Overview of Fiber-Reinforced Concrete Bridge Decks

Final Report
March 2019

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16. Abstract This report summarizes the experience from existing bridge deck and bridge deck overlay construction projects that have employed fiber-reinforced concrete (FRC) materials. Included within this report is a summary of the laboratory and field performance of various FRC bridge decks along with key test methods and specification language developed by state departments of transportation. This document is a companion report to *Fiber-Reinforced Concrete for Pavement Overlays: Technical Overview*, which summarizes the state of the art regarding different fiber types, test methods, structural design, and the construction modifications required to accommodate FRC materials in concrete overlays.			
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OVERVIEW OF FIBER-REINFORCED CONCRETE BRIDGE DECKS

Final Report
March 2019

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INTRODUCTION

Fiber-reinforced concrete (FRC) has been implemented in various structural and pavement applications over the past several decades. For the purposes of this document, only FRC containing structural macrofibers is considered. All types of fibers (steel, synthetic, glass, and natural) have been utilized to enhance the performance of structural and non-structural elements of bridge decks. Nevertheless, limited guidance is available for the design and testing of FRC materials for bridge deck applications.

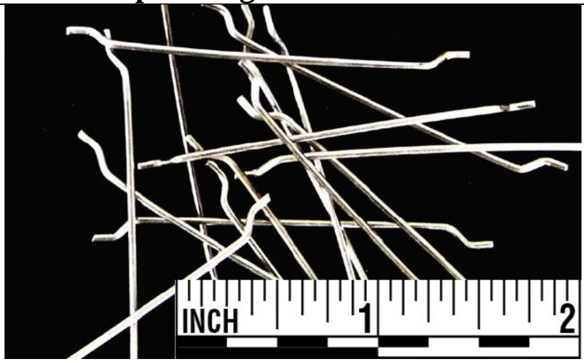
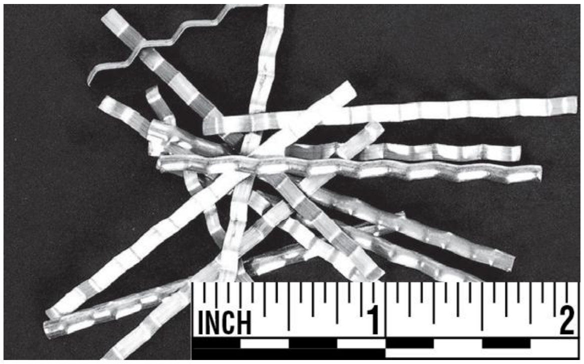
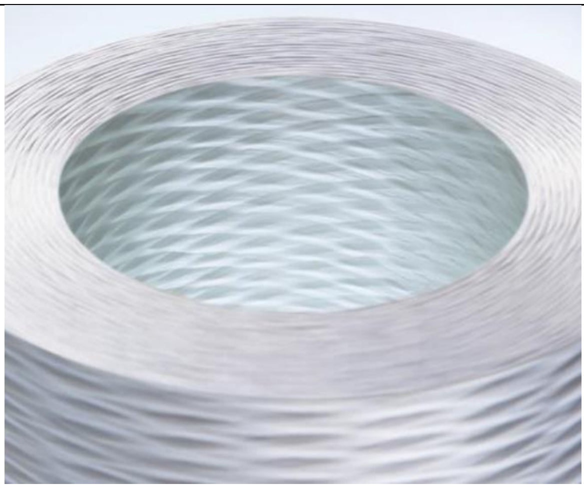
The primary objective in using FRC in bridge decks has been to reduce deck cracking and the widths of cracks resulting from repeated dead and live load applications as well as environmental factors. A reduction in bridge deck cracking has been observed at a variety of fiber dosage levels. At sufficiently high dosages (e.g., 1.0% by volume), macrofibers can significantly increase the post-cracking structural capacity of a deck in a fashion similar to that of reinforcing bars (Zollo 1975). However, the current state of the practice is not at a point where the increased structural capacity from macrofiber reinforcement is fully considered in the design process. Nevertheless, multiple states, e.g., California, Oregon, and Delaware, have required all bridge decks to be constructed using FRC, with the primary goal being to reduce deck cracking.

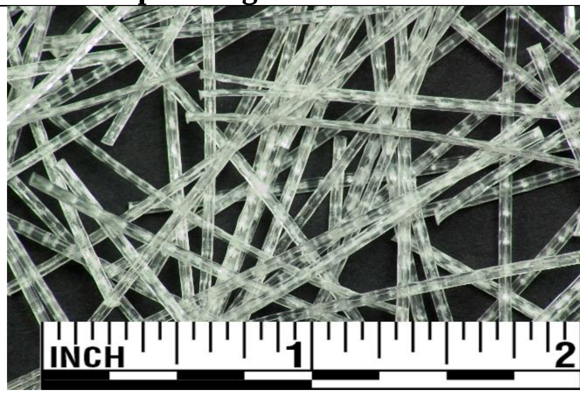
This FRC bridge deck document is a companion report to *FRC for Pavement Overlays* (Roesler et al. 2018), which provides an overview of the state of the art regarding different fiber types, test methods, structural design, and the construction modifications required to accommodate FRC materials in concrete overlays. The scope of the current report is to present existing bridge deck and bridge deck overlay construction projects that have employed FRC materials. Included within this scope is a summary of the laboratory and field performance of various FRC bridge decks along with key test methods and specification language developed by state departments of transportation (DOTs).

General Fiber Characteristics

While numerous fiber types and materials are available to engineers, the two most common fiber types used in bridge decks are steel and synthetic (plastic); glass and natural fibers, while available, have been used minimally. Table 1 lists the four general types of fibers specified in ASTM C1116. The sample images in Table 1 do not fully represent the significant physical variations (i.e., crimping, bent-end, twisted, etc.) that are available for each fiber type.

Table 1. General types of fibers per ASTM C1116

Type	Sample Images	Relevant Standard and Notes
I (Steel)	  Propex, Images Copyright © 2019 Sika Corporation https://fibermesh.com/our-fibers/steel-fibers/usa-canada-latam/	ASTM A820 Ends can be bent as in the first example image, or the entire length can be crimped as in the second example image.
II (Glass)	 © 2017 Owens Corning http://www.ocvreinforcements.com/uploadedFiles/Reinforcement/CemFil/Doc/10010692_Cem-FIL_5325_product_sheet_ww_06-2017_Rev8_EN.pdf	ASTM C1666 In some applications, glass fibers are chopped on-site from a spool as shown in the example image.

