MnDOT Contract, No. 1003325, Work Order No. 56

NRRA Long-term Research Project

Performance Benefits of Fiber-reinforced Thin Concrete Pavement and Overlays

Task-1: Literature Review

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Driven to Discover

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1 INTRODUCTION

Due to increasing budget constraints, there is interest in economizing pavement structures by reducing the panel thickness or increasing the service life of the pavement. Past research has demonstrated definite limits to reducing the panel thickness of conventional undoweled jointed plain concrete pavement (JPCP), thus invoking interest in understanding the potential of using structural fiber reinforced concrete (FRC) to either allow slab thickness reduction or service life increase. The research need arises in understanding the contribution of structural fibers in mitigating panel fatigue cracking and transverse joint faulting in thin concrete overlays and thin concrete pavement on grade. There is interest in understanding the effects fiber reinforced concrete have on panel size as well, especially for much thinner slabs.

Structural fibers generally improve the performance of thin concrete pavement and overlays by (i) holding cracks tight and (ii) transferring the wheel load between adjacent slabs. Several laboratory studies were conducted in the past (Issa, 2017; Kevern et al., 2016; Barman and Vandenbossche, 2014; Mahadik and Kamane, 2014; Roesler et al., 2008; Bordelon, 2005, Ramakrishna, 1987) and are in progress to comprehensively quantify the different benefits of fibers in concrete pavement (Hansen and Barman, 2017). To quantify the benefits in the field, the National Road Research Alliance (NRRA) has designed and constructed seven fiber-reinforced concrete test cells and one control plain concrete cell at the MnROAD facility during June – September, 2017. These cells are equipped with different types of sensors for measuring: (i) dynamic strain due to wheel load, (ii) strain induced by the environmental forces, (iii) temperature gradient, and (iv) joint movement, etc. In addition to collecting the sensor data, the distress data of these cells will be periodically collected to trace the distress initiation and propagation. Distresses such as panel fatigue cracking (transverse, longitudinal and others, if any), transverse joint faulting and other significant distresses (if occurs) will be recorded in the distress survey. Deflection and profile data will be collected monthly or seasonally, as appropriate. The sensor data and periodical distress and performance data will be analyzed annually throughout the duration of this research project (3 years from the time of construction) to understand the influence of the structural fibers on the development and propagation of panel fatigue cracking and joint faulting, and on the panel size.

The entire research work is divided into different tasks. The first task deals with a literature search on the application of FRC in concrete overlays and pavements. Task 2 deals with annual and seasonal performance analyses of the eight cells (seven FRC and one PCC, control). Task 3, 4 and 5 deal with investigating the effect of fibers on the panel fatigue cracking, joint faulting, and panel sizes. These three particular tasks will develop the necessary modifications in the relevant structural response and fatigue performance models to account for the contribution of the structural fibers for future mechanistic-empirical design procedures. Tasks 6 to 8 deal with the final report preparation, publication, and dissemination of the findings.

This report presents the works performed under the scope of Task 1. A literature search was conducted to explore properties of FRC in general and its application in concrete overlays. Discussions are provided on the types of concrete overlays and critical thin concrete pavement and overlay distresses. A survey was conducted to collect data on the distress and performance of concrete overlays constructed with and without fibers; special emphasis was given to the NRRA participating states. In addition to the survey, relevant open access publications, scholarly journals and research reports were reviewed to understand the contribution of fibers in mitigating different distresses that develop in concrete overlays.

2 FIBER REINFORCED CONCRETE

Fiber reinforced concrete is known for its enhanced durability, reduced plastic shrinkage, reduced spalling, and high impact strength. In general, fibers do not significantly increase the compressive strength and modulus of elasticity (Hansen and Barman, 2017), especially when synthetic fibers are used, and tend to decrease the workability (Barman, 2014). Structural fibers improve the post-crack performance (Figure 2-1) of the concrete by increasing the toughness, residual strength (RS) and residual strength ratio (RSR) (ACI 544.1R, 2009; Roesler et al., 2008), load transfer efficiency (LTE) of concrete (Barman and Vandenbossche, 2014), and fatigue resistance (Rollings, 1986). Figure 2-1 shows a photograph in which it can be seen that fibers bridge a crack to provide increased post-crack performance. Based on full-scale slab studies, Beckett (1990) and Falkner et al. (1995) have shown that structural fibers (steel or polymeric) increase the flexural and ultimate load carrying capacity of concrete slabs; the magnitude of the increase is related to the fiber volume and aspect ratio. Roesler (2003) stated that discrete synthetic fibers improve the load-deformation characteristics of concrete slabs. Figure 2-2 shows a representational schematic of load versus deflection curves (4-point bending test) of plain concrete and FRC specimens. This schematic demonstrates the post-peak load or post-crack contribution of fibers. It can be seen that FRC are able to hold some amount of load after the crack development, which is referred as the residual load in this report. The residual load can be a function of the fiber properties. Different types of fibers are used in concrete with varying length, geometry, material composition, aspect ratio, and dosage. This section provides a discussion on the properties of concretes prepared with different types of fibers. The discussion is limited to the fibers that are commonly used in concrete overlays and pavements.

Figure 2-1. Fibers bridging a crack and providing post-crack performance (Gaddam, 2016)

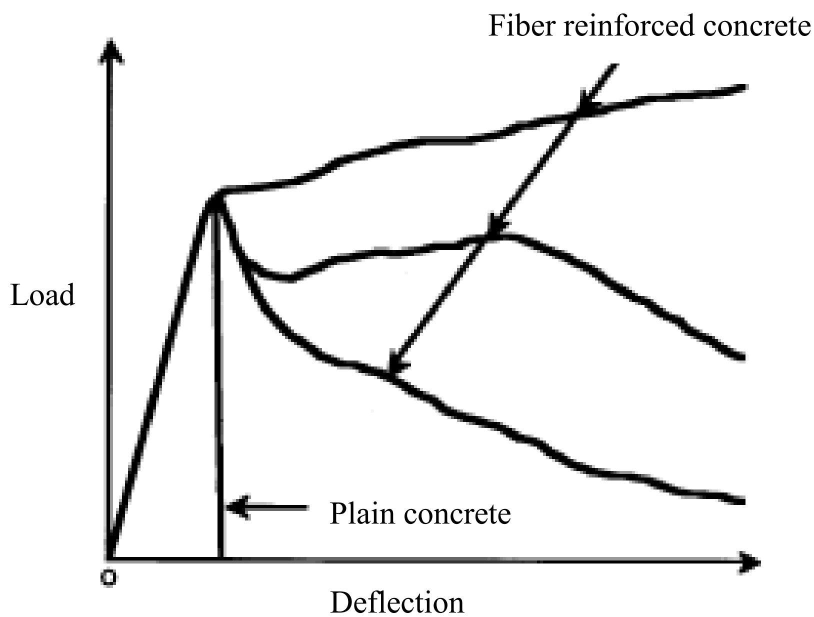


Figure 2-2. Range of load versus deflection curves for plain and reinforced concrete (after ACI 544.1R, 2009)

2.1 Synthetic Fiber Reinforced Concrete (SNFRC)

Structural synthetic fibers are the most commonly used fibers in the concrete pavements or overlays since last few decades. In a survey conducted by Hansen and Barman (2016), it was found that 94 percent of the FRC concrete overlays in this country were constructed with structural synthetic fibers and only six percent were constructed with steel fibers (mostly in Illinois). Comprehensive design methods for synthetic fiber reinforced concrete (SNFRC) for specific applications have not yet been developed, but many manufacturers often provide recommendations (ACI 544.1R, 2009) on the dosages. This section provides a discussion on the different properties of synthetic FRC.

Synthetic fibers are produced from a wide range of materials, such as acrylic, aramid, carbon, nylon, polyester, basalt, polyolefin, polyethylene, and the most popular polypropylene (PCA, 2015). Synthetic fibers can be micro monofilament, micro fibrillated, or macro monofilament. Micro monofilaments are typically small, thin single fibers, as shown in Figure 2-3**.** Fibrillated fibers are long interconnected bundles that unfurl when mixed into the concrete, see Figure 2-4 for an example. Macro fibers, also known as structural fibers, are typically much stiffer and larger than micro monofilaments, as shown in Figure 2-5. Synthetic fibers may also have embossed or textured surfaces to enhance the mechanical bondage. 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. As per Barborak, 2011, structural fibers carry load and can be used to replace traditional reinforcement in certain applications, as well as minimize and/or eliminate both early and late age cracking. In concrete pavements or overlays, the applications of the structural fibers are mainly to reduce the fatigue cracking and joint faulting. Typical lengths for macro-fibers are greater than or equal to 1.5 inches. Non-structural fibers, which are less stiff than structural fibers, are generally utilized to minimize early age cracking. According to ACI 544.3R, "micro-synthetic fibers are defined as fibers with a diameter or equivalent diameters less than 0.012 in (0.3 mm), and macro-synthetic fibers have a diameters or equivalent diameters greater than 0.012 in (0.3 mm)" (ACI Committee 544, 2008).

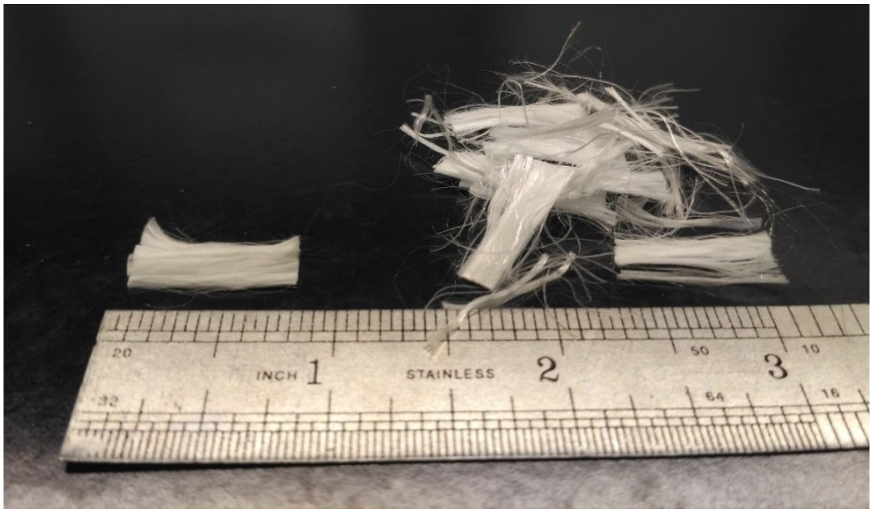


Figure 2-3. Monofilament synthetic fibers

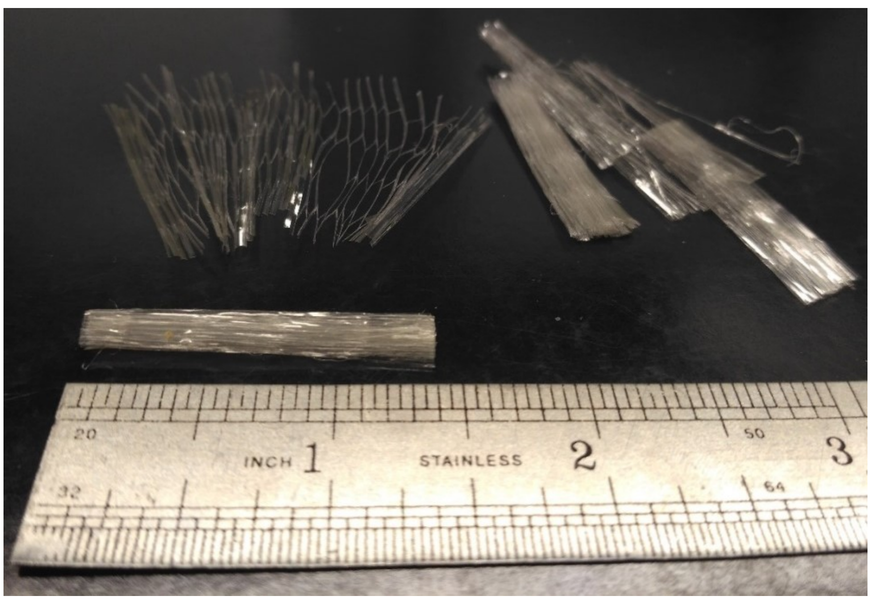


Figure 2-4. Fibrillated synthetic fibers

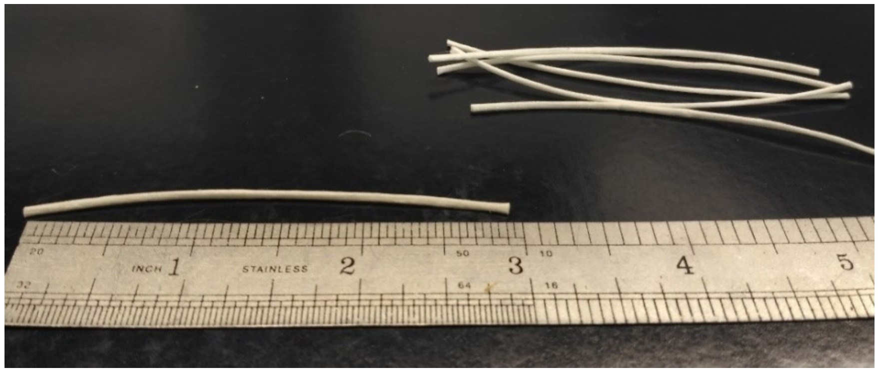


Figure 2-5. Macro synthetic fibers

The most popular synthetic fiber material, polypropylene, is chemically inert, hydrophobic and lightweight. Figure 2-6 shows pictures of two structural polypropylene fibers. The polypropylene fibers are available as slender fibers with a rectangular cross-section or as continuous cylindrical monofilaments, cut to a specified length. They can be of straight, crimped or embossed geometry along the length of the fibers.

