Louisiana Transportation Research Center

Final Report 559

Evaluation of the Fatigue and Toughness of Fiber Reinforced Concrete for use as a New Highway Pavement Design

by

John Kevern, Ph.D., P.E.
Tyson Rupnow, Ph.D., P.E.
Matt Mulheron, E.I.
Zachary Collier, E.I.
Patrick Icenogle, P.E.

LTRC

4101 Gourrier Avenue | Baton Rouge, Louisiana 70808
(225) 767-9131 | (225) 767-9108 fax | www.ltrc.lsu.edu

TECHNICAL REPORT STANDARD PAGE

<table>
<tr><td colspan="2">1. Report No.
FHWA/LA.15/559</td><td>2. Government Accession No.</td><td>3. Recipient's Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle
Evaluation of the Fatigue and Toughness of Fiber Reinforced Concrete for use as a New Highway Pavement Design</td><td colspan="2">5. Report Date
April 2016</td></tr>
<tr><td colspan="2">6. Performing Organization Code
LTRC Project Number: 14-3C
State Project Number: 30001504</td></tr>
<tr><td colspan="2">7. Author(s)
John Kevern, Tyson Rupnow, Matt Mulheron, Zachary Collier,
Patrick Icenogle</td><td colspan="2">8. Performing Organization Report No.</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address

Louisiana Transportation Research Center
4101 Gourrier Avenue
Baton Rouge, LA 70808</td><td colspan="2">10. Work Unit No.</td></tr>
<tr><td colspan="2">11. Contract or Grant No.</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
Louisiana Department of Transportation and Development
P.O. Box 94245
Baton Rouge, LA 70804-9245</td><td colspan="2">13. Type of Report and Period Covered
Final Report</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code</td></tr>
<tr><td colspan="4">15. Supplementary Notes
Conducted in Cooperation with the U.S. Department of Transportation, Federal Highway Administration</td></tr>
<tr><td colspan="4">16. Abstract
Concrete pavement design is currently centered on steel reinforcement, whether that reinforcement be in the form of dowel bars, as is the case in jointed plain concrete pavement (JPCP), or in the form of continuous rebar reinforcement, continuously reinforced concrete pavement (CRCP). The use of steel in concrete pavements presents durability problems due to the corrodibility of steel. This study evaluates the use of polypropylene fibrillated, polypropylene macro, carbon, and steel fibers as primary reinforcement in concrete pavements. Results showed that fiber reinforcement can be used to improve both the fatigue and toughness performance of concrete. When post-cracked strength or toughness is the concern, concrete containing more fibers and fibers with higher tensile strength are desirable. Carbon fibers maintained greater load-carrying capacity at lower deflections than the steel fibers, which produced the greatest ductility. However, toughness and fatigue performance did not correlate for small deflections, suggesting that polypropylene macro fibers may be adequate for repeated, low stress loading.

This study also found that when repeated low deflections are a concern, such as many pavements, there must be sufficient fibers across a crack to maintain a tight crack. Conversely, too many fibers prevent adequate consolidation and aggregate interlock, which negatively influences performance. When considering the pre-cracked fatigue performance of fiber reinforcement, the fibers needed to have sufficient length to reach across the crack and bond with the concrete, and that higher fiber dosages increase the fatigue performance of the concrete. The resulting pavement design, continuously fiber reinforced concrete pavement (CFRCP), will provide an alternative to JPCP and CRCP in highway pavement design that is not susceptible to durability problems associated with corrosion of the reinforcement.</td></tr>
<tr><td colspan="2">17. Key Words</td><td colspan="2">18. Distribution Statement
Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.</td></tr>
<tr><td>19. Security Classif. (of this report)</td><td>20. Security Classif. (of this page)</td><td>21. No. of Pages</td><td>22. Price</td></tr>
</table>

Project Review Committee

Each research project will have an advisory committee appointed by the LTRC Director. The Project Review Committee is responsible for assisting the LTRC Administrator or Manager in the development of acceptable research problem statements, requests for proposals, review of research proposals, oversight of approved research projects, and implementation of findings.

LTRC appreciates the dedication of the following Project Review Committee Members in guiding this research study to fruition.

LTRC Manager

Samuel B. Cooper, III

Materials Research Manager

Members

Chris Abadie

Hector Santiago

John Eggers

Bill Temple

Mike Koenigstein

Ish Keener

Dan Biddle

Bob Grace

Directorate Implementation Sponsor

Janice P. Williams, P.E.

DOTD Chief Engineer

Evaluation of the Fatigue and Toughness of Fiber Reinforced Concrete for use as a New Highway Pavement Design

by

John Kevern, Ph.D., P.E.
Tyson Rupnow, Ph.D., P.E.
Matt Mulheron, E.I.
Zachary Collier, E.I.
Patrick Icenogle, P.E.

Louisiana Transportation Research Center
4101 Gourrier Avenue
Baton Rouge, LA 70808

LTRC Project No. 14-3C
State Project No. 30001504

conducted for

Louisiana Department of Transportation and Development
Louisiana Transportation Research Center

April 2016

ABSTRACT

Concrete pavement design is currently centered on steel reinforcement, whether that reinforcement be in the form of dowel bars, as is the case in jointed plain concrete pavement (JPCP), or in the form of continuous rebar reinforcement, continuously reinforced concrete pavement (CRCP). The use of steel in concrete pavements presents durability problems due to the corrodibility of steel. This study evaluates the use of polypropylene fibrillated, polypropylene macro, carbon, and steel fibers as primary reinforcement in concrete pavements.

Results showed that fiber reinforcement can be used to improve both the fatigue and toughness performance of concrete. When post-cracked strength or toughness is the concern, concrete containing more fibers and fibers with higher tensile strength are desirable. Carbon fibers maintained greater load-carrying capacity at lower deflections than the steel fibers, which produced the greatest ductility. However, toughness and fatigue performance did not correlate for small deflections, suggesting that polypropylene macro fibers may be adequate for repeated, low stress loading.

This study also found that when repeated low deflections are a concern, such as many pavements, there must be sufficient fibers across a crack to maintain a tight crack. Conversely, too many fibers prevent adequate consolidation and aggregate interlock, which negatively influences performance. When considering the pre-cracked fatigue performance of fiber reinforcement, the fibers needed to have sufficient length to reach across the crack and bond with the concrete, and that higher fiber dosages increase the fatigue performance of the concrete. The resulting pavement design, continuously fiber reinforced concrete pavement (CFRCP), will provide an alternative to JPCP and CRCP in highway pavement design that is not susceptible to durability problems associated with corrosion of the reinforcement.

ACKNOWLEDGMENTS

The U.S. Department of Transportation, Federal Highway Administration (FHWA), Louisiana Department of Transportation and Development (DOTD), Louisiana Transportation Research Center (LTRC), Forta Corporation, and Pro-Perma Corporation financially supported this research project.

The efforts of Greg Tullier, Norris Rosser, and Craig Johnson in the LTRC concrete laboratory are greatly appreciated. The authors would also like to acknowledge the engineering research technician, Pat O'Bannon, at UMKC for his assistance with the fatigue testing and patience with the research process.

IMPLEMENTATION STATEMENT

Further investigation is required to validate the findings of this study. No implementation is recommended by the authors at this point. Further recommended research includes construction of full-scale test sections at the Accelerated Loading Facility to offer a better understanding of how fiber reinforcement improves the performance of concrete pavements. Further laboratory testing should also be performed to create a more accurate pavement design curve. Finally, a test highway section should be built to evaluate CFRCP alongside JPCP and/or CRCP in the same climatic conditions to determine if CFRCP will eliminate the need for joints in pavement and perform to the same level as CRCP.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Currently the concrete industry has two options when it comes to concrete pavement, jointed plain concrete pavement (JPCP) and continuously reinforced concrete pavement (CRCP). Both have their strengths and drawbacks. The research presented herein represents a first step in determining the feasibility of utilizing a new pavement structure. The proposed continuously fiber reinforced concrete pavement (CFRCP) will conceivably merge the cost effectiveness of a jointed plain concrete pavement (JPCP) with the smooth ride and superior longevity of a continuously reinforced concrete pavement (CRCP). The initial laboratory results include flexural, fatigue, and toughness testing for a variety of concrete mixtures containing polypropylene fibrillated, polypropylene macro, carbon macro, and steel fibers.

Literature Review

The steel-centric design of concrete pavement allows the steel performance and longevity to dictate the performance and longevity of the pavement. In the case of CRCP, the percentage of steel used in the design has a great influence on the lifetime of the pavement. If the percentage of steel is too low, the spacing between cracks will grow, resulting in punchouts at closely spaced cracks next to larger spaced cracking [*1*]. If too much steel is used in design, then the concrete compressive strength must be increased in order to maintain crack spacing [*1*]. The added steel and labor costs of CRCP have deterred many states from constructing CRCP roadways, even though CRCP has a superior ride quality and longevity. In JPCP the corrosion of steel is less of a factor; instead, joints that are required throughout the pavement become the limiting factor. This deterioration has been combatted in many ways and with large economic impact.

Concrete Pavement Joint Deterioration

When designing JPCP concrete pavement, it is necessary to include both saw cut and formed joints. The joints in concrete pavements allow for the expansion and contraction of the concrete and provide a means for the concrete to crack in a way that is controlled. In the case of JPCP, the use of dowel bars is necessary to ensure that the load transfer of the pavement is maintained between the slabs. The length of the slab is dependent on the thickness of the pavement, thicker pavements have a greater flexural strength and allow a larger distance between joints. No matter what the distance between joints is, the maintenance of the joints must be maintained to improve the life expectancy of the pavement [*2*].

Everything from the timing of the saw cutting to the use of soy methyl ester has been studied to determine the most effective way to improve the durability of concrete joints [*3, 4*]. The use of early entry concrete saws has brought another variable into the timing equation. Early entry concrete saws allow for a shallower cut at an earlier time than using a wet cut concrete saw. Even the use of alternative dowel materials, sleeved dowel bars, and the placement of the dowel reinforcement within the cross section of the slab has been investigated as a way to improve the performance of joints in concrete [*5-7*]. Examples of dowel bar placement and sleeved dowel bars are shown in Figure 1 and Figure 2. The importance of the joint durability is undeniable. The joint provides a path for water to enter the concrete structure, often bringing with it detrimental chemicals, such as chlorides, and accelerate the deterioration of the aggregate and concrete paste, as shown in Figure 3. The deterioration of joints can be accelerated under low intensity, cyclic loading, which increases the need for the understanding and improvement for highway pavements [*8*]. The improvement of joint durability has led to many studies that look at methods for testing the structural integrity of the joints, predicting the deterioration and mechanics of the deterioration [*9-12*].

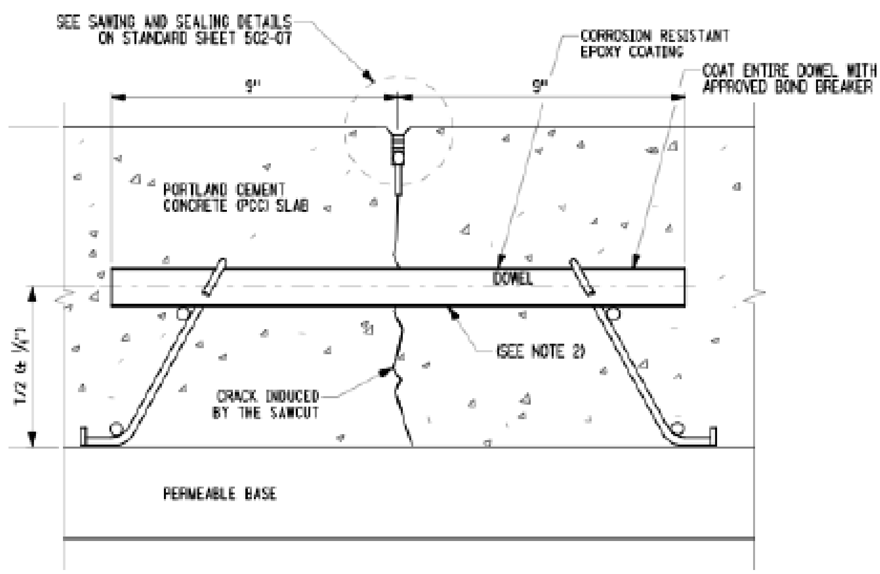

Figure 1
Example dowel bar specification [*13*]

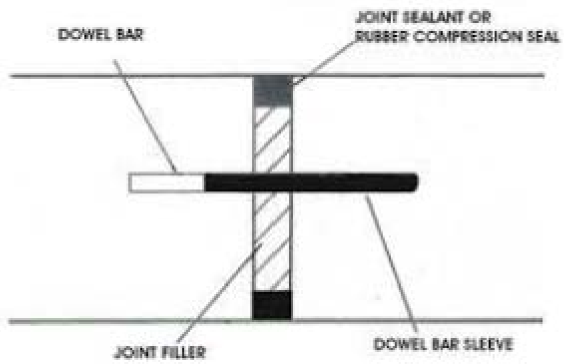

Figure 2
Example of sleeved dowel bar [*14*]

Figure 3
Example of pavement joint deterioration [*15*]

State-of-the-Practice

The issue of joint durability has created many questions when it comes to pavement design. A study of the percentage of joints that have actually cracked, determined that only 30 percent of constructed joints cracked, and prodded a study to look at the effects that un-cracked joints may have on the performance of concrete pavements [*2, 16*]. The un-cracked joints increased the length of the pavement slab and increased the stresses within the concrete. The increase in stresses showed in the form of transverse cracking. Transverse cracking is undesirable in JPCP because the unplanned crack does not have steel reinforcement. The lack of reinforcement could lead to a loss in load transfer capability and faulting or the degradation of the pavement sub base.

