FIBER-REINFORCED CONCRETE FOR PAVEMENT OVERLAYS

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Introduction

The objective of this tech brief is to provide pavement engineers with the information necessary to use fiber-reinforced concrete (FRC) for concrete overlays. This tech brief explains how to determine the appropriate fiber reinforcement performance values to specify and implement in the structural design calculations for bonded and unbonded concrete overlay projects.

A spreadsheet tool called the Residual Strength Estimator was developed to help pavement engineers use FRC in concrete pavement applications. 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 the mechanistic-empirical (M-E) concrete pavement design software.

A comprehensive technical report accompanies this tech brief. The report provides a more detailed summary of the types of macrofibers used in FRC, the expected properties of FRC materials, the effects of different macrofibers on concrete pavement performance, available FRC test methods, best practice guidelines and specifications for FRC materials applied to pavements, and background information on the Residual Strength Estimator spreadsheet tool.

Background

Fiber reinforcement technology for concrete pavements was introduced several decades ago and has since been applied to highways, streets, intersections, parking lots, pavement and bridge deck overlays, bus pads, industrial floors, full-depth slab patches, and airfields. The first US application was a FRC pavement with steel fibers constructed in 1971 at a truck weigh station in Ohio (ACI Committee 544 2009). Additional early FRC applications included overlays for US Navy airfields and commercial airports in the 1970s and 1980s (Rollings 1986).

In the past 15 years, FRC has been successfully implemented in concrete overlays of roadways. Particularly, the use of FRC in bonded concrete overlays on asphalt or composite pavements has seen significant growth in the past 10 years, with overlay thicknesses ranging from 3 to 6 inches. The National Concrete Overlay Explorer lists 89 FRC overlay projects constructed between 2000 and 2018 (http://overlays.acpa.org/webapps/overlayexplorer/index.html).

The known benefits of FRC for pavements include its abilities to provide additional structural capacity, reduce crack widths, maintain joint or crack load transfer efficiency, and extend the pavement's serviceability through reduced crack deterioration.

An Illinois study of FRC overlays reported better performance compared to similar plain concrete overlays (King and Roesler 2014). Moreover, multiple laboratory-scale slab tests of macrofiber reinforcement have shown that the flexural and ultimate load capacity of FRC slabs and the load transfer efficiency between FRC slabs are significantly greater than those of plain concrete slabs (Roesler et al. 2004, Beckett 1990, Barman and Hansen 2018). The magnitude of the increase is dependent on the fiber type and content.

Nevertheless, the use of FRC is still not considered for some concrete pavement projects, sometimes because of the additional material costs, potential mix design modifications, and constructability questions associated with FRC, but primarily because pavement engineers lack experience with FRC.

Given the advantages of FRC, an FRC inlay or overlay is useful where a thinner slab is required, in high-traffic areas with a significant number of repeated heavy loadings, when variable support conditions are required, or on projects in need of a longer design or service life, as illustrated in Figure 1.

In addition, FRC can help reduce slab movement, slab misalignment, plastic shrinkage cracking, and crack widening.

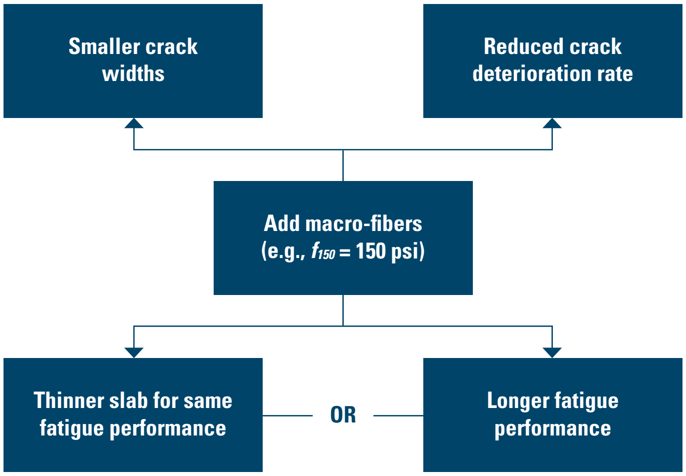


Figure 1. Advantages of FRC inlays or overlays

How does the use of FRC most benefit concrete overlays?