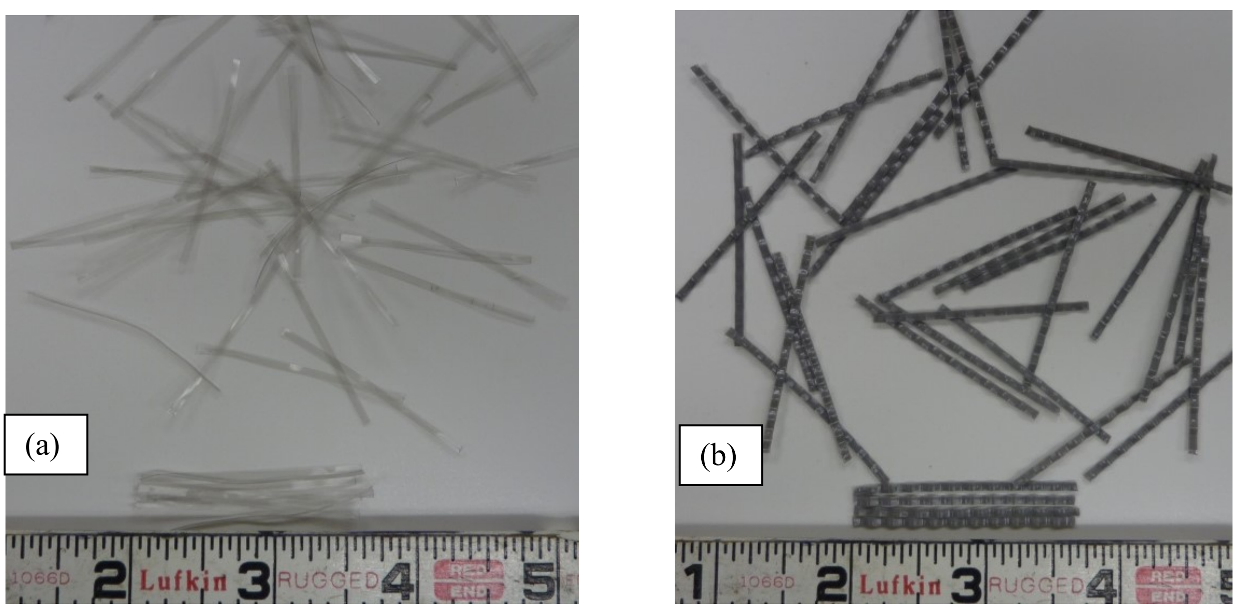


Figure 2-6. Picture of the polypropylene fibers (a) straight geometry, (b) crimped geometry

2.1.1 Plastic (Fresh) Concrete Properties

The addition of fibers generally decreases the workability (slump) depending on fiber dosage, aspect ratio, geometry and a number of other considerations. This reduction in slump, due to the fiber addition, may increase the cohesiveness of the concrete and ultimately improve the slip-form characteristics associated with the mixture (Ludirdja and Yougn, 1992). Synthetic fibers placed in concrete at dosages greater than 1.0% by volume tend to form balls, but typically synthetic fibers perform better than steel or glass in those regards (Ludirdja and Yougn, 1992).

It has also been noted that the addition of fibers may reduce bleeding which is believed to be a result of the reduced aggregate settlement and ultimately fewer capillary bleed channels. This effect reduces inter-granular pressures and shrinkage cracking (ACI 544.1R, 2009). The ongoing MnDOT funded research work at the University of Minnesota Duluth (UMD) drew a number of qualitative conclusions in terms of the fresh concrete behavior, which are summarized as follows:

- Fibers longer than 2 inches showed a greater tendency to ball and form mats; however, balling and matting did not directly correlate with fiber aspect ratio as previously thought.
- Increasing mixing time and adopting an improvised mixing method (Hansen and Barman, 2017) were able to decrease the fiber mating and balling.
- Achieving proper workability for concretes with smaller effective diameter fibers (coincidentally having a higher aspect ratio) was difficult, especially at higher dosages; a higher admixture dosage was required for such FRCs.

2.1.2 Hardened Concrete Properties

2.1.2.1 Mechanical Properties

Hardened concrete shows very little improvement in compressive strength, tensile strength, and modulus of rupture when 0.1% to 0.2% (by volume) polypropylene fiber is added in the concrete (Zollo, 1984). A similar observation was also noted in the Hansen and Barman (2017) study. In the cracked state, synthetic fiber reinforced concrete has displayed excellent post-crack or residual strength and toughness (Hansen and Barman 2017, ACI 544.1R, 2009).

The addition of certain synthetic fibers also has a significant effect on the failure mode of specimens in various test procedures. For example, compressive strength specimens where SNFRC is used tend to fail in a ductile manner and rarely exhibit explosive failure. These specimens can continue to sustain loads well after failure and endure large deformations (ACI 544.1R, 2009).

Research has provided contradictory results for impact strength, where some results show an increase in impact strength while others show no increase. On the other hand, improvement in the post-crack performance of SNFRC is one of the largest arguments for using synthetic fibers in concrete overlays. Its ability to bond in the concrete greatly affects its post-crack performance. It has been found that twisted collated fibrillated polypropylene fibers or fibers with enlargements at its ends had the best mechanical bond strength (ACI 544.1R, 2009). The work previously conducted by Hansen and Barman (2017) found that fibers having twisted, embossed, or crimped outperformed the straight fibers.

2.1.2.2 Durability Characteristics

Limited research is available on the freeze-thaw resistance of SNFRC. Research has shown however that the addition of synthetic fibers does not completely eliminate concrete degradation due to freeze-thaw damage, deeming it still necessary to air-entrain the concrete in question. To this front, Issa (2017) stated that fiber inclusion could improve pavement durability against surface scaling.

2.1.3 Relevant Research Studies on SNFRC

2.1.3.1 Illinois

Several synthetic FRC related research studies (Bordelon, 2011; Roesler et al., 2008; Bordelon, 2005) were conducted in Illinois. A number of factors that affect the performance of FRCs were considered including shapes (for example: straight, crimped and twisted), type, dosage, length, diameter, and aspect ratio of the fibers. Table 2-1 presents the properties of fibers and a few hardened concrete test results for the FRCs prepared with three different synthetic fibers in the Roesler et al. (2008) study. It can be seen that the peak flexural load and modulus of rupture (MOR) slightly vary with the dosage rate, shape and aspect ratio of the fiber, but a certain trend was not observed. The R^2 for the correlation between the fiber volume fraction and MOR was 0.14 for the data included in Table 2-1 , which indicates the MOR is not significantly influenced by the properties of structural synthetic fibers. Dosage rates of 4.5 lb/yd^3 in the straight synthetic fiber category and 4.6 lb/yd^3 in the twisted synthetic fiber category seem to provide the highest peak flexural load and MOR. As shown in Figure 2-7, it appears that the straight synthetic fibers performed better in terms of MOR than the other two shapes in that particular study. For example, the straight fibers performed better than twisted ones at 0.30%- and 0.50%- fiber volume fractions.

Table 2-1. Properties of structural synthetic fibers and FRC in Roesler et al. (2008) study

Fiber type	**Straight synthetic**				**Twisted synthetic**		**Crimped synthetic**
Cross section	Rectangular				Rectangular		Rectangular
Length (in)	1.57				2.13		2.00
Thickness (in)	0.004				NA		0.03
Width (in)	0.05				NA		0.05
Aspect ratio	90				NA		46
Specific gravity	0.92				0.91		0.91
Volume fraction in the mix (%)	0.19	0.26	0.29	0.58	0.30	0.50	0.40
Dosages used (lb/yd^3)	3.00	4.00	4.50	8.90	4.60	7.70	6.10
Peak flexural load (lb)	6623	5472	9276	8939	8101	6487	8160
Modulus of rupture (psi)	556	456	733	745	675	541	673
Testing age (days)	14	14	14	14	14	14	14

The correlation between fiber volume fraction (V_f) and RSR found in a study by Bordelon (2005) is shown in Figure 2-7. The RSR, which is also termed as 'equivalent flexural strength ratio' as per ASTM-C1609, 2010, is determined by a four-point bending test using beam specimens. RSR is expressed as shown below:

$$\mathrm{RSR} = 100\,\frac{\mathrm{f_{e,3}}}{\mathrm{MOR}} \qquad (1)$$

Where, $f_{e,3}$ is the residual strength at mid span for a deflection up to (span)/150 of a 24-in x 6-in x 6-in beam. The span is equal to 18 inches; therefore, the residual strength is measured at a 0.12-in deflection. It can be seen that the residual load capacity (post-crack) increases with the increase in fiber volume fraction. Figure 2-8 shows that FRC with 0.58% fiber volume fraction resulted in a greater residual load capacity as compared to the FRCs with 0.26% volume fraction.

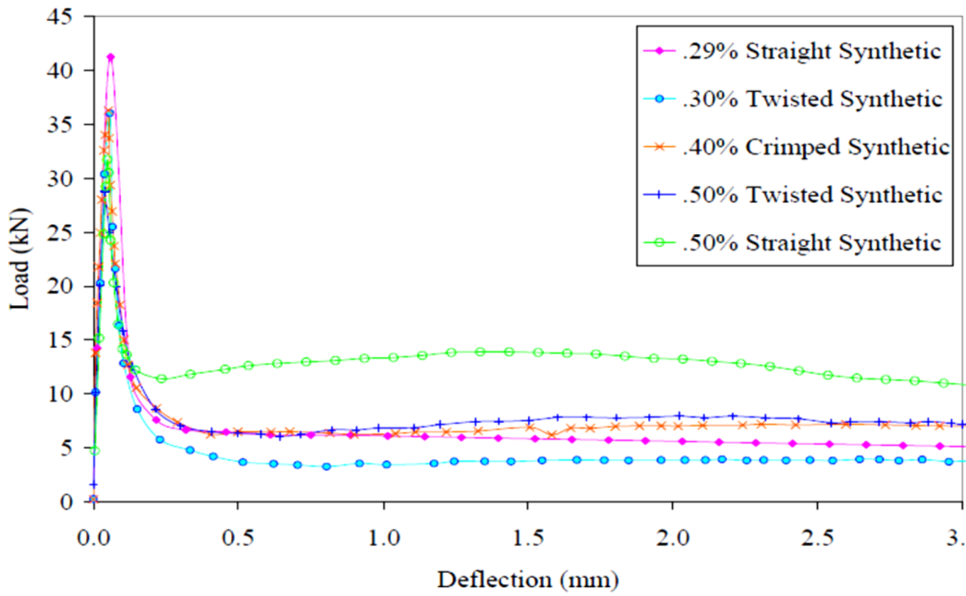


Figure 2-7. Residual load characteristics of different shaped structural synthetic fibers (Bordelon, 2005)

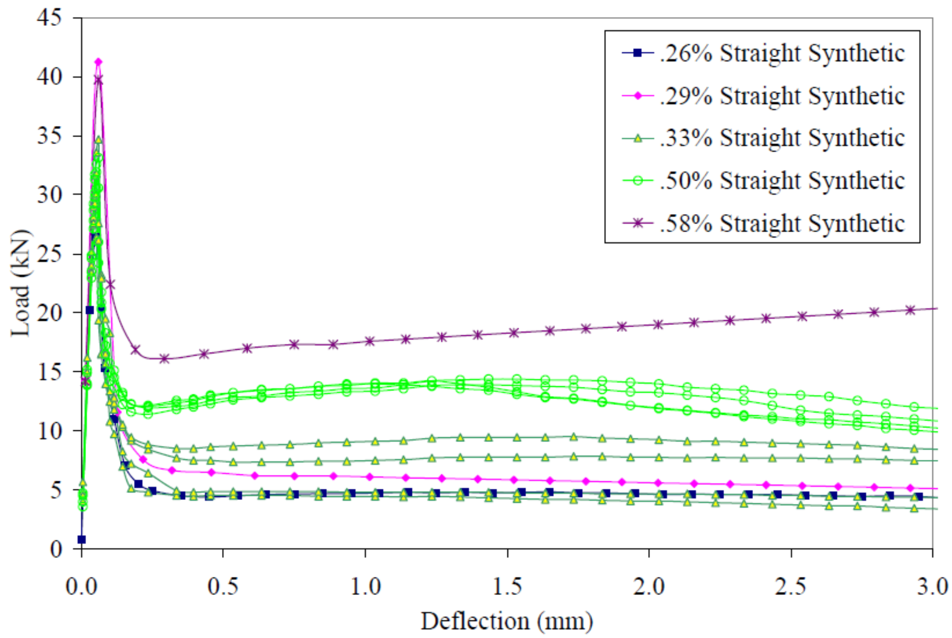


Figure 2-8. Residual load capacities of FRC vs. fiber volume fraction for synthetic fibers (Bordelon, 2005)

Alhassan and Ashur (2012) have investigated the benefit of fiber additions in bridge overlays. The study was conducted to make recommendations and identify the potential benefits of synthetic fibers in concrete bridge overlays. These benefits were found to include a reduction in shrinkage cracking, an increase in toughness, additional post-crack strength, and an increase in crack resistance.

Figure 2-9 shows the results of shrinkage vs. curing time for various combinations of plain and fiber reinforced concrete mixes. The FRC mixes showed less shrinkage than the plain mix. On an average, the drying shrinkage was found to be 17% lower for FRC mixes than the plain concrete mix.

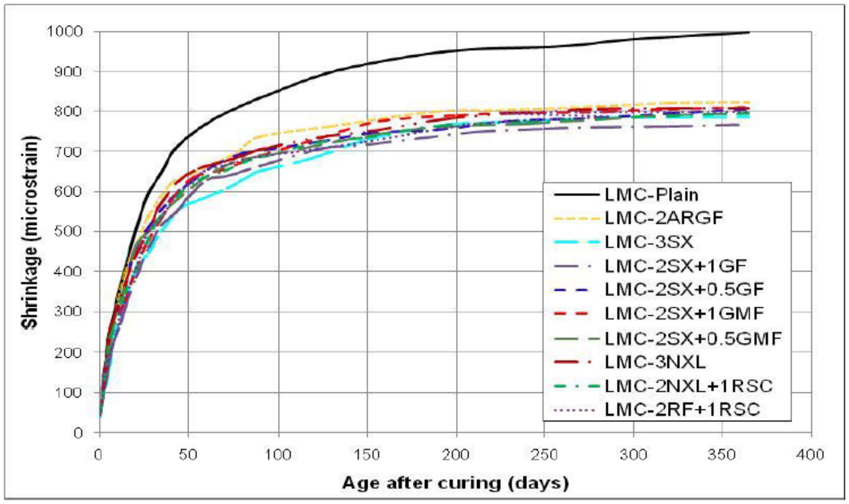


Figure 2-9. Shrinkage vs. curing time for plain and FRC mixes in Alhassan and Ashur (2012) study (LMC = latex modified concrete; ARGF = alkali resistant glass fiber; SX= microtype polyolefin fiber; GF = micro type 100% virgin; NXL = macrotype polyolefin fiber; RSC = microtype polyvinyl alcohol fiber; RF = macrotype polyvinyl alcohol fiber).

