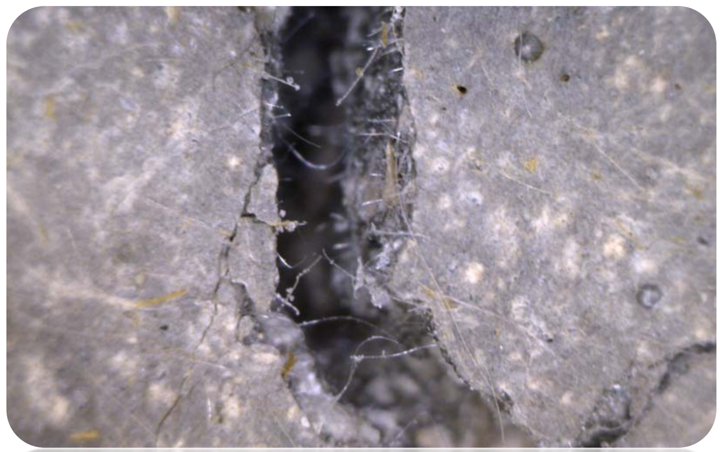
Use of Fiber Reinforced Concrete for Concrete Pavement Slab Replacement

Draft Final Report
Contract No. BDK80 TWO 977-27
March 2014



Prepared by:
Florida Institute of Technology
and Florida International University

Prepared for:
Research Center
Florida Department of Transportation

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Prepared for:

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March 2014

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

METRIC CONVERSION CHART

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
SYMBOL	**WHEN YOU KNOW**	**MULTIPLY BY**	**TO FIND**	**SYMBOL**
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
NOTE: volumes greater than 1000 L shall be shown in m^3				

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Mr. Donald Vanwhervin of the District 4/6 Materials Office at the Florida Department of Transportation served as the Project Manager for this project.

16. Abstract

Unlike ordinary concrete pavement, replacement concrete slabs need to be open to traffic within 24 hours (sooner in some cases). Thus, high early-strength concrete is used; however, it frequently cracks prematurely as a result of high heat of hydration that leads the slab to develop plastic shrinkage. FRC is known to provide good resistance to plastic shrinkage and has a proven record in the building industry particularly with slab-on-grade application. However, the current specification does not address the use of FRC in civil infrastructure. The only specification under development for FRC usage is for bridge deck application which does not address the use of FRC in controlling plastic shrinkage. This research project explored the potential use of fiber reinforced concrete (FRC) in concrete pavement slab replacement particularly in controlling plastic shrinkage. Five different fiber types, including steel, glass, basalt, nylon, and polyethylene fibers were investigated. Additionally, the effect of fiber length was also investigated for the polyethylene fiber. The fibers were added at low-dosage amounts of 0.1% and 0.3% by volume. Retrained shrinkage tests were conducted to assess the cracking potential of the concrete mixtures and the ability for each fiber type to resist cracking. Results indicated that both polyethylene and nylon fibers provided the best resistance to early-age shrinkage. However, balling was a problem for nylon fiber reinforced concrete. Short fibers (< 1-in.) also had the best performance in resisting early-age shrinkage, while long fibers (> 1-in.) provided additional post-cracking capacity. For replacement slab, it is recommended that a short polyethylene fiber be used to eliminate uncontrolled cracking.

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EXECUTIVE SUMMARY

The Florida Department of Transportation's (FDOT) Specification 353 on concrete pavement slab replacement requires the contractor to replace concrete slab should any uncontrolled cracks appear during the life of the contract at no expense to FDOT. Although this should not be of any concern to the FDOT since the contractor is responsible for the replacement costs, some contractors may seek litigation as a means to opt out from their responsibility to provide a product that will perform satisfactorily during its service life. The problem with litigation is that it is difficult to determine if the uncontrolled cracks were formed as a result of contractor misconduct. Other factors such as slab design and heavy traffic may attribute to the early-age cracks. The litigation process not only costs the FDOT time, but also disrupts the completion of the project, which adversely affects the public.

One solution to avoid litigation is to use fiber reinforced concrete (FRC) in concrete pavement slab replacement. FRC provides good plastic shrinkage resistance such as polymeric fiber, which is known to provide excellent early-age crack control. However, its application in concrete pavement is limited as there is no standard specification. The only specification under development for FRC usage is for bridge deck application, which is designed for strength and ductility enhancement. The primary objective of this research project is to evaluate the potential use of FRC for concrete pavement slab replacement, specifically in preventing early-age cracking. Several types of fiber, including steel, glass, basalt, polypropylene, and nylon fibers, were investigated for their plastic properties, mechanical properties and cracking performance. Steel, glass, basalt, and nylon fibers were 0.5-in. long monofilament fibers with variable diameters. Three types of polypropylene fiber were used, which consisted of 1) 0.5-in. long multifilament fibers, 2) 0.75-in. long fibrillate fibers, and 3) 1.5-in. long macro-synthetic fibers. Additionally, demonstration slabs were constructed to monitor the construction of FRC pavement slab.

As a first step in exploring the potential used of FRC in concrete pavement slab replacement, the mixture proportion, mixing procedure, workability, and method of consolidation were investigated. The mixture proportion was based on FRC manufacturer recommendations and published articles on the use of FRC in preventing early-age shrinkage. Based on this information, low-dosage (<0.5% by volume) FRC was used and evaluated for its potential in eliminating early-age cracking. Two mixing procedures were investigated: 1) mixing the fiber to the dried ingredients before adding water to the mixture; and 2) mixing the fiber to plastic concrete after all ingredients, including the water, have been mixed together. Both procedures provided good distribution of fiber in concrete but the latter procedure was selected because the ease of preparation under field condition. As there is no active standard to evaluate the workability of FRC, withdrawn standard, ASTM C995, was used. This standard measures the workability in term of time of flow of FRC mixture through an inverted slump cone under internal vibration. This standard was withdrawn because of the inherent bias in the result generated by the variability in the operation of the vibrator. Thus, to minimize the bias in the result, a designated operator was used in this study to control a constant frequency and vibrator's operation. The FRC mixture was consolidated using external vibration (i.e., vibrating table) that had been calibrated to operate at a constant frequency to yield the best consolidation.

