



www.cproadmap.org

March 2019

ROAD MAP TRACK 8

PROJECT TITLE

**Fiber-Reinforced Concrete for
Pavement Overlays**

AUTHORS

Jeffrey Roesler, PhD, PE
University of Illinois

Amanda Bordelon, PhD, PE
Utah Valley University

Alexander Brand, PhD
Virginia Tech

Armen Amirkhanian, PhD, PE
University of Alabama

EDITOR

Sabrina Shields-Cook

SPONSORS

**Federal Highway Administration
National Concrete Consortium**

MORE INFORMATION

Dale Harrington
HCE Services, Inc.
dharrington@hceservices.com

The Long-Term Plan for Concrete Pavement Research and Technology (CP Road Map) is a national research plan developed and jointly implemented by the concrete pavement stakeholder community. Publications and other support services are provided by the Operations Support Group and funded by the Federal Highway Administration.

Moving Advancements into Practice (MAP) Briefs describe innovative research and promising technologies that can be used now to enhance concrete paving practices. The March 2019 MAP Brief provides information relevant to Track 8 of the CP Road Map: Concrete Pavement Sustainability.

This MAP Brief is available at www.cproadmap.org/publications/MAPbriefMarch2019.pdf.

“Moving Advancements into Practice”

MAP Brief March 2019

Best practices and promising technologies that can be used now to enhance concrete paving

Fiber-Reinforced Concrete for Pavement Overlays

The objectives of this MAP Brief are to provide pavement engineers with necessary information to apply fiber-reinforced concrete (FRC) to concrete overlays and determine the appropriate fiber-reinforcement performance values to be specified in a project and implemented into the structural design calculations for bonded and unbonded concrete overlays.

A spreadsheet tool, the Residual Strength Estimator, has also been developed. The tool provides an estimate of the FRC performance value to specify for a project as well as the effective flexural strength to input into a mechanistic-empirical concrete pavement design software. A comprehensive technical report accompanies this tech brief [1], which provides a more detailed summary of types of macrofiber, expected properties of FRC materials, effects of macrofibers on concrete pavement performance, available FRC test methods, best practice guidelines and specifications for FRC materials applied to pavements, and background on the Residual Strength Estimator spreadsheet tool.

The information provided in this brief is not intended as a promotion or advertisement of any specific product or manufacturer, as such costs or details on exact fiber details are intentionally excluded.

Introduction

Fiber-reinforcement technology for concrete pavements was introduced several decades ago and has been applied to highways, streets, intersections, parking lots, pavement overlays, bus pads, industrial floors, full-depth slab patching, bridge deck overlays and airfields. The first US application was an FRC pavement with steel fibers constructed in 1971 at a truck weigh station in Ohio [2]. Additional early FRC applications were

used as overlays for Navy airfields and commercial airports in the 1970s and 1980s [3]. In the past 15 years, FRC has been successfully implemented for concrete overlays of roadways. Particularly, FRC with bonded concrete overlay on asphalt or composite pavements has seen significant growth in the past 10 years with the overlay thickness ranging from 3 to 6 in.

The National Concrete Overlay Explorer (overlays.acpa.org) lists 89 FRC overlay projects from 2000 to 2018. An Illinois study of FRC overlays reported better performance compared to similar plain concrete overlays [4]. Multiple laboratory-scale slab tests with macrofiber reinforcement have shown that the flexural and ultimate load capacity of FRC slabs and the load transfer efficiency (LTE) between FRC slabs significantly increase relative to plain concrete slabs [5–7]. The magnitude of this increase is dependent on the fiber type and content.

The known benefits of FRC for pavements (Figure 1) are providing additional structural capacity, reducing crack widths, maintaining joint or crack LTE, and extending the pavement's serviceability through reduced crack deterioration. The application of FRC to