Type	Sample Images	Relevant Standard and Notes
III (Synthetic)	 Image Copyright © 2018 GCP Applied Technologies, Inc. https://gcpat.com/en/about/project-profiles/strux-strengthens-floor-top-quality-construction#challenge	ASTM D7508 (only for polyolefin fibers) The example image shows one of the many different types of fiber geometries available.
IV (Natural)	 Image Copyright © Solomon Colors, Inc. http://www.solomoncolors.com/Products/Ready-Mix/ReadyMixUltraFiber-500/	ASTM D7357 (only for cellulose-style fibers) The example image shows the typical delivery state of cellulose fibers.

Regardless of the material, a few universal terms are used to describe fibers. The aspect ratio describes the ratio of the length of the fiber to its width or diameter. The majority of fibers have aspect ratios in the range of 20 to 100. 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. Another set of terms used to describe fibers is straight and deformed, both of which describe the general shape of the fiber. A straight fiber is visually straight, although it may have various surface textures and embossings. A deformed fiber is one that has permanent out-of-plane deformations, such as hooks, loops, or bends, which enhance the mechanical interlock ability of the fiber within the cementitious matrix. Steel fibers are typically deformed, while synthetic fibers are often straight and smooth or straight with surface textures or embossings. This report focuses on macrofibers that are classified as steel (Type I) or synthetic (Type III), given that these are the most used fiber types for bridge decks.

Steel Fiber Characteristics

ASTM A820-16 classifies steel fibers based on the manufacturing process and whether the fiber is straight or deformed. The five manufacturing processes are cold-drawn wire, cut sheet, melt-extracted, mill cut, and modified cold-drawn wire. Fibers made from any of these processes can be either straight or deformed. Regardless of the manufacturing process or the physical characteristics of the fiber, all steel fibers must meet a minimum average tensile strength of 50,000 psi, with no single fiber failing below 45,000 psi. No other requirements are explicitly stated in the standard.

Synthetic Fiber Characteristics

Similar to steel fibers, a variety of straight and deformed synthetic fiber types are available (Figure 1).

Jerod Gross

Figure 1. Synthetic macrofibers for concrete

Numerous specifications use the term polyolefin to specify synthetic fibers because this is the term used in ASTM D7508-10. The term polyolefin is broad, and ASTM D7508-10 specifies that this term is used to describe any long-chain polymer containing at least 85% by weight ethylene and/or propylene monomer units. This means that polypropylene and polyethylene are two types of polymers that are acceptable for use as synthetic fibers in concrete mixtures.

The general requirements for macro synthetic fibers according to ASTM D7508-10 (reapproved 2015) are that the individual fibers have a diameter greater than or equal to 1/8 in. and a tensile strength greater than 50,000 psi. The cut length can be between 1/2 in. and 2.5 in. Fibers are usually added to the concrete mixture in dissolvable paper bags or in bundles with dissolvable glue. A few states explicitly outline the method for adding fibers to the mixture.

Ultra-High Performance Concrete

Nearly all types of commercially available ultra-high performance concrete (UHPC) mixtures contain significant volume fractions of fibers. There are several definitions of what constitutes UHPC. The Portland Cement Association (PCA) states that UHPC is any cementitious material that has a compressive strength greater than 17,000 psi (PCA 2018), while the Federal Highway Administration (FHWA) defines UHPC as any cementitious material with a water-to-cementitious materials (w/cm) ratio less than 0.25 and a compressive strength greater than 21,700 psi (FHWA 2018). Steel fibers are primarily utilized in UHPC mixtures, but synthetic and carbon fibers are also used in addition to or as a replacement for steel fibers.

Various UHPC mixtures have been used in bridge deck construction. The FHWA has published multiple documents on the topic, most notably a comprehensive review by Russel and Graybeal (2013). Other notable research and design guidance on UHPC for bridge deck construction is provided in a report by Aaleti et al. (2013). Given the uniqueness of UHPC and because most of the implementation has been done using commercial products or generic packaged alternatives, UHPC is not discussed in the present report.

FRC MATERIALS FOR BRIDGES: TESTING AND IMPLEMENTATION

A number of research studies and field projects have examined FRC materials for bridge decks. This chapter provides a brief summary of published laboratory research on FRC materials for bridges and field applications of FRC for either new bridge decks or bridge deck overlays. Several DOTs have led the effort to implement FRC for bridge decks, with California being the most progressive in mandating that all bridge decks, regardless of type, incorporate macrofiber reinforcement. By far the most common application of FRC materials has been for thin concrete overlays on existing bridge decks.

Laboratory Testing

In the mid-1970s, Zollo (1975) examined the feasibility of using steel fibers in orthotropic bridge deck systems. Conventionally reinforced portland cement concrete (PCC) exceeded the thickness at which it was economical to use concrete instead of asphalt concrete mixtures for orthotropic bridge decks. Chopped high-strength steel wire with a diameter of 0.015 cm and a length of 1.27 cm that was coated in brass was used at a dosage rate of 2% by volume to create an FRC mixture. For an orthotropic bridge deck with grating, it was suggested that the tested FRC material may only need to be 2.54 cm thick.

In a 2004 laboratory study, Naaman and Chandrangsu (2004) examined the application of a high-performance fiber-reinforced concrete composite (HPFRCC) for bridge decks. Following the current American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) specifications, the proposed deck design would have required 1.28% steel reinforcement by volume. The researchers proposed a hybrid design using 0.4% conventional reinforcing steel and 1.5% high-density polyethylene (HDPE) macrofibers by volume. Compared to the control specimen with reinforcing steel in the upper and lower portions of the composite beam, the specimen with reduced reinforcement and macrofibers exhibited a lower peak load capacity but a 60% increase in post-peak load capacity.

The Oklahoma DOT (ODOT) funded a research project to examine bridge deck cracking and the role that FRC can play in reducing cracking percentage and crack widths (Ramseyer and Myers 2009). Concrete mixtures with four different synthetic fiber types were tested for compression, tension, flexure, and unrestrained drying shrinkage. It was found that the inclusion of fibers either maintained or enhanced the strengths measured compared to mixtures without fibers. The dosage range for each fiber type varied, and the conclusion was that any of the macrofibers should be able to reduce cracking percentage and crack width. No field study was performed to complement the laboratory study.

A comprehensive laboratory study examining fiber-reinforced bridge deck overlays was conducted by researchers at Indiana University – Purdue University Fort Wayne for the Illinois DOT (IDOT) (Alhassan 2007; Alhassan and Ashur 2012, 2011; Alhassan and Issa 2010). Three types of bridge deck overlay materials were examined, including latex-modified concrete (LMC), microsilica concrete (MSC), and fly ash concrete (FAC), along with seven different synthetic fiber types, four of them macrofibers. Based on IDOT’s previous experience with FRC, the total fiber dosage was limited to 3 lb/yd^3 regardless of the combination or type of fiber used for a particular mixture. The LMC was the primary mixture examined and therefore had the largest number of trial fiber type combinations, including blends of micro- and macrofibers. Even with a relatively low fiber dosage (3 lb/yd^3), all three mixture types exhibited improvements in drying shrinkage behavior (up to 15% reduction) and residual strength, with a maximum strength of 75 psi. Alhassan and Ashur (2012) noted that blending micro- and macrofibers together may help reduce early and long-term cracking.