Results indicated that FRC provides many benefits for concrete pavement slab replacement, particularly on enhancing the replacement slab cracking performance. In term of plastic properties, the addition of FRC at low-dosage (<0.5% by volume) had very little impact on the workability for all mixtures produced for this study. The mixtures that had slight reductions in workability were mixtures containing steel and long (1.5-in.) polypropylene fibers; but the reductions were insignificant with about 2 to 3 seconds increase in the time of flow as compared to conventional concrete. Additionally, fiber balls were encountered on mixtures containing nylon fibers even at a low volume fraction of 0.1% regardless of the mixing procedure used. Nylon fibers would also stick to the mixer blades, which means not all fibers are disburse in the mixture. For these reasons, nylon fiber is not recommended for concrete pavement slab replacement unless the contractor can demonstrate its experiences with the use of nylon fiber.

In term of mechanical properties, the FRC increased the compressive strength particularly at 6-hour, but at low-dosage amount its impact is less significant. The mixture containing long (1.5-in.) polypropylene fiber provided the highest compressive strength, while mixtures containing basalt and nylon fibers did not provide any additional gain in compressive strength when comparing to conventional concrete. All mixtures containing fibers had an increase in the modulus of rupture. Similarly to the compressive strength result, both steel and long (1.5-in.) polypropylene fibers had the highest modulus of rupture, while the short (0.5-in.) polypropylene fibers had little effect on the modulus of rupture. On the other hands, there was very little impact on the residual strength and flexural toughness of FRC at the low-dosage amount. Only the steel and long polypropylene fibers provided significant gain in residual strength and flexural toughness at the low-dosage amount. More fibers would have to be added to see significant improvement in the residual strength and flexural toughness.

For the cracking performance, only short (<1-in) polyethylene and nylon fibers significantly enhanced the ability of concrete to resist plastic shrinkage, which prevent early-age cracking. Increasing the volume fraction from 0.1% to 0.3% did improved the concrete's resistance to cracking but not significant enough to warrant the additional cost. It should be noted, however, that fiber balls were found in mixture containing nylon fibers and prevent proper consolidation of concrete especially around corners. Nylon fibers were also found stuck on the mixer blade. Thus, special care should be made for mixing nylon fibers into concrete. It is recommended that only experienced ready-mix producers be allowed to use nylon fibers for concrete pavement slab replacement.

The 0.5-in. and 0.75-in. long polypropylene fibers were further evaluated for their potential used in concrete pavement slab replacement by constructing demonstration slabs. The demonstration slabs consisted of five 6-ft × 6-ft × 0.5-ft slabs, which were one control slab with conventional concrete, two slabs with 0.1% and 0.3% volume fraction of 0.5-in. long polypropylene fibers, and two slabs with 0.1% and 0.3% volume fraction of 0.75-in. long polypropylene fibers. In term of cost, there is no significant difference other than the fiber materials, which generally cost additional of $6.00 to $12.00 per cubic yard (or an increase of 5% to 10% when comparing to conventional concrete). This is minimum considering the increase in cracking performance found in the laboratory. As of the writing of this report, there was no crack detected on all slabs but this could be attributed to the slabs not being restrain. Therefore, it is recommended that a real demonstration FRC slab be constructed to better assess its potential in controlling early-age cracking.

In summary, FRC, specifically short (<1-in.) polyethylene fibers, presents a viable solution in controlling early-age cracking for concrete pavement slab replacement application. Only a low-dosage (0.1% or 1.5 lb/yd^3) of fibers is needed to control early-age cracking. However, one problem that limits FDOT for adopting FRC pavement slab is the lack of standard for accessing the workability of FRC. Withdrawn standard do exist but the inherent bias would make it difficult to adopt the standard as part of the quality control process. More research is needed in developing a test for assessing the workability of FRC.

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CHAPTER 1
INTRODUCTION

Unlike ordinary concrete pavement slabs, replacement slabs require very high early-strength concrete to allow them to be immediately opened to traffic. One of the most crucial requirements for replacement slabs is its plastic property; specifically, a 6-hour compressive strength needs to reach 2,200 psi. To this end, the concrete mixture tends to have a very low water-cement ratio and contains large amounts of Portland cement—as much as 9 sacks per cubic yard (approximately 850 lb/yd^3). Additionally, to ensure the compressive strength of 2,200 psi is reached in 6 hours, concrete accelerators are added. All these factors lead the replacement slabs to be highly susceptible to early-age and drying shrinkage, which could potentially cause the replacement slabs to crack.

1.1 Concrete Pavement Slab Replacement Standards

The Florida Department of Transportation (FDOT) Design Standards [FDOT, 2014a] require a full depth replacement of concrete slab with severe distresses. The construction standards and requirements of the replacement slab are provided in Section 353 of the Standard Specifications for Road and Bridge Constructions [FDOT, 2014b]. Two of the most important acceptance criteria for the replacement slab are the plastic property, specifically the 6-hour compressive strength of 2,200 psi, and the 24-hour compressive strength of 3,000 psi. The 6-hour compressive strength is also used as the determination point to opening the slab to traffic, and therefore, it is highly emphasized in the standard specifications. In fact, if the replacement slab does not meet the plastic property requirements and the engineer determines that this will severely impact the replacement slab service life, the contractor would have to replace the slab at no cost to the FDOT. Thus, to ensure the replacement slab meets the plastic property requirements, low water-cement ratio concrete and concrete accelerators are used. As a consequence, the heat of hydration increases causing larger early-age shrinkage, which could potentially lead to cracking [Bentz and Peltz, 2008; Bentz et al., 2009; Bernard and Brühwiler, 2002; and Byard et al., 2010]. As a consequence, the FDOT also specified a limit on the concrete temperature not to exceed 100°F and requires the contractor to cure the slab with curing compound and cover the surface with white burlap-polyethylene curing blanket immediately after the slab hardens. Furthermore, if uncontrolled cracks appear on the replacement slab during the life of the contract, the contractor will have to replace the slab free of charge.