Figure 2-10 shows the flexural test results of FRC mixes prepared with SX fibers mixed at 3 lb/yd^3 fiber dosage, for two different curing periods. Table 2-2 shows the results of residual strength for various combinations of FRC mixes. The FRC mix with SX fiber at 3 lb/yd^3 showed higher residual strength than other combinations. This table also presents other hardened concrete properties for the FRC mixes used in the Alhassan and Ashur (2012) study.

The study recommends a synthetic fiber content of 3 lb/yd^3 for bridge overlays. It was found that higher fiber contents resulted in poor dispersion characteristics with balling and clumping during mixing, placing, and finishing. At fiber contents near 3 lb/yd^3, drying shrinkage was reduced by up to 15%, and an increase in flexural strength was observed due to internal confinement. It was also recommended that fibers be held between 0.75 inches and 1.75 inches in length.

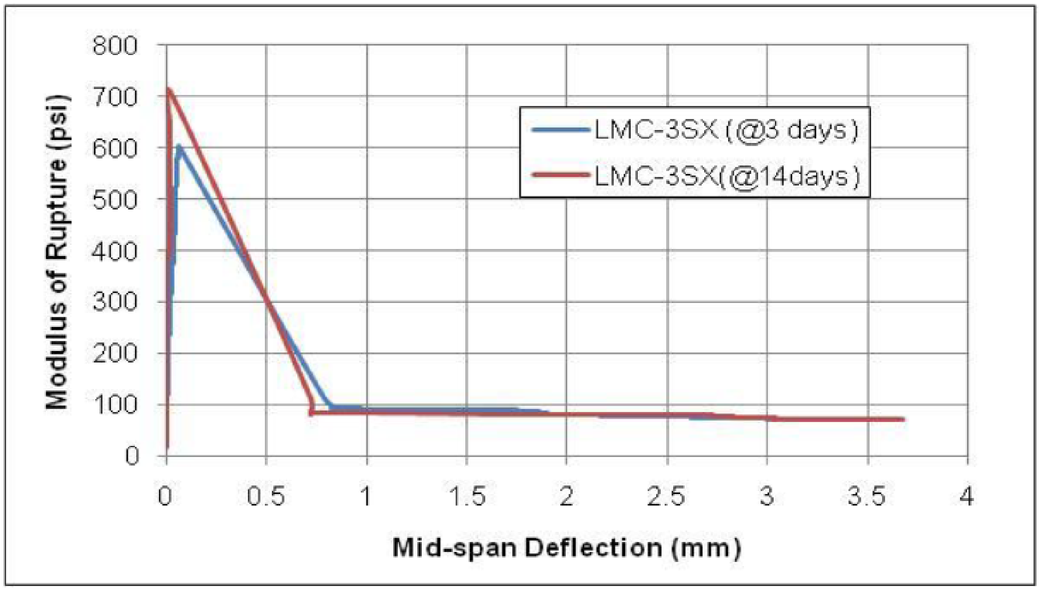


Figure 2-10. Modulus of rupture for fibrous LMC-3SX mix (Alhassan and Ashur, 2012).

Table 2-2. Hardened concrete properties of the FRC mixes used in Alhassan and Ashur (2012) study.

Mix Design	Compressive strength, psi	Modulus of Rupture, psi	Residual Strength, psi	Residual strength ratio (%)
LMC-3SX	4,420	600	78	13
	6,660	715	78	10.9
LMC-2SX+1GF	4,600	650	52	8
LMC-2RF+1RSC	4,330	600	40	6.7

Isaa (2017) has studied the effect of early-age properties of fiber reinforced concrete on the fatigue damage of concrete pavements. The aim of that study was to minimize the traffic closure times during concrete pavement construction and rehabilitation activities. The study utilized two types of polypropylene based structural synthetic fibers: straight (Strux 90/40, aspect ratio = 90) – referred as "F1" and embossed (Master Fiber MAC Matrix, aspect ratio = 67) – referred as "F2". Two types of mixes were considered in that study: (i) concrete patch mix (PP) and (ii) concrete pavement mix (PV); these mixes were prepared with variable fibers dosage such as, 4, 6 and 8 lb/yd^3. Various properties of concretes such as compressive strength, modulus of elasticity, flexure strength and toughness, and load transfer efficiency were studied to investigate the early-age behavior of concrete. Two curing regime temperatures such as, 45°F and 75°F were utilized, and the samples were tested after 12 hours, 1, 3, 7, and 28 days of curing.

It was found that the synthetic fibers did not have a significant influence on the compressive strength and flexural strength of the PP and PV concrete mixes. The influence of fiber dosages on the flexural toughness was apparent though. Figure 2-11shows the load vs displacement relationships for three PV specimens prepared with three dosages of F1 fibers, tested at 14 days. Figure 2-12 shows the toughness vs flexural strength for these specimens. It can be seen that even though the residual strength at 0.12-inch net displacement ratios look similar, the flexural toughness which depends on the area of the load vs displacement curves were different and positively influenced by the fiber dosage.

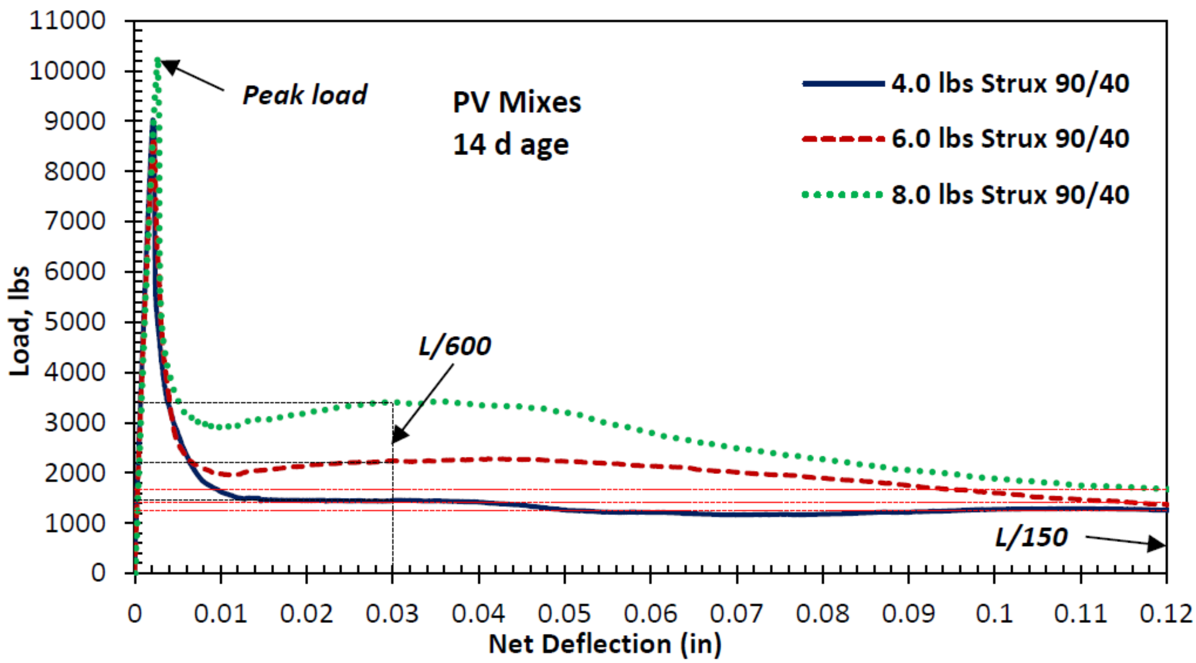


Figure 2-11. Load vs displacement curves for PVF1 mixes prepared with 4, 6, and 8 lb/yd^3 fiber dosages (Issa, 2017).

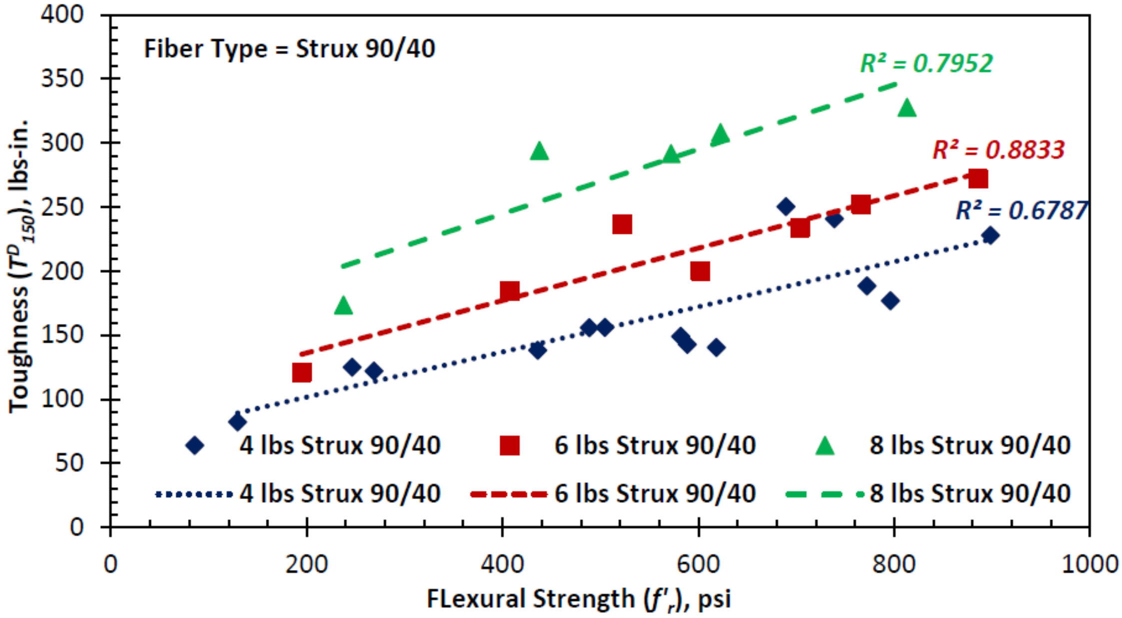


Figure 2-12. Flexural toughness vs flexural strength relationships for PVF1 mixes prepared with 4, 6, and 8 lb/yd^3 fiber dosages (Issa, 2017).

Figure 2-13 shows toughness vs. flexural strength relationships for the PV mixes with F1 and F2 fibers at 4 lb/yd^3 dosage. The mix with F2 fiber showed better flexural toughness than mix with F2 fiber. The authors opined that this could be due to the embossed and deformed texture of F2 (MACMatrix) fiber that had provided better bonding within the concrete mix.

Figure 2-14 shows the results of the relative dynamic modulus (RDM) test performed according to ASTM C666 (rapid freeze-thaw cycles, procedure A) for various specimens among which some were subjected to fatigue loading. These specimens were prepared with 7% entrained air content. All the specimens passed the minimum criteria of 60% RDM irrespective of fiber dosage and fatigue loading. It confirms the insignificant role of fiber towards the concrete durability against freeze-thaw cycles, and significance of 7% air content to allow water expansion at freezing temperatures. The mass loss due to freeze-thaw cycles found consistent between same mixes irrespective of fatigue loading and ranged from 0.74% to 1.65% for all mixes. It was also found that the mixes with a higher dosage of synthetic fibers showed increased resistance to scaling by a higher degree.

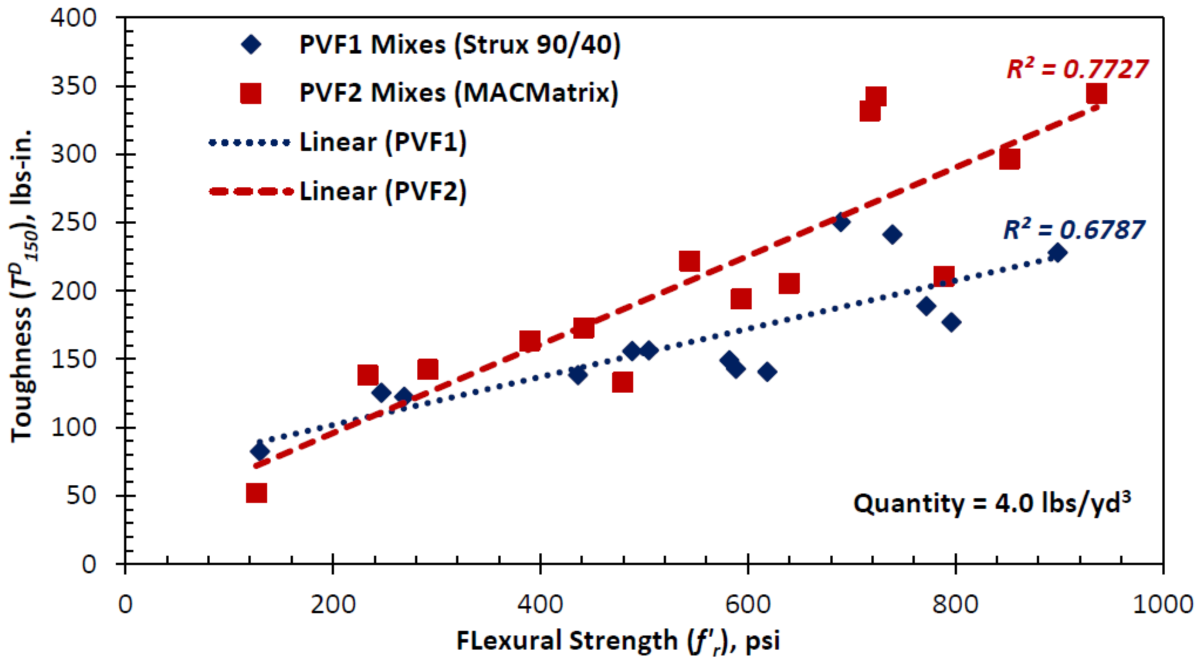


Figure 2-13. Flexural toughness vs flexural strength relationships for PVF1 and PVF2 mixes prepared with 4 lb/yd^3 dosage (Issa, 2017).