The main advantages of FRC are improved residual strength of the concrete material, smaller crack widths, and slower rates of crack deterioration. In addition, FRC can help reduce slab movement, slab misalignment, plastic shrinkage cracking, and crack widening and can help maintain load transfer efficiency.

Pavement Design for Concrete Overlays

FRC can be applied to bonded or unbonded concrete overlays. The most common design tools for bonded concrete overlays on asphalt are bonded concrete overlay of asphalt mechanistic-empirical (BCOA-ME) design (Li et al. 2016), the American Concrete Pavement Association's (ACPA's) Pavement Designer, and the American Association of State and Highway Transportation Official's (AASHTO's) AASHTOWare Pavement ME. For unbonded concrete overlays, AASHTOWare Pavement ME and Optipave 2.0 (Covarrubias et al. 2011) can be used to design traditional-sized slabs and short slabs, respectively, with macrofibers.

Several new M-E methods for designing unbonded overlays with traditional jointed and shorter slab systems are under development and will become available soon. The joint spacing of unbonded overlays may need to be reduced when macrofibers are used to decrease the required slab thickness.

The benefits of FRC are accounted for in all of the design tools by updating the plain concrete flexural 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, as follows:

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

Typical residual strength values (f_{150}) used in FRC overlays are between 100 and 200 psi (Barman and Hansen 2018, Bordelon and Roesler 2012). The specified residual strength value can vary depending on the traffic level, condition of the existing pavement, desired design life, slab geometry, slab thickness constraints, and requirements for crack width control. While the residual strength is specified for a particular project and overlay design, different macrofiber types require different dosage levels to achieve the same residual strength value. The macrofiber's geometry, stiffness, surface texture, and other characteristics, along with the concrete strength, all affect the residual strength.