With respect to bridge decks, electrically conductive concrete can facilitate deicing through resistive heating. Several researchers have created unique combinations of steel fibers with metal shavings to produce electrically conductive concrete mixtures (Tuan 1999, Xie et al. 1996, Yehia et al. 2000). In one trial mixture, steel fibers were added at a volume percentage of 1.5%, with the metal shavings introduced at 20% by volume. Upon application of an electric current, the system had a power consumption of 516 W/m^2 while raising the temperature of the 1 ft by 1 ft by 2 in. thick trial slab from -1.1°C to 15.6°C in 30 minutes (Yehia et al. 2000).

Fiber-Reinforced Bridge Deck Overlays

FRC applications for bridge decks have commonly been in the form of FRC overlays with steel or synthetic fibers; some studies have evaluated bridge decks constructed using FRC, but that type of application has been less common. The details of individual projects vary significantly because of variations in local materials, the varying levels of engineering expertise required for different projects, and a lack of formal design procedures for FRC bridge deck overlays. Additional details on the design of FRC overlays can be found in the companion report, *FRC for Pavement Overlays* (Roesler et al. 2018).

The following summarizes the experience from a variety of projects in several states that have used FRC for bridge deck overlays:

- In 1984, the New Mexico State Department of Highways and Transportation tested a slurry-infiltrated fiber concrete (SIFCON) bridge deck overlay. The steel fiber content was 10% by volume. Unlike traditional concrete mixtures, SIFCON introduces the cement slurry (typically without coarse aggregates) over the extremely high volume of fibers. After six years, no cracking or corrosion was observed in core samples, but surface abrasion was a noted issue. It was recommended that a high-friction layer be added to the SIFCON overlay immediately after or during construction (Krstulovic-Opara et al. 1995, Mondragon 1984, Schneider 1992, Schneider et al. 1984).
- In 1992, the Ohio DOT used FRC for a bridge deck overlay on US 30. Steel macrofibers with a 2 in. length were dosed at 0.8% by volume without any significant cracking noted during the observation period (Baun 1993, Krstulovic-Opara et al. 1995).
- During the winter of 2000, a test section in Virginia was constructed that consisted of two bridge decks with and without fibers (Ozyildirim 2005). Synthetic fibers were dosed at a rate of 8.75 lb/yd^3 (0.5% by volume). Four visits over the subsequent five years revealed that at the end of the five-year period, the average crack length decreased by 60% and the average crack width decreased by 45% due to the addition of macrofibers. Another bridge constructed

in Virginia, the Linville Creek Bridge over State Route 1421, used a combination of shrinkage-reducing admixtures (SRAs) and synthetic macrofibers at a dosage rate of 3 lb/yd^3 (0.2% by volume) to reduce bridge deck cracking (Nair et al. 2017). After 14 months, the bridge deck was surveyed and was found to exhibit crack densities similar to those of other bridges in Virginia that employed shrinkage-reducing techniques.

- During 2006 and 2007, a number of bridges on the Dan Ryan Expressway in Chicago, Illinois, were overlaid with a microsilica concrete that contained polypropylene macrofibers with a specified dosage rate of 3 lb/yd^3 (0.2% by volume). During an earlier demonstration on one of the bridges, it was noted that the finishers were unable to properly finish the surface when the dosage rate was 4 lb/yd^3 (0.25% by volume). It was suggested that the smaller aggregates in the microsilica concrete overlay mixture had insufficient mass to disperse the fibers, which resulted in significant fiber balling (Alhassan and Ashur 2012).
- In 2007, the Pit River Bridge on I-5 over Shasta Lake, California, underwent a deck-on-deck rehabilitation. Several different concrete mixtures, one of which was an FRC mixture with an SRA, were used at various longitudinal locations of the bridge. The polyolefin macrofibers for the FRC mixture were dosed at 3 lb/yd^3 (0.2% by volume), with the SRA dosage ranging from 0.75 to 1.5 gallons/yd^3. After five years, this deck area exhibited little cracking, and cores taken at the crack locations revealed that the cracks were arrested near the surface (Figure 2). A companion section on the bridge without SRA or macrofibers exhibited significant cracking within six weeks of opening (Maggenti et al. 2013).

Fereira 2013, 2014, Caltrans

Figure 2. Reinforcing steel layout of deck-on-deck overlay (left) and cores taken after five years at cracked locations showing arrested cracks near the surface (right)

- In 2010, two overlay sections consisting of LMC mixtures with and without glass macrofibers were constructed on a bridge over the EJ&E railroad along Irving Park Road in Chicago, Illinois. The existing bridge surface, constructed in 1986, was prepared using hydro-demolition. The LMC overlay section with glass macrofibers utilized a dosage rate of 2.4 lb/yd^3 (0.1% by volume) of monofilament alkali-resistant glass. There were no reported issues with construction or finishing. When the bridge deck overlay sections were examined one year after construction, no cracking was observed in the fibrous section while hairline cracks were observed in the section without fibers (Alhassan and Ashur 2012).
- In 2011, a bridge on Illinois Route 106 over the Sny River was overlaid with an FRC mixture with a relatively low dosage rate of 3 lb/yd^3 (0.2% by volume) of polypropylene macrofibers.

The macrofibers were charged to the mixture via water-soluble bags. Prior to application of the FRC overlay, the deck surface was prepared using hydro-demolition. During construction, the resident engineer noted that the fibers stuck to the float when the concrete was fresh. However, when floating was delayed slightly, fewer fibers stuck to the float. One week after construction, no cracking was visible upon inspection (Alhassan and Ashur 2012).

- In 2011, a 5 in. deck overlay was constructed on a bridge over Craig Creek on State Route 99 near Red Bluff, California. Similar to the previous FRC deck constructed in California on the Pit River Bridge, an SRA was used in addition to the synthetic macrofibers. The SRA was added at a dosage rate of 0.75 gallons/yd^3, and the macrofibers were added at a dosage rate of 3 lb/yd^3 (0.2% by volume). The concrete mixture, which used 705 lb/yd^3 of portland cement and had a three-day minimum strength of 4,000 psi, was opened to traffic three days after construction. After 14 months, no cracking was visible in the deck overlay (Maggenti et al. 2013).
- In December 2018, the High Bridge in St. Paul, Minnesota, was opened to traffic after a deck rehabilitation project. The deck overlay incorporated 5 lb/yd^3 of synthetic macrofiber (Figure 3).

