# Fiber Reinforced Concrete for Bridge Deck Overlays

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**16. Abstract**

This report reviews available research literature and reports on Fiber Reinforced Concrete (FRC) mixtures to recognize best practices of using FRC overlay mixtures and identify products with the potential of being successfully utilized in Missouri. State DOT representatives were surveyed to consolidate the current state of practice as it relates to the use of FRC, particularly for bridge decks. The survey shows that there are a variety of approaches and implementation methods from coast to coast. Also reported are the findings of a laboratory program involving evaluation of twelve fibers, representing a broad spectrum of available fiber types. Each fiber was intermixed into a representative concrete mixture at three different dosages to evaluate the performance of the recommended range. Testing was carried out for standard physical strength metrics, durability performance, and specialized FRC toughness. Additionally, the impact of fibers on restrained shrinkage cracking and tensile bond strength of FRC was evaluated. Results indicated that fibers can be introduced to concrete mixtures to obtain workable mixtures with little change to the underlying concrete mixture proportions. A generalized trend could not be established between fiber characteristics and mechanical or durability properties. Good correlation was observed between flexural toughness and fiber dosage. A noticeable difference was documented between the performance of synthetic and steel fibers when subjected to the ASTM C1609 test. The ASTM C1550 test indicated varying behaviors at different prescribed deflection levels. Restrained shrinkage testing showed the lower dosages recommended showed little improvement over the non-FRC control mixture; higher fiber dosages showed improvements in resistance to restrained shrinkage cracking. Many concerns regarding the inclusion of fibers in concrete were overcome and, if eliminated, FRC can result in mixtures with similar strength and durability characteristics to traditional non-FRC concrete with improved crack resistance. These are ideal characteristics of an overlay concrete that needs to be compliant with the underlying concrete while not reflecting through any existing cracks to prolong the life of the underlying structural concrete.

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# 1. OVERVIEW AND PROBLEM STATEMENT

Transportation agencies face pressure to extend the service life of existing bridge decks in response to limited tolerance from the public for closures and limited repair and rehabilitation budgets. Bridges are essential elements of any transportation system and any deficiency in their performance reduces the mobility of the public and leads to higher expenses and increased travel times. The United States is in need of significant investments every year in the construction, maintenance, preservation, repair, and rehabilitation of the nation's transportation systems, including concrete bridge decks [1].

Bridge deck deterioration is primarily caused by environmental factors and heavy traffic use. Being the most exposed element of bridges, concrete bridge decks are often the main contributor to the reduction in serviceability of a bridge. Cracking, freezing and thawing, and chloride ingress are the predominant deterioration mechanisms affecting the performance of the concrete bridge decks in Midwest states, such as Missouri, where de-icing salts are widely used [2]. For these reasons, concrete overlays have been used as a traditional but advanced tool to extend the life of the reinforced concrete pavements and bridge decks [3].

With the growing interest in the use of concrete overlays, the number of overlay types has been significantly increasing. This includes, but is not limited to, fiber reinforced concrete (FRC), ultra-high-performance concrete (UHPC), low slump concrete, latex modified concrete, concrete incorporating silica fume, and fly ash modified concrete overlays. Such variety in overlay technology has led to not only a wide range of placement, finishing, curing, methods, and requirements but also different design criteria causing challenges for the design engineers, contractors, owners, and agencies who lack the proper tools to identify the most efficient methods and products. Additionally, the parameters that define satisfactory utilization, performance, and maintenance of the concrete overlays are not entirely agreed upon and are subject to periodic changes with novel products and tools being continuously introduced to the industry.

Among many other challenges in incorporating fibers in concrete overlays, fiber dispersion is the most frequently encountered performance challenge associated with FRCs [4], [5]. Improper distribution of the fibers can lead to agglomeration which will affect the performance of FRC in both fresh and hardened states. Although thin concrete overlays are assumed to have improved bond with the substrate when they contain fiber reinforcements, bond of FRC overlays with the substrate is also another element that has been overlooked by the literature. Fiber dispersion problems can vary depending on the fiber type and mixture proportion, and therefore, necessitate the appropriate combination of fiber type and concrete mixture proportions. Another challenge to the use of FRC for overlays is coming up with the correct combination of fiber type and dosage. The dose of fiber necessary to achieve a certain level of performance will vary from one fiber to the next so it isn't enough to specify a certain dosage of fiber. This can be overwhelming due to the wide variety of fibers available in the market and the inherent effect of the use of different fibers on concrete performance.

Overlay history suggests that the most common failure modes are mid panel and panel corner cracking, joint faulting, curling, lack of ductility, and fatigue are common and collective failure. Fiber reinforcement can help mitigate all of these failure modes [6]–[8]. Improved resistance to crack propagation, controlled thermal and moisture stresses, increased elasticity, higher tensile, flexural, and fatigue strengths, and greater impact and abrasion resistance are some improvements in concrete performance that are generally achieved with the use of FRC compared to plain concrete overlays [9], [10]. Also, past construction examples have revealed limits to the minimum overlay thickness when made with plain concrete (JPCP), where the use of structural fibers has been found very effective, allowing for reduced thickness [11], [12]. The use of FRC can mitigate many of the common failure modes in concrete overlays by utilizing the ability of FRC to hold cracks tight and to bridge over underlying joints/cracks without allowing the crack to reflect through to the surface of the overlay. This will result in added toughness and fatigue life to the overlay.

Despite many laboratory and field studies [7], [13]–[18] carried out in the past to study the use of FRC for overlays there are a myriad different exposure and use conditions such that there is no universally agreed upon set of criteria and tests for evaluating FRC for overlays. This lack of agreement means there is still a need for study into the appropriate methods of evaluating the value of using FRC in a variety of intended service conditions. From a concrete producer's point of view, most of the tests being used to measure the adequacy of an FRC mixture, besides being labor-intensive, are either expensive or simply not readily accessible at typical commercial laboratories. Indeed, concrete paving specifications have not kept pace with advancements in concrete science, and innovations in testing technologies are the main drawback for using FRC overlays.

For this purpose, the development of a Performance Engineered Mixtures (PEM) program for FRC overlay is essential to provide the tools for agencies to identify concrete manufacturers to produce and deliver, and the contractors to place a concrete mixture that is reliable, sustainable, and meets the needs for concrete infrastructure. The goal of a PEM is to achieve the service life of the design through measuring and controlling the concrete mixture by the engineering features that relate to the performance of the concrete.

AASHTO published a provisional guide specification, PP84 [19], in April 2017. The specification is structured around the recommendations of an expert task group concerning the critical parameters that control concrete mixture performance for concrete pavement production. FRC overlay as a growing material in this industry requires more work under the PEM program that follows two main steps: 1. Develop a provisional specification and 2. Upgrade existing and/or develop new test methods. This requires identifying the properties controlling the FRC overlay mixture performance, followed by developing correlations among the available test methods and the controlling-performance properties.

Therefore, there is a need to (1) establish a systematic and functional process that can guarantee the success of the FRC overlay application, (2) develop performance criteria for acceptability, (3) establish defined protocols for agencies to be able to evaluate a product that is submitted for approval, and (4) identify methodologies that facilitate the decision-making process.

## 2. TYPES OF FIBER

Different types of fibers are used in concrete with varying lengths, geometry, material composition, aspect ratio, and dosage. According to ASTM C1116 [20], fiber materials are classified as synthetic, steel, glass, and/or natural. Figure 1 depicts for each fiber classification one representative form or geometry. For each fiber classification there are multiple available geometries sold on the market. The representative steel fiber (Figure 1(a)) is an example of a crimped steel fiber. There are many varieties of steel fibers with different hook shapes on the ends as well. See section 3.2 for more information regarding these characteristics. These materials are defined in terms of the FRCs that are made with them. The four FRC classifications are summarized in Table 1. The use of FRC with each type of fiber is discussed below.

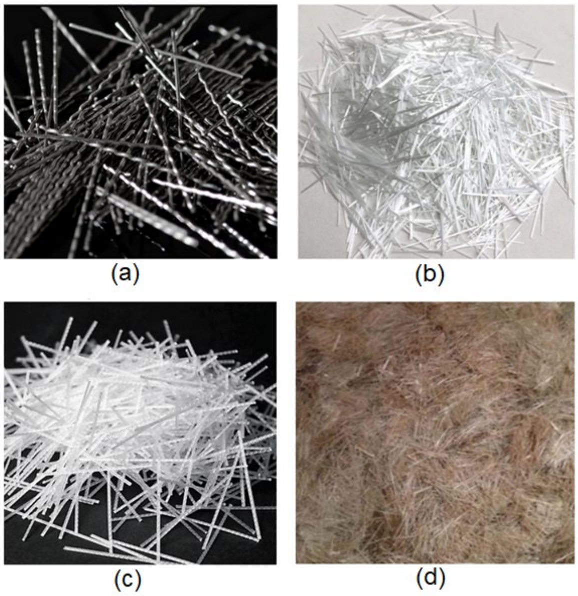


**Figure 1. Different types of fibers*;*** (a) Steel Fiber: https://m.made-in-china.com, (b) Glass Fiber: https://concretecooperation.com, (c) Synthetic Fiber: https://exactconcreteflooring.co.uk, (d) Natural Fiber: https://frontiersin.org

**Table 1. FRC Types and Classifications**

| Type | Classification | Definition | Most Common Materials / Origin | Standard |
|---|---|---|---|---|
| I | Steel FRC | Concrete made with carbon steel, alloy steel, or stainless-steel fibers. | Carbon steel, Alloy steel, Stainless-steel | ASTM A820 [21] |
| II | Glass FRC | Concrete made with alkali-resistant glass fibers. | Glass Fiber | ASTM C1666 [20] |
| III | Synthetic FRC | Concrete made with synthetic fibers that have been proven to be resistant to deterioration by the cement paste environment* over the useful life of the structure. | Polypropylene, Nylon, Acrylic, Aramid, Carbon, Nylon, Polyester, Basalt, Polyolefin, Polyethylene | Note 1 |

| | | | | |
|---|---|---|---|---|
| IV | Natural FRC | Concrete made with natural fibers that have been proven to be resistant to deterioration by the cement paste environment* over the useful life of the structure. | Wood, Hast, Leaf, Seed/Fruit, Wool/Hair, Silk/Other Filament | Note 2 |

*e.g., moisture, alkaline pore solution, and chemical admixtures.

Note 1: Currently, only polyolefin fibers have a standard specification for use in concrete (ASTM D7508 [22]). Note 2: Cellulose fibers have a standard specification for use in concrete (ASTM D7357 [23]).

## 2.1. Steel FRC Overlays

ASTM A820 [21] identifies five general categories of steel fibers based on the material source and production process including Type I: cold drawn wire, Type II: cut sheet, Type III: melt extracted, Type IV: mill cut, and Type V: modified cold drawn wire. Additionally, the method requires a minimum of 50 ksi tensile strength and capability of being bent around a 0.125-inch diameter pin to an angle of 90° at a temperature not greater than 60°F without breaking.

Steel FRCs have been studied since the 1960s for replacing secondary reinforcement used for crack control [24]. However, the benefits of utilizing steel fibers, such as improved toughness, greater modulus of elasticity (MOE) among others, are now understood. Although steel fibers have been used in FRC overlays, they are used less frequently than synthetic fibers. One identified concern with the use of steel fibers is fiber-reinforcement corrosion (although mostly surficial) [25], especially where deicing salts are commonly applied to the surface. Difficulty in introducing the fibers in the batching process and the higher costs of steel versus polymeric fiber material are other reasons cited. To overcome the corrosion-related issues associated with steel FRC, stainless steel and coated steel fibers have been made available to reduce the risk of corrosion [26], but at a considerably higher cost. On the other hand, it has been demonstrated that with proper concrete mixture design and adequate fiber selection, the potential of internal steel fiber corrosion can be mitigated. In this direction, many successful applications of FRC with steel fibers have been reported.

## 2.2. Synthetic FRC Overlays

Synthetic micro-fibers were presented to the construction industry in the 1980s for minimizing the early-age plastic shrinkage cracks [27]. In the 2000s, synthetic macro-fibers began to become a popular option to improve the toughness of concrete materials and have since been adopted for a variety of applications including, but not limited to, slab-on-grade, concrete pavement, overlays, and bridge decks.

According to a survey conducted in 2016 [28], structural synthetic fibers are the most commonly used fibers in concrete pavements or overlays and have been for the last few decades. The survey showed that 94 percent of FRC concrete overlays in the U.S. were constructed with structural synthetic fibers and only 6 percent were constructed with steel fibers. Compared to steel FRCs, synthetic FRCs are more susceptible to agglomeration. They are produced from a wide range of materials, such as those listed in Table 1. They can be micro monofilament, micro fibrillated, or macro monofilament [29]. Synthetic fibers may also have embossed or textured surfaces to enhance the mechanical bond. ACI 544.3 [30] defines micro-synthetic fibers as fibers with a diameter or equivalent diameters less than 0.012 inches, and macro-synthetic fibers as fibers with diameters equal or greater than 0.012 inches. Polypropylene and polyethylene are the most common commercially available synthetic or polymer materials and are classified as polyolefins. The term “polyolefin” is used to describe any long-chain polymer containing at least 85% by weight ethylene and/or propylene monomer units. Therefore, polypropylene and polyethylene are the two types of polymers that are approved by the industry for use as synthetic fibers in concrete mixtures.

### 2.3. Natural and Glass FRC Overlays

Natural fibers are produced or processed from organic sources, such as cellulose, coconut husks, hemp, sisal, jute, bamboo, etc., which are the products of the materials listed in Table 1. They are often selected due to local sources. They are typically chemically processed to avoid decomposition when used in the concrete. The limited literature available demonstrated the viability of these fibers, specifically glass, carbon, asbestos, and basalt fibers, which have been studied for use in concrete but there is little research into their performance in FRC pavements and overlays. Although more common than natural fibers, glass fibers are known to have low strain capacity, and are not conducive to compatibility in concrete joints that experience large crack widths and expansion and contraction of cracks. They are also susceptible to alkali attack and the long-term durability is a concern [26].

## 3. CHARACTERISTICS OF FIBERS

In addition to the type, fibers are normally presented by aspect ratio, texture, and shape. The term "aspect ratio" is the length-to-diameter ratio of the fiber that is generally between 20 to 100 for the majority of fibers [31]. If the fiber is not rounded, effective diameter shall be used which is calculated based on the actual cross-sectional area of the fiber.

With respect to the shape characteristics, fibers are either "straight" or "deformed". A deformed fiber has designed out-of-plane deformations (i.e., hooks, loops, or bends) to enhance the pullout resistance by increasing the interlock between fiber and cementitious matrix while a straight fiber is visually straight regardless of its surface texture.

Generally, the fiber's aspect ratio and geometry are selected based on the fiber's tensile strength and the strength of its bond with the concrete matrix to maximize pullout resistance so that the fiber does not break. Each of these characteristics is discussed in more detail as follows:

### 3.1. Fiber Size

Fibers can be differentiated based on three (3) main size classifications: macro-fibers, micro-fibers, and nanofibers. Macro-fibers, also known as structural fibers, are typically much stiffer and larger than micro monofilaments. Misconceptions still exist with many engineers about the difference between structural and non-structural fibers; however recent improvements in testing standards have given engineers better tools to differentiate between the two. Structural fibers can carry loads and may be used to replace traditional reinforcement in certain applications, as well as minimize or eliminate both early and late age cracking [32]. In concrete pavements or overlays, the applications of the structural fibers, with a typical length of equal or greater than 1.5 inches, are mainly to reduce fatigue cracking and joint faulting [33]. Non-structural fibers (micro-fibers), which are less stiff than structural fibers, are generally utilized to minimize plastic shrinkage [34]. Nanofibers are experimental and not currently suitable for concrete pavement applications [6].

The fiber size characteristics (i.e., length, diameter, and aspect ratio) can vary depending on the fiber type. For instance, synthetic macro-fibers are usually manufactured by a length of 0.5 to 2.25-inch and diameters smaller than 0.01-inch while steel macro-fibers normally have a length of 0.75 to 2.5-inch and diameters/thicknesses ranging from 0.005 to 0.04-inch [35].

As discussed earlier, the aspect ratio is a function of length and effective diameter and represents the total surface area for the concrete-fiber bonding. As the aspect ratio increases, the interfacial area between fiber and concrete expands leading to improved bonding. However, FRC production does not necessarily benefit from a higher aspect ratio as it can increase the potential for fiber clumping together causing "balling" issues (see Figure ***2***). Balling not only raises complexities in the placement and consolidation of the mixture but also, if not resolved, affects the stability and uniformity of the mixture.

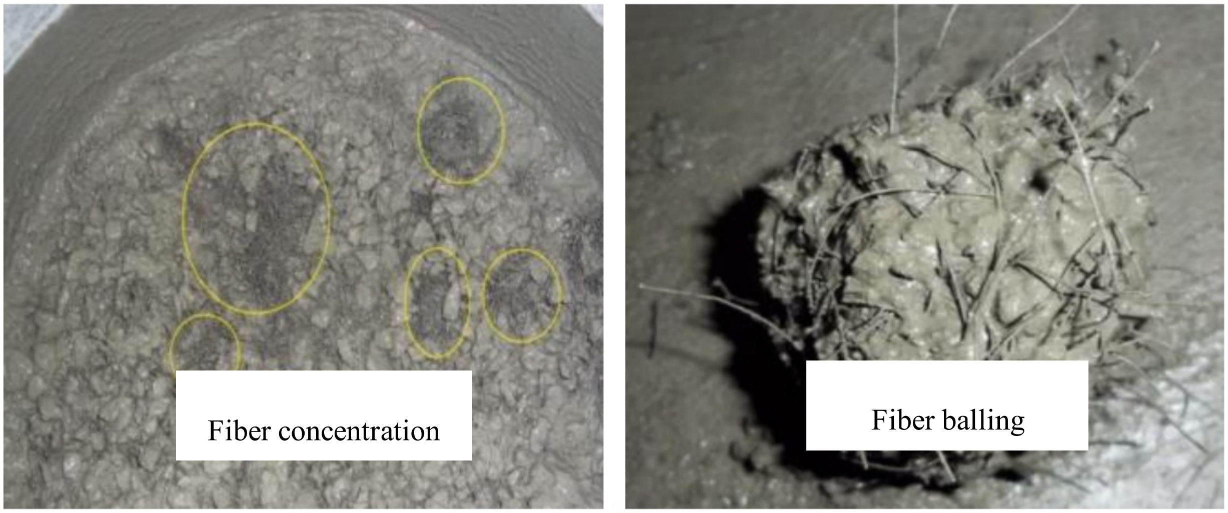


**Figure 2. Fresh concrete mix showing fiber concentration and balling effect [36]**

### 3.2. Texture and Shape

Fibers have been manufactured with various shapes and textures to provide improved tensile strength and/or bonding with the concrete. Some of these variations include, but are not limited to, embossed, twisted, crimped, or hooked-end fibers. Synthetic fibers are commonly being produced in forms of monofilament (single strand fiber), multifilament (blend of monofilament with different lengths), or fibrillated (a fiber with a branched network structure), while being embossed, twisted, crimped, or hooked-end are more common forms of steel fiber. Examples of some fiber shapes and textures are shown in Figure 3. The various shapes, types, sizes, and textures of commercially available fibers and lack of independent studies on the performance of the available fibers have indeed made it challenging for transportation agencies to identify the best option.

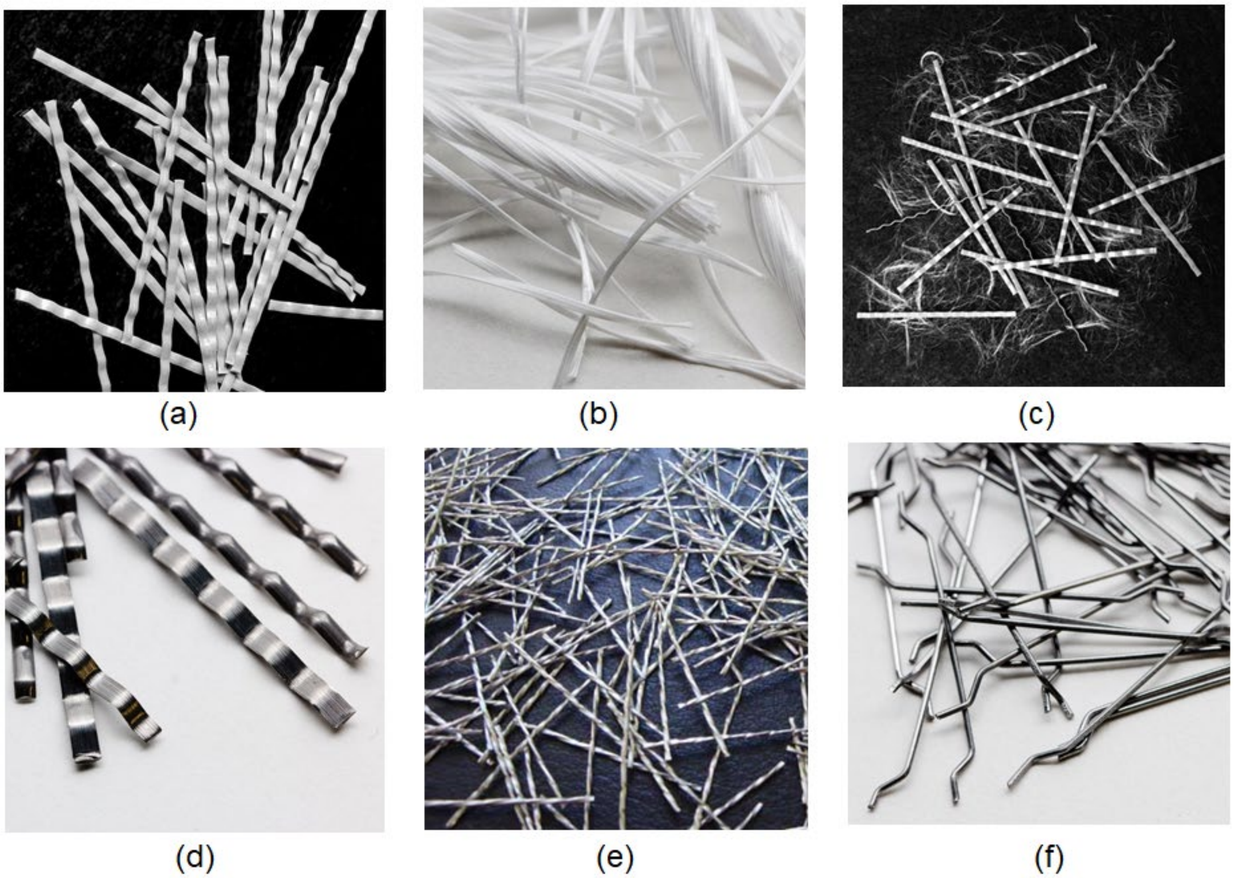


**Figure 3. Examples of some fiber shapes and textures; (a) sinusoidal deformed macro-synthetic fibers: https://fibermesh.com (b) Twisted macro mono-filament Polypropylene: https://nycon.com (c) blend of sinusoidal deformed macro-synthetic fibers with polypropylene: https://fibermesh.com (d) continuously deformed stainless steel fibers: https://nycon.com (e) Twisted Steel Fiber: http://www.steelfiberswest.com (f) Hooked-end steel fiber: https://nycon.com**

## 4. EFFECT OF FIBER ON FRC PERFORMANCE

FRC performance can be affected by several factors including type, size, volume, geometry, aspect ratio, and texture or shape of the fibers as well as the mixing and placement procedures that can impact the orientation and dispersion of the fibers within the FRC matrix. The effect of these factors on the fresh and hardened properties of concrete is discussed in the following sections.

In addition, the FRC response to external loading could vary depending on the sample size, loading rate, and test configuration [37]. For example, Bindiganavile [38] tested the flexural response of three different sizes of geometrically similar steel FRC beams and demonstrated an increase in the specimen size resulted in a decrease in the flexural toughness under impact loading (See Figure 4). The results in the figure demonstrate that changes in the size of the specimen resulted in different peak stress values and changed the shape of the stress vs deflection curve. The change in shape of the curve for the resulting data is an indication that the results of toughness testing are dependent on the size of the specimen and that one should use caution in scaling up or down a test as the resulting toughness parameters are not comparable. Further there is no quantified scaling factor for comparing results of one test geometry across multiple sizes. [37].

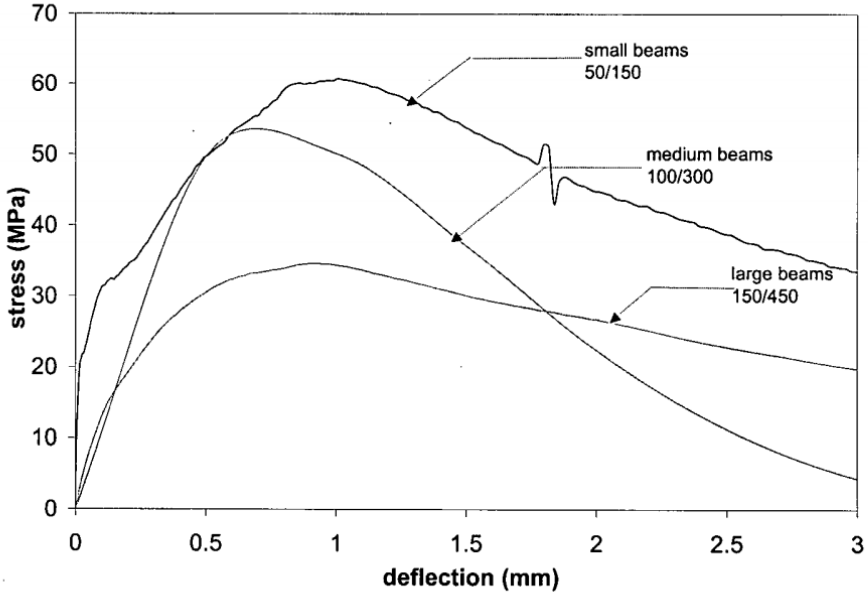


**Figure 4. Relationship between Stress and deflection responses of beams with different depth:span ratios under impact loading [38].**

### 4.1. Fresh Properties

It is understood by the concrete industry that a workable and constructable mixture is necessary for achieving the designed hardened performance. Despite the complex influence of the fibers on both fresh and hardened properties of the concrete, unsuitably, most research associated with FRC performance available in the literature has mainly focused on its hardened properties, while only a few studies investigated the FRC performance in the fresh state [17], [39]–[41]. S.H. Chu et al. [40] demonstrated that the parameters affecting the fresh properties may not be the same as those affecting the hardened characteristics. It is likely that the type (i.e., synthetic or steel) and aspect ratio of the fibers would have governing effects on the fresh properties [42]. For example, the addition of steel fibers would generally lead to lower packing density [43], while the addition of synthetic fiber results in higher packing density [44]. In spite of many benefits that incorporation of fibers in concrete can offer, adding fiber to the concrete will reduce the workability, i.e., compatibility, mobility, finishability, and stability [24], [45], and therefore, require additional adjustments to the mixture proportions.

As a result of their relatively high specific surface area, the incorporation of fibers leads to higher water demand and therefore, affects the concrete fresh properties. Harrington and Fick [35] showed that the addition of macro-fibers up to 1.5% by volume can lead to 1 to 4-inch slump reduction. Similar results were demonstrated by S.H. Chu et al. [40], shown in Figure 5.

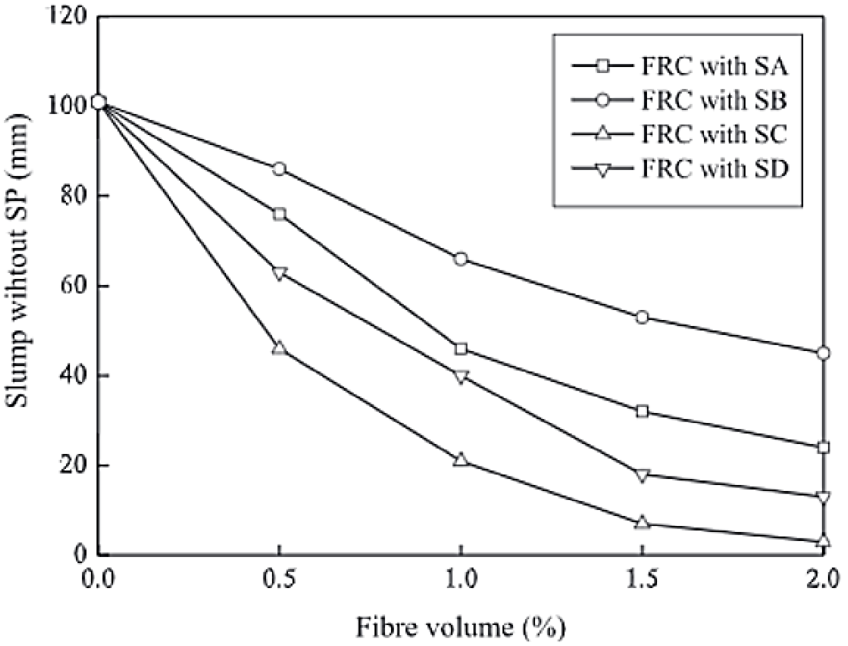


**Figure 5. Effect of fiber content on the slump of FRC, SA: l/d = 30/0.55, SB: l/d = 30/0.75, SC: l/d=60/0.75, SD:l/d = 60/0.92, all values in millimeters [40] (note the spelling of "fibre" is from the source document, which is spelled using the British-English standard).**

To offset the negative effect of the fibers on workability, increasing the total cementitious content is a common practice. This not only could help with the workability, but also can ensure enough paste to coat the fibers and provide adequate bonding. Also, adding or increasing the dosage of a high range water reducing admixture (HRWRA) to the mixture may be necessary. In addition, employing crushed aggregates and well-graded particle size distribution are other techniques that can assist to achieve the required workability when fibers are used.

Uniform dispersion of the fibers in concrete is another concern when using FRC. Depending on the fiber properties, proper dispersion can be a challenge, where fibers entangle and result in a non-uniform distribution in the concrete matrix (see Figure 2). Consequently, an FRC that cannot be placed and consolidated properly will reduce constructability, and raise the risk of not achieving the designed mechanical or durability characteristics of the material and of the overall structure [46]. This aspect underscores the importance of carefully evaluating the fresh properties of FRC related to workability. For practicality, fibers are usually added to the mixture as the last constituent, and this can increase the risk of balling. To overcome this challenge, adding the macro-fibers to the mixture before or simultaneously with the aggregates may be the best approach. Applications of angular and well-graded aggregates are also found helpful with preventing the balling issue. Other factors that can influence the fiber dispersion in FRC mixtures are known to be the type of macro-fiber, the volume fraction of the fiber, cementitious content, the batching sequence of FRC constituents, the type and speed of the concrete mixer. Given the variety of factors that can also vary from one fiber to another, the best practice is to start with the fiber manufacturer's recommendations regarding the mixing procedure to achieve the best dispersion and minimize the risk of balling.

### 4.1.2. Evaluation of Fresh Properties

Several methodologies have been utilized to measure the adequacy of FRC for placement. Some of these methods include slump [47], [48], Vebe test [47], [49], inverted cone test [50], compacting factor test [51], DIN flow table test [52] and rheometers [51], all of which were primarily developed for normal concrete. Although it has been shown that the slump test is not a good measure of constructability of FRC under vibration [53], it is the most commonly being used method. The Vebe Test (Figure 6) has limited use and is mostly applicable to low workability and low slump concretes and is not a good indication of pumpability. The compacting factor test (Figure 7) [54] measures the degree of compaction for a standard amount of work, and the inverted cone and DIN flow table (Figure 8) [55] methods are used to evaluate the concrete flowability. The inverted cone method was withdrawn by ASTM C995 committee in 2008. Although useful, a concrete rheometer, which is used to characterize the rheological parameters for concrete, is also an uncommon test method for evaluating fresh properties due expensive and relatively rare testing devices and a lack of industry knowledge as to their use and applicability. Besides, none of these methods are necessarily developed to measure the constructability of FRC-overlays. Therefore, a novel method or a combination of currently available tests may be necessary to collect enough information regarding the FRC constructability (i.e., pumpability, placeability, and finishability). It is worth noting that to the best of the authors knowledge, V-Kelly (Figure 9) and box tests have not been used to study the fresh properties of FRC mixtures.

Figure 6. Vebe test setup

Figure 7. Compaction Factor test setup

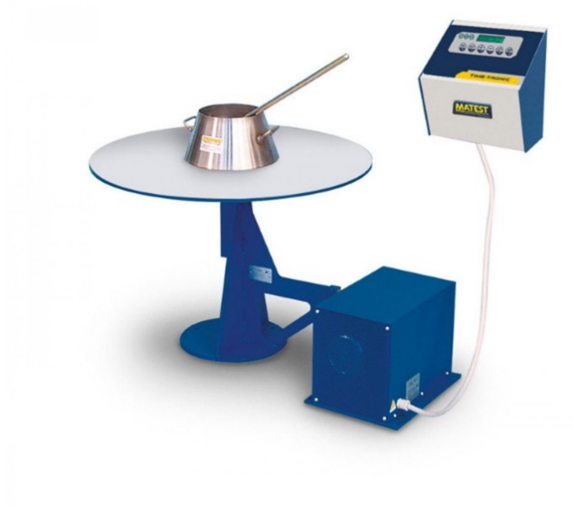


Figure 8. DIN Flowability test setup

Figure 9. V-Kelly test setup

## 4.2. Hardened Properties

There are numerous laboratory-based studies on the effect of fibers on concrete hardened performance, with most of these studies being focused on steel fibers. As discussed in the earlier sections, fibers can be incorporated into the concrete overlays to improve the corner cracking [56], joint faulting [57], curling [58], lack of ductility [59], and fatigue failure [60]. Additionally, utilizing fiber offers some value-added improvements such as enhanced resistance to crack propagation, controlled thermal and moisture stresses, increased elasticity, higher tensile, flexural, and fatigue strengths, and greater impact and abrasion resistance.