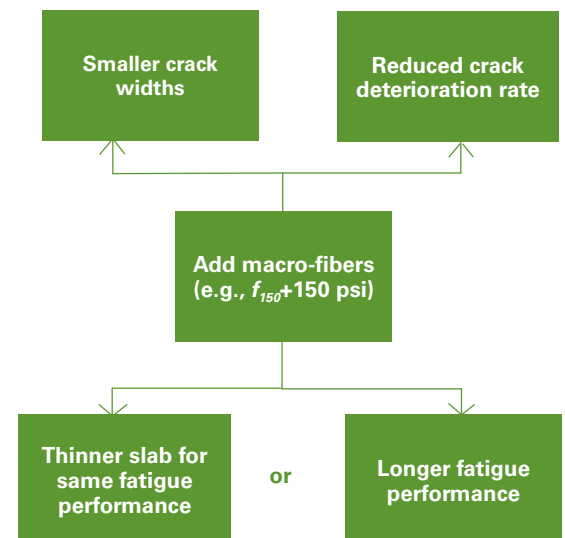


Figure 1. Benefits of fiber reinforcement

concrete pavements is still not considered in some projects because of additional material costs, potential mix design modifications, and constructability questions; however, the lack of experience with FRC by pavement engineers is the primary reason for the lack of implementation. Given the advantages of FRC, an FRC inlay or overlay is useful where a thinner slab is required, in higher traffic areas with more heavy repeated loadings, under variable support conditions, or on projects in need of an increased design or service life. In addition, FRC can assist with reducing slab movement, slab misalignment, plastic shrinkage cracking, and crack widening.

Pavement Design for FRC Concrete Overlays

FRC can be applied to bonded or unbonded concrete overlays. The most common design methodologies for bonded concrete overlays of asphalt are BCOA-ME [8], ACPA Pavement Designer, and AASHTOWare Pavement ME. For unbonded concrete overlays, the AASHTOWare Pavement ME for traditional slab sizes and Optipave 2.0 [9] for short slabs technology can be used to design with macrofibers. Several new M-E unbonded overlay methods for traditional jointed and shorter slab systems are under development and will be available soon. The joint spacing of unbonded overlays may need to be reduced when macrofibers are used to decrease the required slab thickness.

The benefit of FRC is accounted for in all of these design methodologies by updating the plain concrete flexural

Common Question 1:

When do I need to use macrofibers in an FRC overlay?

The main advantages of FRC are improved concrete material residual strength, smaller crack widths, and slower rates of crack deterioration. Therefore, an FRC inlay or overlay is useful where a thinner slab is required, in higher traffic areas with more heavy repeated loadings, under variable support condition, or on projects in need of an increased design or service life. In addition, FRC can assist with reducing slab movement, slab misalignment, plastic shrinkage cracking, crack widening, and maintaining LTE.

strength, also known as the modulus of rupture (MOR), with an effective flexural strength (f_{eff}) that accounts for the effect of macrofibers on the slab's flexural capacity:

$$f_{eff} = MOR + f_{150}$$

Typical residual strength values (f_{150}) used in FRC overlays are between 100 to 200 psi [7,10]. The specified residual strength value can vary depending on the traffic level, condition of the existing pavement, design life, slab geometry, slab thickness constraints, and crack width control. While the residual strength is specified for a particular project and overlay design, distinct macrofiber types will require different dosage levels in order to achieve the same residual strength value. The fiber's geometry, stiffness, surface and characteristics along with the concrete strength all affect the residual strength. Research has shown macrofibers can maintain the LTE of contraction joints under repeated loading [7,11], similar to the mechanism of tie bars in contraction joints. However, FRC materials should not be substituted in joints that require dowel bars to control faulting.

Residual Strength Estimator for FRC Concrete Overlays

A spreadsheet tool that assists in selecting a residual strength value (f_{150}) for a given set of concrete overlay inputs has been developed to complement this technical brief (Figure 2). The pavement engineer must input the conditions and design requirements of the project to determine the estimated range of residual strength for the overlay structural design and to later verify the FRC material requirements. Because most FRC applications have been bonded overlays of asphalt pavements, the software is based on this assumption. Thus, the tool estimates a residual strength range for a given set of inputs, but warns the pavement engineer if an unbonded design should be considered instead. Following are the key inputs considered in the FRC residual strength recommendations:

Common Question 2:

Will FRC change a bonded overlay to an unbonded overlay?

FRC overlays can be bonded or unbonded. The addition of macrofibers should not be used to move an unbonded overlay to a bonded overlay design. Deciding if an overlay is to be bonded or unbonded is based primarily on the condition of the underlying pavement and not on the use of fibers. If the existing asphalt pavement is in a fair to good condition, then a bonded overlay can be designed.