Figure 3. High Bridge, St. Paul, Minnesota

Due to the success of the two field projects in California, language regarding both new construction and overlays for bridge deck applications was added to California's specifications in 2016. In most cases, the new language requires the use of FRC mixtures for bridge decks, among other changes (see Appendix A). It has been estimated that the implementation of FRC and SRA could reduce the maintenance costs of bridges in California by $480 million over 10 years (Fereira 2013). The cost of incorporating FRC and SRA has been estimated to increase up-front costs from $0.60 to $0.80 per square foot (Fereira 2013).

Another state with significant experience in researching and implementing FRC bridge deck overlays is South Dakota. During the 1990s, the South Dakota DOT (SDDOT) sponsored several research studies to evaluate the performance of FRC overlays and develop design specifications.

The first of these bridge overlay projects was conducted in 1994 for an overpass over I-90 at Exit 212 near Spearfish, South Dakota (Ramakrishnan and Deo 1998). The FRC deck overlay was 330 ft by 40 ft. Polyolefin macrofibers were added to the mixture at a dosage rate of 25 lb/yd^3 (1.7% by volume). With such a high dosage rate of macrofibers, balling was a major concern. However, this high dosage was achievable because of the unique fiber bundling introduced by the manufacturer, which allowed for good dispersion during the mixing process. During construction, no surface defects in the FRC overlay were observed. However, approximately six months after construction, fiber clumps became exposed in the deck surface. These fiber balls occurred in locations where inadequate mixing and dispersion of the fibers had been noticed during construction. After nearly two years in service, a total of 44 cracks were counted, with only 12 of the cracks having widths greater than 0.007 in. (Ramakrishnan and Deo 1998). The recommendation at the time (ACI Committee 224 1990) was that the maximum crack opening for a deck exposed to deicing chemicals should be no more than 0.007 in. (0.2 mm).

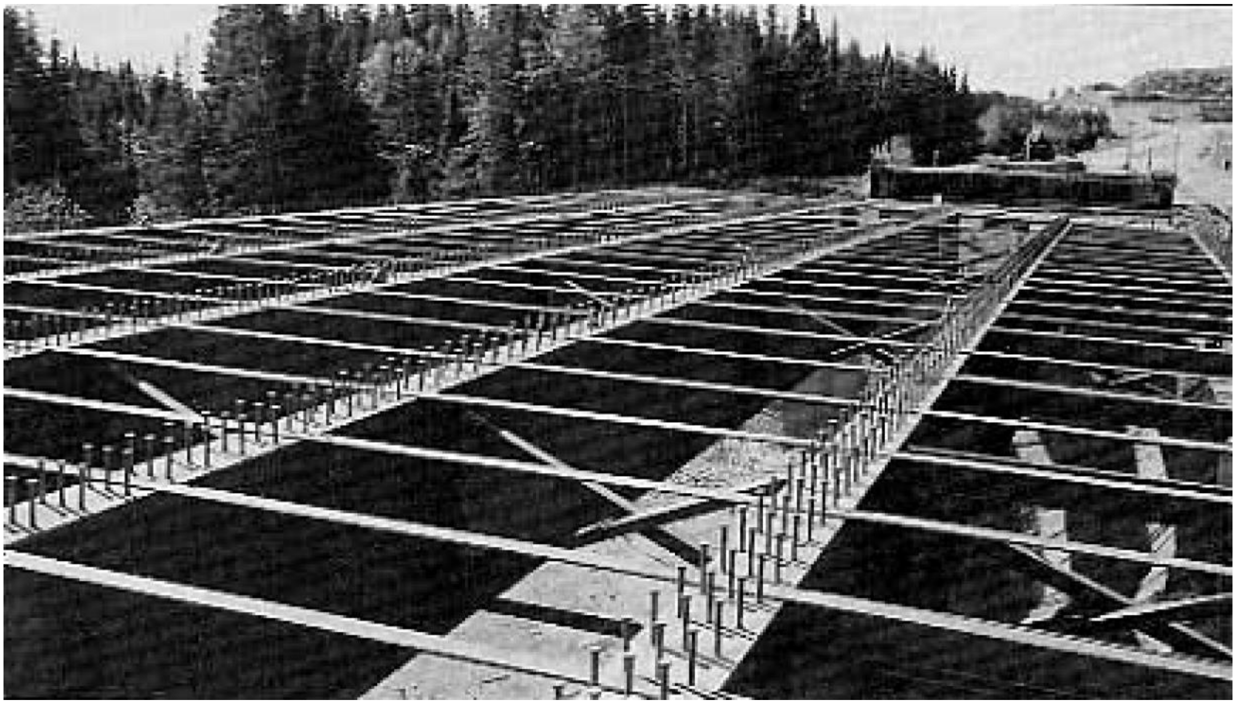
The conclusion from this first trial in South Dakota was that the addition of macrofibers did not adversely affect the fresh properties or the pumpability of the concrete mixture. Surprisingly, no superplasticizers were added to this high-volume-fraction FRC mixture. Ramakrishnan and Deo (1998) stated that it may be possible to increase the fiber dosage so that all overlay cracking above a threshold width of 0.007 in. could be eliminated (Ramakrishnan and Deo 1998).

Based on the results from the 1994 bridge deck overlay project, SDDOT commissioned a second research project. For this project, two decks at Exit 32 on I-90 were overlaid with FRC (Ramakrishnan 1998, Ramakrishnan and Santhosh 2000). The same macrofiber type and dosage used in the previous SDDOT project were applied. One difference was that SDDOT desired to use a mobile mixer for batching the FRC. Because of the presence of macrofibers, mobile mixing was difficult, and the FRC was subsequently batched and mixed at a ready-mix concrete plant. Future projects would not be able to utilize mobile mixers because of concerns with achieving the proper fiber dosage. Overall, the performance of the second FRC overlay project in terms of crack percentage and crack width was observed to be similar to that the original project.

Fiber-Reinforced Concrete Bridge Decks

A review of the literature revealed only a single project in which a bridge deck was designed with FRC and without conventional reinforcing steel. Opened in December 1995, the Salmon River Bridge, which is part of the Trans-Canada Highway, incorporated polypropylene macrofibers as the primary reinforcement (Newhook and Mufti 1996). Companion sections were designed with steel reinforcing bars following traditional deck design procedures. The motivation to remove the steel reinforcing bars from the bridge deck came from the bridge deck’s location with respect to the ocean, which made the deck susceptible to saltwater corrosion from wind-driven ocean spray. In addition, its northern location meant that significant amounts of deicing salts would be applied during the winter months.