Determining the economic impact of joint maintenance is also a topic that must be considered when designing pavements. The Indiana Department of Transportation commissioned a study to find out, through literature review, if joint maintenance was economically beneficial, as the state of Indiana spends an estimated four million dollars annually on joint maintenance [*17*].

Fiber Reinforced Concrete

Fiber reinforcement has proven to be beneficial in many applications. The fiber reinforcement of portland cement is designed to improve the tensile and shear strengths of concrete, depending on the application. Fibers have been used to improve the punching shear resistance of the column and slab interface by placing the fiber within the concrete slab to traverse the failure surface, punching shear failure shown in Figure 4 [*18,19*]. Fiber reinforcement has also been studied as a way to retrofit steel reinforced concrete structures and increase the seismic resistance of the structure [*20*].

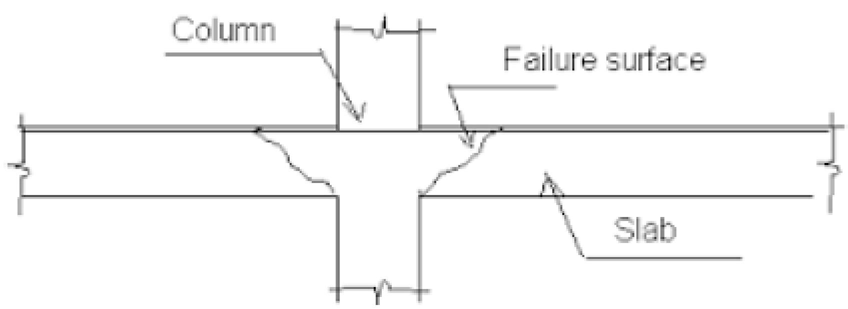

Figure 4
Punching shear failure plain [*21*]

The use of fiber reinforcement has proven to be beneficial when designing concrete structures for resistance to blast and fire resistance. A study of steel fiber reinforcement in composite concrete floors showed that the fiber reinforcement improved the ductility and resistance to fire damage at elevated temperatures, with a maximum load carrying capability around 500^{0}C [*22*]. The increased load carrying capability of the fiber reinforced slabs increases the safety of the slab in the case of fire. Fiber reinforcement has also been shown to improve the blast and impact resistance of concrete bridges, making infrastructure less dangerous in the event of an attack [*23*]. The fiber reinforcement changed the brittle nature of concrete to a ductile nature, when exposed to a blast, which decreased the amount of spalling that was observed. Figure 5 illustrates the improvement in performance in blast resistance that can be achieved with fiber reinforcement.

Figure 5
Comparison of traditional reinforced concrete (top) and fiber reinforced concrete (bottom) to blast [*24*]

The tensile strength that fiber reinforcement provides has also been used to control cracking in on grade slabs; both shrinkage and plastic shrinkage cracking are shown in Figure 6. The reduction in cracking has been taken a step further to show that fiber reinforcement could provide the necessary increase in tensile strength to reduce the number of joints in slabs on grade [*25, 26*]. Fiber reinforcement in concrete does not prevent the concrete from cracking, rather reduces the propagation of cracking by bridging the crack [*27*].

Figure 6
Example of shrinkage cracking (right) and plastic shrinkage cracking (left) [28, 29]

Fiber Reinforced Pavement

Laboratory testing of cyclic loading on fiber reinforced concrete showed significant improvements in fatigue behavior and promise for thin overlays and repair sections [30, 31]. One of the early studies that explored the use of fiber reinforcement in pavements was done in Iowa beginning in 1978. This study looked at the possibility of using steel fiber reinforcement in 2- and 3-in. overlays. The study concluded that the fiber reinforcement performed well but that it was not economically feasible at the time [32]. Another related study performed for the Florida DOT investigated the fatigue behavior of various fiber types for use as a thin concrete overlay. That study concluded that lower dosages of fibrillated polypropylene fibers (0.1percent by volume) produced a superior fatigue response compared to a much higher dosage (1.6 percent) of monofilament polyolefin fibers [33]. The Florida DOT also sponsored a study that used polypropylene fibers, in the same low dosages, as a way to minimize early stage cracking in concrete pavements [34]. The same polyolefin fibers and dosage were then used to construct a section of US highway 83 near Pierre, South Dakota in 1996. When allowed to crack randomly in uncut sections, cracks were uniformly spaced at 85 feet [35]. In Texas the addition of fiber reinforcement to CRCP has been used as a way to control spalling and provide secondary reinforcement; an example of pavement tested is shown in Figure 7 [36]. Very few studies have investigated the possibility of fiber as the primary reinforcement for full-depth pavements.

Figure 7
Example of fiber reinforced pavement used in Texas to control spalling [*36*]

OBJECTIVE

This study presents the first approach to developing a new concrete pavement structure reinforced only with fibers. This research will identify probable combinations of fibers (dosage and length combinations) that will adequately perform in repeated load fatigue tests. While fibers and high dosage fiber combinations have been previously used in concrete, these combinations have never before been used in a DOT pavement structure. The major difference between previous applications and the current objective is the number and level of load applications. The fundamental objective of this research is to determine how CFRCPs behave under highway-type loading.

The specific objectives of the study include:

1. Characterize the fresh and hardened properties of CFRCP concrete.
2. Determine the comparative fatigue resistance of different fibers, and differing fiber blends and dosage rates.
3. Provide recommendations for future research, including full-scale loading and possible field implementation sites.

SCOPE

Much of the focus in recent years has been to create crackless industrial floors, the previous interest in fiber reinforcing for highways having dwindled. The fiber market now includes many more types, shapes, and applications for fiber-reinforced concrete, and with the increasing cost of steel, these options have become cost-effective. The objective of this research is to develop a CFRCP system which will ultimately produce a series of normal, random cracks similar to a CRCP pavement but without the cost of steel materials and construction. The first step is to determine how various types and dosages of the currently available fibers impact fatigue and toughness when used in a standard DOT concrete pavement mixture.

The driving motivation for this project was to determine if fiber reinforcement could be used as a viable alternative to steel reinforcement in pavement design. The fiber dosages used in this project were selected for their cost relative to that of steel currently used in CRCP and JPCP. Table 1 shows a comparison of known benefits and shortcomings with CRCP and JPCP, expected benefits and shortcomings of CFRCP, along with a delta cost analysis.

Table 1
Comparison of CRCP, JPCP, and CFRCP

Pavement type	Benefits	Shortcomings	Difference in cost
CRCP	-Smooth driving surface -Fewer joint durability concerns	-Labor intensive -Potential corrosion of steel leading to durability issues	-Added steel cost -More labor cost
JPCP	-Less steel -Less labor intensive than CRCP	-Joint maintenance	-Lower steel cost than CRCP -Less labor cost than CRCP
CFRCP	-No steel -Smooth driving surface		-Fiber cost comparable to steel cost of CRCP -Less labor cost

METHODOLOGY

This research evaluated the replacement of steel reinforcement with fiber reinforcement in concrete pavement in a laboratory setting. The testing methods used were a combination of available testing methods and testing methods based on previous research. This section describes the methods selected and the instrumentation used to record data and evaluate the fatigue and toughness performance of the fiber reinforced concrete.

Materials

The testing was performed on concrete beams with a 6-in. by 6-in. cross section that were 20 in. in length. The beams were prepared in accordance with ASTM C192 using a vibrator for consolidation [*37*]. The concrete mixture proportions used for this study were a standard DOTD highway mix design used for JPCP, shown in Table 2. Note that the portland cement and class C fly ash content were kept constant at 400 and 100 pounds per cubic yard, respectively. A polycarboxylate high range water reducer was used to ensure workability of the mixtures.

The fiber dosages were selected based on cost compared to the difference in construction and materials between JPCP and CRCP. Each of the mixtures, except for the steel fiber mixture (added at a rate of 0.9 percent or 85 pounds per cubic yard) included one dosage rate above that commonly used or previously investigated. Three dosage rates for the polypropylene fibrillated fiber were used, 0.1, 0.2, and 0.3 percent corresponding to 1.5, 3.0, and 4.5 pounds per cubic yard, respectively.

Four dosage rates of the polypropylene macro fibers, 0.3, 0.5, 0.7, and 1.0 percent, were included because a wider range of dosages is common in practice. This corresponds to 4.5, 7.5, 10.5, and 15.0 pounds per cubic yard, respectively. The polypropylene macro fiber was a twisted bundle that dispersed during mixing.

Three dosage rates for the carbon fiber were used, 0.3, 0.7, and 1.02 percent corresponding to 9.0, 21.0, and 30.5 pounds per cubic yard, respectively. The carbon fibers contained a large number of individual fibers held together with a nylon mesh.

To prevent any balling concerns, all fibers were added by hand to the fresh concrete once all of the other components had been incorporated.

Table 2
Mixture proportions

Coarse Aggr. (lb/yd^3)	Fine Aggr. (lb/yd^3)	Water (lb/yd^3)	Polypropylene Macro Fibers (lb/yd^3)	Carbon Fibers (lb/yd^3)	Steel Fibers (lb/yd^3)	Polypropylene Fibrillated Fibers (lb/yd^3)
1938	1290	250				
1911	1267	250				1.5
1907	1268	250				3.0
1899	1270	250				4.5
1895	1274	250	4.5			
1894	1267	250	7.5			
1900	1253	250	10.5			
1888	1252	250	15.0			
1895	1274	250		9.0		
1890	1259	250		21.0		
1883	1251	250		30.5		
1888	1266	250			85	

The fiber properties are shown in Table 3 and Figure 8 illustrates the fibers before being mixed into the concrete mixture.

Table 3
Properties of reinforcing fiber

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

Figure 8
Polypropylene fibrillated fiber (left), polypropylene macro fiber (left middle), carbon fiber (right middle) and steel fiber (right)

Fatigue Testing

The fatigue testing was based on a study performed by the University of Illinois where a clip gage is placed across a notch in the beam and monitored during loading to measure crack mouth opening displacement (CMOD) [*30* ,*31*]. The beams were notched to ensure that the cross sectional area was a consistent 4 in. by 6 in. for all samples, as shown in Figure 9. After notching the beams, plastic clips were glued on either side of the notch approximately 10 millimeters apart, as recommended by the manufacturer. The gap between the clips kept the clip gage in a readable range for both expansion and contraction of the CMOD. The beam was then placed on supports that were 18 in. apart and loaded in the center of the beam, directly above the notch, as shown in Figure 10.

Figure 9
Wet saw setup for notching beams

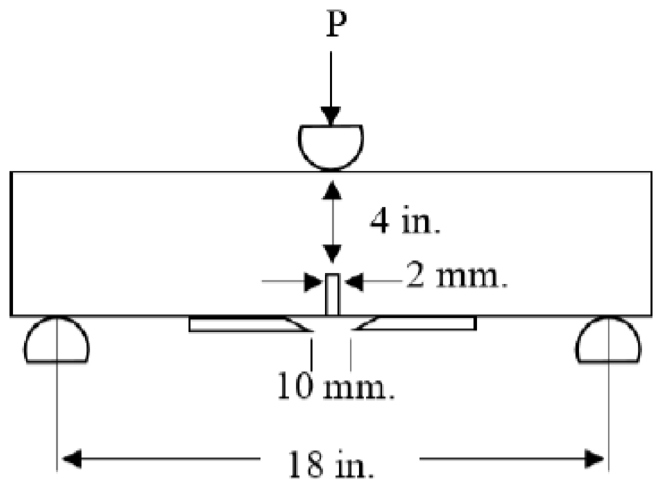

Figure 10
Notched beam testing arrangement

The test required the cyclic loading of the concrete beam at a frequency of four hertz, which is the performance limit for the INSTRON loading frame. The beams were loaded to 90 percent and 70 percent of the ultimate strength. The previously mentioned stress ratios were kept constant for the different fiber dosage rates. The maximum target loading for each dosage rate and stress ratio is shown in Table 4.