1.2 Problem Statement

While Section 353 is comprehensive and provides many levels of protection to the FDOT, replacement slabs do crack. If cracks are discovered during the contract period then the contractor will be responsible for replacing the slab again at his expense. However, some contractors may file a lawsuit against the FDOT to avoid their contractual obligation. Regardless of the outcome, further delay to the roadway, in which the slab is constructed, opening to traffic would have a direct impact on the traveling public. Therefore, there is a need in a better solution that can prevent or at least minimize the number of cracks for replacement slabs.

One proposed solution is to replace ordinary concrete used in the construction of replacement slabs with fiber reinforced concrete (FRC). The use of FRC in slab-on-grade is not new as the building industry had been benefitting from it for over 30 years [ACI 360, 2010]. However, unlike slabs-on-grade in buildings, replacement slabs on roadways are exposed to the outdoor environment and need to withstand heavy truck traffic. Hence, the FDOT had sponsored a research project titled "Durability of Fiber-Reinforced Concrete in Florida Environment" that was conducted by Dr. Roque of the University of Florida in the past, which had demonstrated the benefits of using FRC for Florida infrastructure [Roque et al, 2009]. While the study provides lots of information, its emphasis were on structural concrete applications, in which high volume fraction of fiber were used—between 0.5% and 1.0%. For replacement slabs where plastic shrinkage are the main concern, lower fiber volume fraction are needed. Furthermore, the study did not provide guidelines on FRC with high early strength, which tends to have poor cracking performance as compared to ordinary strength concrete.

1.3 Project Objectives

The main purpose of this project is to explore the potential use of FRC for concrete pavement slab replacement. Accordingly, this project has four objectives:

1. Develop FRC replacement slab mixtures;
2. Evaluate the performance of FRC mixtures particularly on early-age cracking;
3. Evaluate the performance of FRC slab using demonstration slabs; and
4. Develop guidelines for proportioning, mixing, placing, finishing and curing of FRC replacement slab.

1.4 Report Organization

The rest of the report is organized as follows. Chapter 2 discusses the literature review on various types of fibers and applications of FRC. Chapter 3 covers the experimental program and laboratory test setup. Chapter 4 discusses the results of the laboratory experiments and key summary. Chapter 5 details the construction of demonstration slabs using FRC as compare to ordinary concrete. Finally, Chapter 6 provides the relevant conclusions and recommendations for further investigation.

CHAPTER 2
LITERATURE REVIEW

Understanding the current state-of-practice on the use of FRC in concrete pavements is vital in developing new guidelines for FRC replacement slabs. This review also helps in developing the experimental program for this study. This information was obtained from online databases including TRID (a transportation research database), Engineering Village, the International Concrete Abstracts Portal (an American Concrete Institute (ACI) led collaboration with technical organizations in the concrete industry to offer the most comprehensive collection of published concrete abstracts), and Google Scholar. The information was narrowed down to three main categories focusing on characteristics of FRC that minimize early-age cracking. These three categories include: 1) construction practices, 2) mechanical properties, and 3) cracking performance of FRC.

2.1 Construction Practices

This section provides a general overview of current construction practices, particularly on fiber types, mixing procedure, placing and finishing, and curing, and protection of FRC.

Fiber Type: The type of fiber can greatly affect the performance of concrete. There are four types of fiber that are used in FRC: 1) steel, 2) glass, 3) synthetic, and 4) basalt fibers. The steel fiber is the most used in civil infrastructure and is commonly found in bridge decks to enhance the deck toughness and ductility. It is typically added at higher dosage amount ranging between 1% and 2% by volume to improve toughness, fatigue and in controlling crack width of concrete [Folliard Kevin, 2006]. When adding fiber to reinforce concrete, the inner area of the concrete gains a good bearing capacity [Beatrice et al, 2008] and as a result smaller slab thickness could be used to resist the same load carrying capacity as conventional concrete, which also reduces the joint construction and cost [Kearsley and Elsaigh, 2003]. The cost reduction can be as much as 12% for a 30% slab thickness reduction [Nayar and Gettu, 2012]. Despite its clear advantage in increasing the post-cracking behaviors, it is not widely used in civil infrastructure because any exposed fibers have the tendency to corrode, especially in Florida's environment [Roque et al., 2009]. Although the corrosion in the fiber may not adversely impact the overall structural performance, corrosion is unaesthetic and would result in the slab eventually needing replacement. Another fiber type that is also typically added at a high-dosage amount is glass fiber. Glass fiber can significantly improve the hardness of concrete and, as a result, it is often used in concrete countertops and facades [Sravana et al., 2010, Hasan et al., 2011, Mariappan Mahalingam et al., 2013]. On the other hand, synthetic fiber is added at a low-dosage amount ranging between 0.1% and 0.5 % by volume. It is used primarily to control cracking and plastic shrinkage, but it does not improve toughness [Hasan et al., 2011; Józsa and Fenyvesi, 2010; Richardson et al, 2010; Roesler et al., 2006]. The fiber size also has an impact on the overall performance of FRC. Jongvivatsakul et al. (2013) studied the effect of fiber on concrete shear capacity. They discovered that the shear capacity of FRC with approximately 2-in. steel fiber was greater than 1-in. steel fiber due to its post-cracking behavior in the tension.

Mixing: There are some important differences in mixing FRC in a transit mixer or revolving drum mixer compared to conventional concrete. One of these is the effect of fiber balling that prevents good dispersion of the fiber in concrete. There are two methods that have been effectively used in the past to prevent fiber balling of steel fiber: 1) to add fibers to transit mix truck after all ingredients have been added and mixed, and 2) to add fiber to aggregate on a conveyor belt. More details of these methods can be found in the ACI document. ACI 304 recommends mixing FRC at least 130 revolutions before discharging. Adding fiber into concrete will also lead to an increase in surface area that decreases the slump of concrete and causes a loss in workability [ACI 544]. Using vibration is necessary for consolidating the concrete, and therefore, traditional slump cone test cannot be used for quality control. Although increasing the fiber amount could potentially improve the concrete properties, it will lead to several challenges, such as balling and clumping of fiber during mixing. Therefore, ACI 544 recommends adding no more than 2% by volume or 1% by volume for high aspect ratio (length/diameter) of fiber in concrete.

Placing and finishing: According to literature [Folliard et al., 2006; Göteborg, 2005; Roque, 2009] there are few differences between the methods for placing and finishing conventional concrete and FRC. One difference for slab construction is that vibration is needed for the FRC since the material tends to hang together. Additionally, high-range water-reducing admixtures should be added to the FRC mixture to increase the workability of the mixture and for easy placement.