The FRC bridge deck, while containing no reinforcing bars, did employ welded steel straps to connect the steel girders (Figure 4).

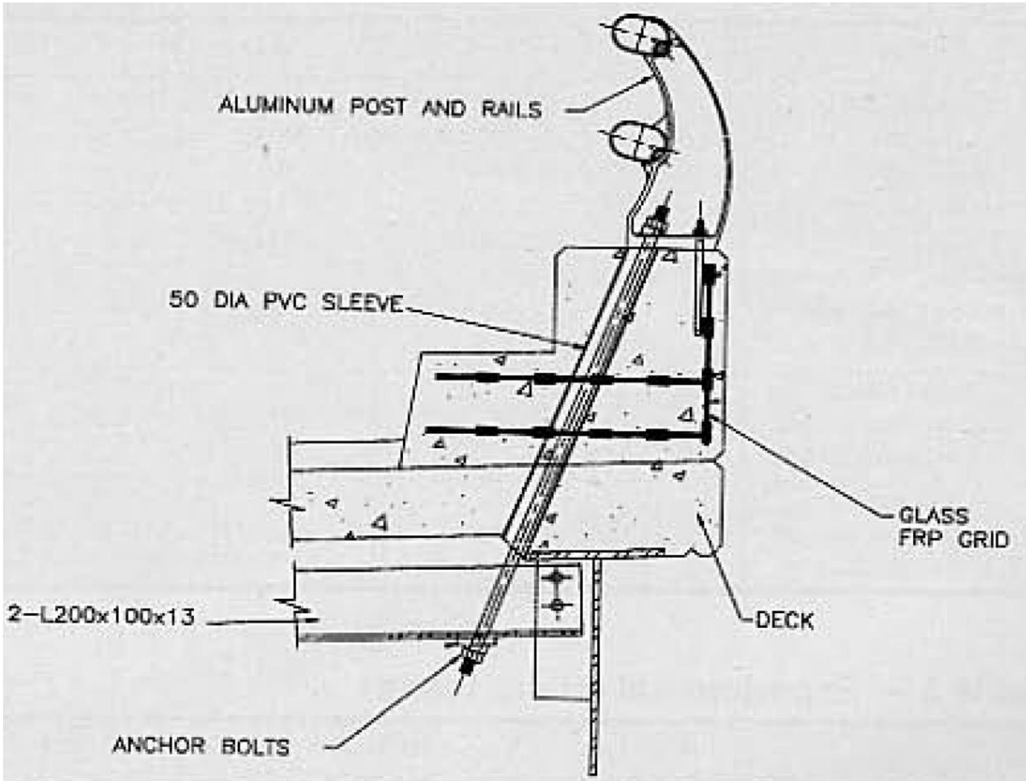


Newhook and Mufti 1996, authorized reprint from the American Concrete Institute

Figure 4. Steel girders prior to FRC deck construction, with welded steel straps continuous across the steel girders

The concrete mixture used for the FRC bridge deck section was not significantly modified from a conventional deck mixture, with the exception of the addition of macrofibers. During laboratory testing, a mixture created at the proposed polypropylene macrofiber content of 0.8% by volume was difficult to place and finish. The researchers studying the bridge (Newhook and Mufti 1996) recommended reducing the macrofiber dosage to 0.55% by volume, which was the dosage ultimately applied to the bridge deck project.

Because the portions of the bridge with FRC did not use anchoring steel for the parapet and post/rail structure, a novel system was developed to sufficiently anchor the parapet and post/rail structure to the bridge structure (Figure 5).



Newhook and Mufti 1996, authorized reprint from the American Concrete Institute

Figure 5. Parapet and post design for FRC bridge deck

In order to minimize corrosion potential, all of the reinforcing steel in the parapet wall was replaced with glass fiber-reinforced plastic (FRP) bars. For this particular project, it was noted that alkali-silica reaction (ASR) was not a concern, which justified the application of the glass FRP over other materials such as carbon fiber.

A cost analysis was able to be done for the project because companion sections were constructed at the same time whose costs could be compared. The cost of construction for the traditional bridge deck was \$143/m^2 (CAD), while the cost of the FRC deck was \$152/m^2 (CAD). The cost of the concrete for the traditional section was \$420/m^3 (CAD), while the cost of the FRC mixture was \$542/m^3 (CAD). Newhook and Mufti (1996) noted that the increased price of the FRC section resulted from several factors, including the contractor building in contingency for a novel construction process, and that the prices reflected pre-construction estimates and not actual post-construction costs.

Based on successful completion of the project, Newhook and Mufti (1996) made several recommendations, including that (1) the deck thickness could be reduced from 8 to 7 in. and (2) the macrofiber dosage could be reduced from 0.55% to 0.40% by volume. However, these recommendations have not been implemented into subsequent bridge decks.

CURRENT STATE OF THE PRACTICE

There is not a single dosage rate that is recommended for all FRC materials used for bridge decks. Rather, macrofiber content varies depending on the fiber's material, shape, texture, and aspect ratio; the field application; and the desired composite performance. Typical ranges used for previous bridge deck applications have been between 3 and 8 lb/yd^3 for polyolefin fibers and between 20 and 90 lb/yd^3 for steel fibers, which correspond to volume percentage ranges between 0.2% and 1% for both polyolefin and steel fibers.

Many states require the macrofiber dosage for FRC bridge deck applications to be determined based on a residual strength test, which is similar to the requirement for FRC pavement overlays (Roesler et al. 2018). The residual strength test provides an assessment of the fiber's ability to resist pullout from the concrete matrix, slow crack growth, and absorb fracture energy. The two most commonly specified tests are ASTM C1399 and ASTM C1609. ASTM C1399 utilizes a steel plate underneath a flexural beam, which is removed after the peak load is reached. The subsequent loading of the beam without the steel plate is measured, and an average residual strength (ARS) value is calculated. This test is not currently recommended by the American Concrete Institute's (ACI's) *Guide to Design with Fiber-Reinforced Concrete* (ACI Committee 544 2018). In contrast to ASTM C1399, ASTM C1609 requires a closed-loop system to execute the flexural beam test (Figure 6). This test method provides a better indication of the performance of the macrofibers in combination with the concrete material selected and therefore is the preferred method (ACI Committee 544 2018).