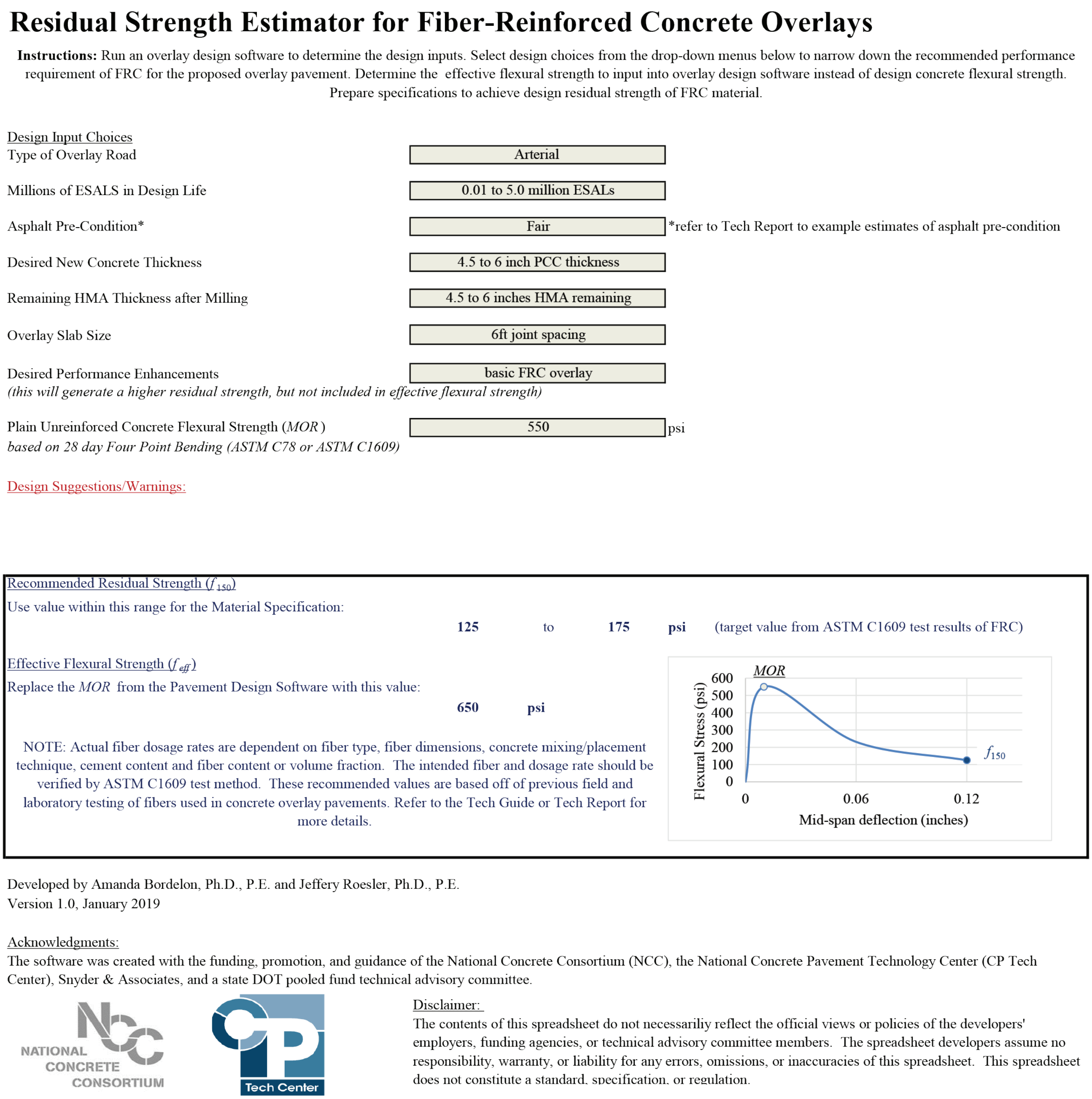
Research has shown that macrofibers can maintain the load transfer efficiency of contraction joints under repeated loading (Barman and Hansen 2018, Barman et al. 2015), similarly to the mechanism of tie bars in contraction joints. However, FRC materials should not be substituted for tie bars in joints that require dowel bars to control faulting.

Residual Strength Estimator for Concrete Overlays

To complement this work, a Residual Strength Estimator spreadsheet tool (available at https://cptechcenter.org/publications/ under the Spreadsheets category), as illustrated in Figure 2, was developed to assist in the selection of a residual strength value (f_{150}) for a given set of concrete overlay inputs.

The pavement engineer enters the conditions and design requirements of the project to determine the estimated range of residual strength for the overlay structural design, as well as 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. Therefore, 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.



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 (*MOR*) *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 necessariliy 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

The following are the key inputs considered in the FRC residual strength recommendations:

- Roadway functional class
- Equivalent single-axle loads (ESALs) in the design life
- Asphalt pavement condition prior to overlay placement; this is a subjective rating, but it 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
- Approximate new concrete overlay thickness
- New slab size, with slab sizes of 4 ft recommended only for non-channelized traffic such as parking lots
- Design flexural strength (MOR) for the plain concrete mixture
- Enhanced performance option in terms of reduced crack deterioration rate or enhanced load transfer efficiency, which increases the specified residual strength for extra fiber toughness performance

In addition to the residual strength range, the tool also calculates an effective flexural strength value that accounts for the benefits of the macrofibers. The effective flexural strength can be entered into a concrete design procedure. The macrofiber type and content can be separately selected and tested with a paving concrete mixture to verify the specified residual strength.

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 (Barman and Hansen 2018), and then be verified using ASTM C1609-12. Fiber content can be adjusted linearly to achieve the target residual strength value.

The following steps, divided into designer and contractor/material supplier responsibilities, summarize the process for selecting the FRC performance value (f_{150}) for a new concrete overlay.

Designer responsibilities:

1. Determine existing pavement conditions and collect design inputs.
2. Decide whether the new concrete overlay is a bonded or unbonded system based on the existing conditions and pavement design inputs.
3. Use the Residual Strength Estimator tool to determine the FRC's residual strength (f_{150}) and effective flexural strength (f_{eff}) (see Figure 3).
4. Design the concrete overlay thickness in a pavement design program using the effective flexural strength.