Curing and protection: There is no special treatment when fibers are added to concrete. Like conventional concrete, FRC also needs proper protection when placing during hot and cold weather.

2.2 Mechanical Properties

The improvement on mechanical properties of FRC has been well documented [ACI 544, Roque et al., 2009 and many others]. This report will only focus on the post-cracking properties, namely the ductility and toughness, to determine their influence on early-age cracking.

2.2.1 Ductility

FRC is known to provide higher ductility than ordinary concrete. Ductility is the ability of concrete to undergo maximum plastic deformation before collapse. It is considered a good warning indicator before failure. Mahalingam et al. (2013) studied the ductility behavior of steel fiber on concrete beams. They used steel fiber content of 0.5, 1 and 1.5 % by volume. They concluded that the ultimate load carrying capacity of concrete beams was improved 14, 20 and 32%, respectively, more than conventional reinforced concrete beam. Ductility could also be increased using synthetic fiber [Roesler et al, 2006; Sountharajan and Sivakumar, 2013]. However, ductility in concrete beams could only be achieved with higher dosage of fiber added and its role on early-age shrinkage is not well established. Considering that only low-dosage amount of fiber are needed, ductility would have very little effect on early-age shrinkage.

2.2.2 Fracture Toughness

Fracture toughness measures the energy absorption capacity of material under static or dynamic or impact load. Fracture toughness is used to evaluate the post-cracking behavior for concrete at the deflection at mid span. Much literature reports how toughness affects fiber type, dosage, fiber material properties, and bonding conditions, which can be found in more details in ACI 544 report and elsewhere [Roesler et al., 2006, Sravana et al., 2010; Richardson et al., 2010]. Overall, both steel and synthetic fibers improved the concrete fracture toughness. The improvement depends on the dosage amount but in most cases the fracture toughness increases with increasing dosage rate. On the other hands, there is no increase in fracture toughness for glass fiber. Less information is available on basalt fiber and will be studied as part of this project. Nevertheless, similarly to ductility it seems that there is little correlation between fracture toughness and the ability to resist early shrinkage.

2.3 Shrinkage and Cracking Properties

There are four main types of shrinkage cracks in concrete: 1) autogenous, 2) plastic, 3) drying, and 4) carbonation shrinkage. Autogenous shrinkage is associated with the loss of water due to the hydration process of concrete at early age and is considered relatively small compared to drying shrinkage. However, for high-early strength concrete as a result of high heat of hydration, autogenous shrinkage contributes quite significantly, and in some cases (concrete with high volume silica fume) it could be as high as drying shrinkage [Nassif et al., 2003]. Plastic shrinkage occurs when the rate of evaporation exceeds the bleeding rate or, in other words, the concrete dries too fast due to the combination of heat and wind of the surrounding area. Plastic shrinkage is more critical for high-early strength concrete because of its low water-cement ratio leading it to have a very low bleeding rate [Andrew, 2009]. For typical concrete pavement, the plastic shrinkage could be controlled by applying proper curing practices, i.e., moist curing [Nassif et al., 2003]. However, for replacement slab traditional moist curing for 7 days could not be achieved because the roadway will need to be reopened to traffic within 24 hours. Thus, both autogenous and plastic shrinkages (or could be lumped together as early-age shrinkage) are a big problem for concrete pavement slab replacement that could potentially lead the slab to crack. The other two types of shrinkage cracks are not a potential problem for concrete pavement slab.

The concrete cracks because of its poor performance in resisting tensile stresses. Thus, by reinforcing the concrete with fiber, it could bridge the cracks to prevent further expansion by redistributing the stress concentration as shown in Figure 2.1 [Nataraja, 2002]. This can also be observed by further examining the stress redistribution mechanism caused by the fibers. As shown in Figure 2.2, the fibers restrain cracks in concrete matrix at crack surface. Wecharatana and Shah (1983) and Göteborg (2005) suggested that three distinct regions exist and can be identified as: 1) traction free zone which occurs for relatively large crack openings; 2) fiber bridge zone where stress transfers result by frictional slip of fiber; 3) macro and micro crack growth zones where aggregates interlock and transfer stress.

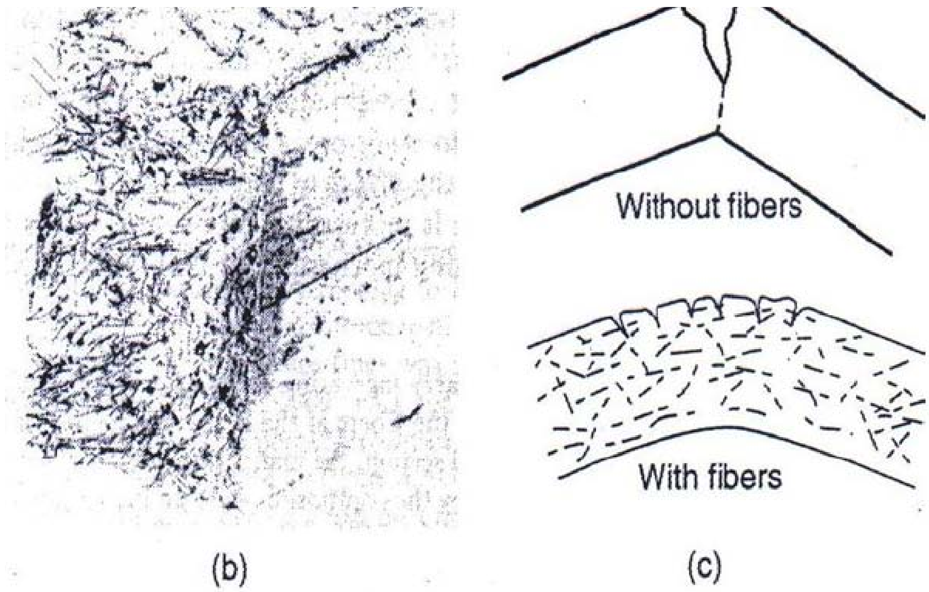


Figure 2.1 - The effect of fibers on failure mechanism (Folliard Kevin, 2006)