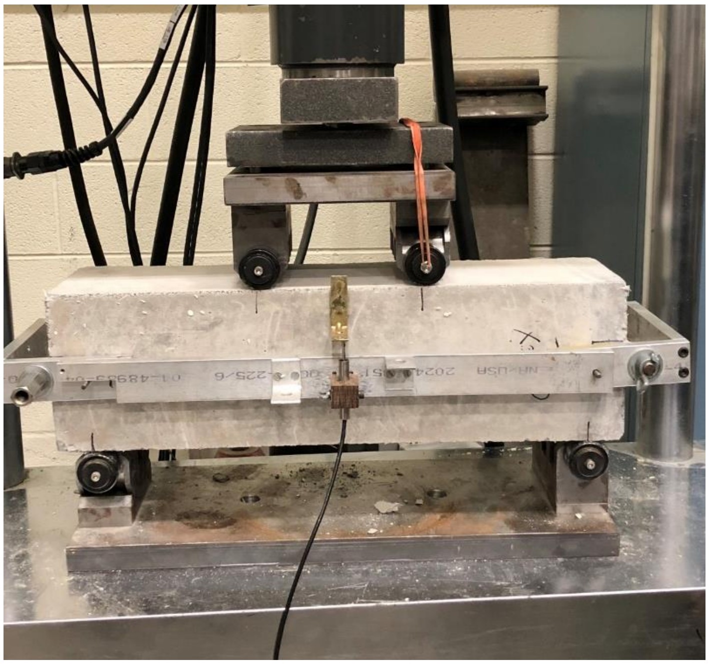


Figure 6. ASTM C1609 beam test for FRC materials

In ASTM C1609, a residual strength (f_{150}^{D}) value and equivalent flexural strength ratio ($R_{T,150}^{D}$) are calculated based on monotonic loading of a beam specimen until 1/8 in. of deflection is achieved. Note that past versions of ASTM C1609 referred to residual strength as $f_{e,3}$ and the residual strength ratio as $R_{e,3}$. Additionally, a 2019 revision to ASTM C1609 specifies that the roller type to use for the beam supports should be that specified in ASTM C1812.

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 (Table 2). Special provisions were also examined when available.

Table 2. Summary of state DOT specifications and/or special provisions for the use of macrofibers in bridge decks and overlays

State/Agency	Year	Section	Notes
Alabama	2018	N/a	None.
Alaska	2017	N/a	None.
Arizona	2008	N/a	None.
Arkansas	2014	N/a	None.
California	2015[1]	51-1.02B	"Concrete for concrete bridge decks 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	2017	601.03	"Where Fiber-Reinforced Concrete is specified…a minimum of 3.5 pounds per cubic yard of polyolefin fiber reinforcement…shall meet the requirements of ASTM C1116 and ASTM D7508." "Where Macro Fiber-Reinforced Concrete is specified…a minimum of 4.0 pounds per cubic yard of macro polyolefin fiber reinforcement…showing the mix design has a residual strength of 170 psi as determined in accordance with ASTM C1609."
		601.05	"Concrete for bridge sidewalk shall be Macro Fiber-Reinforced…"
		606.02	"Concrete for bridge rail shall be Macro Fiber-Reinforced…"
Connecticut	2018	N/a	None.
Delaware	2016	1022.01.3	"Use fibers that conform to the requirements of ASTM C1116, Type III with a minimum fiber length of 1/2 in. and a maximum length of 1 1/2 in."
		1022.03.2	"…concrete for decks require the use of nonferrous reinforcement fibers at a rate of 1.5 pounds per cubic yard."
		1046.02.2	For microsilica overlays: 1.5 lb/yd^3.

State/Agency	Year	Section	Notes
Florida	2018	Dev. Spec. 346-FRC	Allowable fiber types are polymeric, steel, and basalt. "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	2016	N/a	None.
Hawaii	2005[2]	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.
Illinois	2018	N/a	"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 ($R_{150,3}$) of 20.0 percent according to Illinois Modified ASTM C1609. The maximum dosage rate shall not exceed 5.0 lb/yd^3 (3.0 kg/m^3), 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." See Appendix B.
Indiana	2018	N/a	Fibers on approved material list
Iowa	2018[3]	Special Provision BRFN-018-3(100)-39-55	For ultra-high performance concrete overlays: "Steel Fibers - ASTM A820, Type 1, cold drawn high-carbon steel with a minimum tensile strength of 300 ksi, length of 12 to 13 mm, and diameter of 0.220 to 0.225 mm. Minimum steel fiber content will be 3.25% of the mix's dry volume."

State/Agency	Year	Section	Notes
Kansas	2015	Special Provision 15-17006-R01	"Provide fibers, which when tested using the procedure described in subsection 1722.4b., result in a minimum equivalent flexural strength ($f_{e,3}$) of: Minimum required $f_{e,3}$ = 140 + .015 (x – 4000) psi. In the above equation, (x) is the average concrete compressive strength as defined in subsection 1722.4b.(2)(c)." "Provide fibers, which when tested using the procedure described in subsection 1722.4b., result in a minimum strength ratio ($R_{e,3}$) of 25%."
Kentucky	2012	N/a	None.
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 in. 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	2014	N/a	None.
Maryland	2017	902.15	For any concrete: "When synthetic fibers are specified in the Contract Documents, the fibers shall be 1/2 to 1 1/2 in. long and conform to C1116, Type III. The manufacturer shall furnish certification as specified in TC-1.03. The quantity of fibers used and their point of introduction into the mix shall conform to the fiber manufacturer's recommendations."
Massachusetts	1988[4]	N/a	None.
Michigan	2012	703.02D	For silica fume modified concrete overlays: "Virgin polypropylene collated fibers at 2 lb/yd³."
		903.05	"Use 100 percent virgin polypropylene fibers, 3/4 in. long, that meet the requirements of ASTM C1116, Type III."

State/Agency	Year	Section	Notes
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." Minimum 25% $R^{D}_{T,150}$ 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 in. 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 ($R_{150,3.0}$) 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."
Missouri	2016	506.10.2.1	For bonded concrete overlays on asphalt (BCOA): "Fibrillated polypropylene fibers shall be added at a rate of 3.0 pounds per cubic yard."
	2018	BSP-505-04	Special provision: "The steel fiber dosage rate shall be 80 pounds per cubic yard of concrete."
Montana	2014	N/a	None.
Nebraska	2017	N/a	None.
Nevada	2014	N/a	None.
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	2007[5]	N/a	None.

State/Agency	Year	Section	Notes
New Mexico	2014	509.2.7	“Use fibers in the concrete mix at a minimum dosage rate of 1.5 pounds per cubic yard of concrete. Use only 100% virgin polypropylene fibrillated fibers, containing no reprocessed olefin Materials, and specifically manufactured for use in PCC.”
New York	2018	711-01	“Synthetic, fibrillated fibers, specifically engineered and manufactured for use as secondary concrete reinforcement meeting ASTM C1116 Type III.”