Table 4
Target loading for fatigue testing

Fiber Type	Fiber Dosage (pcy)	Target Loading for 90% Stress Ratio (lbs)	Target Loading for 70% Stress Ratio (lbs)
Control	-	3690	2870
Polypropylene	1.5	3920	3050
Fibrillated Fiber	3.0	3680	2860
	4.5	3700	2880
Polypropylene	4.5	3750	2920
Macro Fiber	7.5	3640	2830
	10.5	3640	2830
	15.0	3760	2930
Carbon Fiber	9.0	3930	3050
	21.0	4250	3310
	30.5	4160	3240
Steel Fiber	85.0	3860	3010

During testing, the loading, CMOD, and the time of the test were recorded. The peak loading for each cycle was taken from the data and averaged to determine the average stress ratio, and the maximum peak loading was found to determine the maximum stress ratio. Figure 11 illustrates the load versus time output for a test that required approximately a 3000-pound peak loading. Due to the change in stiffness of the beam after cracking begins, the loading tends to fluctuate after initial cracking, also illustrated in Figure 11.

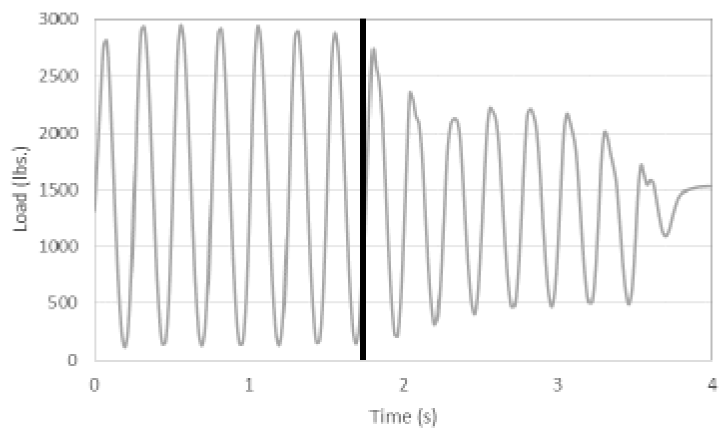

Figure 11
Recorded loading curve with initial cracking indicated by vertical line

In order to accommodate the deflection caused by the preloading used during testing, the initial CMOD was determined by taking the minimum recorded CMOD of the first five cycles, when testing allowed. When the test did not last more than five cycles, the minimum CMOD of the first two cycles was used. Figure 12 shows how the CMOD changed with an increase in load cycles. The one millimeter failure criterion was used to be consistent with previous research [*31*]. Samples had a very rapid increase in CMOD when cyclic loading was continued beyond the one millimeter failure criteria.

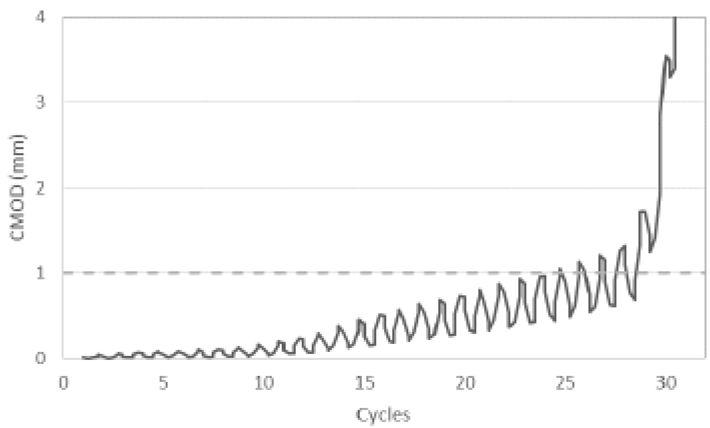

Figure 12
Observed CMOD versus cycles during fatigue testing with 1 mm failure criteria shown by dashed line

All samples tested for fatigue were tested until ultimate failure. Ultimate failure was determined to be when the load carrying capability of the beam fell below the 100-pound limit. The loading limit was set to prevent the testing apparatus from losing contact with the beam, which would cause undesired impact loading during testing. Figure 13 illustrates a failed beam on the testing apparatus with the clip gage still attached.

Figure 13
Notched beam testing after failure

Pre-Cracked Fatigue Testing

During fatigue testing, it was discovered that loading the fiber reinforced beams at a 50 percent stress ratio produced data that was considered to be infinite, greater than 10 million cycles per beam. Therefore, a reevaluation of the testing was performed and a new test was determined. The new test pre-cracked the beams in order to determine the performance of the fiber reinforced concrete under stress ratios of 50 percent or less. The beams were notched to ensure that the cross sectional area was a consistent 4 in. by 6 in. for all samples. The pre-cracking was performed on notched beams in accordance with the procedural steps 8.1 through 8.5 of ASTM C1399 [*38*]. The pre-cracked beam was then removed from the apparatus and the plastic clips were glued on either side of the notch approximately 10 millimeters apart, as recommended by the manufacturer. During testing, the CMOD, loading, and number of cycles were recorded. The clip gage was zeroed upon installation, before preloading, in order to better track the growth of the CMOD and not just the change. The beams were loaded using a third point loading system, so the loading would not be concentrated on the crack, shown in Figure 14.

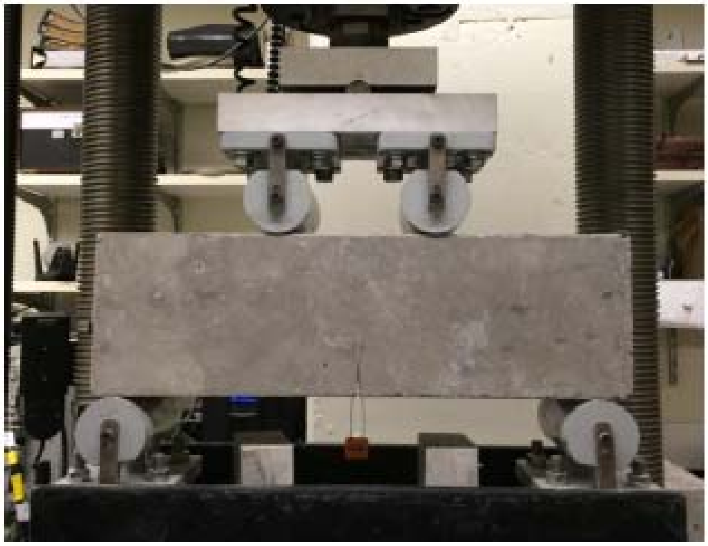

Figure 14
Testing setup for pre-cracked testing, using third point loading

The cyclic loading was performed at a constant stress ratio of 50 percent of the ultimate strength for each dosage rate. The loading was kept at a rate of 4 hertz to be consistent with the fatigue testing. The target loading for each fiber type and dosage rate are shown in Table 5. The control mixture design was not included in the pre-cracked testing, due to the lack of reinforcement.

Table 5
Target loading for the pre-cracked fatigue test

Fiber Type	Fiber Dosage (pcy)	Target Loading for 50% Stress Ratio (lbs)
Polypropylene	1.5	2060
Fibrillated Fibers	3.0	2050
	4.5	2180
Polypropylene	4.5	2080
Macro Fibers	7.5	2020
	10.5	2020
	15.0	2090
Carbon Fibers	9.0	2180
	21.0	2360
	30.5	2310
Steel Fibers	85.0	2150

The pre-cracked testing was performed until the sample reached ultimate failure or one million cycles. Ultimate failure was determined to be the point at which the sample was unable to support a minimum loading of 100 pounds. The failure criteria was determined by graphing the CMOD versus cycles for the different samples and comparing the graphs to determine when rapid failure started to occur, shown in Figure 15. The failure criteria for analysis was determined to be a growth in CMOD of four millimeters.

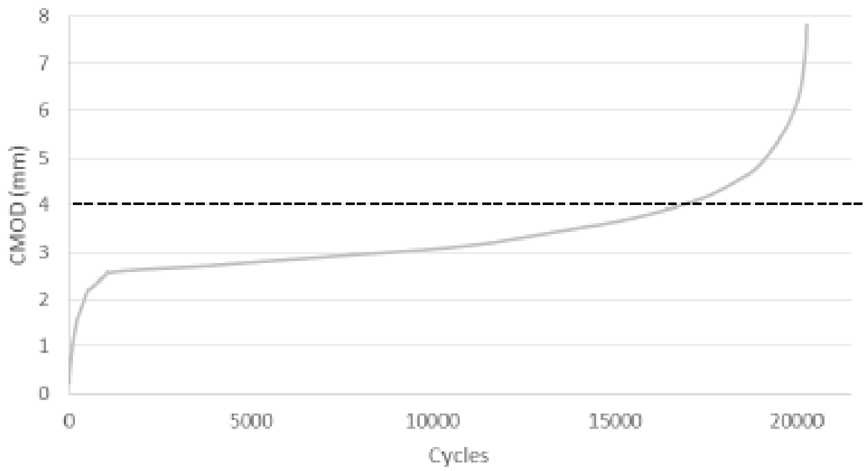

Figure 15
CMOD vs. cycles graph for pre-cracked fatigue testing, with dashed horizontal line showing failure criteria

Toughness Testing

The toughness testing was performed in accordance with ASTM C1609 [*39*]. In order to meet the deflection rate requirement specified in ASTM C1609, 0.002 to 0.005 in. per minute, the displacement of the loading piston was set to move upward at a steady rate. Until the net deflection reaches L/600, in this case is equal to 0.03 in., the specified deflection rate then widens to 0.002 to 0.010 in. per minute and the upward movement of the piston was decreased to account for the decrease in stiffness of the sample after cracking. An example of the recorded deflection versus time curve with the specified bands is shown in Figure 16.

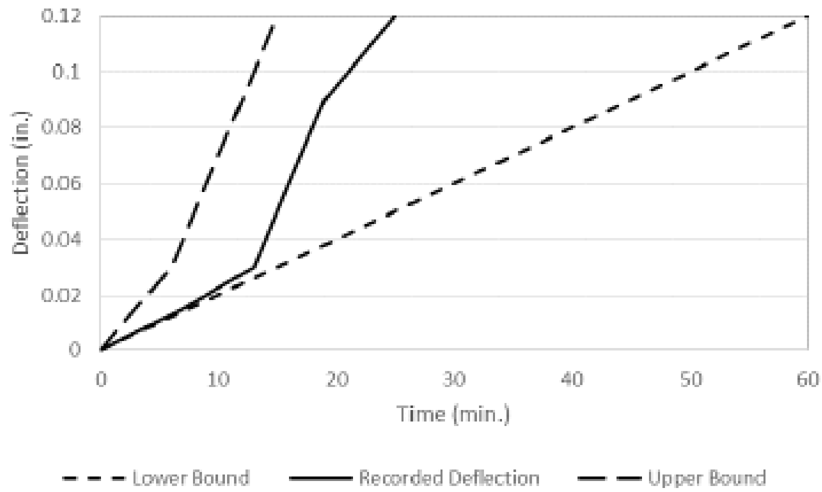

Figure 16
Recorded deflection rate of ASTM C1609 testing with upper and lower bounds shown

During the toughness test, the deflection of the sample, load on the sample, and time of the test were recorded. The data was recorded at a rate of 2.5 hertz to ensure that the peak loading was recorded. The testing setup was modeled after Figure 2 of ASTM C1609; the actual testing setup is shown in Figure 17 and Figure 18. ASTM C1609 requires that the deflection be measured on both sides of the sample, to account for any twisting that may occur. Linear variable differential transformers (LVDT) were used to measure the deflection on either side of the beam, one LVDT was recorded by the program and the other was read manually on 15-second intervals. The measurements for both LVDTs were then averaged to determine the net deflection. Table 6 illustrates an example of the data taken during the toughness testing with the peak loading underlined on the table. The results of the testing will be shown by graphing the load versus the average deflection.

