would be most efficient to go with the most economical option. In this case, it would be Fibermesh 650 and FORTA-FERRO fibers as shown in Table 5.1.

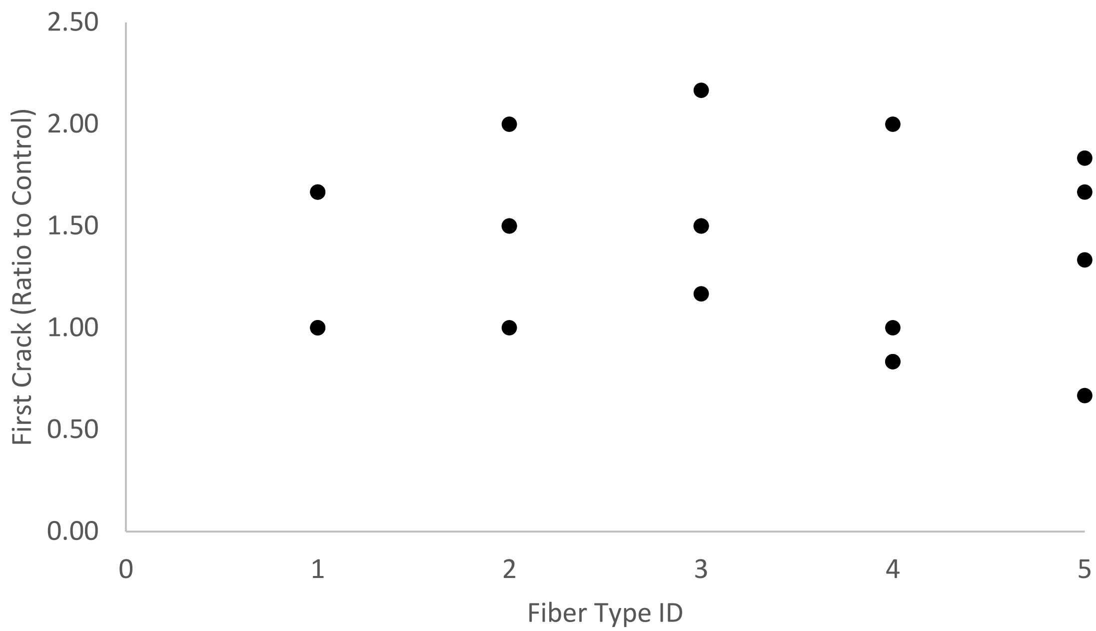

Figure 6.10 Effect of fiber type on the first crack point of the impact test

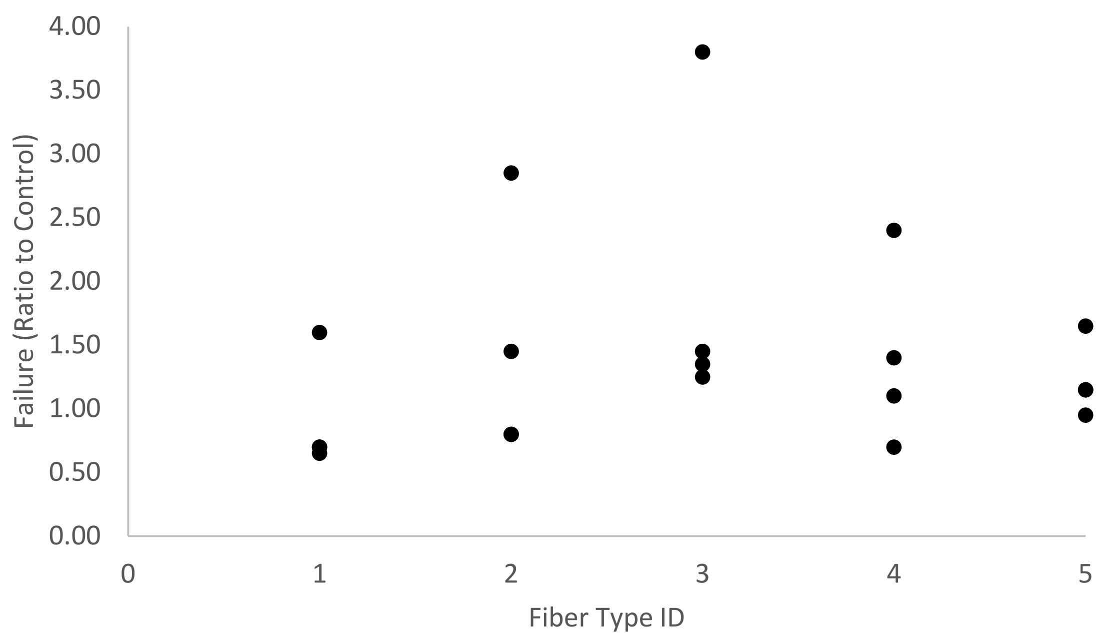

Figure 6.11 Effect of fiber type on the failure point of the impact test

6.4 Effect of Fiber Dosage

6.4.1 Slump

As discussed in Section 6.2, slump was one of the concrete properties affected by the fiber dosage, with a p-value of 0.0017. Figure 6.12 shows the significant drop in the slump value as the fiber dosage increased, reaching more than a 50% drop for the highest dosage. This trend is consistent with the information found in the literature (Dunn and Wolf, 2001) and is explained by the fact that the interlocking between the fibers and the cement paste makes it difficult for concrete to flow. Therefore, the higher the fiber content, the harder it is for concrete to flow, and, therefore, the lower the slump. The measured slump values for the mixes considered in this study were within the SDDOT acceptable slump range of 1.0 inch to 4.5 inches for general structural concrete applications (SDDOT, 2015). For bridge decks, SDDOT requires slump values to be between 2.0 inches and 4.0 inches (SDDOT, 2015). Table 6.1 indicates that a synthetic fiber volumetric ratio of 0.55% would be ideal for this application. For bridge deck non-latex overlays, SDDOT specifies a dense concrete mix with a maximum allowable slump of 1.0 inch (SDDOT, 2015), which is not met by any of the mixes adopted in this study. It is, however, possible to meet this specification by lowering the air entraining agent dosage or further increasing the fiber dosage. In relatively recent bridge deck overlays constructed in South Dakota, SDDOT construction plans specified synthetic FRC mix with a slump range of 2.75 inches to 5.25 inches (Grannes and Hodges, 2014). In this case, FRC mixes with synthetic fiber content less than 0.34% is recommended.

For pavement repair, the same SDDOT construction plans specified FRC mix with 0.55% synthetic fiber content and a slump range of 1.0 inch to 3.5 inches (Grannes and Hodges, 2014), which is met by all synthetic FRC mixes presented in this study. For FRC applications in Jersey barriers, a slump range of 4.0 inches to 6.0 inches has been recommended to facilitate the placement and consolidation of FRC around the relatively congested steel reinforcement (Ramakrishnan, 1997). Given the results obtained in this study, synthetic FRC mixes with 0.21% fiber content is suggested for this application. Synthetic FRC mixes with 0.34% fiber content can also be used if the air entraining agent dosage is increased.

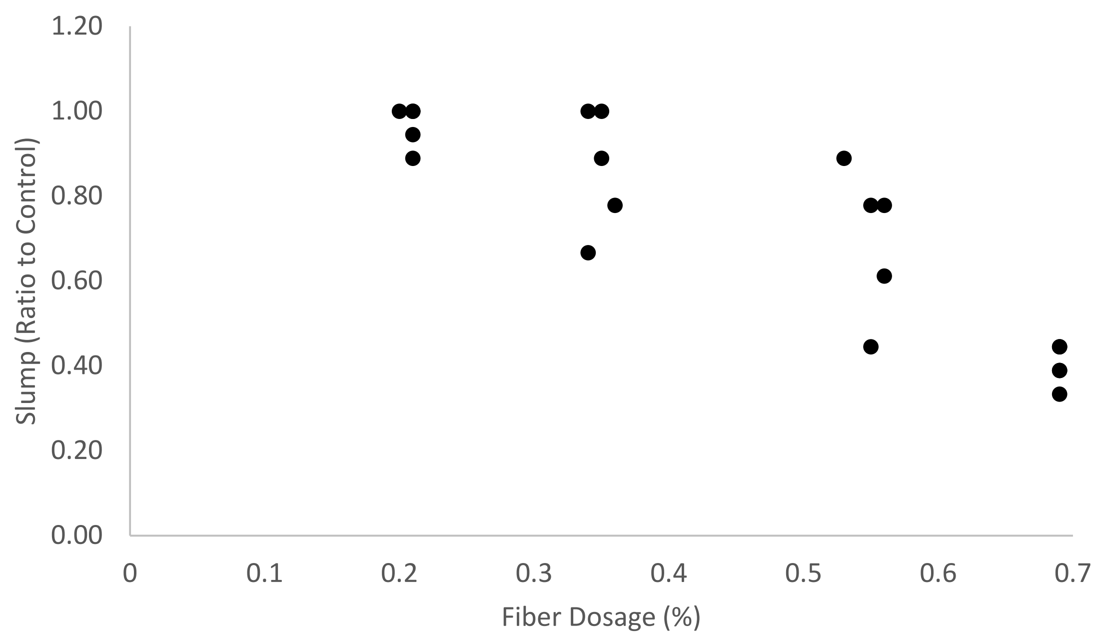

Figure 6.12 Effect of fiber dosage on slump

Since the effect of the fiber type on the slump was found to be insignificant, it is possible to come up with a universal (i.e., for all five fiber types) quadratic regression by averaging the slump values across all fiber types. The regression is shown in Figure 6.13.

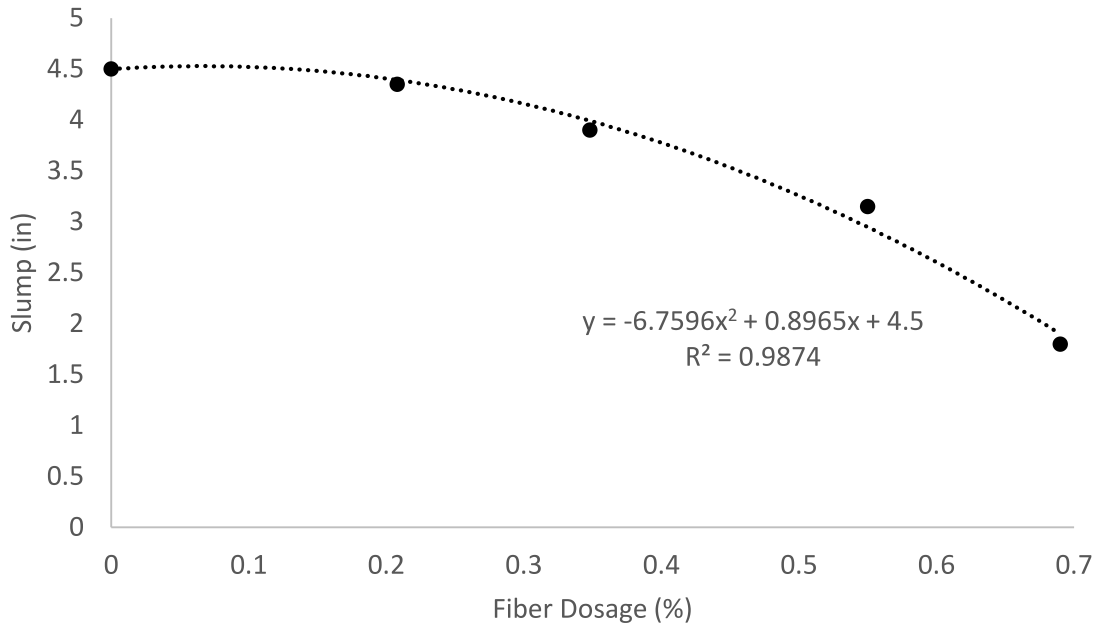

Figure 6.13 Quadratic regression for slump

6.4.2 Flexural Performance

As discussed in Section 6.2, statistical analysis indicated no effect of fiber dosage on the compressive strength and modulus of elasticity. On the other hand, its effect on the flexural performance was very evident from both the statistical data and Figure 6.14 through Figure 6.17. The increase in toughness, equivalent flexural strength, modulus of rupture, and average residual strength between the lowest and the highest dosages was very significant as observed in these figures. If we exclude the steel FRC mixes, the increase in toughness and average residual strength was from an average of about 181 lb.in to 495 lb.in and from an average of about 180 psi to 495 psi, respectively. Equivalent flexural strength and modulus of rupture increased from an average of about 20% to 54% and from an average of about 615 psi to 828 psi, respectively. These findings are consistent with those found in the literature (Noushini et al., 2013; Roesler et al., 2004). This improved flexural performance was attributed to the mechanism of crack-bridging by fibers, which occurs when cracks start to form under flexural loading. Therefore, the greater the fiber amount, the better the crack-bridging performance.

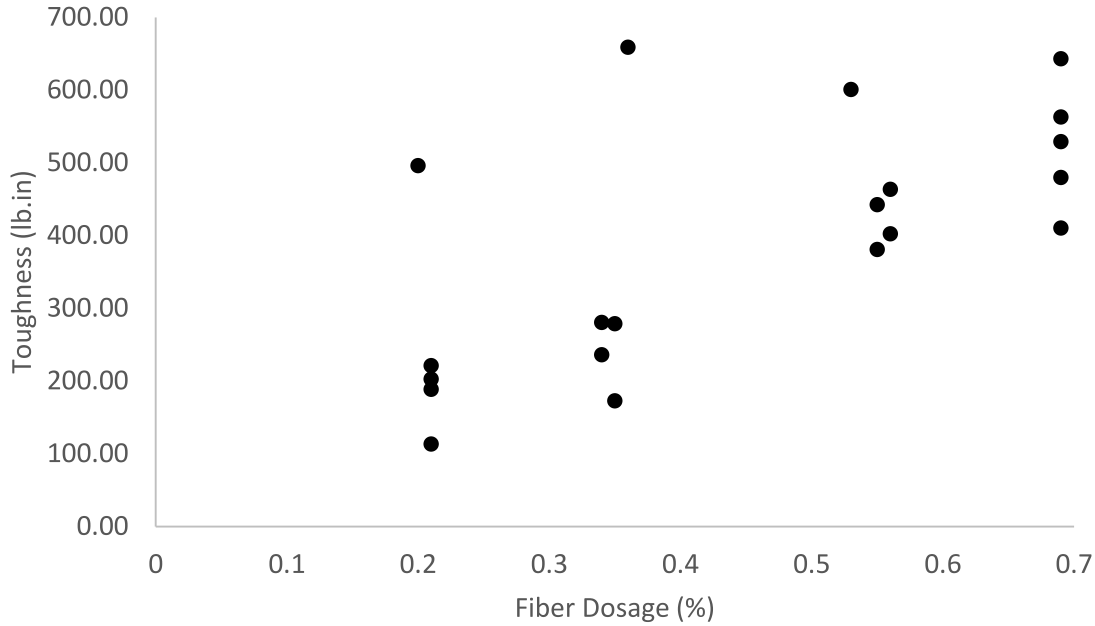

Figure 6.14 Effect of fiber dosage on toughness

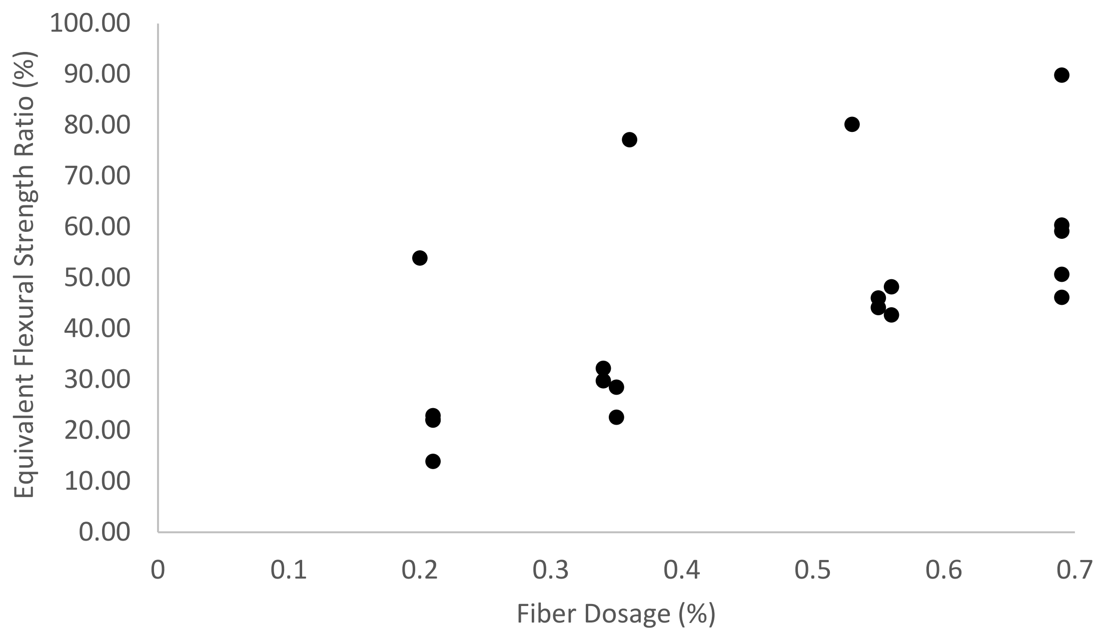

Figure 6.15 Effect of fiber dosage on equivalent flexural strength ratio

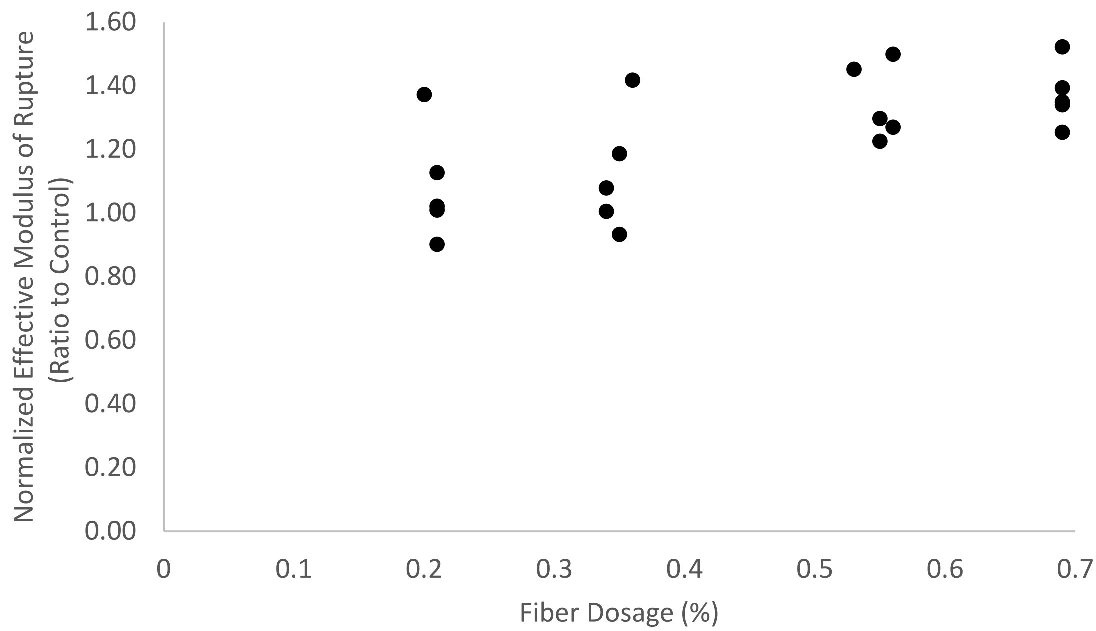

Figure 6.16 Effect of fiber dosage on normalized effective modulus of rupture

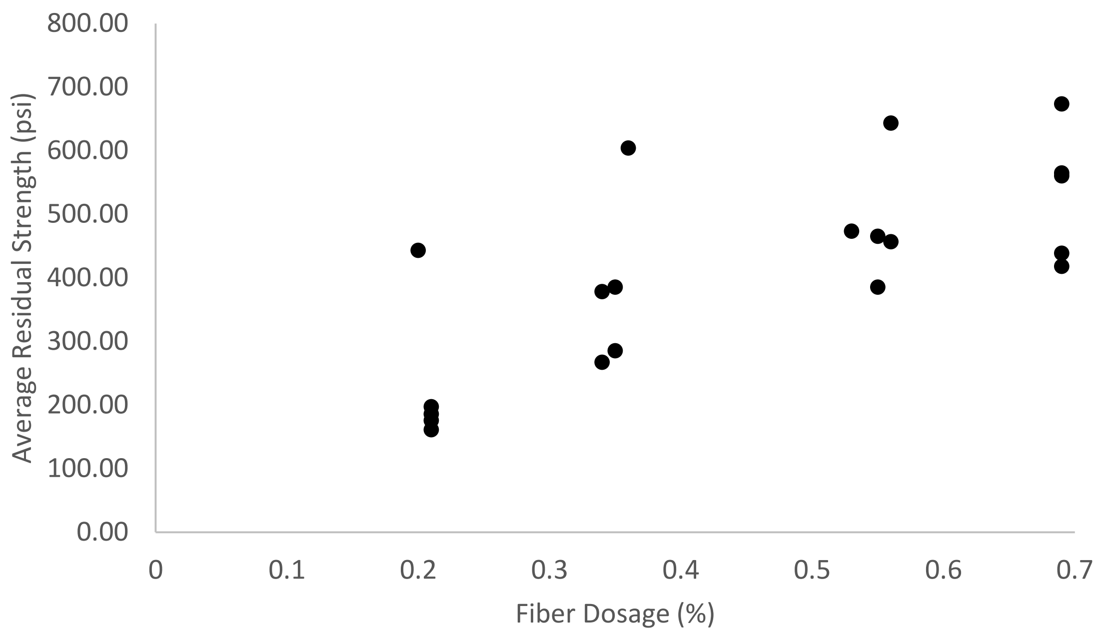

Figure 6.17 Effect of fiber dosage on average residual strength

The obtained equivalent flexural strength values for some FRC mixes with Strux 90/40 and TUF-STRAND SF fibers were compared with available manufacturers' claims (Appendix D). While not exactly the same, the results seemed to be in very good agreement with the claims as shown in Table 6.4.