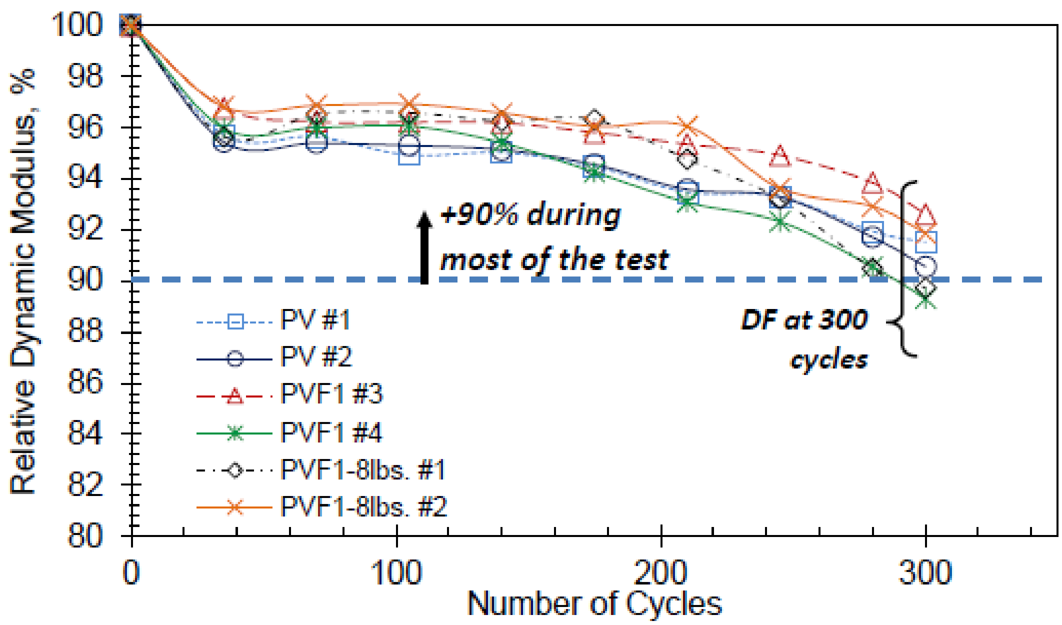


Figure 2-14. Relative dynamic modulus (RDM) vs number of F-T cycles for various PV F1 mixes (Issa, 2017).

Flexural fatigue testing was conducted on 6 x 6 x 21 in. beams for all mixes with and without fibers. Cyclic loading at 4 Hz. frequency was applied using a four-point bending configuration. Specimens were tested at 12 hours, and 1, 3, and 7 days. The stress levels considered in fatigue tests were 0.9, 0.8, 0.7 and 0.6 for all the mixes. Based on the fatigue test results, Issa (2017) made the following conclusions:

(i) Concrete at 12 hours can exhibit bond failure in flexural fatigue due to low mortar strength;

(ii) The introduction of higher amounts of fibers (e.g., 8 lb/yd^3) can improve fatigue life for a stress level of 0.6 even at 12 hours;

(iii) Cement paste can gain bond strength at 24 hours to improve the fatigue performance when higher amounts of fibers (e.g., 8 lb/yd^3) is used;

(iv) S-N curves showed that mixes with 8 lb/yd^3 fibers fail at higher number of load. cycles for any given stress level, when compared with the plain-concrete PV mixes;

(v) The two fibers considered in the study did not present any significant difference in fatigue performance when compared with plain-concrete PV mixes;

(vi) 4 lb/yd^3 of fiber may not be enough to provide any considerable fatigue resistance at early-age.

2.1.3.2 Minnesota

A comprehensive laboratory study was conducted by UMD for the State of Minnesota to understand the contributions of fibers on the post-crack performance of concrete overlays (Barman et al., 2018). Based on the existing literature and field survey, nine synthetic fibers were included in that study; these fibers were different from each other with respect to geometry, length, aspect ratio, stiffness and manufacturer. Table 2-3 summarizes the details of nine types of fibers used in the study. Low, intermediate and high dosages (0.25, 0.50, and 0.75 percent volume fraction (V_f) of the total volume of concrete) for each fiber type were considered in that study.

Table 2-3. Summary of details of fibers used in Barman et al. (2018) study

Fiber Serial Number	Geometry / Type	Length (inch)	Aspect ratio, specific gravity, modulus of elasticity (ksi),tensile strength (ksi)
Fiber 1	Straight / Synthetic	1.5 or 2	*94, 0.91, N/A, 70
Fiber 2	Straight / Synthetic	1.5 or 2	*100, 0.91, N/A, 70
Fiber 3	Straight / Synthetic	1.55	90, 0.92, 1378, 90
Fiber 4	Straight / Synthetic	*1.63	96.5, 0.91, N/A, 70
Fiber 5	Twisted Straight / Synthetic	2	74, 0.92, 1380, 87-94
Fiber 6	Continuously Crimped / Synthetic	2.0	*60, 0.91, N/A, N/A
Fiber 7	Embossed / Synthetic	2.1	70, 0.91, N/A, 85
Fiber 8	Embossed / Synthetic	1.89	*66, 0.90-0.92, 1450, 93
Fiber 9	Embossed / Synthetic	2.1	70, 0.91, N/A, 85

* Measured, not found in manufacturer's sheet.

Table 2-4 shows the basic mixture design and mix designation employed in the study. The designations describe each mixture according to the fibers material type, geometry, and fiber number. For example, the mixture designation 'S.E.7' represents a mixture comprised of synthetic fibers (S), a fiber with an embossed (E) geometry and a fiber with a serial number of 7 (see Table 2-3 for the length, aspect ratio, density, etc.). A total of thirty FRC mixes and one plain concrete mix were tested. The required adjustments in the FRC mix design were exercised to produce identical concrete batches.

Table 2-4. Base mixture design for concrete mixes and mix designations

Base mixture design		
Ingredients	*Volume (%)*	*Mass (lb/yd^3)*
Cement (Type I)	11.6	615.0
Course Aggregate	42.0	2024.0
Fine Aggregate	25.1	1188.8
Potable Water	13.2	222.2
Fibers	varied	Varied
BASF MasterAir® 400 (fl. Oz)	negligible	6.08
MasterPolyheed® 1020 (fl. Oz)	negligible	36.5
Mix designations		
Fiber Material	*Geometry*	*Fiber Number*
Synthetic (S)	Crimped (C); End Crimped (EC); Embossed (E); Straight (S); Twisted (T)	See Table 2-3

The flexural performance of concrete beams was evaluated by determining the modulus of rupture (MOR), residual strength (RS), and residual strength ratio (RSR) using the ASTM C1609 test. Also, the compressive strength and modulus of elasticity of hardened concrete cylinders were measured. Figure 2-15 (a) and (b) show the results of variation in compressive strength and modulus elasticity with variation in reinforcement index (RI). Note that the reinforcement index is the product of aspect ratio (AR) and volume fraction (V_f) of fibers. The compressive strength and modulus of elasticity of synthetic FRC were minimally influenced with respect to the increase in RI. The results of the modulus of rupture also showed the similar trends (Figure 2-15 (c)). Figure 2-15 (d) shows that the modulus of rupture inconsistently varied with the change in fiber property and V_f.

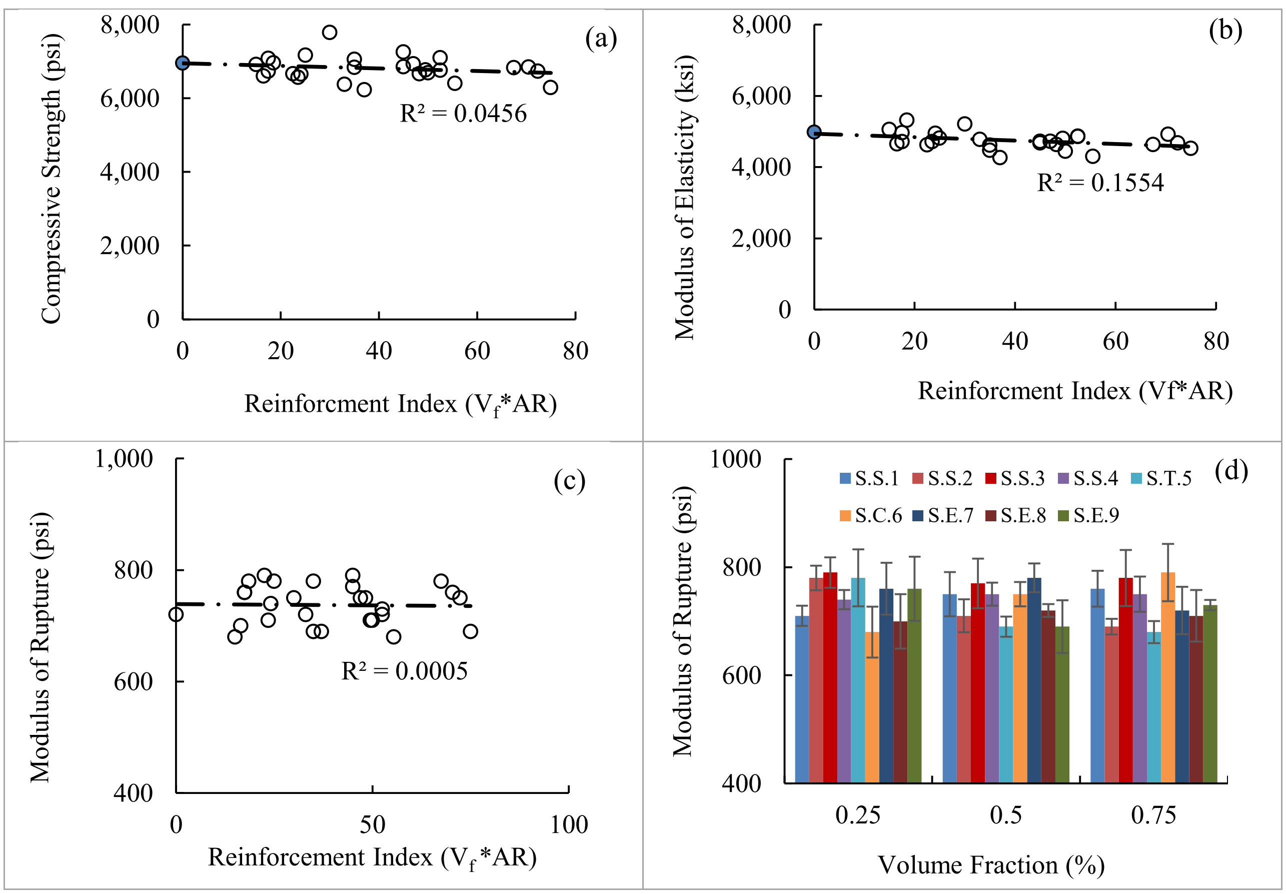


Figure 2-15. (a) Compressive strength, (b) modulus of elasticity, and (c) and (d) modulus of rupture as a function of reinforcement index and fibers' volume fraction.

Figure 2-16 (a) and (c) show the variation in RSR and RS, respectively, for all the fiber types with a change in V_f. It can be seen that RSR greatly increased with increase in V_f for all the fiber types. Overall, the RSR and V_f has an excellent correlation (R^2 = 0.86) as seen in Figure 2-16 (b). In general, these figures suggest that embossed, twisted and crimped fibers perform better on average than straight synthetic fibers when the comparison is made in terms of RSR or RS. For an example, if the required RSR is 30 percent, then that can be achieved using 0.36 percent V_f (5.25 to 5.75lb/yd^3) of S.E.9 fibers, whereas 0.66 percent V_f (9.75 to 10.25 lb/yd^3) of S.E.8 or S.S.1 fibers would be required.

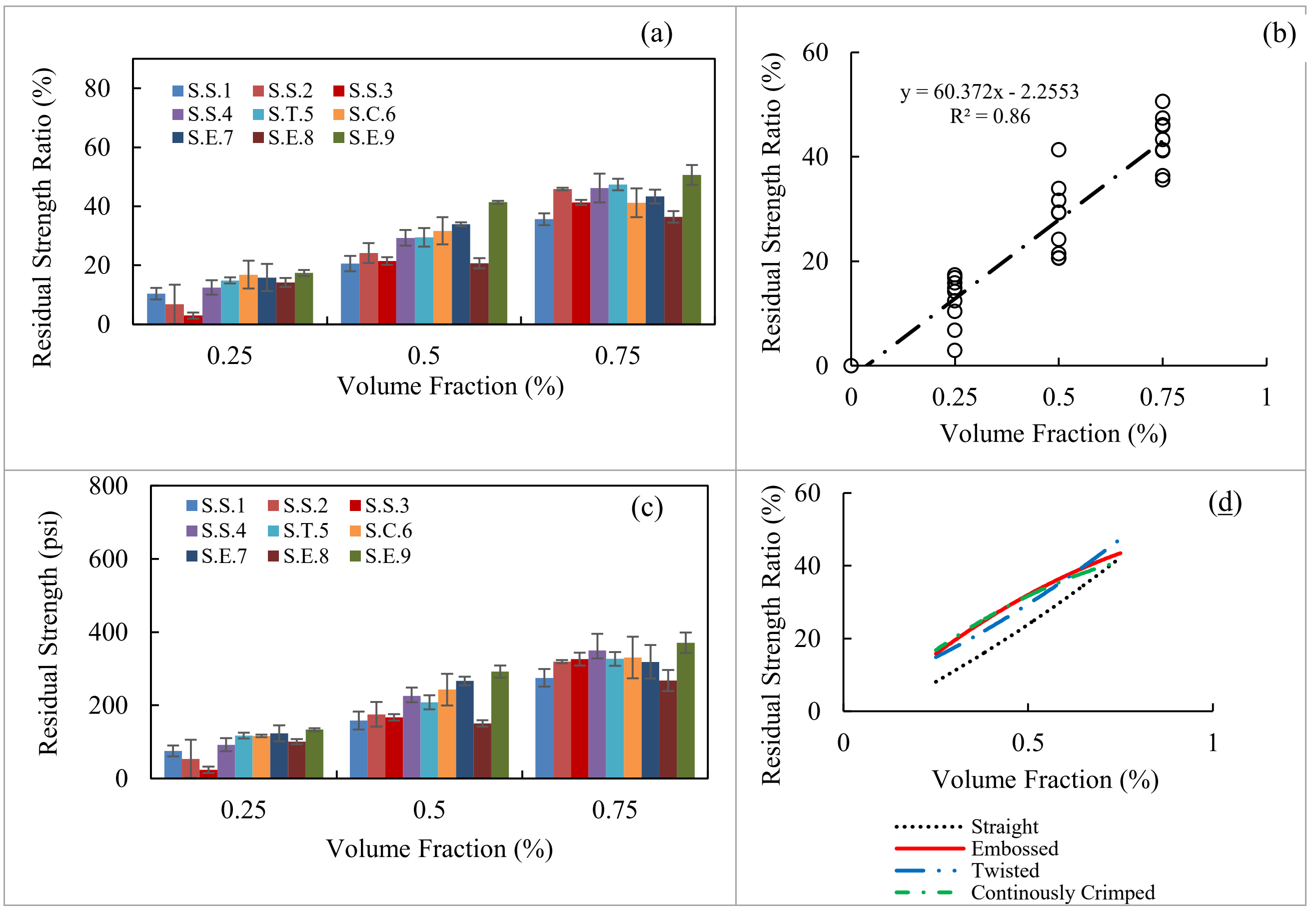


Figure 2-16. (a) RSR vs. V_f, (b) Correlation between RSR and V_f, (c) RS vs. V_f, (d) RSR as a function of V_f and fiber geometry.