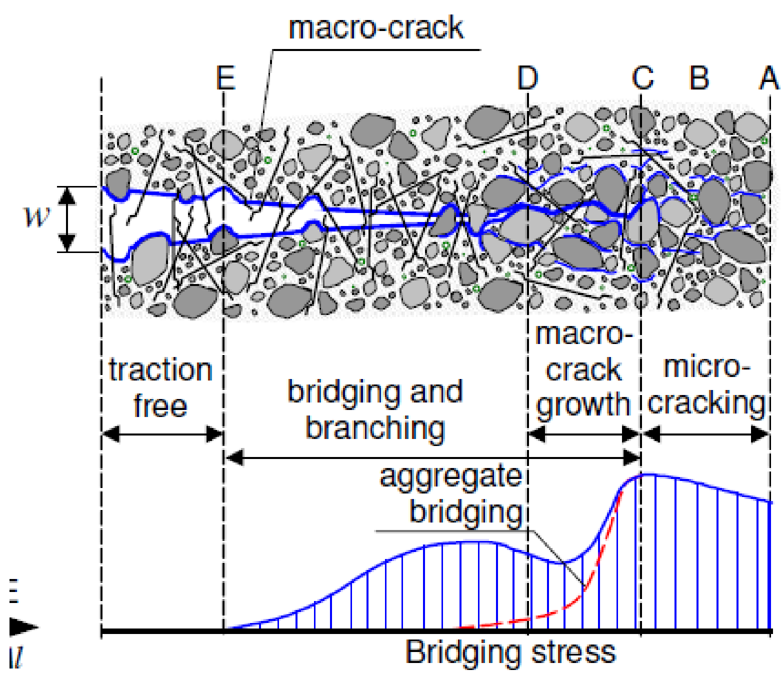


Figure 2.2: - Schematic description of the effect of fibres on the fracture process in uniaxial tension (Göteborg, 2005).

It has been illustrated that the use of fiber [Józsa and Fenyvesi, 2010 and Urooj et al., 2011 for glass fiber; Weiss and Furgeson, 2001; Haejin et al., 2003, Ardeshana and Atul, 2012, Trottier et al., 2002, Soulioti et al., 2011 and Folliard et al., 2006 for synthetic fiber] reduce both the early-age and drying shrinkage in concrete. The fiber controls and restrains micro cracks in the concrete and prevents the creation of larger macro-cracks at early ages.

2.4 Summary

In summary, FRC can enhance concrete in many different ways. Concrete fracture toughness and ductility can be improved using steel and synthetic fibers at high-dosage amount (>1% by volume). The glass fiber can improve fracture toughness but does not provide ductility enhancement. At low-dosage amount (<0.5%), synthetic fibers can be used to provide concrete resistance to plastic shrinkage and have been used for many years in building construction for the construction of slab-on-grade. Despite all these advantages, there are some drawbacks with the use of fiber as well. First, there is no standard specification for its application in civil infrastructure. Second, exposed steel fibers would corrode particularly in Florida's environment. Third, the FRC needs to be externally vibrated. Internal vibration would cause the fibers to cling together. Fourth, during mixing the fibers tend to cling together forming clumps and balls instead of being evenly distributed throughout the concrete matrix. These clumps and balls cause void pockets in the concrete, which potentially lead the concrete to fail prematurely. This balling effect could be even more pronounced when used for concrete pavement slab replacement because of the lean concrete mixture and low workability needed for immediately opening the replacement slab to traffic. Furthermore, the impact on basalt fiber on concrete cracking performance is not well established. For these reasons, more research is needed to better understand the characteristic of FRC with high-early strength.

CHAPTER 3
EXPERIMENTAL PROGRAM

This chapter describes the experimental program, which consisted of various laboratory experiments to quantify the plastic properties, mechanical properties and cracking performance of FRC concrete consisting of ten concrete mixtures. Additionally, the mixing procedure, concrete mixture proportions, and the preparation and storage of specimens are also described in this section. The plastic properties were determined by the unit weight and the time of flow test. Visual observation was also carried out to inspect for any clumps and balls caused by the fiber clinging together. The compressive strength, modulus of rupture, flexural toughness, and residual strength tests were used to evaluate the concrete mechanical properties, while the restrained shrinkage test was used to evaluate the cracking performance in concrete.

3.1 Experimental Setup

A total of ten concrete mixtures were investigated in this study. One mixture consisted of a control mixture provided by the FDOT that was commonly used in concrete pavement slab replacement projects. The other nine mixtures were made by modifying the control mixture with the addition of fibers to it. The materials used for this project was obtained from sources that are on the Qualified Products List.

All concrete mixtures developed for this project were made with the consideration of Section 353 strength requirements for replacement slabs. Hence, all mixtures were required to have a minimum 6-hour compressive strength of 2,200 psi and a minimum 24-hour compressive strength of 3,000 psi. In order to achieve the high-early strength in concrete, the mixtures had high cement content (>800 lb/yd^3), low water-cement ratio (<0.37, which is typical for replacement slab), superplasticizer and concrete accelerating admixture.

A broad range of tests was performed on each mixture to assist in the determination of the effect of fibers on cracking performance. Table 3.1 summarizes a list of tests performed in this study.

Table 3.1 – Laboratory tests performed on the different mixes

Test	Number of specimens per mix	ASTM standard used	Curing condition	Age at testing
Unit weight	1	ASTM-C138	None	fresh
Time of flow	1	ASTM-C995	None	fresh
Compressive strength	3	ASTM-C39	wet	6hr, 24hr, 28 days
Modulus of rupture	3	ASTM-C78	28 days wet	28 days
Flexural toughness	3	ASTM-C1018	28 days wet	28 days
Residual strength	2	ASTM-C1399	28 days wet	28 days
Restrained shrinkage	2	ASTM-C1581	None	6hr – 28, 40 days

3.2 Material Properties

The raw materials used in this project were obtained from sources and suppliers that are approved by the Qualify Product List. Bulk Portland cement from a single source was used to eliminate discrepancies and variations in material properties. The fine and coarse aggregates were also obtained from a single supplier and obtained in one batch. The chemical admixtures were obtained from two suppliers. However, for consistency only the admixtures from one supplier were used in preparing the specimens. The fibers were obtained from various sources and were not in compliance with the current Qualify Product List in order to expand the list of fiber types. Tables 3.2 and 3.3 list the materials and fibers used in this project along with their suppliers.