Several surveys have been performed on the projects using FRC overlays during the past few years [6], [28], [61]. These surveys indicate that the application of FRC in concrete overlays has mostly led to promising results. Although few projects have shown undesirable outcomes, the reason is often linked to insignificant fiber dosage, poor-quality fibers, and fiber dispersion, fiber balling, or problems with FRC placement and consolidation or insufficient supporting layers. Some advantages of using fibers are discussed in more detail in the coming sections.

### 4.2.1. Compressive, Flexural, and Tensile Strength, and MOE

In general, fibers are not known as an enhancer for compressive strength or MOE, especially when non-steel fibers are used. According to ACI 544.1R, 2009 [26], the addition of steel fibers can increase the ultimate strength between 0% and 15%, although there are studies showing more considerable improvement. Additionally, it has been shown that compressive strength can be affected negatively when high-volume fractions of steel fibers are used. For instance, Zhang et al. [62] studied the effect of steel fiber content on the concrete compressive strength using different curing conditions. As shown in Figure 10, their results indicated that up to 4% steel fiber has improved the compressive strength up to 33%, comparing to normal concrete. It can be seen from the figure that increasing the fiber content from 4% to 5% has led to a 5-10% reduction in compressive strength. In a different study performed by Akhil and Grace Itti Eipe [16], Figure 11, it is shown that the effect of fiber on the compressive strength of concrete is somehow negligible when synthetic fibers are utilized, while it is more pronounced for mixtures made with steel fiber.

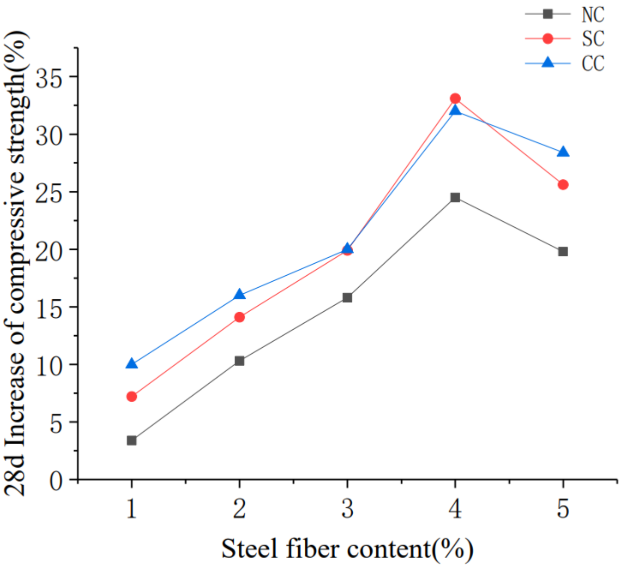


**Figure 10. Effect of steel fibers on compressive strength of FRC.NC: Natural Curing (room condition), SC: Standard curing (moist curing), CC: Curing Compound Curing [62].**

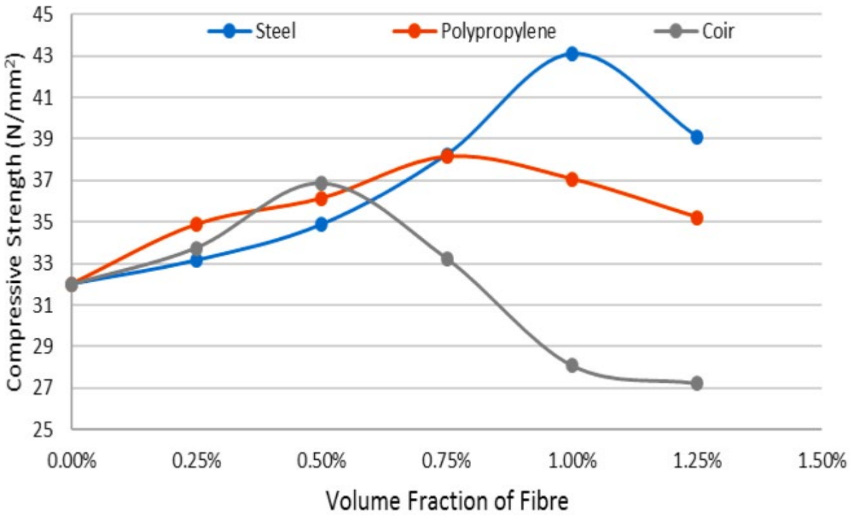


**Figure 11. Effect of fiber content on different fiber types on concrete compressive strength [16].**

With respect to flexural and tensile strength, where concrete is the weakest, the incorporation of fibers has reportedly enhanced the load-bearing capacity of the concrete. It is shown that utilizing steel fibers at 1.5% volume fraction can increase the flexural strength by 150% and the direct tensile strength by up to 40% [29]. The available literature agrees with this statement while showing a higher impact on flexural and tensile strength. Mahoutian et al. [63] investigated the effect of steel fiber content on the flexural and tensile strength of lightweight concrete. Their results, demonstrated in Figure 12, show about 450% higher flexural strength by using 2% steel fiber. Moreover, another study [16] showed an increase in both flexural and tensile strength by using hooked-end steel (diameter = 0.5 mm; aspect ratio = 60), synthetic polypropylene (diameter = 0.44 mm; aspect ratio = 114), and natural coconut fibers (diameter = 0.25 mm; aspect ratio = 120); see Figure 13. It can be observed from the figure that incorporation of any type of fiber up to a certain content has improved the flexural and tensile strength, while after a certain limit it could have opposite effects. Therefore, the increase in fiber content does not linearly increase the mechanical properties of the concrete.

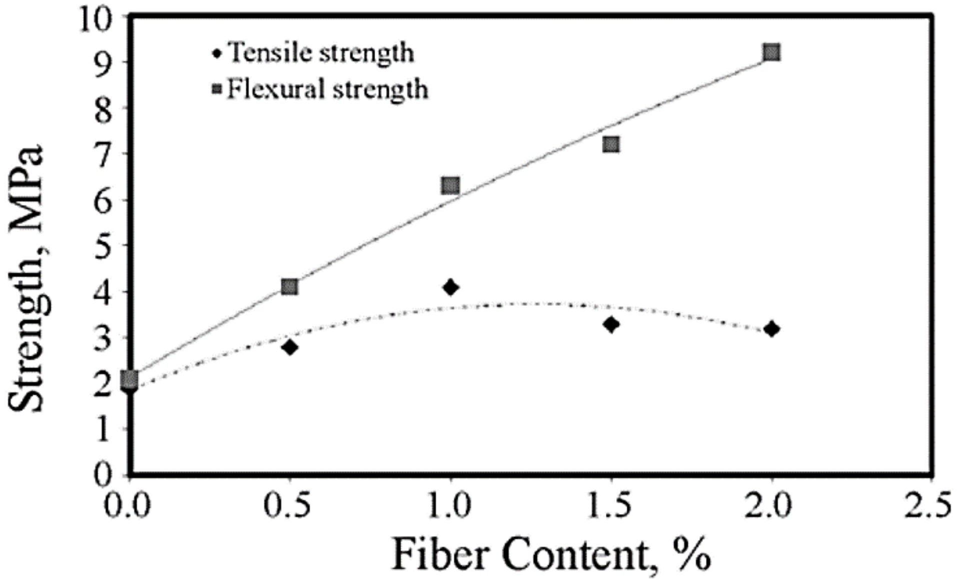


Figure 12. Effect of steel fiber on flexural and tensile strength of concrete [63].

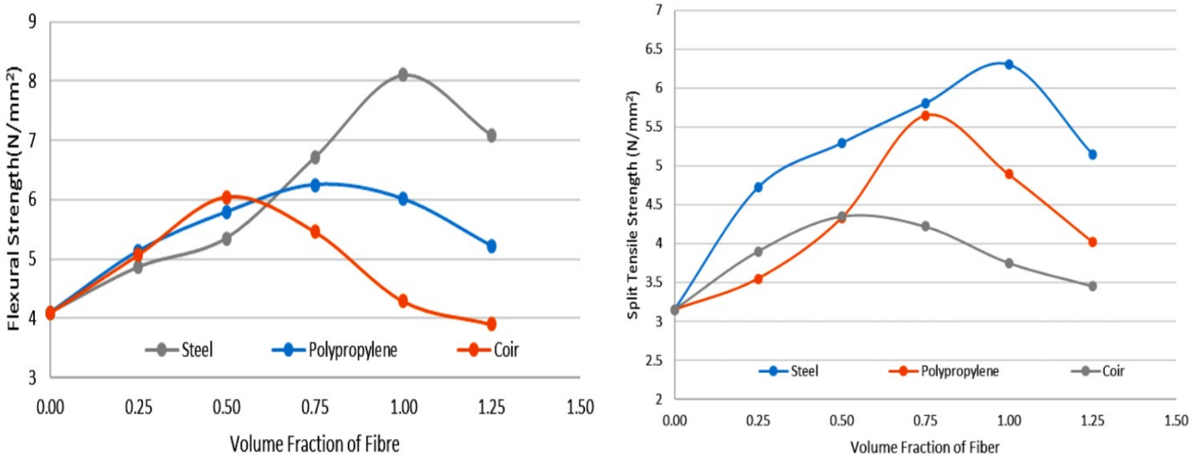
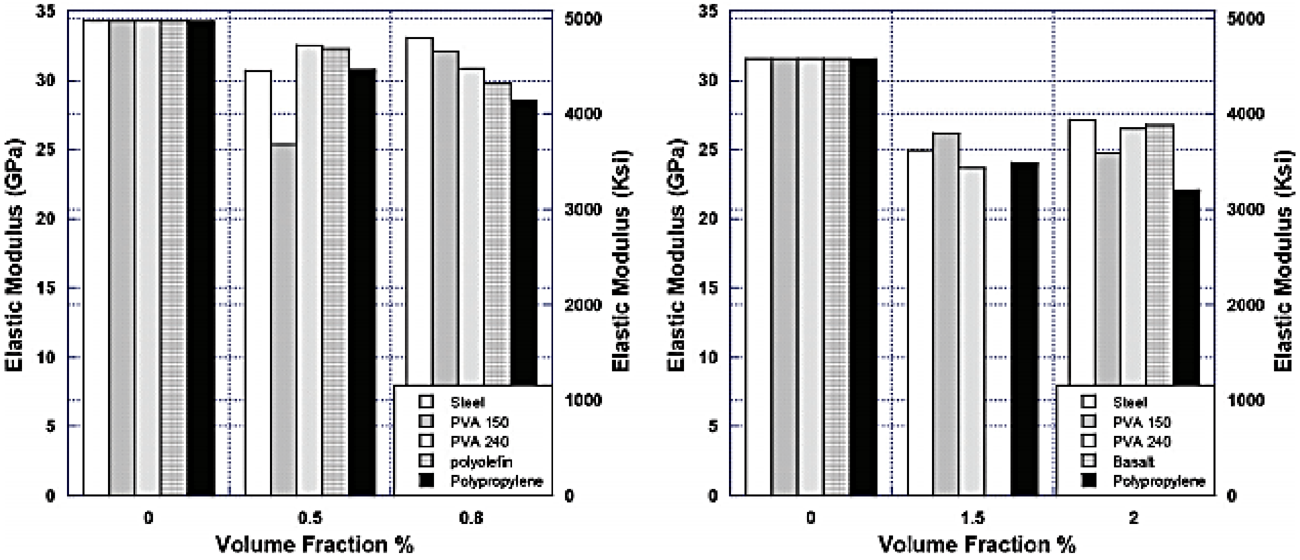


Figure 13. Effect of the fiber content of different fiber types on concrete compressive strength [16].

Kakooei et al. [64] investigated the effect of polypropylene on the compressive strength of an FRC overlay showing improvement compared to a normal concrete, where the best results were achieved when a fiber volume fraction of 0.2 to 0.3% was used. Another study performed by Olivito et al. [65] provided similar results reporting that concrete containing steel fibers in volume fractions of 0.1 and 0.2%, exhibited slight improvement in concrete overlay mechanical properties. In a different study [15] it was shown that incorporation of 0.5% fiber by volume, the compressive strength was increased by 25% when steel fiber was used, while the FRC made with polypropylene exhibited about 10% less compressive strength compared to that of normal concrete. Their results indicated improvement in flexural strength for both fibers with steel fibers showing superior effects. Although the literature is in general agreement about the effect of fibers on the compressive and flexural performance of the FRC, the slight variation in the results indicates that identifying the fibers and FRC properties is crucial for designing any FRC structure such as overlays.

Regarding the effect of fibers on the MOE of concrete, there are conflicting results in the literature. Some have been reporting little or no effect on the MOE of concrete by fibers [66], [67], while others showing that incorporating fibers can lead to considerable MOE variation [68]. According to ACI 544.1R [26], the Poisson's ratio and MOE of FRC are similar to those of normal concrete until the fiber volume fraction exceeds 2%, a value rarely exceeded in practice. The disagreement in the literature may be explained by the other factors affecting the MOE such as the amount of coarse aggregate in the concrete mixture. Coarse aggregate is one of the main tools in controlling the MOE of concrete and has a great impact due to its large stiffness value and large volume fraction in concrete [69], [70].

Suksawang et al. [14] investigated the effect of different types of fibers on the MOE of concrete mixtures made with different coarse-to-fine aggregate (C/S) ratios: C/S>1 and C/S<1. According to their results shown in Figure 14, although the incorporation of fibers led to lower MOE values in all cases, for mixtures made with C/S >1 including fibers in the mixture appears to have a limited effect on the MOE of the mixtures (<10% reduction). On the other hand, for mixtures made with C/S<1, the effect of fiber on MOE was more pronounced with an average 20% reduction in the MOE of the FRC mixtures compared to that of normal concrete. One possible explanation for this observation is that fibers parallel to the load direction could act like voids [71], as well as the fact that the addition of fibers can impact the consolidation and consequently reduces the elastic modulus [72].



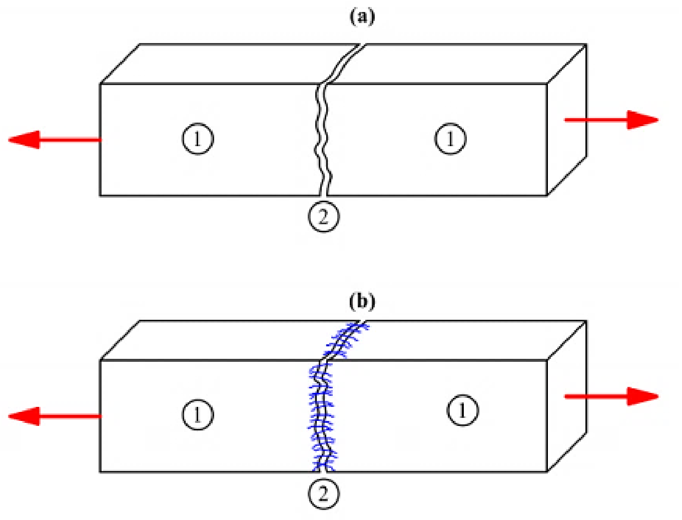
(a) (b)

**Figure 14. MOE of FRC mixtures made with (a) C/S > 1, and (b) C/S <1 . [14].**

In summary, no significant change in the compressive strength and MOE is expected in FRC overlays, while depending on the mixture design properties and fiber characteristics, using fibers can offer considerable improvement in flexural strength and post crack performance properties such as residual strength and residual strength ratio. This conclusion can be backed up by the fact that for fibers to have a considerable effect on compressive strength and MOE, the volume fraction of the fiber used in the mixture should reportedly be around 1% to 3%[24]. This volume fraction of fiber that would lead to an increase in the strength or reduction in the MOE of an FRC material is known as the theoretical critical fiber volume. Because in practice the fiber dosage used for pavement overlays is usually not enough to reach the critical fiber volume (e.g., < 0.5% [6]), little change in compressive or elastic modulus is expected.

### 4.2.2. Post Crack Properties; Toughness

Fracture-mechanical parameters such as absorbed fracture energy and fracture energy as well as fatigue response are critical elements to achieve the desired performance of concrete overlays due to the frequently repeated loading and expected discontinuities (joints and cracks) in the underlying bridge deck layers. Fibers enhance the post-crack performance (i.e., Fracture-mechanical parameters) of concrete through bridging cracks and boosting the toughness and residual strength [26], [73], load transfer efficiency [74], and fatigue resistance [75] of concrete. The most cited effect of incorporating fibers in concrete is primarily improving toughness and fracture energy, with the literature being in strong agreement that incorporation of fibers could improve the toughness and residual strength of the concrete and consequently improves the potential fatigue cracking [13], [76]–[80]. The fracture-mechanical parameters (i.e., size of the fracture energy) indicate the extent of energy required for the formation of cracks, and thus can be used for predicting crack formation [81]. Figure 15 schematically demonstrates the difference in the post crack behavior of normal concrete and FRC. As shown in the figure, in the case of normal concrete, after the concrete reaches the peak stress, the load-deformation diagram shows an exponential trend indicating a sudden break. On the other hand, incorporating fibers in the concrete drastically reshapes the load-displacement diagram. Literature is in general agreement regarding this observation [82]–[84].



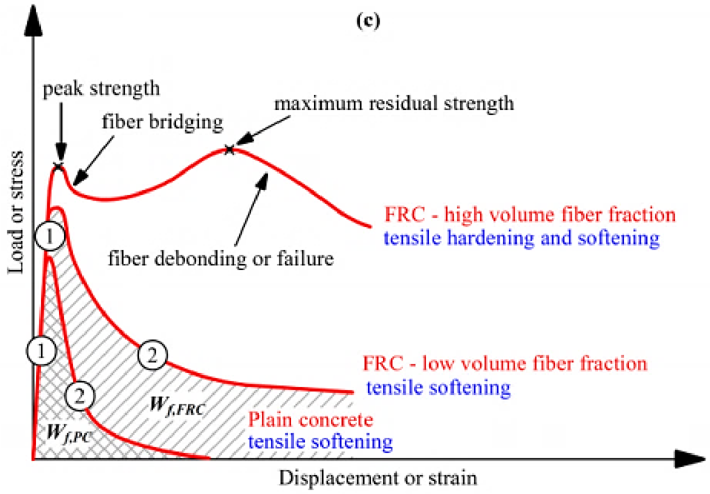


**Figure 15. The behavior of plain concrete and fiber-reinforced concrete: (a) plain concrete; (b) fiber-reinforced concrete; (c) load–displacement diagrams [85]**

Two general strain behaviors can be identified in concrete and FRC load-displacement diagrams; strain softening and strain hardening [86], shown in Figure 16. Whether strain hardening occurs and for how long, is mainly affected by the type and content of fibers used in the FRC. The strain-softening behavior is expected in normal concrete and FRCs containing micro-fibers or a low volume of macro-fibers (Figure 16). When strain hardening occurs, another peak can be observed in the load-displacement diagram, which is the residual strength (see Figure 15). Residual strength is the load or force (usually mechanical) that a damaged object or material can still carry without failing. At this point, the tensile capacity is exhausted, and the tensile strength of the concrete product is exceeded. Another term that is commonly used is "residual strength ratio", which is the ratio of FRC flexural strength and residual strength. In general, the residual strength increases as fiber volume, fiber aspect ratio, and fiber stiffness increase [82].

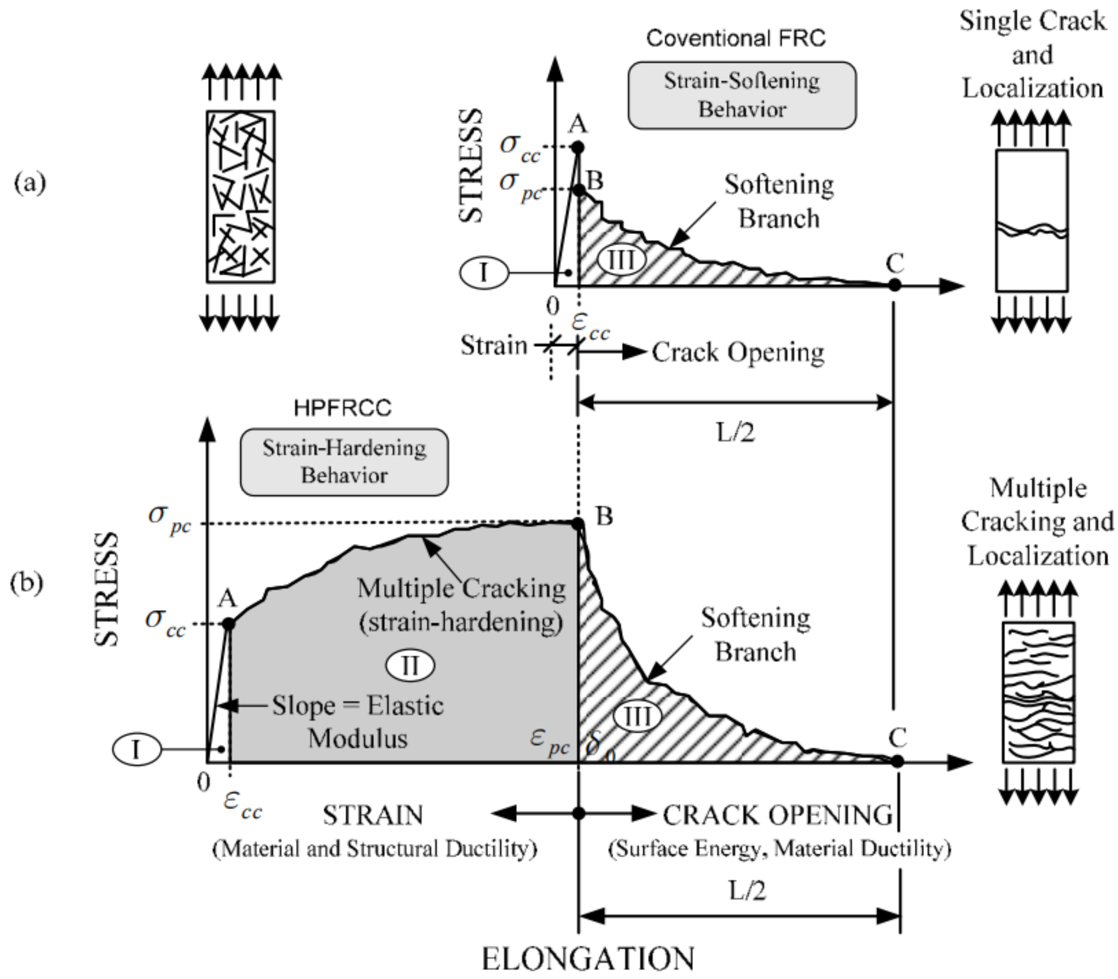


**Figure 16. Typical stress-strain or elongation curve in tension up to complete separation: (a) Conventional strain-softening FRC composite; (b) Strain-hardening FRC composite or HPFRCC [86]**

The residual strength may not continue to increase with concrete age depending on the strength of the fiber-concrete matrix, type of fiber, and fiber content. It should be noted that many studies of residual strength will evaluate the residual strength ratio at various deflection points, such as *l*/900, *l*/600, *l*/300, *l*/150, etc. where *l* is the span between supports of the specimen (in flexural mode testing).

The strain hardening can be explained by the fact that in brittle composites subjected to uniaxial tensile loading, immediately after reaching the peak stress (concrete strength) macro-cracks begin to form, opening in length and depth quickly while resisting the applied strain [83].

Thereafter, the fibers act as load-transfer tools sharing the load across the crack by bridging and transferring the load through the fibers interface within the matrix [87]. By transferring load, the concrete is subjected to new cracks, and the process repeats until the matrix is broken with a series of subparallel cracks [88]. This process results in a significant increase in ductility (tensile deformation) [89]. As the applied stress increases, the fiber-concrete interface de-bonds, and consequently, the fiber stretches until ruptured or pulled out. This is when the final failure happens. Such resistance to breaking apart occurs by absorbing energy known as flexural toughness, which is the area under the load-deflection curve (strain hardening zone).

Figure 17 shows a schematic representation of fibers bridging across a crack under tension. There is a traction-free zone, where the crack is wide enough for all fibers to have pulled out; a fiber-bridging zone in which stresses are transferred by a frictional slip of the fibers, and a micro-cracked matrix process zone with enough aggregate interlock to transfer some stress within the matrix itself [90].

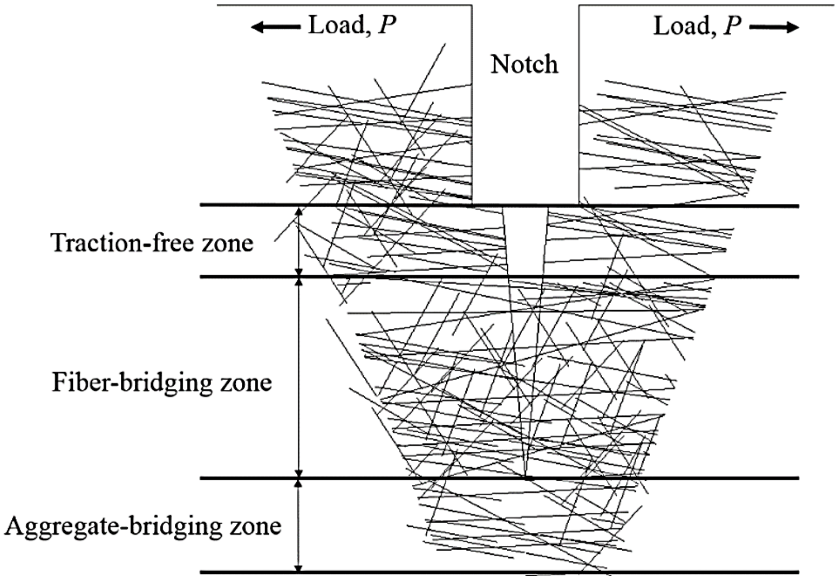


**Figure 17. Schematic demonstration of fibers bridging across a crack under tension [61].**

At the fiber bridging zone, the matrix cannot carry the load across the crack surface, but the fibers carry all post-cracking loads taken by the composite. In this bridging zone, the fibers will tend to transfer tensile stress to the matrix through shear frictional bond stresses.

The optimum performance of the FRC with respect to toughness has been shown to depend on the compatibility of the fiber and concrete matrix in terms of strength, elasticity, and bonding capacity [82], among which elastic modulus of the fiber has been shown to be the more important factor [91]. Nevertheless, fibers with lower modulus can still improve concrete properties, in relation to strain capacity, toughness, impact resistance and crack control [92]. A more considerable increase in the total fracture energy has been observed with the addition of fibers to concrete with limestone or recycled concrete aggregates [93].

In addition to the aforementioned fiber characteristics, the geometry, length, aspect ratio, and stiffness of fibers have a significant influence in improving the post-crack properties of concrete. Crimped, embossed, or twisted fibers showed better performance than straight synthetic fibers [57], and steel fibers with hooked ends give the best toughness results [94].

### *4.2.2.1. Post-Crack Performance Evaluation*

There are several methods being commonly used to evaluate the post crack performance of FRC including American test methods (ASTM C1399 [95], ASTM C1609 [96], and ASTM C1550 [97]), European test methods (EN 14651 [98], EN 14488-5 [99]), Japanese test method (JSCE-SF4) and possibly others (e.g., RILEM TC 162-TDF [100]). For this project, however, only American test methods will be considered; ASTM C1609, ASTM C1399, and ASTM C1550. ASTM C1609 was introduced in year 2006, as an alternative to ASTM C1018, and is considered an enhancement over the former method. In general, ASTM C1609 is used to evaluate the post-crack performance of high-performance FRC. This method evaluates the flexural performance of FRC using parameters derived from the load-deflection curve. The specimens are tested in flexure using a third point loading arrangement according to ASTM C78 [101]. Two primary points termed “first-peak” and “residual load” are specified deflections identified on the curve and are used to calculate flexural performance parameters. The flexural behavior of the FRC represented by the first-peak strength is up to the onset of cracking, while the residual capacity after cracking represented by residual strengths at specified deflections.

ASTM C1399 is used to obtain the average residual-strength of FRC made with relatively low fiber volumes [102]. The method allows for comparative analysis among beams having different fiber characteristics. The average residual strength (ARS) is estimated using specified beam deflections that are obtained from a beam cracked in a standard manner and presents an indication of the post-cracking performance of the FRC. It should also be noted that flexural strength cannot be computed using this method, and compared to ASTM C1609 methodology, the residual strength values obtained from this method appear to be lower than those obtained using ASTM C1609.

Regarding ASTM C1550, although it is being used to evaluate the performance of FRC, it is most common for evaluating the toughness of fiber reinforced shotcrete or tunnel linings and sees most use in the mining industry. The main advantage it offers, besides similar results to other toughness test, is the lower variation. The method employs relatively large and heavy round FRC panels, which are difficult to handle and require additional labor. This test method covers the determination of flexural toughness of FRC expressed as energy absorption in the post-crack range using a round panel supported on three symmetrically arranged pivots and subjected to a central point load. The energy absorption is considered from the beginning of loading and the specified central deflection, which is the area under the load-net deflection curve between the origin and the specified central deflection.

### 4.2.3. Shrinkage

Shrinkage cracks are the source of several challenges in concrete overlays, such as curling, gaps in joints, debonding between two layers, etc. Concrete is subjected to shrinkage in both the plastic state and the hardened state, both relatively common in concrete pavement applications. Plastic shrinkage is caused due to the water lost from the concrete surface, exerting tensile stresses that the surface of the concrete cannot undergo in the fresh state, and consequently leads to the formation of cracks known as plastic cracks. This is typically a top-down cracking mechanism due to induced moisture differentials within the concrete related to the moisture loss at the surface. Drying shrinkage, to be simply explained is the volume reduction in hardened concrete caused by the evaporation of water within the porous structure of the concrete matrix as the hydration of cement consumes the water, exerting pressure high enough to cause cracking. The use of micro-fiber, particularly synthetic micro-fibers, with a volume fraction below 0.5% has been found fairly effective in preventing plastic shrinkage cracking [34]. For example, Rahmani et. al [103] studied the effectiveness of different fibers in reducing the plastic shrinkage cracking of concretes. Their results indicated that the crack characteristics and pattern could vary depending on the fiber characteristics (i.e., steel, glass, and polypropylene). For the same volume fraction, the effect of fiber reinforcement on the crack pattern is illustrated in Figure 18. The maximum crack width relative to normal concrete has been reported to vary from 30% to 50% for different fiber-reinforced concretes, with steel fiber being the most effective followed by glass and polypropylene fibers.

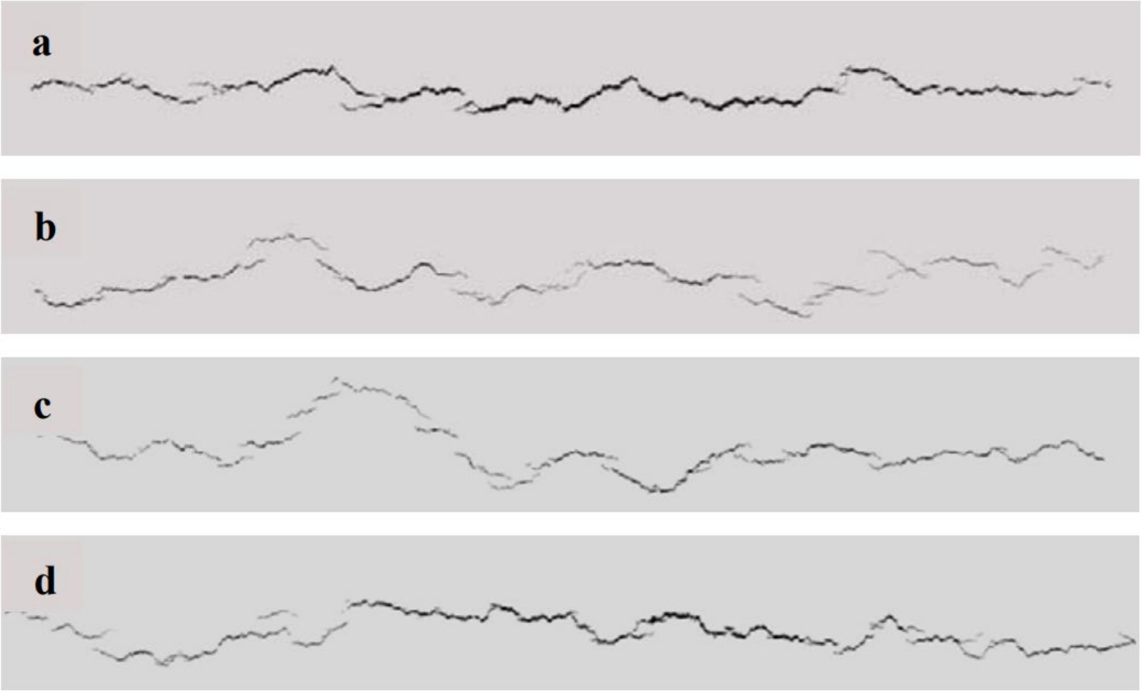


**Figure 18. Crack pattern obtained from image analysis, (a) no fiber, (b) steel fiber, (c) glass fiber, (d) polypropylene fiber** [103]

On the other hand, the literature suggests no aid from micro- or macro-fibers in reducing the potential of drying shrinkage [84], [104], [105].

#### 4.2.4. Compatibility

Primary forms of failure in overlay repairs are caused by differences between new and old concrete leading to overlay debonding for a repair concrete [106]. Bond strength at the interface is one of the most critical factors affecting the repair of concrete structures. Debonding in concrete overlays comes from different stresses starting from edges, joints, or cracks [1]. The bond must be strong enough to hold different strength loadings in both the old and new concrete. The bond must also endure the stresses caused by volume changes or loads.