Table 6.4 Comparison between measured and claimed equivalent flexural strength ratio

Fiber	Study Results		Fiber Data Sheet	
	Dosage Rate (lb/yd^3)	Ratio (%)	Dosage Rate (lb/yd^3)	Ratio (%)
Strux 90/40	3	22	3	20
	5	30	5	28.5
	8	46	7.75	40.5
TUF-STRAND SF	5	32	5	35

A similar comparison was also carried out for average residual strength values of FRC mixes with TUF-STRAND SF fiber. The manufacturer's data sheet (Appendix D) provided a value of 179 psi for a mix with 3.7 lb/yd^3 dosage rate, while this study showed values of 161 psi and 268 psi for mixes with 3 lb/yd^3 and 5 lb/yd^3, respectively. By fitting the data of TUF-STRAND SF mixes with a linear regression and forcing the y-intercept to be zero, it was possible to estimate a value of 174 psi for a dosage rate of 3.7 lb/yd^3, which is very close to the value claimed by the manufacturer.

Since it was shown in Section 6.3 that, apart from steel fibers, fiber type did not have any significant effect on the flexural performance, it is possible to come up with a linear regressions that could be used to estimate the synthetic fiber dosage (up to 0.69% by volume) needed to achieve certain values for certain properties regardless of the fiber type used (Figure 6.18 through Figure 6.21). It is important to note, however, that these regressions would only be applicable for the specific mix design and synthetic fiber types used in this study. It is possible to use these regression lines to conclude that an increase of 0.1% in the fiber dosage results in an increase of 74 lb.in, 8%, 37 psi, and 81 psi in toughness, equivalent flexural strength ratio, modulus of rupture, and average residual strength, respectively. This conclusion is comparable to that obtained from the literature where an increase of 94 psi in average residual strength was observed for an increase of 0.1% in steel fiber dosage (Lee, 2017).

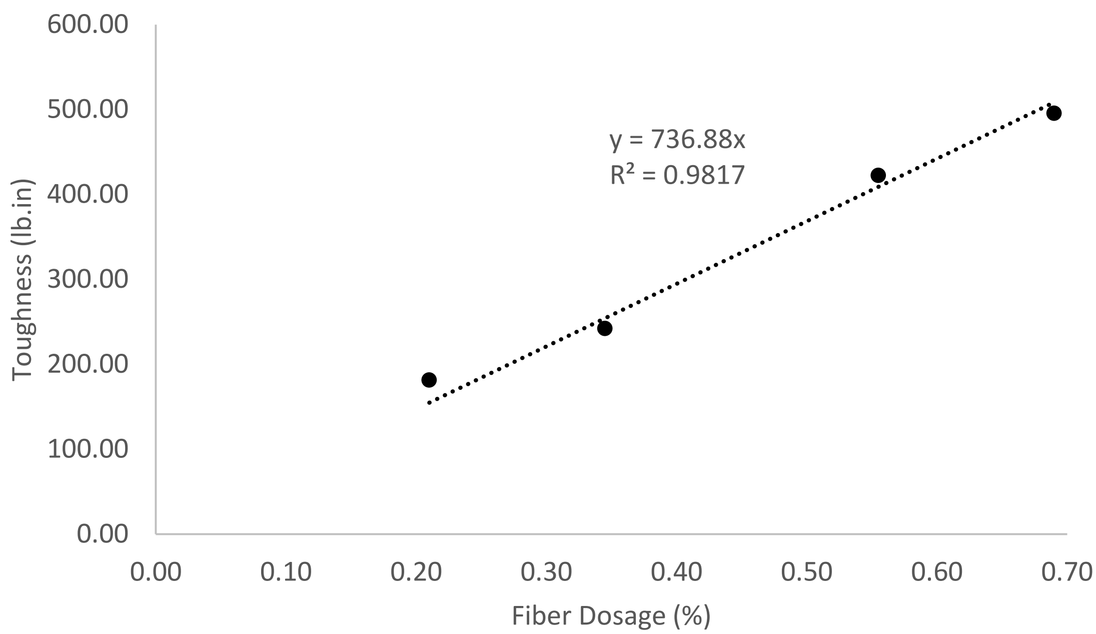

Figure 6.18 Linear regression for toughness

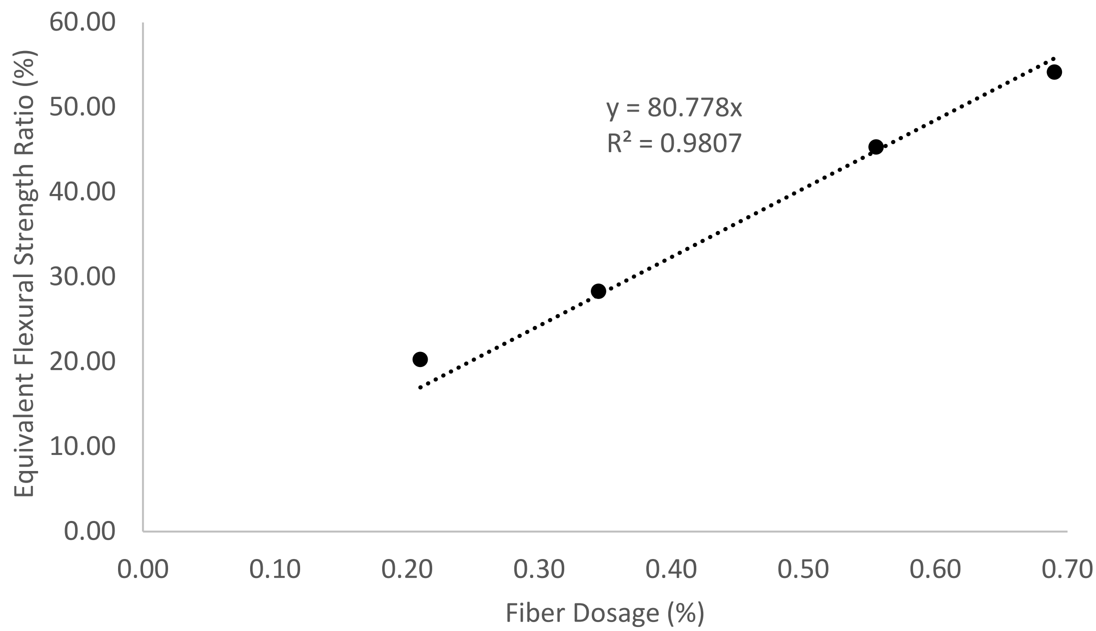

Figure 6.19 Linear regression for equivalent flexural strength

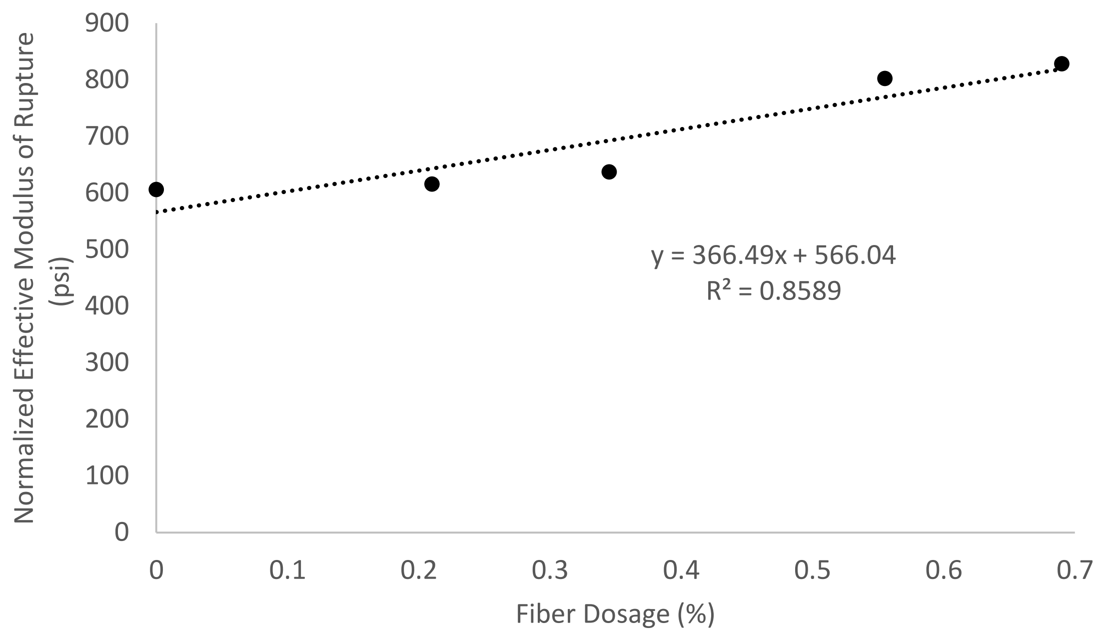

Figure 6.20 Linear regression for normalized effective modulus of rupture

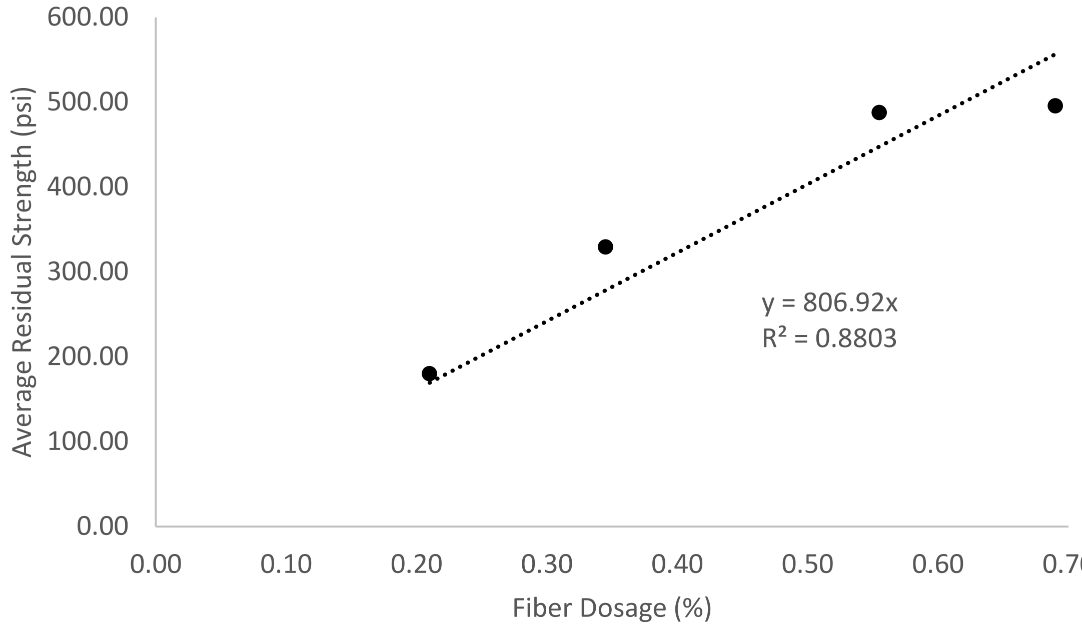

Figure 6.21 Linear regression for average residual strength

While no specifications for average residual strength of FRC mixes were found in SDDOT Standard Specifications for Roads and Bridges, some specifications for certain applications were obtained from other DOTs. For instance, Georgia DOT requires the FRC average residual strength to be a minimum of 150 psi with a synthetic fiber dosage between 5 lb/yd^3 and 10 lb/yd^3 for general structural applications (Waters, 2014). This limit was satisfied by all FRC mixes adopted in this study, even those with 3 lb/yd^3 synthetic fiber dosage. For curb, gutter, sidewalk, and riprap applications, Texas DOT Department Materials Specification requires the FRC average residual strength to be a minimum of 115 psi, which was also met by all adopted FRC mixes. Washington DOT Standard Specifications for Road, Bridge, and Municipal Construction specifies an average residual strength of 175 psi with a minimum synthetic fiber dosage of 3.75 lb/yd^3 for precast drainage unit FRC applications. This limit was also met by all synthetic FRC mixes with dosages greater than or equal to 3.75 lb/yd^3.

6.4.3 Impact Strength

Similar to fiber type, fiber dosage did not seem to have had a great effect on the impact performance of FRC except for the 0.69% dosage rate, where improvement in the failure point was observed as shown in Figure 6.23. Overall, there seems to have been an improvement in impact performance for most mixes regardless of dosage rate. However, some mixes attained a lower number of blows at failure compared with the control mix. This could be due to the difference in failure modes between the control specimen and the FRC specimens. When the control specimen failed, it was divided into two separate pieces. However, when the FRC specimens failed, they were typically divided into at least three separate pieces. Since the control mix specimen was split into only two pieces, it was only displaced in two directions, normal to the cracking plane, when the impact load was applied. Therefore, the cracked specimen was able to reach two of the positioning lugs relatively easily, while it took longer for it to reach a third positioning lug due to it only being displaced in a direction normal to the cracking plane. Therefore, the result for the control mix may have been skewed due to the different failure modes between the control specimen and the FRC specimens. The different failure modes in FRC could be attributed to the transfer of stresses across the initial cracking plane by the fibers. Since the stresses were not able to be alleviated at the initial cracking plane, the stresses were then transferred to a different, uncracked section of the specimen in order to help absorb a portion of the impact loading. When the stresses became too large for the uncracked section, another crack formed, which was responsible for the separation of the specimen into more than two pieces. Another explanation for this discrepancy could be because saw-cutting the FRC specimens might have had created unwanted stresses due to the presence of fibers, leading to premature failure. However, since not all specimens experienced reduced impact performance, the authors believe these readings were just outliers caused by a lack of sample replications. This becomes even more evident considering the erraticism of the readings obtained from replicates in other tests.

This test could be considered qualitative in nature and not very telling of the actual impact resistance of FRC. The authors believe there are much more accurate experiments, such as testing cylinders under dynamic loading with variable strain rates. Previous studies showed enhanced compressive strength and energy absorption capacity of FRC under dynamic loading (Zhang and Mindess, 2010; Pyo, 2016).

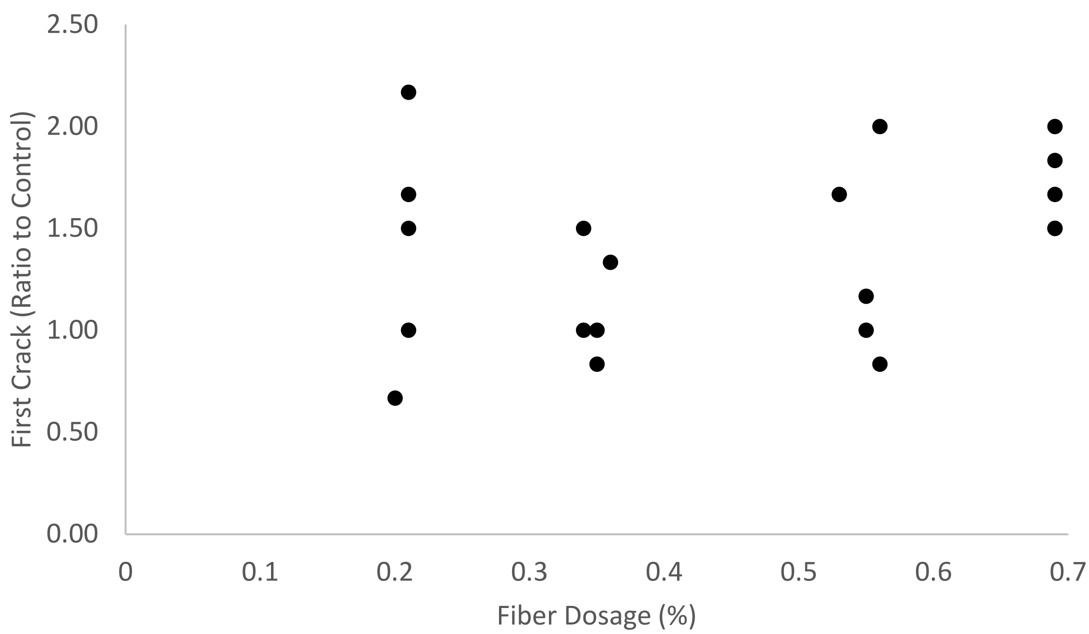

Figure 6.22 Effect of fiber dosage on the first crack point of the impact test

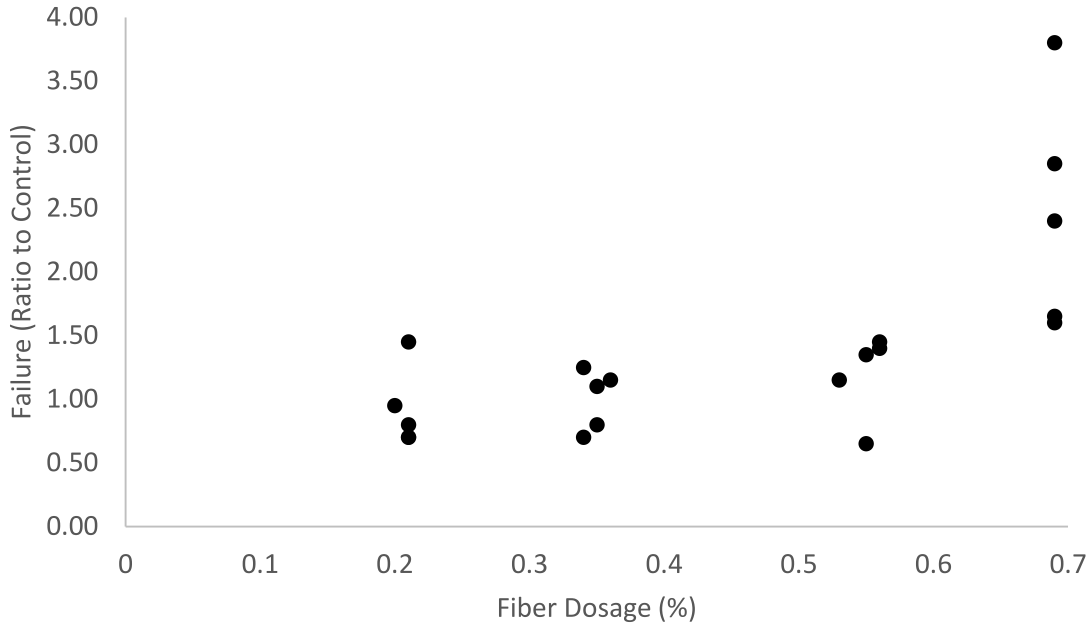

Figure 6.23 Effect of fiber dosage on the failure point of the impact test

6.5 Fiber Distribution

An example of a cut synthetic FRC specimen is shown in Figure 6.24, and an example of a cut steel FRC specimen is shown in Figure 6.25. As observed in these figures, the fibers seemed to be distributed uniformly throughout the concrete, indicating that the mixing procedure was acceptable for all five fibers used. Also, there was no fiber balling observed on the cut surfaces, which confirmed initial observations during mixing. Therefore, all these fibers can successfully be added to a concrete mix using standard mixing and consolidation procedures at volume fractions less than 0.70% without having any fiber balling or distribution issues.