Figure 17
Side view of testing rig for ASTM C1609

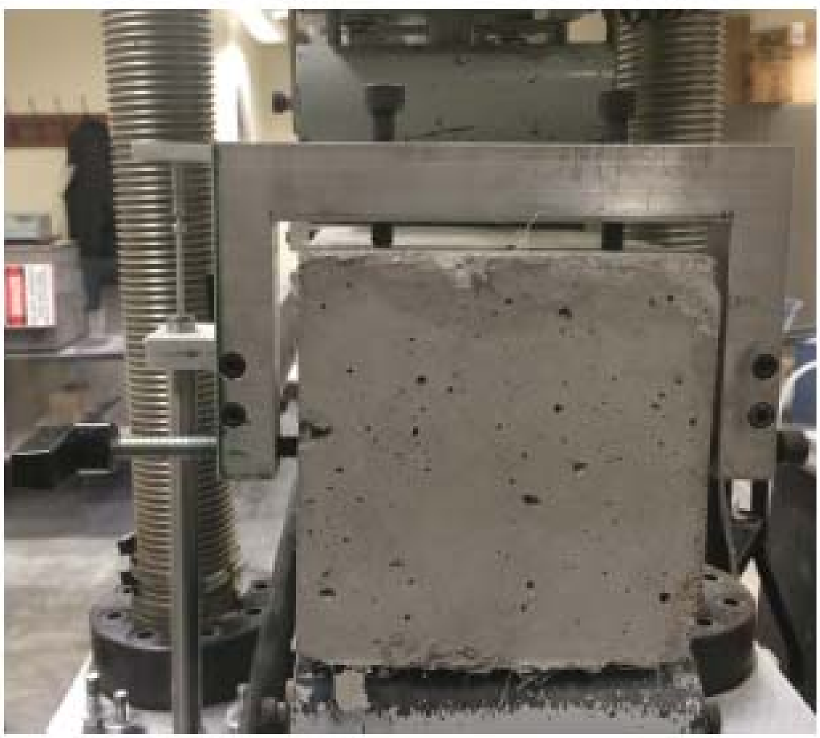

Figure 18
End view of testing rig for ASTM C1609

Table 6
Example of recorded deflection measurements with peak load underlined

Load (lbs.)	INSTRON deflection (in.)	Manually read deflection (in.)	Average deflection (in.)
82	-0.00005	0.0000	-0.0000
1977	0.00023	0.0005	0.0004
4693	0.00077	0.0012	0.0010
8012	0.00153	0.0021	0.0018
<u>11290</u>	<u>0.00276</u>		<u>0.0028</u>
3856	0.06659	0.0900	0.0783
4586	0.07887		0.0789
4414	0.09537	0.1130	0.1042
4034	0.11126	0.1320	0.1216
3468	0.12051	0.1510	0.1358
3062	0.12616	0.1620	0.1441
2997	0.12879	0.1660	0.1474
2957	0.13047	0.1698	0.1501
2923	0.13374	0.1732	0.1535
2887	0.13646		0.1365
2852	0.13872	0.1800	0.1594
2838	0.14033	0.1837	0.1620
2823	0.14240	0.1870	0.1640
3086	0.25021	0.3264	0.2883

Toughness testing was performed on three beams of each fiber type and dosage. The first peak load (P1) is the first point on the load versus displacement curve where the loading begins to decrease as the displacement increases. Peak load (P_p) refers to the maximum load that was experienced by the specimen. The residual load ($P_{150,0.75}$ and $P_{150,3.0}$) is the loading experienced by the specimen when the deflection is equal to L/600, $P_{150,0.75}$, and L/150, $P_{150,3.0}$. The values of the different loads were determined graphically and then used to determine the first-peak strength (f_1), peak strength (fp), and the residual strengths ($f_{150,0.75}$ and $f_{150,3.0}$). The toughness tests were performed until a deflection of 0.25 in. was achieved. Continuing to deflect the samples past the L/150 point, 0.12 in. for the testing rig used, ensured that there were no unexpected increases in load carrying capabilities as the load transferred from the concrete to the fiber.

Fresh and Hardened Concrete Testing

This section details the test methods for determining the fresh and hardened concrete properties. The compressive strength was tested at seven and 28 days of age, while the flexural strength was measured at 28 days of age. All specimens were produced and tested in triplicate. The following test methods were used to determine the fresh and hardened concrete properties.

- ASTM C39 [Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens] [*40*]
- ASTM C78 [Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)] [*41*]
- ASTM C138 [Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete] [*42*]
- ASTM C143/143M [Standard Test Method for Slump of Hydraulic-Cement Concrete] [*43*]
- ASTM C231 [Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method] [*44*]

DISCUSSION OF RESULTS

Fresh and Hardened Property Results

Table 7 shows the fresh and hardened properties of the CFRCP. The results are generally what are expected of fiber reinforced concrete.

Table 7
Fresh and hardened properties of the fiber reinforced concrete

Fiber Type	Fiber Dosage (pcy) (% volume)	Slump (in.)	Unit Weight (lb/ft³)	7 Day Compressive Strength, psi (COV)	28 Day Compressive Strength, psi (COV)	Flexural Strength, psi (COV)
Control	-	5.00	145	4,540 (2.2)	6,230 (1.4)	770 (10.7)
Polypropylene	1.5 (0.1%)	5.75	142	3,800 (1.7)	5,060 (1.0)	770 (7.0)
Fibrillated	3.0 (0.2%)	3.50	145	4,790 (0.5)	6,290 (1.9)	765 (6.0)
Fiber	4.5 (0.3%)	1.75	146	5,340 (9.0)	7,420 (1.4)	815 (8.3)
Polypropylene	4.5 (0.3%)	2.25	145	5,080 (18)	6,540 (2.6)	780 (8.1)
Macro Fiber	7.5 (0.5%)	0.75	147	5,450 (1.1)	7,030 (3.9)	760 (7.7)
	10.5 (0.7%)	1.00	148	5,550 (2.1)	7,090 (2.5)	760 (5.1)
	15.0 (1.0%)	0.25	147	4,920 (2.0)	5,850 (3.9)	785 (8.9)
Carbon Fiber	9.0 (0.3%)	0.75	144	5,130 (3.3)	6,310 (5.4)	820 (2.8)
	21.0 (0.7%)	0.50	145	5,030 (6.4)	6,630 (6.6)	885 (4.2)
	30.5 (1.0%)	0.25	145	5,720 (10.0)	6,340 (5.8)	865 (8.7)
Steel Fiber	85.0 (0.9%)	4.00	147	4,610 (2.7)	5,880 (1.6)	805 (9.1)

Fatigue Testing Results

The fatigue testing results for the carbon fiber, polypropylene macro fiber, and polypropylene fibrillated fiber were compared to the results of the steel fiber reinforced concrete samples to determine the impact the fiber dosages would have on performance. The results of the included data were averaged and plotted to graphically show this impact.

The polypropylene fibrillated fibers increased the fatigue performance at a 90 percent stress ratio, when compared to the non-reinforced concrete sample, but did not provide a greater improvement than the steel fiber reinforcement. At a stress ratio of 70 percent, the dosage rate of 3 pcy provided an increase in the fatigue performance greater than that of the steel fiber reinforcement, shown in Figure 19. The polypropylene fibrillated fibers were the shortest of the fibers used in this study. The shorter length made the fibers easier to pull out of the concrete. Figure 20 shows a broken section of a polypropylene fibrillated fiber reinforced section and illustrates the shortness of the polypropylene fibrillated fibers.

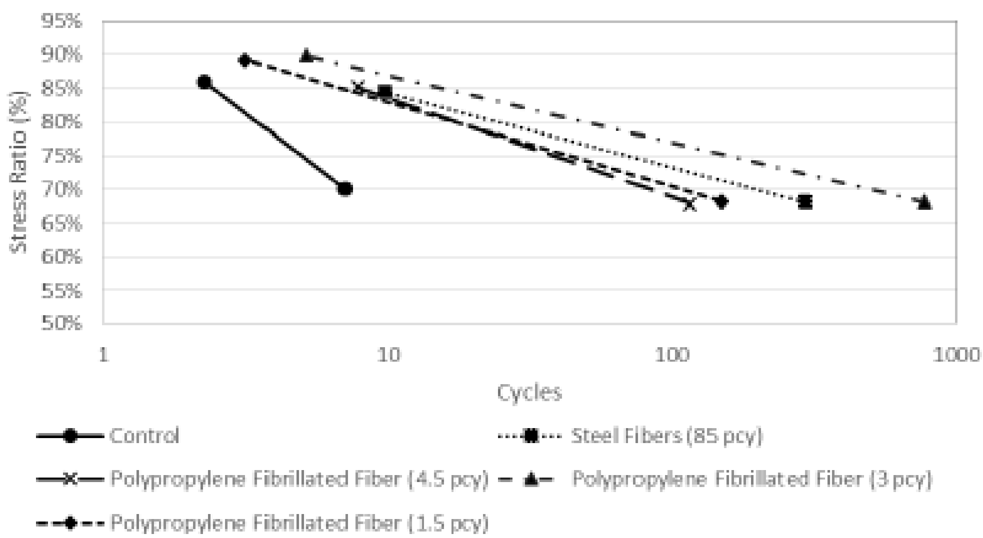

Figure 19
Results of fatigue testing of polypropylene fibrillated fibers

The polypropylene macro fiber reinforcement had a similar impact on performance at the 90 percent stress ratio to the polypropylene fibrillated fiber. The polypropylene macro fiber increased the performance of the samples at a 70 percent stress ratio, when compared to the steel fiber reinforcement, shown in Figure 21. The length of the polypropylene macro fibers increased the resistance of the fiber to pulling out of the concrete and increased the performance of the fiber reinforced concrete after cracking started. The 15 pcy dosage increased the performance at 90 percent stress ratio and at 70 percent stress ratio, when compared to the steel fiber. This increase in performance at a higher stress ratio is due to the toughness increase in the fiber reinforced concrete. The subsequent decrease at lower stress ratios is due to an interference the fiber has in aggregate friction across the crack, which improves performance at low deflections.

Figure 20
Broken section of polypropylene fibrillated fiber reinforced sample showing the length of the fibers reaching across the crack

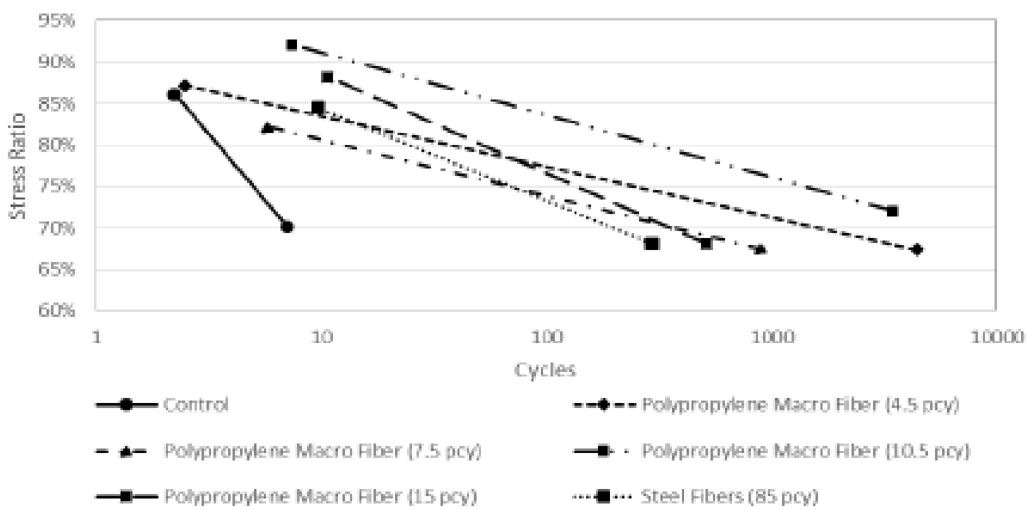

Figure 21
Results of fatigue testing of polypropylene macro fibers

The carbon fiber reinforced samples performed in a similar fashion as the steel fiber reinforcement, as shown in Figure 22. The fatigue data for the 9 pcy dosage of carbon fiber reinforced samples had a wide range at the 70 percent stress ratio, shown in Table 8. The variation in the range was due to the number of fibers that were across the crack. The number of fibers that crossed the crack varied between 3 and 8, for this dosage, causing the variation in the number of cycles that the sample was able to withstand. The low number of fibers across the crack also contributed to the lower number of cycles that the samples were able to withstand at the 90 percent stress ratio.

Table 8
Data for carbon fiber reinforcement at 70 percent stress ratio

Sample	Stress Ratio	Cycles
1	67%	1349
2	67%	2340
3	69%	659

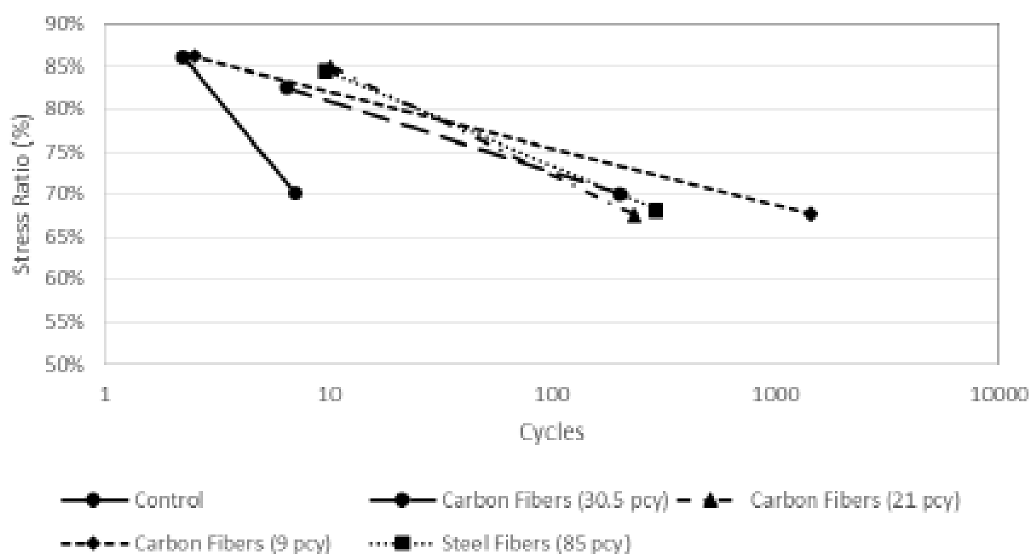

Figure 22
Results of fatigue testing of carbon fibers

When comparing the results for all of the fiber types, at the 70 percent stress ratio, it can be seen that the polypropylene macro fibers at 4.5 pcy and 10.5 pcy showed the greatest improvement in performance, as shown in Figure 23. When comparing the results at the 90 percent stress ratio, the 15 pcy dosage of polypropylene macro fibers and 21 pcy dosage of carbon fibers showed the greatest improvement, shown in Figure 24.