The MOE and shrinkage should be comparable between old and new concrete layers, otherwise stress differences will develop and result in different mechanical responses between the layers. Similar materials properties between two layers are needed to avoid improper distribution of stress [107]. Considering the limited effect of fibers on MOE and shrinkage of concrete, FRC is expected to have no or negligible effects on the bond strength between the FRC overlay and subbase. That being said, there are very limited studies investigating the effect of fibers on bonding strength. Field experimental studies [1], [18] have shown a stronger bond with steel macro-fiber FRC overlays as compared to unreinforced normal concrete. Also, they revealed better bonding performance from steel fibers than synthetic fibers. Granju and Chausson [108], showed that the superior bonding performance of mixtures made with steel fiber has no direct relationship with bond strength, but is due to the delayed crack opening after the formation of the initial cracks. According to their findings, shown in Figure 19, an FRC mixture containing 1% volume fraction of steel fiber exhibited initial debonding when the first crack developed. However, the presence of steel fibers appeared to help with the delay in propagation of the debonded area. In a different study, Kim and Bodelon [61] showed that overlays with high fracture energy (such as with FRC) may have reduced joint opening widths, reduced debonding lengths, and reduced interfacial vertical lift-off deflections. Additionally, they performed a simulation through Finite Element Method (FEM) concluding that implementing an FRC mixture with a fracture energy higher than an optimized limit would not provide additional reduction in crack opening, debonding length, or vertical deflection movement. According to their results, this "optimized limit" is dependent on the various factors including, but not limited to, environmental loading condition and the joint spacing. Other factors may affect optimized FRC fracture energy or toughness properties.

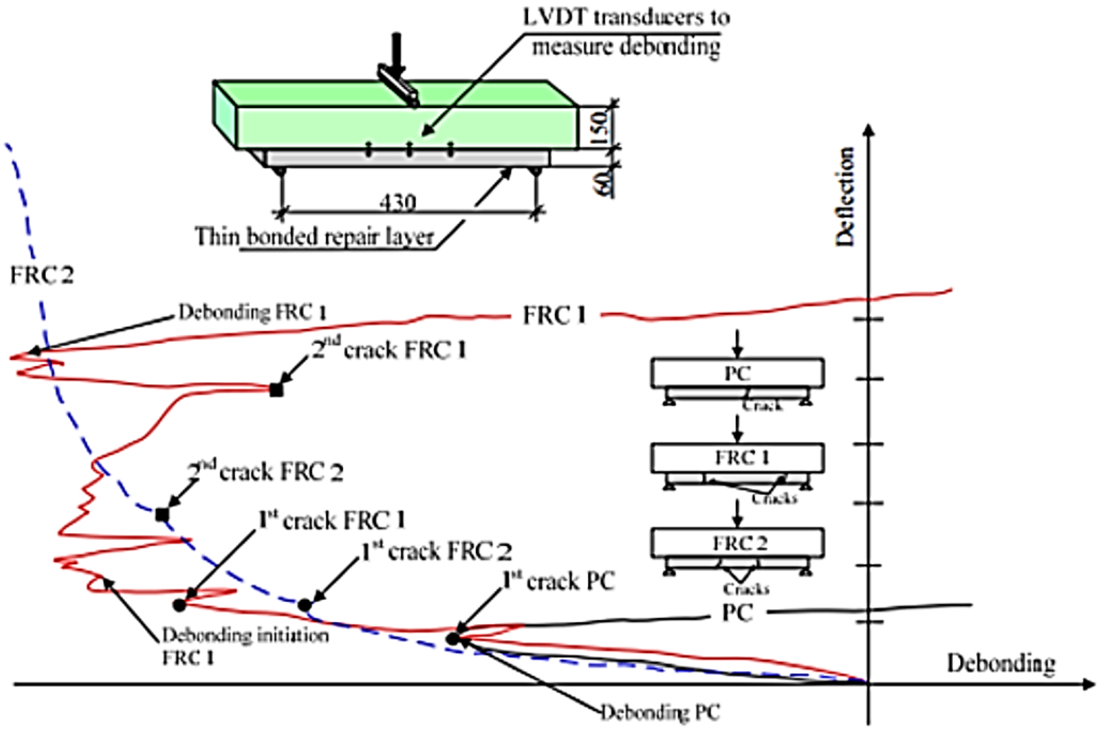


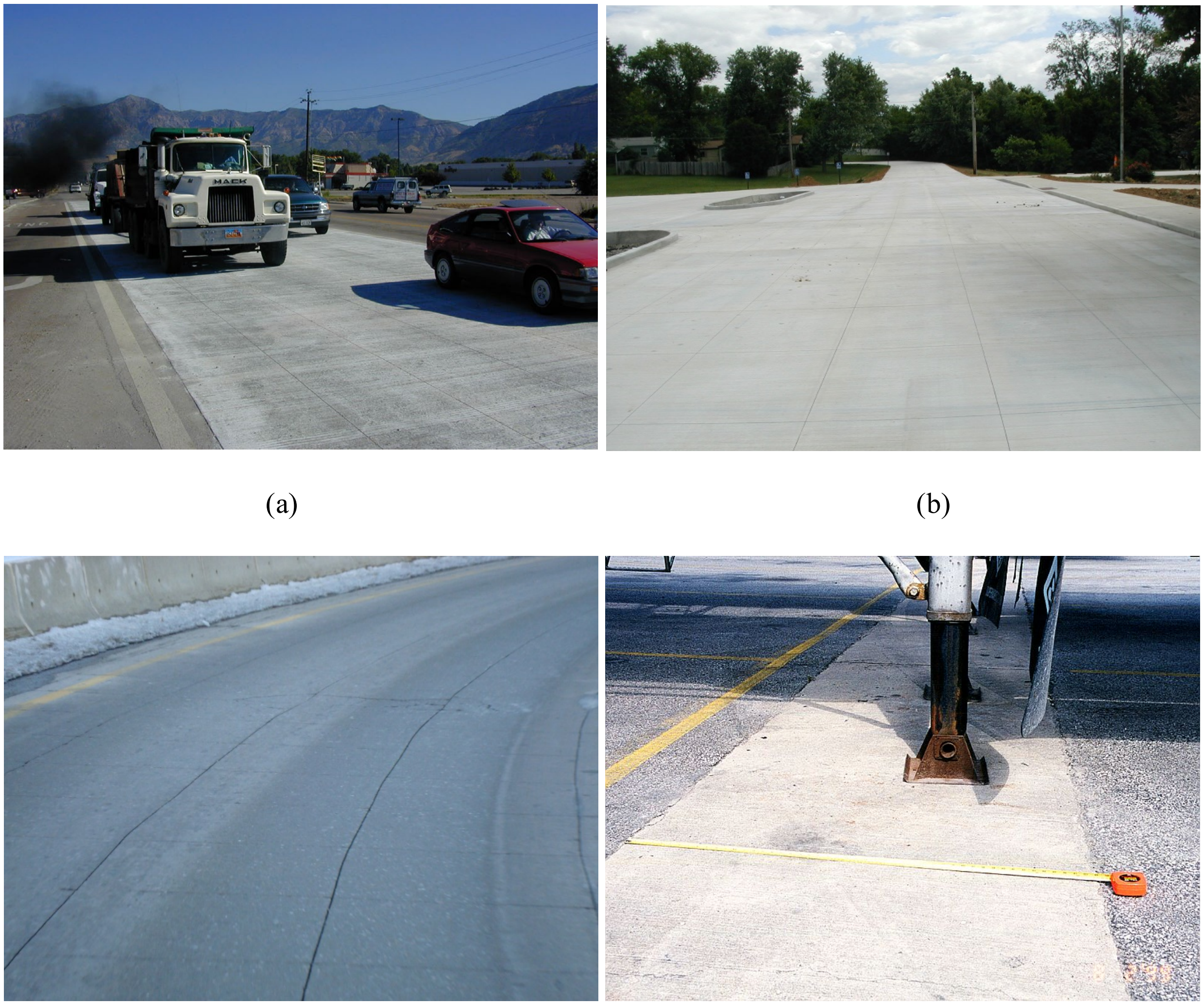
**Figure 19. Influence of 1% volume fraction of steel fibers on the debonding and cracking of repair layers** [108]**.**

Age is another factor contributing to the crack formation and debonding of the overlay layer. McCullough and Dossey [109] reported that the size of cracks that are formed at early ages increases at a rate larger than the crack formed at later ages.

## 5. BACKGROUND ON FIBER REINFORCED CONCRETE (FRC) OVERLAYS FOR BRIDGE DECKS

FRC is essentially a conventional concrete containing either metallic, polymeric, or natural fibers. However, depending on the fiber type, dosage rate, and application of the FRC, the concrete mixture is commonly engineered to adapt the incorporation of fiber while maintaining the producibility of the FRC and achieving the required performance.

FRC overlay technology has been adopted and employed for many horizontal applications including all forms of pavement and bridge decks. (see Figure 20).



(a) (b)

(c) (d)

**Figure 20. Street/Road (FRC bonded on asphalt), (b) Parking lot (FRC Unbonded on Asphalt), (c) Highway (FRC Unbonded on Concrete), (d) Industrial Pavement/Trucking Facility (FRC bonded on asphalt)**

The first known FRC overlay on record appears to have been constructed in 1972 at the Tampa International Airport in Florida. The placement included two sections of deteriorated taxiway overlaid with 4 and 6 in of FRC. Since then, American Concrete Pavement Association (ACPA)[1], which maintains the data on nationwide constructed concrete overlays, shows 99 FRC overlay projects with the first being reported in 1985 as a bonded concrete resurfacing of concrete pavement with a thickness of 2.5-inch over a 32 years old jointed reinforced concrete pavement (JRCP) in the state of Pennsylvania.

Although the use of FRC overlays has been receiving more attention during the past decade, their use for bridge deck rehabilitation has been a less common practice. The key objective in utilizing the FRC in bridge deck overlays has been to reduce widths of cracks resulting from repeated loading under traffic as well as environmental factors [10]. For the same purpose, multiple state DOTs including, but not limited to, Illinois, Oregon, and Georgia have implemented FRC overlays for bridge decks. A summary of the previous FRC overlay for bridge deck projects is listed in Table 2. Although the overall experience of using FRC overlays for bridge decks appears to be satisfactory, there are few cases that did not obtain the desirable performance. The possible factors contributing to an unsatisfactory performance of FRC overlays is discussed in Section 4.2.

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[1] http://overlays.acpa.org/webapps/overlayexplorer/index.html

**Table 2. Review of the previous projects using FRC overlay for bridge decks.**

| State | Year | Location | Fiber info | Dosage (% by volume) | Experience | Reported Issue | Reference |
|---|---|---|---|---|---|---|---|
| New Mexico | 1984 | -- | Steel | 10 | No cracking or corrosion was observed in core samples After 6 years | Surface abrasion | [110], [111] |
| Ohio | 1992 | US 30 | Steel, 2-inch | 0.8 | No cracking during the observation period | No information found | [110], [112] |
| South Dakota | 1994 | overpass over I-90 at Exit 212 near Spearfish | Polyolefin | 1.7 | No information found | Fiber clumps exposed in the deck surface 6 months after construction.<br>These fiber balls occurred in locations where inadequate mixing and dispersion of the fibers had been noticed during construction.<br>After 2 years in service, a total of 44 cracks were counted, with only 12 of the cracks having widths greater than 0.007 in. | [113] |
| South Dakota | -- | Exit 32 on I-90 | Polyolefin | 1.7 | Similar to the one built in 1994 | No information found | [113] |
| Virginia | 2000 | Test Section | Synthetic | 0.5 | Average crack length decreased by 60% and the average crack width decreased by 45% | No information found | [114] |
| Virginia | -- | Linville Creek Bridge, State Route 1421 | Synthetic + SRA* | 0.2 | Similar to those of other bridges with applied shrinkage reducing techniques | No information found | [115] |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Illinois | 2006-2007 | Dan Ryan Expressway | Polypropylene | 0.2 | No information found | Unable to properly finish the surface when the dosage rate was 0.25% by volume | [116] |
| State | Year | Location | Fiber info | Dosage (% by volume) | Experience | Reported Issue | Reference |
| California | 2007 | Pit River Bridge on I-5 over Shasta Lake | Polyolefin + SRA | 0.2 | After 5 years, exhibited little cracking, and cores taken at the crack locations revealed that the cracks were arrested near the surface | A companion section on the bridge without SRA or macrofibers exhibited significant cracking within six weeks of opening | [117] |
| Illinois | 2010 | over the EJ&E railroad along Irving Park Road in Chicago | Alkali-resistant glass Fiber | 0.1 | No reported issues with construction or finishing. No cracking after 1 year | A companion section on the bridge without fiber exhibited hairline cracks | [116] |
| Illinois | 2011 | Illinois Route 106 over the Sky River | Polypropylene | 0.2 | One week after construction, no cracking was visible upon inspection | Fibers stuck to the float delayed floating slightly | [116] |
| California | 2011 | over Craig Creek on State Route 99 near Red Bluff | Synthetic + SRA | 0.2 | After 14 months, no cracking was visible in the deck overlay | No information found | [117] |

*SRA: Shrinkage Reducing Admixture

# 6. SURVEY OF FIBER REINFORCED CONCRETE OVERLAYS FOR BRIDGE DECKS

A survey was conducted to review the use of FRC-overlay projects in the past and some of the challenges in associated with the use of FRC overlays on a national and international scale. This survey summarizes different aspects of using fibers including the types of fibers utilized, quality assurance methods, construction specifications, and FRC-overlay performance in terms of requirements specified by the agencies. From all the agencies, only fifteen (15) national agencies responded to the survey, out of which only three (3) agencies indicated that their projects include FRC overlay placement for bridge decks. Although some of the other agencies have performed FRC overlays for bridge decks in the past, it appears that their projects currently do not include such placements.

- 4/15 indicated that are using other types of overlays (i.e, Latex modified, silica fume modified, and polymer overlays), with proven performance.
- 5/15 indicated tendency for using FRC-overlays in the future projects. 2/5 are currently performing research projects.
- 6/15 have approved list of fibers.

A summary of the survey is illustrated in Table 3 to Table 9.

**Table 3. Survey of Fiber Reinforced Concrete Overlays for Bridge Decks (1).**

| Agency, DOT | FRC overlay bridge decks projects | Intention to incorporate FRC overlays for bridge deck applications in the Standard Specifications in the future | Accepted fiber type(s) requirements for FRC overlays for bridge deck |
|---|---|---|---|
| Massachusetts | No | No | MassDOT does not use concrete overlays for bridge decks. |
| Michigan | No | No | See special provision. |
| Tennessee | No | No | -- |
| Virginia | No | Yes | We are investigating different fiber types and amounts. |
| Minnesota | No | No | -- |
| Iowa | No | Yes | Polypropylene micro and macro fibers. Type III fibers in accordance with ASTM C1116. |
| Arizona | No | No | fiber glass with proved records |
| Illinois | Yes | Yes | Macro synthetic fibers that are Type III according to ASTM C1116. |
| Oregon | Yes | Yes | ASTM C1116, Section 4.1.3, Type III Synthetic, Polyolefin Fibers. |
| Nevada | No | No | -- |
| Georgia | Yes | Yes | Macro Synthetic Type III 1.5" ASTM C1116 |
| New Hampshire | No | No | -- |
| North Dakota | No | No | -- |
| Kentucky | No | No | -- |
| Pennsylvania | No | No | -- |

**Table 4. Survey of Fiber Reinforced Concrete Overlays for Bridge Decks (2).**

| **Agency, DOT** | **Min criterion for selection of the fiber type** | **Main criterion for selection of the fiber dosage** |
|---|---|---|
| Michigan | See special provision. | See special provision. |
| Virginia | Residual strength and ductility are the main criteria. "Buy America" is also important. | Residual strength and ductility. |
| Iowa | We are in the very early stages of using fibers. We had some success with these fibers for a link slab project that was expanded to include the fibers in a full depth deck pour. Since then, we have done a small trial pour with these fibers that was successful for one of the FRC overlays we will be doing. | I believe some research into this was done by our Materials personnel. |
| Arizona | Based on the performance of the fiber types. | - |
| Illinois | Other than, say, steel fibers or micro synthetic fibers? Ease of use vs steel fibers; while vs micro synthetic fibers, we were looking for more than simply plastic shrinkage crack control. Also, these macro fibers are the same fibers we use in 'whitetopping' and thus are already covered by one of our Qualified Product Lists. | Research: https://apps.ict.illinois.edu/projects/getfile.asp?id=3054 |
| Oregon | Flexural performance and crack width reduction. Although not currently a requirement for inclusion on the QPL (Qualified Product List), Type III Synthetic macro fibers have been used successfully for many years to reduce crack widths. | To determine fiber dosage rates, test a currently approved or new ODOT HPC 4500- ¾″ mix design in accordance with the latest version of ASTM C1609. The dosage rate shall be such that the average residual strength ratio $(RRTT, 150\ DD)$ of fiber-reinforced concrete beams is a minimum of 20.0 percent when the beams are tested in accordance with ASTM C1609. At a minimum, test dosage rates of 3, 4, and 5 lbs/yd$^3$ and select the lowest dosage that provides the minimum required residual strength ratio. |
| Georgia | Standard micro synthetic type III fiber | 3 lbs/yd$^3$ standard |
| New Hampshire | Macro type | Trial and error in the field |

**Table 5. Survey of Fiber Reinforced Concrete Overlays for Bridge Decks (3).**

| Agency | Experience with FRC overlay construction | Most common challenges with FRC overlays for bridge deck constructions |
|---|---|---|
| Michigan | Limited. The special provision sets forth minimum experience requirements of supplier/contractor. | Appropriate placement and wet curing. |
| Virginia | There is an ongoing research project initially laboratory work has been conducted. | Under investigation. |
| Iowa | Minimal. As stated earlier we will try using fibers on two overlay projects this construction season. | -- |
| Illinois | Seems promising for a relatively small added expense. However, incorporating them into latex modified concrete overlays (popular in IL) is maybe more trouble than it's worth when taking into account how well our LMC overlays tend to perform on their own. | Clumping (always a potential issue when using fibers), and batching into latex modified concrete, which is proportioned and batched using a volumetric mobile mixer, is difficult. |
| Oregon | Macro fibers were first used in silica fume overlays with ODOT in the mid 1990's. ODOT has been using macro fibers successfully in bridge overlays for nearly 30 years. They are primarily batched and placed with ready mix trucks, but we also have experience with placing them with mobile mixers. Our overlays are primarily finished with bidwell machines, but we also use rolling screeds occasionally. | Meeting surface tolerances of 1/8" over 12'. Typically requires some form of minor corrective action, typically localized grinding. Our HPC (High Performance Concrete) can be challenging to consistently hit air entrainment requirements. |
| Georgia | Primarily on bridge decks and "whitetopping" applications. | fiber balls- ensuring careful use when added to the loads |
| New Hampshire | It has helped with reducing shrinkage cracking. | -- |

**Table 6. Survey of Fiber Reinforced Concrete Overlays for Bridge Decks (4).**

| Agency, DOT | Most common defects observed using FRC overlays on bridge decks | Agency's concerns for using FRC overlays on bridge decks | Drawbacks for using FRC overlays for bridge decks |
|---|---|---|---|
| Michigan | -- | Appropriate curing. | Cost, contractor experience, and appropriate curing. |
| Tennessee | -- | -- | Satisfied with the program as is. |
| Virginia | -- | Is it needed, is it cost effective? | FRC overlays are under investigation in an ongoing study. |
| Iowa | -- | Not enough experience to comment. | Not enough experience to fully implement. |
| Arizona | -- | not knowing the true benefits of FRC and their tracking records | Too many unknowns |
| Illinois | When clumping occurs, a localized area of non-homogenous concrete where water and deicing agents can collect. | Is the added cost worth the potential* gain in performance?<br>*I say potential because we have yet to see how they perform in the long term (15+ years). | At this time, we've built a number of FRC overlays and are now assessing performance before continuing to mandate all deck overlays be FRC. (Some Districts may still be using FRC overlays at their discretion.) |
| Oregon | -- | Batching macro fibers into mobile mixers has been a challenge. Ensuring there is the proper dosage without fiber balls is an area of concern, but hand batching has been working well to date. An automated system that can batch our QPL approved fibers should be looked into in the future. | Department already use macro fibers in all of our structural overlays. |
| Nebraska | -- | -- | Department is currently overlaying bridge decks with an asphalt overlay with a liner between the concrete and the asphalt. |
| Georgia | fiber balls | -- | -- |
| Nevada | -- | Lack of success with trial batching. | Lack of success with trial batching |
| Kentucky | -- | -- | Do not have significant knowledge of the product. |
| Pennsylvania | -- | The cost of the FRC overlay, ensuring the quality of the constructed overlay, unknowns | -- |

**Table 7. Survey of Fiber Reinforced Concrete Overlays for Bridge Decks (5).**

| **Agency, DOT** | **What are the requirements on mixture design parameters?** |
|---|---|
| Michigan | See special provision. |
| Virginia | Under investigation. Early strength, residual strength, ductility, permeability, freeze-thaw resistance, and shrinkage |
| Iowa | We use our typical HPC-O mix in Iowa DOT Standard Specification 2413.02 D. 2. |
| Illinois | See special provisions for deck overlays:<br>https://idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Bridge-Special-Provisions/gbsp29.pdf<br>https://idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Bridge-Special-Provisions/gbsp30.pdf<br>https://idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Bridge-Special-Provisions/GBSP72.pdf |
| Oregon | - Weight per cubic yard (pounds per cubic yard) of cement, SCM, fine Aggregates and coarse Aggregates (SSD), mix water, concrete modifiers, and chemical admixtures<br>- Absolute volumes of cement, SCM(s), fine Aggregates and coarse Aggregates (SSD), mix water, air content, concrete modifiers, and chemical admixtures<br>- Dosage rates for chemical admixtures (ounces per cubic yard)<br>- w/cm Ratio including all chemical admixtures – HPC designs have a max w/cm ratio of 0.40<br>Section 02001 of the Standard Specification |
| Nebraska | See Section 1002 in the specifications |
| Georgia | Fast track overlay- 3000 psi in 24 hours; 3500 psi in 28 days |
| New Hampshire | Same as for our concrete class AA |

**Table 8. Survey of Fiber Reinforced Concrete Overlays for Bridge Decks (6).**

| Agency, DOT | What are the performance requirements for mechanical properties of FRC overlays for bridge decks? |
|---|---|
| Michigan | See special provision. |
| Virginia | Under investigation. Crack control and low permeability. |
| Iowa | Flexural strength test in accordance with Iowa DOT Standard Specifications Article 2403.03, N, 2.<br>We also require a trial batch and test placement approximately 2 inches in thickness and 100 square feet minimum in plan dimensions. |
| Illinois | See special provisions for deck overlays:<br>https://idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Bridge-Special-Provisions/gbsp29.pdf<br>https://idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Bridge-Special-Provisions/gbsp30.pdf<br>https://idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Bridge-Special-Provisions/GBSP72.pdf |
| Oregon | - 4500 psi at 28 days<br>- HPC4500 – ¾” has air entrainment requirement of 5.0+/-1.5 in moderate exposure. 6.0+/-1.5 in severe exposure.<br>- Bond strength of 175 psi<br>- The finished surface, when tested with a 12-foot straightedge, shall not vary by more than 1/8 inch. |
| Georgia | Satisfying compressive strength. |

**Table 9. Survey of Fiber Reinforced Concrete Overlays for Bridge Decks (7).**

| Agency, DOT | Durability requirements | Additional performance requirements |
|---|---|---|
| Michigan | See special provision. Typical freeze-thaw dilation of aggregates per MDOT Standard Specifications. | -- |
| Virginia | Crack control and freeze thaw resistance. | Under investigation. |
| Illinois | Durability requirements are handled by preapproving component material sources, including air entrainment where applicable, etc. Alkali-silica reaction is mitigated by minimum replacement of cement w/ SCMs based on type of overlay. | See special provisions for deck overlays:<br>https://idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Bridge-Special-Provisions/gbsp29.pdf<br>https://idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Bridge-Special-Provisions/gbsp30.pdf<br>https://idot.illinois.gov/Assets/uploads/files/Doing-Business/Manuals-Guides-&-Handbooks/Highways/Bridges/Bridge-Special-Provisions/GBSP72.pdf |
| Oregon | For HPC designs, except designs for precast bridge rail elements, the following additional requirements apply:<br>Test / Test Method / Acceptance Value<br>Length Change / AASHTO T 160 / -0.045%<br>Permeability / AASHTO T 277 / 1,000 Coulombs (max.) at 90 days | Wet cure for a minimum of 7 days.<br>Perform a deck delamination survey, in the presence of the Engineer, using chain drag or other approved methods. Repair all delaminated areas of 1 square foot or greater. Delaminated areas of less than 1 square foot will not require repair. Repair limits to be approved by the Engineer. |

## 6.1. Lessons Learned from the Survey

According to the survey and the available literature, some of the challenges in incorporating fibers into concrete overlay design have involved educating engineers, agencies, contractors, and material suppliers on several frequent comments

- Is it needed?
- Is it cost effective?
- Contractor experience.
- Not knowing the true benefits of FRC and their tracking records.
- Too many unknowns, not enough experience to fully implement.
- Lack of success with trial batching.

- Is the added cost worth the potential gain in long-term performance (15+ years).
- Proven success with other types of overlays. A new product such as FRC brings along uncertainty.

Additional questions/comments may include

- What type and dosage of macro-fiber should be used?
- What design methodology should be used to design FRC overlays?
- What standard tests should be run to characterize the impact of a particular macro-fiber?
- How the macro-fiber type and properties impact the design of a structural overlay?
- What variables should be accounted for in design, production, construction, and maintenance of the FRC overlay?
- What are the best practices to adjust the fresh and hardened property changes that occur with the addition of macro-fibers?
- What are the necessary adjustments to the construction and finishing processes?

Although several transportation agencies have used FRC overlays over the bridge decks, there are very limited formal specification requirements for fiber types or characteristics, dosage rates, or experience with the use of FRC. A review of Standard Specifications and related special provisions (Table X) by Amirkhanian and Roesler [6] in a national scale reveals that even for those states with a developed specification for FRC, the requirements widely vary from state-to-state, are mostly prescriptive, and do not necessarily consider the need to modify concrete mixture proportions depending on the fiber type and properties. According to their review, several states list fibers as an approved material but without any developed specification guidance.

## 6.2. Fiber-Reinforced Concrete in Practice

This section aims to respond to some of the concerns and questions regarding the use of fibers and FRC overlays that are not discussed in the previous sections.

Given the variety of fiber types, textures, dimensions, and required dosage rates, it is crucial that fibers are adequately added and mixed to allow for proper placement and finishing. The adequate batching process of FRC concrete greatly depends on the type and dosage rate of the fiber as well as the mixing system being used for concrete batching. Therefore, it is vital to follow the fiber manufacturer's recommended batching sequence to minimize the risk of balling in the mixture and to maximize the uniform dispersion of the fibers. The fiber manufacturer is the best source of batching recommendations for their material.

### 6.2.1. Synthetic Fiber

Synthetic fibers are usually best to be added along with the aggregates and other materials to minimize the risk of balling or cement packing. Most synthetic fibers are packaged in repulpable bags or melt-away bags that disintegrate in concrete, that allow the bags to be added directly to the batch without the need to first open then and melt the fibers into the drum mixer or the aggregate belts. However, if the FRC is being used for flatworks such as overlay, cautions should be used regarding the use of repulpable bags. The Silica Fume Association has reported several instances which the bags have failed to disintegrate as intended, resulting in the appearance of fragments of paper in the surface of the concrete. Similar concern applies to use of repulpable bags for fibers.

Some fibers are also packaged in pucks or supplied loose in super sacks and added to the batch through a fiber-dispensing system. However, the use of loose fibers greatly depends on the size of the project and the dosage rate. Fiber bags should be added one, or a few, at a time while the drum is in motion for uniform dispersion of the fiber in the mixture. The manufacturer recommendations should be followed closely especially when high fiber dosage is being employed. Additional cautions should be used when adding fibers to a small (less than full) load to avoid fiber bags sticking to the drum wall.

Depending on the fiber type and dosage, mixing time and speed for uniform fiber dispersion may vary. Slow agitation of mixer during the hauling time is usually not sufficient for any additional dispersion. Also, increasing the mixer speed should not be used as a mean to reduce the required mixing time recommended by the supplier.

### 6.2.2. Steel Fiber

Steel fibers are best to be added along with the fine and coarse aggregate to the fresh concrete. Adding the Steel fibers to the mixture should follow the manufacturer's guideline for maximum fiber weight per minute rate of addition. Depending on the fiber characteristics, steel fibers are typically added within the range of 5-75 lb/min. When using steel fibers in concrete batching, extra caution should be used with respect to safety. Gloves and eye protection should always be used when handling steel fibers and adding them to the concrete mixture.

Similar to synthetic fibers, mixing time for steel fibers may vary depending on the shape, length and dosage, and therefore, the fiber's manufacturer recommendations should be followed closely. As a rule of thumb, a minimum of 5 minutes after all fibers added to the concrete will be needed for uniform dispersion of the steel fibers. Due to the wide variety of the fiber types, dosage rates, and mixing systems, trial batches are recommended to determine the ideal process.

### 6.2.3. Finishing of FRC

As discussed in Section 4.1, most common method, but not the best method, for evaluating the workability of FRC being used by the industry is slump. Considering that fibers affect the concrete fresh properties in different ways that could be captured by slump test, visual inspection is crucial. It is also important not add more water in excess to the design water content to obtain the desired workability. If additional workability is needed during the placement, water reducing admixtures within the range specified by the admixture manufacturer may be used. Excessive use of admixture can also lead to undesired fresh properties and increase the risk of balling and clumping.

With respect to finishing, there is no absolute guarantee that fibers will not be visible on a finished surface, but a variety of finishing tips are provided by the manufacturers to help minimize the surface disruption and number of the fibers present. Starting with a properly proportioned concrete mix to accommodate fibers is important as well as ensuring that a mix is not "over-watered" to improve flow. Timing of the finishing operation can sometimes be tricky because the FRC may look like the concrete is setting up more quickly due to the cohesive nature of the material. Generally, any practices that disrupt the concrete surface will naturally also affect the appearance of fibers that are present the surface of the concrete. For instance, a textured or broomed exterior surface finish will have a tendency to pull more fibers to the surface than a smooth, hard-troweled finish. When a broom finish is required, it is important that the equipment used to apply the broom finish is maintained in a clean state and that the angle of the broom is low with all passes being made in the same direction. Broom finishes will usually pull fibers of any type to the surface of concrete.

With respect to synthetic fibers, if necessary, a torch may be used to burn the fibers at the surface of the concrete. When high dosage of steel fiber is used, a laser screed or vibrating screed is recommended for finishing.

## 7. CURRENT STATE OF THE PRACTICE IN USA

Because no national guidance documents are available for FRC bridge decks and bridge deck overlays, a review of all 50 states' pavement specifications was undertaken for this project and a summary of the available requirements set forward by different national agencies is listed in Table 10 through Table 17. The agencies are listed in alphabetic order. Special provisions were also examined when accessible or if provided by the agency through the conducted survey in Section 6 of this study. It is worth noting that several states list fibers as an approved material with no specification, meaning that lack of specification does not necessarily mean the absence of FRC overlays from the state.