However, if the existing pavement is in a poor and deteriorated condition, then an unbonded overlay design should seriously be considered. A number of possible mechanistic-empirical design methodologies are available depending on if a bonded or unbonded overlay is chosen. The Guide to Concrete Overlays [12] provides a very thorough discussion of the selection process when considering an unbonded versus a bonded overlay.

- Roadway functional class (local road/street, collector street, arterial, highway, bus pad, parking lot, or unknown).
- ESALs in the design life (<0.01, 0.01 to 5.0, 5 to 15, or > 15 million ESALs).
- Asphalt pavement condition prior to an overlay placement (poor throughout, localized poor sections, fair overall, good or excellent overall); this is a subjective rating, but can be internally selected based on characteristics, such as a resilient modulus, stiffness, percent cracking, structural number, etc.
- Remaining thickness of existing pavement after pre-overlay surface preparation (< 3, 3 to 4.5, 4.5 to 6, or > 6 in.).
- Approximate new concrete overlay thickness (3 to 4.5, 4.5 to 6, or >6 in.).
- New slab size (4 ft or 6 ft); 4 ft slab sizes are recommended only for non-channelized traffic such as parking lots, otherwise 6 ft slab sizes should be selected.
- Design flexural strength (*MOR*) for the plain concrete mixture.
- Enhanced performance option in terms of reduced crack deterioration rate or enhanced LTE, which increases the specified residual strength for extra fiber toughness performance.

Residual Strength Estimator for Fiber-Reinforced Concrete Overlays

Instructions: Run an overlay design software to determine the design inputs. Select design choices from the drop-down menus below to narrow down the recommended performance requirement of FRC for the proposed overlay pavement. Determine the effective flexural strength to input into overlay design software instead of design concrete flexural strength. Prepare specifications to achieve design residual strength of FRC material.

Design Input Choices

Type of Overlay Road	Arterial	
Millions of ESALs in Design Life	0.01 to 5.0 million ESALs	
Asphalt Pre-Condition*	Fair	*refer to Tech Report to example estimates of asphalt pre-condition
Desired New Concrete Thickness	4.5 to 6 inch PCC thickness	
Remaining HMA Thickness after Milling	4.5 to 6 inches HMA remaining	
Overlay Slab Size	6ft joint spacing	
Desired Performance Enhancements (this will generate a higher residual strength, but not included in effective flexural strength)	basic FRC overlay	
Plain Unreinforced Concrete Flexural Strength (<i>MOR</i>) based on 28 day Four Point Bending (ASTM C78 or ASTM C1609)	550	psi

Design Suggestions/Warnings:

Recommended Residual Strength (f_{150})

Use value within this range for the Material Specification:

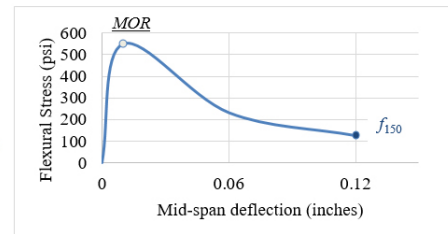
125 to 175 psi (target value from ASTM C1609 test results of FRC)

Effective Flexural Strength (f_{eff})

Replace the *MOR* from the Pavement Design Software with this value:

650 psi

NOTE: Actual fiber dosage rates are dependent on fiber type, fiber dimensions, concrete mixing/placement technique, cement content and fiber content or volume fraction. The intended fiber and dosage rate should be verified by ASTM C1609 test method. These recommended values are based off of previous field and laboratory testing of fibers used in concrete overlay pavements. Refer to the Tech Guide or Tech Report for more details.



Developed by Amanda Bordelon, Ph.D., P.E. and Jeffery Roesler, Ph.D., P.E.
Version 1.0, January 2019

Acknowledgments:

The software was created with the funding, promotion, and guidance of the National Concrete Consortium (NCC), the National Concrete Pavement Technology Center (CP Tech Center), Snyder & Associates, and a state DOT pooled fund technical advisory committee.



Disclaimer:

The contents of this spreadsheet do not necessarily reflect the official views or policies of the developers' employers, funding agencies, or technical advisory committee members. The spreadsheet developers assume no responsibility, warranty, or liability for any errors, omissions, or inaccuracies of this spreadsheet. This spreadsheet does not constitute a standard, specification, or regulation.