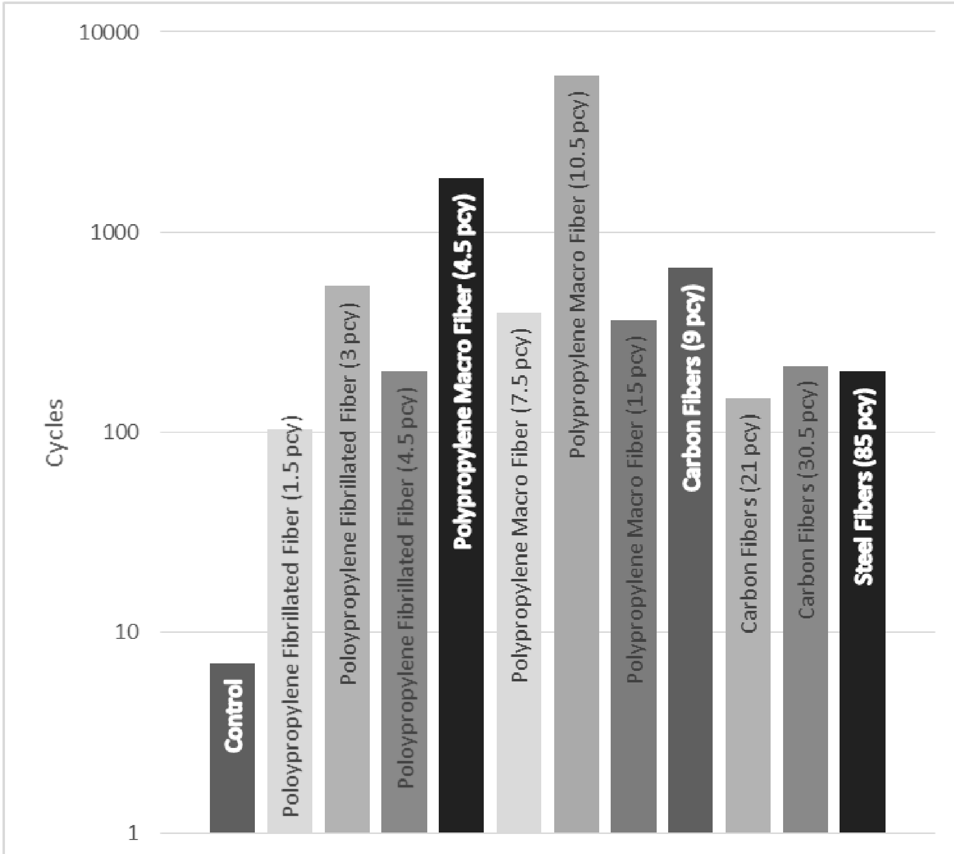

Figure 23
Comparison of different fiber dosages at 70 percent stress ratio

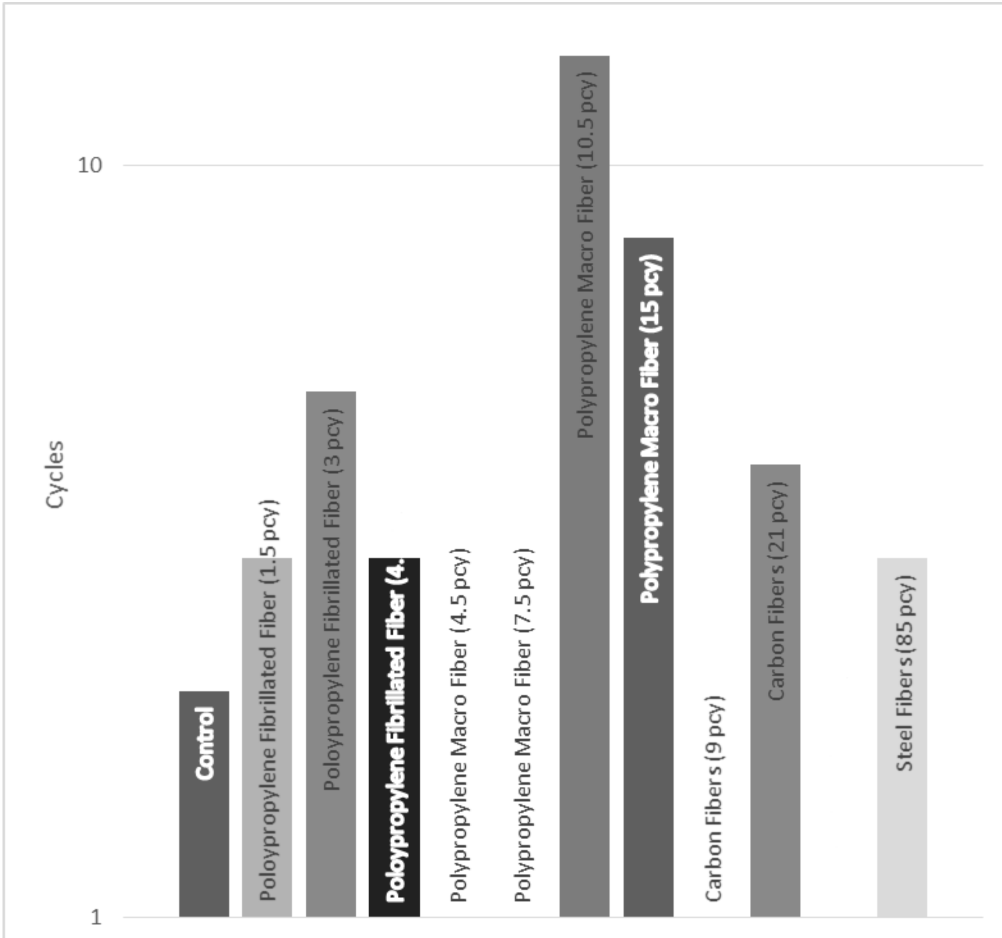

Figure 24
Comparison of different fiber dosages at 90 percent stress ratio

During the fatigue testing, it was observed that some of the fiber types and dosages were able to withstand a larger number of cycles after the 1-mm CMOD failure, but before ultimate failure. In order to quantify this observation, the residual fiber strength ratio (RFS) was used. The RFS used here is defined as the number of cycles to reach 2-mm CMOD divided by the number of cycles taken to reach 1 mm CMOD. The RFS values for each sample are shown in Figure 25 and Figure 26. Under the loading corresponding to the 90 percent stress ratio the only fiber that had a significant impact on the RFS was the high dosage of carbon fiber, 30.5 pcy. When observing RFS for the 70 percent stress ratio, the correlation between the fatigue testing and the toughness testing is illustrated by the larger RFS values. At the 70 percent stress ratio, the highest dosage of carbon fibers along with the steel fiber samples showed good residual performance between the 1-mm and 2-mm CMOD failure criteria.

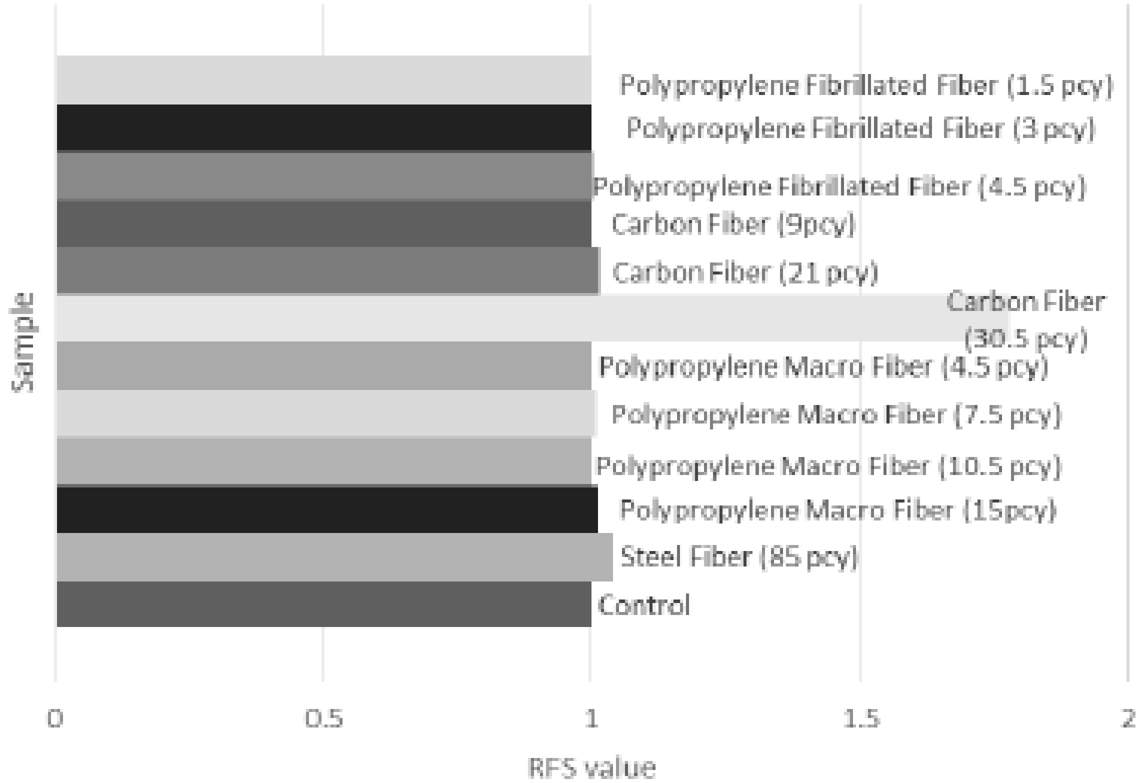

Figure 25
RFS values when subjected to the 90 percent stress ratio

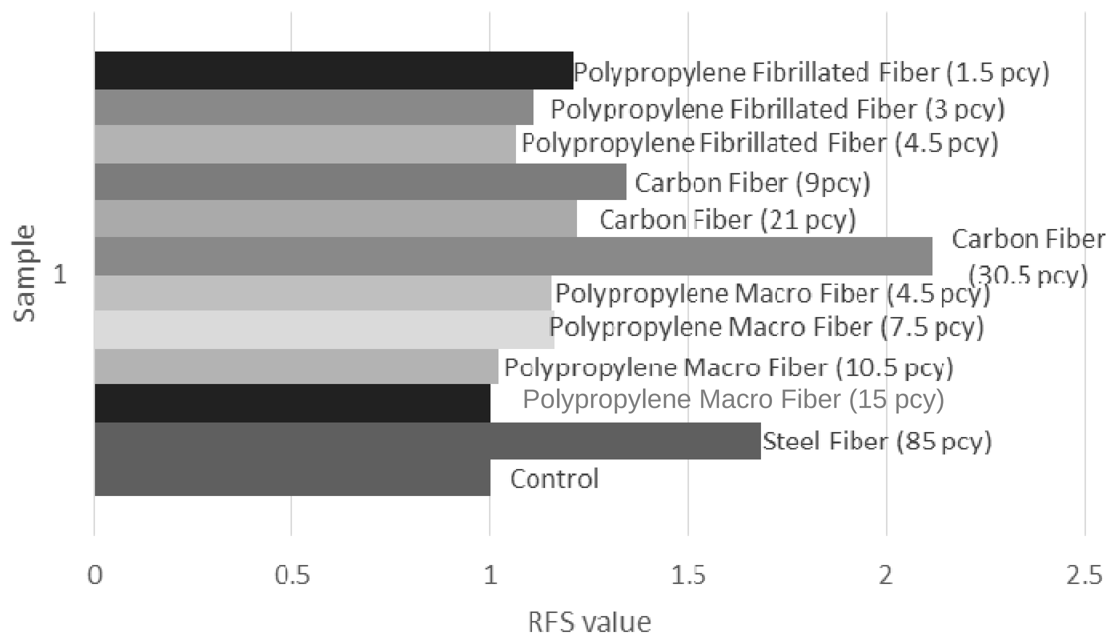

Figure 26
RFS values when subjected to the 70 percent stress ratio

Toughness Testing Results

The calculations described in ASTM C1609 were performed using the first peak load, peak load, and the residual loads, which were graphically determined. The vertical lines on the graphs show the deflection values at which the residual loads were determined, 0.12 in. and 0.03 in. The results of the calculations are shown in Table 9. The results of the calculations illustrate that fiber with a high tensile strength at a high dosage will improve the toughness of the fiber reinforced concrete, especially at larger deflections. The calculations also show that the steel fiber has the greatest residual strength at greater deflections, as shown by the largest $f_{150,3.0}$ value of 590 pounds. The peak strengths of nearly all the fiber types and dosages were improved over both steel fiber reinforced and the control samples.