**Table 10. Nationwide State DOTs' specifications for the use of macro-fibers in bridge decks and overlays for bridge decks (1).**

| State | Year | Section | Requirements |
|---|---|---|---|
| Alabama | 2022 | N/A | N/A |
| Alaska | 2020 | N/A | N/A |
| Arizona | 2021 | N/A | N/A |
| Arkansas | 2014 | N/A | N/A |
| California | 2021 | 51-1.02B | Concrete for concrete bridge decks or PCC deck overlays must contain Polymer fibers. Each cubic yard of concrete must contain at least 1 pound of microfibers and at least 3 pounds of macrofibers. |
| Colorado | 2021 | 601.01 | Concrete for sidewalks on bridge decks and bridge rail shall be macro-fiber reinforced. |
| | | 601.3 | Where Macro Fiber-Reinforced Concrete is specified or designated on the plans, the concrete mix shall include approved macro or hybrid polyolefin fibers at a minimum dosage of 4 lb/cy or the minimum dosage specified on the approved product list (APL), whichever is greater.<br>The dosage of the fiber may be reduced if trial mix data shows a minimum residual strength of 150 psi as determined in accordance with ASTM C1609 using a load support apparatus compliant with the requirements of ASTM C1812, "Standard Practice for Design of Journal Bearing Supports to be Used in Fiber Reinforced Concrete Beam Tests.<br>Mixing shall be as recommended by the manufacturer such that the fibers are evenly distributed in the mix and do not ball up. Macro or hybrid polyolefin fibers shall meet the requirements of ASTM C1116 and ASTM D7508. |
| | | 606.02 | Concrete for bridge rail shall be an approved Macro Fiber-Reinforced |

**Table 11. Nationwide State DOTs' specifications for the use of macro-fibers in bridge decks and overlays for bridge decks (2).**

| | | | |
|---|---|---|---|
| Connecticut | 2020 | N/A | N/A |

| | | | |
|---|---|---|---|
| Delaware | 2021 | 1022.4 | Use fibers that conform to the requirements of ASTM C1116, Type III with a minimum fiber length of 1/2-inch and a maximum length of 1 1/2-inch. |
| | | 1022.8 | Concrete for approach slabs and decks requires the use of nonferrous reinforcement fibers at a rate of 1.5 pounds per cubic yard or 0.5 pounds per cubic yard if using nylon fibers. |
| Florida | 2014 | Developmental Specifications: Dev346FRC | Allowable fiber types are polymeric, steel, and basalt.<br>Produce an Average Residual Strength (ARS) of no less than 215 psi from a test set of 5 beams in accordance with ASTM C1399. |
| Georgia | 2021 | 941.2.01 | 1. Ensure that macro-synthetic fibers are manufactured from virgin polyolefins (polypropylene and polyethylene) and comply with ASTM C1116.4.1.3. Fibers manufactured from materials other than polyolefins must show documentary 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.<br>2. The minimum fiber length required is 1.50 in. (38 mm).<br>3. Ensure that macro-synthetic fibers have an aspect ratio (length divided by the equivalent diameter of the fiber) between 45 and 150. |
| Hawaii | 2005 | 719.01.A | Macro-synthetic fibers shall be manufactured from virgin polyolefins (polypropylene and polyethylene) and comply with ASTM C1116.4.1.3. |
| | | 719.01.E | Minimum dosage rate in pounds of fibers per cubic yard of concrete shall be established by determining a minimum average residual strength of no less than 150 psi when tested in accordance with ASTM C1399. The minimum fiber dosage rate shall be 3 lb/yd$^3$. |
| Idaho | 2018 | 510.02(E) | For silica fume concrete bridge deck overlays, fibers meeting ASTM C1116 with a minimum dosage rate of 1.5 lb/yd$^3$. |

**Table 12. Nationwide State DOTs' specifications for the use of macro-fibers in bridge decks and overlays for bridge decks (3).**

| | | | |
|---|---|---|---|
| Illinois | 2012 | Superiority & Constructability of Fibrous Additives for Bridge Deck Overlays [118] | Total synthetic fiber content (polypropylene and nylon types) of 3 lb/yd$^3$ is recommended for bridge deck concrete overlays.<br>Macro-fibers with mesh-type configurations are not recommended for concrete overlays.<br>The maximum recommended length of macro-fibers is 1.75 in., and the minimum recommended length of micro-fibers is 0.75 in. |
| | 2012 | Special Provision for Portland Cement Concrete Inlay or Overlay | The synthetic fiber shall be a monofilament or bundled monofilament with a minimum length of 1.0 in. (25 mm) and a maximum length of 2 1/2 in. (63 mm) and shall have a maximum aspect ratio (length divided by the equivalent diameter of the fiber) of 150. The quantity of synthetic fiber(s) added to the concrete mixture shall be sufficient to have a residual strength ratio (R150,3) of 20.0 percent according to Illinois Modified ASTM C1609. The maximum dosage rate shall not exceed 5.0 lb/yd3 (3.0 kg/m3), unless the manufacturer can demonstrate through a field demonstration that the concrete mixture will be workable and fiber clumping is not a problem as determined by the Engineer. |
| Indiana | 2020 | N/A | N/A |
| Iowa | 2015 | N/A | N/A |
| | According to survey | | Polypropylene micro and macro fibers. Type III fibers in accordance with ASTM C1116. |
| Kansas | 2015 | 1722 | (1) Provide macro synthetic fibers as defined in ASTM C1116, Type III, and ASTM D 7508.<br>(2) Provide fibers having a minimum length of 1.25 inches, a maximum length of 2.0 inches, and an aspect ratio (length divided by equivalent diameter) between 70 and 100, inclusive.<br>(3) Provide fibers with a minimum tensile strength of 50 ksi.<br>(4) Provide fibers, which when tested, result in a minimum strength ratio ($R_{e,3}$) of 25%. |
| Kentucky | 2019 | N/A | N/A |
| Louisiana | 2016 | 602.10.2.1 | For patching: Add steel fibers complying with ASTM A-820, Type I, or II to the mix. Use fibers with a nominal length not less than 1 in. or no greater than 1-1/2 inch. Use deformed fiber with an aspect ratio not less than 40 or no greater than 60. Provide 85 to 90 pounds of steel fibers per cubic yard of concrete. |
| Maine | 2020 | N/A | N/A |

**Table 13. Nationwide State DOTs' specifications for the use of macro-fibers in bridge decks and overlays for bridge decks (4).**

| | | | |
|---|---|---|---|
| Maryland | 2021 | 902.10.03 | White topping (WT) mix shall contain a high range water reducing admixture, macro-fibers at 3 lbs/yd$^3$ Max, and acceptance will be on a minimum compressive strength of 2500 psi in 24 hours. |
| | | 902.15 | When synthetic fibers are specified in the Contract Documents, the fibers shall be 1/2 to 1-1/2 inch. long and conform to C1116, Type III.<br>The quantity of fibers used and their point of introduction into the mix shall conform to the fiber manufacturer's recommendations. |
| | | 902.15.01 | Macro Polyolefin Fibers. D7508 with a minimum length of 1-1/2 inch. |
| Massachusetts | 2020 | N/A | N/A |
| Michigan | 2012 | 703.02D | For silica fume modified concrete overlays: Virgin polypropylene collated fibers at 2 lb/yd$^3$. |
| | | 903.05 | Use 100 percent virgin polypropylene fibers, 3/4 inch long, that meet the requirements of ASTM C1116, Type III |
| Minnesota | 2018 | SB2018-2401.2 B | Supply Type III fibers in accordance with ASTM C1116. A minimum dosage rate of 4 lb/yd$^3$ is required. The fibers on the A/QPL are a combination of micro and macro non-metallic fibers to provide crack control and improve the long-term performance of the bridge decks. The stated manufacturer purpose of the non-metallic fibers is for controlling plastic shrinkage cracks in concrete (micro-fibers) and to provide increased residual flexural strength in the concrete (macro fibers). Single component macro fibers conforming to the requirements of table HPC-4 may be submitted for approval by the Engineer."<br>Minimum 25% RDT,150 as specified in ASTM C1609 and minimum reduction greater than 85% of crack reduction ratio (CRR) as specified in ASTM C1579. |
| Mississippi | 2017 | 711.04.1 | Use 100 percent virgin polypropylene fibers, 3/4 inch long, that meet the requirements of ASTM C1116, Type III. |
| | | 711.04.2 | The dosage rate shall be such that the average residual strength ratio (R150,3.0) of fiber-reinforced concrete beams is a minimum of 20.0 percent when the beams are tested in accordance with ASTM C1609. |
| | | 804.02.10 | For bridge decks: an approved synthetic structural fiber meeting the requirements of Subsection 711.04 shall be incorporated into the mixture at 1.25 times the approved dosage rate. |

**Table 14. Nationwide State DOTs' specifications for the use of macro-fibers in bridge decks and overlays for bridge decks (5).**

| | | | |
|---|---|---|---|
| Missouri | 2020 | 505.60.2.3 | Steel fibers shall be made from stainless steel and nominally be 2-inch long and meet the physical property requirements prescribed in ASTM A820. One-inch Helix fibers are also allowed. Steel fibers shall have a quantity of at least 2000 fibers per pound and a fiber aspect ratio of 40 to 60. The steel fibers shall not have any hooks or 90-degree bends. The steel fibers shall be free from rust, oil and other deleterious materials. Steel fibers shall be transported, stored and applied to the concrete mixture in accordance with the manufacturer's recommendations. |
| | | 506.10.2.1 | Fibrillated polypropylene fibers shall be added at a rate of 3.0 pounds per cubic yard. All fibers shall be measurable by weight. Fibers may be measured in bags, boxes or like containers with approval from the engineer. The containers shall be sealed by the fiber manufacturer and shall have the weight contained therein clearly marked by the manufacturer. No fraction of container delivered unsealed or left over from previous work shall be used unless weighed. Fibers shall be added to the concrete mix and mixed according to the fiber manufacturer's recommendations. |
| Montana | 2021 | N/A | N/A |
| Nebraska | 2017 | N/A | N/A |
| Nevada | 2014 | N/A | N/A |
| New Hampshire | 2016 | 544.2.5 | Synthetic fiber reinforcement shall be a product as included on the Qualified Products List. |
| | | 544.3.8 | The dosage rate shall be 7 lb/yd$^3$ unless otherwise approved, in writing, by the Engineer |
| New Jersey | 2021 | N/A | N/A |
| New Mexico | 2019 | 509.2.6 | If specified, steel fibers shall conform to ASTM A820, and synthetic fibers conform to ASTM C1116. |
| New York | 2022 | 711-01 | Synthetic, fibrillated fibers, specifically engineered and manufactured for use as secondary concrete reinforcement meeting ASTM C1116 Type III. Acceptance will be based on the product name and manufacturer appearing on the Department's Approved List and material certification that states the product conforms to this specification. |

**Table 15. Nationwide State DOTs' specifications for the use of macro-fibers in bridge decks and overlays for bridge decks (6)**

| | | | |
|---|---|---|---|
| North Carolina | 2018 | 1077-7(B)(3) | Manufacture from virgin polyolefins (polypropylene and polyethylene) and comply with ASTM D7508. Fibers manufactured from materials other than polyolefins. Submit test results certifying resistance to long-term deterioration when in contact with the moisture and alkalis present in cement paste and/or the substances present in air-entraining and chemical admixtures.<br>Fiber length shall be no less than 1.5 in. Use macro-synthetic fibers with an aspect ratio (length divided by the equivalent diameter of the fiber) between 45 and 150, a minimum tensile strength of 40 ksi when tested in accordance with ASTM D3822 and a minimum modulus of elasticity of 400 ksi when tested in accordance with ASTM D3822. |
| | | 1077-7(B)(4) | Approved structural fibers may be used as a replacement of steel reinforcement in allowable structures of Roadway Standard Drawings Nos. 840.45 and 840.52. The dosage rate, in pounds of fibers per cubic yard, shall be as recommended by the fiber manufacturer to provide a minimum average residual strength of concrete, tested in accordance with ASTM C1399, of no less than that of the concrete with the steel reinforcement that is being replaced and no less than 5 lb/yd$^3$.<br>Use fiber-reinforced concrete with a 4.5% ± 1.5% air content and a compressive strength of at least 4,000 psi in 28 days. Determine workability of the concrete mix in accordance with ASTM C995. The flow time shall at least 7 seconds and no greater than 25 seconds. Assure the fibers are well dispersed and prevent fiber balling during production. After introduction of all other ingredients, add the plastic concrete and mix the plastic concrete for at least 4 minutes or for 50 revolutions at standard mixing speed. |
| North Dakota | 2020 | N/A | N/A |
| Ohio | 2019 | N/A | N/A |
| Oklahoma | 2019 | 701.15 (A-1) | Polypropylene Fibers: Use synthetic fibers that are 100 percent polypropylene, collated, fibrillated fibers manufactured to graduated lengths of equal proportions for secondary reinforcement. Provide fibers in accordance with ASTM C1116 for Type III. |
| | | 701.15 (A-2) | Steel Fibers: Use steel fiber in accordance with ASTM A 820, for Type II, cut-sheet steel. Provide steel fibers with an aspect ratio of 30:60 and from 1-⅛ inch [30 mm] to 2-inch [50 mm] long. |

**Table 16. Nationwide State DOTs' specifications for the use of macro-fibers in bridge decks and overlays for bridge decks (10).**

| | | | |
|---|---|---|---|
| Oregon | 2021 | 02001.31 (f) | Use synthetic fiber reinforcing from the QPL and according to Section 02045 in all high-performance concrete. Use synthetic fiber reinforcing according to the manufacturer's recommendations at the rate designated on the QPL. Fiber packaging is not allowed in the mixed concrete. |
| | | 2045.2 | Synthetic Macro Fiber Reinforcing - Furnish synthetic polyolefin macro fiber reinforcing from the QPL. |
| | | 2045.3 | Synthetic Blended Fiber Reinforcing - Furnish synthetic polyolefin blended fiber reinforcing from the QPL. |
| Pennsylvania | 2021 | 548.2 (d) | Except for overlays with depth less than 7 inches use concrete reinforced with polypropylene fibers according to ASTM C1116, Type III 4.13 and ASTM C1116 (Ref: ASTM C1018) Performance Level 1 outlined in Section 21, Note 17 and Residual Strength. Use 100% virgin polypropylene (PE) manufactured to an optimum gradation for use as concrete reinforcement.<br>Use a synthetic fiber that is a monofilament or bundled monofilament with a minimum length of 1.0 inches and a maximum length of 2-1/2 inches and has a maximum aspect ratio (length divided by the equivalent diameter of the fiber) of 150. Add a sufficient quantity of synthetic fiber(s) to the concrete mixture to have a residual strength ratio ($R_{150,3}$) of 20.0 percent according to Illinois Modified ASTM C1609.<br>Do not exceed the maximum dosage rate of 5.0 pounds per cubic yard, unless the manufacturer can demonstrate, through a field demonstration, that the concrete mixture will be workable and fiber clumping is not a problem. |
| Rhode Island | 2018 | N/A | N/A |
| South Carolina | 2007 | N/A | N/A |
| South Dakota | 2015 | N/A | N/A |
| Tennessee | 2021 | N/A | N/A |
| Texas | 2014 | N/A | N/A |
| Utah | 2022 | 03055 (2.2.F.2) | Macro synthetic fiber:<br>a. Use 4 lb/$yd^3$ of concrete mix.<br>b. Provide a minimum flexural strength ratio ($R_{e,3}$) of 25 percent when tested according to ASTM C1609. |
| Vermont | 2018 | N/A | N/A |

**Table 17. Nationwide State DOTs' specifications for the use of macro-fibers in bridge decks and overlays for bridge decks (11).**

| | | | |
|---|---|---|---|
| Vermont | 2018 | N/A | N/A |
| Virginia | 2020 | 412.e.8 | Steel fibers and Synthetic fibers shall be from the Materials Division's Approved Products Steel fibers and Synthetic fibers shall be from the Materials Division's Approved Products |
| Washington | 2022 | N/A | N/A |
| West Virginia | 2017 | N/A | N/A |
| Wisconsin | 2022 | N/A | N/A |

Out of the 50 agencies listed in tables above, in addition to fiber content requirements Colorado, Illinois and Minnesota require fiber dosage verification through ASTM C1609. Florida, Hawaii, and North Carolina require fiber dosage to be determined using ASTM C1399, while Mississippi, Pennsylvania, and Utah call for ASTM C1609 for evaluating the fiber dosage rate. California, Delaware, Louisiana, Maryland, Michigan, New Hampshire and Idaho only specify maximum fiber content, and the rest of the agencies with requirements for FRC (if any) only specify fiber type, geometry, and properties.

Among those specifying fiber content as the requirement for FRC production, the fiber dosage varies between 1.5 lb/yd$^3$ and 5lb/yd$^3$, except for Louisiana which specifies 85 to 90 lb/yd$^3$ of steel fiber.

# 8. EXPERIMENTAL PROGRAM

As noted in the Overview and Problem Statement section of this report, the objective of the current research program is to (1) establish a systematic and functional process that can guarantee the success of the FRC overlay application, (2) develop performance criteria for acceptability, (3) establish defined protocols for agencies to be able to evaluate a product that is submitted for approval, and (4) identify methodologies that facilitate the decision-making process.

To accomplish these objectives, twelve different fibers that can be broadly classified under the categories of synthetic and steel fiber types were procured from different manufacturers available in the US. A summary of technical data provided by different manufacturers for different fibers are summarized in Table 18. For each fiber type, three dosage levels were identified for use in concrete. The dosage levels (low, medium, and high) for this experimental program were selected based on the manufacturer recommendation of dosage for each fiber. A visual comparison of different fibers is shown in Figure 29.

**Table 18. Details of different fibers used in the research study (information provided by manufacture; '--' indicates not provided)**

| Fiber ID | Type | Material | Form | Length (in.) | Eq. Diameter (in.) | Aspect Ratio | Suggested Dosage Rate (lb/yd$^3$) | Tensile Strength (ksi) |
|---|---|---|---|---|---|---|---|---|
| F1 | Synthetic | Virgin Copolymer / Recycled Polypropylene | Monofilament / Fibrillated Macro | 5 in | -- | -- | 5 | 83 to 96 |
| F2 | Synthetic | Virgin Copolymer | Monofilament Macro | 2.17 | 0.02 | 98 | 3 to 7 | -- |
| F3 | Synthetic Blend | Virgin Polypropylene and Polyethylene Blend | Macro and Micro Fibers Blend | 1.25 (macro); 0.75 (micro) | 0.017 | 75 | 4 to 7.5 | 90 (macro); 15.6 (micro) |
| F4 | Synthetic | Virgin Polypropylene | Continuous Embossing | 1.89 | -- | -- | 4.2 to 8.4 | 92 |
| F5 | Synthetic Blend | Virgin Polypropylene | Continuously Deformed Macro and Monofilament Micro | 1.85 (macro); 0.5 to 0.75 (micro) | 0.03 (macro); 0.0012-0.002 (micro) | 58 (macro); 250 to 630 (micro) | 5 to 10 | -- |
| F6* | Steel-Synthetic Blend | Cold Drawn Steel Wire plus Polypropylene Micro-synthetic Fiber | Macro Steel and Fibrillated Micro Synthetic | 1.5 (Steel); 0.5 to 0.75 (synthetic) | -- | 34 (steel) | 24 to 96 | 140 to 180 |
| F7 | Steel | Stainless Steel | Melt Extract | 1.375 | 0.025 | 55 | 20 to 60 | 130.5 |
| F8 | Steel | Carbon Steel Fiber (Cut Sheet) | Continuous Deformed | 1 | 0.023 | 43 | 20 to 60 | 100 |
| F9 | Steel | Cold Drawn Collated | Collated Hooked End Steel Fiber | 1.4 | 0.02 | 65 | 35 to 80 | 181 |
| F10 | Steel | Steel | End Deformed and Bundled | 2.36 | 0.03 | 65 | 15 | 232 |
| F11 | Steel | Duplex Stainless Steel | Melt Extract | 1.375 | 0.025 | 55 | 20 to 60 | 116 |
| F12 | Synthetic Blend | Polypropylene/ Polyethylene Marco; Polypropylene Micro | Macro; Monofilament Micro | 1.5 (macro); 0.75 (micro) | 0.027 | 55 (macro) | 4 | 87 to 94 (macro) |

*F6 included micro synthetic fiber which was meant to minimize plastic shrinkage and not significantly affect the flexural toughness.

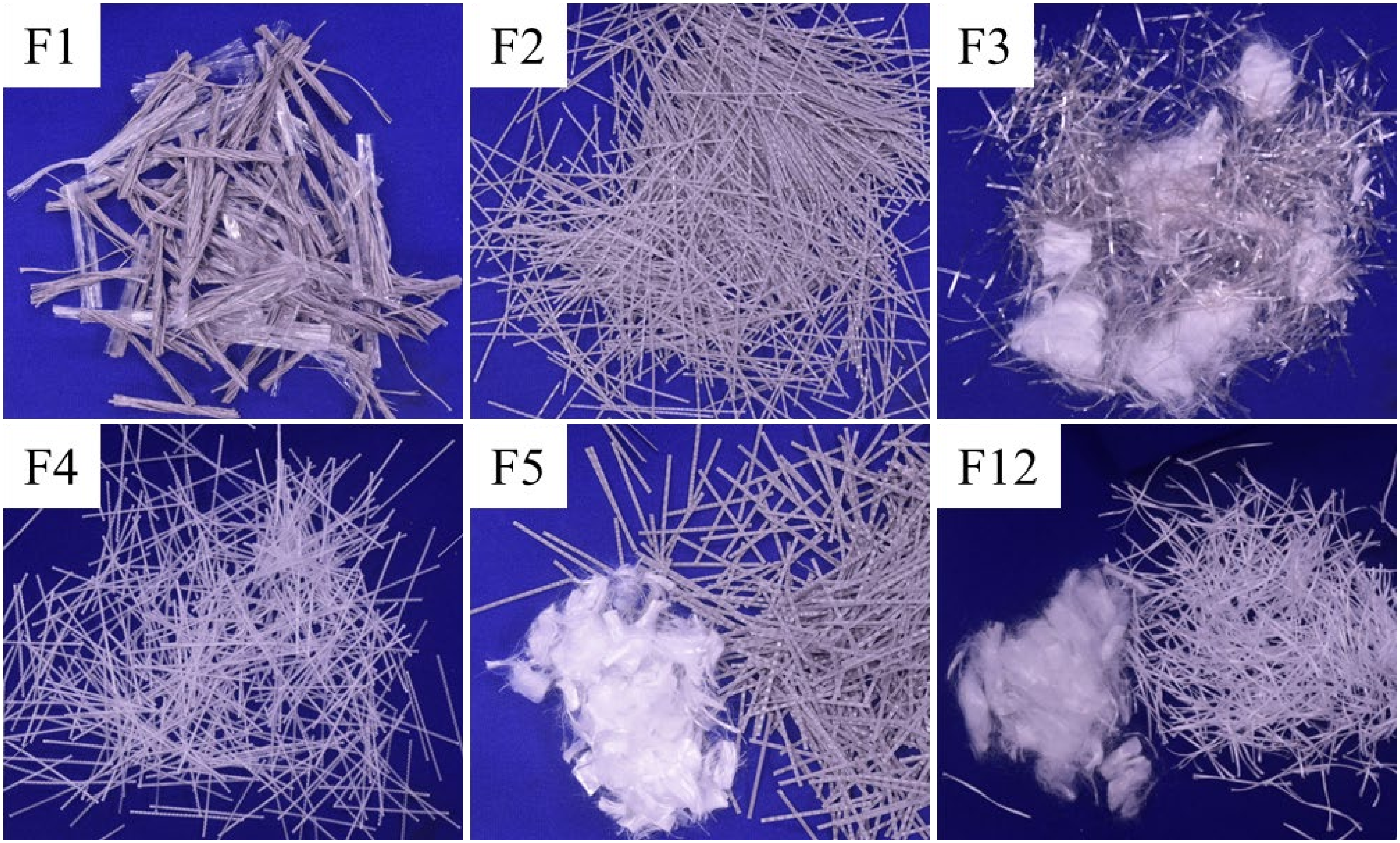

Figure 21. Images of fibers considered in this study

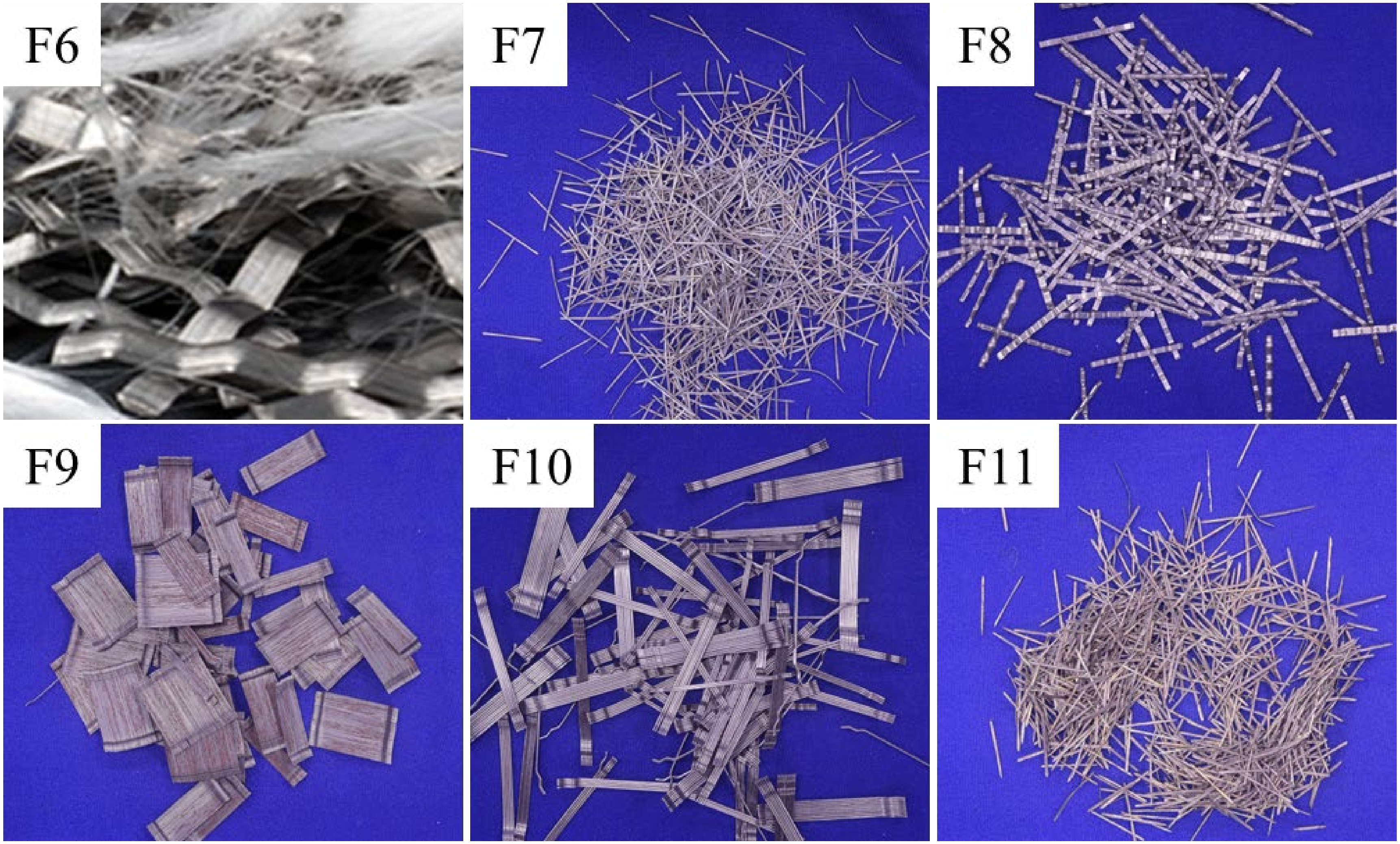

**Figure 21. (cont'd) Images of fibers considered in this study**

MODOT MB-2 class concrete was selected as the base mixture with a minimum cementitious content of 600 lb/cy, a fly ash replacement level of 20%, and a water-to-cementitious materials ratio (w/cm) of 0.42, with an expectation to increase the paste content where needed to accommodate for the increased fiber surface area at higher dosages. However, such an adjustment was deemed unnecessary for all concrete mixtures except Mix 1-3.

Blended Cement (Type 1L) and Fly Ash were procured from Continental Cement, St Louis, MO and Boral Resources, Festus, MO, respectively. A ¾ inch nominal maximum size limestone coarse aggregate (CM-11) that complies with Missouri DOT (MODOT) specification was used for all concrete batches. The coarse aggregate was provided by Vulcan Materials, IL. A concrete sand that meets MODOT aggregate gradation requirements was used for all concrete batches. Concrete sand was procured from Ozinga, Mc Henry, IL. Summary of test results for gradation, deleterious substances, and physical properties are summarized in Table 19 and Table 20. A summary of concrete mixture proportions for different batches investigated in this study are summarized in Table 21.

**Table 19. ASTM C136 sieve analysis results for coarse and fine aggregates**

| Sieve ID | Coarse Aggregate | | Fine Aggregate | |
|---|---|---|---|---|
| | % Cumulative Passing | MODOT Gradation D Limits | % Cumulative Passing | MODOT Limits |
| 1" | 100 | 100 – 100 | — | — |
| ¾" | 86 | 85 – 100 | — | — |
| ½" | 47 | — | — | — |
| ⅜" | 23 | 15 – 55 | 100 | 100 – 100 |
| #4 | 3 | 0 – 10 | 100 | 95 – 100 |
| #8 | 1 | — | 89 | 70 – 100 |
| #16 | — | — | 68 | 45 – 90 |
| #30 | — | — | 44 | 15 – 65 |
| #50 | — | — | 13 | 5 – 30 |
| #100 | — | — | 5 | 0 – 10 |
| #200 | — | — | 1.6 | — |
| Pan | 0 | — | 0 | — |

**Table 20. Summary of evaluation results for deleterious substances and physical properties**

| Test Method | Coarse Aggregate | | Fine Aggregate | |
|---|---|---|---|---|
| | **Result** | **MODOT Limit** | **Result** | **MODOT Limit** |
| Dry Rodded Unit Weight, ASTM C29 | 100 lb/ft$^3$ | — | 111 lb/ft$^3$ | —— |
| Specific Gravity (SSD), ASTM C127/C128 | 2.74 | — | 2.69 | |
| Absorption, ASTM C127/C128 | 1.6% | 3.5% | 1.8% | — |
| Clay Lumps and Friable Particles, ASTM C142 | 0.00% | — | 0.43% | 0.25% |
| Chert (SG 2.4), ASTM C123 | 0.0% | 4.0% | — | — |
| Sum of Clay Lumps, Friable Particles and Chert ASTM C142 + ASTM C123 (SG 2.4) | 0.0% | 6.0% | Not Evaluated | 0.5% |
| Material Finer than 0.075 mm (No. 200 sieve), ASTM C117 | 1.3% | 2.5% | 1.4% | 2.0% |
| Coal & Lignite (SG 2.0), ASTM C123 | 0.0% | 1.0% | 0.0% | 0.5% |
| Abrasion, ASTM C131 | 21% | 50% | — | — |
| Magnesium Sulfate Soundness, ASTM C88 | 17% | 18% | 12% | — |
| Organic Impurities, ASTM C40 | — | — | No Impurities | No Impurities |
| Fineness Modulus, ASTM C136 | — | — | 2.82 | — |

**Table 21. Mixture proportions (Specific Gravity values: Cement = 3.15; Fly Ash = 2.68)**

| Mixture ID | Fiber ID | Specific Gravity of Fiber | Fiber Dosage Rate (lb/yd$^3$) | Blended Cement (lb/yd$^3$) | Fly Ash (lb/yd$^3$) | Coarse Aggregate (lb/yd$^3$) | Concrete Sand (lb/yd$^3$) | Water (lb/yd$^3$) |
|---|---|---|---|---|---|---|---|---|
| C | -- | -- | -- | 480 | 120 | 1748 | 1356 | 252 |
| 1-1 | F1 | 0.91 | 3 | 480 | 120 | 1744 | 1351 | 252 |
| 1-2 | F1 | 0.91 | 13.5 | 480 | 120 | 1726 | 1337 | 252 |
| 1-3 | F1 | 0.91 | 30 | 680 | 170 | 1415 | 1096 | 357 |
| 2-1 | F2 | 0.91 | 3 | 480 | 120 | 1740 | 1348 | 252 |
| 2-2 | F2 | 0.91 | 5 | 480 | 120 | 1735 | 1350 | 252 |
| 2-3 | F2 | 0.91 | 7 | 480 | 120 | 1736 | 1345 | 252 |
| 3-1 | F3 | 0.91 | 4 | 480 | 120 | 1740 | 1348 | 252 |
| 3-2 | F3 | 0.91 | 5.25 | 480 | 120 | 1740 | 1348 | 252 |
| 3-3 | F3 | 0.91 | 7.5 | 480 | 120 | 1736 | 1345 | 252 |
| 4-1 | F4 | 0.91 | 4.2 | 480 | 120 | 1740 | 1348 | 252 |
| 4-2 | F4 | 0.91 | 10.5 | 480 | 120 | 1732 | 1342 | 252 |
| 4-3 | F4 | 0.91 | 16.8 | 480 | 120 | 1721 | 1334 | 252 |
| 5-1 | F5 | 0.91 | 4 | 480 | 120 | 1740 | 1348 | 252 |
| 5-2 | F5 | 0.91 | 10.5 | 480 | 120 | 1732 | 1342 | 252 |
| 5-3 | F5 | 0.91 | 15 | 480 | 120 | 1721 | 1334 | 252 |
| 6-1 | F6 | 7.8 | 24 | 480 | 120 | 1743 | 1351 | 252 |
| 6-2 | F6 | 7.8 | 60 | 480 | 120 | 1736 | 1346 | 252 |
| 6-3 | F6 | 7.8 | 96 | 480 | 120 | 1730 | 1339 | 252 |
| 7-1 | F7 | 7.8 | 20 | 480 | 120 | 1745 | 1352 | 252 |
| 7-2 | F7 | 7.8 | 40 | 480 | 120 | 1741 | 1349 | 252 |
| 7-3 | F7 | 7.8 | 60 | 480 | 120 | 1737 | 1346 | 252 |
| 8-1 | F8 | 7.34 | 20 | 480 | 120 | 1745 | 1352 | 252 |
| 8-2 | F8 | 7.34 | 40 | 480 | 120 | 1741 | 1349 | 252 |
| 8-3 | F8 | 7.34 | 60 | 480 | 120 | 1737 | 1346 | 252 |
| 9-1 | F9 | 7.86 | 35 | 480 | 120 | 1745 | 1352 | 252 |
| 9-2 | F9 | 7.86 | 57.5 | 480 | 120 | 1741 | 1349 | 252 |
| 9-3 | F9 | 7.86 | 80 | 480 | 120 | 1737 | 1346 | 252 |
| 10-1 | F10 | 7.86 | 7.5 | 480 | 120 | 1742 | 1350 | 252 |
| 10-2 | F10 | 7.86 | 12.5 | 480 | 120 | 1738 | 1347 | 252 |
| 10-3 | F10 | 7.86 | 17.5 | 480 | 120 | 1734 | 1344 | 252 |
| 11-1 | F11 | 7.86 | 20 | 480 | 120 | 1742 | 1350 | 252 |
| 11-2 | F11 | 7.86 | 40 | 480 | 120 | 1738 | 1347 | 252 |
| 11-3 | F11 | 7.86 | 60 | 480 | 120 | 1734 | 1344 | 252 |
| 12-1 | F12 | 0.91 | 4 | 480 | 120 | 1742 | 1350 | 252 |
| 12-2 | F12 | 0.91 | 10 | 480 | 120 | 1738 | 1335 | 252 |
| 12-3 | F12 | 0.91 | 16 | 480 | 120 | 1734 | 1315 | 252 |

All batches were evaluated for fresh properties including slump (ASTM C143), fresh air content (ASTM C231), temperature (ASTM C1064), unit weight (ASTM C138), edge slump (AASHTO PP 84), and bleeding (ASTM C232). The initial thinking of the research group was to also evaluate SAM number for all batches per AASHTO PP84. However, due to equipment failure during the execution of the experimental program, this was not accomplished. All mixtures were designed to achieve a target slump between 0 and 3 inches and target fresh air content between 3.5 and 6.5%. The dosages of high range water reducer (MasterGlenium 7920) and air-entraining admixture (MasterAir AE 90) were adjusted as needed to achieve these targets. A hydration stabilizer (Master Devlo) was also used for all batches at a dosage rate of 3.5 fl-oz/cwt.

To assess the effect of fiber type and dosage on hardened properties of concrete, several 4x8-in. nominal cylindrical specimens, 3 × 3 × 11.25-in. prismatic specimens, 6 × 6 × 21 in. beam specimens, 31.5 in diameter cylindrical specimens (thickness = 3 inches), and 12 × 12 × 3-in. slab specimens were fabricated for each of the 37 batches. The properties that were evaluated as part of the testing program included compressive strength (ASTM C39), MOE (ASTM C469), split-tensile strength (ASTM C496) at 7-day and 28-days of age, surface resistivity (AASHTO T 358) at 28 days, drying shrinkage (ASTM C157), freeze-thaw resistance (ASTM C666), salt scaling resistance (ASTM C672), and abrasion resistance (ASTM C778). For the control batch without fibers (Mix ID: C), the nominal 6 × 6-in. beam specimens were evaluated for flexural strength per ASTM C78. For concrete batches with fibers, these were used to evaluate peak flexural strength, flexural toughness, and flexural strength ratio per ASTM C1609. The nominal 31.5-inch diameter specimens were used to evaluate the flexural toughness per ASTM C1550.