Figure 6.24 Cut surface of a synthetic FRC specimen

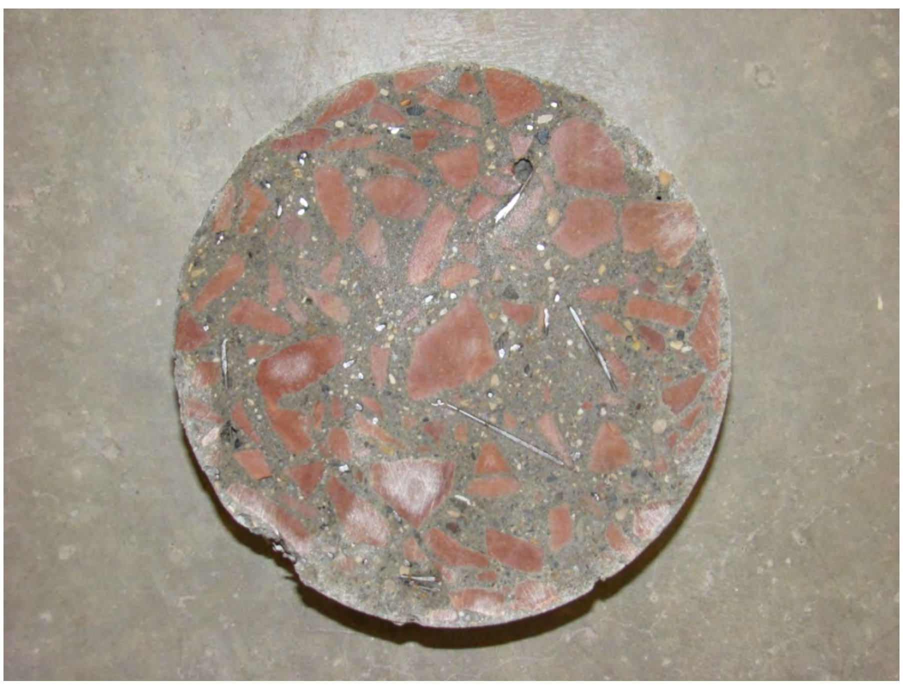

Figure 6.25 Cut surface of a steel FRC specimen

The finished surface of FRC with high dosage rates did not come out to be as smooth as the finished surface of FRC with a small amount of fibers. This is illustrated in Figure 6.26, which shows a “hairy” finished surface of a synthetic FRC specimen with a dosage rate of 10 lb/ yd^3. This hairy finish did not diminish any of the specimen’s properties, but it made the specimen less aesthetically pleasing. This would have been an important factor if the FRC is used for an application requiring a smooth architectural finish. However, this is generally not a concern for driving surfaces such as bridge decks and approach slabs, which were two of the main focuses in this research.

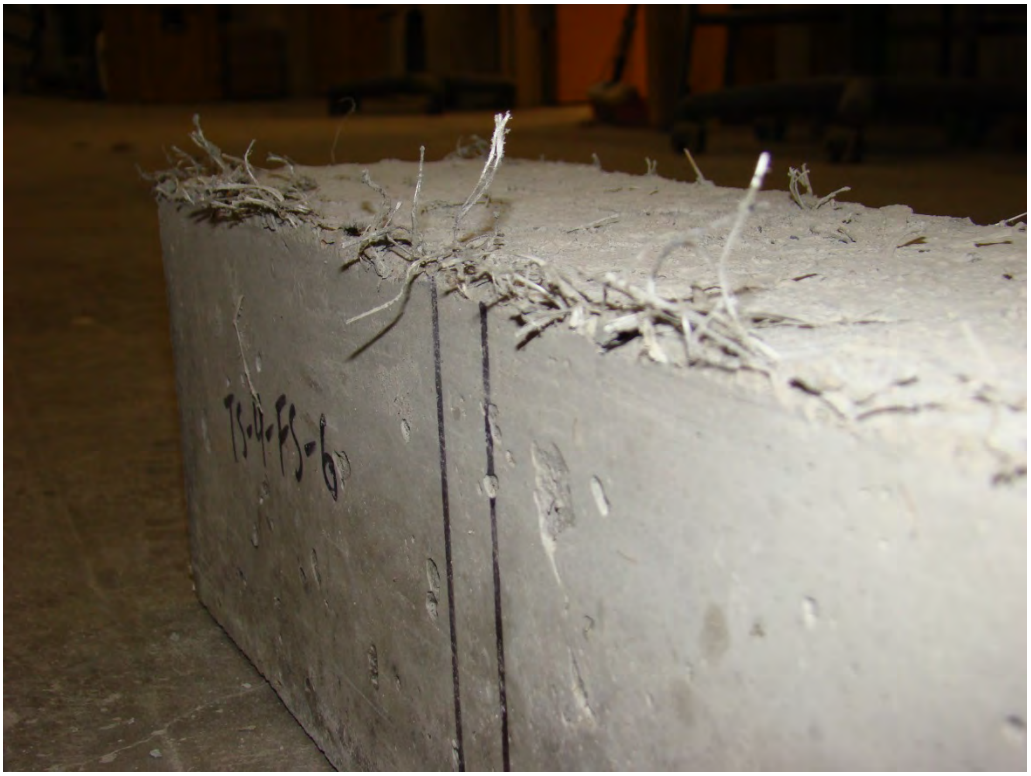

Figure 6.26 Hairy finished surface of a synthetic FRC specimen

For the steel FRC finished surfaces, there were more hazards introduced. Steel fibers occasionally protruded from the surface of the concrete specimen, creating a sharp hazard. Figure 6.27 shows an example of this where a couple of steel fibers were sticking out of the concrete surface. This hazard could potentially be very dangerous if located near places where pedestrians could injure themselves on a sharp steel fiber. However, if this is present on an application such as a bridge deck, where pedestrians should not be walking and traffic should be driving over it often, the protruding steel fibers will likely be worn off (Maggenti et al., 2013). Therefore, steel fibers sticking out of the concrete is potentially a hazard for some applications, but could be considered acceptable for other applications.

Figure 6.27 Steel fibers sticking out of the concrete surface

7. FINDINGS AND CONCLUSIONS

The study presented in this report was conducted to 1) identify best practices for design and construction of fiber reinforced concrete (FRC) in transportation structural applications, 2) perform an exhaustive review of past performance, costs, benefits, and drawbacks of FRC, and 3) develop guidance for design, material selection, construction, testing, and application of FRC in South Dakota. The following findings and conclusions are based on the literature review, interviews, and experimental tests that were carried out in this study.

7.1 Literature Findings and Conclusions

Following are the findings and conclusions that are mainly based on the literature review and interviews.

- Fibers enhance the ductility, toughness, impact resistance, tensile strength, flexural strength, post-crack load-carrying capacity, fatigue life, abrasion resistance, scaling resistance, shrinkage cracking resistance, durability, and cavitation resistance of the concrete (Ramakrishnan & Deo, 1998; Ostertag & Blunt, 2008).
- There is a lack of comprehensive guidance and specifications regarding design, material selection, construction, and testing of FRC.
- While SDDOT has no current specifications, there are some brief specifications available from Georgia DOT, Texas DOT, Illinois DOT, and Washington DOT. SDDOT has some plan notes from previous FRC projects (Waters, 2014; Krstulovich, 2014; Grannes & Hodges, 2014).
- There is a lack of sufficient studies looking at the effect of fiber type and fiber dosage on the various fresh and hardened properties of FRC.
- Fibers can significantly decrease the consistency of fresh concrete (Dunn & Wolf, 2001).
- Increasing paste content can increase the slump of FRC while maintaining the required strength (Ramakrishnan, 1997).
- Mix design, preparation, mixing, testing, and finishing procedures of FRC are similar to that of PCC except as detailed in Appendix G.
- Fiber balling can be minimized by increasing mixing time, increasing paste volume, and choosing fibers with low aspect ratios (Ramakrishnan & Deo, 1998; Ramakrishnan & Tolmare, 1998; Grannes & Hodges, 2014; Johnston, 2014; Strand et al., 2014).
- Fibers alter the compressive failure mode of concrete cylinders (Noushini et.al, 2014).
- The effect of fibers on the compressive strength of FRC is inconsistent among the different studies found in the literature (Noushini et al., 2014; Saad et al., 2015; Li, 1992; Kim, et al., 2013).
- Fibers can increase the flexural strength by 25% to 55% compared with conventional PCC (Roesler et al., 2004).
- Fibers improve crack growth resistance, energy absorption capacity, and compressive strength under impact loading conditions (Bindiganavile & Banthia, 2005; Pyo, 2016; Zhang and Mindess, 2010).
- Fibers can decrease exposed aggregates on the surface of concrete when subjected to freeze-thaw conditions by alleviating bond deterioration (Ostertag & Blunt, 2008).

- Fibers do not seem to significantly alter the permeability of concrete except for the case of UHPC where it could reduce permeability (Ramakrishnan & Santhosh, 2000; Bierwagen, 2014).
- Macro fibers can increase the abrasion resistance by 14% compared with a 7% increase due to micro fibers, which could be due to the better bond that macro fibers have with the paste (Grdic et al., 2012).
- Fibers do not decrease the bond strength (Ramakrishnan & Santhosh, 2000).
- FRC develops many small shrinkage cracks compared with few large shrinkage cracks for conventional PCC (Lawler et al., 2005).
- FRC is commonly evaluated in the field through the bond strength test and surface inspection (Dunn & Wolf, 2001; Ramakrishnan & Santhosh, 2000).
- Crack widths of FRC can be further reduced by using higher mortar content (Ramakrishnan, 1997).
- The high cost of the fibers can sometimes result in the doubling of the cost of the overall structural component. UHPC is even more expensive, but could be justified for critical applications (Enbrecht, 2014; Gilsrud et al., 2014; Hedman, 2014; Letcher, 2014; Whitney, 2014; Abu-Hawash, 2014; Juntunen, 2014).
- Depending on the structural component, FRC demolition can sometimes be costly and tedious due to the tendency of the fibers to hold broken concrete pieces together (Maggenti et al., 2013).
- Early-age cracking could be better mitigated through the use of a combination of synthetic micro fibers and macro fibers (Maggenti et al., 2013).

2.1. Experimental Findings and Conclusions

Following are the findings and conclusions that are mainly based on experimental results.

- The difference in results between the specimen replicates for each test can be very significant for FRC due to possible differences in fiber distribution among the specimens.
- Regardless of fiber type or dosage, fibers have resulted in the reduction of compressive strength and modulus of elasticity of concrete by an average of 18 % and 13%, respectively. These findings matched some studies in the literature, but other studies made opposite conclusions.
- The type of synthetic fibers used in the concrete has no significant effect on any of the fresh and hardened concrete properties that were measured in this study.
- Steel FRC has superior flexural properties compared with synthetic FRC, but there is a concern of it being susceptible to corrosion (which was not examined in this study). Since it is not directly exposed to deicer salt, Jersey barrier is one application where steel fibers could be used.
- Steel fibers are twice the cost of synthetic fibers, but they can perform better or at least as good as synthetic fibers at half the dosage rate, giving an additional advantage of increased workability.
- The most cost-effective synthetic fibers among the tested ones are Fibermesh 650 and FORTA-FERRO fibers.
- Fiber dosage does not have any significant effect on the temperature, unit weight, or fresh air content of concrete.

- Slump decreases nonlinearly with the increase in fiber dosage. The average maximum slump drop was about 2.75 inches at the highest dosage rate of 0.69%.
- For the specific mix design adopted in this study and for synthetic FRC with fiber dosages between 0.21% and 0.69%, data showed that an increase of 0.1% in fiber dosage results in an increase of:
    - 74 lb.in in toughness
    - 8% in equivalent flexural strength ratio
    - 37 psi in modulus of rupture
    - 81 psi in average residual strength
- Experimental results were in good agreement with available manufacturers' claims.
- The adopted impact test gave inconclusive results due to its qualitative nature and due to the lack of specimen replicates.
- Saw-cut surfaces of FRC cylinders showed uniform fiber distribution and no fiber balling, indicating the adequacy of five minutes of additional mixing.

8. RECOMMENDATIONS

Based on the findings of this study, the research team offers the following recommendations.

8.1 Fiber Type and Dosage

Table 8.1 presents recommendations for fiber type and dosage.

Table 8.1 Recommendations for fiber type and dosage

Srl. No.	Recommendation	Justification
1	Fibers with low aspect ratios should be used (less than 100, but not less than 40)	Minimize fiber balling
2	Steel fibers should be avoided in components that would be exposed to chloride penetration	Susceptibility to corrosion
3	Among the tested synthetic fibers, FORTA-FERRO should be used	Its cost-effectiveness and low aspect ratio
4	Minimum fiber volume fraction should be 0.2%	Manufacturer suggestion and lack of data for lower dosages
5	The minimum fiber dosage that satisfies required properties should be chosen	Ensure cost-effectiveness and higher slump values

8.2 Design

Table 8.2 presents recommendations for FRC design.

Table 8.2 Recommendations for FRC design

Srl. No.	Recommendation	Justification
1	Higher slump values, compared with PCC mixes, should be targeted for FRC mixes	To compensate for the reduced workability of FRC mixes
2	Fine to coarse aggregate ratio should be increased	To provide higher mortar content that is helpful in increasing workability, minimizing fiber balling, and reducing crack widths
3	Up to 20% and 15% reduction in compressive strength and modulus of elasticity, respectively, should be taken into consideration when designing FRC mixes	This reduction was observed in the data

8.3 Construction

Table 8.3 presents recommendations for construction of FRC.

Table 8.3 Recommendations for construction of FRC

Srl. No.	Recommendation	Justification
1	A bridge deck paver should be used for FRC applications, such as bridge deck overlays, instead of a low-slump paver	Better and easier consolidation
2	Manual consolidation should be completely avoided	Insufficient consolidation
3	FRC tining should be modified by either reducing the tining angle, turning the tining rake over, or grinding the tining grooves after hardening	To avoid pulling fibers from the surface of concrete
4	A burlap drag or a broom should be used instead of a carpet drag	To avoid pulling fibers from the surface of concrete

8.4 Laboratory and Field Testing

Table 8.4 presents recommendations for laboratory and field testing of FRC.

Table 8.4 Recommendations for laboratory and field testing of FRC

Srl. No.	Recommendation	Justification
1	For laboratory testing, 5 minutes of additional mixing time should be provided for FRC mixes	To ensure uniform fiber distribution and minimize fiber balling
2	Flexural laboratory tests should be given emphasis. The average residual strength test is especially the most important	Flexural properties are the ones affected most by the introduction of fibers
3	FRC mixes should be at least duplicated to ensure better statistical confidence	High variability in the results of FRC mixes
4	For each hardened test, at least 5 specimens should be tested to ensure better statistical confidence	High variability in the results of FRC mixes
5	Field surface inspections should be carried out on FRC structures periodically to monitor their long-term performance	Lack of long-term testing data for FRC
6	Bond strength testing of extracted cores from the field should be conducted for composite components	To ensure adequate bond between FRC components and other components

8.5 Guidelines for FRC Material Selection, Mix Design, Construction, and Testing

Based on the above recommendations, guidelines for FRC material selection, mix design, construction, and testing for South Dakota are presented in Appendix G of this report.

8.6 Future Research

Table 8.5 presents recommendations for future FRC research.

Table 8.5 Recommendations for future FRC research

Srl. No.	Recommendation	Justification
1	Instead of the empirical correlations that are usually obtained from experimental results, it is better to come up with theoretical correlations and then verify them against comprehensive experimental results obtained from very different mixes	Empirical correlations cannot be guaranteed to work under all circumstances due to limitations in the testing matrix
2	For future studies, mixes should be at least duplicated to attain better statistical confidence in the correlations	High variability in the results of FRC mixes
3	The effect of other aspects of the mix design such as mortar content, water to cementitious materials ratio (w/c), coarse aggregate, and cementitious materials should be studied	Lack of data
4	Other, more informative, workability measurements such as rheology should be explored	To better correlate fiber dosage to workability of FRC mixes
5	Effect of fiber type and dosage on impact performance of FRC structures should be studied using more reliable instrumental impact tests incorporating compressive and tension loading with variable strain rates	Unreliability of the Drop-Weight Impact test due to its qualitative nature
6	Effect of fiber type and dosage on fatigue resistance, abrasion resistance, and durability of FRC structures should be studied since they are very important for transportation applications	Lack of data

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APPENDIX A: FRC CATALOG

Descriptions for each of the fibers that were discovered during the literature review are provided on the following pages in the form of a fiber catalog. For each fiber, the fiber classification, properties, benefits, and general applications are provided along with a picture of the fiber obtained from the manufacturer's website. The fibers presented are listed in alphabetical order. The steel fibers are shown first and are followed by the synthetic fibers. It is important to note that two of the fibers listed have been discontinued (Dramix RC-80/60 and 3M Polyolefin). These fibers were both commonly used in South Dakota and the surrounding region.

A-1: Steel Fibers

- Dramix 5D
- Dramix RC-80/60

Dramix 5D

Manufacturer:

- Bekaert

Classification:

- Steel Fiber

Properties:

- Length: 2.4 in
- Aspect Ratio: 65
- Specific Gravity: 7.85
- Tensile Strength: 333.5 ksi
- Modulus of Elasticity: 30,000 ksi

Benefits:

- According to Bekaert, Dramix 5D:
  - Provides perfect anchorage with its non-deformable hook, which keeps the fibers firmly in place inside the concrete.
  - Enhances concrete strength and ductility with the elongation of the ductile wire.

Applications/Experience:

- Bekaert recommends usage at a minimum dosage rate of 25 lb/yd^3 in:
  - Bridges
  - Structural floors
  - Foundation slabs
  - Suspended structures

Dramix RC-80/60
(Fiber discontinued/replaced with Dramix 3D/4D/5D series)

Manufacturer:

- Bekaert

Classification:

- Steel Fiber

Properties:

- Length: 2.36 in.
- Aspect Ratio: 75
- Specific Gravity: 7.85
- Tensile Strength: 180 ksi
- Modulus of Elasticity: 30,000 ksi

Benefits:

- According to Bekaert, Dramix RC-80/60:
    - Provides high ductility and load bearing capacity.
    - Provides optimum anchorage and controlled pull-out with its hooked ends.
    - Offers an efficient and cost-effective alternative for WWM or light rebar reinforcement.

Applications/Experience:

- Bekaert recommends usage at a minimum dosage rate of 20 lb/yd^3 in:
    - Structural elements
    - Precast elements
    - Industrial floors
- SDDOT has used Dramix RC-80/60 fibers at 66 lb/yd^3 in:
    - Full-depth pavement on Sheridan Lake Road in Rapid City, SD, in 1992 (Ramakrishnan, 1997).
        - Provided a slight increase in flexural strength, and a considerable increase in toughness, impact, fatigue, and post-crack load-carrying capacity.