The toughness results for the polypropylene fibrillated fibers are shown in Figure 27. The shorter fibrillated fibers had little impact on the toughness of the samples. The relative ease that the fibers were pulled from the concrete provided little resistance to deformation after cracking started, which happens when peak loading is achieved.

Table 9

Results of ASTM C1609 calculations

Sample	Net deflection at first peak load (δ_1) (in.)	First peak load (P_1) (lbs.)	First-peak strength (f_1) (lbs.)	Peak load (P_P) (lbs.)	Peak strength (f_P) (lbs.)	Residual load at span/600 ($P_{150,0.75}$) (lbs.)	Residual strength at span/600 ($f_{150,0.75}$) (lbs.)	Residual load at span/150 ($P_{150,3.0}$) (lbs.)	Residual strength at span/150 ($f_{150,3.0}$) (lbs.)
Control	0.002025	9638	805	9638	805	1000	85	900	75
Polypropylene Macro Fiber (10.5 pcy)	0.00276	11290	940	11290	940	8100	675	3700	310
Carbon Fiber (30.5 pcy)	0.00352	11943	995	11943	995	3200	265	4300	360
Polypropylene Macro Fiber (15pcy)	0.00282	10724	895	10724	895	5800	485	4600	385
Polypropylene Macro Fiber (7.5 pcy)	0.00297	11800	985	11800	985	4100	340	2500	210
Polypropylene Macro Fiber (4.5 pcy)	0.00255	10598	885	10598	885	4000	335	800	65
Carbon Fiber (21 pcy)	0.002615	12100	1010	12481	1040	9000	750	4000	335
Carbon Fiber (9pcy)	0.00247	11358	950	11358	945	3900	325	2000	165
Steel Fiber (85 pcy)	0.00331	9388	780	9388	780	7700	640	6700	590
Polypropylene Fibrillated Fiber (4.5 pcy)	0.00298	12082	1010	12082	1010	3300	275	700	60
Polypropylene Fibrillated Fiber (3 pcy)	0.0028	10116	840	10116	845	1000	85	700	60
Polypropylene Fibrillated Fiber (1.5 pcy)	0.0026	9571	800	9571	800	1800	150	1000	85

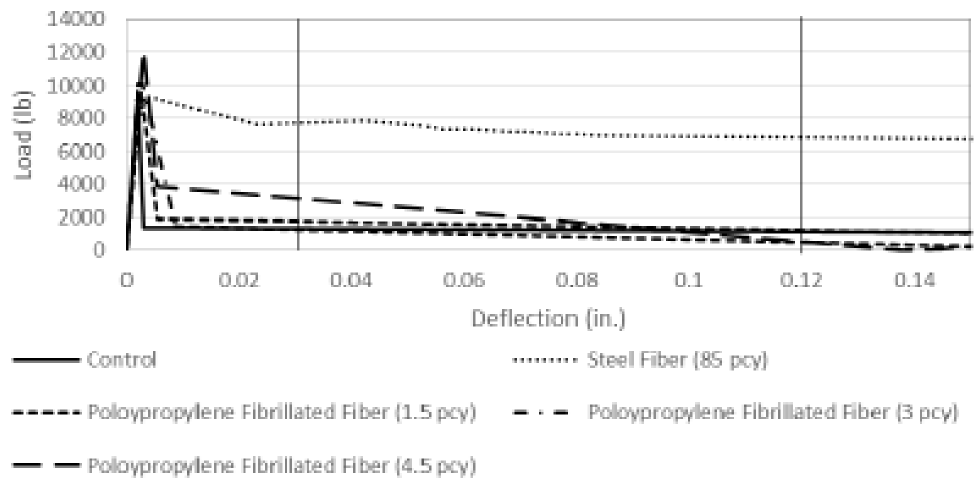

Figure 27
Toughness results for polypropylene fibrillated fiber with L/50 (right vertical line) and L/600 (left vertical line) shown

The toughness results for the polypropylene macro fibers are shown in Figure 28. The two higher dosages provided improved toughness performance when the deflection was below the first residual load deflection. All of the polypropylene macro fiber dosages showed improved performance, when compared to the control samples. The polypropylene macro fiber also showed improved performance graphically compared to the performance of the polypropylene fibrillated fiber.

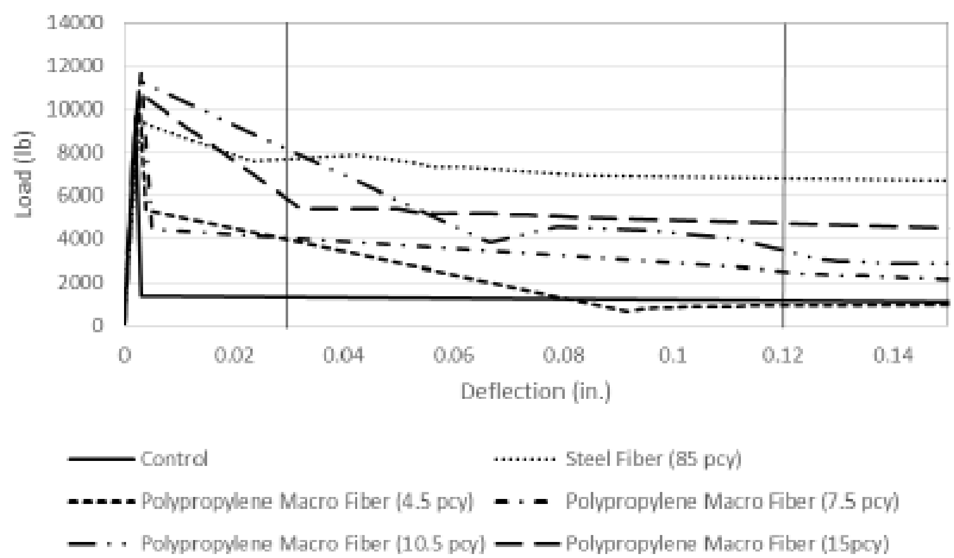

Figure 28
Toughness results for polypropylene macro fiber with L/150 (right vertical line) and L/600 (left vertical line) shown

The carbon fiber showed the greatest improvement in toughness, shown in Figure 29. The high tensile strength of the carbon fiber showed when comparing the toughness results for the three different fiber types. The carbon fiber dosage of 21 pcy was the only sample to show a difference between the first peak load and the peak load. The carbon fiber dosages of 21 pcy and 30.5 pcy also showed improved toughness performance until the first residual load, even when compared to the steel fiber reinforcement.

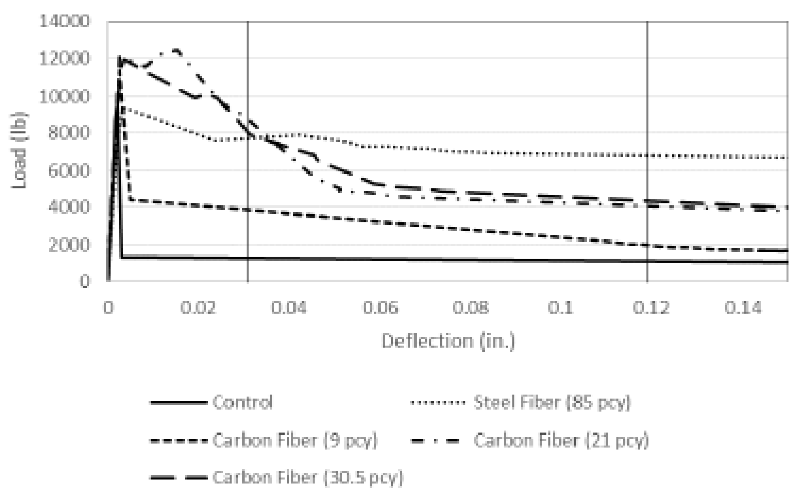

Figure 29
Toughness results for carbon fiber with L/150 (right vertical line) and L/600 (left vertical line) shown

Pre-Cracked Fatigue Testing Results

The pre-cracked fatigue testing results for the carbon fiber, polypropylene fibrillated, and polypropylene macro fibers were compared to the results of the steel fiber to determine the effectiveness of the fibers to withstand low intensity, high-volume loading after the concrete had failed. Pre-cracked fatigue results showed that there were four distinct regions of the curve, as seen in Figure 30. The first region is the phase where the fibers have not engaged and the aggregate interlock is starting to fail. The second region is the phase where the fibers have taken over and are holding the sample together, as shown by the change to a linear growth in the CMOD. The third region is where the fibers are beginning to fatigue and the CMOD growth rate increases. The fourth region is where the fibers start to break, illustrated in Figure 31, and the CMOD begins to grow exponentially. The fourth region begins when the CMOD reaches 4 mm, which is why 4 mm was set as the failure criteria for the pre-cracked fatigue testing.

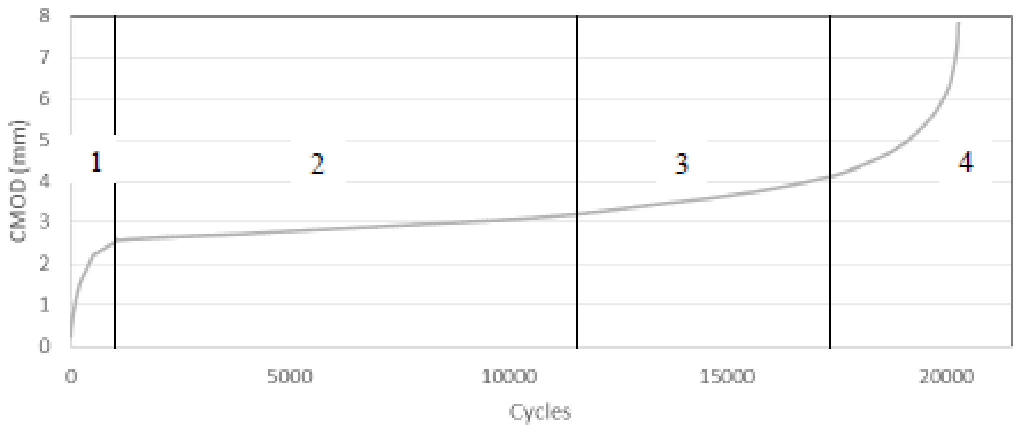

Figure 30
CMOD vs. cycles for pre-cracked fatigue test, with four fatigue sections labeled

Figure 31
Failed pre-cracked sample showing broken fibers

The fiber dosages that exhibited good toughness also performed well in the pre-cracked fatigue testing. The polypropylene fibrillated fibers were unable to hold the preload at the 50 percent stress ratio, shown by the lack of data in Figure 32. The highest dosage of the polypropylene macro fibers exhibited a two stage failure. The second stage was due to the high fiber dosage. When the fibers in the lower portion of the beam fatigue enough to break, the fibers in the upper portion of the beam were able to take the stress and prolong the failure of the sample, as shown in Figure 33.

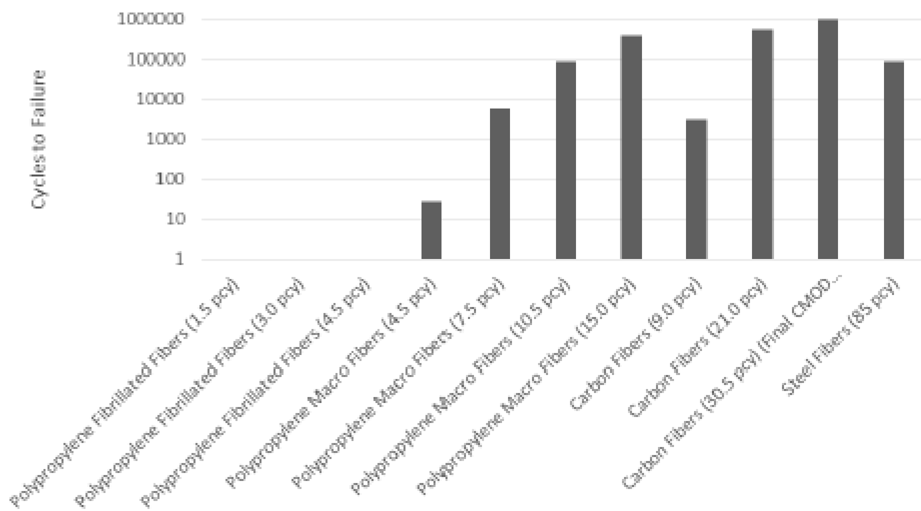

Figure 32
Results of pre-cracked fatigue testing

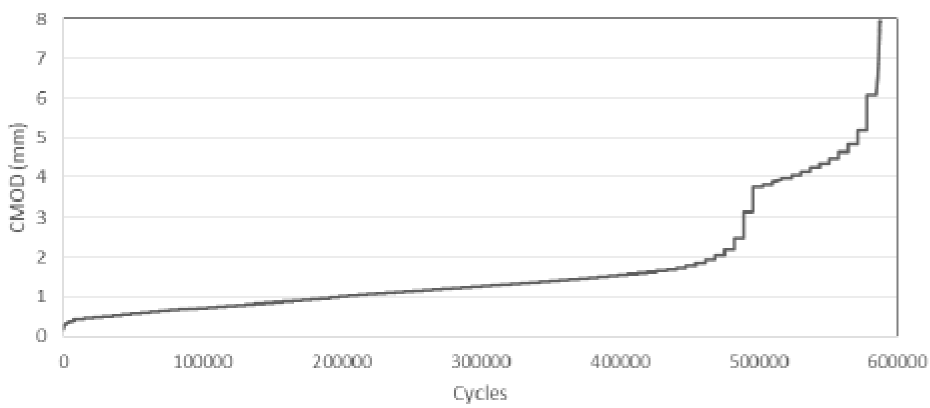

Figure 33
Example of two-stage failure for polypropylene macro fiber 15 pcy sample

During the pre-cracked fatigue testing, the samples were examined along the face of the failure to look for any abnormalities. The steel fiber reinforced sample showed signs that the steel fiber pulled out of the concrete, rather than fatigue and rupture as the polypropylene and carbon fibers. Figure 34 illustrates the holes left behind in the failure face where the fibers were pulled out and by the CMOD versus cycles graph for the steel fiber. The steel fiber curve does not change slope when the fiber begins to fatigue, rather the sample exhibits progressive failure as the fibers begin to pull out of the concrete, as illustrated in Figure 35.