ASTM C1609 requires the use of a displacement-controlled testing system and a three-point loading approach to capture the load-deflection behavior up to a net mid-span deflection of *l/150* (0.12 inches for a 6×6-inch cross section prism), where *l* represents the span length. The method also permits use of a variable load rate depending on the deflection — 0.0015 to 0.004 inch/min for a net deflection below 0.02 inches and 0.002 to 0.012 inch/min for a net deflection above 0.02 inches (all values stated correspond to 6×6-inch cross section prisms). Preliminary testing on low-fiber dosage specimens from Mix 2-1 indicated punch-through failures post peak load, even at a rate of 0.0015 inch/min, the lowest load rate specified in ASTM C1609. A study conducted by Banthia and Islam indicated that the ASTM C1609 loading rate can be too high for capturing a stable load-deflection curve for concrete mixtures with low levels of fiber dosage [119]. The low dosage level considered by the authors was 0.11% by volume, which is representative of some low dosage levels considered in the current research study. The authors recommended a revision to the loading rate or imposition of minimum fiber dosage for future revisions of ASTM C1609. It should be noted that the findings of the study conducted by Banthia and Islam was published in 2013, whereas the loading rate reported by ASTM C1609 remained consistent through all revisions of the standard document conducted 2012 or after. While the longer testing time is undesired, it is generally anticipated that a reduction in loading rate should not significantly affect the load-deflection curve pattern and should only assist in capturing a more stable pattern.

Through trial-and-error, a loading rate of 0.0005 inch/min (one-third of the lowest specified loading rate) has been determined to minimize the occurrence of punch-through failure scenarios immediately after the post-peak load. The reduced load rate is also beneficial to avoid punch-through failure in the net deflection range of 0.02 to 0.12 inches and better captures the residual load behavior. To keep the testing methodology consistent, a loading rate of 0.0005 inch/min was adopted throughout the test for all concrete batches. Because of the longer testing time involved due to reduced load rate (~ 4-4.5 hours per specimen) and high number of testing specimens, the testing age varied for different batches and generally ranged between 56 and 90 days. As expected, data generated from this test indicated limited effect of concrete age on strength, and that the residual strength behavior is primarily dependent on the type and dosage rate of fibers. This will be discussed in more detail in the following sections. For ASTM C1550 testing, the load rate of 0.195 inch/min was used and testing was discontinued when the net deflection reached 1.8 inches. Testing was conducted between the ages of 90 and 120 days.

**Figure 22. A schematic of ASTM test setups to evaluate flexural toughness of FRC mixtures**

ASTM C1609 and ASTM C1550 test results were used as reference to identify two fiber types one from each fiber category (synthetic and steel) that exhibited low performance with respect to flexural toughness. For each of the fiber types that exhibited low performance (i.e., lower flexural toughness), restrained shrinkage specimens (ring specimens; ASTM C1581) were cast (at low and high fiber dosage rates as specified in **Table 21**) to evaluate average peak shrinkage strain over a period of 28 days and average time to cracking, if any. In addition to specimens containing fibers, ring specimens were cast for control concrete batch without fibers (Mix ID: C). The objective behind the evaluation of low-performance fibers through ASTM C1581 testing is to identify the relative performance of fiber-reinforced concrete mixtures compared to Portland cement concrete without fibers More information of different fiber IDs considered for ASTM C1581 testing are discussed in the following sections. In addition to ASTM C1581 testing, mixtures containing low performance fibers were evaluated for substrate compatibility through ASTM C1583 testing.

# 9. RESULTS AND DISCUSSION

## 9.1 Fresh Concrete Properties

A summary of the mixtures' fresh properties is tabulated in Table 22 and Table 23. The data collected from the workability performance test are also presented in the table. One of the chief concerns with the use of fibers is that their inclusion will negatively impact slump. The testing in this project did not require modifications to the paste content of the mixture even with the inclusion of fibers (with the exception of mixture 1-3) at all dosages. As can be seen in these tables, the slump value for the mixtures remained consistent, indicating sufficient pate content despite the addition of fibers. Specifically, the control mixture with no fibers had a slump of 1.75-inches and the experimental mixtures had slumps varying from 1.25- to 2.75-inches. The measured air content was observed to fall in the range defined for this project (5% ± 1.5%). On the other hand, the edge slump test results exhibited some susceptibility to the variation of fiber type and dosages, while all results remained within the designed ranges. Although no clear correlation could be established between the type of fiber and bleeding potential, the results indicate that FRC mixtures are generally more susceptible to bleeding which is prone to increase as the fiber dosage is increased.

**Table 22. Summary of fresh properties recorded for control mixture and mixtures with synthetic fibers (1 in. = 25.4 mm; 1 lb/yd$^3$ = 0.593 kg/m$^3$; 1 ml/cm$^2$ = 0.218 oz/in$^2$)**

| Mixture ID | Fiber ID | Fiber Dosage (lbs/yd$^3$) | Fiber Dosage (ft$^3$/yd$^3$) | Fiber Dosage (% concrete volume) | ASTM C143 Slump (in.) | ASTM C231 Plastic Air (%) | ASTM C138 Density (lb/yd$^3$) | AASHTO PP84 Edge-Slump (in.) | ASTM C232 Bleeding (ml/cm$^2$) |
|---|---|---|---|---|---|---|---|---|---|
| C | -- | -- | -- | -- | 1.75 | 5.2 | 147.8 | 0.25 | 0.03 |
| 1-1 | F1 | 3 | 0.053 | 0.196 | 1.25 | 4.1 | 146.8 | 0.25 | 0.00 |
| 1-2 | F1 | 13.5 | 0.238 | 0.881 | 1.25 | 4.9 | 144.8 | 0.25 | 0.04 |
| 1-3 | F1 | 30 | 0.528 | 1.957 | 1.25 | 4.5 | 142.3 | 0.25 | 0.02 |
| 2-1 | F2 | 3 | 0.053 | 0.196 | 2.25 | 5.1 | 146.4 | 0.5 | 0.06 |
| 2-2 | F2 | 5 | 0.088 | 0.326 | 1.25 | 5 | 147.6 | 0.25 | 0.03 |
| 2-3 | F2 | 7 | 0.123 | 0.457 | 1.5 | 5.2 | 146.2 | 0.25 | 0.03 |
| 3-1 | F3 | 4 | 0.070 | 0.261 | 2.75 | 4.3 | 147.6 | 0.25 | 0.07 |
| 3-2 | F3 | 5.25 | 0.092 | 0.342 | 1.75 | 5.2 | 145.6 | 0.25 | 0.04 |
| 3-3 | F3 | 7.5 | 0.132 | 0.489 | 1.75 | 5.5 | 145 | 0.38 | 0.05 |
| 4-1 | F4 | 4.2 | 0.074 | 0.274 | 2.5 | 5 | 146.6 | 0.19 | 0.06 |
| 4-2 | F4 | 10.5 | 0.185 | 0.685 | 2.5 | 5 | 146 | 0.38 | 0.07 |
| 4-3 | F4 | 16.8 | 0.296 | 1.096 | 1.75 | 4.9 | 146.6 | 0.25 | 0.07 |
| 5-1 | F5 | 4 | 0.070 | 0.261 | 2 | 5 | 147.2 | 0.38 | 0.07 |
| 5-2 | F5 | 10.5 | 0.185 | 0.685 | 2.25 | 5.5 | 144.8 | 0.25 | 0.08 |
| 5-3 | F5 | 15 | 0.264 | 0.978 | 1.75 | 5.6 | 143.8 | 0.06 | 0.08 |
| 12-1 | F12 | 4 | 0.070 | 0.261 | 2 | 5.2 | 146.5 | 0.25 | 0.02 |
| 12-2 | F12 | 10 | 0.176 | 0.652 | 1.5 | 5.2 | 145.1 | 0.22 | 0.05 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 12-3 | F12 | 16 | 0.282 | 1.044 | 1.25 | 5 | 145.1 | 0 | 0.03 |

**Table 23. Summary of fresh properties recorded for mixtures with steel fibers (1 in. = 25.4 mm; 1 lb/yd$^3$ = 0.593 kg/m$^3$; 1 ml/cm$^2$ = 0.218 oz/in$^2$)**

| Mixture ID | Fiber ID | Fiber Dosage (lbs/yd$^3$) | Fiber Dosage (ft$^3$/yd$^3$) | Fiber Dosage (% concrete volume) | ASTM C143 Slump (in.) | ASTM C231 Plastic Air (%) | ASTM C138 Density (lb/yd$^3$) | AASHTO PP84 Edge-Slump (in.) | ASTM C232 Bleeding (ml/cm$^2$) |
|---|---|---|---|---|---|---|---|---|---|
| 6-1 | F6 | 24 | 0.049 | 0.182 | 3.25 | 5.2 | 146.6 | 0.44 | 0.08 |
| 6-2 | F6 | 60 | 0.123 | 0.454 | 3.5 | 5.6 | 146.4 | 0.55 | 0.10 |
| 6-3 | F6 | 96 | 0.196 | 0.727 | 4 | 5.5 | 145.6 | 0.19 | 0.10 |
| 7-1 | F7 | 20 | 0.041 | 0.152 | 3 | 5.2 | 147.3 | 0.25 | 0.07 |
| 7-2 | F7 | 40 | 0.082 | 0.304 | 3 | 3.5 | 150.6 | 0.69 | 0.11 |
| 7-3 | F7 | 60 | 0.123 | 0.457 | 2.75 | 3.7 | 151.6 | 0.38 | 0.11 |
| 8-1 | F8 | 20 | 0.044 | 0.162 | 3.25 | 3.6 | 150.8 | 0.25 | 0.14 |
| 8-2 | F8 | 40 | 0.087 | 0.323 | 2.75 | 3.5 | 151.4 | 0.25 | 0.09 |
| 8-3 | F8 | 60 | 0.131 | 0.485 | 3 | 3.8 | 150.8 | 0.25 | 0.10 |
| 9-1 | F9 | 35 | 0.071 | 0.264 | 1.5 | 3.9 | 151.1 | 0 | 0.04 |
| 9-2 | F9 | 57.5 | 0.117 | 0.434 | 1.5 | 3.7 | 152.1 | 0 | 0.05 |
| 9-3 | F9 | 80 | 0.163 | 0.604 | 1.75 | 3.8 | 151.8 | 0 | 0.04 |
| 10-1 | F10 | 7.5 | 0.015 | 0.057 | 2.25 | 5 | 148 | 0.31 | 0.04 |
| 10-2 | F10 | 12.5 | 0.025 | 0.094 | 3 | 4.6 | 147.8 | 0.37 | 0.06 |
| 10-3 | F10 | 17.5 | 0.036 | 0.132 | 3.25 | 5 | 147.6 | 0.5 | 0.06 |
| 11-1 | F11 | 20 | 0.041 | 0.151 | 2 | 3.9 | 149.1 | 0.31 | 0.05 |
| 11-2 | F11 | 40 | 0.082 | 0.302 | 3.75 | 5.9 | 147.3 | 0.37 | 0.04 |
| 11-3 | F11 | 60 | 0.122 | 0.453 | 2.5 | 6 | 145.1 | 0.25 | 0.05 |

## 9.2 Hardened Concrete Properties

### 9.1.1 Compressive Strength, Splitting Tensile Strength, and MOE

Table 24 and Table 25 summarize the average and standard deviation of compressive strength, splitting tensile strength, and MOE test results. Figure 23 thru Figure 28 show a comparison of average test values for each test between different fiber types and dosage levels. The dotted line shown in all figures represents the average test value recorded for the control mixture.

The results obtained from compressive strength evaluation of the FRC mixtures indicate that the fiber type and dosage could considerably influence the compressive strength of the mixture. Although in most cases the effect of fiber incorporation resulted in a slight decrease in compressive strength, there were instances that addition of fiber resulted in up to 25% reduction in the compressive strength. For example, a mixture made with a blend of synthetic macro and microfiber (F5) exhibited about 2,000 psi lower compressive strength even at low dosages, compared to that of control mixture. In addition, for majority of fiber types (excluding F1, F2, and F7), there was a slight improvement in average compressive strength value with increase in respective dosage levels from low to medium, and a further increase in in dosage level (medium to high) dropped the average compressive strength value. The observed trend in compressive strength results agrees with the earlier research on FRC cited in section 4.2.1 of this document. Data indicates that additional measures need to be considered from a concrete mixture design standpoint to compensate loss in compressive strength, if any, due to inclusion of fibers.

Similar observations can be made in splitting tensile test results, although, the number of FRC mixtures exhibiting an average tensile strength higher than that of the control mixture is higher compared to the respective number for compressive strength test results. This is likely due to the mechanism of failure involved in testing since the incorporation of fibers is expected to provide some residual strength after the development of concrete fracture. Figure 23 thru Figure 26 also indicate that the scatter in compressive and splitting tensile test results observed across different synthetic fiber types is relatively higher for synthetic fibers compared to steel fibers.

With respect to MOE test results, it can be observed that in most cases the mixtures made with steel fiber resulted in slightly improved MOE while on a few occasions less MOE was obtained compared to that of control mixture. On the other hand, generally less MOE could be expected when synthetic fibers are utilized.

Overall, the high variation observed in the strength and MOE test results lead to the conclusion that relationships between these properties and fiber characteristics cannot be effectively generalized.

**Table 24. Summary of strength and MOE results for control mixture and mixtures with synthetic fibers (SD = standard deviation; average strength results are rounded to nearest 10 psi; average MOE results are rounded to nearest 50 ksi; all standard deviation values are rounded to the nearest 10 units)**

| Mix ID | Fiber ID | Fiber Dosage (lbs/yd$^3$) | Fiber Dosage (ft$^3$/yd$^3$) | Fiber Dosage (% concrete volume) | ASTM C39 Compressive Strength, psi | | | | ASTM C496 Splitting Tensile Strength, psi | | | | ASTM C469 MOE, ksi | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 7 days | | 28 days | | 7 days | | 28 days | | 7 days | | 28 days | |
| | | | | | Average | SD | Average | SD | Average | SD | Average | SD | Average | SD | Average | SD |
| C | -- | -- | -- | -- | 5500 | 70 | 7870 | 65 | 600 | 15 | 805 | 20 | 4150 | 75 | 4900 | 85 |
| 1-1 | F1 | 3 | 0.053 | 0.196 | 6200 | 60 | 7910 | 105 | 620 | 10 | 800 | 15 | 4200 | 75 | 4950 | 75 |
| 1-2 | F1 | 13.5 | 0.238 | 0.881 | 5400 | 40 | 6810 | 75 | 685 | 20 | 870 | 20 | 4000 | 75 | 4200 | 30 |
| 1-3 | F1 | 30 | 0.528 | 1.957 | 5790 | 65 | 7000 | 115 | 740 | 15 | 980 | 20 | 3700 | 50 | 4400 | 30 |
| 2-1 | F2 | 3 | 0.053 | 0.196 | 6270 | 50 | 7950 | 55 | 680 | 40 | 860 | 30 | 4200 | 50 | 4800 | 60 |
| 2-2 | F2 | 5 | 0.088 | 0.326 | 6320 | 30 | 7450 | 45 | 740 | 10 | 830 | 35 | 4600 | 100 | 4800 | 50 |
| 2-3 | F2 | 7 | 0.123 | 0.457 | 6040 | 30 | 7470 | 25 | 730 | 15 | 890 | 20 | 4250 | 0 | 4700 | 75 |
| 3-1 | F3 | 4 | 0.070 | 0.261 | 5320 | 10 | 6760 | 60 | 550 | 20 | 785 | 20 | 4200 | 155 | 4600 | 60 |
| 3-2 | F3 | 5.25 | 0.092 | 0.342 | 6070 | 60 | 7550 | 65 | 640 | 15 | 770 | 25 | 4200 | 30 | 4950 | 60 |
| 3-3 | F3 | 7.5 | 0.132 | 0.489 | 5370 | 70 | 6680 | 100 | 560 | 20 | 795 | 15 | 4100 | 85 | 4650 | 30 |
| 4-1 | F4 | 4.2 | 0.074 | 0.274 | 5310 | 50 | 6890 | 75 | 585 | 10 | 820 | 20 | 4050 | 30 | 4450 | 75 |
| 4-2 | F4 | 10.5 | 0.185 | 0.685 | 5590 | 30 | 7070 | 55 | 620 | 15 | 780 | 15 | 3800 | 50 | 4350 | 50 |
| 4-3 | F4 | 16.8 | 0.296 | 1.096 | 5540 | 50 | 6870 | 100 | 625 | 25 | 815 | 25 | 4500 | 30 | 4400 | 30 |
| 5-1 | F5 | 4 | 0.070 | 0.261 | 5480 | 60 | 6130 | 25 | 570 | 20 | 740 | 30 | 4250 | 30 | 4300 | 30 |
| 5-2 | F5 | 10.5 | 0.185 | 0.685 | 5070 | 75 | 6250 | 65 | 480 | 20 | 715 | 15 | 4100 | 75 | 4400 | 30 |
| 5-3 | F5 | 15 | 0.264 | 0.978 | 5520 | 35 | 5930 | 75 | 550 | 20 | 740 | 15 | 3800 | 75 | 4200 | 60 |
| 12-1 | F12 | 4 | 0.070 | 0.261 | 5060 | 45 | 6430 | 45 | 550 | 20 | 610 | 25 | 4050 | 50 | 4500 | 30 |
| 12-2 | F12 | 10 | 0.176 | 0.652 | 5430 | 15 | 6540 | 70 | 580 | 20 | 680 | 25 | 4150 | 60 | 4650 | 75 |
| 12-3 | F12 | 16 | 0.282 | 1.044 | 5270 | 60 | 6270 | 65 | 570 | 15 | 600 | 25 | 3950 | 30 | 4350 | 30 |

**Table 25. Summary of strength and MOE results for mixtures with steel fibers (SD = standard deviation; average strength results are rounded to nearest 10 psi; average MOE results are rounded to nearest 50 ksi; all standard deviation values are rounded to the nearest 10 units)**

| Mix ID | Fiber ID | Fiber Dosage (lbs/yd$^3$) | Fiber Dosage (ft$^3$/yd$^3$) | Fiber Dosage (% concrete volume) | ASTM C39 Compressive Strength, psi | | | | ASTM C496 Splitting Tensile Strength, psi | | | | ASTM C469 MOE, ksi | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | 7 days | | 28 days | | 7 days | | 28 days | | 7 days | | 28 days | |
| | | | | | Average | SD | Average | SD | Average | SD | Average | SD | Average | SD | Average | SD |
| 6-1 | F6 | 24 | 0.049 | 0.182 | 5540 | 50 | 6830 | 65 | 485 | 15 | 735 | 30 | 3800 | 50 | 4600 | 50 |
| 6-2 | F6 | 60 | 0.123 | 0.454 | 5060 | 120 | 6900 | 105 | 505 | 15 | 735 | 20 | 4000 | 50 | 4550 | 50 |
| 6-3 | F6 | 96 | 0.196 | 0.727 | 5450 | 75 | 6720 | 60 | 530 | 15 | 690 | 20 | 4100 | 65 | 4400 | 50 |
| 7-1 | F7 | 20 | 0.041 | 0.152 | 5290 | 30 | 7500 | 65 | 550 | 15 | 770 | 20 | 4400 | 50 | 4800 | 75 |
| 7-2 | F7 | 40 | 0.082 | 0.304 | 5440 | 55 | 7380 | 80 | 540 | 15 | 870 | 20 | 4350 | 30 | 4650 | 175 |
| 7-3 | F7 | 60 | 0.123 | 0.457 | 5360 | 75 | 7400 | 15 | 535 | 20 | 815 | 15 | 4500 | 60 | 4800 | 0 |
| 8-1 | F8 | 20 | 0.044 | 0.162 | 5210 | 45 | 7580 | 65 | 565 | 25 | 855 | 30 | 4450 | 50 | 5200 | 50 |
| 8-2 | F8 | 40 | 0.087 | 0.323 | 5420 | 45 | 8220 | 70 | 550 | 20 | 905 | 20 | 4450 | 30 | 5150 | 75 |
| 8-3 | F8 | 60 | 0.131 | 0.485 | 5600 | 45 | 7800 | 95 | 545 | 15 | 820 | 30 | 4400 | 50 | 5000 | 75 |
| 9-1 | F9 | 35 | 0.071 | 0.264 | 5510 | 25 | 6760 | 30 | 560 | 20 | 780 | 30 | 4500 | 85 | 5000 | 115 |
| 9-2 | F9 | 57.5 | 0.117 | 0.434 | 5180 | 15 | 7050 | 85 | 540 | 20 | 825 | 20 | 4250 | 30 | 4900 | 235 |
| 9-3 | F9 | 80 | 0.163 | 0.604 | 5520 | 25 | 7040 | 65 | 535 | 20 | 780 | 30 | 4250 | 115 | 5150 | 145 |
| 10-1 | F10 | 7.5 | 0.015 | 0.057 | 5600 | 35 | 7210 | 15 | 575 | 10 | 765 | 20 | 4400 | 30 | 4800 | 50 |
| 10-2 | F10 | 12.5 | 0.025 | 0.094 | 6030 | 30 | 7650 | 80 | 625 | 15 | 755 | 30 | 4300 | 100 | 4750 | 115 |
| 10-3 | F10 | 17.5 | 0.036 | 0.132 | 5730 | 85 | 6830 | 235 | 600 | 10 | 730 | 25 | 4450 | 75 | 4800 | 100 |
| 11-1 | F11 | 20 | 0.041 | 0.151 | 5290 | 50 | 6870 | 65 | 550 | 5 | 760 | 10 | 4000 | 75 | 4250 | 175 |
| 11-2 | F11 | 40 | 0.082 | 0.302 | 5420 | 20 | 7070 | 60 | 620 | 20 | 785 | 20 | 4100 | 30 | 4250 | 30 |
| 11-3 | F11 | 60 | 0.122 | 0.453 | 5400 | 20 | 6660 | 90 | 610 | 15 | 745 | 10 | 4000 | 50 | 4250 | 60 |

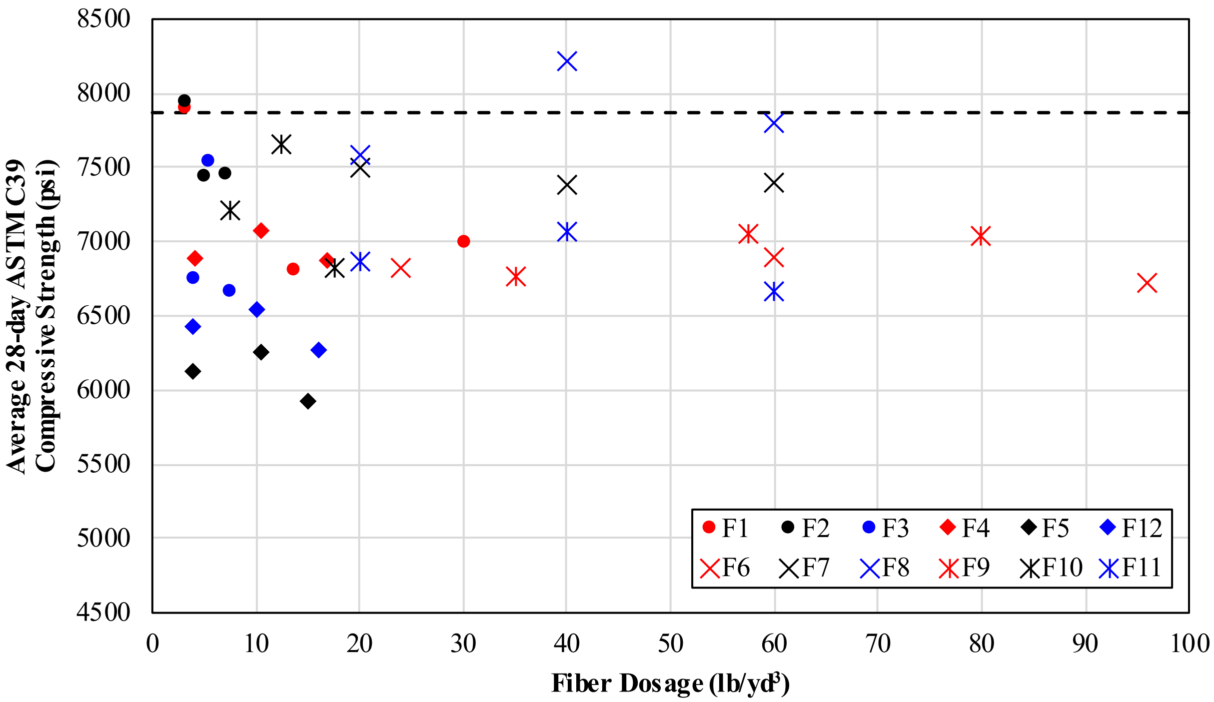

Figure 23. Effect of fiber type and fiber dosage (by weight) on 28-day compressive strength (ASTM C39) test results; the dotted line represents the control mixture without fibers

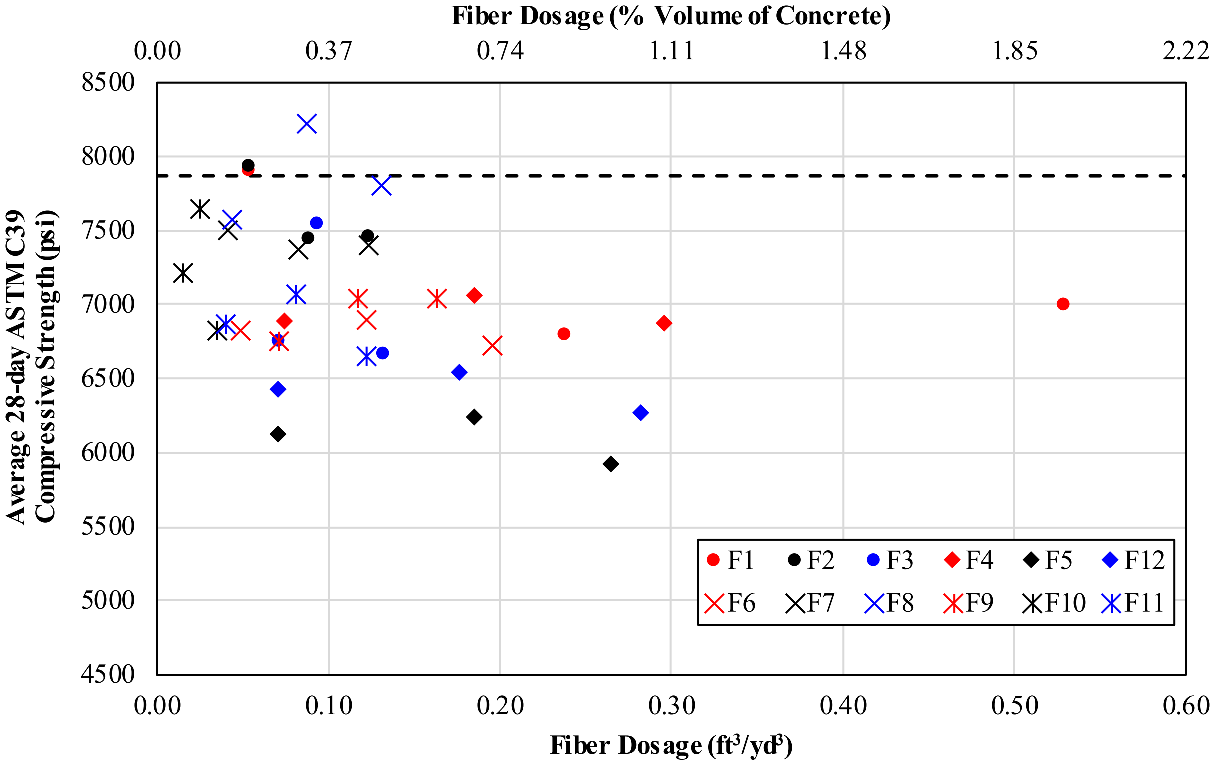

Figure 24. Effect of fiber type and fiber dosage by volume on 28-day compressive strength (ASTM C39) test results; the dotted line represents the control mixture without fibers

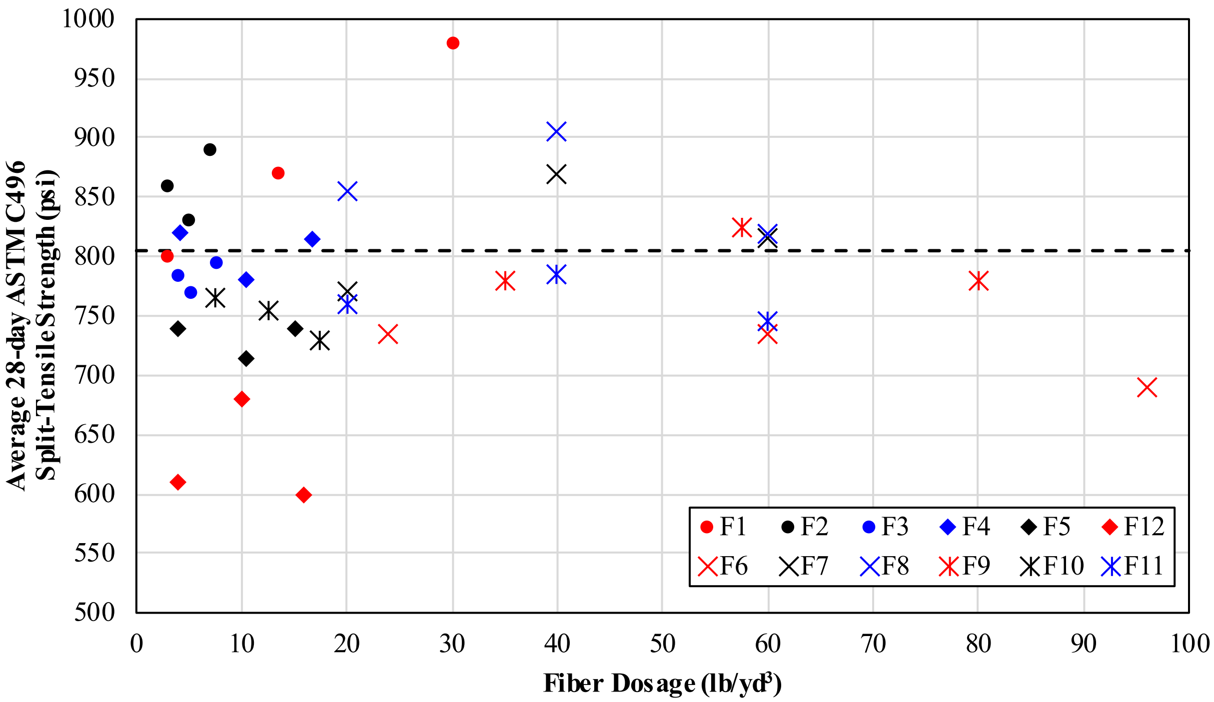

Figure 25. Effect of fiber type and fiber dosage (by weight) on 28-day split-tensile strength (ASTM C496) test results; the dotted line represents the control mixture without fibers

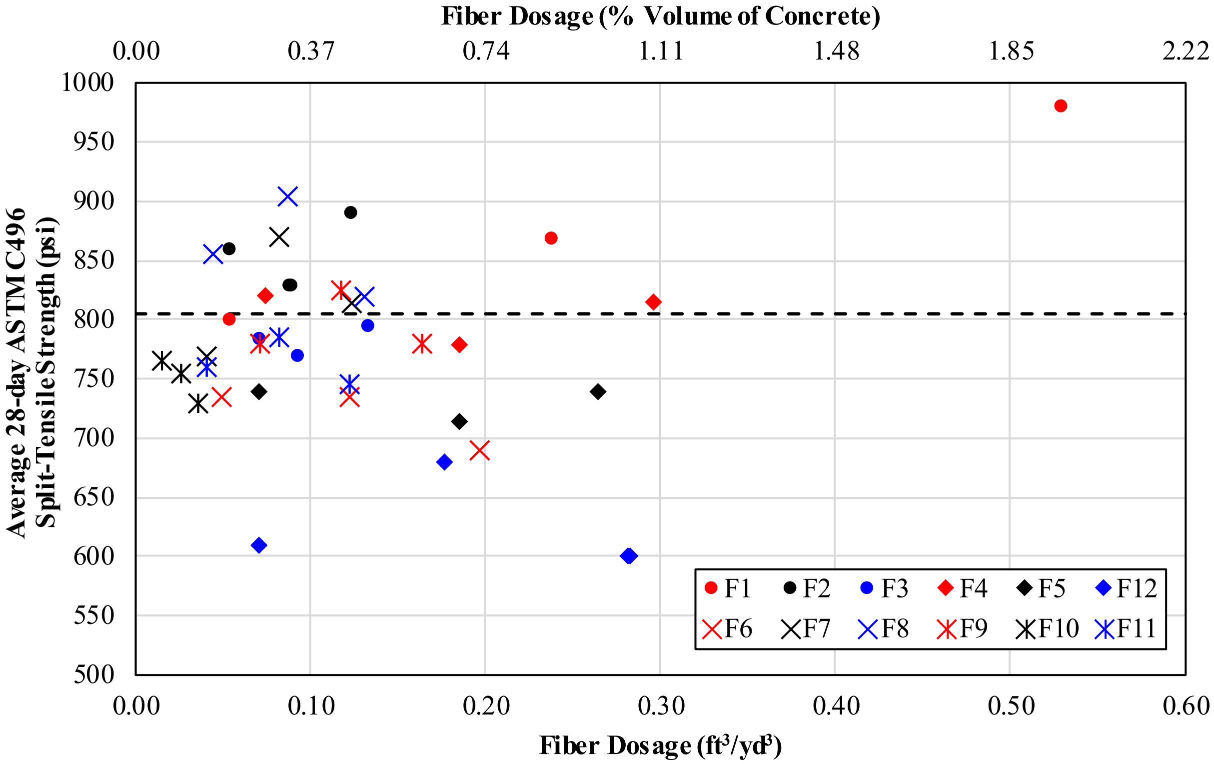

Figure 26. Effect of fiber type and fiber dosage (by volume) on 28-day split-tensile strength (ASTM C496) test results; the dotted line represents the control mixture without fibers