- Missouri DOT (MoDOT) has used Dramix RC-80/60 fibers at 75 lb/yd^3 in:
    - Unbonded PCC pavement overlay on I-29 in Atchison County, Missouri, in 2000 (Chojnacki, 2000).
        - Increased the cost of the concrete by \$47/yd^3 when compared with plain concrete.
        - Had no influence on compressive or flexural strength.
        - Exhibited more transverse cracking than an adjacent unbonded PCC pavement overlay that was reinforced with 3M Polyolefin fibers.
        - Restricted the opening of cracks more than the 3M Polyolefin fibers.

A-2: Synthetic Fibers

- 3M Polyolefin
- Fibermesh 650
- FORTA-FERRO
- Novomesh 950
- RF4000
- RSC15
- Strux 90/40
- TUF-STRAND MaxTen
- TUF-STRAND SF

3M Polyolefin
(Fiber discontinued)

Manufacturer:

- 3M

Classification:

- Synthetic Macro Fiber
    - Polyolefin

Properties:

- Length: 2 in.
- Aspect Ratio: 80
- Specific Gravity: 0.91
- Tensile Strength: 40 ksi
- Modulus of Elasticity: 384 ksi

Benefits:

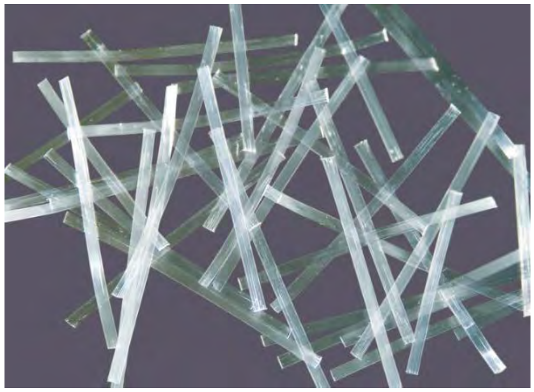
- According to 3M, 3M Polyolefin:
    - Enhances toughness, flexural strength, impact strength, and fatigue endurance.
    - Controls thermal cracking, along with plastic and drying shrinkage cracking, as a three-dimensional reinforcement.
    - Disperses uniformly throughout the concrete.
    - Provides an alternative to WWF and other secondary reinforcement.

Applications/Experience:

- 3M recommends usage at a dosage rate of 25 lb/yd^3 in:
    - Pavements and whitetoppings
    - Bridge deck overlays
    - Precast elements
- SDDOT has used 3M Polyolefin fibers at a dosage rate of either 20 or 25 lb/yd^3 in:
    - Full-depth pavement, bridge deck overlays, Jersey barriers, and whitetopping during a project in 1994 (Ramakrishnan, 1997).

  - Full-depth bridge deck and Jersey barriers during a project in 1995 (Ramakrishnan and Deo, 1998).
  - Full-depth pavement during a project in 1996 (Ramakrishnan and Tolmare, 1998).
  - Bridge deck overlays during a project in 1997 (Ramakrishnan and Deo, 1998).
    - Considerable increase in toughness, impact, fatigue, endurance limit, and post-crack load-carrying capacity.
    - Was determined to not be a favorable material for construction of full-depth pavements, due to its high initial cost.
- MoDOT has used 3M Polyolefin fibers at a dosage rate of 25 lb/yd^3 in:
  - Unbonded PCC pavement overlay on I-29 in Atchison County, Missouri in 2000 (Chojnacki, 2000).
    - Increased the cost of the concrete by \$47/yd^3 when compared to plain concrete.
    - Exhibited less transverse cracking than an adjacent unbonded PCC pavement overlay that was reinforced with Dramix RC-80/60 fibers.
    - Restricted the opening of cracks less than the Dramix RC-80/60 fibers.
- North Dakota DOT (NDDOT) has used 3M Polyolefin fibers at a dosage rate of 25 lb/yd^3 in:
  - Whitetopping an I-94 bridge over Hay Creek near Bismarck, ND, in 2001 (Dunn and Wolf, 2001).
    - Seemed to help control cracks from widening.
    - Distresses in whitetopping were believed to have occurred due to a weak subgrade.

Fibermesh 650



Manufacturer:

- Propex

Classification:

- Synthetic Macro Fiber
  - Polypropylene

Properties:

- Length: 1.5 - 1.75 in.
- Aspect Ratio: 96.5
- Specific Gravity: 0.91
- Tensile Strength: 89 ksi
- Modulus of Elasticity: 1088 ksi

Benefits:

- According to Propex Fibermesh, Fibermesh 650:
  - Provides increased flexural toughness (residual strength) due to greater surface area, and enhanced impact, abrasion, and shatter resistance.
  - Improves concrete ductility and durability, and controls drying shrinkage and temperature cracking.
  - Provides concrete secondary reinforcement when used as an alternate to WWF and light rebar.

Applications/Experience:

- Propex Fibermesh recommends usage at a minimum dosage rate of 3 lb/yd^3 in:
  - Slabs-on-ground
  - Overlays and toppings
  - Composite metal decks
- South Dakota DOT (SDDOT) has used Fibermesh 650 fibers at 8 lb/yd^3 for:
  - Bridge deck overlay on I-90 bridge at Exit 30 in 2010.
  - Bridge deck overlay on I-90 bridge over 218th St. near Piedmont in 2013.
  - Bridge deck overlay on Highway 20 near Camp Crook in 2013.

FORTA-FERRO

Manufacturer:

- Forta Corporation

Classification:

- Synthetic Macro Fiber
    - 100% virgin copolymer/polypropylene

Properties:

- Length: 1.5 in., 2.25 in.
- Aspect Ratio: 79.5
- Specific Gravity: 0.91
- Tensile Strength: 83 - 96 ksi
- Modulus of Elasticity: 690 ksi

Benefits:

- According to Forta Corporation, FORTA-FERRO:
    - Is non-corrosive and non-magnetic, and reduces plastic and hardened concrete shrinkage
    - Improves impact strength, fatigue resistance, and concrete toughness.
    - Provides enhanced durability, structural enhancements, and effective secondary/temperature crack control.

Applications/Experience:

- Forta Corporation recommends usage at a dosage rate between 3 - 30 lb/yd^3 in:
    - Bridge decks
    - Industrial floors
    - Precast products

- Forta Corporation recommends using FORTA-FERRO at the following dosage rates for the corresponding desired effects:
    - 3 lb/yd^3 → Temperature and shrinkage reinforcement only
    - 5 lb/yd^3 → Moderate benefits to reduce cracking
    - 7.5 lb/yd^3 → Best benefits and highest probability to reduce cracking from tension, curling, and fatigue
- Birdwell and Associates in Lakeland, FL used FORTA-FERRO at 7.5 lb/yd^3 for a “roller rink” floor (FORTA Corporation, 2013).
    - Fibers distributed evenly throughout the concrete, reduced slab shrinkage and curling, and controlled cracking.

Novomesh 950

Manufacturer:

- Propex

Classification:

- Synthetic Microfiber and Macro Fiber blend
  - 100% virgin polypropylene microfibers
  - Polypropylene/polyethylene macro fibers

Properties:

- Microfibers:
  - Length: 0.5 - 0.75 in.
  - Specific Gravity: 0.91
- Macro fibers:
  - Length: 1.8 in
  - Aspect Ratio: 55
  - Specific Gravity: 0.91

Benefits:

- According to Propex, Novomesh 950:
  - Provides impact, abrasion, and shatter resistance.
  - Improves durability and residual strength.
  - Controls drying shrinkage and temperature cracking.
  - Provides an alternate form of secondary reinforcement in place of WWM and light rebar.

Applications/Experience:

- Propex recommends usage at a minimum dosage rate of 5 lb/yd^3 in:
  - Overlays and toppings
  - Pavements
  - Slabs-on-ground

- Oregon DOT (ODOT) has used Novomesh 950 at an unknown dosage rate in:
    - Full-depth bridge deck on the I-5 Willamette River Bridge in 2012 (ODOT, 2012).
        - Durability of the bridge deck was increased and cracking decreased.

RF4000

Manufacturer:

- Nycon Corporation

Classification:

- Synthetic Macro Fiber
  - Polyvinyl Alcohol

Properties:

- Length: 1.25 in.
- Aspect Ratio: 50
- Specific Gravity: 1.3
- Tensile Strength: 120 ksi

Benefits:

- According to Nycon Corporation, RF4000:
  - Improves impact, shatter, and abrasion resistance of concrete.
  - Enhances durability and toughness of concrete.
  - Reduces formation of plastic shrinkage cracking by providing a multi-dimensional reinforcement.

Applications/Experience:

- Nycon Corporation recommends usage at a dosage rate of 6 lb/yd^3 combined with Nycon's RSC15 fibers at a dosage rate of 3 lb/yd^3 in:
  - Slab-on-ground
  - Precast elements
- Minnesota DOT (MNDOT) has used RF4000 fibers with RSC15 fibers at equal dosage rates, varying between 16 - 24 lb/yd^3 total, for thin bonded pavement overlay in 2011 (Akkari, 2011).
  - Determined that the increase in strength provided by the fibers in their concrete mix was not high enough to be found suitable for an overlay application.

RSC15

Manufacturer:

- Nycon Corporation

Classification:

- Synthetic Microfiber
  - Polyvinyl Alcohol

Properties:

- Length: 0.375 in.
- Aspect Ratio: 250
- Specific Gravity: 1.3
- Tensile Strength: 210 ksi

Benefits:

- According to Nycon Corporation, RSC15:
  - Improves impact, shatter, and abrasion resistance of concrete.
  - Enhances durability and toughness of concrete.
  - Reduces formation of plastic shrinkage cracking by providing a multi-dimensional reinforcement.

Applications/Experience:

- Nycon Corporation recommends usage at a dosage rate of 3 lb/yd^3 combined with Nycon's RF4000 fibers at a dosage rate of 6 lb/yd^3 in:
  - Slab-on-ground
  - Precast elements
- MNDOT has used RSC15 fibers with RF4000 fibers at equal dosage rates, varying between 16 - 24 lb/yd^3 total, for thin bonded pavement overlay in 2011 (Akkari, 2011).
  - Determined that the increase in strength provided by the fibers in their concrete mix was not high enough to be found suitable for an overlay application.

Strux 90/40

Manufacturer:

- Grace Concrete Products

Classification:

- Synthetic Macro Fiber
  - Polypropylene/polyethylene blend

Properties:

- Length: 1.55 in.
- Aspect Ratio: 90
- Specific Gravity: 0.92
- Tensile Strength: 90 ksi
- Modulus of Elasticity: 1378 ksi

Benefits:

- According to Grace Concrete Products, Strux 90/40:
  - Enhances toughness, impact, and fatigue resistance of concrete.
  - Is abrasion and corrosion resistant, and controls plastic and drying shrinkage cracks.
  - Evenly distributes throughout the concrete matrix, which eliminates concerns of proper positioning of reinforcement.
  - Is designed to replace secondary reinforcement (e.g., WWF, steel fibers, and light rebar), which decreases labor costs and construction time.
  - Provides flexural toughness values, according to ASTM C1609, for a 4000 psi concrete as follows:
    - Dosage rate = 3 lb/yd^3 → Toughness = 160 lb-in
    - Dosage rate = 5 lb/yd^3 → Toughness = 240 lb-in
    - Dosage rate = 7.75 lb/yd^3 → Toughness = 330 lb-in

Applications/Experience:

- Grace Concrete Products recommends usage at a dosage rate between 3 - 12 lb/yd^3 in:
  - Slab-on-ground flooring
  - Thin-walled precast elements
  - Composite steel floor deck
- California DOT (Caltrans) has used Strux 90/40 fibers at 3 lb/yd^3 with shrinkage reducing admixture (SRA) at 0.75 - 1.5 gal/yd^3 to attempt to create a "crackless" concrete for:
  - "Deck-on-deck" rehabilitation of the Pit River Bridge in 2007 (Maggenti et al., 2013).
    - After five years of service, concrete with Strux 90/40 and SRA exhibited very limited cracking with very thin cracks being kept intact by the fibers.
    - Within just six weeks, control sections without Strux 90/40 and SRA exhibited substantial cracking.
  - 5-inch thick bridge deck on precast box beams over Craig Creek on SR 99 in 2011 (Maggenti et al., 2013).
    - After 14 months of service, no visible cracking was noted during inspection.
- South Dakota DOT (SDDOT) has used Strux 90/40 fibers at 8 lb/yd^3 in:
  - Bridge deck overlays over Highway 18 on Highway US385 in Fall River County in 2014.

TUF-STRAND MaxTen

Manufacturer:

- The Euclid Chemical Company

Classification:

- Synthetic Macro Fiber
    - 100% virgin blended copolymer

Properties:

- Length: 0.75 in, or 1.5 in.
- Aspect Ratio: 39 or 79
- Specific Gravity: 0.91
- Tensile Strength: 90 - 100 ksi
- Modulus of Elasticity: 1380 ksi

Benefits:

- According to The Euclid Chemical Company, TUF-STRAND MaxTen:
    - Increases impact, shatter, and abrasion resistance of concrete.
    - Increases overall durability, fatigue resistance, and flexural toughness.
    - Reduces segregation, plastic settlement, and shrinkage cracking of concrete.
    - Provides a three-dimensional reinforcement against micro- and macro-cracking.
    - Provides a cheaper alternate to steel fibers and WWM.

Applications/Experience:

- The Euclid Chemical Company recommends usage at a dosage rate between 3 - 5 lb/yd^3 in:
    - Bridge decks
    - Whitetoppings and pavements
    - Industrial and residential floors
    - Thin walled precast

TUF-STRAND SF

Manufacturer:

- The Euclid Chemical Company

Classification:

- Synthetic Macro Fiber
  - Polypropylene/polyethylene blend

Properties:

- Length: 2.0 in.
- Aspect Ratio: 74
- Specific Gravity: 0.92
- Tensile Strength: 87 - 94 ksi
- Modulus of Elasticity: 1380 ksi

Benefits:

- According to The Euclid Chemical Company, TUF-STRAND SF:
  - Increases durability, abrasion resistance, fatigue resistance, and flexural toughness.
  - Controls plastic shrinkage cracking and provides a three-dimensional reinforcement against micro and macro-cracking.
  - Provides equivalent strengths to WWM and light rebar.
  - Provides average residual strength (ARS) values, according to ASTM C1399, as follows:
    - Dosage rate = 3.7 lb/yd^3 → ARS = 179 psi
  - Provides flexural toughness values, according to ASTM C1609, as follows:
    - Dosage rate = 5 lb/yd^3 → Toughness = 310 lb-in

Applications/Experience:

- The Euclid Chemical Company recommends usage at a dosage rate between 3 - 20 lb/yd^3 in:
  - Thin walled precast
  - Pavements
  - White-toppings
  - Slab-on-grade

APPENDIX B: SDDOT INTERVIEWEE LIST AND INTERVIEW GUIDE

B-1: SDDOT Interview List

A list of the selected personnel who participated in the SDDOT interview process is shown in Table B.1.

Table B.1: List of the selected SDDOT interviewees.

Interviewee	Office	Date	Time
Gil Hedman	Pavement Design	2/27/14	9:30 AM - 10:00 AM
Tom Grannes Darin Hodges	Materials Lab Materials Lab	2/27/14	10:30 AM - 12:30 PM
Dan Strand Paul Nelson Rick Gordon	Pierre Region Pierre Region Engr. Pierre Area Engr.	2/27/14	1:00 PM – 2:00 PM
Tom Gilsrud Kevin Goeden Hadly Eisenbeisz	Bridge Bridge Bridge	2/27/14	2:00 PM – 3:00 PM
Ron McMahon	FHWA Ops Team Leader	2/27/14	3:00 PM – 4:00 PM
Brad Letcher (phone)	Huron Area/Engr. Supervisor	3/12/14	1:30 PM – 2:00 PM
Joel Flesner (phone)	Belle Fourche Area	3/12/14	2:45 PM – 3:15 PM
Harry Johnston (phone)	Custer Area Engr.	3/12/14	3:30 PM – 4:00 PM
Brenda Flottmeyer (phone)	Rapid City Region	3/13/14	10:00 AM – 10:30 AM
Jeff Hrabanek (phone)	Winner Area Engr.	3/13/14	12:00 PM – 12:15 PM
Randy Sauter (phone)	Rapid City Engr.	3/27/14	4:15 PM – 4:30 PM
Larry Engbrecht (phone)	ACPA (Pierre, SD)	4/3/14	8:30 AM – 9:00 AM
Bill Whitney (phone)	Stanley Johnson Contractors (RC, SD)	4/4/14	10:00 AM – 10:30 AM

B-2: SDDOT Interview Guide

The questionnaire that was used to survey the selected SDDOT personnel is shown on the following pages. This list provided general questions to help initiate the conversation between the research team and the interviewees during the interviews.

SDDOT Interview Guide

SD2013 -07: Fiber-Reinforced Concrete for Structure Components

Previous Experience

1. What has been your previous experience/involvement with FRC materials?
2. Why was FRC used?
3. Are you aware of any FRC projects that are still in service?
4. What types of structural applications do you have experience with?
5. What types of fibers have you had experience with?
    - Steel Fibers:
        - How/why was this type of fiber selected?
        - Shape? (Crimped/Hooked-End/others)
        - Size? (Length and diameter?)
        - How/why were the shape and size selected?
        - Any concerns? (Fiber corrosion, placement, finishing?)
        - What was the fiber dosage rate and how was it determined?
    - Synthetic Fibers:
        - How/why was this type of fiber selected?
        - Fiber material? (Polypropylene/Polyvinyl alcohol/etc.)
        - Size? (Macro vs. Micro, length and diameter?)
        - How/why were the material and size selected?
        - Any concerns?
        - What was the fiber dosage rate and how was it determined?
    - Other?
6. Are you aware if projects were designed for FRC? If so, how? Lessons learned?
7. What do you estimate the percent increase (or increase in the cost per ton/yard) of concrete was with the addition of fibers? In your estimation, were the benefits gained worth the additional cost?
8. In your estimation, what factors contributed to differences in the cost of FRC projects? (i.e., labor, fibers, etc.)
9. In relation to projects you have had involvement with, what would you estimate is the condition of FRC structures, or how would you describe the performance of the FRC-amended materials compared to PCC?

Field/Construction/Demolition

1. In your experience, were methods used to place FRC the same as they are for PCC? If not, how did placement differ?
2. Mixing/dispersal?
3. Consolidation? (Internal vibration? External vibration? Other?)

4. Finishing?
5. Curing?
6. Admixtures?
7. In your experience, were there any complications with air entrainment admixtures affecting fiber anchorage/adhesion of fibers to the concrete matrix?
8. In your experience, were there construction issues?
9. Significant problems or costs associated with demolition of FRC structures compared with standard PCC?
10. Lessons learned?

Current/Future Practice

1. Between the structural cracking and the shrinkage cracking control, which do you think would be of more interest to the SDDOT for FRC application?
2. What bridge components are currently, or potentially of interest in SD?
    - DOT interest?
    - Personal suggestions?

SDDOT Specifications

1. Would you amend or add Specifications, Plan Notes, or Special Provisions with regard to:
    - Materials testing requirements?
    - Placement/Construction/Finishing?
    - Mix Design?
2. In your opinion, what should we make sure to focus on during our research?

Other State DOTs

1. Do you have any experience/knowledge with FRC projects within other state DOT agencies?
2. Do you know any personnel within other state DOT agencies having experience with FRC?
    - Contact information?
3. Do you have any knowledge on other state FRC specifications?

Fiber Manufacturers/Suppliers

1. What are some of the most commonly used concrete reinforcing fiber manufacturers/suppliers in the region? In the country?
    - Contact information?
2. In previous experience, did you assess any manufacturer’s claims regarding properties of fibers? If so, how?

Fiber Types

1. Do you know of any new fiber technology that has surfaced in structural applications in the past 5-10 years?
2. Do you have any personal experience with:
   - High-Performance FRC, such as Engineered-Cementitious-Composite (ECC)?
   - Hybrid FRC (HyFRC) mixes? (i.e., use of two different types/sizes of fibers in one FRC matrix)
   - Ultra-High-Performance-Concrete (UHPC)?