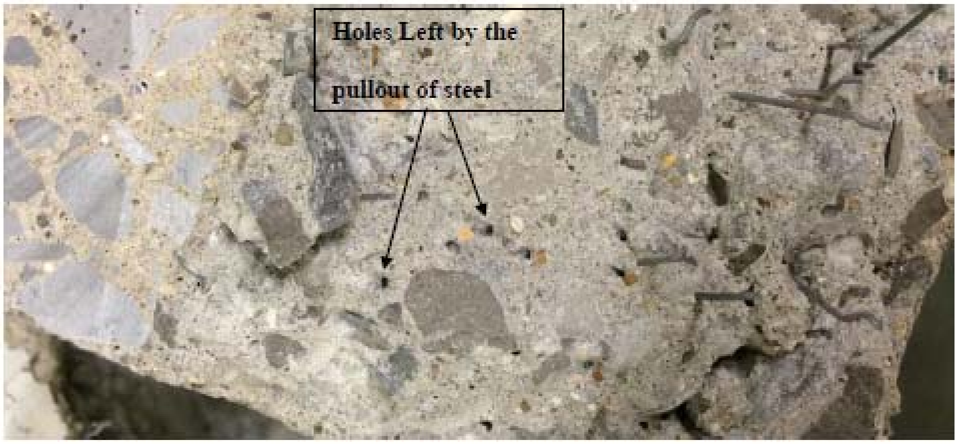

Figure 34
Example of hole left behind by steel fiber pulling out

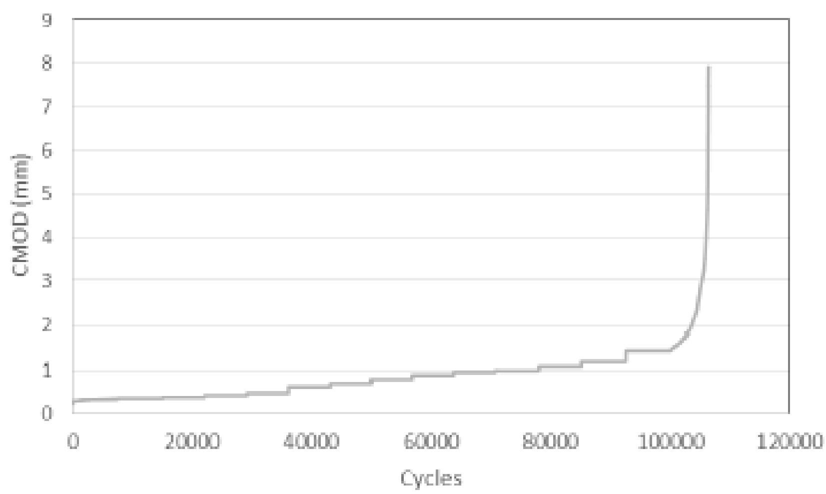

Figure 35
CMOD vs. cycles graph for pre-cracked fatigue test with steel fiber reinforcement

Pavement Design

The increase in fatigue performance exhibited by the CFRCP design has led to an evaluation of the increase in performance that CFRCP would have on currently used pavement design methods. In order to accurately predict the performance, only the fatigue data was used, not including the pre-cracked fatigue data. The analysis performed was modeled after a study that evaluated roller compacted concrete pavement design versus portland cement concrete, JPCP, and pavement design [*45*]. The analysis used the McCall form for portland cement fatigue [*46*]. The McCall model is in the following form:

$$\log N = \left[\frac{-SR^{-\alpha}\log(1-P)}{\beta}\right]^{\gamma} \tag{1}$$

Where N = number of cycles, SR = stress ratio, P = probability of failure, and α, β, and γ are the model coefficients.

The data was first grouped by stress ratio, as shown in Table 10 and Figure 36.

Table 10
Grouping for CFRCP data for model calibration

SR Range	Mean SR	Number of Samples
0.60 < SR < 0.80	0.68	31
0.80 < SR < 1.00	0.88	33

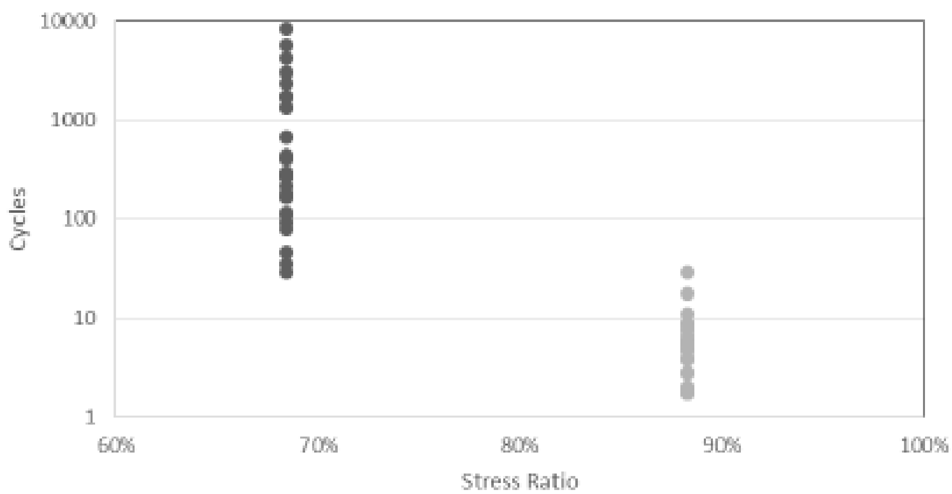

Figure 36
Cycles vs. stress ratio for model calibration groupings

A Kaplan-Meier survival analysis was then performed on the different groups to determine the probability of survival for a given number of load cycles, shown in Figure 37. Figure 38 illustrates how the McCall form fits the data.

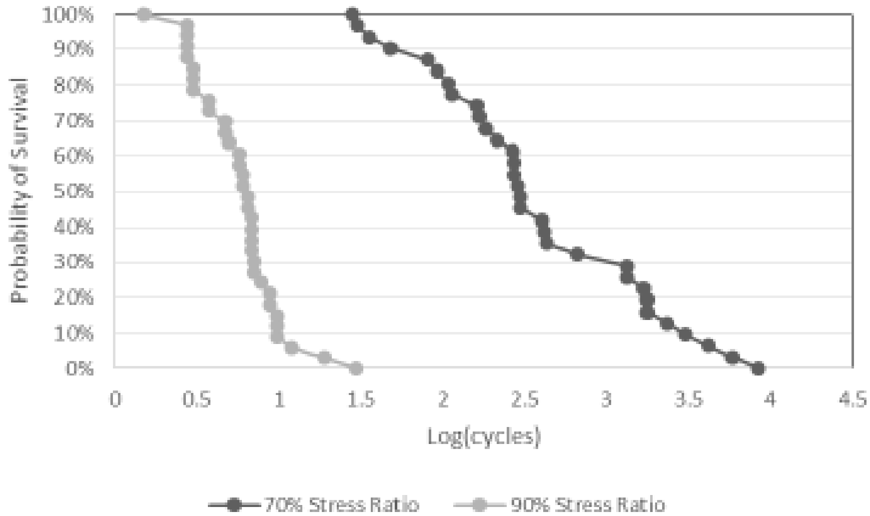

Figure 37
Kaplan-Meier survival analysis for each stress ratio

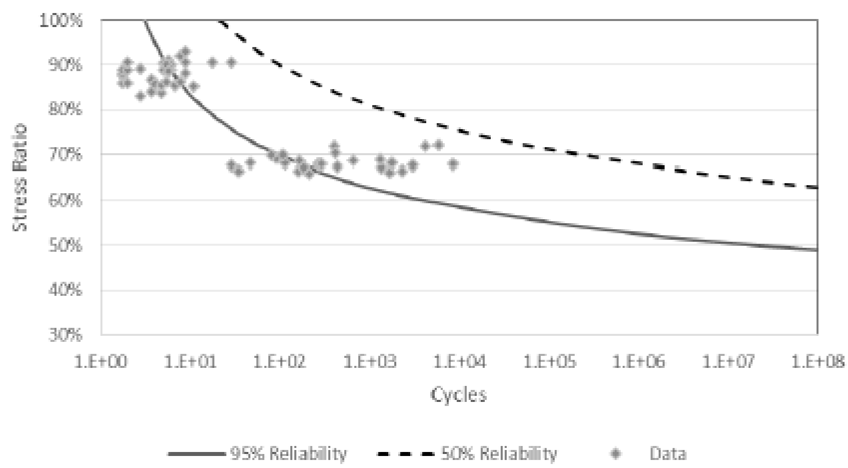

Figure 38
CFRCP curve based on McCall form

After ensuring that the McCall form fit the data, the McCall curves were compared to the StreetPave curves; see Figure 39. Based on the comparison the following observations can be made:

1. JPCP has a better performance at high stress ratios, when compared to CFRCP. Meaning that, at higher stress ratios, the thickness of CFRCP will be thicker than JPCP.

2. After a stress ratio of approximately 60 percent, when using the 95 percent reliability curve, the CFRCP begins to outperform JPCP. Meaning that, at stress ratios lower than 60 percent, CFRCP will be thinner than JPCP.

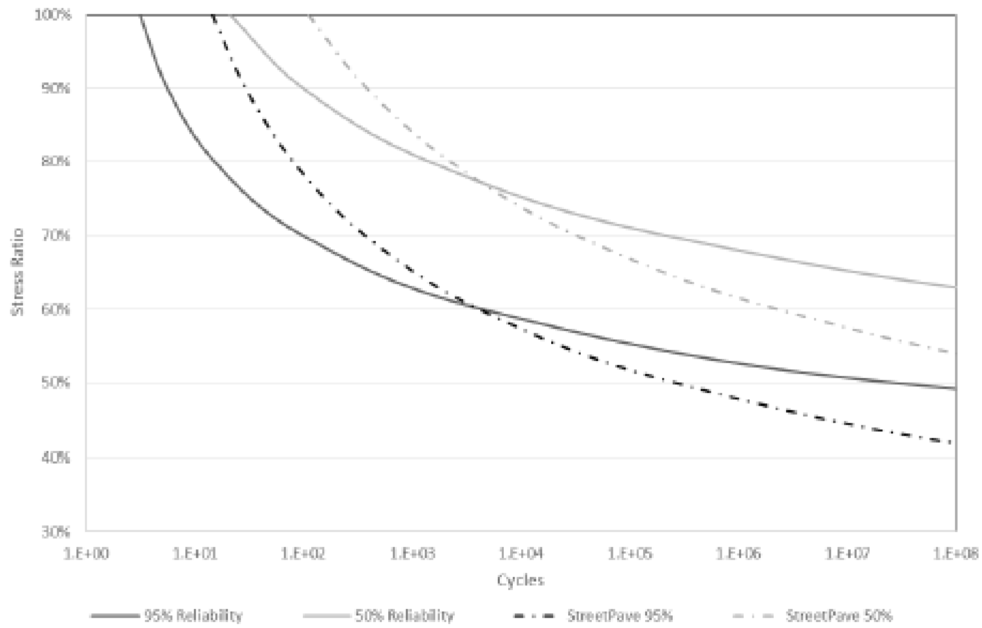

Figure 39
StreetPave vs. McCall fit

CONCLUSIONS

The results of this laboratory evaluation of fiber reinforced concrete led to the following conclusions. Test results showed that the use of fiber reinforcement improves the performance of portland cement concrete with respect to fatigue. The results showed that polypropylene, both fibrillated and macro, increase the fatigue performance of fiber reinforced concrete more than steel fiber reinforced concrete, when used in the correct dosages. The results also showed that carbon fibers increase the fatigue performance, when dosed above 21 pcy. There is, however, a point at which the fiber reinforcement inhibits fatigue performance of the concrete. The performance was not reduced below that of unreinforced concrete, but was reduced below the performance of steel fiber reinforced concrete.