Figure 2. Residual Strength Estimator spreadsheet tool that calculates the effective flexural strength to account for the benefit of the macrofibers, which is then entered into a concrete design procedure. The fiber type and content can be separately selected and tested with a paving concrete mixture to verify the specified residual strength. The Residual Strength Estimator spreadsheet tool is available at <https://cptechcenter.org/>

Concrete Overlay and FRC Material Design Process

There are several ways for the designer and contractor/material supplier to determine the required fiber content given a target FRC performance value. An agency can establish a qualified product list based on laboratory residual strength tests for a standard concrete paving mixture; or an initial estimate of the required fiber dosage can be obtained from the fiber manufacturer or past laboratory tests [7] and then verified with ASTM C1609. Fiber content can be adjusted linearly to achieve the target residual strength value. The following steps summarize the process to select the FRC performance value (f_{150}) for a new concrete overlay.

Designer Responsibilities (Figure 3):

1. Determine existing pavement conditions and collect design inputs.
2. Decide if new concrete overlay is bonded or unbonded system based on the existing condition and pavement design inputs.
3. Run Residual Strength Estimator tool to determine FRC residual strength value (f_{150}) and effective flexural strength (f_{eff}).
4. Design concrete overlay thickness with pavement design program using the effective flexural strength.

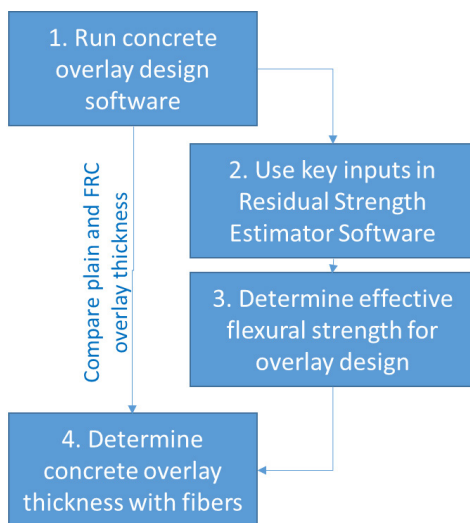


Figure 3. Designer responsibilities

Contractor/Material Supplier Responsibilities (Figure 4):

5. Select potential macrofiber types and fiber contents based on published laboratory data, a qualified product list, or fiber manufacturer data.
6. To verify fiber performance, a concrete mixture with macrofibers is cast for each fiber type. If estimated fiber content is not known, it is recommended that at least two volume fractions of FRC beams be cast, e.g., 0.25% and 0.50%.

7. Run ASTM C1609 at a fixed age (e.g., 14 days) and calculate the residual strength (f_{150}) versus fiber volume fraction for each fiber type.
8. Select fiber volume fraction (%) or fiber content (lb/yd³) based on the specified residual strength.
9. Check macrofiber content in the field during construction by weighing fibers contained in a unit volume

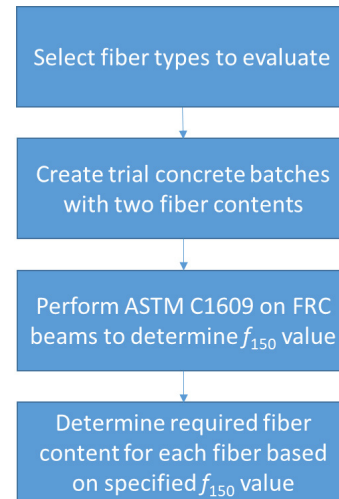


Figure 4. Contractor/material supplier responsibilities

Macrofiber Types and Content

A wide variety of fibers are commercially available for use in FRC. The two primary types of macrofibers used for pavements and overlays are synthetic and steel (Figure 5). Macrofibers come in different geometries, shapes, and surface textures. Generally, macrofibers are 1 to 2.5 in. in length with an aspect ratio of 30 to 100. Synthetic macrofibers are overwhelmingly used on concrete overlay applications.

The required macrofiber content, volume percentage, or dosage rate depends on the specified residual strength value, concrete constituents and proportions, and strength

Common Question 3:

How much macrofiber do I need to add?

Typical fiber contents for concrete overlays can range from 0.2% to 0.5% by volume. The amount depends on many technical factors (slab flexural capacity, service life, crack width criteria, joint LTE) and costs. For bonded concrete overlays of asphalt, a minimum residual flexural strength (f_{150}) of 100 to 150 psi should be specified depending on the design requirements. The fiber type and volume fraction can be adjusted accordingly to meet the specified residual strength requirement.