APPENDIX C: STATE DOT INTERVIEWEE LIST AND INTERVIEW GUIDE

C-1: State DOT Interviewee List

A list of the selected personnel who participated in the state DOT interview process is shown in Table C.1.

Table C.1: List of the selected state DOT and manufacturers interviewees.

Int. #	Interviewee	Agency	Date	Time	Method
1	Hamzah Najjar	BASF	5/2/14	2:00PM - 2:30PM	Phone
2	Bernard Izevbekhai	MN DOT	8/18/14	N/A*	E-mail
3	Ahmad Abu-Hawash	IA DOT	8/27/14	10:00AM - 10:30AM	Phone
4	Todd Hanson	IA DOT	8/27/14	1:00PM - 1:30PM	Phone
5	James Krstulovich	IL DOT	8/27/14	N/A*	E-mail
6	Clayton Schumaker	ND DOT	8/28/14	9:00AM - 9:30AM	Phone
7	David Juntunen	MI DOT	8/28/14	9:30AM - 10:00AM	Phone
8	Cliff MacDonald	Forta	9/2/14	9:30AM - 12:30PM	In person
9	Dean Bierwagen	IA DOT	9/2/14	3:00PM - 3:30PM	Phone
10	Tim Durning	W.R. Grace	9/3/14	1:00PM - 1:30PM	Phone
11	Mike Mahoney	Euclid	9/4/14	1:00PM - 1:30PM	Phone

N/A indicates “not applicable”

C-2: State DOT Interview Guide

The questionnaire that was used to survey the selected state DOT personnel is shown on the following pages. This list provided general questions to help initiate the conversation between the research team and the interviewees during the interviews.

Other State DOT Interview Guide

SDDOT SD2013-07: Fiber-Reinforced Concrete for Structure Components

Previous Experience

1. What has been your previous experience/involvement with FRC materials?
2. Why was FRC used in these applications?
3. What types of structural applications have been tried in your state?
4. What types of fibers have been tried in your state?
    - Steel Fibers:
        - How/why was this type of fiber selected?
        - Shape? (Crimped/Hooked-End/others)
        - Size? (Length and diameter?)
        - How/why were the shape and size selected?
        - Any concerns? (Fiber corrosion, placement, finishing?)
        - What was the fiber dosage rate and how was it determined?
    - Synthetic Fibers:
        - How/why was this type of fiber selected?
        - Fiber material? (Polypropylene/Polyvinyl alcohol/etc.)
        - Size? (Macro vs. Micro, length and diameter?)
        - How/why were the material and size selected?
        - Any concerns?
        - What was the fiber dosage rate and how was it determined?
    - Other?
5. Were there ever any issues with manufacturer's claims regarding properties of fibers? If so, please describe?
6. Are you aware if projects were designed for FRC? If so, how? Lessons learned?
7. What do you estimate the percent increase (or increase in the cost per ton/yard) of concrete was with the addition of fibers? In your estimation, were the benefits gained worth the additional cost?
8. In your estimation, what factors contributed to differences in the cost of FRC projects? (i.e., labor, fibers, etc.)
9. In relation to projects you have had involvement with, what would you estimate is the condition of FRC structures, or how would you describe the performance of the FRC-amended materials compared to PCC?

Field/Construction/Demolition

1. In your experience, were methods used to place FRC the same as they are for PCC? If not, how did placement differ?

2. Mixing/dispersal?
3. Consolidation? (Internal vibration? External vibration? Other?)
4. Finishing?
5. Curing?
6. Admixtures?
7. In your experience, were there construction issues?
8. Significant problems or costs associated with demolition of FRC structures compared with standard PCC?
9. Lessons learned?

Specifications

1. Are there specifications, plan notes, or special provisions in your state regarding FRC materials?
2. Would you amend or add to any of the above Specifications, Plan Notes, or Special Provisions?
3. What bridge components are currently of interest for FRC application within your state?

Other State DOTs

1. Do you have any knowledge of FRC projects or expertise in other states?
    - Contact information?

Fiber Manufacturers/Suppliers

1. What companies/suppliers do you commonly use for FRC materials?
    - Contact information?

APPENDIX D: FIBER DATA SHEETS

D-1: Synthetic Fiber Data Sheets

The data sheets for the selected synthetic fibers are shown on the following pages in Figure D.1 through Figure D.4. These data sheets provide additional properties for the fibers, common applications, results from various ASTM standard tests, and more.

Grace Concrete Products

GRACE

STRUX® 90/40

Synthetic macro fiber reinforcement

ASTM C1116

Product Description

STRUX® 90/40 synthetic macro fiber reinforcement is a unique form of high strength, high modulus synthetic macro reinforcement that is evenly distributed throughout the concrete matrix. STRUX 90/40 adds toughness, impact and fatigue resistance to concrete. Unlike traditional microfiber reinforcement, STRUX 90/40 is specifically engineered to provide high, post-crack control performance. Reinforced concrete with STRUX 90/40 has been shown to reliably achieve average residual strength values in excess of 150 psi (1.0 MPa) at dosages that can easily be batched and finished. It consists of synthetic macro fibers 1.55 in. (40 mm) in length with an aspect ratio of 90 that have specifically been designed to replace welded wire fabric, steel fibers, light rebar and other secondary reinforcement in slab-on-ground flooring, thin-walled precast applications and composite steel floor deck. STRUX 90/40 is a user-friendly fiber reinforcement which is easier and safer to use, compared to these other types of reinforcement.

Uses

Slab-on-Ground

STRUX 90/40 is specially designed for ease of use, rapid dispersion, good finishability and improved pumpability in slab-on-ground flooring and many precast applications. STRUX 90/40 may be used in commercial floors, industrial floors, residential floors, other flat work applications and form work applications. The addition rate of STRUX 90/40 can be easily calculated using Grace's SDS Software, using several factors such as compressive strength of concrete, modulus of sub-grade reaction, thickness of concrete and applied load. Please consult your Grace sales representative for proper addition rate of STRUX 90/40 for your application. Always consult local building codes (refer to Engineering Bulletin 1).

Composite Steel Floor Deck for Normal and Lightweight Concrete

STRUX 90/40 can be used as a suitable alternative to WWF specified for temperature and shrinkage reinforcement for composite steel floor decks. STRUX 90/40 complies with *American National Standards Institute/Steel Deck Institute* (ANSI/SDI C-1.0) design code provision for minimum reinforcing at minimum addition rate of 4 lbs/yd³ (2.4 kg/m³). STRUX 90/40 is UL (U.S.) and ULC (Canada) classified with fire ratings up to 2 hours for D700, F700, D800, F800, D900 and F900 except 909 at a maximum addition rate of 5 lbs/yd³ (3.0 kg/m³).

Product Advantages

- Savings from lower labor costs and fewer construction days
- Enhances safety by eliminating handling of steel fibers, welded wire fabrics or light rebar
- Eliminates concerns of proper positioning of reinforcement
- Provides superior crack control due to the geometry and elastic modulus
- Abrasion resistance and will not corrode
- Controls plastic and drying shrinkage cracks

Addition Rates

STRUX 90/40 addition rates are dependent on the specific application and desired properties and will vary between 3.0 to 12.0 lbs/yd³ (1.8 to 7.0 kg/m³).

Mix Design

The utilization of STRUX 90/40 may require the use of a superplasticizer such as ADVA® to restore the required workability. In addition, slight increases in fine aggregate contents may be needed.

STRUX 90/40 may be added to concrete at any point during the batching or mixing process. After fiber addition, the concrete must be mixed at the minimum of 70 revolutions to ensure adequate dispersion.

Please contact your Grace representative with any questions. For more detailed instructions refer to Technical Bulletin TB-1200.

CLASSIFIED c UL US

STRUX® 90/40 fiber as marketed by W. R. Grace & Co.–Conn. is classified by Underwriters Laboratories Inc. for use as an alternative, or in addition to, the welded wire fabric in 1, 1½ and 2 hr floor-ceiling D700, F700, D800, F800, D900 and F900 (except 909) Series Designs. Fibers to be added to the concrete mix at maximum addition rate of 5 lbs/yd³ (3.0 kg/m³).

Compatibility with Other Admixtures and Batch Sequencing

STRUX 90/40 is compatible with all Grace admixtures. Their action in concrete is mechanical and will not affect the hydration process of the cement or compressive strength. Each liquid admixture should be added separately to the concrete mix.

Packaging

STRUX 90/40 is available in 1.0 lb or 5.0 lb (.5 kg or 2.3 kg) Concrete-Ready™ bags.

STRUX 90/40 Properties

Specific gravity	0.92
Absorption	None
Modulus of elasticity	1,378 ksi (9.5 GPa)
Tensile strength	90 ksi (620 MPa)
Melting point	320°F (160°C)
Ignition point	1,094°F (590°C)
Alkali, acid & salt resistance	High

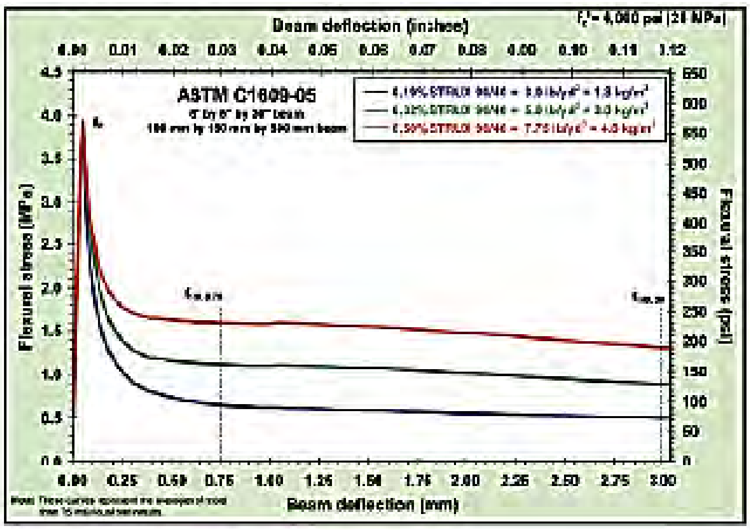
Flexural Strength and Toughness (Compressive Strength: 4,000 psi) according to ASTM C1609-05

STRUX 90/40 Dosage Rate	Specimen cross-section Width (in.)	Depth (in.)	Peak Load P_p (lbf)	Peak Strength f_p (psi)	Peak-load deflection δ_p (in.)	Residual loads $P_{600,3.0}$ (lbf)	$P_{150,3.0}$ (lbf)	Residual strengths $f_{600,3.0}$ (psi)	$f_{150,3.0}$ (psi)	Toughness $T_{150,3.0}$ (lbf-in.)	JCI-SF4[1] f_{eq} (psi)	TR-34[2] $R_{e,3}$ (%)
0.19% (3.0 lb/yd³)	6.00	5.95	6,702	565	0.0019	1,299	952	110	80	160	115	20.0%
0.32% (5.0 lb/yd³)	6.00	6.00	7,066	595	0.0020	1,905	1,508	160	130	240	165	28.5%
0.50% (7.75 lb/yd³)	6.00	5.95	6,690	560	0.0020	2,730	2,231	230	190	330	230	40.5%

Flexural Strength and Toughness (Compressive Strength: 28 MPa) according to ASTM C1609-05

STRUX 90/40 Dosage Rate	Specimen cross-section Width (mm)	Depth (mm)	Peak Load P_p (N)	Peak Strength f_p (MPa)	Peak-load deflection δ_p (mm)	Residual loads $P_{600,3.0}$ (N)	$P_{150,3.0}$ (N)	Residual strengths $f_{600,3.0}$ (MPa)	$f_{150,3.0}$ (MPa)	Toughness $T_{150,3.0}$ (Joule)	JCI-SF4[1] f_{eq} (MPa)	TR-34[2] $R_{e,3}$ (%)
0.19% (1.8 kg/m³)	152	151	29,813	3.90	0.048	5,776	4,226	0.75	0.55	18	0.80	20.0%
0.32% (3.0 kg/m³)	152	152	31,422	4.10	0.050	8,472	6,932	1.10	0.90	27	1.15	28.5%
0.50% (4.6 kg/m³)	152	151	30,213	4.00	0.050	12,323	10,012	1.60	1.30	37	1.60	40.5%

1) Japan Concrete Institute (JCI) [illegible] Japan Concrete Institute, 1983. 2) The Concrete Society Technical Report 34 [illegible], The Concrete Society, 2003.



www.graceconstruction.com

North American Customer Service: 1-877-4AD-MIX1 (1-877-423-6491)

GRACE

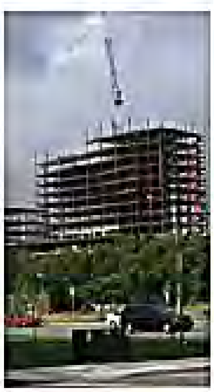
Figure D.1: Data sheet for Strux 90/40 fiber from W.R. Grace (2 pages).

FIBERMESH® 650

PRODUCT DATA SHEET

SPECIFY FIBERMESH® 650 FIBERS:

- REDUCED PLASTIC SHRINKAGE CRACKING
- ALTERNATE TO TRADITIONAL STEEL FOR TEMPERATURE/ SHRINKAGE AND FLEXURAL REINFORCEMENT
- IMPROVED IMPACT, SHATTER AND ABRASION RESISTANCE
- INCREASED LEVELS OF RESIDUAL STRENGTH/ FLEXURAL TOUGHNESS
- IMPROVED DUCTILITY
- IMPROVED DURABILITY



FIBERMESH® 650 SYNTHETIC FIBER

Fibermesh 650 is an engineered graded macro-synthetic fiber used for secondary reinforcement for concrete—an alloy polymer macro-synthetic fiber featuring e3® patented* technology manufactured to an optimum gradation and highly oriented to allow greater surface area contact within the concrete resulting in increased interfacial bonding and flexural toughness efficiency. Fibermesh 650 is specifically engineered and manufactured in an ISO 9001:2000 certified facility for use as concrete secondary reinforcement at a minimum addition rate of 3.0 lbs per cubic yard (1.8 kg per cubic meter). Complies with ASTM C 1116/C 1116M, Type III fiber reinforced concrete. *Covered by US Patent # 5628822, 5456752

ADVANTAGES

Requires no minimum amount of concrete cover • Is always uniformly positioned in the concrete and in compliance with codes • Safe and easier to use than traditional reinforcement • Saves time and hassle

FEATURES & BENEFITS

- Graded macro-synthetic fiber for concrete secondary reinforcement used as an alternate to welded wire reinforcement and light rebar
- Inhibits the formation of plastic shrinkage and plastic settlement cracking
- Provides impact, abrasion and shatter resistance
- Greater surface area provides increased flexural toughness (residual strength)
- Improved ductility
- Provides improved durability
- Control of drying shrinkage and temperature cracking
- Good finishing characteristics
- Pumpable reinforcement

PRIMARY APPLICATIONS

- Slabs-on-ground
- Sidewalks / Driveways
- Parking areas
- Overlays & toppings
- Exterior pavements
- Non-magnetic applications
- Shotcrete
- Composite metal decks

CHEMICAL AND PHYSICAL PROPERTIES

Absorption	Nil	Melt Point	324°F (162°C)
Specific Gravity	0.91	Acid & Salt Resistance	High
Fiber Length*	Graded	Aspect Ratio	86.5
Electrical Conductivity	Low		

MAKE SURE IT'S TRUE FIBERMESH FIBERMESH.COM

FIBERMESH® 650

PRODUCT DATA SHEET

PRODUCT USE

MIXING DESIGNS AND PROCEDURES: Fibermesh® 650 reinforcing is a mechanical, not a chemical process. Due to fiber efficiency, minor mix design modifications may be required depending on the application. Consult your Propex Concrete Systems representative for recommendations. Fibermesh 650 macro-synthetic fiber is added to the mixer before, during or after batching the other concrete materials. Mixing time of at least 5 minutes at mixing speed is required as specified in ASTM C 94.

FINISHING: Fibermesh 650 reinforced concrete can be finished with normal finishing techniques in accordance with ACI 304, Section C.3.

APPLICATION RATE: The minimum application rate for Fibermesh 650 macro-synthetic fiber is 3.0 lbs per cubic yard (1.8 kg per cubic meter) of concrete. For Shotcrete or specialty concrete performance consult your Propex Concrete Systems representative for specific dosage recommendations.

GUIDELINES

Fibermesh 650 macro-synthetic fibers should not be used to replace structural reinforcement. Fibermesh 650 fibers should not be used as a means of using thinner concrete sections than original design. For joint spacing, follow industry standard guidelines suggested by PCA and ACI.

COMPATIBILITY

Fibermesh 650 is compatible with all commonly used concrete admixtures and performance enhancing chemicals.

PACKAGING

Fibermesh 650 macro-synthetic fibers are available in 1.5 lb toss-in degradable bags. Bags are packed into cartons, shrink wrapped and palletized for protection during shipping.

TECHNICAL SERVICES

Trained Propex Concrete Systems specialists are available worldwide to assist and advise in specifications and field service. Propex Concrete Systems representatives do not engage in the practice of engineering or supervision of projects and are available solely for service and support of our customers.

REFERENCE DOCUMENTS

- ASTM C 94/C 94M Standard Specification for Ready-Mixed Concrete.
- ASTM C 1116/C 1116M Standard Specification for Fiber-Reinforced Concrete.
- ASTM C 1399 Standard Test Method for Obtaining Average Residual-Strength of Fiber-Reinforced Concrete.
- ASTM C 1436 Standard Specification for Materials for Shotcrete.
- ASTM C 1609 /C 1609M Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading). Replaces ASTM C 1018.
- ASTM C 1550 Standard Test Method for Flexural Toughness of Fiber Reinforced Concrete (Using Centrally Loaded Round Panel).
- JCI-SF4 Method of Test for Flexural Strength and Flexural Toughness of Fiber Reinforced Concrete.
- ACI 304 Guide for Measuring, Mixing,Transporting and Placing Concrete.
- ACI 506 Guide for Shotcrete.

UL® Classified: Type Fibermesh 650 fibers. For use as an alternate or in addition to the welded wire fabric in 1, 1-1/2, 2, 2-1/2 and 3 hr Floor-Ceiling D700, D800 and D900 Series Designs. Fiber added to concrete mix at a rate up to a maximum of 5.0 lb of fiber for each cubic yard of concrete.

SPECIFICATION CLAUSE

Fibermesh 650 graded macro-synthetic fiber shall be used for shrinkage and temperature reinforcement. Fibermesh 650 with e3® patented technology shall be specifically manufactured to an optimum gradation for use as concrete secondary reinforcement. Application rate shall be a minimum of 3.0 lbs per cubic yard (1.8 kg per cubic meter) of concrete. Fiber manufacturer shall document evidence of satisfactory performance history, ISO 9001:2000 certification of manufacturing facility, and compliance with ASTM C 1116/C 1116M, Type III fiber reinforced concrete. Fibrous concrete reinforcement shall be manufactured by Propex Operating Company, LLC, 6025 Lee Highway, Ste 425, PO Box 22788, Chattanooga,TN 37422, USA, tel: 423 892 8080, fax: 423 892 0157, web site: fibermesh.com.

Propex™ Fibermesh®

NORTH AMERICA
Propex Operating Company, LLC
6025 Lee Highway, Suite 425
Chattanooga, TN 37421
Tel: 800 621 1273
Tel: 423 892 8080
Fax: 423 892 0157

INTERNATIONAL
Propex Concrete Systems Ltd.
Propex House
9 Royal Court, Basil Close
Chesterfield, Derbyshire, S41 7SL
United Kingdom
Tel: +44 (0) 1246 564200
Fax: +44 (0) 1246 465201

Figure D.2: Data sheet for Fibermesh 650 fiber from Propex Fibermesh (2 pages).