Toughness testing showed that tensile strength and dosage rate were critical components in the ductility of the sample. Fibers with high tensile strengths had a greater residual load-carrying capability and carried greater loads at larger deflections. Not unlike the fatigue testing, there was a point where the fiber dosage offered diminishing returns for the performance of the sample. The diminishing returns are hypothesized to be a result of the fibers interfering with the aggregate interlock that occurs in concrete.

Pre-cracked fatigue testing showed that tensile strength is not the only component that contributes to the performance of fiber reinforced concrete. The length of the fiber is also crucial to the performance. The shorter polypropylene fibrillated fiber did not develop a strong enough bond with the concrete to prevent pull out, even though the fibrillated fiber had the same tensile strength as the polypropylene macro fiber. The pre-cracked fatigue test did not show the same diminishing returns for overly reinforced samples because the fibers were supporting the entire loading.

Summary

Results show that the investigated levels and types of fiber reinforcement can be used to improve both the fatigue and toughness performance of concrete. When post-cracked strength or toughness is the concern, concrete containing more fibers and fibers with a higher tensile strength are desirable. Carbon fibers maintained greater load-carrying capacity at lower deflections than the steel fibers, which produced the greatest ductility.

However, toughness and fatigue performance did not correlate for small deflections. This study also found that when repeated low deflections are a concern, such as with pavements, the following conclusions can be drawn:

1. Polypropylene fibrillated fibers offer increased fatigue performance but do not offer any significant support to the concrete after the sample has cracked.
2. Carbon fibers provide the greatest toughness and post crack performance, but do not necessarily correlate to greater fatigue performance.
3. Polypropylene macro fibers, in the range of 7.5 pcy to 10.5 pcy, provide the greatest combination of fatigue, toughness, and pre-cracked fatigue performance.
4. The use of fiber reinforcement has an effect on the thickness design of pavements, and can result in a reduced pavement thickness for low stress, high-volume pavements.

RECOMMENDATIONS

Further investigation is required to validate the findings of this study. The construction of full-scale testing sections to evaluate the performance of CFRCP with different subgrade support systems will further the understanding of how fiber reinforcement improves the performance of concrete pavements. Further laboratory testing should be performed to create a more accurate pavement design curve. The limited number of data points in this study leave room for bias in statistical analysis. Finally, a test highway section should be built to evaluate CFRCP alongside JPCP and/or CRCP in the same climatic conditions to determine if CFRCP will eliminate the need for joints in pavement and perform to the same level as CRCP.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

ASTM	American Society for Testing and Materials
ACI	American Concrete Institute
ASTM	American Society of Testing and Materials
DOTD	Louisiana Department of Transportation and Development
LTRC	Louisiana Transportation Research Center
DOT	Department of Transportation
FHWA	Federal Highway Administration
PCC	portland cement concrete
JPCP	jointed plain concrete pavement
CRCP	continuously reinforced concrete pavement
CFRCP	continuously fiber reinforced concrete pavement
COV	coefficient of variation
CMOD	crack mouth opening displacement
LVDT	Linear variable differential transformers
RFS	residual fiber strength ratio
in.	inch(es)
mm.	millimeter(s)
pcy	pound(s) per cubic yard
w/cm	water to cementitious materials ratio
ft.	feet
lbs.	pounds

REFERENCES

1. Huang, Y. H. 2004. *Pavement Design and Analysis*. Pearson/Prentice Hall.

2. Lee, S. 2003. "A Probabilistic Model for Joint-movements in Jointed Concrete Pavement." *KSCE Journal of Civil Engineering* 7, (2) (03): 141-146

3. Raoufi, K., Radlinska, A., Nantung, T., and Weiss, J. 2008. "Methodology for Determining the Timing of Saw Cutting in Concrete Pavements." *Transportation Research Record 2081*: 110-117.

4. Golias, M., Castro, J., Peled, A., Nantung, T., Tao, B., and Weiss, W. 2012. "Can Soy Methyl Esters Improve Concrete Pavement Joint Durability?" *Transportation Research Record 2290*: 60-68.

5. Benmokrane, B., Ahmed, E. A., Montaigu, M., and Thebeau, D. 2014. "Performance of Glass Fiber-Reinforced Polymer-Doweled Jointed Plain Concrete Pavement under Static and Cyclic Loadings." *ACI Structural Journal 111*, (2): 331.

6. Vyce, J.M. 1987. "Performance of Load-Transfer Devices." Engineering Research and Development Bureau, New York State Department of Transportation.

7. Basham, K. 2009. "Reinforcement for crack width control." *Concrete Contractor* 9, (7): 17.

8. Austin, S., Arnold, S., Fleming, P. and Robins, P. 2009. "Deterioration of Concrete Joints under Low-Intensity, High-Cycle Loading," Magazine of Concrete Research 69: 679-690.

9. Pour-Ghaz, M. 2011. "Detecting Damage in Concrete using Electrical Methods and Assessing Moisture Movement in Cracked Concrete." Japan Association for Earthquake Engineering.

10. Arnold, S., Austin, S., Fleming, P., Robins, P. 2005. "A Test Method and Deterioration Model for Joints and Cracks in Concrete Slabs," *Cement and Concrete Research* 35: 2371-2383.

11. Gaedicke, C., Villalobos, S., Roesler, J., and Lange, D. 2007. "Fracture Mechanics Analysis for Saw Cutting Requirements of Concrete Pavements." *Transportation Research Record 2020*: 20-29.

12. Larralde, J. and Chen, W. 1986. "Estimation of Mechanical Deterioration of Highway Rigid Pavements." *Journal of Transportation Engineering*, 113.

13. “Concrete Roads.” Sigmadg.com. Accessed March 21, 2015. http://www.sigmadg.com/mateenfrp/Concreteroads.html.

14. “Concrete Construction Joints - How To Minimize Cracking In Concrete Slabs.” Everything-about-concrete.com. Accessed March 21, 2015. http://www.everything-about-concrete.com/concrete-construction-joints.html.

15. Kronick, R. 2013. “Long Live Concrete Pavements.” Minnesota LTAP Technology Exchange 21(3).

16. Chon, B. J., and Woo Lee, S. 2007. “Effects of Uncracked Joints in Jointed Concrete Pavements.” *KSCE Journal of Civil Engineering* 11, (3): 141-144.

17. Hand, A. J. P., Galal, K. A., Ward, D. R. P., & Fang, C. 2000. “Cost-Effectiveness of Joint and Crack Sealing: Synthesis of Practice.” *Journal of Transportation Engineering*, 126 (6), 521-529.

18. Keller, T., Kenel, A., and Koppitz, R. 2013. “Carbon Fiber-Reinforced Polymer Punching Reinforcement and Strengthening of Concrete Flat Slabs.” *ACI Structural Journal* 110, (6): 919-927.

19. Khaleel, G. I., Shaaban, I. G., Elsayedand, K. M., and Makhlouf, M. H. 2013. “Strengthening of Reinforced Concrete Slab-Column Connection Subjected to Punching Shear with FRP Systems.” *International Journal of Engineering and Technology* 5, (6): 657.

20. Bedirhanoglu, I., Alper I., and Nahit, K. 2013. “Precast Fiber Reinforced Cementitious Composites for Seismic Retrofit of Deficient RC Joints - A Pilot Study.” *Engineering Structures* 52: 192-206.

21. “Design Steps of RCC Member for Shear and Torsion.” The Constructor. April 9, 2013. Accessed March 21, 2015. http://theconstructor.org/structural-engg/design-for-shear-and-torsion-of-rcc-member/7671/.

22. Bednář, J., Wald, F., Vodička, J., and Kohoutková, A. 2013. “Experiments on Membrane Action of Composite Floors with Steel Fiber Reinforced Concrete Slab Exposed to Fire.” *Fire Safety Journal* 59: 111-121.

23. Foglar, M., and Kovar, M. 2013. “Conclusions from Experimental Testing of Blast Resistance of FRC and RC Bridge Decks.” *International Journal of Impact Engineering* 59: 18-28.

24. Wilson, C. 2013. "Using Fiber-Reinforced Concrete." ICF Builder Magazine 11.

25. Collepardi, M., Troli, R., Bressan, M., Liberatore, F., Sforza, G. 2008. "Crack-Free Concrete for Outside Industrial Floors in the Absence of Wet Curing and Contraction Joints." *Cement and Concrete Composites* 30.10: 887-891.

26. Bischoff, P. H., Valsangkar, A. J., and Irving, J. 2003. "Use of Fibers and Welded-Wire Reinforcement in Construction of Slabs on Ground." *Practice Periodical on Structural Design and Construction* 8.1: 41-46.

27. Banthia, N. 1994. "Fiber Reinforced Concrete" ACI SP-142ACI, Detroit, MI: 91-119.

28. Uno, P. 2011. "Cracks in Freshly Placed Concrete." *Australian Concrete Construction*, 24 (6), 20.

29. "Shrinkage Cracking." Pavementinteractive.com April 2, 2009. Accessed March 21, 2015. http://www.pavementinteractive.org/article/shrinkage-cracking/.

30. Roesler, J., Paulino, G., Gaedicke, C., Bordelon, A., Park, K. 2007. "Fracture Behavior of Functionally Graded Concrete Materials for Rigid Pavements." *Transportation Research Record 2037*.1: 40-49.

31. Bordelon, A. 2011. "Flowable Fibrous Concrete for Thin Pavement Inlays," Ph.D. Dissertation, University of Illinois, Urbana-Champagne.

32. Marks, V. J. 1989. "Fifteen Year Report for Iowa Highway Research Board Research Project HR-165," Iowa Department of Transportation Highway Division Office of Materials, Ames, Iowa.

33. Tawfiq, K., Armaghani, J., and Ruiz, R. 1999. "Fatigue Cracking of Polypropylene Fiber Reinforced Concrete." *ACI Materials Journal*, 96 (2): pp. 226-233.

34. Suksawang, N. 2014. "Use of Fiber Reinforced Concrete for Concrete Pavement Slab Replacement." Florida Department of Transportation, Florida Institute of Technology.

35. 3M Scotchcast Polyolefin Fibers Case History, brochure, www.3m.com/corrosion.

36. Folliard, K., Sutfin, D., Turner, R., Whitney, D. P. 2007. "Fiber in CRCP Pavements." Center for Transportation Research, University of Texas at Austin.

37. ASTM Standard C192 “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory,” *Annual Book of ASTM Standards,* Vol. 04.02, ASTM, Philadelphia, PA, 2014.

38. ASTM Standard C1399 “Standard Test Method for Obtaining Average Residual-Strength of Fiber-Reinforced Concrete,” *Annual Book of ASTM Standards,* Vol. 04.02, ASTM, Philadelphia, PA, 2014.

39. ASTM Standard C1609 “Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading),” *Annual Book of ASTM Standards,* Vol. 04.02, ASTM, Philadelphia, PA, 2014.

40. ASTM Standard C39 “Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens,” *Annual Book of ASTM Standards,* Vol. 04.02, ASTM, Philadelphia, PA, 2014.

41. ASTM Standard C78 “Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading),” *Annual Book of ASTM Standards,* Vol. 04.02, ASTM, Philadelphia, PA, 2014.

42. ASTM Standard C138 “Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete,” *Annual Book of ASTM Standards,* Vol. 04.02, ASTM, Philadelphia, PA, 2014.

43. ASTM Standard C143 “Standard Test Method for Slump of Hydraulic-Cement Concrete,” *Annual Book of ASTM Standards,* Vol. 04.02, ASTM, Philadelphia, PA, 2014.

44. ASTM C231 “Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method.” *Annual Book of ASTM Standards,* Vol. 04.02, ASTM, Philadelphia, PA, 2014.

45. Rodden, R. 2013. “RCC Fatigue Model Development by the American Concrete Pavement Association (ACPA) – Interim Report.” TRB Presentation.

46. McCall, J. T. 1958. “Probability of Fatigue Failure of Plain Concrete.” *ACI Journal Proceedings*, 55 (8) ACI.

This public document is published at a total cost of $250
42 copies of this public document were published in this first printing at a cost of $250. The total cost of all printings of this document including reprints is $250. This document was published by Louisiana Transportation Research Center to report and publish research findings as required in R.S. 48:105. This material was duplicated in accordance with standards for printing by state agencies established pursuant to R.S. 43:31. Printing of this material was purchased in accordance with the provisions of Title 43 of the Louisiana Revised Statutes.