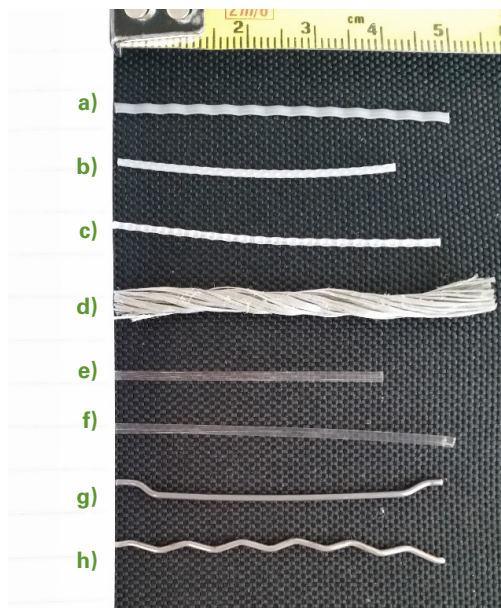


Figure 5. Examples of different macrofibers: (a-c) crimped, embossed or bi-tapered synthetic, (d) twisted synthetic, (e-f) straight fibrillated synthetic, and (g-h) hooked end or crimped steel.

of the concrete. Typical macrofibers ranges used in past concrete overlay applications are between 3 to 8 lb/yd³ for synthetic and 25 to 75 lb/yd³ for steel or approximately 0.2% to 0.5% by volume.

The residual strength (f_{150}) is the primary performance parameter used to quantify FRC materials as well as an input to the structural design of concrete overlays with macrofibers. Ideally, the selection of the fiber type and content should be the contractor's decision and the pavement engineer should only specify the residual strength that is required to achieve the objectives of the overlay design.

Table 1 lists examples of several fiber types, dosage rates, and concrete mixtures and their corresponding measured residual strengths. Macrofibers should not be specified based on the fiber geometry, shapes, or surface texture but on the residual strength value.

Table 1. Examples of FRC mixture residual strength performance

Fiber type (manufacturer details omitted)	Age, days	Fiber volume, percent of total concrete volume	Fiber dosage, lb/cy [kg/m ³]	f_{150} value, psi [MPa]
Synthetic Fiber #1	14	0.27%	4.0 [2.4]	90 [0.65]
Synthetic Fiber #1	28	0.38%	5.8 [3.4]	155 [1.05]
Synthetic Fiber #2	28	0.27%	4.1 [2.5]	160 [1.10]
Synthetic Fiber #2	28	0.38%	5.8 [3.5]	225 [1.10]
Synthetic Fiber #3	28	0.50%	7.6 [4.5]	160 [1.10]
Steel Fiber	28	0.19%	25.1 [14.9]	175 [1.21]

Common Question 4:

What specific fiber type should I use and how does the fiber type affect dosage?

While both steel and synthetic fibers have successfully been implemented in FRC overlays, synthetic macrofibers have become the most prevalent because they are easier to handle and less prone to balling. Regardless of the fiber type, the fiber content can be adjusted to achieve the specified residual strength performance. For example, in one study the desired residual strengths were achieved using fiber volumes of 0.26% synthetic (straight fiber), 0.40% synthetic (crimped fiber), 0.5% synthetic (twisted fiber), 0.19% steel (hooked-end fiber), or 0.50% steel (crimped fiber) [9]. Therefore, the concrete residual strength (ASTM C1609) should be specified, and then verified through laboratory testing to determine the fiber content for a particular fiber type.

Fresh and Hardened Properties of FRC

Several of the standard fresh and hardened concrete properties will change with the addition of macrofibers. When considering fresh properties, workability should be expected to decrease with the addition of macrofibers. In some cases, the slump can be reduced by up to 4 in. (100 mm) but this will depend on the type of fiber and content as well as the concrete mixture constituents and proportions. Generally, the addition of water reducing admixtures or other mixture modifications can easily compensate for the slump loss so that the effect on workability is minimal. These adjustments will also improve finishability. The air content has been reported to be affected by the addition of fibers. Adjustments in air content can be made through changes in the air-entraining admixture during the FRC trial batches. Trial batches are always recommended to confirm that the FRC mixture can meet all fresh property specifications.