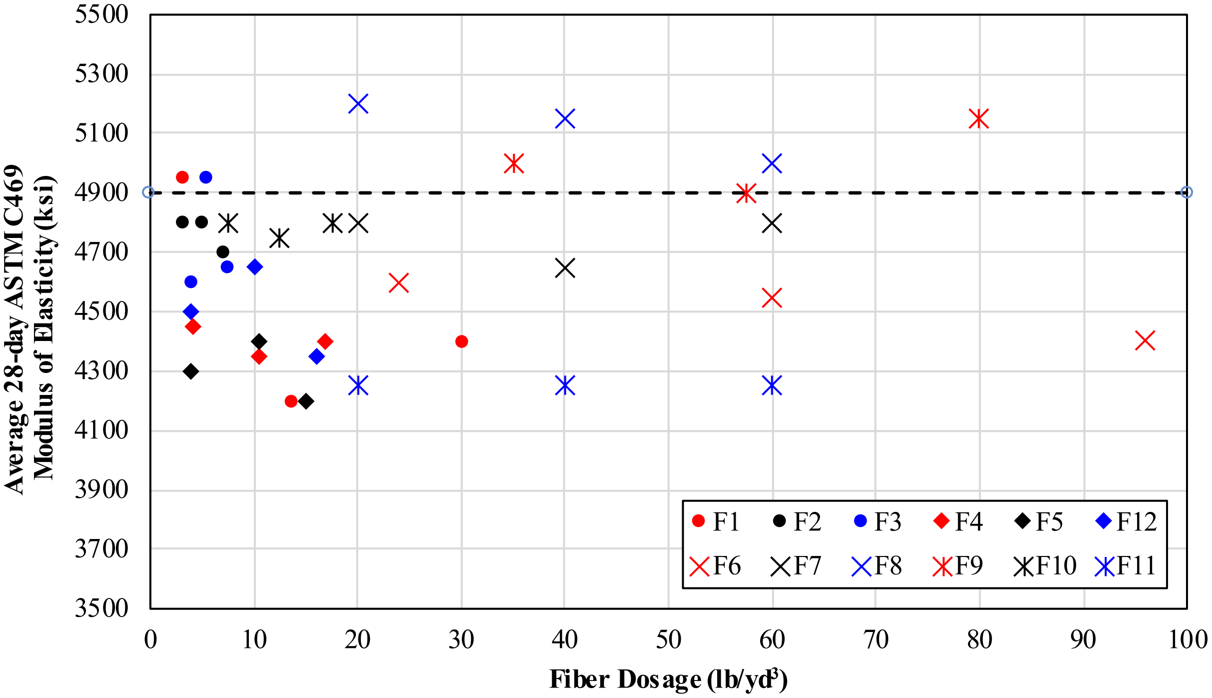

Figure 27. Effect of fiber type and fiber dosage (by weight) on 28-day MOE (ASTM C469) test results; the dotted line represents the control mixture without fibers

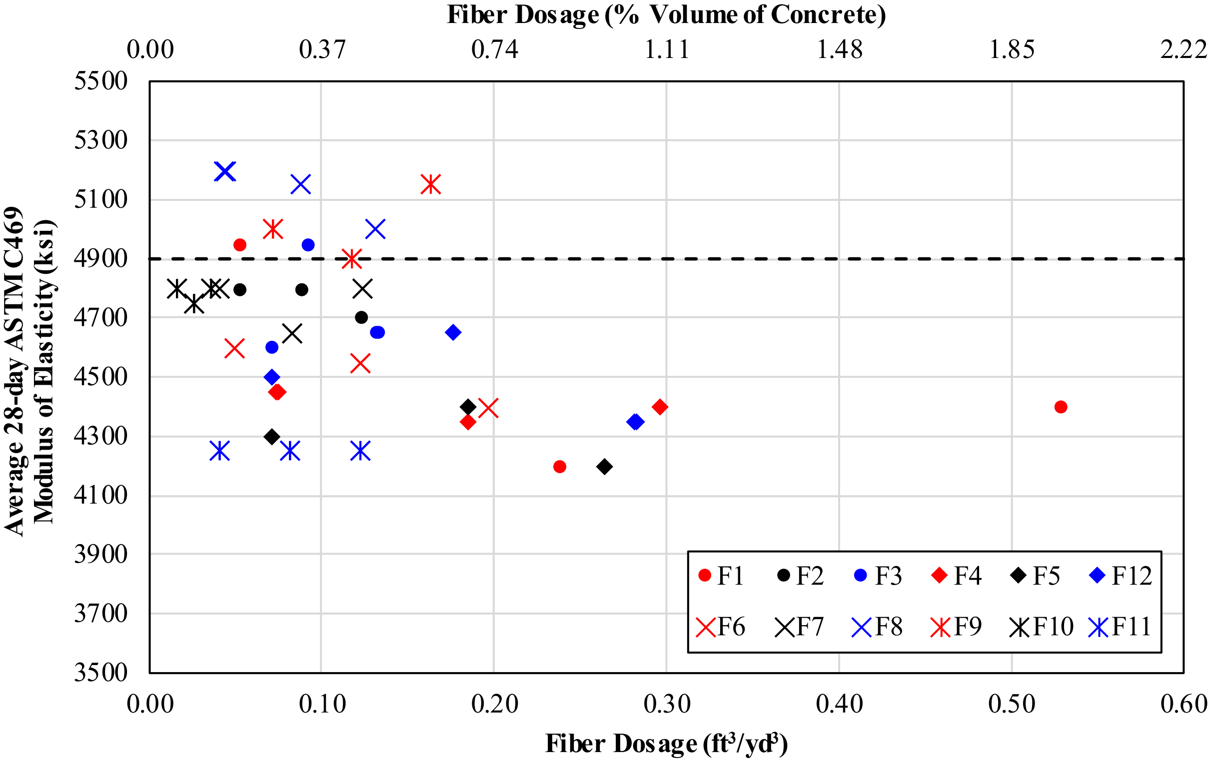

Figure 28. Effect of fiber type and fiber dosage (by volume) on 28-day MOE (ASTM C469) test results; the dotted line represents the control mixture without fibers

### 9.1.2 Resistivity, Unrestrained Shrinkage, Freeze-thaw Resistance, Salt Scaling Resistance, and Abrasion Resistance

This section reports results of tests that evaluate durability performance of concrete. An overview of test results for surface resistivity, unrestrained length change, freeze-thaw resistance, scaling, and abrasion resistance is provided in Table 26 and Table 27. Figure 29 thru Figure 33 represent the average test results as a function of mixture ID (shrinkage only), fiber type, and fiber dosage.

The effect of fiber type and dosage appeared to be minimal on the surface resistivity of the tested specimens except for specimens made with steel fibers F9, F10, and F11 fibers, where up to 40% reduction in surface resistivity was observed. The surface resistivity is predominantly affected by type and content of cementitious materials, and water-to-cementitious materials ratio, which remained consistent for all mixtures (except Mix 1-3). The observed reduction in surface resistivity, specifically with increasing dosage of steel fibers, is anticipated to occur due to conductivity of steel fibers and can vary with different types of steel [120].

Like the outcome on mechanical test results, no generalization could be made on the relationship between the fiber characteristics on unrestrained length change. However, at high dosage levels, mixtures with steel fibers seem to exhibit lower unrestrained shrinkage when compared to mixtures with synthetic fibers, which agrees with previous research in this area [121], [122].

It is recognized that the resistance of concrete to freezing and thawing (F-T) can be significantly improved by the intentional use of entrained air [123]. Given that all the fabricated specimens contained adequate air entrainment (~3-6%), an acceptable F-T resistance was expected. It can be observed that all mixtures exhibited an RDM of above 80% (see Table 26 and Table 27), which is an indication of excellent F-T resistance [124]. The slight variation in the results could be attributed to the actual air content.

The effect of fiber type and dosage on the salt-scaling resistance of FRC mixtures is shown in Figure 30 and Figure 31. The dotted line on the figures represents the average test result of the control mixture without fibers. It is evident that the incorporation of fiber regardless of the type and dosage considerably improved the scaling resistance of the mixtures. The control mixture exhibited a scaling mass loss of ~0.27 lb/ft$^2$ which is an indicator of a category four (4) scaling with moderate to severe scaling. The addition of fiber to the mixture decreased the scaling mass loss to slight to moderate scaling depending on the fiber characteristics. This improving effect of fibers on scaling resistance may be explained by the bridging effect of fibers that could reduce the rate of crack propagation and retard the performance deterioration of the concrete against salt scaling damage. Additionally, it is possible that the use of fiber improves the surface resistance against the surface tension induced through glue spalling, a salt scaling damage mechanism [125].

The effect of fiber type and dosage on the abrasion resistance of FRC mixtures is shown in Figure 32 and Figure 33. Nearly all FRC mixtures showed increased abrasion relative to the control mixture with no clear trend between fiber dosage and abrasion loss. That is, mixtures with some fiber types showed increased abrasion loss with increased fiber dosage while some exhibited reduced abrasion loss with increased fiber dosage. Some fiber types did not exhibit any trend between average abrasion and dosage. There is no precision and bias statement included in the underlying ASTM test method so evaluating the magnitude of the scatter in the results is difficult to quantify. While studies conducted by other researchers indicate that inclusion of fibers generally improve abrasion resistance [126], [127], this trend was not observed in this study. Based on our past experience with this test, this level of scatter (amongst all results) is typical, and the actual values obtained are indicative of average performing concrete.

**Table 26. Summary of resistivity, unrestrained drying shrinkage, freeze-thaw, salt scaling, and abrasion test results for control mixture and mixtures containing synthetic fibers (SD = standard deviation)**

| Mixture ID | Fiber ID | Fiber Dosage (lbs/yd$^3$) | Fiber Dosage (ft$^3$/yd$^3$) | Fiber Dosage (% concrete volume) | Average AASHTO T358 Surface Resistivity, kΩ-cm | 28-day dry ASTM C157 length change, % | | Average ASTM C666 RDM, % | Average ASTM C672 salt scaling, lb/ft$^2$ | Average ASTM C779 Depth of Wear, in. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Average | SD | | | |
| C | -- | -- | -- | -- | 10.5 | 0.04 | 0.003 | 96 | 0.282 | 0.026 |
| 1-1 | F1 | 3 | 0.053 | 0.196 | 9.5 | 0.043 | 0.003 | 97 | 0.060 | 0.019 |
| 1-2 | F1 | 13.5 | 0.238 | 0.881 | 8.3 | 0.046 | 0.002 | 97 | 0.124 | 0.032 |
| 1-3 | F1 | 30 | 0.528 | 1.957 | 9.1 | 0.053 | 0.001 | 97 | 0.074 | 0.023 |
| 2-1 | F2 | 3 | 0.053 | 0.196 | 8.9 | 0.039 | 0.001 | 97 | 0.053 | 0.030 |
| 2-2 | F2 | 5 | 0.088 | 0.326 | 8.8 | 0.034 | 0.002 | 97 | 0.076 | 0.029 |
| 2-3 | F2 | 7 | 0.123 | 0.457 | 9.0 | 0.047 | 0.004 | 97 | 0.060 | 0.027 |
| 3-1 | F3 | 4 | 0.070 | 0.261 | 9.0 | 0.046 | 0.001 | 98 | 0.063 | 0.033 |
| 3-2 | F3 | 5.25 | 0.092 | 0.342 | 9.8 | 0.042 | 0.002 | 98 | 0.027 | 0.036 |
| 3-3 | F3 | 7.5 | 0.132 | 0.489 | 9.5 | 0.043 | 0.001 | 98 | 0.025 | 0.043 |
| 4-1 | F4 | 4.2 | 0.074 | 0.274 | 9.5 | 0.043 | 0.001 | 98 | 0.053 | 0.050 |
| 4-2 | F4 | 10.5 | 0.185 | 0.685 | 9.2 | 0.050 | 0.003 | 98 | 0.044 | 0.036 |
| 4-3 | F4 | 16.8 | 0.296 | 1.096 | 9.1 | 0.042 | 0.001 | 98 | 0.055 | 0.042 |
| 5-1 | F5 | 4 | 0.070 | 0.261 | 9.1 | 0.043 | 0.002 | 98 | 0.057 | 0.043 |
| 5-2 | F5 | 10.5 | 0.185 | 0.685 | 9.4 | 0.053 | 0.001 | 98 | 0.053 | 0.034 |
| 5-3 | F5 | 15 | 0.264 | 0.978 | 9.7 | 0.052 | 0.001 | 98 | 0.068 | 0.023 |
| 12-1 | F12 | 4 | 0.070 | 0.261 | 8.3 | 0.046 | 0.003 | 98 | 0.094 | 0.028 |
| 12-2 | F12 | 10 | 0.176 | 0.652 | 8.0 | 0.046 | 0.003 | 98 | 0.087 | 0.029 |
| 12-3 | F12 | 16 | 0.282 | 1.044 | 8.9 | 0.043 | 0.001 | 98 | 0.093 | 0.028 |

**Table 27. Summary of resistivity, unrestrained drying shrinkage, freeze-thaw, salt scaling, and abrasion test results for mixtures containing steel fibers (SD = standard deviation)**

| Mixture ID | Fiber ID | Fiber Dosage (lbs/yd$^3$) | Fiber Dosage (ft$^3$/yd$^3$) | Fiber Dosage (% concrete volume) | Average AASHTO T358 Surface Resistivity, kΩ-cm | 28-day dry ASTM C157 length change, % | | Average ASTM C666 RDM, % | Average ASTM C672 salt scaling, lb/ft$^2$ | Average ASTM C779 Depth of Wear, in. |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Average | SD | | | |
| 6-1 | F6 | 24 | 0.049 | 0.182 | 10.0 | 0.039 | 0.002 | 96 | 0.137 | 0.042 |
| 6-2 | F6 | 60 | 0.123 | 0.454 | 10.6 | 0.041 | 0.001 | 96 | 0.144 | 0.038 |
| 6-3 | F6 | 96 | 0.196 | 0.727 | 8.6 | 0.040 | 0.002 | 96 | 0.145 | 0.029 |
| 7-1 | F7 | 20 | 0.041 | 0.152 | 8.8 | 0.037 | 0.003 | 95 | 0.179 | 0.030 |
| 7-2 | F7 | 40 | 0.082 | 0.304 | 11.2 | 0.032 | 0.002 | 96 | 0.180 | 0.023 |
| 7-3 | F7 | 60 | 0.123 | 0.457 | 11.7 | 0.040 | 0.001 | 96 | 0.185 | 0.027 |
| 8-1 | F8 | 20 | 0.044 | 0.162 | 8.9 | 0.034 | 0.003 | 96 | 0.142 | 0.028 |
| 8-2 | F8 | 40 | 0.087 | 0.323 | 11.1 | 0.032 | 0.001 | 96 | 0.153 | 0.029 |
| 8-3 | F8 | 60 | 0.131 | 0.485 | 11.7 | 0.034 | 0.002 | 96 | 0.160 | 0.030 |
| 9-1 | F9 | 35 | 0.071 | 0.264 | 7.8 | 0.043 | 0.002 | 96 | 0.059 | 0.034 |
| 9-2 | F9 | 57.5 | 0.117 | 0.434 | 5.9 | 0.044 | 0.003 | 96 | 0.066 | 0.030 |
| 9-3 | F9 | 80 | 0.163 | 0.604 | 6.7 | 0.048 | 0.004 | 96 | 0.067 | 0.035 |
| 10-1 | F10 | 7.5 | 0.015 | 0.057 | 6.3 | 0.044 | 0.002 | 96 | 0.109 | 0.037 |
| 10-2 | F10 | 12.5 | 0.025 | 0.094 | 5.5 | 0.043 | 0.003 | 96 | 0.111 | 0.038 |
| 10-3 | F10 | 17.5 | 0.036 | 0.132 | 5.0 | 0.042 | 0.003 | 96 | 0.129 | 0.045 |
| 11-1 | F11 | 20 | 0.041 | 0.151 | 6.0 | 0.049 | 0.002 | 96 | 0.067 | 0.043 |
| 11-2 | F11 | 40 | 0.082 | 0.302 | 5.5 | 0.047 | 0.001 | 96 | 0.070 | 0.038 |
| 11-3 | F11 | 60 | 0.122 | 0.453 | 5.2 | 0.044 | 0.002 | 96 | 0.070 | 0.025 |

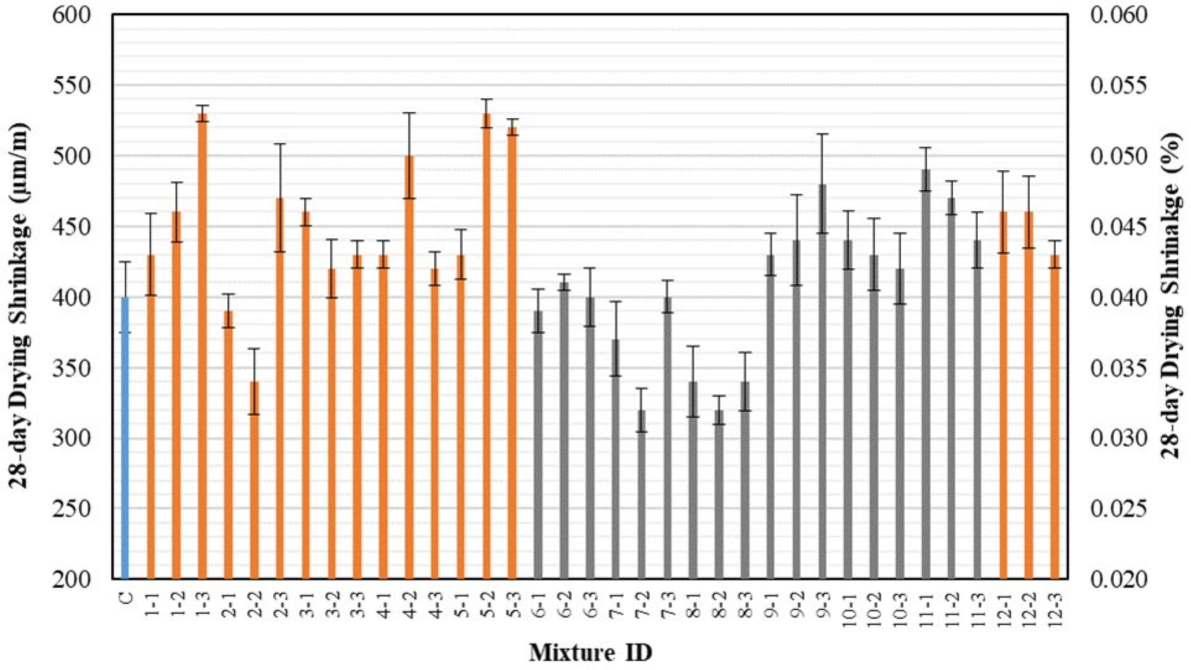

**Figure 29. Summary of length change test (ASTM C157) results recorded at the end of 28-day drying period**

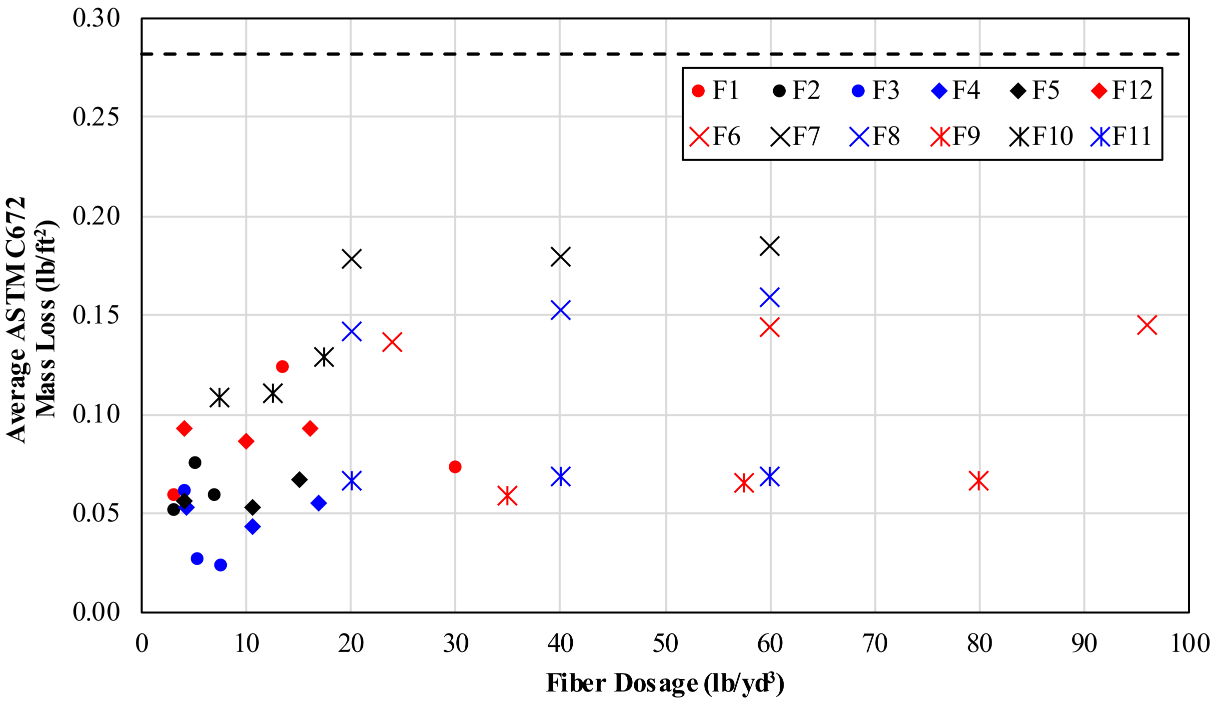

**Figure 30. Effect of fiber type and fiber dosage (by weight) on mass-loss due to scaling (ASTM C672)**

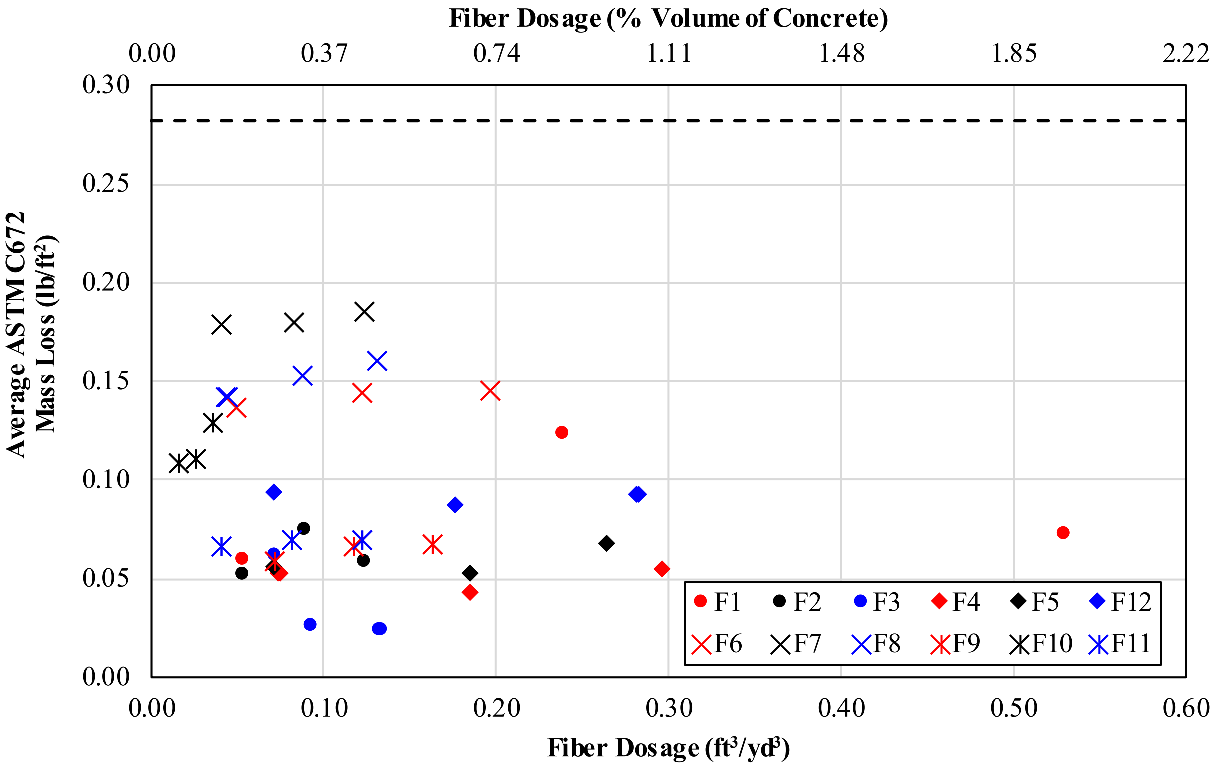

**Figure 31. Effect of fiber type and fiber dosage (by volume) on mass-loss due to scaling (ASTM C672); the dotted line represents the control mixture without fibers**

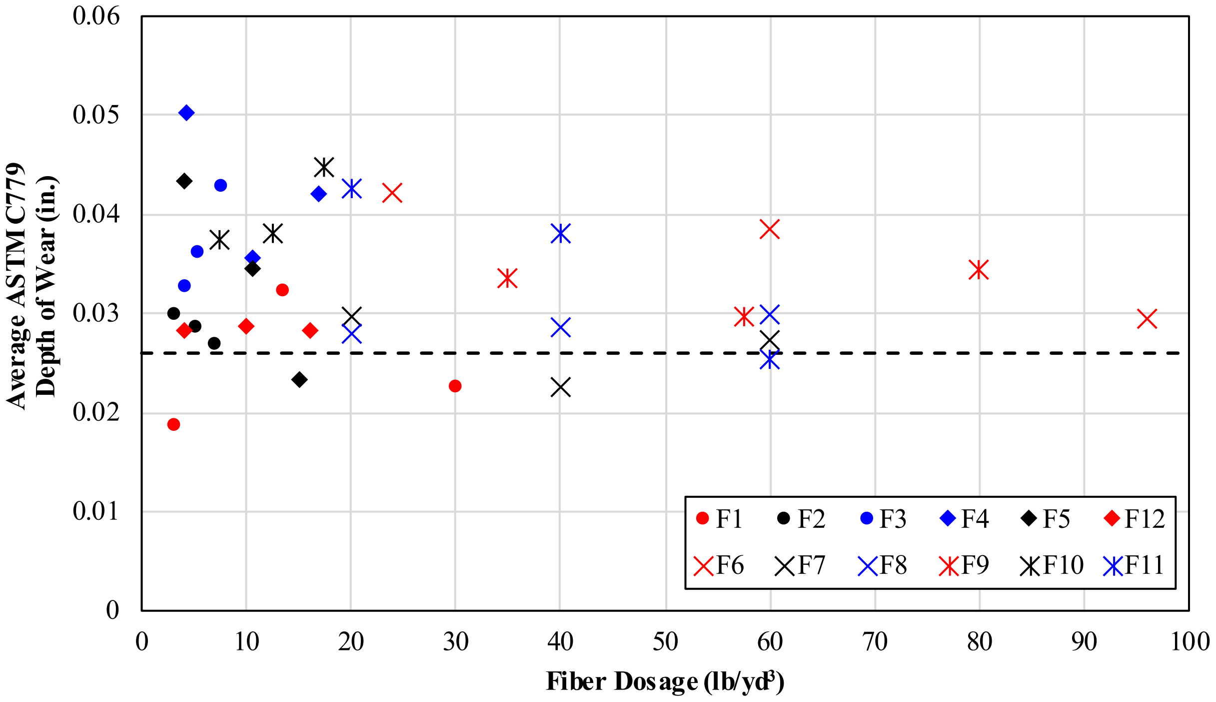

**Figure 32. Effect of fiber type and fiber dosage (by weight) on depth of wear due to scaling (ASTM C779); the dotted line represents the control mixture without fibers**

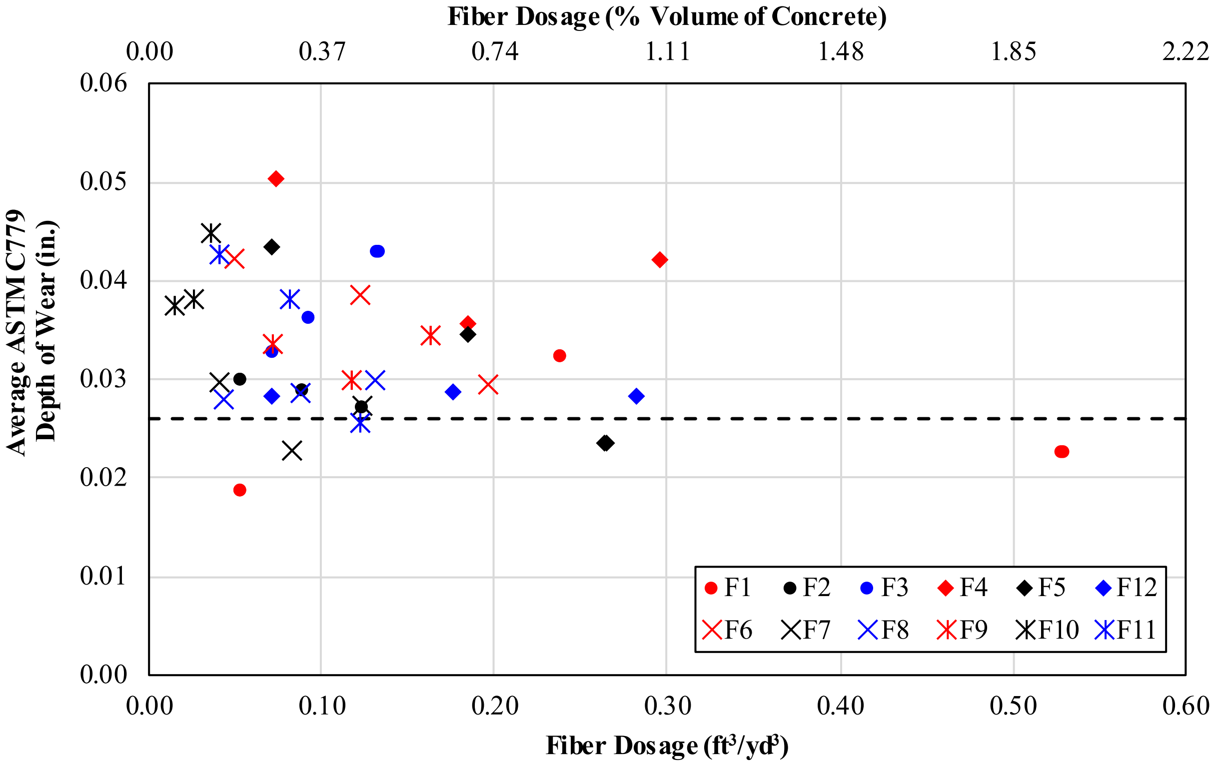

**Figure 33. Effect of fiber type and fiber dosage (by volume) on depth of wear due to scaling (ASTM C779); the dotted line represents the control mixture without fibers**

### 9.1.3 Flexural Toughness Evaluation (ASTM C1609)

The results of the ASTM C1609 testing are summarized in Table 28 (synthetic fibers) and Table 29 (steel fibers) and graphed on Figure 34 thru Figure 37. The dotted line on figures showing peak flexural strength results represents the average peak strength of control mixture without fibers evaluated through ASTM C78.

Fibers are expected to have limited impact on strength (assuming all other mixture parameters are held constant). Results shown in Figure 34 and Figure 35 indicated no generalized trend relationship between fiber characteristics or dosage levels on peak flexural strength. While data indicates that the inclusion of fibers can either slightly increase or decrease the peak flexural strength, this variation is found to be negligible for the fibers evaluated in this study.

Figure 36 and Figure 37 plot the flexural strength ratio values for each mixture as a function of fiber dosage. Results indicate that fiber type, shape and texture, and dosage can significantly affect the residual strength behavior of FRC, although, the effect of fiber dosage on residual strength is more pronounced compared to other fiber characteristics. This is evident from the good R-squared values (> 0.80) obtained from linear fitting of strength versus fiber dosage for each of the fiber categories (i.e., synthetic versus steel). It should also be noted that R-squared value for synthetic fiber category is greater than the corresponding value for steel fiber category This indicates that the level of influence of fiber shape and texture on relationship between flexural strength ratio and fiber dosage level is relatively higher in steel FRC mixtures compared to synthetic FRC mixtures. Data shown in the figures indicate that mixtures with deformed steel fibers (F10, F9, F8) generally exhibited higher flexural strength ratios compared to mixtures with undeformed steel fibers (F6, F7, F11)., whereas mixtures with fibrillated or embossed synthetic fibers exhibited higher flexural strength ratio values compared to mixtures with undeformed synthetic fibers. These trends align with findings of past research [57], [94].

When considering the plot of flexural strength ratio as a function of the fiber dosage on a volume basis (Figure 37), it can be seen that to achieve a given flexural strength ratio the steel fibers achieve the target flexural strength ratio value with a reduced volume fraction of fibers. This is evidenced by the steeper slope of the line (the linear fit slope value of 70.495) as compared to the synthetic fibers (with a liner fit slope value of 42.768). The weight dosage plot, Figure 36, makes the difference look more significant but by looking at the results on a volume fraction basis the impact of the different densities of the fiber materials is negated.