What is the difference between bonded and unbonded overlays with FRC?

FRC overlays can be bonded or unbonded. The addition of macrofibers should not be used to convert an unbonded overlay design to a bonded overlay design. If the existing asphalt pavement is in fair to good condition, a bonded overlay can be designed. However, if the existing pavement is in a poor and deteriorated condition, an unbonded overlay design should seriously be considered.

A number of possible ME design methodologies are available depending on whether a bonded or unbonded overlay is chosen. The *Guide to Concrete Overlays* provides a thorough discussion of the selection process when considering an unbonded versus a bonded overlay (Harrington and Fick 2014).

How many macrofibers do I need to add?

Typical fiber content for concrete overlays can range from 0.2% to 0.5% by volume, and the amount depends on many technical factors (e.g., slab flexural capacity, desired service life, crack width criteria, and joint load transfer efficiency) 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.

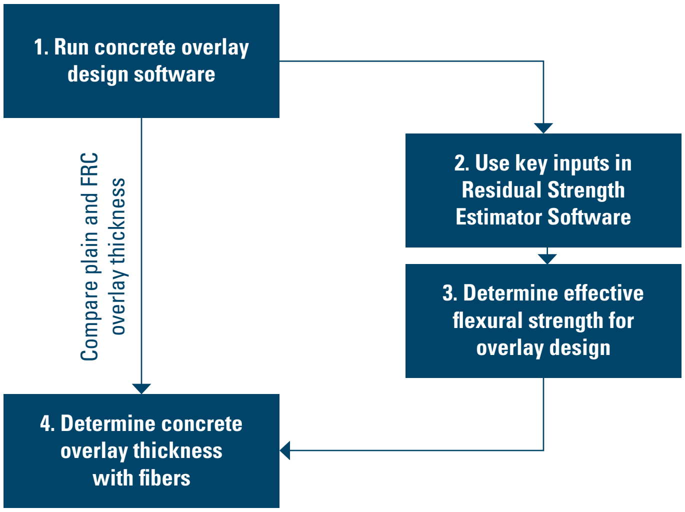


Figure 3. Designer process flow for FRC overlay performance specification

Contractor/material supplier responsibilities (see Figure 4):

1. Select potential macrofiber types and fiber contents based on published laboratory data, a qualified product list, or data from the fiber manufacturer.
2. To verify fiber performance, cast a concrete mixture with macrofibers for each fiber type. If the estimated fiber content is not known, it is recommended that FRC beams with at least two volume fractions be cast.
3. Use ASTM C1609-12 at a fixed age and calculate the residual strength (f_{150}) versus fiber volume fraction for each fiber type.
4. Select the fiber volume fraction (%) or fiber content (lb/yd³) based on the specified residual strength.
5. During construction, check the macrofiber content in the field by weighing the fibers contained in a unit volume.

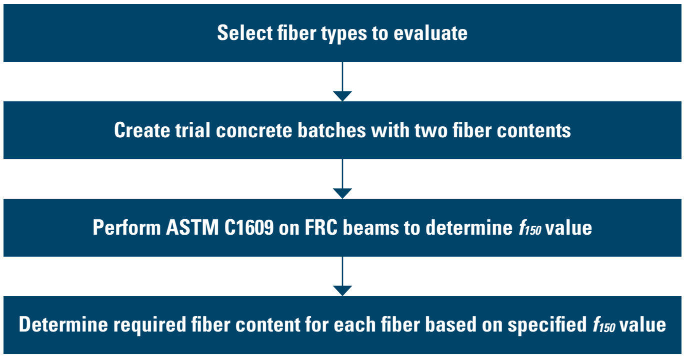


Figure 4. Contractor/material supplier process flow for FRC overlay specification

Macrofiber Types and Contents

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 (see Figure 5).