For fiber volume contents used in pavements (<0.5%), the compressive and flexural strength are not expected to change relative to plain concrete. The post-cracking strength and toughness are the primary hardened concrete properties that are improved with the addition of macrofibers. Fibers have been shown to improve the flexural fatigue performance of concrete.

The LTE of FRC can be increased by 30% compared to plain concrete, especially when crack widths are greater, i.e., >1.0mm [7]. Macrofibers have also been shown to reduce the number of cracks and the average crack width under restrained shrinkage testing. The durability of FRC may be improved compared to plain concrete particularly

with the reduction in the average crack width. FRC has also been shown to retain significant residual strength even after a large number of freeze/thaw cycles.

Test Method for FRC Performance

The primary test method used to link the performance benefit of macrofibers on concrete pavement design is ASTM C1609-12 (Figure 6 and Figure 7), which is very similar to flexural beam test (ASTM C78) with several main differences:

- the test is controlled by mid-span vertical displacement instead of load;
 - the test is continued beyond when a macro-crack forms to a total displacement equal to $L/150$, where L is the span length. Typically, this is 0.12 inch (3 mm) deflection.
 - ASTM C1609 specifies a low friction roller assembly (ASTM C1812);
 - the 6 inch (150 mm) square cross-section beam is recommended for pavement applications over the 4 inch (100 mm) beam depth; and
- the specification should state a testing age (e.g., 14 days) and identify the target (average) residual strength (f_{150}) for the FRC material. Note: experience has shown that later testing ages (e.g., 28 days) may require a stiffer and higher capacity testing frame to properly control the ASTM C1609 test.

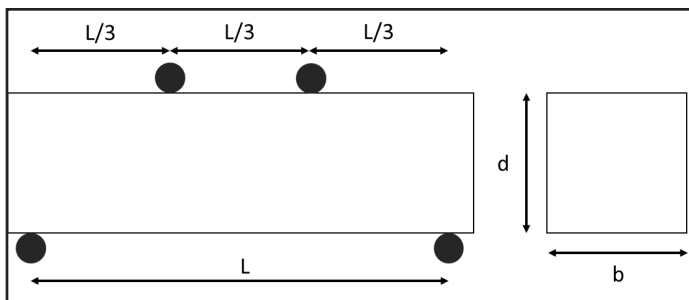


Figure 6. Geometry of the ASTM C1609 beam setup. Typical dimensions include a cross section depth d of 6 in., width b of 6 in., and span L of 18 in.

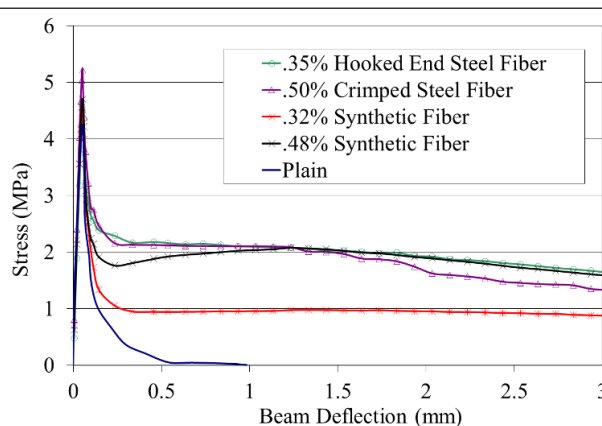


Figure 7. ASTM C1609-12 testing (left) and a typical load-deflection response for several macrofiber beams (right) with $b=d=6$ in. and $L=18$ in..

From ASTM C1609-12, the residual strength (f_{150}) is calculated from the load-deflection plot (Figure 7). P_{150} is the corresponding load when the displacement reaches a value of $L/150$ (Figure 6), L is the span of the beam between the supports, b is the width of the beam, and d is the height of the beam:

$$f_{150} = \frac{P_{150} L}{bd^2}$$

While alternative test methods to characterize the post-cracking performance of FRC have been proposed, it is recommended [12] that ASTM C1609 be used to evaluate the residual strength value for a given concrete mixture, fiber type, and fiber content for concrete pavement overlay designs.