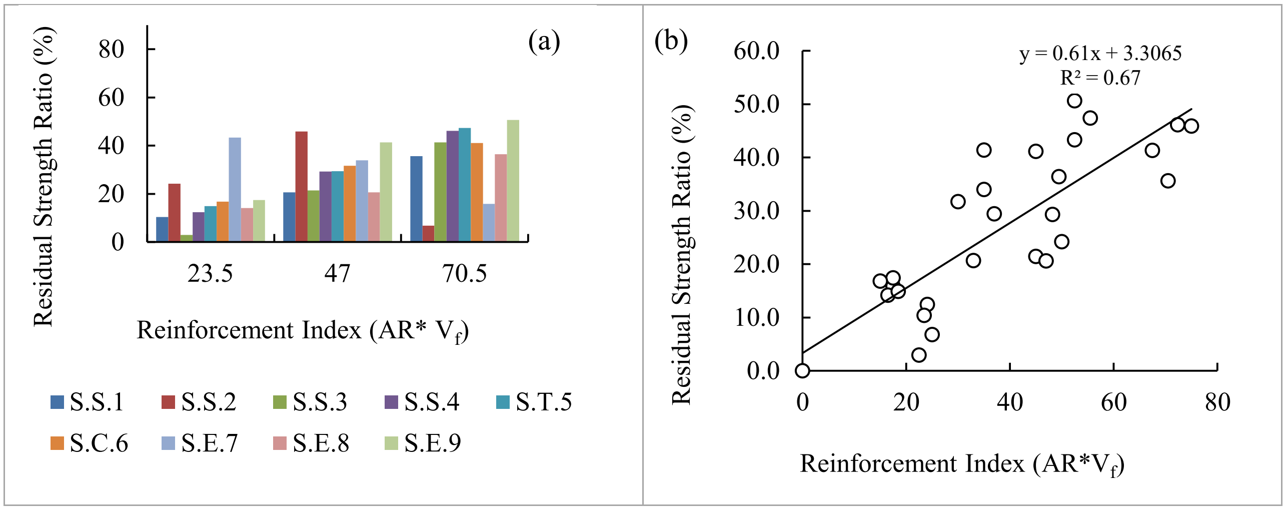


Figure 2-17. (a) RSR vs RI, (b) correlation between the RSR and RI.

Figure 2-17 (a) shows the results of the RSR with a change in RI for all the fiber types. The observed trends are somewhat similar to the trends of RSR and V_f. A good correlation (R^2 = 0.68, considered good for the reason of having a large number of variables involved) was found between RSR and RI (Figure 2-17 (b)). This correlation may be useful for the selection of fibers for certain value of RSR when several commercial fibers are available to choose from.

2.2 Other Fibers for FRC

A number of other fiber types are available for use in FRC. Those types include steel, glass and natural fibers (ASTM C1116, 2015). A number of concerns have made these fibers undesirable and as a result, have had limited use in concrete overlays. Natural fibers have been shown to absorb moisture and have poor durability. Glass fibers are subject to embrittlement of the fiber bundles due to alkali attack, even when alkali resistant glass is used the long-term durability is a concern (ACI 544.1R, 2009). Glass fibers also have a low strain and are not conducive to compatibility in concrete joints that will experience large crack widths. Steel fibers have shown promise in overlays placed in Illinois; however, concerns associated with steel FRC include corrosion of fibers in large cracks and their heavy-weight as compared to synthetic fibers.

3 MITIGATING CONCRETE OVERLAY DISTRESSES USING FRC

Thin concrete pavements are used for a number of applications, including slabs-on-ground (parking lots, low traffic volume roads, etc.) and as a rehabilitation technique (bonded/unbonded concrete overlays on existing asphalt or concrete). Structural fibers improve the post-crack performance of concrete (Rollings 1986, Roesler et al. 2003, Kevern et al. 2016) by keeping cracks tight which help reduce the panel fatigue crack (e.g., longitudinal, corner, and transverse cracks) severity and increase the load transfer between concrete slabs (Barman 2014) which decreases joint deterioration and subsequently joint faulting. In the last few decades, transportation agencies have used varieties of structural fibers varying in length, geometry, aspect ratio (AR), and parent materials. The dosages of fibers used were widely varied; however, without any mechanistic basis: 3 to 25 lb /yd^3 for synthetic structural fibers and 40 to lb /yd^3 for steel fibers. Based on the observed performance of FRC overlays constructed in different parts of the country, it is evident that structural fibers positively influence the performance of concrete overlays. However, because of a lack of significant studies involving companion field sections, neither the quantitative benefits of structural fibers have been identified, nor the benefits are accounted for in the existing mechanistic-empirical design procedures. This chapter discusses different types of concrete overlays, common distresses in thin concrete pavement and overlays, and the potential mitigation of distresses using FRC.

3.1 Types of Concrete Overlays

Fick (2016) recognized six different concrete overlay types. Those overlay types include a combination of design principles and materials, including bonded or unbonded, and the use of concrete or asphalt as a substrate material. Figure 3-1 shows the six different overlay types, and a more in-depth explanation of these overlay types is available in [1]Harrington and Fick (2014). Due to the inherent tendency for thinner concrete pavements to warp and curl due to environmental effects, thin concrete pavements/overlays are often designed with smaller panel sizes (Rasmussen and Rozycki 2004). In addition, due to physical limitations and the desire to reduce costs, thin concrete overlays are often constructed without dowel bars spanning the transverse joints (Harrington et al. 2014). In general, the bonded concrete overlays are thinner than the unbonded ones.

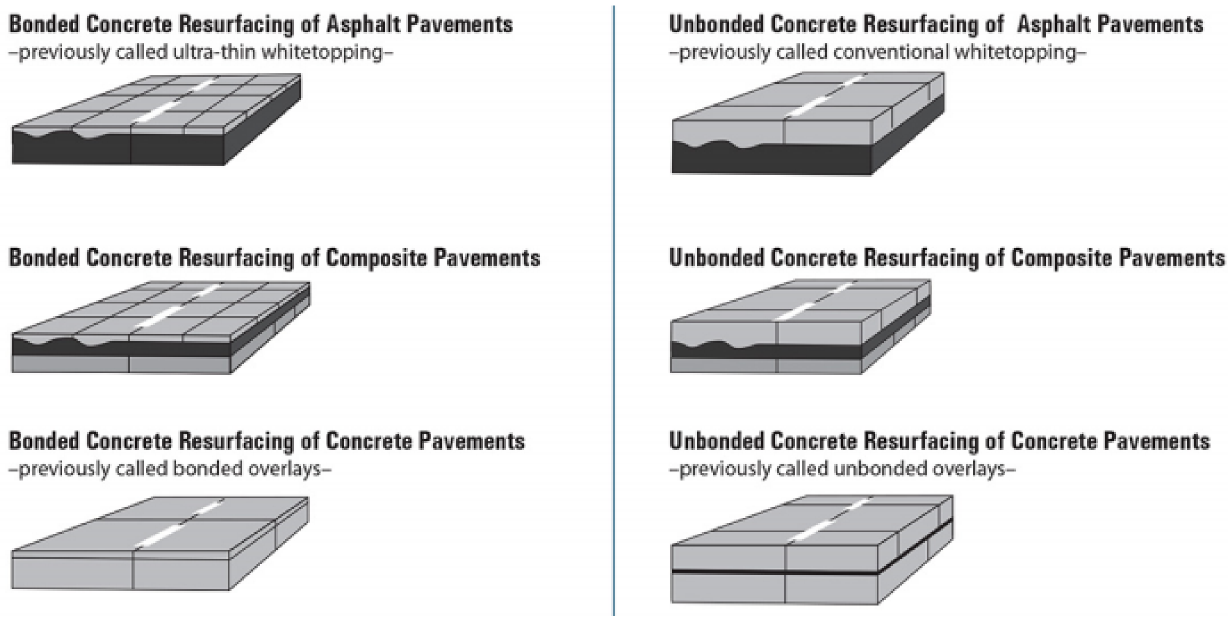
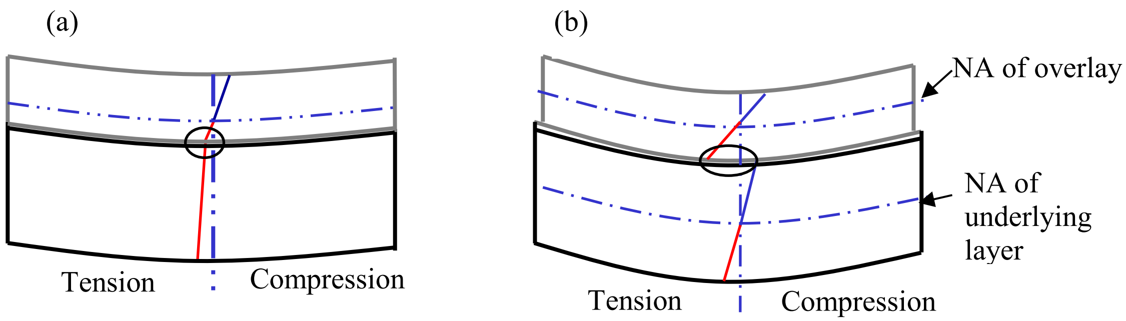


Figure 3-1. Types of concrete overlays (Harrington and Fick, 2014)

Concrete overlays are an economically proven method to rehabilitate deteriorated pavements. Thickness wise, three types of thin concrete overlays are most common in practice: (i) conventional overlays (thickness, h_s) > 6 in; (ii) thin overlays (h_s = 4 to 6 in); and (iii) ultra-thin overlays ($h_s \leq 4$ in). In ultra-thin and thin overlays, a bond between the concrete overlay and the underlying layer is essential to achieve the desired performance of the overlay. The bond between the layers ensures that the two layers' act like a single composite layer. This eventually reduces the tensile stress in the overlay, as depicted in the schematic in Figure 3-2. Bonded concrete overlays are constructed where existing pavement distresses can easily be removed via milling or repaired prior to the overlay placement.



Lower tensile stress at the bottom of overlay

Higher tensile stress at the bottom of overlay

Figure 3-2. Schematic showing stresses in concrete overlays: (a) bonded, (b) unbonded

3.2 Pavement Distress

The following sections summarize thin concrete pavement/overlay distresses. The most common distresses in thin concrete pavements/overlays are transverse, longitudinal and corner panel cracking, and transverse joint faulting.

3.2.1 Panel Fatigue Cracking

Panel cracking occurs in three different fashions, diagonally at the corner (corner cracking), transverse to the direction of travel (transverse cracking) or parallel with the direction of travel (longitudinal) (Vandenbossche, 2003). Corner cracks are full depth and vary in severity. The FHWA design manual identifies a low severity corner crack as a break that has little spalling, no measurable faulting, and the corner break is not broken into more than one piece. A high severity corner crack typically has significant spalling, and the corner break is broken into multiple pieces. Corner cracks are typically a result of slab curling, fatigue levels, loss of support or poor load transfer across the joint.

The FHWA defines low severity longitudinal and transverse cracks as having no spalling and a small crack width (less than 3 mm). High severity longitudinal cracks are typically associated with large crack widths (13 mm), spalling (greater than 75 mm) and joint faulting (greater than 13 mm). High severity transverse cracks are also typically associated with large crack widths (6 mm), spalling (greater than 75 mm) and joint faulting (greater than 13 mm) (Miler and Bellinger, 2003). These cracks are typically caused by loss of support, fatigue, and slab curling (Huang, 2004).

3.2.2 Joint Distresses / Faulting

The primary distress observed at joints is faulting and is defined as the difference in elevation between an approach slab and leave slab across a joint or crack. Faulting is a result of soil or base erosion that causes a loss of support under the slab (Huang, 2004). In concrete overlays over asphalt pavement, faulting can also occur because of stripping in the asphalt material or any other damages that results in permanent deformation in the asphalt layer. Poor joint performance or poor load transfer or between the adjacent slabs can accelerate the faulting. Joint performance is a function of a number factors and includes joint face texture, mechanical mechanisms (fibers, dowel bars, etc.), and crack width (Issa, 2017; Barman, 2014, Huang, 2004). As a result of faulting, panel cracking may occur and poor ride quality will ensue. Taylor et al. (2016) suggested that joint deterioration may also be caused by poor drainage, poor entrained air systems, and ponding which leads to freeze-thaw damage and chemical attack as a result of expansive calcium oxychloride.

3.3 Mitigation of Distresses using FRC

The addition of fibers into the concrete mixture increases fatigue capacity, reduces crack widths and enhances the concrete's post-crack performance (Barman, 2014; ACI 544, 2009). From work conducted in a previous MnDOT research project, it was found that polypropylene fibers provide post-crack toughness and increase the concrete's joint performance. The joint performance comes from two aspects, (1) the direct increase in load transfer due to the dowel action of the fibers and (2) by restraining and reducing macro cracks indirectly increasing joint performance. Fibers were also found to decrease the early-age shrinkage cracking (Alhassan and Asur, 2012); however, work conducted by Suksawang et al. (2014) showed that larger diameter and longer length (greater than 1.5 inches) macro fibers increased the flexural performance of the concrete but did not greatly influence the shrinkage properties of the concrete.

3.3.1 Reducing Panel Fatigue Cracking

Rollings (1986) noted the increased fatigue resistance of FRC over plain concrete pavements for equivalent stress. Roesler (2003) stated that discrete synthetic fibers improve the load-deformation characteristics of slabs. Louisiana Transportation Research Center (LTRC) conducted research investigating the fatigue and toughness characteristics of FRC (Kevern et al., 2016). This study evaluated the use of polypropylene fibrillated, polypropylene macro, carbon, and steel fibers as primary reinforcement in concrete pavements. The properties of the fibers are provided in Table 3-1. Figure 3-3 shows pictures of different fibers used in that study. In general, it was found that the polypropylene fibers perform better than the steel fibers against fatigue when used in the correct dosages. Regarding the toughness of the concrete, this study suggests that fibers with high tensile strength results in better residual load carrying capacity and carry a greater load at larger deflections.