Synthetic macrofibers are overwhelmingly used in concrete overlay applications. Macrofibers come in different geometries, shapes, and surface textures. Generally, macrofibers are 1 to 2.5 in. long with an aspect ratio of 30 to 100.

The required macrofiber content, volume percentage, or dosage rate depends on the specified residual strength value, concrete constituents and proportions, and the required strength of the concrete. Typical macrofiber ranges used in past concrete overlay applications have been between 3 and 8 lb/yd³ for synthetic and 25 to 75 lb/yd³ for steel, or approximately 0.2% to 0.5% by volume.

Residual strength (f_{150}) is the primary performance parameter used to quantify the benefits of FRC materials and is used as an input for 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.

Macrofibers should not be specified based on the fibers' geometries, shapes, or surface textures but on their effect on the concrete's residual strength value (see the accompanying report).

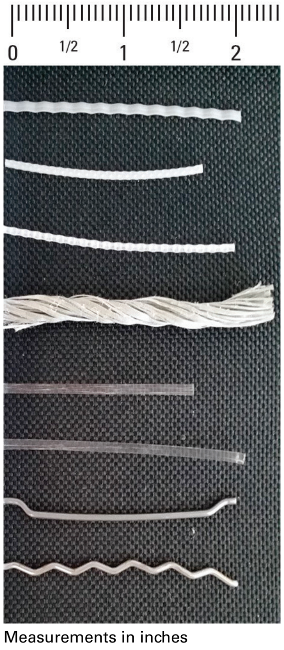


Figure 5. Examples of different macrofibers, top to bottom: crimped, embossed, and bi-tapered synthetic; twisted synthetic; straight fibrillated synthetic (two images); and hooked end and crimped steel

Which 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 commonly used 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. Therefore, the concrete residual strength (ASTM C1609-12) 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 change with the addition of macrofibers.

Fresh Properties

- Workability should be expected to decrease with the addition of macrofibers.
- In some cases, slump can be reduced by up to 4 in., but the magnitude of the reduction depends on the fiber type and content as well as the concrete mixture's 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 also improve finishability.
- 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 when mixing the FRC trial batches.
- Trial batches are always recommended to confirm that the FRC mixture can meet all of the fresh property specifications.

Hardened Properties

- For fiber volume contents used in pavements (less than 0.5% by volume), the compressive and flexural strengths 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 load transfer efficiency of FRC can increase by 30% compared to plain concrete, especially when crack widths are relatively large, i.e., greater than 1.0 mm (Barman and Hansen 2018).
- 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 given the reduction in 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 quantify the performance benefits of macrofibers in concrete pavement design is ASTM C1609-12 (Figures 6, 7, and 8).

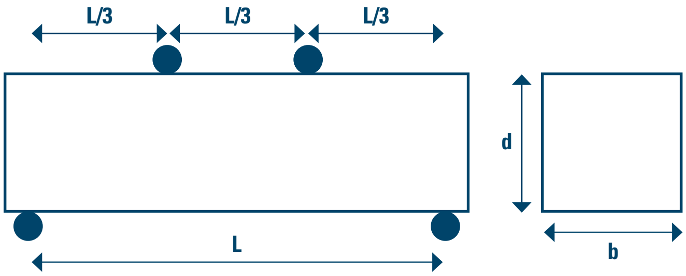


Figure 6. Geometry of the ASTM C1609-12 beam setup

Figure 7. ASTM C1609-12 testing apparatus

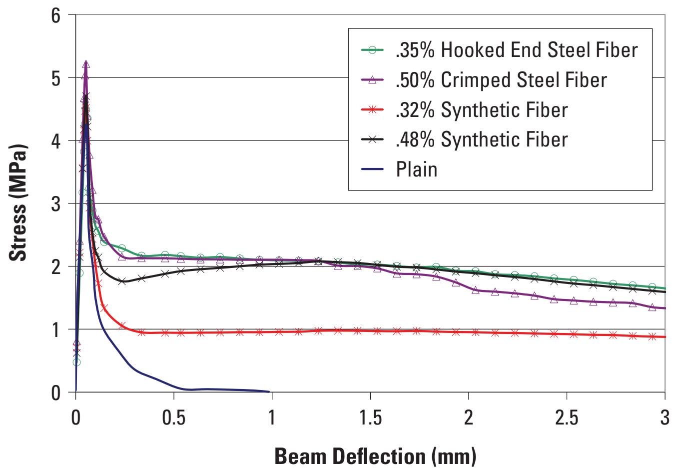


Figure 8. Typical load-deflection responses for several macrofiber beams with a typical width (*b*) and cross-section depth (*d*) of 6 in. and span (*L*) of 18 in.