Mixture Proportioning and Construction Modifications for FRC Overlays

In general, for the typical low to moderate fiber dosages used for FRC pavement overlays (e.g., <0.5% by volume), the concrete mix design does not necessarily need to be adjusted except for accommodating the volume of fibers. Best practices for standard proportioning of concrete paving mixtures should be followed. Trial batches are always recommended to assess if the FRC mix design is sufficient for uniform mixing, transporting, casting/placement, consolidation, and finishing.

Increasing the total cementitious content and/or introducing a water-reducer may be warranted to ensure a good fiber-paste bond and adequate workability. The w/cm ratio should be still selected for the desired workability, strength, and durability performance. As an example, FRC used for concrete overlays have included the following mixture proportions: w/cm ratios of 0.38 to 0.45, air contents of 5% to 7%, supplementary cementitious material (e.g., fly ash or slag) replacements of cement of 15% to 35%, and well-graded aggregates [13].

Macrofibers can be successfully introduced at any phase of the mixing process but the manufacturer's recommendation should be initially followed. Fiber balling, clumping, or entanglement has occurred with any or multiple combinations of the following conditions:

- the macrofiber volume is too high;

- the macrofibers are added too quickly to the mixer;
- the macrofibers are added to the mixer before other ingredients ;
- the macrofibers are already clumped together in delivery bags;
- the macrofiber has a high aspect ratio (fiber length/diameter);
- the concrete mixer is inefficient or has worn blades;
- the concrete mixture is too stiff or has insufficient paste; and
- the concrete is mixed too long after macrofibers are added

When fiber balling happens, the contractor or material supplier should decide the necessary adjustments to the concrete mixture design, batching, and mixing process to minimize future balling problems.

Proper sawcut timing is an important factor in FRC overlays, given that the concrete material is more resistant to crack growth. In addition, if shorter panel sizes are utilized, they do not generate as much internal stress in the material to cause joint development. Field observations of FRC overlay joints have shown that contraction joint activation can occur initially at every 4 to 20 joints. Transverse contraction joints in FRC overlays should be sawcut as early as possible with early-entry saws while minimizing joint raveling. Long-term monitoring has shown that almost all contraction joints activate over time, especially under traffic loading. Transverse contraction joints should be cut to 1/4 of the depth or at least 1-inch depending on the type of saw and assuming joint cutting is properly timed.

Longitudinal joints can be cut after the transverse joints, but typically must start within a few hours after the transverse joint cutting commences. These longitudinal joints should be sawcut deeper, approximately 1/3 of the depth [14], given the lower transverse stress state in the FRC overlay. Extra saws and personnel are often required for FRC overlays given the large number of contraction joints required to cut per lineal foot of pavement.

FRC Overlay Maintenance

Macrofibers maintain tight joint and crack openings, e.g., less than 0.5 to 1.0 mm. The typical practice with FRC overlays is to not seal the contraction joints, but this practice depends on the overlay design life and the number of lanes. Even if cracks form in the mid-panel area, as long as the crack widths remain sufficiently small, there is no need to seal.

If the FRC overlay eventually exhibits unacceptable roughness or faulting, then diamond grinding may be used to improve the ride and friction. Since fibers increase the toughness of the concrete pavement, diamond grinding or slab removal methods may require additional energy. Any replacement slabs or patches will not have the fiber bridging effect across the new construction joints; and, therefore, a thicker replacement panel may be warranted to offset the greater panel stresses.

Summary

The concrete overlay type and structural design are significantly linked to the existing pavement condition, traffic level, and roadway elevation constraints. Macrofibers have been shown to improve the flexural and ultimate capacity of concrete slabs, which can be used in the design of the concrete overlay thickness and slab size.

There are numerous macrofibers available that have different materials (steel or polymeric), shapes and diameters (round, rectangular, etc.), lengths, and surface texture / embossings. The effectiveness of a macrofiber is related to its material properties, geometry, surface enhancements, and interaction with the concrete matrix. Macrofibers should not be specified based on geometry, shape, or surface texture but on residual strength performance within a particular concrete matrix.

Batching and mixing macrofibers are important to the successful construction of FRC overlays. Ideally, macrofibers should be continuously added to the concrete mixture at the central drum plant with the other concrete constituents; however, adjustments may have to be made based on the available equipment and pre-packaging of the specific macrofiber. Best practices of concrete paving should be followed with slight adjustments for finishing and texturing to avoid pulling out fibers from the surface.