Figure 3-3: Fibers used in the (Kevern et al., 2016) study: polypropylene fibrillated fiber (left), polypropylene macro fiber (left middle), carbon fiber (right middle) and steel fiber (right)

Table 3-1. Properties of fibers in Kevern et al. (2016) study

Properties of reinforcing fiber

Fiber Type	Specific Gravity	Length (in.)	Tensile Strength (ksi)
Polypropylene Fibrillated	0.91	1.50	83-96
Polypropylene Macro	0.91	2.25	83-96
Carbon	1.70	4.00	600
Steel	7.85	2.00	152

The fatigue property of the concrete was studied by applying cyclic load on the pre-notched beam specimens as per RILEM procedure developed by Jenq and Shah (1985). Pre-notched fatigue testing showed that both the tensile strength and length of fibers influence the fatigue properties of fibers. This study provided the following conclusions: (i) polypropylene fibrillated fibers offer increased fatigue performance in general but do not offer any significant post-crack performance, (ii) polypropylene macro fibers used at a dosage between 7.5 lb/yd^3 and 10.5 lb/yd^3 provided the greatest combination of fatigue, toughness and pre-notch fatigue performance, and (iii) the use of fiber reinforcement can result in a reduced pavement thickness.

Nayar and Gettu (2014) provided design guidance for fiber reinforced concrete pavement panels. This study summarized several stress versus cycle repetition models for FRC and then provided a model for determining the allowable pavement moment in terms of repetitions and stress ratios. This report uses the assumption that the limiting moment in the pavement is the sum of the positive plastic (cracked concrete strength) and the negative moment (uncracked concrete strength). Using this assumption, Equation 2 was developed, where the concrete's allowable moment capacity is calculated using reduction factors to account for the concrete's fatigue characteristics. Figure 3-4 gives an example of S-N curve; however, the authors note that S-N models should be used that correspond with the materials being used (i.e., fibers, aggregates, etc.).

$$M_{all} = (Xf_{clk} + Yf_{e,150})\frac{h^2}{6} \quad (2)$$

Where:

M_{all} is the allowable moment applied to the pavement

f_{clk} is the flexural strength of the concrete

$f_{e150,k}$ is the equivalent flexural strength ratio from ASTM C1609

h is the slab thickness

X and Y are the reduction factors for crack initiation and post crack regime

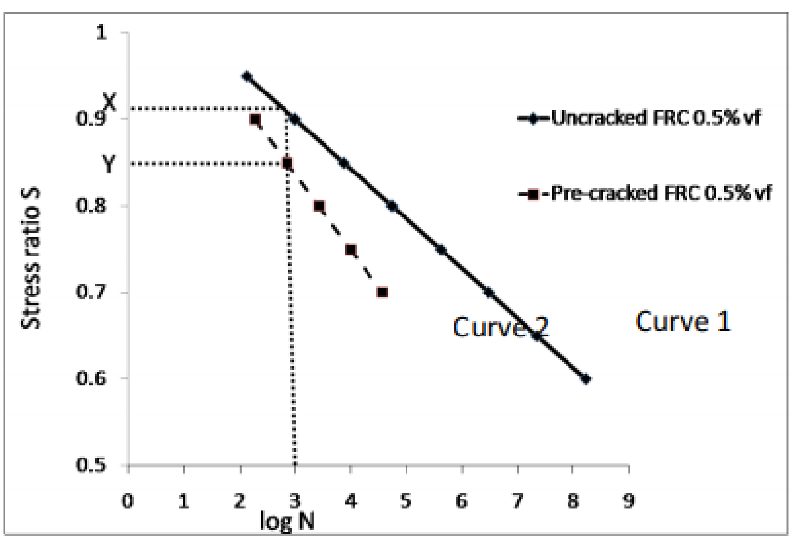


Figure 3-4. Example of a S-N chart to get reduction factors (Nayar and Gettu, 2014)

3.3.2 Reducing Joint Faulting

The University of Pittsburgh (Barman and Vandenbossche, 2014) conducted a finite element based study for bonded concrete overlay on asphalt (BCOA) to investigate the load transfer shared by the asphalt layer and the concrete overlay. It was found that 68% to 95% of the wheel load is transferred through the asphalt layer and the remaining load is transferred by the concrete slabs. Even though asphalt layer transfers a vast majority of the load, it is very important to achieve the load transfer through the concrete slabs especially to reduce the interlayer debonding. It was found that the debonding can increase the magnitude of the critical stress by up to a maximum of 40% to 55% (Barman et al., 2017).

In order to understand the contribution of structural fibers in increasing the load transfer efficiency (LTE), a comprehensive laboratory study was conducted (Barman and Vandenbossche, 2014). A small-scale LTE test procedure was developed with a vision to make the LTE evaluation task very simple and economical so that the test can be conducted using readily available laboratory resources or with a marginal investment. In the small-scale procedure, the LTE of concrete can be evaluated by using the conventional 24-in x 6-in x 6-in beam specimens. The test setup was designed to replicate the abrasive action that occurs on the joints of an in-service concrete pavement loaded with an 18-kip single axle load. The loading configuration in the small-scale test procedure was established through a finite element analysis. The small-scale test results were validated by comparing them with the LTE results from a large-scale study in which full-size slabs were used to test the LTE.

The LTE of plain concretes and fiber reinforced concretes were compared in the laboratory study. Two types of structural synthetic fibers were used in that study: (i) straight synthetic-Strux 90/40 fibers and (ii) crimped synthetic fibers- Enduro 600. Fiber dosages were selected based on the 20% residual strength ratio criteria as suggested in Roesler, 2008 study. Based on the literature data (mainly Illinois studies) on the residual strength ratio of fiber reinforced concrete, a correlation was developed between the RSR and fiber reinforced index. The volume fraction and dosages of the two fibers mentioned above are provided in Table 3-2. The LTE test results indicated that the straight synthetic fibers (Strux 90/40, see Figure 2-6a) and crimped synthetic (Enduro 600, see Figure 2-6b) exhibited somewhat similar LTE vs. crack width relationships. Overall, it was found that the structural fibers can increase the LTE of the concrete.

FRC prepared with 5.25 to 6.5 lb/yd^3 structural synthetic fibers transfer 20% more load than that can be transferred through the plain concrete slabs. As anticipated, LTE of FRC decreases with the increase in crack width and number of load applications. However, the structural synthetic fibers do not experience any significant fatiguing even after several million of load repetitions. The abrasion of the crack faces under the load repetitions were the main reason for the drop in the LTE. Also, the length of the fibers was sufficient enough as neither of the two fiber types was found to be pulling out of the concrete, even after millions of load applications.

Table 3-2. Volume fraction and dosages of two selected fibers in Barman (2014) study

Straight synthetic, STRUX: 90/40, 1.55-inch long		**Crimped synthetic, Enduro 600, 2 inch long**	
Volume fraction (percent)	Dosage (lb/yd^3)	Volume fraction (percent)	Dosage (lb/yd^3)
0.36	5.25	0.43	6.20

Arnold et al. (2005) studied the peak differential displacement, as a function of dosages, of hooked end steel fibers. It can be seen in Figure 3-5 that an increase in fiber dosage resulted in a decrease in peak differential displacement. In that study, the failure criterion was established as when the differential displacement reaches 0.06 inch. It can be seen that when the fiber was used in the concrete, failure occurs at a wider crack width (Arnold et al., 2005) indicating benefits of fibers in reducing the displacement or in other words in increasing the LTE. In addition to the above-mentioned studies, UMD's ongoing MnDOT funded FRC project is also investigating the contribution of synthetic fibers in increasing the joint performance. As the work is still in progress, this report does not include the results from that study.

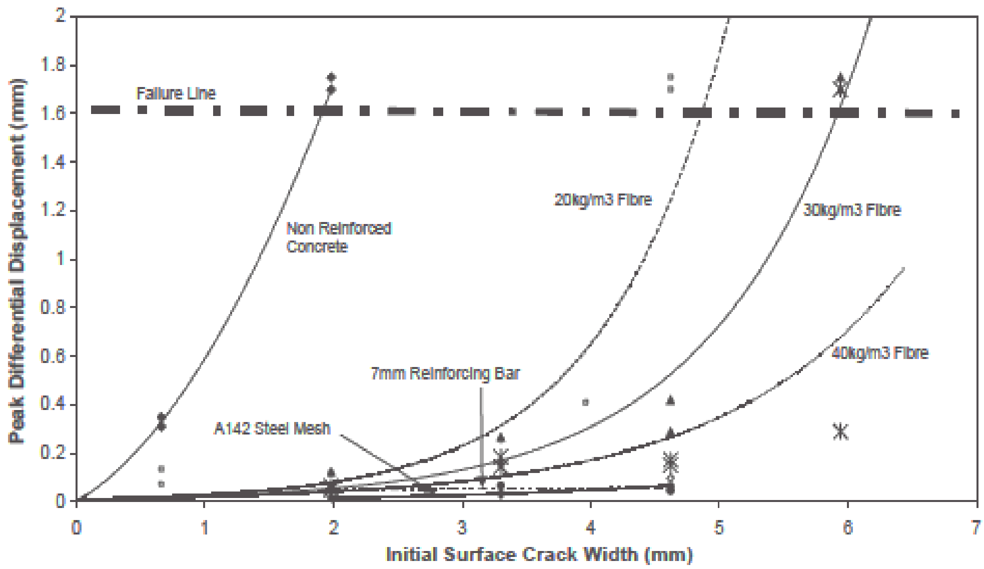


Figure 3-5. Effect of fiber reinforcement in peak differential displacement
(after Arnold et. al., 2005)

4 REVIEW OF OVERLAYS CONSTRUCTED WITH FRC

One of the important objectives of the task 1 was to collect information on the types and dosages of the structural fibers used and their contribution to the performance of concrete pavement/overlay projects. A survey questionnaire was developed and circulated to various states with a special emphasis on the NRRA participating states. Also, a similar survey was previously (in 2016) conducted for the UMD’s other MnDOT funded FRC study. Survey data collected in both these studies mentioned above and concrete overlay performance data available in other research reports are discussed in this chapter. At the time of writing this report, data has been collected from following states: Georgia, Illinois, Iowa, Kansas, Missouri, South Carolina, Virginia, and Oklahoma. Information on the MnROAD’s FRC concrete overlay cells were collected from the relevant MnDOT publications.

4.1 Georgia

Many ultra-thin overlays have been placed in Georgia as early as 1998, and FRC was used in the projects constructed between 2003 and 2010. Table 4-1 presents the details including project location, construction year, overlay thickness, fiber type, and dosage for these projects. It was found that all of these projects were constructed with 4 inch thick overlays using polypropylene fibers at a dosage rate of 3 lbs/yd^3. No information was available about the fiber geometry or performance of the fibers in these projects. However, the qualified fibers specification of the Georgia DOT was collected and summarized in Table 4-2.

Table 4-1. Details of fiber reinforced ultra-thin projects in Georgia (Wouter, 2016)

Project Name	Location	Year of Const.	Thickness (inch)	Dosage (lbs/yd^3)	Fiber type
US 82 / US 84	Ware	2003	4	3	Polypropylene
SR196 / SR119	Liberty	2005	4	3	Polypropylene
SR204	Chatham	2007	4	3	Polypropylene
SR4 & Woodlawn	Appling	2007	4	3	Polypropylene
US80 / SR26	Chatham	2007	4	3	Polypropylene
SR 99	Glynn	2008	4	3	Polypropylene

Table 4-2. Approved macro-synthetic fibers for concrete reinforcement for Georgia DOT (Wouter, 2016)

Source	Fiber trade name	Length (inch)	Aspect ratio, specific gravity, modulus of elasticity (ksi),tensile strength (ksi)
ABC Polymer Industries	(i)Tuf-Max DOT™ (ii) Performance Plus DOT™	1.5 or 2.0	(i) N/A, 0.91, 800, 70 (ii) N/A, 0.91, 800, N/A
BASF Corporation	(i) MasterFiber® MAC 100 (ii) MasterFiber® MAC Matrix	(i) 1.5 (ii) 2.1	(i) 59, 0.91, N/A, N/A (ii) 70, 0.91, N/A, 85
Elasto Plastic Concrete	Bar chip 48 (BC48)™	1.89	N/A, 0.90-0.92, 1450, 93
Forta Corporation	FORTA-FERRO®	1.5 or 2.25	N/A, 0.91, N/A, 83-90
Propex Operation Co., LLC	NOVOMESH® 950	1.8-varies	N/A, 0.91, N/A, N/A
The Euclid Chemical Corporation	Tuf-Strand SF™	2	74, 0.92, 1380, 87-94
W.R. Grace	Strux® 90/40	1.55	90, 0.92, 1378,90

N/A: information not available; all of the above-mentioned are structural synthetic fibers.

4.2 Illinois

Illinois Department of Transportation has used fiber reinforced concrete in approximately 25 ultra-thin and thin concrete overlay projects. Table 4-13 presents various details including overlay thickness, traffic, fiber type, and dosage for some of these projects. It was found that the thickness of these projects varied from 2 to 6 inches with a most common thickness of 4 inches. A majority of the projects used synthetic fibers at a dosage range between 3 lb/yd^3 and 7.5 lb/yd^3, except for few projects with steel fibers at a dosage range between 40 lb/yd^3 and 80 lb/yd^3. Based on the data collected through the survey (Personal communications: Wienrank, 2017 and Riley, 2016) and King and Roesler (2014), it was found that fibers have shown to reduce slab migration and joint separation, faulting, and increasing ride quality. Figure 4-1 shows one of such projects (North Lorang Road, Kane County) with a 4.5 inch thick FRC overlay and 4lb/yd^3 synthetic fiber, which was performing excellently and even exceeded the design life expectations, though it carries approximately 120 quarry trucks per day. The structural fibers have kept the joints tight and reduced the rate of crack deterioration. This overlay also did not experience any slab migration (Personal communication: Riley, 2016). Based on King and Roesler (2014) study, a few overlays in which fibers were not used experienced slab migration, as shown in Figure 4-2. It was also found that a loss of bond at the overlay and asphalt interface was the cause for some distresses in the non-fiber reinforced concrete overlays. The poor load transfer at the joints likely resulted in joint deteriorations. As mentioned above, the contribution of the synthetic fibers was well recognized in Illinois; thus, the Illinois DOT approved a few synthetic fibers for use in thin concrete overlays. The list of these fibers is presented in Table 4-5.