ASTM C1609-12 is very similar to the flexural beam test (ASTM C78) but with several important differences:

- The test is controlled by mid-span vertical displacement instead of load.
- The test is continued beyond when a macro-crack forms until a total displacement equal to *L/150* is achieved. Typically, the deflection is 0.12 in.
- ASTM C1609-12 specifies a low-friction roller assembly (ASTM C1812).
- A 6-in. square cross-section beam depth is recommended for pavement applications instead of the 4-in. beam depth recommended in ASTM C78.
- The specification should state a testing age and identify the target (average) residual strength (f_{150}) for the FRC material. Experience has shown that later testing ages may require a stiffer and higher-capacity testing frame to properly control the ASTM C1609-12 test.

In ASTM C1609-12, the residual strength (f_{150}) is calculated from the load-deflection plot (see Figure 7 for an example) as follows:

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

where P_{150} is the corresponding load when the displacement reaches a value of *L/150*, *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.

While alternative test methods for characterizing the post-cracking performance of FRC have been proposed, it is recommended that ASTM C1609-12 be used to evaluate the residual strength value for a given concrete mixture, fiber type, and fiber content for concrete pavement overlay designs (ACI Committee 544 2018).

Mixture Proportioning and Construction Modifications for FRC Overlays

In general, for the typical low to moderate fiber dosages used for FRC pavement overlays (i.e., less than 0.5% by volume), the concrete mix design does not necessarily need to be adjusted except to accommodate the volume of the fibers. Best practices for standard proportioning of concrete paving mixtures should otherwise be followed.

Trial batches are always recommended to assess whether 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. However, the water-to-cementitious material (w/cm) ratio should still be selected to achieve the desired strength and durability performance.

For example, FRCs used for concrete overlays have had 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 (Harrington and Fick 2014).

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

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

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

Proper sawcut timing is an important factor for FRC overlays, given that the concrete material is more resistant to crack growth than traditional overlay materials. In addition, if shorter panel sizes are utilized, they do not generate as much of the internal stress in the material necessary for joint development.

Field observations of FRC overlay joints have shown that contraction joint activation can occur initially at every 4 to 20 joints. Long-term monitoring has shown that almost all contraction joints activate over time, especially under traffic loading.

Transverse contraction joints in FRC overlays should be sawcut as early as possible with early-entry sawcuts, while minimizing joint raveling. These joints should be cut to 1/4 of the depth or to at least 1 in., depending on the type of saw and assuming that the joint cutting is properly timed.

Longitudinal joints can be cut after the transverse joints, but longitudinal cutting typically must start within a few hours after the transverse joint cutting commences. Longitudinal joints should be sawcut more deeply than the transverse joints, approximately 1/3 of the depth (ACI Committee 544 2008), given the relatively low transverse stresses in the FRC overlay.

Extra saws and personnel are often required for FRC overlays given the large number of contraction joints required to be cut per lineal foot of pavement.

FRC Overlay Maintenance

Macrofibers maintain tight joint and crack openings, e.g., less than 0.02 to 0.04 in. The typical practice with FRC overlays is to not seal the contraction joints, but this practice depends on the overlay's design life and the number of lanes paved. Even if cracks form in the mid-panel area, there is no need to seal them as long as the crack widths remain sufficiently small.

If the FRC overlay eventually exhibits unacceptable roughness or faulting, diamond grinding may be used to improve the ride and friction. Given that fibers increase the toughness of the concrete pavement, diamond grinding may require greater energy than would be needed for traditional concrete materials.