TUF-STRAND SF

TUF-STRAND SF

SYNTHETIC MACRO-FIBER

FIBERS

DESCRIPTION

TUF-STRAND SF "structural fibers" are a patented polypropylene / polyethylene synthetic macro-fiber successfully used to replace steel fibers, welded wire mesh and conventional reinforcing bars in a wide variety of applications. TUF-STRAND SF fibers comply with ASTM C1116, Standard Specification for Fiber Reinforced Concrete and Shotcrete, and are specifically designed to provide equivalent tensile and bending resistance to conventional reinforcement requirements. Concrete reinforced with TUF-STRAND SF will have three-dimensional reinforcing with enhanced flexural toughness, impact and abrasion resistance and will also help mitigate the formation of plastic shrinkage cracking in concrete. Dosage rates will vary depending upon the reinforcing requirements and can range from 3.0 lbs/yd (1.8 kg/m³) to 20 lbs/yd (12 kg/m³). TUF-STRAND SF synthetic macro-fibers comply with applicable portions of the International Code Council (ICC) Acceptance Criteria AC32 for synthetic fibers, are UL certified for composite metal deck construction and are recognized within ACI 360 and SDI/ANSI-C1.0 as a reinforcing alternate to WWF.

PRIMARY APPLICATIONS

- Thin walled pre-cast (septic tanks, vaults, walls, etc.)
- Shotcrete for tunnel linings, pool construction and slope stabilization
- Pavements and white-toppings
- Slab on Grade and elevated construction (distribution centers, warehouses, etc.)

FEATURES/BENEFITS

- Equivalent strengths to WWM and rebar provided by engineering calculations
- Controls and mitigates plastic shrinkage cracking and reduces segregation and bleed-water
- Provides three-dimensional reinforcement against micro and macro-cracking
- Reduces equipment wear, fiber rebound and increases build-up thickness compared to steel fibers for shotcrete applications
- Increases overall durability, fatigue resistance and flexural toughness
- Reduction of in-place cost versus wire mesh for temperature / shrinkage crack control
- Easily added to concrete mixture at any time prior to placement
- Tested in accordance with ASTM C 1399, C 1550, C 1609 and C 1018
- Applicable for design by ACI 360 R-06
- Certified for use by UL/ULC for D500 Series metal deck assemblies as alternate to WWF (CBXQ.R13773)

TECHNICAL INFORMATION

Typical Engineering Data

Material..............polypropylene/polyethylene blend
Specific Gravity 0.92
Typical dosage rate: 3 to 20 lbs/yd (1.8 to 12 kg/m³)
Available lengths ....2" (51 mm)
Aspect Ratio 74
Tensile Strength.............87-94 ksi (600 to 650 MPa)

Modulus of Elasticity (EN 14889.2)...1380 ksi (9.5 GPa)
Flash point (ASTM D1929) ....625°F (330°C)
Electrical Conductivity ....low
Water absorption .... negligible
Acid and Alkali Resistance ....excellent
Color ....white

SHELF LIFE

3 years in original, unopened package.

PACKAGING

TUF-STRAND SF fibers are packaged in 3.0 lb (1.36 kg), 4.0 lb (1.81 kg) and 5.0 lb (2.27 kg) water soluble bags.

TUF-STRAND SF

Master Format #: 03 2400

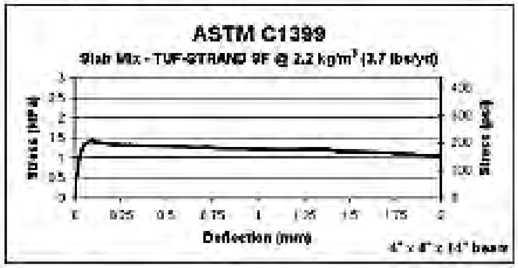
The Euclid Chemical Company
19218 Redwood Rd. - Cleveland, OH 44110
Phone: [216] 531-9222 - Toll-free: [800] 321-7628 - Fax: [216] 531-9596
www.euclidchemical.com

An RPM Company

DIRECTIONS FOR USE

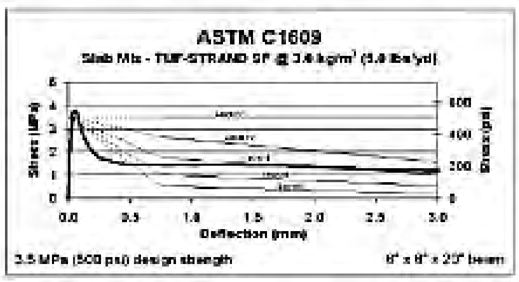
TUF-STRAND SF fibers can be added to the concrete mixture at any time prior to placement of the concrete. It is generally recommended to add any fiber material at the ready-mix concrete plant during batching. Fibers must be mixed with concrete for a minimum of three (3) to five (5) minutes at maximum mixing speed to ensure complete dispersion and uniformity. When adding 3 to 5 lbs/yd (2 to 3 kg/m3), a slump loss of 2" (50 mm) can be expected for a typical ready-mix concrete design. For dosages of 6 to 12 lbs (4 to 7 kg/m3), a slump loss of 3 to 5 in (75 to 125 mm) can be expected. The use of water reducers and/or superplasticizers, such as Eucon 37, 1037 or the Plastol series of admixtures may be necessary to maintain desired workability.

Add other admixtures independently from fiber addition. TUF-STRAND SF is compatible with all other Euclid Chemical admixtures. When used properly, and placed in a concrete mix of sufficient workability, the fibers will not adversely alter the compressive or flexural strength of concrete or shotcrete.



Average Residual Strength (ARS) at given deflection					
deflection	0.5 mm	0.75 mm	1 mm	1.25 mm	Average
ARS - MPa	1.29	1.24	1.21	1.19	1.23
ARS - psi	187	180	176	172	179

single test analysis - individual results may vary



P	f	P	f	T	JSCE	R (%)
10.5 kN	1.4 MPa	9.0 kN	1.2 MPa	35 J	1.41 MPa	34.8
2360 lbs	200 psi	2020 lbs	175 psi	310 in lb	206 psi	

single test analysis - individual results may vary

CLEAN-UP

Loose fiber material may be disposed in proper receptacles for refuse. Finishing equipment with fibers embedded in concrete should be thoroughly cleaned.

PRECAUTIONS/LIMITATIONS

- Use of fibers may cause an apparent loss in measured slump of concrete. This may be offset with the use of a water reducing admixture if necessary.
- Fibers should never be added to a "zero-slump" concrete. Ensure a minimum concrete slump of 3" (80 mm) prior to addition of any fiber material. Fibers may also be added in loose form to aggregate charging devices.
- In all cases, consult the Material Safety Data Sheet before use.

Rev. 10.10

Figure D.3: Data sheet for TUF-STRAND SF fiber from The Euclid Chemical Company (2 pages).

FORTA-FERRO®

FORTA

FACT-DATA©

MANUFACTURER

FORTA CORPORATION, 100 Forta Drive, Grove City, PA, U.S.A., 16127-6399
TELEPHONE: 1-800-245-0306, (724) 458-5221;
FAX: (724) 458-8331; **www.forta-ferro.com**

GENERAL DESCRIPTION

FORTA-FERRO® is an easy to finish, color blended macrosythetic fiber, made of 100% virgin copolymer/polypropylene consisting of a twisted bundle non-fibrillating monofilament and a fibrillating network fiber, yielding a high-performance concrete reinforcement system. **FORTA-FERRO®** is used to reduce plastic and hardened concrete shrinkage, improve impact strength, and increase fatigue resistance and concrete toughness. This extra heavy-duty macrosynthetic fiber offers maximum long-term durability, structural enhancements, and effective secondary/temperature crack control by incorporating a truly **unique synergistic fiber system** of long length design. **FORTA-FERRO® is non-corrosive, non-magnetic, and 100% alkali proof!**

APPLICATIONS

FORTA-FERRO® is mainly used with performance concrete applications such as industrial floors, bridge decks, shotcrete, loading docks, precast products – anywhere that steel reinforcement reduction or replacement is the objective. Contact FORTA Corporation for design assistance.

INSTALLATION

Recommended dosage rate of FORTA-FERRO® is **0.2% to 2.0% by volume of concrete** (3 to 30 lbs. per cubic yard) added directly to the concrete mixing system during, or after, the batching of the other ingredients and mixed at the time and speed recommended by the mixer manufacturer (usually four to five minutes).

PHYSICAL PROPERTIES

Materials..................Virgin Copolymer/Polypropylene
Form.......................Monofilament/Fibrillated Fiber System
Specific Gravity.........0.91
Tensile Strength.......83-96 ksi. (570-660 MPa)
Length.....................2.25" (54mm), 1.5" (38mm)

Color.............................Gray
Acid/Alkali Resistance....Excellent
Absorption ....Nil
Compliance....................A.S.T.M. C-1116
Compliance....................A.S.T.M. D-7508

AVAILABILITY

FORTA-FERRO® can be purchased from FORTA Corporation or an authorized FORTA® products distributor, dealer or representative.

PACKAGING

Convenient incremental pound or kilogram mixer-ready bag packaging.

WARRANTY

FORTA® products are warranted to be free of defects in material and meet all quality control standards set by the manufacturer. FORTA Corporation specifically disclaims all other warranties, express or implied. The exclusive remedy for defective product shall be to replace the product or refund the purchase price. No agent or employee of this company is authorized to vary the terms of this warranty notice. FORTA Corporation has no control over the design, production, placement, or testing of the concrete products in which FORTA® products are incorporated, and therefore FORTA Corporation disclaims liability for the end product.

U. S. Patent Nos. 6,753,081 and 7,168,232. Additional patents pending.

FORTA Corporation's technical recommendations regarding synthetic fiber characteristics are based on years of engineering research and scores of concrete projects. FORTA® has developed a simple "4-C's" formula to help the specifier choose the right fiber for any concrete project application. By making a decision with each of the FORTA® "4-C's" categories – Configuration, Chemistry, Contents, and Correct Length–specifiers are assured of obtaining the desired fiber performance level for a given project. The following 4-C's formula specification has been prepared to accommodate the stated reinforcement objective for this FORTA® product grade.

REINFORCEMENT OBJECTIVE: To inhibit plastic and settlement shrinkage cracking prior to the initial set, and to reduce hardened concrete shrinkage cracking, improve impact strength, and enhance concrete toughness and durability as an alternate secondary/temperature/structural reinforcement.

DIVISION – CONCRETE
SECTION – CONCRETE REINFORCEMENT
SUB-SECTION – SYNTHETIC FIBROUS REINFORCEMENT

Synthetic fibrous reinforcement shall be used in the areas denoted in plans, and shall comply with the following fiber characteristics:

1. Configuration – Fiber should be a macrosynthetic synergistic combination of a twisted-bundle non-fibrillating monofilament and a fibrillating network fiber system.
2. Chemistry – Fiber shall be made of 100% virgin materials in the form of fully-oriented copolymer/polypropylene, gray in color.
3. Contents – Fiber shall be used at a rate of ___% by volume of concrete, resulting in a dosage of ___pounds per cubic yard [i.e. 0.2%, 3.0 lbs. / cu. yd; 0.33%, 5.0 lbs. / cu. yd; 0.5%, 7.5lbs. / cu. yd; etc]
4. Correct Length – Fiber Length shall be ¾", 19mm; 1 ½", 38mm, 2 ¼". 54mm.

Compliance: Fibers shall comply with A.S.T.M. C-1116 "Standard Specification for Fiber Reinforced Concrete and Shotcrete" and A.S.T.M. D-7508 "Standard Specification for Polyeolefin Chopped Strands for Use in Concrete". The approved product is FORTA-FERRO® macrosynthetic fiber as manufactured by FORTA Corporation, Grove City, PA, U.S.A. Phone: 1-800-245-0306 or 1-724-458-5221; Fax: 1-724-458-8331.

FORTA®

FORTA Corporation
100 Forta Drive, Grove City, PA 16127-6399 U.S.A.
1-800-245-0306 or 1-724-458-5221
Fax: 1-724-458-8331
www.forta-ferro.com

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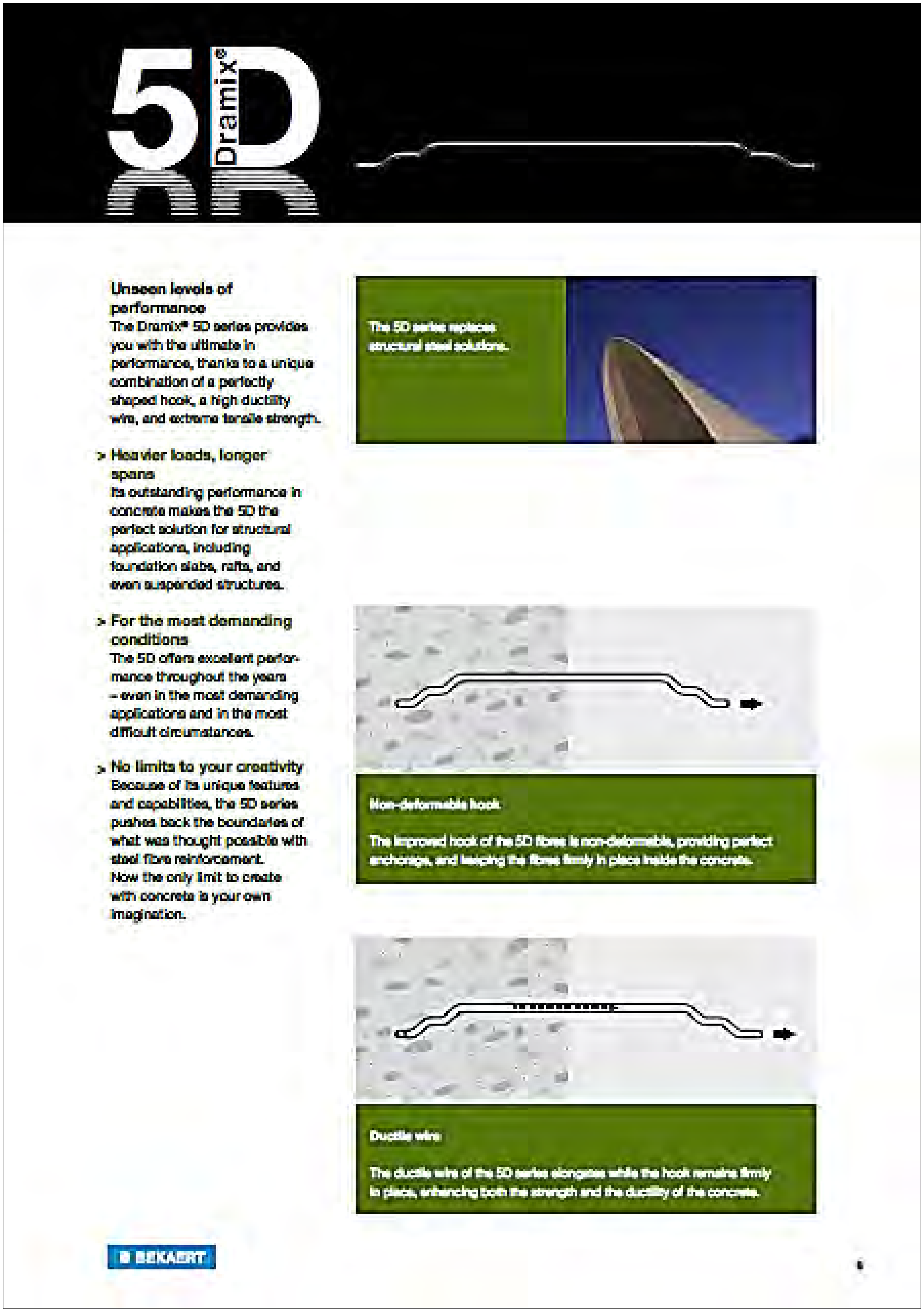
Figure D.4: Data sheet for FORTA-FERRO fiber from Forta Corporation (2 pages).

D-2: Steel Fiber Data Sheets

The data sheet for the selected steel fiber is shown on the following page in Figure D.5. Data sheets provide additional properties for the fibers, common applications, results from various ASTM standard tests, and more.



5D Dramix®

Unseen levels of performance

The Dramix® 5D series provides you with the ultimate in performance, thanks to a unique combination of a perfectly shaped hook, a high ductility wire, and extreme tensile strength.

> Heavier loads, longer spans

Its outstanding performance in concrete makes the 5D the perfect solution for structural applications, including foundation slabs, rafts, and even suspended structures.

> For the most demanding conditions

The 5D offers excellent performance throughout the years – even in the most demanding applications and in the most difficult circumstances.

> No limits to your creativity

Because of its unique features and capabilities, the 5D series pushes back the boundaries of what was thought possible with steel fibre reinforcement. Now the only limit to create with concrete is your own imagination.

The 5D series replaces structural steel solutions.

Non-deformable hook

The improved hook of the 5D fibres is non-deformable, providing perfect anchorage, and keeping the fibres firmly in place inside the concrete.

Ductile wire

The ductile wire of the 5D series elongates while the hook remains firmly in place, enhancing both the strength and the ductility of the concrete.

BEKAERT

Figure D.5: Data sheet for Dramix 5D from Bekaert.

APPENDIX E: CHEMICAL ADMIXTURES DATA SHEET

PRODUCT DATA SHEET

gcp applied technologies

WRDA® 82

Water-reducing and retarding admixture

ASTM C494 Type A and D

Product Description

WRDA® 82 is an aqueous solution of modified lignosulfonates containing a catalyst which promotes more complete hydration of Portland cement. It does not contain calcium chloride. WRDA 82 is manufactured under rigid control which provides uniform, predictable performance. It is supplied as a dark brown, low viscosity liquid, ready-to-use as received. One gallon weighs approximately 10 lbs (1.2 kg/L).

Uses

WRDA® 82 makes a workable mix and yields a stronger, less permeable and more durable concrete. It is used in ready-mix plants, job site plants and concrete pavers, for normal weight and light weight concrete, in block, precast and prestressed concrete plants.

Performance

WRDA 82 is a chemical admixture meeting the requirements of *Specification for Chemical Admixtures for Concrete*, ASTM Designation: C494 as a Type A and D admixture.

As a dispersing agent, WRDA 82 lessens the natural interparticle attraction between cement grains in water. It does this by colloidal action, by adsorption on the cement particles thus reducing their tendency to clump together and makes the mix more workable with less water. As a cement catalyst, WRDA 82 effects a more complete hydration of the cement, beginning immediately after the cement and water come together at the lower additions of WRDA 82 or immediately after a period of designed and controlled hydration at the higher additions. WRDA 82 increases the gel content of the concrete, the paste or binder that "glues" the concrete aggregates together. The increased gel content adds to the water retention and internal cohesiveness of the mix, reducing bleeding and segregation as it increases workability and placeability.

Product Advantages

- Superior water reduction and set times
- Consistent set time
- Improves performance concrete containing supplementary cementitious materials
- Produces concrete that is more workable, easy to place and finish
- High compressive and flexural strengths

Addition Rates

The addition rate range of 3 to 5 fl oz/100 lbs (195 to 326 mL/100 kg) of cement or cementitious is typical for most applications. However, addition rates of 2 to 10 fl oz/100 lbs (130 to 652 mL/100 kg) of cement or cementitious may be used if local testing shows acceptable performance. In some cases it may be necessary to slightly modify the addition rate due to variations in cement, aggregate or other job conditions.

Compatibility with Other Admixtures and Batch Sequencing

WRDA 82 is compatible with most GCP admixtures as long as they are added separately to the concrete mix, usually through the water holding tank discharge line. In general, it is recommended that WRDA 82 be added to the concrete mix near the end of the batch sequence for optimum performance. Different sequencing may be used if local testing shows better performance. Please see GCP Technical Bulletin TB-0110, *Admixture Dispenser Discharge Line Location and Sequencing for Concrete Batching Operations* for further recommendations.

Pretesting of the concrete mix should be performed before use, as conditions and materials change in order to assure compatibility, and to optimize dosage rates, addition times in the batch sequencing and concrete performance. For concrete that requires air entrainment, the use of an ASTM C260 air entraining agent (such as Daravair® or Darex® product lines) is recommended to provide suitable air void parameters for freeze-thaw resistance. Due to a synergistic effect of WRDA 82, the quantity of air-entraining admixtures added to WRDA 82 admixtured concrete may be reduced by 25%-50%. Please consult your GCP Applied Technologies representative for guidance.