Figure 4-1. Picture of an excellent performing FRC overlay (ADT=120 trucks per day) (King and Roesler, 2014)

Figure 4-2. Slab migration at the outside longitudinal joint of a overlay project in Illinois (Schank Avenue, Mundelein: (King and Roesler, 2014))

Table 4-3. Details of FRC Overlay Projects in Illinois (Riley, 2016; ACPA, 2016; King and Roesler, 2014)

Project Name	Location	Year of Const.	Overlay Thickness (inch)	Average Daily Traffic	Fiber type	Brand	Dosage (lbs/yd^3)	Aspect Ratio
Stage Coach Trail Rd.	Stephanson County	1998	3	4500	Structural Synthetic	N/A	3	N/A
N/A	Mendota	1999	4.5	N/A	Structural Steel	N/A	80	N/A
Marion Street	Oak Park	2001	4	3470	Structural Steel	N/A	40	N/A
Jefferson streel Hybrid	Peoria	2002	3	12600	Structural Synthetic	N/A	3	N/A
Cook County Hwy. dept.	Chicago	2003	4	N/A	Structural Synthetic	N/A	N/A	N/A
Il DOT Dist. Parking Lot	Schaumburg	2004	2,3,4,6	N/A	Structural Synthetic	N/A	N/A	N/A
CO HW 6 Xenia Lola Rd	Clay County	2010	5	700	Structural Synthetic	GRT Advantage	4	N/A
Tower Hill	Shelby County	2010	5	1650	Structural Synthetic	GRT Advantage	4	N/A
Western University Dr.	Village of Lombard	2011	5	6700	Structural Synthetic	GRT Advantage	4	N/A
Il Route Old 66	N/A	2012	4	8600	Structural Synthetic	Strux 90/40	4	90
North Ind. Dr.	Village of Lombard	2014	4	3100	Structural Synthetic	Strux 90 /40	4	90

N/A: Information not available

Table 4-4. Details of FRC Overlay Projects in Illinois (Riley, 2016; ACPA, 2016; King and Roesler, 2014 (Continued..)

Project Name	Location	Year of Const.	Overlay Thickness (inch)	Average Daily Traffic	Fiber type	Brand	Dosage (lbs/yd^3)	Aspect Ratio
South Michigan Ave. Bus stops	Chicago	2004	4	Bus pads	Structural Synthetic	N/A	4	N/A
Kaneville Quarry entrance	Kane County	2004	4.5	80-120 gravel trucks	Structural Synthetic	N/A	4	N/A
Lake St. Glenview	Cook County	2004	4	27600	Structural Synthetic	N/A	7.5	N/A
Shank Ave	Mundelein	2005	4	11700	Structural Synthetic	N/A	4	N/A
Macomb	Macomb	2009	4	Commercial traffic	Structural Synthetic	N/A	4	N/A
Logan Co Hwy	Logan Co.	2009	5.25	N/A	Structural Synthetic	N/A	4	N/A
Gladstone	Henderson	2010	5	800	Structural Synthetic	N/A	4	N/A
County HW 9	Richland CO.	2010	5.5	550	Structural Synthetic	N/A	4	N/A
Left Ramp	Gilman	2011	4	N/A	Structural Synthetic	N/A	7.5	N/A
Finley Rd.	Village of Lombard	2012	5	N/A	Structural Synthetic	N/A	4	N/A
53 North Bound	Wilmington Center Point	2012	4	1350	Structural Synthetic	N/A	4	N/A

N/A: Information not available

Table 4-5. Qualified product list of synthetic fibers for Illinois DOT (September 2, 2016)

Source	Fiber Trade Name	Length (inch)	Aspect ratio, specific gravity, modulus of elasticity (ksi),tensile strength (ksi)
General Resource Technology	Advantage structural fiber	1.5 or 2	N/A, 0.91, N/A, 70
Propex	Fibermesh 650	Graded	96.5, 0.91, N/A, 70
ABC Polymer Industries	Tuf-Max DOT™	1.5 or 2	N/A, 0.91, 800, 70
BASF Corporation	MasterFiber® MAC Matrix	2.1	70, 0.91, N/A, 85
The Eucild Chemical Company	Tuf-Strand SF™	2	74, 0.92, 1380, 87-94
Forta Corporation	FORTA-FERRO®	1.5 or 2.25	N/A, 0.91, N/A, 83-90
GCP Applied Technology	Strux® 90/40	1.55	90, 0.92, 1378,90

N/A: Information Not Available

4.3 Iowa

The Iowa DOT has a significant history of using overlays as a rehabilitation technique but has few fiber reinforced concrete overlay projects on record. One known project exists on the SH-13 north of Manchester, IA and includes multiple research sections that utilize multiple fiber types (monofilament, fibrillated and structural at 1, 3 and 3 lb/yd^3, respectively). The overlay was constructed in 2002 and has needed very minimal repairs as of 2014. Later studies showed the significant bonding between the asphalt and overlay even though it was designed as an unbonded overlay ([2] Harrington and Fick, 2014).

4.4 Kansas

Several projects utilizing FRC were identified in Kansas that had mixed success. Several projects show little distress while others exhibited faulting, spalling and panel cracking. Table 4-6 presents a list of these projects and the known applicable data. These projects used polypropylene fibers at a typical dosage rate of 3 lb/yd^3. As of 2015, Kansas DOT has approved Tuf-Strand SFTM by Euclid Chemical Co. and Strux 90/40 by W.R. Grace & Company for use in their UTW sections.

Table 4-6. Whitetopping projects in Kansas (ACPA, 2016)

Project Name	Location	Year Const.	Overlay Thickness (inch)	Average Daily Traffic	Fiber Type	Dosage (lb/yd^3)	Comments
UTW 21st street East Witten berg	Topeka	1997	2, 3	1640	Polypropylene Structural	3	2" section has fair cracking. Bottom 1/3 of 3" is badly cracked
UTW Quivira rd. and Johnson Drive	Shawnee	1997	3	11720	Polypropylene Structural	3	Good
UTW Mission Road 83rd street NB appr.	Prairie Village	1998	3	17500	Polypropylene Structural	3	Overall the UTW is in good condition.
UTW Nieman rd 47th St.	Shawnee	1998	3	6100	Polypropylene Structural	3	Excellent Condition
UTW US 24, Rochester rd. to Kansas ave.	Topeka	1998	3.5	17400	Polypropylene Structural	3	Significant distress near Rochester rd. intersection. Several sections have been replaced
UTW central Ave. East 119th	Wichita	1999	3	5700	Polypropylene Structural	3	Excellent. Some patching accomplished
Rehabilitation US504 Lola and La Harpe	Lola	2000	2.8	4750	Structural	N/A	Significant faulting, some greater than ¼ inch. Significant cracking and spalling
UTW intersection Quivira amd 65th	Shawnee	2000	3	14000	Polypropylene Structural	3	Good. Distress is minimal.

N/A: Information not available

4.5 Minnesota

The state of Minnesota and local counties have a long history of using bonded and unbonded overlays to rehabilitate its roadways. There are or have been approximately 11 cells at MnROAD where fiber-reinforced thin and ultra-thin concrete overlays were constructed, observed, and tested until 2016; seven more cells have been constructed during last Summer and Fall (June to September, 2017). A test section was also constructed on US-169 near Elk River in 1997 on a very thin asphalt layer which provided a good conclusion on the minimum allowable thickness of the existing asphalt layer. See Table 4-7 for a list of known projects in Minnesota constructed with structural synthetic fibers.

4.5.1 MnROAD Cells 93, 94, 95 and 96

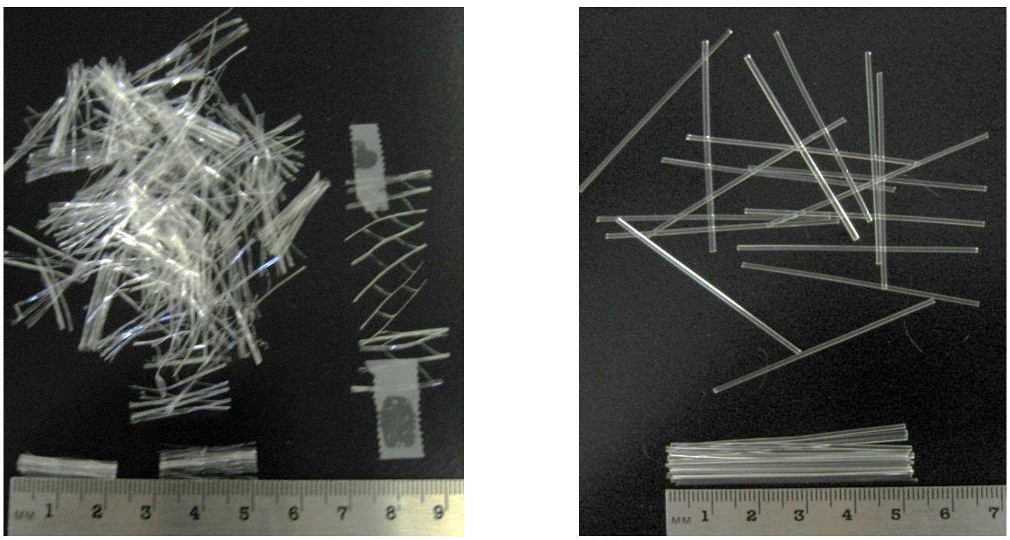
In 1997, six whitetopping cells (Cells 92 to 97) were built on I-94 at the MnROAD pavement test facility that used polypropylene and polyolefin fiber reinforced concrete. Among these cells, Cell 93, 94 and 95 were UTWs. The performance of these UTW cells and the other three TWT cells was found to be directly related to traffic volume, joint spacing and interface bonding. The importance of keeping the longitudinal joints away from wheel paths was understood from the performance data of these projects (Burham, 2005). To evaluate the contribution of fibers in the performance of the overlays, the LTEs of the two (Cell 94 and 95) of these cells were compared in this section. Cell 94 was constructed with non-structural polypropylene fibers, and the Cell 95 was constructed with structural polyolefin fibers. Figure 4-3 shows a picture of the two types of fibers used in the Cell 94 and 95. Joint LTE data for these two cells were compared to determine whether the slabs in Cell 95 exhibited higher LTEs than the slabs of Cell 94. It can be seen in Figure 4-4 that the LTEs in Cell 95 were always higher than the LTEs in Cell 94. Another observation is that the contribution of the fibers is greater in the winter when the crack width is larger. The slabs with structural fibers had tighter joints than those with the non-structural fibers. The non-structural fibers cannot keep the crack width narrower because of their low stiffness and tensile strength. During the summertime, when thermal expansion forces the joints to be relatively tight, the LTE for the two cells does not differ significantly. Therefore, it can be concluded that structural fibers contributed to increasing LTE, but non-structural fibers did not appear to provide any benefit to the slabs.

Table 4-7. Details of FRC Overlay Projects in Minnesota (Vandenbossche and Rettner, 1998; Vandenbossche, 2003)

Project Name	Location	Year Const.	Overlay Thickness (inch)	Average Daily Traffic	Fiber Type	Brand	Dosage (lb/yd^3)	Aspect Ratio
Cell 92	MnROAD	1997	6	14000	Polypropylene (non-structural)	Propex Fibermesh	3	N/A
Cell 93	MnROAD	1997	4	14000	Polypropylene (non-structural)	Propex Fibermesh	3	N/A
Cell 94	MnROAD	1997	3	14000	Polypropylene (non-structural)	Propex Fibermesh	3	N/A
Cell 95	MnROAD	1997	3	14000	Polyolefin (structural)	3M	25	50
Cell 96	MnROAD	1997	6	14000	Polyolefin (structural)	3M	25	N/A
Cell 97	MnROAD	1997	6	14000	Polypropylene (non-structural)	Propex Fibermesh	3	50
Cell 160	MnROAD	2013	5	28000	Synthetic (structural)	Propex Fibermesh	6.5	N/A
Cell 161	MnROAD	2013	5	28000	Synthetic (structural)	Propex Fibermesh	6.5	N/A
Cell 162	MnROAD	2013	4	28000	Synthetic (structural)	Propex Fibermesh	6.5	N/A
Cell 163	MnROAD	2013	4	28000	Synthetic (structural)	Propex Fibermesh	6.5	N/A
US - 169	Elk River	2013	3	16000	Varies: Polypropylene / polyolefin (structural & non-structural)	varies	3	50

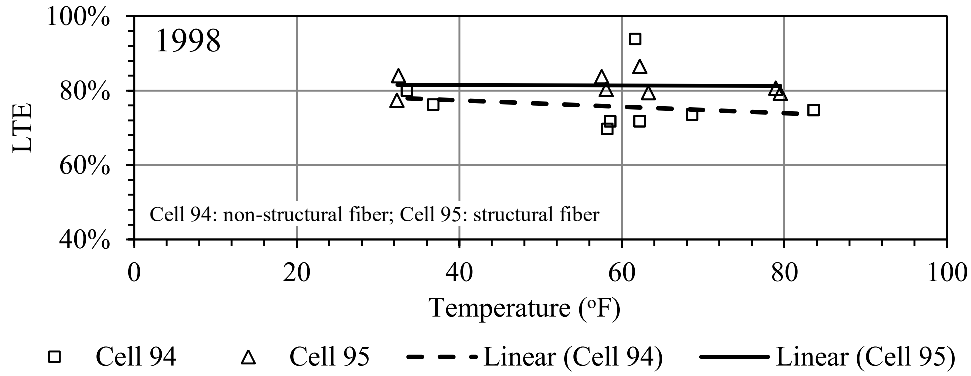
N/A: Information not available

It shall be noted, however, that Cell 95 was constructed with a fiber content that was much higher than the other projects reported in this study, which may not be cost-effective for larger projects. Also, it was found that Cell 96, which was adjacent to Cell 95 and contained 25 lb/yd^3 polyolefin fibers, developed joint faulting, leading to diamond grinding in the 14^{th} year of service. The exact reason for the joint faulting is not known, but the high fiber content in the concrete mixture might have accelerated the deterioration of the joints (Burnham and Andersen, 2015).