Table 3.2 – List of materials and suppliers

	Material	Supplier
Portland Cement	Type II	Titan America
Coarse Aggregate	#57 stones	Cemex
Fine Aggregate	Silica sand	Cemex
Air Entraining Admixture	MB-AE 90	BASF
	Darex AEA	W R Grace
High Range Water Reducing Admixture	Glenium 3030 NS	BASF
	ADVA CAST 575	W R Grace
Accelerating Admixture	Pozzolith 122 HE	BASF
	Daraccel	W R Grace
Water	Tap water	-

Table 3.3 – List of fibers and suppliers

Fiber type ASTM C1116		Material	Supplier
Steel I		NYCON-SF Type I	Nycon
Fiber glass II		NYCON-AR-DM	Nycon
Synthetic III	Basalt	GeoTechFiber	BasaltLabs
	Polypropylene	MONO-PRO	ABC polymers
		GRACE FIBERS	W. R. Grace
		FIBERMESH 150	Propex
		FIBERMESH 300	Propex
		FIBERMESH 650	Propex
	Nylon	NYCON-MULTIMESH	Nycon

3.3 Materials, Sample Preparation and Plastic Properties

This section describes all aspects of the materials used, sample preparation methodology and plastic properties test methods. First, it discusses the mixture proportions of the ten concrete mixtures. The mixing procedure is described next followed by the method of consolidation. The method for determining the workability and unit weight are also discussed. The last two subsections are devoted to the specimens fabrication and methods for curing and storage.

3.3.1 Mixture Proportions

Specimens were prepared with ordinary Portland cement manufactured by Titan America in Medley, Florida. Silica sand with a fineness modulus of 2.48 and #57 stones were used for the fine and coarse aggregates, respectively. All mixtures were proportioned to comply with the FDOT provisions for minimum required workability and strength. It should be noted that no attempt was made to optimize the mixture containing fibers in order to isolate the fiber's effect on concrete properties. Air-entraining, accelerating, and water-reducing admixtures were used to achieve the desired level of strength and workability. Two dosages of fibers were used in this project. A dosage of 0.1% by volume of fibers was used for mixtures M02 – M08, while the last two mixtures, M09 and M10 had a fiber volume fraction of 0.3%. Mixture M01 was a control mixture with no added fiber content. All mixtures had the same mixture proportion except for the fiber type and dosage amount used. The general mixture proportion is given in Table 3.4.

Table 3.4 - Mixture Proportion (all units are in lb/yd^3, unless noted)

	Cement	Fine Aggregate	Coarse Aggregate	Water	Admixtures		
					Air-Entraining	Type C	Type F
Material	Type II	Silica Sand	#57 Stone	Tap	MB-AE 90	Pozzolith 122 HE	Glenium 3030 NS
Quantity	840	1200	1500	274	2.1 oz	672 oz	135 oz

Note: w/c $\leq$ 0.378 (w/c contains 43.7 lb/yd^3 of water from Pozzolith 122 HE)
Unit weight = 141 lb/ft^3, 6-hour compressive strength = 3.35 ksi
Aggregates weight is given in SSD condition
The amount of Pozzolith 122 HE must be adjusted for cold and hot weather casting

As mentioned earlier, the mixture M01 was the control mixture using plain concrete with no fiber added to it. Mixtures M02, M07, and M08 had polypropylene fibers with different lengths and mechanical properties. Mixtures M02 and M07 had a 0.5-in long and 1.5-in long polypropylene fibers, respectively, while M08 had a 1-in long fibrillated fiber. These three variations of the polypropylene fiber were tested in order to compare the effect of fiber length and anchorage mechanism within the same type of fiber. Mixtures M03, M04, and M05 consisted of steel, glass, and basalt fibers, respectively. Nylon fiber was used in mixtures M06 and M09. Table 3.5 summarizes the fiber type and volume fraction used in each mixture.

Table 3.5 - Fiber type and volume fraction of the mixtures

Mix	Fiber type	Volume fraction (%)
M01	None	0
M02	Polypropylene 0.5" multifilament	0.1
M03	Steel 0.5" monofilament	0.1
M04	Glass 0.5" monofilament	0.1
M05	Basalt 0.5" monofilament	0.1
M06	Nylon 0.5" monofilament	0.1
M07	Polypropylene 1.5" macro synthetic	0.1
M08	Polypropylene 3/4" fibrillated	0.1
M09	Nylon 0.5" monofilament	0.3
M10	Polypropylene 3/4" fibrillated	0.3

3.3.2 Mixing Procedure

The coarse and fine aggregates were first added to the mixer. After the coarse and fine aggregates were thoroughly mixed, one-third (1/3) of the mixing water was added followed by the air-entraining admixture while the mixer was still running. The cement and the remainder of the mixing water were added to the mixer after a minute. All ingredients were mixed together in the mixer for another minute before the fiber was added. The mixing continued for two more minutes before allowing the mixture to rest for two minutes. After the mixture was allowed to hydrate and absorb some water, the mixer was started again and the water-reducing and accelerating admixtures were added at one minute intervals. Finally the whole mixture was mixed for two more minutes. The total mixing time including the resting time was ten minutes. A twelve cubic feet rotary mixer was used to mix the concrete. The mixer used in this project is shown in figure 3.1.

3.3.3 Method of Consolidation

Unlike ordinary concrete, external vibration is recommended for FRC to prevent damage to the fibers. In this study, a variable frequency-vibrating table was used to consolidate the specimens. The vibration time was first calibrated by comparing the slump of plain concrete consolidated using the conventional slump cone method with a vibrating table. A vibration time of 15 seconds yielded the same slump, and hence, it was used throughout the project. Figure 3.1 shows the vibrating table used in this project.