Slab removal may also require greater energy for the same reason. Additionally, because replacement slabs or patches cannot take advantage of the fiber bridging effect across the new construction joints, thicker replacement panels 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 strength and ultimate capacity of concrete slabs, both of which can be used in the design of a concrete overlay's thickness and slab size. Numerous macrofibers are available that are made from different materials (steel or synthetic) and that have different shapes (round, rectangular, etc.), diameters, lengths, and surface textures/embossings.

The effectiveness of a macrofiber is related to its material properties, geometry, surface enhancements, and interactions with the concrete matrix. Macrofibers should not be specified based on geometry, shape, or surface texture but on their effect on residual strength performance within a particular concrete matrix.

The proper batching and mixing of macrofibers is important to the successful construction of FRC overlays. Ideally, macrofibers should be continuously added to the concrete mixture at the central drum plant along with the other concrete constituents, but adjustments may need to be made based on the available equipment and the pre-packaging of the specific macrofiber used.

Best practices for concrete paving should be followed with slight adjustments to the finishing and texturing processes to avoid pulling out fibers from the overlay's surface. The contraction joints of an FRC overlay should be sawcut at the proper time and depth to ensure that the joints activate as soon as possible and to avoid premature cracking and the development of 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 C1609-12, has been shown to quantify the benefits of macrofibers relative to plain concrete slabs. Residual strength values for concrete overlay applications typically range from 100 to 225 psi. Adding the residual strength (f_{150}) to the actual concrete flexural strength (MOR) yields an effective flexural strength value (f_{eff}) that can be used in existing structural design programs for concrete overlays.

A Residual Strength Estimator spreadsheet was developed to help engineers determine the appropriate residual strength value (f_{150}) given the existing pavement conditions and the overlay design inputs. The residual strength value for an FRC should be incorporated into the project's material specifications. Multiple state departments of transportation (e.g., Illinois, Minnesota, and Utah) specify the residual strength parameter when employing macrofibers in concrete overlays.

Macrofibers should not be specified by volume fraction or weight, given that various fiber materials and properties produce the same residual strength values at different fiber contents.

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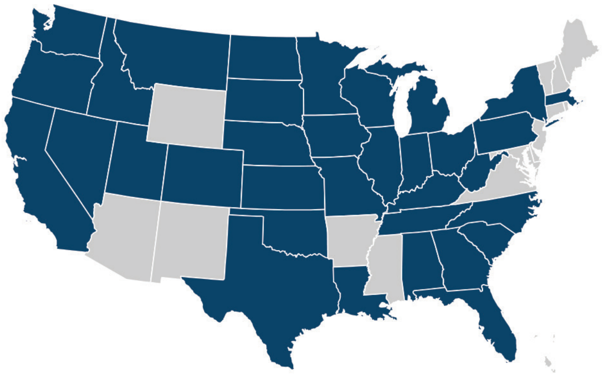
Technology Transfer Concrete Consortium

The goal of the Technology Transfer Concrete Consortium (TTCC) Transportation Pooled Fund TPF-5(313) is to help state departments of transportation (DOTs) design and build longer life concrete pavements that result in a higher level of user satisfaction for the public. One of the strategies for achieving longer life pavements is to use innovative materials and construction optimization technologies and practices.

Thirty-four states currently participate in the TTCC: Alabama, California, Colorado, Florida, Georgia, Idaho, Illinois, Indiana, Iowa (lead state), Kansas, Kentucky, Louisiana, Massachusetts, Michigan, Minnesota, Missouri, Montana, Nebraska, Nevada, New York, North Carolina, North Dakota, Ohio, Oklahoma, Oregon, Pennsylvania, South Carolina, South Dakota, Tennessee, Texas, Utah, Washington, West Virginia, and Wisconsin



About the National Concrete Pavement Technology Center

The mission of the National Concrete Pavement Technology Center is to unite key transportation stakeholders around the central goal of advancing concrete pavement technology through research, tech transfer, and technology implementation.