Packaging & Handling

WRDA 82 is available in bulk, delivered by metered tank trucks, totes and drums.

WRDA 82 will freeze at about 28°F (-2°C) but will return to full strength after thawing and thorough agitation.

Dispensing Equipment

A complete line of accurate, automatic dispensing equipment is available. WRDA 82 may be added to the concrete mix on the sand or in the water.

Specifications

Concrete shall be designed in accordance with *Standard Recommended Practice for Selecting Proportions for Concrete*, ACI 211.1.

The water-reducing admixture shall be WRDA 82 as manufactured by GCP Construction Products, or proved equal. The admixture shall not contain calcium chloride. It shall meet the requirements of *Specification for Chemical Admixtures for Concrete* ASTM Designation C494 as a Type A and D admixture when used at an addition rate of 3 to 5 fl oz/100 lbs of WRDA 82 (195 to 326 mL/100 kg) of cementitious materials. Certification of compliance shall be made available on request. The admixture shall be considered part of the total mixing water.

The admixture shall be delivered as a ready-to-use liquid product and shall require no mixing at the batching plant or job site.

gcpat.com | North America Customer Service: 1-877-4AD-MIX1 (1-877-423-6491)

GCP Applied Technologies Inc., 62 Whittemore Avenue, Cambridge, MA 02140 USA.

In Canada, 294 Clements Road, West, Ajax, Ontario, Canada L1S 3C6.

GCP0083 DW-8-1116

gcp applied technologies

Figure E.1: Data sheet for WRDA 82 from W.R. Grace (2 pages).

DARAVAIR® M

Air-entraining admixture

ASTM C260, AASHTO M 154

Product Description

Daravair® M air-entraining admixture is an aqueous solution of completely neutralized vinsol resin. Daravair M is a clear, dark brown liquid intended for use as supplied. One gallon weighs approximately 8.9 lbs (1.07 kg/L).

Uses

Daravair M may be used wherever the purposeful entrainment of air is required by concrete specifications. It is particularly useful in mass concrete and in high cement factor, low slump paving mixes, which require efficient, effective air-entraining admixtures. Daravair M entrains air readily even under adverse conditions such as described above or when fly ash or manufactured sand is used in the concrete mix.

Performance

Air is incorporated into the concrete by the mechanics of mixing, and stabilized into millions of discrete semi-microscopic bubbles in the presence of a specifically designed air-entraining admixture such as Daravair M.

These air bubbles act much like flexible ball bearings increasing the mobility, or plasticity and workability of the concrete. This permits a reduction in mixing water with no loss of slump. Placeability is improved. Bleeding, green shrinkage and segregation are minimized.

Through the purposeful entrainment of air, Daravair M markedly increases the durability of concrete to all exposures, particularly to freezing and thawing. It has also demonstrated a remarkable ability to impart resistance to the action of frost and de-icing salts as well as sulfate, sea and alkaline waters.

Product Advantages

- Readily entrains air under adverse air entrainment conditions
- Uniform air entrainment in paving applications

Addition Rates

There is no standard addition rate for Daravair M. The amount to be used will depend upon the amount of air required for job conditions, usually in the range of 4% to 8%. Typical factors which might influence the amount of air-entraining admixture required are temperature, cement, sand gradation and the use of extra fine materials such as fly ash. Typical Daravair M addition rates range from 0.25 to 6.0 fl oz/100 lbs (16 to 400 mL/100 kg) of cement.

The air-entraining capacity of Daravair M is usually increased when other concrete admixtures are contained in the concrete, particularly water-reducing admixtures and water-reducing retarders. This may allow a reduction of up to ⅓ in the amount of Daravair M required.

Concrete Mix Adjustment

Entrained air will increase the volume of the concrete and, consequently, it will be necessary to adjust the mix proportions to maintain the cement factor and yield. This is partly accomplished by the permissible reduction in water requirement and additionally by a reduction in the fine aggregate content.

Compatibility with Other Admixtures and Batch Sequencing

Daravair M is compatible with most GCP admixtures as long as they are added separately to the concrete mix. In general, it is recommended that Daravair M be added to the concrete mix near the beginning of the batch sequence for optimum performance, preferably by "dribbling" on the sand. Different sequencing may be used if local testing shows better performance. Please see GCP Technical Bulletin TB-0110, *Admixture Dispenser Discharge Line Location and Sequencing for Concrete Batching Operations* for further recommendations. Daravair M should not be added directly to heated water.

Pretesting of the concrete mix should be performed before use, as conditions and materials change in order to assure compatibility, and to optimize dosage rates, addition times in the batch sequencing and concrete performance. Please consult your GCP Applied Technologies representative for guidance.

Packaging & Handling

Daravair M is available in bulk, delivered by metered tank trucks, totes and drums.

Daravair M will freeze at about 30 °F (-1 °C), but its air-entraining properties are completely restored by thawing and thorough agitation.

Dispensing Equipment

A complete line of accurate automatic dispensing equipment is available. These dispensers can be located to discharge into the water line, the mixer, or on the sand.

Specifications

Concrete shall be air entrained concrete, containing 4% to 8% entrained air. The air contents in the concrete shall be determined by the pressure method (ASTM Designation C231), volumetric method (ASTM Designation C173) or gravimetric method (ASTM Designation C138). The air-entraining admixture shall be a completely neutralized vinsol resin solution, such as Daravair M, as manufactured by GCP Applied Technologies, or equal, and comply with standard specification for air-entraining admixtures (ASTM Designation C260). The air-entraining admixture shall be added at the concrete mixer or batching plant at approximately 0.25 to 6.0 fl oz/ 100 lbs (16 to 400 mL/100 kg) of cement, or in such quantities as to give the specified air contents.

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GCP0083 AIR-12-1216

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Figure E.2: Data sheet for DARAVAIR M from W.R. Grace (2 pages).

APPENDIX F: HARDENED CONCRETE PROPERTIES

F-1: Compressive Strength Test Results

The results obtained from the ASTM C39 compressive strength test are shown on the following pages in Table F.1 through Table F.6.

Table F.1: Compressive strength testing results for the control mix.

Concrete Mix	Compressive Strength		Modulus of Elasticity	
NA-0-1	7946	psi	5320	ksi
NA-0-2	7545	psi	5110	ksi
NA-0-4	7633	psi	5140	ksi
Average	7708	psi	5190	ksi

Table F.2: Compressive strength testing results for the Strux 90/40 mixes.

Concrete Mix	Compressive Strength		Modulus of Elasticity	
ST-1-1	7108	psi	4930	ksi
ST-1-2	6872	psi	4550	ksi
ST-1-3	6931	psi	5010	ksi
Average	6970	psi	4830	ksi
ST-2-1	6410	psi	4810	ksi
ST-2-2	6102	psi	4750	ksi
ST-2-3	6003	psi	4640	ksi
Average	6172	psi	4733	ksi
ST-3-1	6946	psi	4610	ksi
ST-3-2	6843	psi	4630	ksi
ST-3-3	6952	psi	4700	ksi
Average	6914	psi	4647	ksi
ST-4-1	6407	psi	4620	ksi
ST-4-2	6440	psi	4680	ksi
ST-4-3	6246	psi	4430	ksi
Average	6364	psi	4577	ksi

Table F.3: Compressive strength testing results for the Fibermesh 650 mixes.

Concrete Mix	Compressive Strength		Modulus of Elasticity	
FM-1-1	6500	psi	4890	ksi
FM-1-2	6570	psi	4780	ksi
FM-1-3	6578	psi	4880	ksi
Average	6549	psi	4850	ksi
FM-2-1	6503	psi	5070	ksi
FM-2-2	6392	psi	4900	ksi
FM-2-3	6638	psi	4970	ksi
Average	6511	psi	4980	ksi
FM-3-1	6437	psi	4640	ksi
FM-3-2	6460	psi	4800	ksi
FM-3-3	6664	psi	4750	ksi
Average	6520	psi	4730	ksi
FM-4-1	6619	psi	4430	ksi
FM-4-2	6632	psi	4490	ksi
FM-4-3	6736	psi	4690	ksi
Average	6662	psi	4537	ksi

Table F.4: Compressive strength testing results for the TUF-STRAND SF mixes.

Concrete Mix	Compressive Strength		Modulus of Elasticity	
TS-1-1	6229	psi	4530	ksi
TS-1-2	6198	psi	4520	ksi
TS-1-3	6183	psi	4560	ksi
Average	6203	psi	4537	ksi
TS-2-1	6800	psi	4570	ksi
TS-2-2	6641	psi	4490	ksi
TS-2-3	6430	psi	4590	ksi
Average	6624	psi	4550	ksi
TS-3-1	6189	psi	4480	ksi
TS-3-2	6003	psi	4490	ksi
TS-3-3	5996	psi	4450	ksi
Average	6063	psi	4473	ksi
TS-4-1	5767	psi	4410	ksi
TS-4-2	5727	psi	4380	ksi
TS-4-3	5708	psi	4310	ksi
Average	5734	psi	4367	ksi

Table F.5: Compressive strength testing results for the FORTA-FERRO mixes.

Concrete Mix	Compressive Strength		Modulus of Elasticity	
FF-1-1	6770	psi	4430	ksi
FF-1-2	6683	psi	4490	ksi
FF-1-3	6556	psi	4600	ksi
Average	6670	psi	4507	ksi
FF-2-1	6106	psi	4380	ksi
FF-2-2	5983	psi	4340	ksi
FF-2-3	5918	psi	4440	ksi
Average	6002	psi	4387	ksi
FF-3-1	5422	psi	4040	ksi
FF-3-2	5511	psi	4110	ksi
FF-3-3	5310	psi	4200	ksi
Average	5414	psi	4117	ksi
FF-4-1	6707	psi	4760	ksi
FF-4-2	6636	psi	4580	ksi
FF-4-3	6672	psi	4460	ksi
Average	6672	psi	4600	ksi

Table F.6: Compressive strength testing results for the Dramix 5D mixes.

Concrete Mix	Compressive Strength		Modulus of Elasticity	
DR-1-1	6296	psi	4590	ksi
DR-1-2	6491	psi	4440	ksi
DR-1-3	6248	psi	4470	ksi
Average	6345	psi	4500	ksi
DR-2-1	6875	psi	4600	ksi
DR-2-2	6648	psi	4590	ksi
DR-2-3	6549	psi	4590	ksi
Average	6691	psi	4593	ksi
DR-3-1	5122	psi	4070	ksi
DR-3-2	5318	psi	3950	ksi
DR-3-3	5217	psi	3920	ksi
Average	5219	psi	3980	ksi
DR-4-1	5791	psi	4210	ksi
DR-4-2	5583	psi	4150	ksi
DR-4-3	5654	psi	4190	ksi
Average	5676	psi	4183	ksi

F-2: Average Residual Strength Test Results

The results obtained from the ASTM C1399 average residual strength test are shown on the following pages in Table F.7 through Table F.26.

Table F.7: ARS testing results for Strux 90/40 fibers at 3 lb/yd^3.

	Load Readings								Ave Residual Strength	
	1		2		3		4			
ST-1-1	690	lb	730	lb	820	lb	820	lb	143	psi
ST-1-2	890	lb	930	lb	1000	lb	1070	lb	182	psi
ST-1-3	460	lb	700	lb	800	lb	870	lb	133	psi
ST-1-4	1170	lb	1130	lb	1150	lb	1110	lb	214	psi
ST-1-5	870	lb	1080	lb	1180	lb	1310	lb	208	psi
							Average		176	psi

Table F.8: ARS testing results for Strux 90/40 fibers at 5 lb/yd^3.

	Load Readings								Ave Residual Strength	
	1		2		3		4			
ST-2-1	1570	lb	1790	lb	1890	lb	1930	lb	337	psi
ST-2-2	2660	lb	2870	lb	2970	lb	3040	lb	541	psi
ST-2-3	2890	lb	3150	lb	3300	lb	3360	lb	595	psi
ST-2-4	870	lb	1100	lb	1260	lb	1440	lb	219	psi
ST-2-5	1030	lb	1050	lb	1080	lb	1160	lb	203	psi
							Average		379	psi

Table F.9: ARS testing results for Strux 90/40 fibers at 8 lb/yd^3.

	Load Readings								**Ave Residual Strength**	
	1		**2**		**3**		**4**			
ST-3-1	2560	lb	2730	lb	2900	lb	3010	lb	525	psi
ST-3-2	3310	lb	3650	lb	3810	lb	3210	lb	655	psi
ST-3-3	2360	lb	2670	lb	2890	lb	3060	lb	515	psi
ST-3-4	1620	lb	1730	lb	1840	lb	1950	lb	335	psi
ST-3-5	1110	lb	1580	lb	1760	lb	1920	lb	299	psi
							Average		466	psi

Table F.10: ARS testing results for Strux 90/40 fibers at 10 lb/yd^3.

	Load Readings								**Ave Residual Strength**	
	1		**2**		**3**		**4**			
ST-4-1	1570	lb	1620	lb	1700	lb	1770	lb	312	psi
ST-4-2	1800	lb	2060	lb	2300	lb	2590	lb	410	psi
ST-4-3	1520	lb	1640	lb	1750	lb	1800	lb	315	psi
ST-4-4	2220	lb	2350	lb	2410	lb	2500	lb	444	psi
ST-4-5	3080	lb	3210	lb	3320	lb	3400	lb	610	psi
							Average		418	psi

Table F.11: ARS testing results for Fibermesh 650 fibers at 3 lb/yd^3.

	Load Readings								Ave Residual Strength	
	1		2		3		4			
FM-1-1	1020	lb	900	lb	820	lb	860	lb	169	psi
FM-1-2	1220	lb	1410	lb	1500	lb	1510	lb	264	psi
FM-1-3	810	lb	810	lb	870	lb	970	lb	162	psi
FM-1-4	1160	lb	1130	lb	1170	lb	1070	lb	212	psi
FM-1-5	830	lb	890	lb	990	lb	1120	lb	180	psi
							Average		197	psi

Table F.12: ARS testing results for Fibermesh 650 fibers at 5 lb/yd^3.

	Load Readings								Ave Residual Strength	
	1		2		3		4			
FM-2-1	2340	lb	2530	lb	2660	lb	2770	lb	483	psi
FM-2-2	2110	lb	2230	lb	2320	lb	2350	lb	422	psi
FM-2-3	1040	lb	1270	lb	1350	lb	1400	lb	237	psi
FM-2-4	2470	lb	2530	lb	2570	lb	2610	lb	477	psi
FM-2-5	1530	lb	1620	lb	1680	lb	1760	lb	309	psi
							Average		386	psi

Table F.13: ARS testing results for Fibermesh 650 fibers at 8 lb/yd^3.

	Load Readings								Ave Residual Strength	
	1		2		3		4			
FM-3-1	2550	lb	2970	lb	3290	lb	3610	lb	582	psi
FM-3-2	1810	lb	1960	lb	2070	lb	1950	lb	365	psi
FM-3-3	2010	lb	2380	lb	2700	lb	2880	lb	467	psi
FM-3-4	2420	lb	2600	lb	2790	lb	2950	lb	504	psi
FM-3-5	1710	lb	1900	lb	2030	lb	2180	lb	367	psi
							Average		457	psi

Table F.14: ARS testing results for Fibermesh 650 fibers at 10 lb/yd^3.

	Load Readings								Ave Residual Strength	
	1		2		3		4			
FM-4-1	3070	lb	3440	lb	3840	lb	4190	lb	682	psi
FM-4-2	3020	lb	3330	lb	3660	lb	4000	lb	657	psi
FM-4-3	2140	lb	2500	lb	2810	lb	3040	lb	492	psi
FM-4-4	2270	lb	2520	lb	2780	lb	3010	lb	496	psi
FM-4-5	2330	lb	2600	lb	2790	lb	2940	lb	500	psi
							Average		565	psi

Table F.15: ARS testing results for TUF-STRAND SF fibers at 3 lb/yd^3.

	Load Readings								Ave Residual Strength	
	1		2		3		4			
TS-1-1	500	lb	530	lb	570	lb	680	lb	107	psi
TS-1-2	840	lb	1050	lb	1180	lb	1240	lb	202	psi
TS-1-3	840	lb	850	lb	870	lb	890	lb	162	psi
TS-1-4	760	lb	800	lb	880	lb	950	lb	159	psi
TS-1-5	800	lb	920	lb	1020	lb	1050	lb	178	psi
							Average		161	psi

Table F.16: ARS testing results for TUF-STRAND SF fibers at 5 lb/yd^3.

	Load Readings								Ave Residual Strength	
	1		2		3		4			
TS-2-1	850	lb	980	lb	1010	lb	1120	lb	186	psi
TS-2-2	1210	lb	1380	lb	1440	lb	1470	lb	258	psi
TS-2-3	1560	lb	1590	lb	1670	lb	1730	lb	307	psi
TS-2-4	1370	lb	1410	lb	1470	lb	1540	lb	271	psi
TS-2-5	1410	lb	1650	lb	1790	lb	1890	lb	316	psi
							Average		268	psi

Table F.17: ARS testing results for TUF-STRAND SF fibers at 8 lb/yd^3.

	Load Readings								Ave Residual Strength	
	1		2		3		4			
TS-3-1	1850	lb	2110	lb	2340	lb	2490	lb	412	psi
TS-3-2	1780	lb	1820	lb	1930	lb	2050	lb	355	psi
TS-3-3	1910	lb	2070	lb	2150	lb	2190	lb	390	psi
TS-3-4	2150	lb	2220	lb	2490	lb	2610	lb	444	psi
TS-3-5	1560	lb	1710	lb	1780	lb	1910	lb	326	psi
							Average		386	psi

Table F.18: ARS testing results for TUF-STRAND SF fibers at 10 lb/yd^3.

	Load Readings								Ave Residual Strength	
	1		2		3		4			
TS-4-1	1740	lb	1910	lb	2080	lb	2280	lb	375	psi
TS-4-2	2160	lb	2500	lb	2840	lb	2980	lb	491	psi
TS-4-3	1710	lb	1910	lb	2140	lb	2320	lb	379	psi
TS-4-4	1980	lb	2270	lb	2520	lb	2750	lb	446	psi
TS-4-5	2300	lb	2560	lb	2830	lb	3040	lb	503	psi
							Average		439	psi

Table F.19: ARS testing results for FORTA-FERRO fibers at 3 lb/yd^3.

	Load Readings								Ave Residual Strength	
	1		2		3		4			
FF-1-1	870	lb	910	lb	970	lb	970	lb	174	psi
FF-1-2	710	lb	750	lb	790	lb	820	lb	144	psi
FF-1-3	940	lb	1010	lb	1140	lb	1280	lb	205	psi
FF-1-4	920	lb	1050	lb	1170	lb	1250	lb	206	psi
FF-1-5	1080	lb	1090	lb	1060	lb	1050	lb	201	psi
							Average		186	psi

Table F.20: ARS testing results for FORTA-FERRO fibers at 5 lb/yd^3.

	Load Readings								**Ave Residual Strength**	
	1		**2**		**3**		**4**			
FF-2-1	1280	lb	1400	lb	1500	lb	1610	lb	271	psi
FF-2-2	1320	lb	1400	lb	1560	lb	1720	lb	281	psi
FF-2-3	1860	lb	1880	lb	1820	lb	1860	lb	348	psi
FF-2-4	1340	lb	1490	lb	1620	lb	1680	lb	287	psi
FF-2-5	1020	lb	1170	lb	1350	lb	1590	lb	240	psi
							Average		286	psi

Table F.21: ARS testing results for FORTA-FERRO fibers at 8 lb/yd^3.