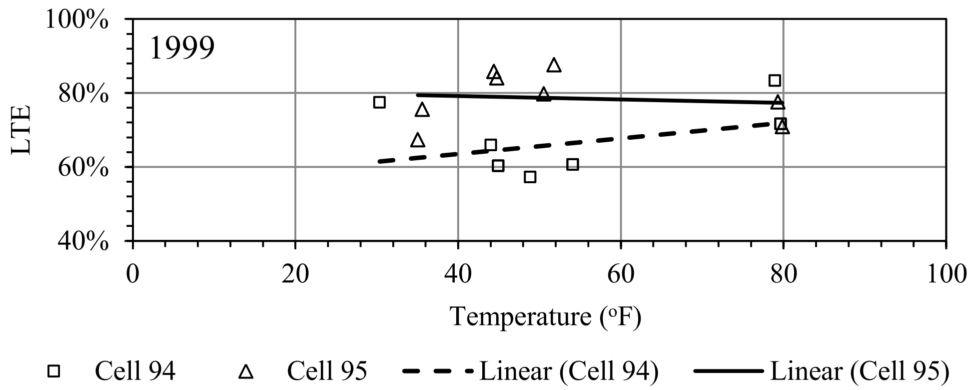


(a) (b)

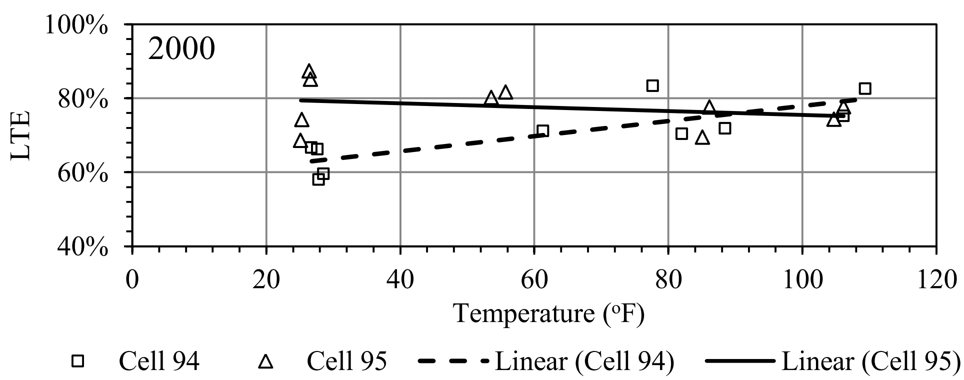
Figure 4-3. Picture of two types of synthetic fibers used in MnROAD Cells 94 and 95: (a) non-structural polypropylene and (b) structural polyolefin



(a)



(b)



(c)

Figure 4-4. Load transfer efficiency of MnROAD Cells 94 and 95 in (a) 1998, (b) 1999, and (c) 2000

4.5.2 MnROAD Cells 140, 160-163

In 2013, several asphalt pavement cells (previously 60-63) were constructed with bonded fiber reinforced overlays on the MnROAD mainline. These cells were constructed using Propex Fibermesh 650, a macro-synthetic fiber, for reinforcement. A dosage rate of 6.5 lb/yd^3 was used for this project. See Table 4-7 for further details on this project. These cells are still young, and some localized distresses were observed. Burnham and Andersen (2015) noted that the fibers are not contributing well in the failed section, at least in terms of holding the cracks together. Figure 4-5 shows a localized distress observed in Cell 162. This observation brings up the question whether 6.5 lb/yd^3 of fibers was a sufficient dosage or if the type of the fiber was not suitable. It may be noted that the dosages of the fibers were selected based on the 20% residual strength ratio criteria as suggested by the Illinois ultrathin concrete overlay design procedure (Roesler et al., 2008).

Figure 4-5. (a) Localized distress in Cell 162, (b) concrete broken to replace the slab (Burnham and Andersen, 2015)

4.5.3 US-169

The Minnesota Department of Transportation constructed three intersections with thin and ultra-thin overlays at US-169. These overlays were in Elk River near Jackson, School, and Main Streets. All of these projects contained either polypropylene or polyolefin fibers (Vandenbossche and Rettner, 1998). The existing asphalt was severely rutted and had locations of raveling. It was found that longitudinal deterioration significantly impacts the performance of these projects, because a quality bond between layers could not be obtained. Each test section also developed distinct cracking patterns that included corner breaks, longitudinal cracks and transverse cracks. These test sections showed that ultra-thin concrete overlays can be placed on as little as 3 inches of asphalt as long as the existing layer is uniform and is not susceptible to raveling. However, no concrete information was available to understand the contribution of the structural fibers in the US-169 project.

4.6 Missouri

A bonded concrete overlay project was conducted on US 60, near Neosho MO in 1999 that totaled 1.14 miles in length. In that project, two inches of existing asphalt was milled off and replaced with 4 inches of FRC. Panel cracking and IRI data are available for this project, and fiber benefits were observed. According to Donahue (2017), the fibers did not reduce panel cracking but did reduce crack widths and joint degradation. No faulting was observed on this project and may be related to the use of fibers.

Several other concrete overlay projects have also been conducted in Missouri that used FRC. According to Barman et al. (2011), those projects all utilized 3 lb/yd^3 polypropylene fibers, were 4 inches thick and included 3 ft x 3 ft and 4 ft x 4 ft panel sizes. According to available distress data, those sections had between 1.7 and 3 percent cracked panels. No data was available on joint faulting or crack widths.

4.7 Oklahoma

In Oklahoma, multiple FRC overlay projects were identified throughout the state. The Oklahoma ACPA chapter was contacted for information on those projects, but no significant information could be gathered. However, it was found that they are typically 5 inches thick and used fibrillated polypropylene fibers at a dosage of 3 lb/yd^3 (Burwell, 2016). Per the ACPA database, these projects are performing well, with little distress (ACPA, 2016).

A field performance investigation was conducted by Rotithor, 2010 on I-69 in areas between Atoka and McAlester. This study indicated that whitetopping can be effective even with heavy truck traffic. Some of these sections had thick asphalt layers (10 inches), which may have significantly contributed to the success of these projects. These projects were distressed primarily at the corners and at the transition of whitetopping and adjacent pavement (Rotithor, 2010).

4.8 South Carolina

In 1998 and 1999, three 4-inch concrete overlay projects were completed in South Carolina. These projects were specified to use chopped and fibrillated polypropylene fibers with a length of 1 to 2 inches, at a dosage rate of 3 lbs/yd^3 (Johnson, 2016). The rehabilitation of US-301 intersection at US-21 and the rehabilitation of US-21 at SC-48 were completed in 1999 with a 4-inch slab thickness and 3 ft. joint spacing. It was found that the existing asphalt was only 2 to 3 inches thick and that lead to significant distress soon after construction. The US-21/SC-48 project has a few minor cracks in the panels, and several panels at the stop are severely fractured, see Figure 4-6. The US-21 project has remained serviceable due to the fibers (Johnson, 2016).

The whitetopping project on SC-215 near Columbia, SC was completed in 1998 with 4 ft. panels. SCDOT considered using fibrillated and monofilament fibers for this project and found that the monofilament fibers provided a greater residual flexural strength. At current, 20-30% of the panels are cracked, and the serviceability is beginning to fail (Figure 4-7). It was noted that the panels would have come apart much sooner without the fibers (Johnson, 2016).

Figure 4-6. Intersection of US-21 and SC-48 (Johnson, 2016)

Figure 4-7. Whitetopping project on SC-215 near Columbia, SC (Google Maps, 2016)

4.9 Virginia

In 1995, Virginia DOT placed three test sections: I-85 near Petersburg, I-295 near Richmond and Route 29 South of Charlottesville, all bonded overlays but on different types of existing layers. The existing pavement on I-85 and I-295 was continuously reinforced concrete pavement (CRCP). These sections were overlaid with concrete to prevent spalling caused by an insufficient concrete cover over the reinforcement. The existing pavement on Route 29 was asphalt and was overlaid to correct rutted asphalt pavement. Overlay thicknesses varied between 2 and 4 inches and included 6 different fiber types. The fiber selection included hooked-end steel fibers, two different brands of monofilament polypropylene, a fibrillated polypropylene and two different polyolefin fiber lengths (Sprinkel and Ozyildirim, 2000).

Severe corner cracking was observed on Route 29 after the lanes were opened. Cracks in the transverse direction occurred on I-85 and I-295, but no patching was needed after 4 years of service, unlike Route 29 which was patched in 1999. Crack data from Route 29 indicated the highest percentage of cracking occurred in the polypropylene sections because the fibers were unable to hold the sections together. The sections that utilized polyolefin fibers exhibited good resiliency to minimizing cracking and crack width. The hooked-end steel fibers also had a high percentage of cracking. Data from Route 29 showed that the steel fibers were unable to hold sections together. The 5-year evaluation report of these sections concluded that concrete overlays can be successfully placed on both CRCP and asphalt pavement (Sprinkel and Ozyildirim, 2000).

4.10 Other States

A summary of FRC overlay project in other states and the corresponding information was extracted from Barman (2011) and provided in Table 4-8.

Table 4–8. Summary FRC project details in other states (Barman, 2011)

State	Project details	Year of Const.	Traffic (ADT)	Overlay Thickness, Inches	Fiber type and dosage (lb/yd^3)	Distress data
Pennsylvania	Intersection of State Route (SR)-133 and SR-100, Chester County	1988	36,079	4	Polypropylene, 3	N/A
Texas	Intersections on LP-250 at Wadley Road, Holiday Hill Road and Midland Drive, Midland	2005	26,650	3	Polypropylene, 3	A mid slab and corner cracks were observed after one or two years of construction which could be due to the heavy traffic and wheel path adjacent to the longitudinal joint.
Texas	Intersection of LP-250 at Midkiff Road and Garfield Road, Midland	2001	25,000	3	Polypropylene, 3	N/A
New York	Intersection at Waldon Avenue and Central Avenue, near Buffalo	2002	12,250	4	Polypropylene fibers, N/A	Corner cracks along the free longitudinal joints were found.
New York	NY-408 and SH -622, Rochester	2002	9,350	4	Polypropylene fibers, N/A	Corner cracks along the free longitudinal joints were found.
Michigan	Patterson Avenue, from 44th Street to 36th Street, Kentwood	2006	31,891	4	fibrillated polypropylene, 1.5	The overall performance of the project found good; however, there are few distress due to improper alignment of edge of existing asphalt layer and the joint between the white topping and full depth widening.

4.11 NRRA MnROAD Sections

To supplement existing data, new FRC cells were constructed at MnROAD in 2017. Table 4-7 presents a summary of the designs and materials used in these fiber-reinforced concrete pavement test cells. Out of the seven FRC cells (plus 1 control section without fibers), Cells 506 through 806 are thin pavement on grade mainly varying with the fiber content (0% to 0.75% volume fraction); Cells 139 and 239 are ultra-thin (3 inch) and thin (4 inch) concrete pavement on grade (city street design), respectively, mainly varying the panel thickness and an enhanced fiber dosage (See Table 4-7 for the dosage information); and Cells 705 and 805 are thin unbonded concrete overlays constructed with varied panel sizes and a standard fiber dosage (20% RSR). These cells were constructed during June-September, 2017. These cells are equipped with different types of sensors for measuring: (i) dynamic strain due to wheel load, (ii) strain induced by the environmental forces, (iii) temperature gradient, and (iv) joint movement.

Table 4-7. Summary of the 2017 NRRA MnROAD FRC Cells.

<table>
<tr><th>Cell number</th><th>Length (ft)</th><th>Pavement/ overlay Type</th><th>Underlying layer (constr. year)</th><th>Type of concrete/ fiber dosage*</th><th>Panel size W ft x L ft</th><th>Panel thickness (inch)</th></tr>
<tr><td>506</td><td>144</td><td rowspan="4">Thin pavement on grade</td><td rowspan="4">11 in. class 5Q aggregate base (2017)</td><td>Plain concrete</td><td rowspan="4">6 x 6</td><td rowspan="4">5</td></tr>
<tr><td>606**</td><td rowspan="3">138</td><td>FRC/ standard</td></tr>
<tr><td>706</td><td>FRC/ enhanced</td></tr>
<tr><td>806</td><td>FRC/ high</td></tr>
<tr><td>139</td><td>270</td><td>Ultra-thin Pavement on grade</td><td rowspan="2">6 in. class 5 aggregate base (2017)</td><td rowspan="2">FRC/ enhanced</td><td>6 x 6</td><td>3</td></tr>
<tr><td>239</td><td>273</td><td>Thin Pavement on grade</td><td>6 x 6</td><td>4</td></tr>
<tr><td>705</td><td>144</td><td rowspan="2">Thin unbonded overlay</td><td rowspan="2">Concrete (1993)</td><td rowspan="2">FRC/ standard</td><td>Driving: 14 x 12 Passing: 13 x 12</td><td>5</td></tr>
<tr><td>805</td><td>124</td><td>Driving: 6 x 12 and 8 x 12 Passing: 6 x 12 and 7 x 12</td><td>5</td></tr>
</table>

** Fiber dosages: standard - corresponding to 20% residual strength ratio (ASTM C1609); enhanced - corresponding to 30% residual strength ratio (ASTM C1609); high – corresponding to 0.75 fibers volume fraction.*
*** Even though the design thickness was 5 inches, the actual measured thickness was found to be 6 inches*

5 CONCLUSION

This report presented a discussion on (i) the properties of structural fiber reinforced concrete (FRC), (ii) use of FRC in mitigating the distresses of concrete pavements/overlays, and (iii) existing FRC concrete overlays in various states in the country. The required information was collected through (i) two surveys--one conducted under the scope of this project (2017) and the other conducted for an ongoing FRC related research project at UMD (2016), and also (ii) reviewing the open access publications and research reports. Several laboratory-based research studies concluded that fibers can improve the toughness and residual strength of the concrete and thus can mitigate the panel fatigue cracking. A research study conducted at the University of Pittsburgh concluded that fibers can increase the load transfer between the concrete slabs. From the literature review and survey, it can be stated that fiber reinforced concrete has been used in concrete overlays mostly with positive results. For some projects in which no benefit is shown, it is assumed that those projects were probably constructed with either insignificant fiber dosage or poor quality fibers or insufficient supporting layers. The following are some specific observations noted in this literature survey:

- Approximately 94 percent of the FRC overlays of this country were constructed with structural synthetic fibers.
- Structural synthetic fibers do not significantly improve the compressive strength, modulus of elasticity and modulus of rupture of concrete.
- The post-crack performance (residual strength and residual strength ratio) of synthetic structural FRC is improved with the increase in fiber dosages or fiber reinforcement index.
- The early-age property of the concrete can be improved by incorporating a good amount of (~8 lb/cy) structural synthetic fibers to minimize the traffic closure time.
- The geometry, length, aspect ratio and stiffness of synthetic fibers have a significant influence in improving post-crack properties of concrete. Crimped, embossed, or twisted fibers showed better performance than straight synthetic fibers.

Lastly, it may be stated that data collection process will be continued throughout the project duration. As the long-term goal of this project is quantifying and accounting the benefits of fibers, any field data comparing the distresses and performances of companion plain and fiber reinforced concrete overlays and slabs-on-grade would be immensely helpful in accomplishing the goal.

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