State/Agency	Year	Section	Notes
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 alkalies present in cement paste and/or the substances present in air-entraining and chemical admixtures. 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. Submit the recommendations of the manufacturer that correlate the toughness of steel-reinforced concrete with that of the recommended dosage rate for the fiber-reinforced concrete. 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	2014[6]	N/a	None.
Ohio	2016	N/a	None.

State/Agency	Year	Section	Notes
Oklahoma	2009	513.04(c)(2)	"If approved as part of the mix design, add fibers."
		701.15(a)(1)	"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)	"Use steel fiber in accordance with ASTM A820, for Type II, cut-sheet steel. Provide steel fibers with an aspect ratio of 30:60 and from 1 1/8 in. [30 mm] to 2 in. [50 mm] long."
Oregon	2018	02001.31(g)	"Use synthetic fiber reinforcing from the QPL and according to Section 02045 in all bridge deck and silica fume overlay 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."
		02045.00	All fibers must be from the QPL.
Pennsylvania	2016[7]	N/a	Several specifications for unbonded PCC overlays and ultra-thin PCC overlays for pavements.
Rhode Island	2004[8]	604.02.2	"Fibers shall be specifically designed to mitigate surface cracking and have the ability to be added to the concrete mix during production. Fiber density shall be a minimum of 50 million individual fibers per pound. Concrete shall be mixed for a minimum of 20 minutes at the required mixing speed once the fibers are added."
South Carolina	2007	N/a	None.
South Dakota	2015	N/a	None.
Tennessee	2015	N/a	None.
Texas	2014	N/a	Fiber specifications available for PCC materials other than bridge decks.
Utah	2017[9]	03055S-(2.2)F.2	"Use 4 lb/yd^3 of concrete mix." "Provide a minimum flexural strength ratio ($R_{e,3}$) of 25 percent when tested according to ASTM C1609."
Vermont	2018	N/a	None
Virginia	2016	N/a	None
Washington	2018	N/a	None
West Virginia	2017	N/a	None
Wisconsin	2019	N/a	None

State/Agency	Year	Section	Notes
Wyoming	2010	515.4.2	Minimum of 2 lb/yd^3 of fibers.
		801.5	“Use 100 percent polypropylene collated, fibrillated fibers with the physical properties shown in Table 801.5-1, Synthetic Fiber Properties.”

[1] Current specification date; special memorandum proposes adding fiber language not currently in specification manual.
[2] Found in a special provision for federal, state, and locally funded projects dated October 7, 2007.
[3] Only applies to one county in Iowa.
[4] The Massachusetts DOT only added supplemental updates to the 1988 specification manual. The current date of the latest supplemental update is 2012.
[5] The New Jersey DOT only added supplemental updates to the 2007 specification manual. The current date of the latest supplemental update is 2018.
[6] Includes supplemental updates up to October 1, 2017.
[7] Includes supplemental changes effective on October 5, 2018.
[8] Amended in 2013.
[9] Found in a special provision dated September 13, 2018.

This search of state DOT specifications and special provisions did not include a check for material qualification lists because those are not specific to bridge decks and bridge deck overlays. In fact, several states list fibers as an approved material but without specification guidance. If a state does not currently have a specification regarding FRC bridge decks or overlays, it does not necessarily mean that those types of decks are absent from the state. For example, several states (primarily South Dakota) have implemented fiber-reinforced bridge decks in the past but have not developed specifications.

Twenty-two states explicitly define FRC specifications for bridge decks and overlays (Figure 7).

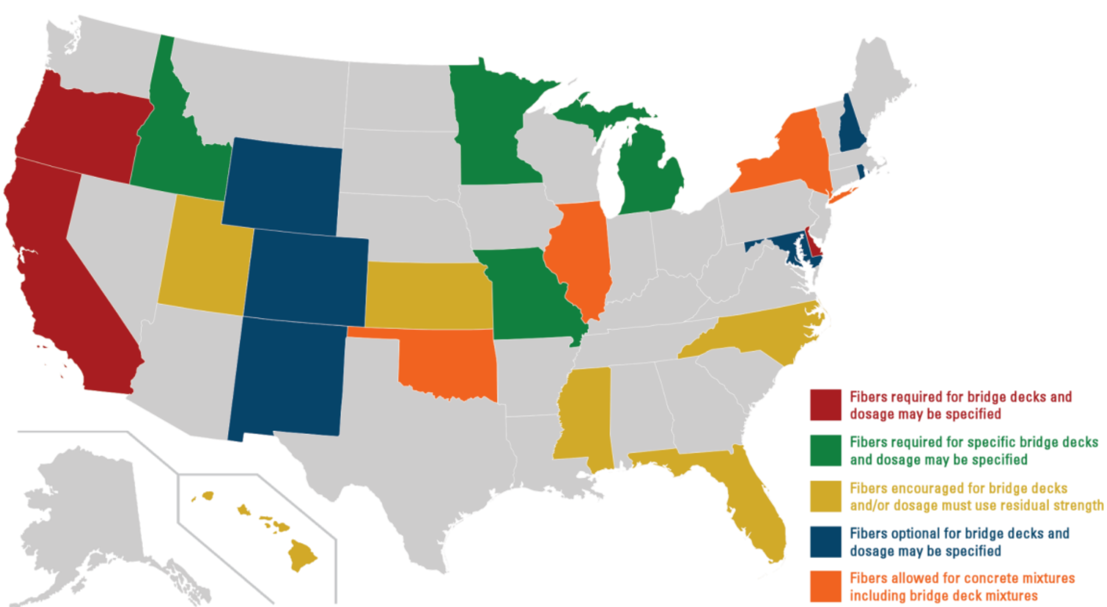


Figure 7. State DOTs with fiber specifications and the level of detail in the specifications

The map in Figure 7 only shows states that have explicitly incorporated language on fiber reinforcement into their standards and specifications manuals. Iowa is not highlighted because its specification only applies to a single county. Additionally, the map does not reflect states that currently have an inventory of fiber-reinforced bridge decks or states that routinely approve fiber-reinforced concrete mixtures for bridge deck applications unless those states also explicitly incorporate language on fiber reinforcement into their standards and specifications manuals.