	Load Readings								**Ave Residual Strength**	
	1		**2**		**3**		**4**			
FF-3-1	3440	lb	3760	lb	3920	lb	4000	lb	709	psi
FF-3-2	2990	lb	3360	lb	3740	lb	4110	lb	666	psi
FF-3-3	2870	lb	3180	lb	3450	lb	3760	lb	622	psi
FF-3-4	3010	lb	3290	lb	3490	lb	3770	lb	636	psi
FF-3-5	2800	lb	3090	lb	3210	lb	3410	lb	586	psi
							Average		644	psi

Table F.22: ARS testing results for FORTA-FERRO fibers at 10 lb/yd^3.

	Load Readings								**Ave Residual Strength**	
	1		**2**		**3**		**4**			
FF-4-1	2770	lb	3050	lb	3270	lb	3390	lb	585	psi
FF-4-2	1840	lb	2420	lb	2960	lb	3230	lb	490	psi
FF-4-3	2320	lb	2860	lb	3380	lb	3570	lb	569	psi
FF-4-4	2310	lb	2730	lb	3000	lb	3240	lb	529	psi
FF-4-5	2750	lb	3190	lb	3580	lb	3930	lb	630	psi
							Average		561	psi

Table F.23: ARS testing results for Dramix 5D fibers at 25 lb/yd^3.

	Load Readings								Ave Residual Strength	
	1		2		3		4			
DR-1-1	1280	lb	1410	lb	1460	lb	1500	lb	265	psi
DR-1-2	2140	lb	2430	lb	2710	lb	2750	lb	470	psi
DR-1-3	2170	lb	2580	lb	2910	lb	3010	lb	500	psi
DR-1-4	1890	lb	2310	lb	2630	lb	2860	lb	454	psi
DR-1-5	2220	lb	2660	lb	3020	lb	3380	lb	529	psi
							Average		444	psi

Table F.24: ARS testing results for Dramix 5D fibers at 45 lb/yd^3.

	Load Readings								Ave Residual Strength	
	1		2		3		4			
DR-2-1	2510	lb	2900	lb	3230	lb	3690	lb	578	psi
DR-2-2	2750	lb	2860	lb	3090	lb	3360	lb	565	psi
DR-2-3	3340	lb	3480	lb	3590	lb	3600	lb	657	psi
DR-2-4	2440	lb	2730	lb	3070	lb	3360	lb	544	psi
DR-2-5	3570	lb	4120	lb	3370	lb	3390	lb	677	psi
							Average		604	psi

Table F.25: ARS testing results for Dramix 5D fibers at 65 lb/yd^3.

	Load Readings								Ave Residual Strength	
	1		2		3		4			
DR-3-1	1390	lb	1580	lb	1740	lb	1910	lb	310	psi
DR-3-2	2400	lb	2740	lb	2910	lb	3160	lb	525	psi
DR-3-3	1780	lb	1980	lb	2100	lb	2280	lb	382	psi
DR-3-4	3390	lb	3610	lb	3250	lb	3290	lb	635	psi
DR-3-5	2550	lb	2730	lb	2880	lb	2830	lb	515	psi
							Average		473	psi

Table F.26: ARS testing results for Dramix 5D fibers at 85 lb/yd^3.

	Load Readings								Ave Residual Strength	
	1		2		3		4			
DR-4-1	3950	lb	4400	lb	4650	lb	4860	lb	837	psi
DR-4-2	4200	lb	4430	lb	4590	lb	4640	lb	837	psi
DR-4-3	3340	lb	3630	lb	4000	lb	4330	lb	717	psi
DR-4-4	3650	lb	2730	lb	2690	lb	2740	lb	554	psi
DR-4-5	2060	lb	2170	lb	2400	lb	2380	lb	422	psi
							Average		674	psi

F-3: Flexural Performance Test Results

The results obtained from the ASTM C1609 flexural performance test are shown on the following pages in Table F.27 through Table F.32.

Table F.27: Flexural performance testing results for the control mix.

Specimen	First-Peak Load	First-Peak Strength	First-Peak Deflection	Peak Load	Peak Strength	Peak Deflection	Residual Loads		Residual Strengths		Toughness	Equivalent Flexural Strength Ratio
							PD,600	PD,150	fD,600	fD,150		
	(lb)	(psi)	(in)	(lb)	(psi)	(in)	(lb)	(lb)	(psi)	(psi)	(in-lb)	(%)
NA-0-1	9,410	784	0.0012	9,410	784	0.0012	-	-	-	-	-	-
NA-0-2	9,980	832	0.0012	9,980	832	0.0012	-	-	-	-	-	-
NA-0-3	9,180	765	0.0012	9,180	765	0.0012	-	-	-	-	-	-
Average	9,523	794	0.0012	9,523	794	0.0012	-	-	-	-	-	-

Table F.28: Flexural performance testing results for the Strux 90/40 mixes.

Specimen	First-Peak Load	First-Peak Strength	First-Peak Deflection	Peak Load	Peak Strength	Peak Deflection	Residual Loads		Residual Strengths		Toughness	Equivalent Flexural Strength Ratio
							PD,600	PD,150	fD,600	fD,150		
	(lb)	(psi)	(in)	(lb)	(psi)	(in)	(lb)	(lb)	(psi)	(psi)	(in-lb)	(%)
ST-1-1	8,260	688	0.0015	8,260	688	0.0015	1520	1850	127	154	263	26.6
ST-1-2	8,330	694	0.0016	8,330	694	0.0016	800	1750	67	146	226	22.6
ST-1-3	8,500	708	0.0016	8,500	708	0.0016	750	1090	63	91	175	17.1
Average	8,363	697	0.0016	8,363	697	0.0016	1023	1563	85	130	221	22.1
ST-2-1	6,680	557	0.0015	6,680	557	0.0015	1520	2780	127	232	276	34.4
ST-2-2	6,430	536	0.0016	6,430	536	0.0016	1080	1990	90	166	215	27.9
ST-2-3	6,700	558	0.0011	6,700	558	0.0011	1180	1890	98	158	218	27.1
Average	6,603	550	0.0014	6,603	550	0.0014	1260	2220	105	185	236	29.8
ST-3-1	7,760	647	0.0019	7,760	647	0.0019	3230	3840	269	320	452	48.5
ST-3-2	8,280	690	0.0023	8,280	690	0.0023	3150	4050	263	338	450	45.3
ST-3-3	8,000	667	0.0026	8,000	667	0.0026	2860	3510	238	293	426	44.3
Average	8,013	668	0.0023	8,013	668	0.0023	3080	3800	257	317	443	46.0
ST-4-1	6,890	574	0.0017	6,890	574	0.0017	3210	3850	268	321	452	54.7
ST-4-2	8,690	724	0.0025	8,690	724	0.0025	3250	3390	271	283	451	43.2
ST-4-3	6,710	559	0.0016	6,710	559	0.0016	2450	2280	204	190	328	40.7
Average	7,430	619	0.0019	7,430	619	0.0019	2970	3173	248	264	410	46.2

Table F.29: Flexural performance testing results for the Fibermesh 650 mixes.

Specimen	First-Peak Load (lb)	First-Peak Strength (psi)	First-Peak Deflection (in)	Peak Load (lb)	Peak Strength (psi)	Peak Deflection (in)	Residual Loads PD,600 (lb)	Residual Loads PD,150 (lb)	Residual Strengths fD,600 (psi)	Residual Strengths fD,150 (psi)	Toughness (in-lb)	Equivalent Flexural Strength Ratio (%)
FM-1-1	5,830	486	0.0014	5,830	486	0.0014	1190	1400	99	117	184	26.3
FM-1-2	7,770	648	0.0025	7,770	648	0.0025	1220	1620	102	135	231	24.8
FM-1-3	8,270	689	0.0025	8,270	689	0.0025	1470	1940	123	162	151	15.2
Average	7,290	608	0.0021	7,290	608	0.0021	1293	1653	108	138	189	22.1
FM-2-1	9,020	752	0.0019	9,020	752	0.0019	2630	3240	219	270	377	34.8
FM-2-2	7,640	637	0.0015	7,640	637	0.0015	1730	0	144	0	167	18.2
FM-2-3	7,510	626	0.0015	7,510	626	0.0015	1800	2710	150	226	294	32.6
Average	8,057	671	0.0016	8,057	671	0.0016	2053	1983	171	165	279	28.5
FM-3-1	7,410	618	0.0022	7,410	618	0.0022	1950	3510	163	293	341	38.3
FM-3-2	7,440	620	0.0022	7,440	620	0.0022	1870	3000	156	250	342	38.3
FM-3-3	8,460	705	0.0026	8,460	705	0.0026	3830	4850	319	404	524	51.6
Average	7,770	648	0.0023	7,770	648	0.0023	2550	3787	213	316	402	42.7
FM-4-1	6,540	545	0.0015	6,540	545	0.0015	3620	5080	302	423	539	68.7
FM-4-2	7,810	651	0.0021	7,810	651	0.0021	3880	4990	323	416	558	59.5
FM-4-3	8,270	689	0.0018	8,270	689	0.0018	3250	4740	271	395	490	49.3
Average	7,540	628	0.0018	7,540	628	0.0018	3583	4937	299	411	529	59.2

Table F.30: Flexural performance testing results for the TUF-STRAND SF mixes.

Specimen	First-Peak Load (lb)	First-Peak Strength (psi)	First-Peak Deflection (in)	Peak Load (lb)	Peak Strength (psi)	Peak Deflection (in)	Residual Loads PD,600 (lb)	Residual Loads PD,150 (lb)	Residual Strengths fD,600 (psi)	Residual Strengths fD,150 (psi)	Toughness (in-lb)	Equivalent Flexural Strength Ratio (%)
TS-1-1	5,220	435	0.0012	5,220	435	0.0012	270	690	23	58	85	13.5
TS-1-2	7,130	594	0.0020	7,130	594	0.0020	210	640	18	53	129	15.1
TS-1-3	7,930	661	0.0020	7,930	661	0.0020	280	480	23	40	127	13.3
Average	6,760	563	0.0017	6,760	563	0.0017	253	603	21	50.3	113	14.0
TS-2-1	7,660	638	0.0020	7,660	638	0.0020	2070	3380	173	282	363	39.5
TS-2-2	6,360	530	0.0018	6,360	530	0.0018	1070	1890	89	158	211	27.6
TS-2-3	7,540	628	0.0022	7,540	628	0.0022	1280	2390	107	199	267	29.6
Average	7,187	599	0.0020	7,187	599	0.0020	1473	2553	123	213	281	32.2
TS-3-1	7,670	639	0.0022	7,670	639	0.0022	2860	3730	238	311	418	45.4
TS-3-2	6,890	574	0.0027	6,890	574	0.0027	2190	3720	183	310	374	45.2
TS-3-3	6,980	582	0.0020	6,980	582	0.0020	1950	3450	163	288	351	41.8
Average	7,180	598	0.0023	7,180	598	0.0023	2333	3633	194	303	381	44.2
TS-4-1	8,420	702	0.0023	8,420	702	0.0023	4170	5160	348	430	576	57.0
TS-4-2	7,920	660	0.0019	7,920	660	0.0019	3580	5200	298	433	529	55.6
TS-4-3	7,100	592	0.0021	7,100	592	0.0021	4290	5330	358	444	585	68.6
Average	7,813	651	0.0021	7,813	651	0.0021	4013	5230	334	436	563	60.4

Table F.31: Flexural performance testing results for the FORTA-FERRO mixes.

Specimen	First-Peak Load (lb)	First-Peak Strength (psi)	First-Peak Deflection (in)	Peak Load (lb)	Peak Strength (psi)	Peak Deflection (in)	Residual Loads PD,600 (lb)	Residual Loads PD,150 (lb)	Residual Strengths fD,600 (psi)	Residual Strengths fD,150 (psi)	Toughness (in-lb)	Equivalent Flexural Strength Ratio (%)
FF-1-1	7,720	643	0.0024	7,720	643	0.0024	1300	1570	108	131	244	26.3
FF-1-2	7,930	661	0.0022	7,930	661	0.0022	310	980	26	82	192	20.2
FF-1-3	6,440	537	0.0021	6,440	537	0.0021	710	1130	59	94	172	22.3
Average	7,363	614	0.0022	7,363	614	0.0022	773	1227	64	102	203	22.9
FF-2-1	6,410	534	0.0018	6,410	534	0.0018	890	940	74	78	155	20.1
FF-2-2	6,810	568	0.0022	6,810	568	0.0022	820	1000	68	83	174	21.3
FF-2-3	5,970	498	0.0017	5,970	498	0.0017	650	1620	54	135	190	26.5
Average	6,397	533	0.0019	6,397	533	0.0019	787	1187	66	99	173	22.6
FF-3-1	7,960	663	0.0021	7,960	663	0.0021	5010	6080	418	507	252	26.4
FF-3-2	8,730	728	0.0027	9,100	758	0.0915	6920	8230	577	686	447	42.7
FF-3-3	7,610	634	0.0023	7,610	634	0.0023	5170	6140	431	512	692	75.8
Average	8,100	675	0.0024	8,223	685	0.0320	5700	6817	475	568	464	48.3
FF-4-1	8,230	686	0.0021	8,230	686	0.0021	3390	4150	283	346	483	48.9
FF-4-2	7,370	614	0.0021	7,370	614	0.0021	2590	3410	216	284	401	45.3
FF-4-3	8,010	668	0.0021	8,010	668	0.0021	3870	5200	323	433	557	57.9
Average	7,870	656	0.0021	7,870	656	0.0021	3283	4253	274	354	480	50.7

Table F.32: Flexural performance testing results for the Dramix 5D mixes.

Specimen	First-Peak Load (lb)	First-Peak Strength (psi)	First-Peak Deflection (in)	Peak Load (lb)	Peak Strength (psi)	Peak Deflection (in)	Residual Loads PD,600 (lb)	Residual Loads PD,150 (lb)	Residual Strengths fD,600 (psi)	Residual Strengths fD,150 (psi)	Toughness (in-lb)	Equivalent Flexural Strength Ratio (%)
DR-1-1	7,880	657	0.0021	7,880	657	0.0021	5460	7040	455	587	762	80.6
DR-1-2	8,040	670	0.0021	8,040	670	0.0021	3040	5640	253	470	194	20.1
DR-1-3	7,260	605	0.0019	7,260	605	0.0019	3170	5310	264	443	533	61.1
Average	7,727	644	0.0020	7,727	644	0.0020	3890	5997	324	500	496	53.9
DR-2-1	7,570	631	0.0023	7,570	631	0.0023	3880	6570	323	548	626	68.9
DR-2-2	7,410	618	0.0019	9,550	796	0.0738	6300	7430	525	619	822	92.4
DR-2-3	6,270	523	0.0018	6,270	523	0.0018	3830	2800	319	233	529	70.3
Average	7,083	590	0.0020	7,797	650	0.0260	4670	5600	389	467	659	77.2
DR-3-1	6,970	581	0.0024	6,970	581	0.0024	3770	5200	314	433	534	63.8
DR-3-2	5,770	481	0.0026	6,770	564	0.1140	4540	6580	378	548	669	96.5
DR-3-3	-	-	-	-	-	-	-	-	-	-	-	-
Average	6,370	531	0.0025	6,870	573	0.0582	4155	5890	346	491	601	80.2
DR-4-1	6,110	509	0.0020	9,270	773	0.1196	6780	9210	565	768	307	41.9
DR-4-2	6,260	522	0.0022	7,250	604	0.0119	6810	5180	568	432	706	94.0
DR-4-3	5,710	476	0.0027	8,840	737	0.1200	7110	8840	593	737	916	133.7
Average	6,027	502	0.0023	8,453	704	0.0838	6900	7743	575	645	643	89.9

APPENDIX G: GUIDELINES FOR FRC MATERIAL SELECTION, MIX DESIGN, CONSTRUCTION, AND TESING

FRC material selection, mix design, construction, and testing shall be carried out in accordance with conventional concrete procedures detailed in SDDOT manuals and ASTM standards except as modified by this document. All guidelines in this document are meant for FRC structures incorporating any type of synthetic fibers except when referred to the synthetic fibers used in this study. They are also meant for all FRC mix designs except when referred to the mix design used in this study.

G-1: Material Selection

- Fibers shall be made of materials that are known for their long-term resistance to deterioration, such as polyolefins.
- Fibers with lower aspect ratios (Less than 100), but not less than 40, are preferred in order to minimize fiber balling.
- Fibers shall be at least 1.5 inches long.
- It is preferred to use fibers with tensile strength and modulus of elasticity of at least 50 ksi and 600 ksi, respectively.
- For applications requiring good abrasion resistance, longer fibers are recommended.
- The FORTA-FERRO fiber is the most cost-effective among the tested fibers in this study.

G-2: Mix Design

- Reduction of 20% and 15% in compressive strength and modulus of elasticity, respectively, shall be assumed.
- For increased workability, minimized fiber balling, and reduced crack widths, higher mortar content is recommended.
- Slump values shall be aimed to be higher than conventional concrete specifications.
- Fiber volume fraction shall not be less than 0.2%.
- For the mix design and the synthetic fibers used in this study, the following equations could be used to determine the required fiber dosage necessary to meet required properties (D is fiber volume fraction [%] and has to be between 0.2% and 0.7%).
  - $Slump\ [in] = -6.7596D^2 + 0.8965D + 4.5$
  - $D = \frac{Toughness\ [lb.in]}{736.88}$
  - $D = \frac{Equivalent\ Flexural\ Strength\ Ratio\ [\%]}{80.778}$
  - $D = \frac{Normalized\ Effective\ Modulus\ of\ Rupture\ [psi] - 566.04}{366.49}$
  - $D = \frac{ARS\ [psi]}{806.92}$
- For the mix design and the synthetic fibers tested in this study, the following dosages for each application could be used (no factor of safety is taken into account):
  - Bridge deck: 0.35% to satisfy an ARS of 150 psi and a slump between 2 and 4 inches.
  - Deck overlay: 0.2% to satisfy an ARS of 150 psi and a slump between 2.75 and 5.25 inches.
  - Approach slab: 0.2% to satisfy an ARS of 150 psi and a slump between 1 and 4.5 inches.
  - Jersey barrier: 0.2% to satisfy an ARS of 150 psi and a slump between 4 and 6 inches.

- Pavement repair: 0.46% to satisfy an ARS of 150 psi and a slump between 1 and 3.5 inches.
- Curb, gutter, sidewalk, and riprap: 0.2% to satisfy an ARS of 115 psi and a slump between 1 and 4.5 inches.
- Precast drainage unit: 0.22% to satisfy an ARS of 175 psi and a slump between 1 and 4.5 inches.

G-3: Construction

- A bridge deck paver is preferred over a low-slump paver.
- Vibration shall always be applied to ensure uniform fiber distribution.
- Tining shall be carried out according to one of the following procedures to avoid catching on fibers:
    - Reducing the tining angle.
    - Turning the tining rake over.
    - Grinding the tining grooves after hardening.
- A carpet drag shall be avoided to prevent pulling out fibers from the surface of concrete. Instead, a burlap drag or a broom could be used.

G-4: Testing

- In order to minimize fiber balling and guarantee uniform fiber distribution, five minutes of additional mixing shall be implemented for laboratory testing.
- For reliability of results, mixes shall be at least duplicated. In addition, five replicate specimens shall be prepared for each hardened test.
- In addition to following the procedures in ASTM C 31, C 42, C 192, and C 1018 for sample preparation, extra care, as per ACI 544.2R-89, shall be taken to minimize preferential fiber alignment and non-uniform distribution.
- The smallest specimen dimension shall be at least three times the larger of maximum aggregate size and fiber length in order to minimize preferential fiber alignment.
- The average residual strength shall be considered the main property representing the performance of the structure since all existing specifications site it as the limiting property.
- Fiber manufacturers shall submit independent laboratory data supporting average residual strength results.
- Third-point loading is preferred for the flexural strength test.
- Splitting tensile strength test, as per ASTM C 496, shall not be conducted beyond the first crack point as the results become difficult to interpret due to unknown stress distribution after first crack.
- For impact resistance testing, instrumented impact tests (ACI 544.2R-89) shall be used instead of the qualitative simple drop-weight test.
- Surface inspections shall be conducted periodically to monitor the structure’s long-term performance.
- Bond strength shall be evaluated by obtaining cores from the field from composite components.