**Table 28. Summary of ASTM C1609 Test results for mixtures containing synthetic fibers (SD = standard deviation; the peak flexural strength for control mixture was evaluated per ASTM C78; NR = Not Registered due to punch-through failure)**

| Mixture ID | Fiber ID | Fiber Dosage (lbs/yd$^3$) | Fiber Dosage (ft$^3$/yd$^3$) | Fiber Dosage (% concrete volume) | ASTM C1609 Test Results | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Peak Flexural Strength, psi | | Flexural Strength Ratio, % | |
| | | | | | Average | SD | Average | SD |
| C | -- | -- | -- | -- | 818 | 21 | -- | -- |
| 1-1 | F1 | 3 | 0.053 | 0.196 | 892 | 46 | 11 | -- |
| 1-2 | F1 | 13.5 | 0.238 | 0.881 | 883 | 71 | 46 | 15 |
| 1-3 | F1 | 30 | 0.528 | 1.957 | 913 | 71 | 64 | 17 |
| 2-1 | F2 | 3 | 0.053 | 0.196 | 950 | 57 | NR | NR |
| 2-2 | F2 | 5 | 0.088 | 0.326 | 803 | 16 | 19 | 5 |
| 2-3 | F2 | 7 | 0.123 | 0.457 | 890 | 42 | NR | NR |
| 3-1 | F3 | 4 | 0.070 | 0.261 | 750 | 10 | 12 | 1 |
| 3-2 | F3 | 5.25 | 0.092 | 0.342 | 850 | 42 | 21 | 2 |
| 3-3 | F3 | 7.5 | 0.132 | 0.489 | 813 | 138 | 27 | 6 |
| 4-1 | F4 | 4.2 | 0.074 | 0.274 | 852 | 95 | 22 | 2 |
| 4-2 | F4 | 10.5 | 0.185 | 0.685 | 777 | 71 | 46 | 5 |
| 4-3 | F4 | 16.8 | 0.296 | 1.096 | 813 | 10 | 69 | 15 |
| 5-1 | F5 | 4 | 0.070 | 0.261 | 825 | 21 | 14 | -- |
| 5-2 | F5 | 10.5 | 0.185 | 0.685 | 770 | 35 | 29 | 4 |
| 5-3 | F5 | 15 | 0.264 | 0.978 | 772 | 53 | 37 | 19 |
| 12-1 | F12 | 4 | 0.070 | 0.261 | 777 | 15 | 11 | 3 |
| 12-2 | F12 | 10 | 0.176 | 0.652 | 810 | 44 | 24 | 5 |
| 12-3 | F12 | 16 | 0.282 | 1.044 | 777 | 32 | 38 | 6 |

**Table 29. Summary of ASTM C1609 Test results for mixtures containing steel fibers (SD = standard deviation; NR = Not Registered due to punch-through failure)**

| Mix ID | Fiber ID | Fiber Dosage (lbs/yd$^3$) | Fiber Dosage (ft$^3$/yd$^3$) | Fiber Dosage (% concrete volume) | ASTM C1609 Test Results | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Peak Flexural Strength, psi | | Flexural Strength Ratio, % | |
| | | | | | Average | SD | Average | SD |
| 6-1 | F6 | 24 | 0.049 | 0.182 | 823 | 15 | 17 | 6 |
| 6-2 | F6 | 60 | 0.123 | 0.454 | 810 | 10 | 38 | 5 |
| 6-3 | F6 | 96 | 0.196 | 0.727 | 807 | 57 | 34 | 10 |
| 7-1 | F7 | 20 | 0.041 | 0.152 | 765 | 82 | 10 | 3 |
| 7-2 | F7 | 40 | 0.082 | 0.304 | 845 | 83 | 17 | 2 |
| 7-3 | F7 | 60 | 0.123 | 0.457 | 828 | 130 | 25 | -- |
| 8-1 | F8 | 20 | 0.044 | 0.162 | 940 | 20 | NR | NR |
| 8-2 | F8 | 40 | 0.087 | 0.323 | 815 | 43 | 21 | 2 |
| 8-3 | F8 | 60 | 0.131 | 0.485 | 957 | 79 | 26 | 16 |
| 9-1 | F9 | 35 | 0.071 | 0.264 | 900 | 33 | 30 | 3 |
| 9-2 | F9 | 57.5 | 0.117 | 0.434 | 913 | 63 | 52 | 13 |
| 9-3 | F9 | 80 | 0.163 | 0.604 | 738 | 49 | 58 | 13 |
| 10-1 | F10 | 7.5 | 0.015 | 0.057 | 785 | 53 | 13 | 7 |
| 10-2 | F10 | 12.5 | 0.025 | 0.094 | 783 | 32 | 22 | 4 |
| 10-3 | F10 | 17.5 | 0.036 | 0.132 | 792 | 38 | 35 | 5 |
| 11-1 | F11 | 20 | 0.041 | 0.151 | 803 | 40 | 8 | 1 |
| 11-2 | F11 | 40 | 0.082 | 0.302 | 797 | 62 | 13 | 2 |
| 11-3 | F11 | 60 | 0.122 | 0.453 | 765 | 13 | 19 | 2 |

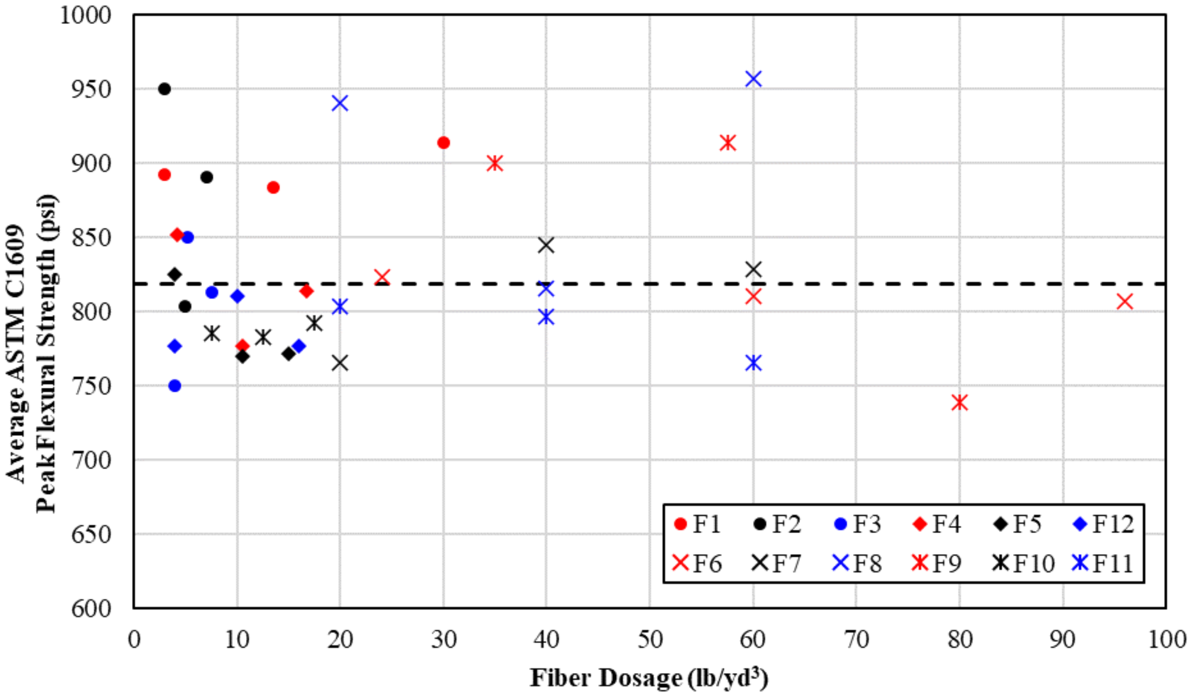

Figure 34. Effect of fiber type and fiber dosage (by weight) on peak flexural strength (ASTM C1609); the dotted line represents the control mixture without fibers

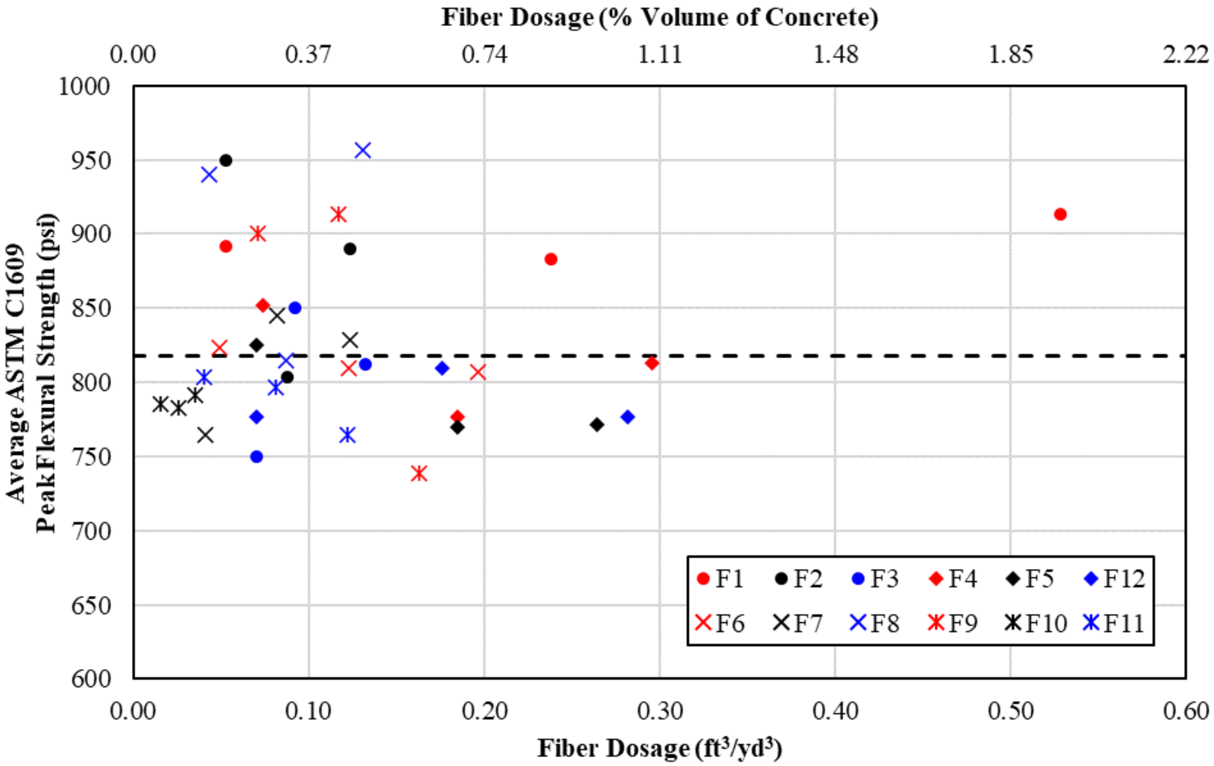

Figure 35. Effect of fiber type and fiber dosage (by volume) on peak flexural strength (ASTM C1609); the dotted line represents the control mixture without fibers

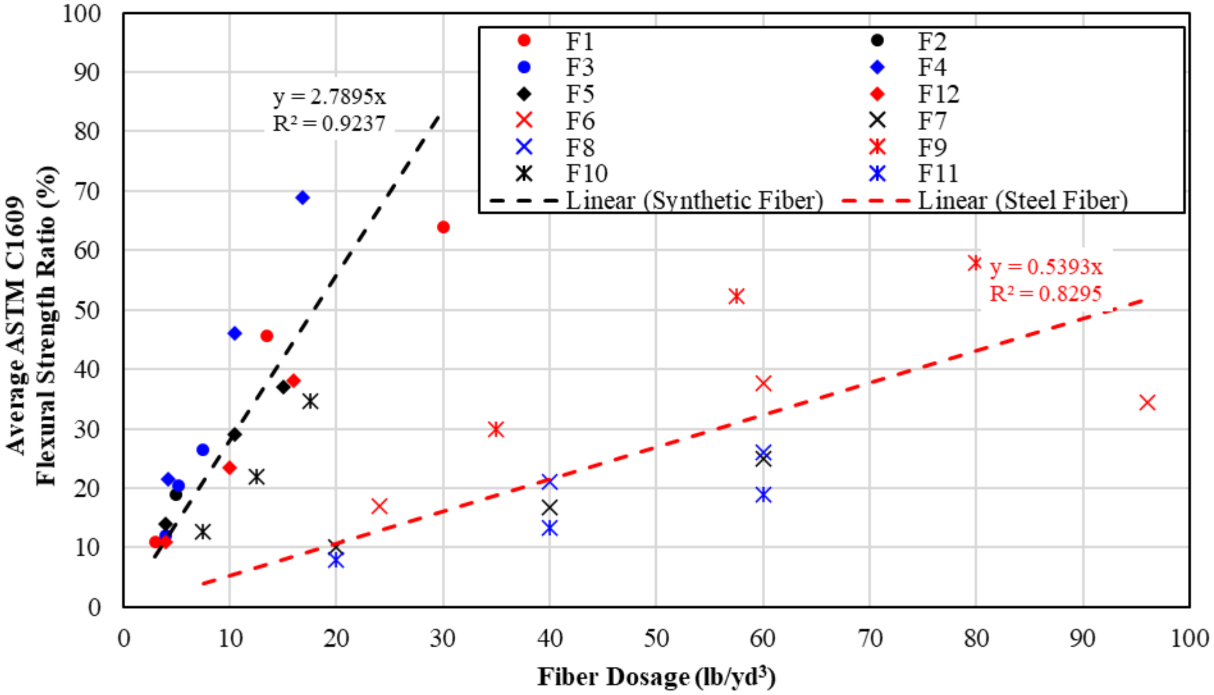

Figure 36. Effect of fiber type and fiber dosage (by weight) on flexural strength ratio (ASTM C1609)

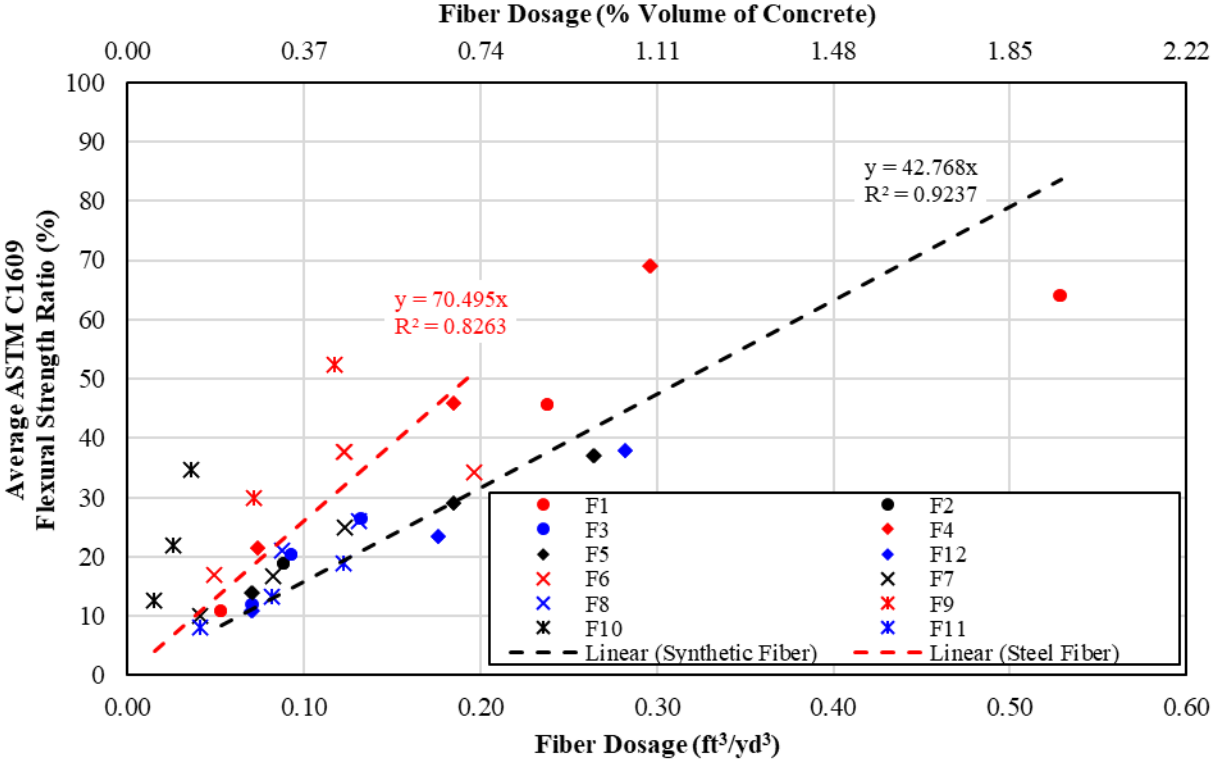

Figure 37. Effect of fiber type and fiber dosage (by volume) on flexural strength ratio (ASTM C1609); the reported trendline equations are based on fiber dosage by percent volume

**Figure 38** and **Figure 39** show the minimum fiber dosage required to achieve a residual strength of 20% or higher for different Fiber IDs considered in this study. On a weight basis, minimum dosage for synthetic fibers is estimated to range between 3.5 and 8 pounds per cubic yard of concrete, which correspond to 0.25% and 0.53% by concrete volume. For steel fibers, the minimum dosage is estimated to range between 11 and 64 pounds per cubic yard on a weight basis, or between 0.08% and 0.48% by concrete volume. It should be noted that steel fiber type F7 and F11 are melt extract fibers with no deformation, whereas the other steel fiber types include some type of deformation. Results indicate that the demand for deformed steel fiber is relatively less compared to the demand for undeformed steel fiber, to achieve a certain residual strength. Also, a comparison between the results of concrete mixtures containing deformed synthetic and deformed steel fibers (F5 versus F8 or F10) indicate that the volume of steel fibers required for achieving a 20% residual strength is lower compared to the corresponding volume of synthetic fibers, although this finding cannot be generalized among all fiber shapes and textures.

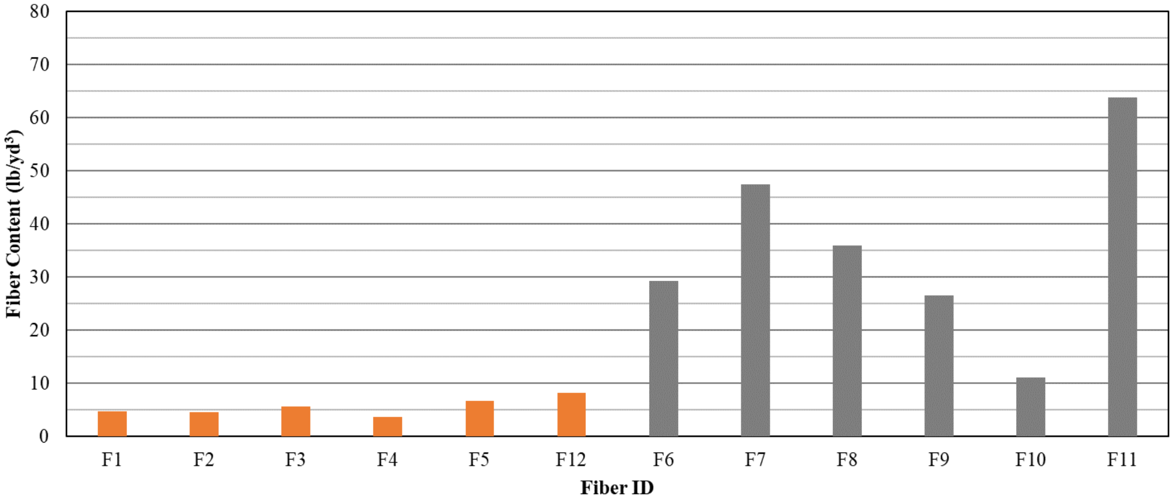

**Figure 38. Estimated fiber dosage by weight for different fiber types to achieve 20% residual strength (flexural strength ratio)**

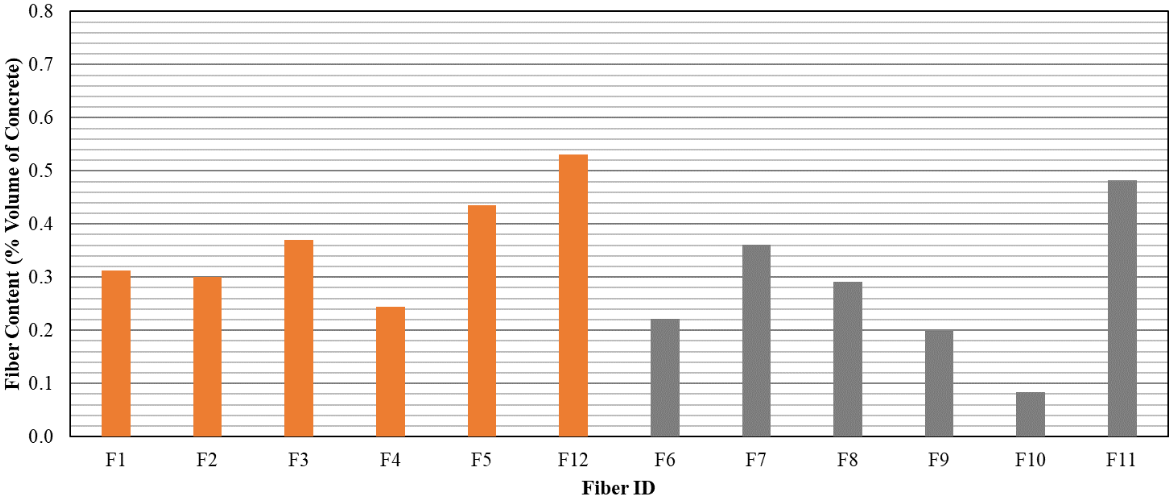

**Figure 39. Estimated fiber dosage by volume for different fiber types to achieve 20% residual strength (flexural strength ratio)**

### 9.1.4 Flexural Toughness Evaluation (ASTM C1550)

The results of the corrected peak load and flexural toughness (energy absorption) results, as evaluated by ASTM C1550, are included in Table 28 and Table 29, some of which are graphed on Figure 40 thru Figure 43.

No generalized relationship was observed between corrected peak load and fiber dosage levels since different fibers exhibited different behaviors. Although, mixtures with steel fibers seemed to exhibit slightly higher peak loads compared to mixtures with synthetic fibers, at a given dosage rate. The average peak load values generally ranged from 29 kN to 38 kN.

Table 28 and Table 29 include energy absorption values at four typically defined central deflection levels (5-, 10-, 20-, and 40-mm). For some mixtures with certain fibers (F6, F7, F8, F11) and dosage levels (generally at low dosages), test specimen failure occurred between the deflection range of 20- and 40-mm. Hence, the energy absorption at 40-mm deflection was not recorded for such specimens. Data reported in tables indicate that, irrespective of fiber type, an increase in fiber dosage rate increases the energy absorption values at each of the four deformation levels, while having little or no impact on peak load values. Because the trends observed between energy absorption values and fiber dosage levels are similar at all deflection levels, only the results of energy absorption at 20-mm deflection levels are graphically presented for brevity (Figure 42 and Figure 43). When looking at the results on fiber dosage by weight basis (Figure 42), it appears as though there is significant difference in the behavior of steel and synthetic fibers. However, when the same data is plotted on a fiber volume basis (Figure 43), the behavior of the steel fibers and the synthetic fibers are nearly identical. It is also worth noting that the conclusions drawn in the earlier section on the influence of fiber shape and texture on ASTM C1609 flexural toughness are also applicable for flexural toughness or energy absorption values estimated through ASTM C1550 testing.

**Table 30. Summary of ASTM C1550 test results for concrete mixtures containing synthetic fibers**

| Mixture ID | Fiber ID | Fiber Dosage (lbs/yd$^3$) | Fiber Dosage (ft$^3$/yd$^3$) | Fiber Dosage (% concrete volume) | ASTM C1550 Test Results | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Corrected Peak Load, N | | Corrected 5-mm absorption, J | | Corrected 10-mm absorption, J | | Corrected 20-mm absorption, J | | Corrected 40-mm absorption, J | |
| | | | | | Average | SD | Average | SD | Average | SD | Average | SD | Average | SD |
| 1-1 | F1 | 3 | 0.053 | 0.196 | 30 | 4.4 | 37 | 4.2 | 59 | 6.4 | 85 | 9.9 | 111 | 11.3 |
| 1-2 | F1 | 13.5 | 0.238 | 0.881 | 35 | -- | 98 | -- | 187 | -- | 305 | -- | 411 | -- |
| 1-3 | F1 | 30 | 0.528 | 1.957 | 29 | 0.6 | 121 | 0.7 | 248 | 4.2 | 440 | 4.2 | 659 | 14.8 |
| 2-1 | F2 | 3 | 0.053 | 0.196 | 38 | 1.7 | 45 | 3.3 | 67 | 2.4 | 95 | 2.7 | 118 | 2.0 |
| 2-2 | F2 | 5 | 0.088 | 0.326 | 31 | 0.5 | 48 | 2.1 | 93 | 5.4 | 166 | 6.3 | 239 | 11.0 |
| 2-3 | F2 | 7 | 0.123 | 0.457 | 29 | 0.3 | 47 | 1.5 | 95 | 3.0 | 178 | 6.9 | 267 | 6.3 |
| 3-1 | F3 | 4 | 0.070 | 0.261 | 30 | 0.5 | 36 | 2.9 | 54 | 1.9 | 83 | 2.1 | 118 | 10.8 |
| 3-2 | F3 | 5.25 | 0.092 | 0.342 | 31 | 0.2 | 41 | 5.0 | 65 | 12.5 | 103 | 24.5 | 147 | 38.5 |
| 3-3 | F3 | 7.5 | 0.132 | 0.489 | 32 | 0.6 | 71 | 0.5 | 119 | 1.4 | 181 | 1.7 | 236 | 4.1 |
| 4-1 | F4 | 4.2 | 0.074 | 0.274 | 29 | 0.1 | 42 | 3.0 | 71 | 5.7 | 115 | 9.3 | 163 | 7.5 |
| 4-2 | F4 | 10.5 | 0.185 | 0.685 | 30 | 0.2 | 68 | 1.4 | 136 | 1.8 | 227 | 0.6 | 327 | 5.4 |
| 4-3 | F4 | 16.8 | 0.296 | 1.096 | 33 | 3.0 | 111 | 9.8 | 225 | 18.4 | 393 | 27.2 | 577 | 33.8 |
| 5-1 | F5 | 4 | 0.070 | 0.261 | 31 | 1.3 | 37 | 1.1 | 61 | 2.5 | 103 | 4.6 | 161 | 5.6 |
| 5-2 | F5 | 10.5 | 0.185 | 0.685 | 32 | 1.6 | 62 | 1.6 | 120 | 9.7 | 214 | 21.6 | 328 | 32.5 |
| 5-3 | F5 | 15 | 0.264 | 0.978 | 32 | 1.2 | 90 | 6.2 | 176 | 6.1 | 301 | 14.5 | 429 | 80.2 |
| 12-1 | F12 | 4 | 0.070 | 0.261 | 31 | 2.2 | 40 | 0.7 | 58 | 2.0 | 90 | 3.8 | 128 | 1.1 |
| 12-2 | F12 | 10 | 0.176 | 0.652 | 33 | 2.3 | 55 | 2.2 | 96 | 6.9 | 164 | 10.5 | 249 | 16.6 |
| 12-3 | F12 | 16 | 0.282 | 1.044 | 31 | 1.4 | 80 | 6.4 | 160 | 16.7 | 296 | 34.4 | 490 | 56.0 |

**Table 31. Summary of ASTM C1550 test results for concrete mixtures containing steel fibers.**

| Mix ID | Fiber ID | Fiber Dosage (lbs/yd$^3$) | Fiber Dosage (ft$^3$/yd$^3$) | Fiber Dosage (% concrete volume) | ASTM C1550 Test Results | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Corrected Peak Load, N | | Corrected 5-mm absorption, J | | Corrected 10-mm absorption, J | | Corrected 20-mm absorption, J | | Corrected 40-mm absorption, J | |
| | | | | | Average | SD | Average | SD | Average | SD | Average | SD | Average | SD |
| 6-1 | F6 | 24 | 0.049 | 0.182 | 30 | -- | 36 | -- | 56 | -- | 77 | -- | -- | -- |
| 6-2 | F6 | 60 | 0.123 | 0.454 | 29 | 0.5 | 57 | 6.4 | 94 | 11.9 | 139 | 13.7 | 177 | 13.5 |
| 6-3 | F6 | 96 | 0.196 | 0.727 | 31 | 2.9 | 92 | 20.3 | 148 | 30.4 | 209 | 42.0 | 249 | 45.0 |
| 7-1 | F7 | 20 | 0.041 | 0.152 | 31 | 0.8 | 35 | 6.2 | 41 | 6.7 | 45 | 8.1 | -- | -- |
| 7-2 | F7 | 40 | 0.082 | 0.304 | 36 | 1.0 | 53 | 5.5 | 67 | 8.4 | 76 | 12.2 | -- | -- |
| 7-3 | F7 | 60 | 0.123 | 0.457 | 35 | 1.4 | 64 | 2.2 | 81 | 4.2 | 94 | 3.9 | -- | -- |
| 8-1 | F8 | 20 | 0.044 | 0.162 | 33 | 1.0 | 40 | 4.3 | 53 | 7.0 | 64 | 8.8 | -- | -- |
| 8-2 | F8 | 40 | 0.087 | 0.323 | 34 | 3.5 | 55 | 0.0 | 78 | 4.6 | 98 | 10.0 | 113 | 13.1 |
| 8-3 | F8 | 60 | 0.131 | 0.485 | 34 | 0.1 | 71 | 2.1 | 105 | 0.4 | 138 | 4.4 | 159 | 11.0 |
| 9-1 | F9 | 35 | 0.071 | 0.264 | 35 | 3.3 | 75 | 2.3 | 113 | 1.5 | 160 | 0.8 | 206 | 0.6 |
| 9-2 | F9 | 57.5 | 0.117 | 0.434 | 38 | 1.7 | 116 | 3.0 | 186 | 6.8 | 269 | 14.2 | 351 | 21.7 |
| 9-3 | F9 | 80 | 0.163 | 0.604 | 34 | 1.1 | 106 | 0.7 | 188 | 4.6 | 294 | 10.7 | 406 | 25.5 |
| 10-1 | F10 | 7.5 | 0.015 | 0.057 | 30 | 1.3 | 31 | 4.1 | 46 | 10.3 | 65 | 25.9 | 90 | 44.5 |
| 10-2 | F10 | 12.5 | 0.025 | 0.094 | 32 | 1.5 | 43 | 3.7 | 63 | 8.4 | 87 | 13.4 | 108 | 23.9 |
| 10-3 | F10 | 17.5 | 0.036 | 0.132 | 33 | 1.7 | 64 | 10.1 | 102 | 12.7 | 145 | 14.1 | 193 | 13.4 |
| 11-1 | F11 | 20 | 0.041 | 0.151 | 32 | 1.4 | 35 | 1.0 | 42 | 1.5 | 48 | 2.2 | -- | -- |
| 11-2 | F11 | 40 | 0.082 | 0.302 | 31 | 1.0 | 42 | 0.2 | 55 | 1.3 | 66 | 1.6 | 71 | 1.9 |
| 11-3 | F11 | 60 | 0.122 | 0.453 | 29 | 0.5 | 55 | 2.6 | 74 | 3.0 | 91 | 2.2 | 100 | 0.3 |

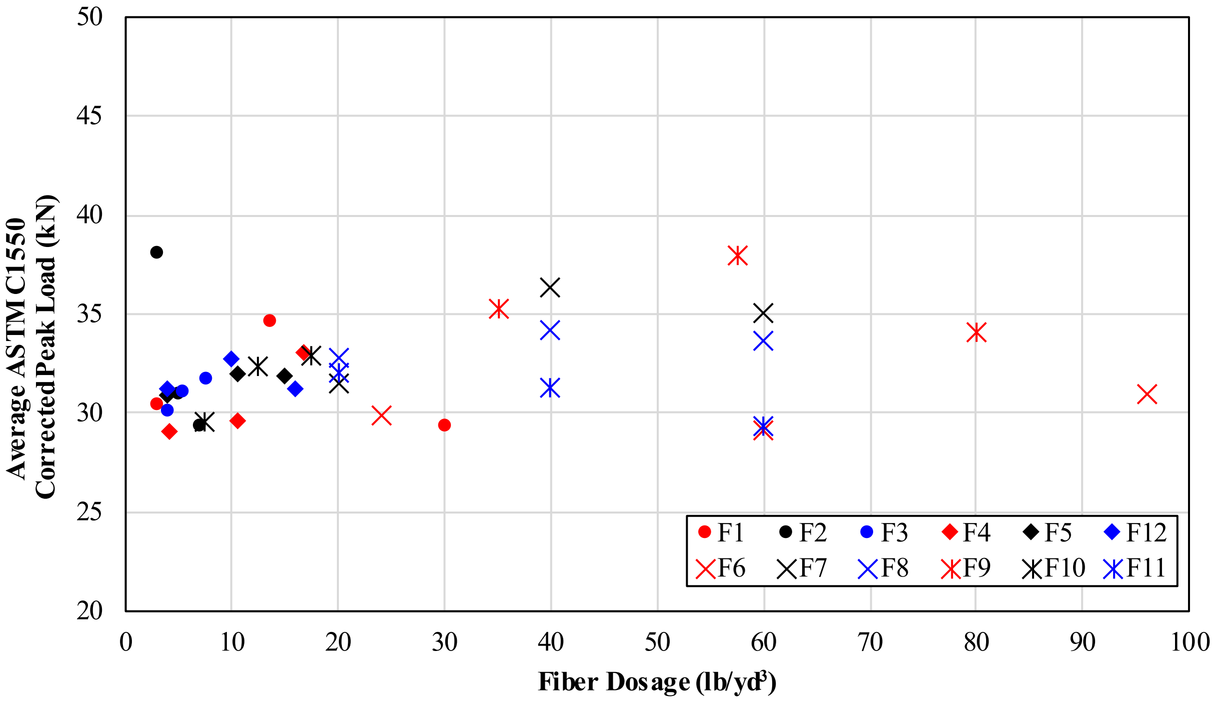

Figure 40. Effect of fiber type and fiber dosage (by weight) on peak load (ASTM C1550)