Figure 3.1 - Mixer used in the project and calibrating the vibrating table

3.3.4 Workability

Although the method of consolidation was developed to produce good consistency in the test specimens, a method for determining the workability is needed for the quality control and quality assurance. Unlike ordinary concrete where a slump cone can be used to determine the workability, FRC cannot be tampered by a steel rod. Thus, the time of flow of the concrete mix through an inverted slump cone under internal vibration was chosen as the measure of workability. This test was carried out according to the obsolete ASTM C995. It is understood that the result obtained using ASTM C995 method could provide significant bias as it depends on the operator and the type of vibrator used, so to minimize this, only a designated operator and the same vibrator operating at the same frequency were used in conducting the workability test. The inverted slump cone used for this test is shown in figure 3.2.

3.3.5 Unit Weight

The unit weight measurement was performed in accordance with ASTM C138 by using a 0.5-ft^3 steel unit weight bucket. The bucket was externally vibrated for 15 seconds and stroke off. The unit weight measurement is shown in figure 3.2.

3.3.6 Specimens Fabrication

A set of two or three specimens per testing sequence was prepared for all tests and mixtures. A 4 × 8-in cylindrical specimen was fabricated for measuring the compressive strength. A 4 × 4 × 14-in prism was used for the modulus of rupture, flexural toughness and residual strength tests. For the restrained shrinkage test, a concrete ring specimen measuring 6-in in height and 13-in and 18-in in inner and outer diameters, respectively, was used.

Figure 3.2 - Unit weight and time of flow measurements

3.3.7 Curing and Storage

The specimens were first covered with polyethylene sheets for six hours to prevent loss of water due to evaporation. After six hours, the molds were removed from the specimens and three specimens were tested for the 6-hour compressive strength. The remaining specimens were placed inside a water bath for continuous moist curing. The cylindrical specimens were cured in a water bath until the time of the test. The prism specimens were cured for 28 days before they were tested. Before testing, the cylindrical and prism specimens' surfaces were towel dried. No curing was applied to the restrained ring specimens. A paraffin wax coating was applied to the top surface of the ring specimens to prevent drying from the top surface and the specimens were allowed to dry only from the sides. The ring specimens were subsequently connected to the data logger and recording started immediately. Figures 3.3 and 3.4 illustrate specimens' conditions prior to testing and the curing method used in this study, respectively.

Figure 3.3 - Specimen surface drying before testing

Figure 3.4 - Specimen protection and curing

3.4 Laboratory Tests

Several laboratory tests were conducted to determine the mechanical properties and cracking performance, which are discussed in this section. The compressive strength, modulus of ruptures, flexural toughness and residual strength were used to determine the mechanical properties. The cracking performance was evaluated using the restrained shrinkage test.

3.4.1 Compressive Strength Test

The compressive strength test for the different mixtures was carried out in accordance with ASTM C39. A 4 × 8-in cylindrical specimen was used for this test. The test was carried out at three ages, specifically at 6-hours, 24-hours, and 28-days. Three specimens were used for each test and the average value was calculated from the test results. The specimens were cured in a water bath until they were tested. A 150-kip compression machine was used for loading the specimens. Rubber paddings were used to compensate for uneven surfaces and to ensure uniform load distribution. The loading rate on the compression machine was kept constant. The specimen was loaded until failure and the ultimate load was recorded. The compressive strength was calculated by dividing the ultimate load by the cross sectional area of the specimen, which was obtained by averaging the measured diameters used for computing the cross sectional area. Figure 3.5 illustrates the compression strength test setup.

Figure 3.5 - Compression test setup

3.4.2 Flexural Test Setup

Three different flexural tests were performed on the prism specimens. The tests included modulus of rupture, flexural toughness and residual strength. A 60-kip universal testing machine was used for these tests. The specimens were cured for 28 days in a water bath prior to testing. The specimen was first surface dried and the loading and support locations were marked with a marker. The mid-span deflections were obtained by using two high precision linear voltage differential transformers (LVDTs) that were placed on each side of the specimen. A rectangular jig fastened to the specimen was also used to hold the LVDTs in place. The whole assembly was placed on the testing machine by aligning the marked support and loading locations. The loading was applied at a constant rate. A data acquisition system was used to simultaneously record the load and deflection. The location of the fracture on the tension surface of the specimen was also checked to see it was laying inside the middle third of the test specimen. Figure 3.6 illustrates the flexure test setup.

Modulus of Rupture: The modulus of rupture was carried according to the ASTM C78. The concrete beam was simply supported and loaded to failure. The ultimate load was recorded and the specimen was inspected to check if the fracture initiated in the tension surface within the middle third of the span length. The modulus of rupture was then calculated by using an appropriate formula depending on the failure mode. Figures 3.7 and 3.8 illustrate the loading to failure and fractured specimen, respectively.

Figure 3.6 - Flexural test setup

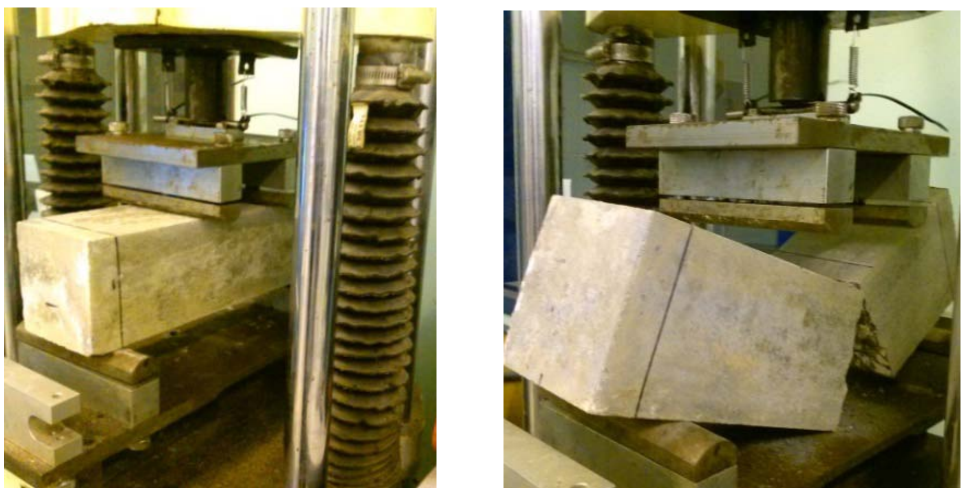


Figure 3.7 - Loading of specimen to failure

Figure 3.8 – Fractured Specimen

Flexural Toughness: The flexural toughness test of the concrete prisms was conducted in accordance with the ASTM C1018. The specimen was first placed in a rectangular jig and simply supported on the loading frame. The LVDTs were then secured in place. The load was then applied until the mid-span deflection of the beam reached 10.5 times the first crack deflection. The applied load and deflection of the beam were recorded simultaneously. The data was later used to create the load-deflection curve and the parameters for the flexural toughness were calculated thereafter. Figure 3.9 illustrates the specimen preparation and plot generated from the data acquisition system.