Proper timing and depth of the sawcut contraction joints ensure FRC overlay joints activate as soon possible and avoid premature cracking and dominant joints. FRC materials should not be used to replace dowel bars but can be considered similar in function to tie bars at contraction joints.

The residual strength (f_{150}) of an FRC mixture, as determined from ASTM C1609, has been shown to quantify the added benefit of macrofibers to plain concrete slabs. By adding the residual strength (f_{150}) to the actual concrete flexural strength (MOR), an effective flexural strength value (f_{eff}) can be used in existing structural design programs for concrete overlays. Residual strength values for concrete overlay applications typically range between 100 and 225 psi.

A Residual Strength Estimator spreadsheet has been developed to assist engineers in determining the appropriate f_{150} given the existing pavement conditions and overlay design inputs. The residual strength value for the FRC should be incorporated into the project's material specification. Multiple state DOTs (e.g., Illinois, Minnesota, and Utah) specify the residual strength parameter when employing macrofibers in concrete overlay. Macrofibers should not be specified by volume fraction or weight given that various fiber materials and properties will produce the same residual strength at different fiber contents.

References

- [1] J.R. Roesler, A. Bordelon, A.S. Brand, A.N. Amirkhahian, Fiber Reinforced Concrete for Pavement Overlays: Technical Overview, 2018.
- [2] ACI Committee 544, Report on Fiber Reinforced Concrete, ACI 544.1R-96 (Reapproved 2009), American Concrete Institute, Farmington Hills, MI, 2009.
- [3] R.S. Rollings, Field Performance of Fiber-Reinforced Concrete Airfield Pavements, Report DOT/FAA/PM-86/26, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 1986.
- [4] D. King, J.R. Roesler, Structural Performance of Ultra-Thin Whitetopping on Illinois Roadways and Parking Lots, Research Report No. FHWA-ICT-14-018, Urbana, Illinois, 2014.
- [5] J.R. Roesler, D.A. Lange, S.A. Altoubat, K.-A. Rieder, G.R. Ulreich, Fracture of plain and fiber-reinforced concrete slabs under monotonic loading, *J. Mater. Civ. Eng.* 16 (2004) 452–460. doi:10.1061/(ASCE)0899-1561(2004)16:5(452).
- [6] D. Beckett, Comparative tests on plain, fabric reinforced and steel-fibre reinforced concrete ground slabs, *Concrete*. 24 (1990) 43–45.
- [7] M. Barman, B. Hansen, Comparison of Performances of Structural Fibers and Development of a Specification for Using Them in Thin Concrete Overlays, Report No. MN/RC 2018-29, Minnesota Department of Transportation, 2018. <http://www.dot.state.mn.us/research/reports/2018/201829.pdf>.
- [8] Z. Li, N. Dufalla, F. Mu, J.M. Vandenbossche, Bonded concrete overlay of asphalt pavements mechanistic-empirical design guide (BCOA-ME): Theory manual, University of Pittsburgh, Pittsburgh, Pennsylvania, 2016.
- [9] J.P. Covarrubias, J. Roesler, J.P. Covarrubias, Design of concrete slabs with optimized geometry, in: 11th Int. Symp. Concr. Roads, 2010: p. Seville, Spain.
- [10] A. Bordelon, J. Roesler, Design with Fiber-Reinforcement for Thin Concrete Overlays Bonded to Asphalt, *J. Transp. Eng.* 138 (2012) 430–435. doi:10.1061/(ASCE)TE.1943-5436.0000339.
- [11] M. Barman, J.M. Vandenbossche, Z. Li, Characterization of Load Transfer Behavior for Bonded Concrete Overlays on Asphalt, *Transp. Res. Rec.* 2524 (2015) 143–151. doi:10.3141/2524-14.
- [12] ACI Committee 544, 544.4R-18: Guide to Design with Fiber-Reinforced Concrete, 2018.
- [13] D. Harrington, G. Fick, Guide to Concrete Overlays: Sustainable Solutions for Resurfacing and Rehabilitating Existing Pavements, 3rd ed., National Concrete Pavement Technology Center, Ames, Iowa, 2014.
- [14] ACI Committee 544, Guide for Specifying, Proportioning, and Production of Fiber-Reinforced Concrete, ACI 544.3R-08, American Concrete Institute, Farmington Hills, MI, 2008.