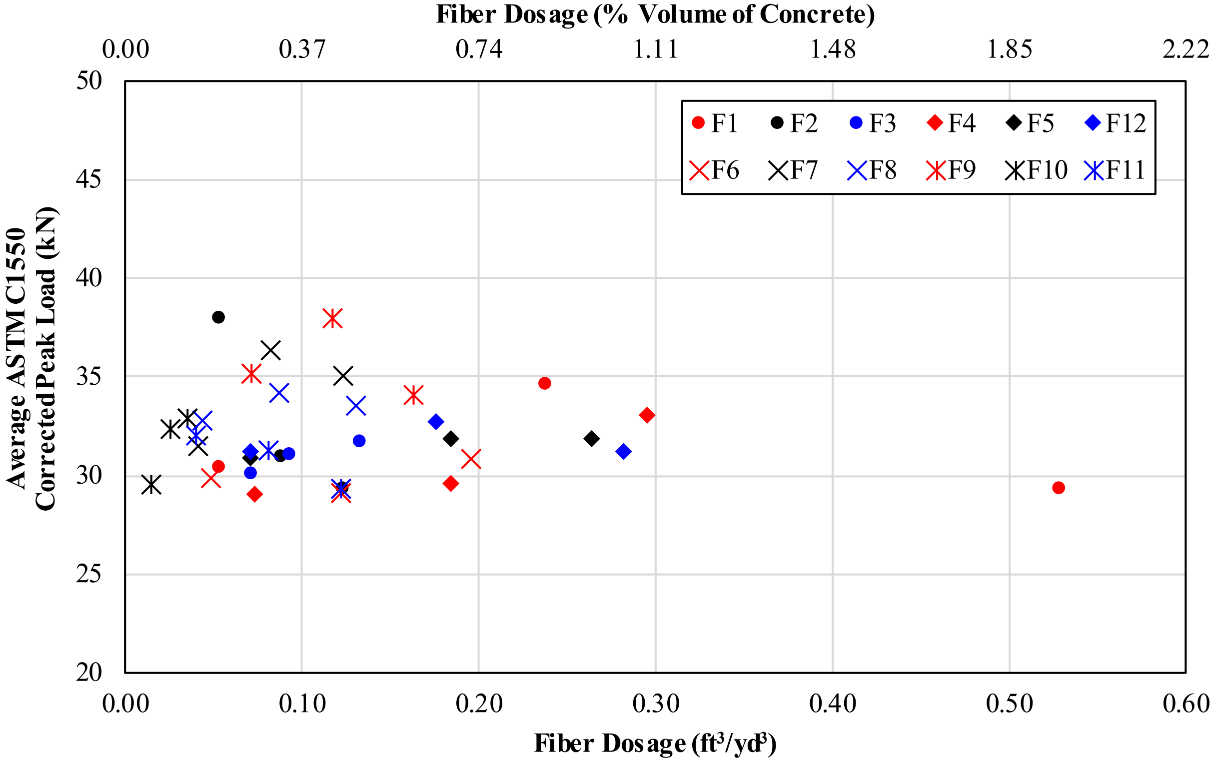

Figure 41. Effect of fiber type and fiber dosage (by volume) on peak load (ASTM C1550)

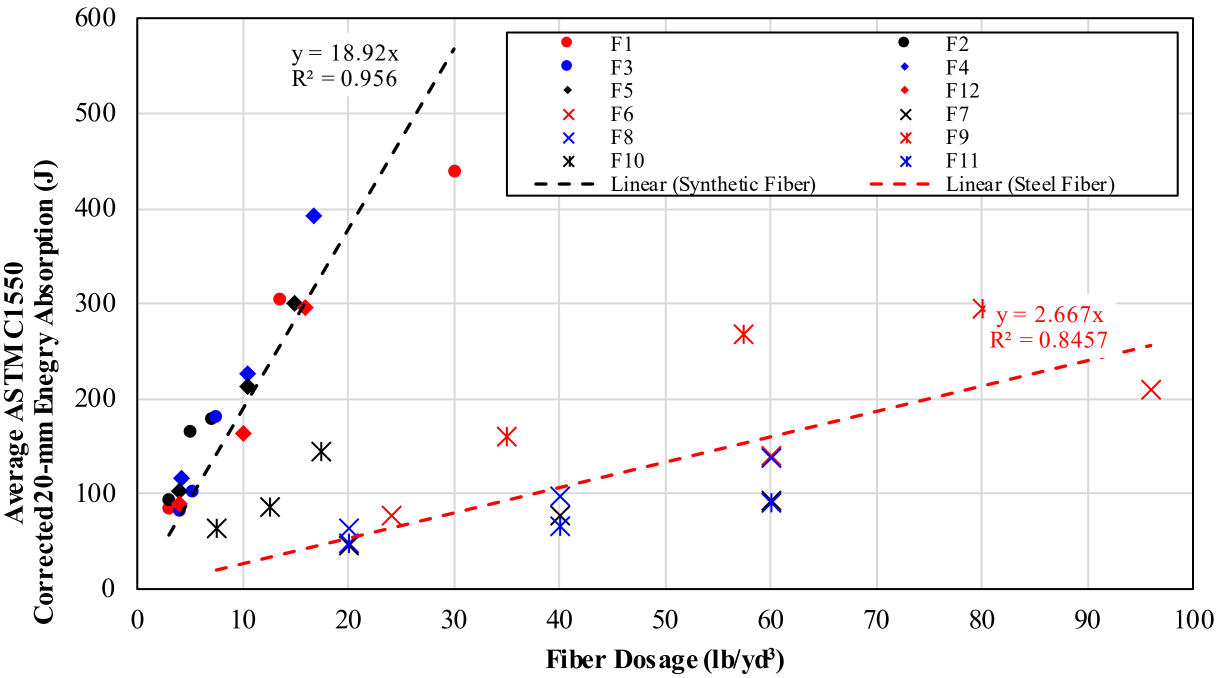

Figure 42. Effect of fiber type and fiber dosage (by weight) on flexural toughness at 20-mm deflection (ASTM C1550)

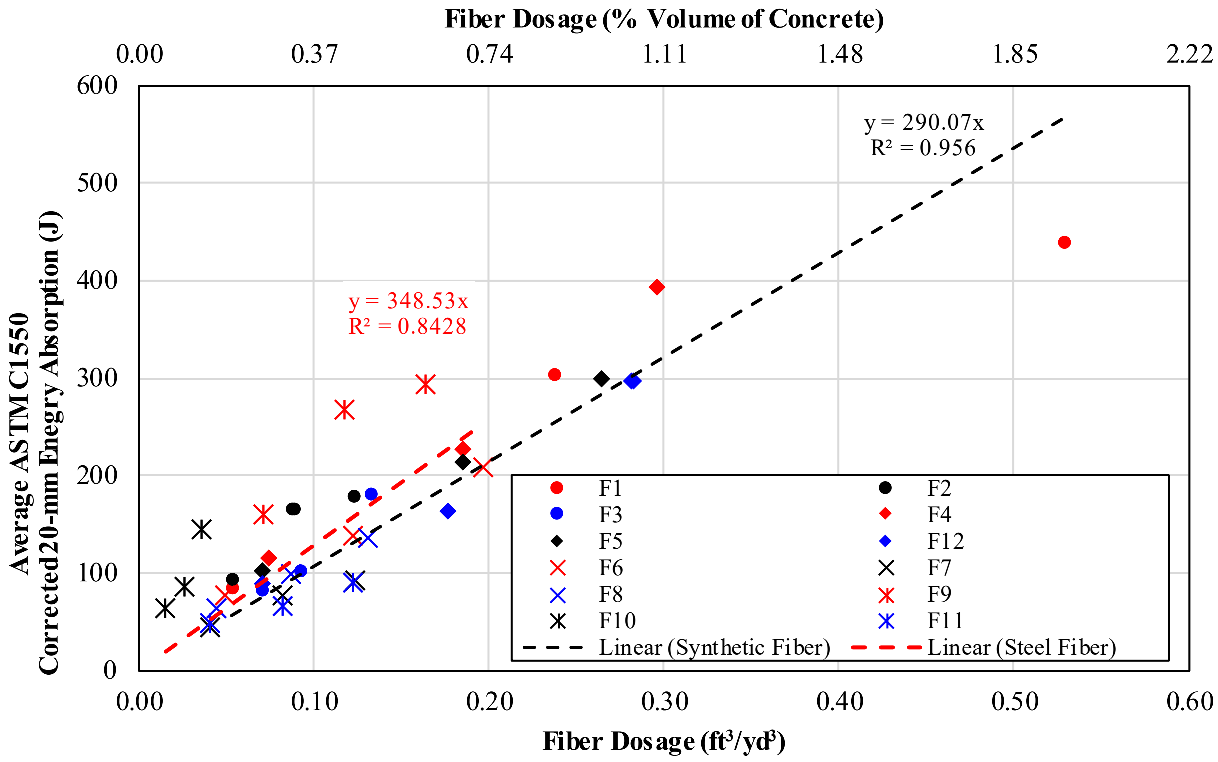

Figure 43. Effect of fiber type and fiber dosage (by volume) on flexural toughness at 20-mm deflection (ASTM C1550); the reported trendline equations are based on fiber dosage by percent volume

### 9.1.5 Comparison of C1609 and C1550 results

The comparison of the results from C1609 and C1550 are presented in Figure 44 thru Figure 46. As demonstrated by the trend lines and resulting linear equations there is very good agreement between the two test methods for the results pooled from the same fiber type (steel or synthetic). It should be noted that slopes of the trend lines can vary significantly, depending on the reference deflection value. One can also notice a good overlap between the data points from synthetic and steel FRC mixtures at 5-mm (Figure 42) and 10-mm (Figure 43) ASTM C1550 deflection levels. Whereas there is a noticeable gap between the bands of data points corresponding to each fiber type at 20-mm ASTM C1550 deflection level, which could also be inferred through significant difference in slopes of trend lines (Figure 44).

Because of the excellent correlations observed between ASTM C1609 and ASTM C1550 flexural toughness results, either of these test parameters can be ideally specified for evaluating FRC overlays. Although, ASTM C1609 testing is more commonly specified in project specifications or guidance documents, partly due to the incapability of many accredited testing laboratories in continental US to run ASTM C1550 testing.

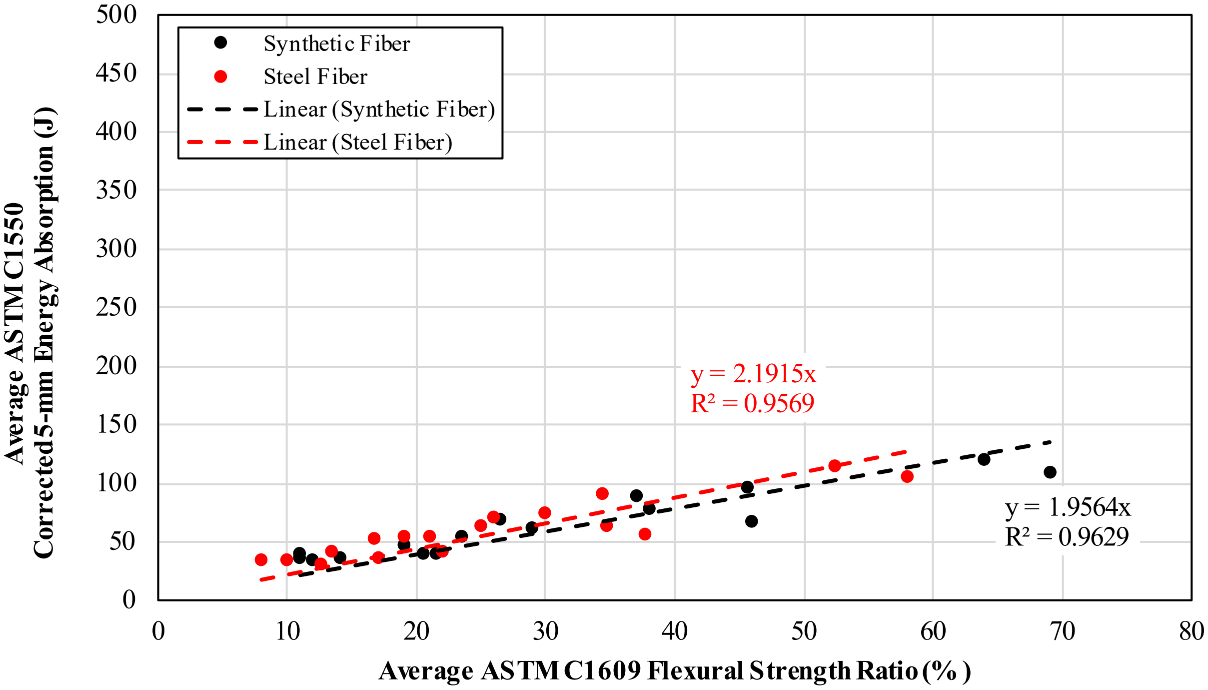

**Figure 44. Comparison of results between ASTM C1609 Flexural Toughness and 5-mm ASTM C1550 Energy Absorption**

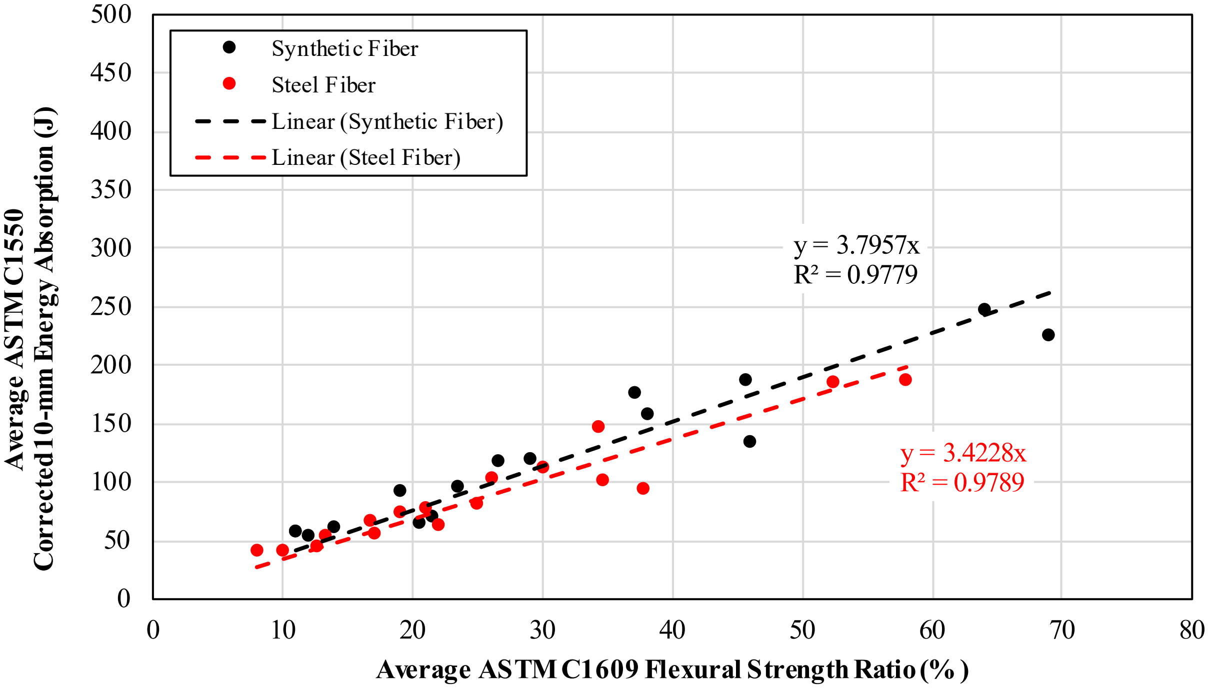

Figure 45. Comparison of results between ASTM C1609 Flexural Toughness and 10-mm ASTM C1550 Energy Absorption

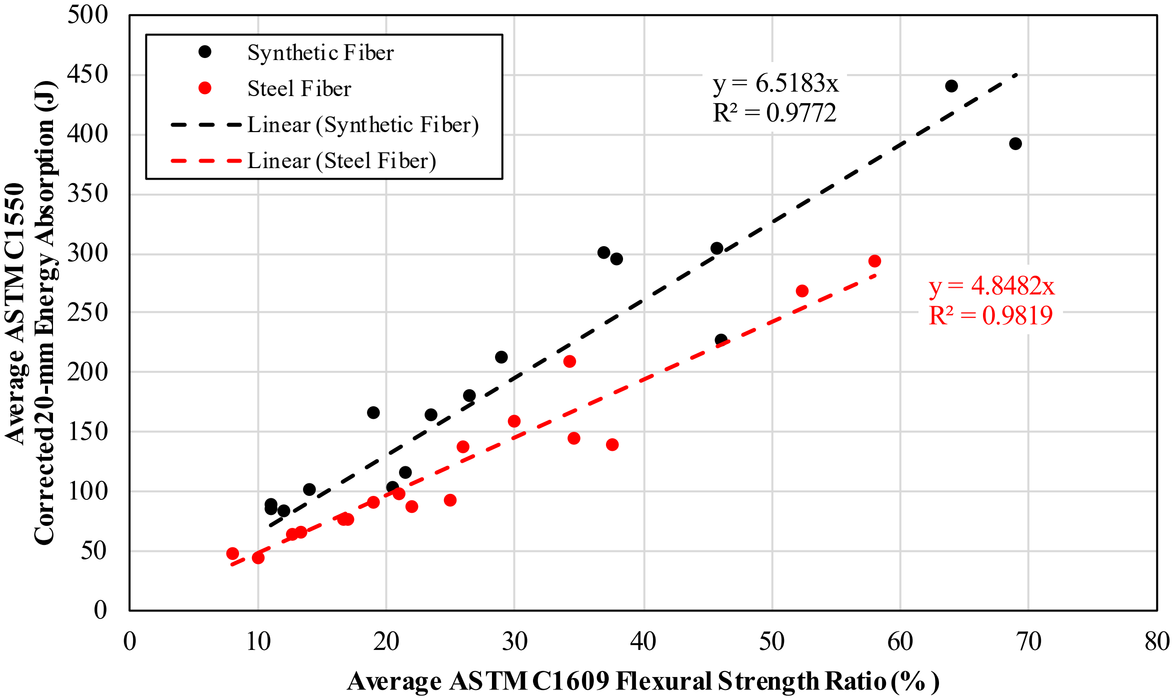

Figure 46. Comparison of results between ASTM C1609 Flexural Toughness and 20-mm ASTM C1550 Energy Absorption

### 9.1.6 Restrained Shrinkage (ASTM C1581) and Substrate Compatibility (ASTM C1583)

Based on the flexural toughness results discussed in the earlier sections, fibers F3 and F7, one fiber from each general category, were selected based on their performance (low compared to other fibers from same category). Five mixtures (Control, 3-1, 3-3, 7-1, 7-3) are each evaluated for restrained shrinkage and substrate compatibility, results of which are tabulated in Table 32 and Table 33, respectively. Figure 47 and Figure 48 show the average shrinkage strain values recorded for each test specimen as a function of testing age.

The low fiber content mixtures (3-1 and 7-1) performed comparably to the control with the control mixture cracking at 11.4 days, mixture 3-1 cracking at an average of 14 days and mixture 7-1 cracking at an average of 11.3 days. An increase in fiber content showed improvements in the restrained shrinkage cracking resistance, as expected, for both fiber types; mixture 3-3 exhibited cracking at 17.9 days, 19.9 days, and no cracking within 28 days. Mixture 7-3 also showed an improvement in cracking resistance with an average of 16.1 days to cracking across all three test specimens. An increase in average time to cracking because of increased fiber dosage rate has been reported to be associated with a reduction in absolute strain rate factor and a relaxation of absolute shrinkage strain [122], [128]. Data recorded from mixtures containing fibers F3 (synthetic) and F7 (steel fibers) is in general agreement with the literature.

A comparison of the pull-off strength test (ASTM C1583) results indicates that the average pull-off strength of an FRC is comparable to that of a control mixture with no fibers. Due to the limited number of tests conducted, meaningful conclusions on the effect of fiber type and dosage on pull-off strength could not be made. The recorded test results generally indicate that inclusion of fibers may influence (decrease based on the average test results) the compatibility of overlay with substrate, although this effect seems to be negligible. Results of the visual inspection of failure locations (typical failure locations shown in Figure 49) indicate that majority of the failures have occurred in the interface between overlay and adhesive, in overlay, or in substrate, indicating good interface compatibility between overlay and substrate.

**Table 32. Summary of ASTM C1581 Test Data**

| Mixture ID | Fiber Dosage (lbs/yd$^3$) / (% concrete volume) | Specimen ID | Time to Cracking, days | Initial Strain, $\varepsilon_o$ (x $10^{-6}$) | Maximum Strain, $\varepsilon_{max}$ (x $10^{-6}$) | Average Strain Rate Factor, $a_{avg}$ | Stress Rate (q), psi/day |
|---|---|---|---|---|---|---|---|
| Control | -- | A | 12.4 | 2.7 | -68.1 | -22.6 | 33.7 |
| | | B | 9.6 | 5.6 | -63.6 | -24.0 | 40.4 |
| | | C | 12.3 | 4.6 | -83.5 | -27.3 | 40.7 |
| | | Average | **11.4** | **4.3** | **-71.7** | **-24.6** | **38.3** |
| | | SD | **1.6** | **1.5** | **10.5** | **2.4** | **4.0** |
| 3-1 | (4) / (0.261) | A | 14.6 | -3.1 | -65.9 | -24.2 | 33.2 |
| | | B | 16.9 | 6.9 | -70.0 | -20.7 | 26.4 |
| | | C | 10.8 | 2.2 | -69.2 | -24.7 | 39.3 |
| | | Average | **14.1** | **2.0** | **-68.3** | **-23.2** | **32.9** |
| | | SD | **3.1** | **5.0** | **2.2** | **2.1** | **6.4** |
| 3-3 | (7.5) / (0.489) | A | 17.9 | 0.8 | -58.1 | -13.3 | 16.5 |
| | | B | No Crack | -5.1 | -55.9 | -13.7 | 13.6 |
| | | C | 19.9 | 3.2 | -58.0 | -15.0 | 17.6 |
| | | Average | **> 22** | **-0.4** | **-57.3** | **-14.0** | **15.9** |
| | | SD | **--** | **4.3** | **1.2** | **0.9** | **2.1** |
| 7-1 | (20) / (0.041) | A | 12.9 | 4.1 | -53.7 | -15.9 | 23.2 |
| | | B | 11.9 | 6.9 | -72.0 | -22.2 | 33.7 |
| | | C | 9.1 | -0.2 | -73.2 | -29.1 | 50.5 |
| | | Average | **11.3** | **3.6** | **-66.3** | **-22.4** | **35.8** |
| | | SD | **2.0** | **3.6** | **10.9** | **6.6** | **13.8** |
| 7-3 | (60) / (0.123) | A | 14.8 | -5.0 | -55.1 | -16.3 | 22.1 |
| | | B | 17.3 | -2.0 | -69.7 | -24.2 | 30.5 |
| | | C | 16.3 | 2.0 | -51.4 | -15.7 | 20.4 |
| | | Average | **16.1** | **-1.7** | **-58.8** | **-18.7** | **24.3** |
| | | SD | **1.2** | **3.5** | **9.7** | **4.8** | **5.4** |

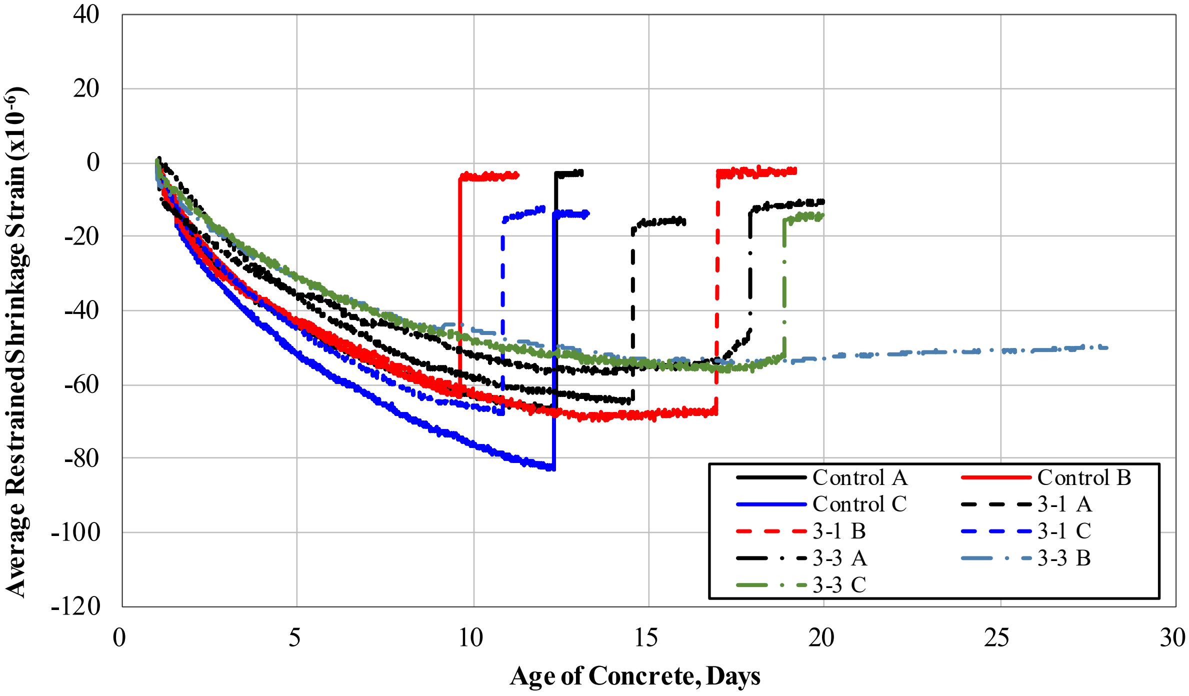

Figure 47. Comparison of restrained shrinkage test results between control, and 3-1 and 3-3 (synthetic fiber) mixtures

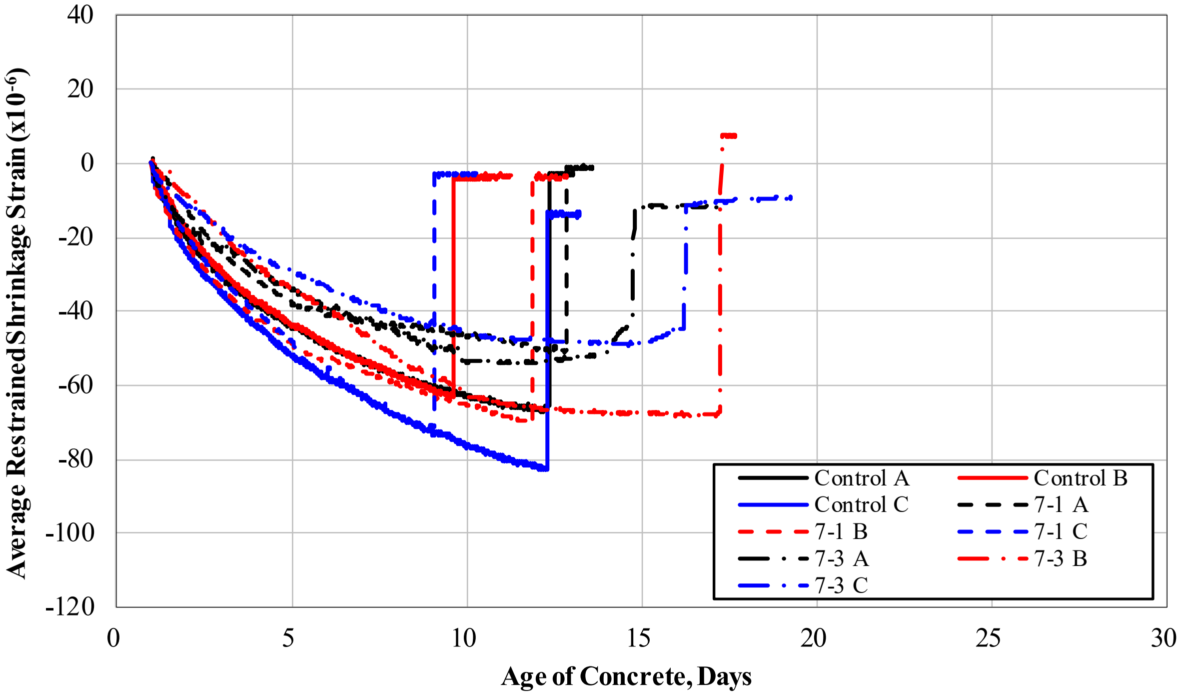

Figure 48. Comparison of restrained shrinkage test results between control, and 7-1 and 7-3 (steel fiber) mixtures

**Table 33. Summary of ASTM C1583 Test Data**

| Mixture ID | Specimen ID | Age of Concrete, days | Tensile Bond Strength, psi | Visual Inspection of Failure Mode (see Figure 45) |
|---|---|---|---|---|
| Control | A | 28 | 458.3 | 100% f |
| | B | 28 | 456.2 | 100% f |
| | C | 28 | 333.0 | 100% e |
| | Average | **--** | **415.8** | **--** |
| | SD | **--** | **71.7** | **--** |
| 3-1 | A | 28 | 407.8 | 60% c, 40% d |
| | B | 28 | 254.5 | 80% c, 20% d |
| | C | 28 | 339.9 | 90% c, 10% d |
| | Average | **--** | **334.1** | **--** |
| | SD | **--** | **76.8** | **--** |
| 3-3 | A | 28 | 468.6 | 100% e |
| | B | 28 | 439.6 | 100% e |
| | C | 28 | 258.2 | 100% f |
| | Average | **--** | **388.8** | **--** |
| | SD | **--** | **114.0** | **--** |
| 7-1 | A | 28 | 304.1 | 100% f |
| | B | 28 | 418.2 | 100% e |
| | C | 28 | 461.6 | 80% c, 20% d |
| | Average | **--** | **394.6** | **--** |
| | SD | **--** | **81.4** | **--** |
| 7-3 | A | 28 | 378.0 | 40% c, 60% d |
| | B | 28 | 353.3 | 40% c, 60% d |
| | C | 28 | 395.4 | 50% c, 50% d |
| | Average | **--** | **375.6** | **--** |
| | SD | **--** | **21.2** | **--** |

**Potential failure locations**

a. Interface between ‘Dolly’ and ‘Adhesive’
b. Adhesive
c. Interface between ‘Adhesive’ and ‘Overlay Concrete’
d. Overlay Concrete
e. Interface between 'Overlay Concrete' and 'Substrate Concrete'
f. Substrate Concrete

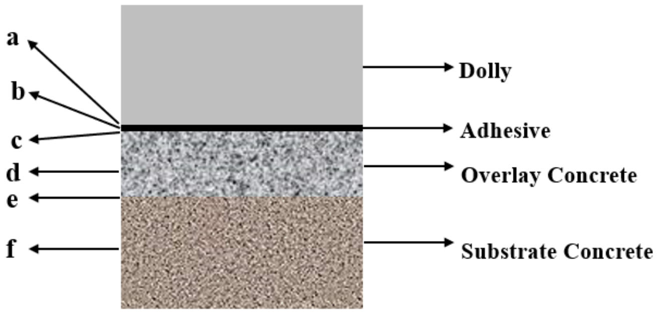

Figure 49. Typical failure locations for ASTM C1583 test specimen

# 10. CONCLUSION AND RECOMMENDATIONS

In this study CTLGroup evaluated the specification, qualification, placement, and performance of FRC overlays for bridge deck applications. The primary objective of this study was to help establish a set of best practices related to FRC overlays. To achieve this objectives, three thrusts were pursued in the present study: (1) a literature review, to establish the state of the art in FRC overlay technology, (2) a survey of state DOT officials to learn the breadth of FRC overlay materials practices across the country, and (3) an experimental program conducted at CTLGroup's laboratories, to evaluate the performance of a spectrum of steel and synthetic fiber types in a range of standard tests.

Survey results show varied experiences with the use of fibers across the country.

1. Although the use of steel and synthetic fibers is used in many states, where there are states that stipulate a specific fiber type, they more often stipulate synthetic. Some states that allow steel stipulate the uses of stainless-steel fibers. These limitations are likely a result of prior experience and a potentially bad result on one or more projects. The experience of other states and review of literature and research shows that either fiber type (synthetic or steel) can lead to successful projects and that it is not necessary to stipulate stainless steel when using steel fibers.
2. Some states have identified other means of reducing cracking in overlays, particularly the use of latex modified concrete.
3. Most states provided feedback about concerns with fiber balling / clumping, and many provided language in their specifications to caution against this phenomenon and require demonstration of an ability to avoid this drawback of incorporation of fibers in concrete.

The experimental research conducted at CTLGroup yielded a number of notable outcomes:

1. In general, fiber reinforcement at the dosages considered has a relatively small impact on strength and modulus of elasticity behavior of concrete. This result is not unexpected and is supported by prior studies in the literature.
2. The incorporation of fiber reinforcement at the dosages considered had little impact on overall durability of concrete and its resistance to freeze thaw induced damage or scaling.
3. ASTM C1609 has been used widely as a qualification specification for FRC overlays. The testing conducted at CTLGroup, as well as other studies [Banthia study], has revealed the limitations of this test for low fiber dosages. Below dosages of 0.5% and more prominently below 0.25%, CTLGroup observed punching style failure due to the relatively large depth to span ratio of the test specimen. For low fiber dosages, it may be preferable to use ASTM C1550 or another qualification in place of C1609.
4. Restrained shrinkage cracking tests via ring tests (ASTM C1581) showed that increasing fiber volumes yielded increases in time to cracking due to shrinkage, which is an expected result. The low fiber dosages didn't show significant increase in time to cracking over the control mixture. As a result, higher fiber dosages should be considered to improve resistance to moisture and chloride ingress to the underlying substrate materials.
5. Bond testing with FRC is a challenge due to the size of the pull off specimen relative to the fiber length. One must either cut the specimen to the size of the dolly and thereby severe fibers in the process, or test without the coring operation and expect some bridging of stress and a conical load path. Fibers themselves, so long as the mixture is proportioned well to avoid clumping or fiber balling, should have minimal impact on bond and bond should be evaluated on the representative mixture but without fibers to properly evaluate the bond of the mixture and rely on the bridging action of fibers reducing the likelihood of debonding.

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