Of the 22 states with explicitly defined FRC specifications, Colorado, Florida, Hawaii, Illinois, Kansas, Minnesota, Mississippi, North Carolina, and Utah require that the fiber dosage be determined by either ASTM C1399 or ASTM C1609. California, Colorado, Hawaii, Idaho, Illinois, Iowa, New Mexico, and Wyoming specify minimum dosages that are independent of any specified residual strength value or manufacturer-recommended dosage. Delaware and New Hampshire specify exact dosages of synthetic fibers of 1.5 lb/yd^3 and 7 lb/yd^3, respectively. In Michigan, for silica fume-modified concrete overlays, synthetic fibers are specified at 2 lb/yd^3. Missouri has a special provision for bridges that specifies the use of steel fibers at 80 lb/yd^3. Finally, Rhode Island has the only specification that refers to individual fiber count: "Fiber density shall be a minimum of 50 million individual fibers per pound."

SUMMARY

Researchers and DOTs have experimented with FRC in bridge decks and deck overlays for nearly four decades. For this research, a literature review was completed that summarizes the use of FRC materials for bridge decks and deck overlays, including the various types of fibers available and their characteristics, a sample of past projects and their reported performance, laboratory testing results, and current FRC bridge deck specifications.

The most common objective for implementing fiber reinforcement in bridge deck overlays is to reduce the amount of cracking and crack widths due to deformations related to load, materials, and environmental factors. Nearly all of the published studies initiated by state DOTs that have experimented with macrofibers showed improvements in performance with respect to crack control. Typical macrofiber dosages have ranged from 3 to 8 lb/yd^3 for synthetic and 20 to 90 lb/yd^3 for steel fibers. Fewer than half of US states have specification language for implementing fiber-reinforced concrete in bridge decks and deck overlays. Even fewer of these states use performance-based specifications to determine the macrofiber dosage rate. Following the ACI's recommendation (ACI Committee 544 2018), the performance test recommended for bridge decks and overlays is ASTM C1609, which links the required macrofiber volume fraction to the specified FRC residual strength (f_{150}).

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APPENDIX A: CALTRANS CHANGES TO SPECIFICATION LANGUAGE

State of California
DEPARTMENT OF TRANSPORTATION

California State Transportation Agency

Memorandum

Serious drought.
Help Save Water!

To: DEPUTY DISTRICT DIRECTORS, Construction
DEPUTY DIVISION CHIEF, Structure Construction
CONSTRUCTION MANAGERS
SENIOR CONSTRUCTION ENGINEERS
RESIDENT ENGINEERS

Date: October 11, 2016

File: Division of Construction
CPD 16-13

From: RACHEL FALSETTI, Chief
Division of Construction

Subject: Bridge Deck Crack Prevention

This directive allows for implementing new specifications to prevent premature bridge deck cracking. Structure Maintenance & Investigations estimated the California Department of Transportation spends $50,000,000 annually on sealing deck cracks. To prevent early-age bridge deck cracking, the Concrete Committee and the Bridge Preservation Committee, over a 14-year period, have developed new construction specifications for concrete bridge decks, including deck overlays.

The new specifications include:

- Limiting the 28-day shrinkage performance of the deck concrete to 0.032 percent.
- Requiring a minimum dosage of shrinkage reducing admixture.
- Requiring polymer fibers in deck concrete.
- Revising the concrete deck curing specifications.

The attached memorandum from the State Bridge Engineer dated August 11, 2016 describes the recommendation that these specification changes be incorporated by change order for ongoing construction projects where administratively possible.

This change will require a new concrete mix design, addition of polymer fibers, and use of shrinkage reducing admixture for bridge deck concrete which will result in increased cost for this change. If the bridge deck concrete placement affects the controlling activity, contract time adjustment may be required for performing concrete shrinkage performance testing and for compressive strength testing for bridge deck concrete that is designated by compressive strength.

A sample change order memorandum, sample change order, and a Federal Highway Administration (FHWA) blanket prior approval for implementing construction specifications to prevent bridge deck cracking are attached to this directive. This directive serves as the delegation of authority from the Division of Construction and approval from FHWA for this change order, except when any of the following apply to the change order:

1. The language is altered.

2. The total absolute value exceeds $200,000.
3. Contract time is extended by more than 40 days.

If you have any questions or comments regarding this directive, contact Richard Yates, Structure Construction, at richard.yates@dot.ca.gov or (916) 227-8984, or Jim Cotey, Division of Construction, at jim.cotey@dot.ca.gov or (916) 227-5709.

Attachments:
1. Sample CEM-4900, "Change Order Memorandum"
2. Sample CEM-4903, "Change Order"
3. Change Order Attachment—Bridge Deck Crack Prevention Specifications
4. Division of Engineering Services Memorandum, "Construction Specifications for Bridge Deck Crack Prevention," dated August 11, 2016
5. FHWA Form CA-358 (c), "Record of Blanket Prior Approval for Major Contract Change Order"

APPENDIX B: ILLINOIS SPECIAL PROVISION EXCERPT FOR FRC OVERLAYS

Illinois Department of Transportation
Bureau of Materials

Synthetic Fibers for use in Portland Cement Concrete Inlay or Overlay
Submittal for Review and Approval

Effective: July 27, 2007
Revised: March 9, 2018

A. Scope

The following guidelines are provided to clarify the submittal requirements and expedite the review process for approving synthetic fibers according to the Department's Special Provision for Portland Cement Concrete Inlay or Overlay (Check Sheet #34).

B. Procedure

When submitting synthetic fibers to the Department:

First Phase of Submittal Process:

- The manufacturer shall select an Independent Laboratory accredited by the AASHTO Materials Reference Laboratory (AMRL) for Portland Cement Concrete (required methods in ASTM C 1077). The lab shall be equipped to perform the Illinois Modified ASTM C 1609 test method on a submitted synthetic fiber product.
- Prior to the Independent Laboratory testing, the laboratory name, material sources, and mix design shall be submitted to the Department for approval.

Second Phase of Submittal Process:
The Manufacturer shall provide the following to the Department:

- The specific product brand name,
- Independent laboratory test results which show the product meets Department specifications,
  - Residual strength ratio
  - The test report shall contain the length of fibers used for testing.
- Name and address of the company extruding the fiber,
- Zip top bag containing a small representative sample of the submitted product,
- Safety Data Sheet,
- Technical Data Sheet,
- Contact person's name, title, address, email address, and phone number,
- A letter stating the subject material will not be changed without prior written notification to IDOT,
- A letter stating the material complies with the following requirements from the Special Provision for Portland Cement Concrete Inlay or Overlay (BDE):

  Synthetic fibers shall be Type III according to ASTM C 1116. 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 ($R_{150,3}$) of 20.0 percent according to Illinois Modified ASTM C 1609. The maximum dosage rate shall not exceed 5.0 lb/cu yd (3.0 kg/cu m), 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.
- Acknowledgement by Company. If your company does not already have a product included on an IDOT QPL, please submit a signed copy of the company acknowledgement form with your product submittal.

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National Concrete Pavement
Technology Center

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