Figure 3.9 - Specimen preparation and data plot

Residual Strength: The residual strength test of the specimens was performed in accordance with the ASTM C1399 as shown in Figure 3.10. The simply supported beam was pre-cracked under loading by inserting a 0.5-in thick stainless steel plate under the beam. Once the beam cracked the steel plate was removed and the cracked beam was reloaded. The load and mid-span deflections were recorded simultaneously. The load-deflection curve was then generated from which the desired parameters were obtained.

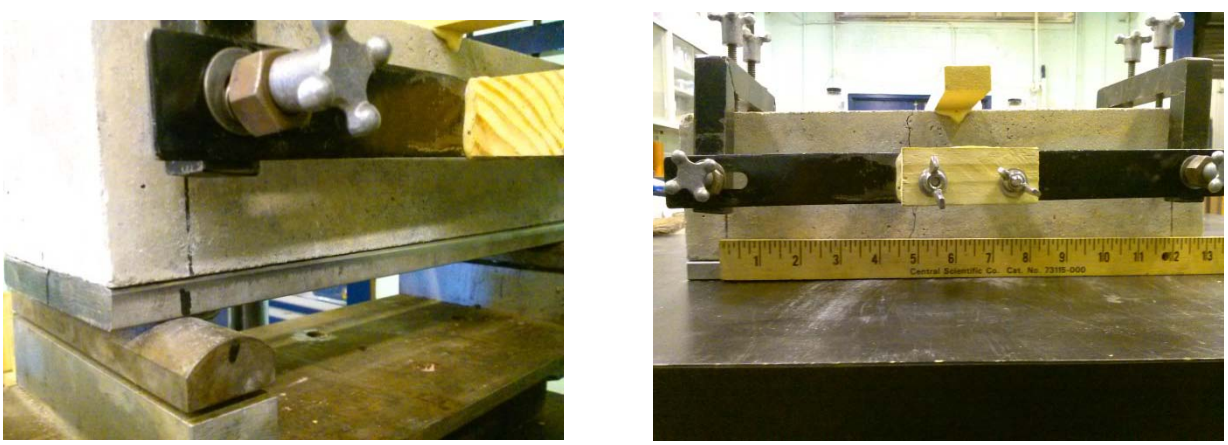


Figure 3.10 - Specimen setup for residual strength

3.4.3 Restrained Shrinkage Test

The restrained shrinkage test was performed in accordance with the ASTM C1581 with slight modifications. A 6-in concrete ring with inside diameter of 13-in and outer diameter of 18-in was cast around a 0.5-in thick steel ring. Figure 3.11 illustrates the schematic diagram of the test setup. The specimen was placed on a nonabsorbent base. Six hours after casting, the molds were removed from the specimens and the top surface of the concrete was coated with paraffin wax to avoid evaporation as shown in Figure 3.12. The specimen was left to dry only from the sides and the stress measurements started right away. Two strain gages (Figure 3.12) were placed at mid height on diametrically opposite sides of the steel ring to measure the induced steel strain. A data-logger was used to continuously collect the data from different specimens. The data was then plotted to obtain the age at cracking. A drop in strain of more than 30 microstrain indicates a crack. In case the specimen did not crack within 28 days it was allowed to continue until it finally cracks.

The specimens were inspected for visible cracks with the aid of a digital microscope. A Dino-Lite AM-413TA digital microscope with the capabilities to detect micro cracks and measure the width of cracks was used. The crack width at the end of 28 days was then recorded for each specimen. Figures 3.13 and 3.14 illustrate the testing detail of the restrained shrinkage test and the inspection of cracks, respectively.

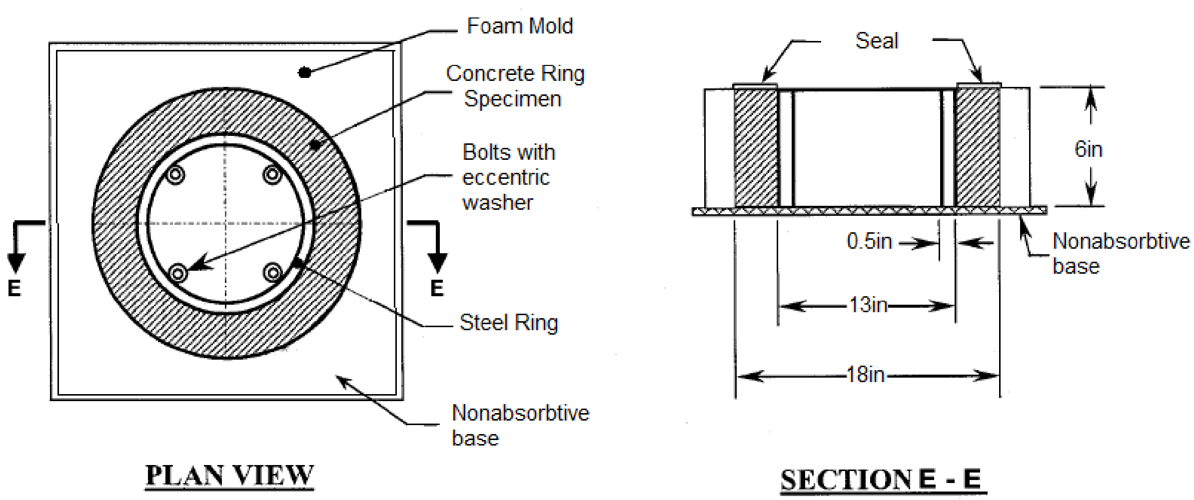


Figure 3.11 - Ring specimen details

Figure 3.12 - Restrained shrinkage specimen and strain gages

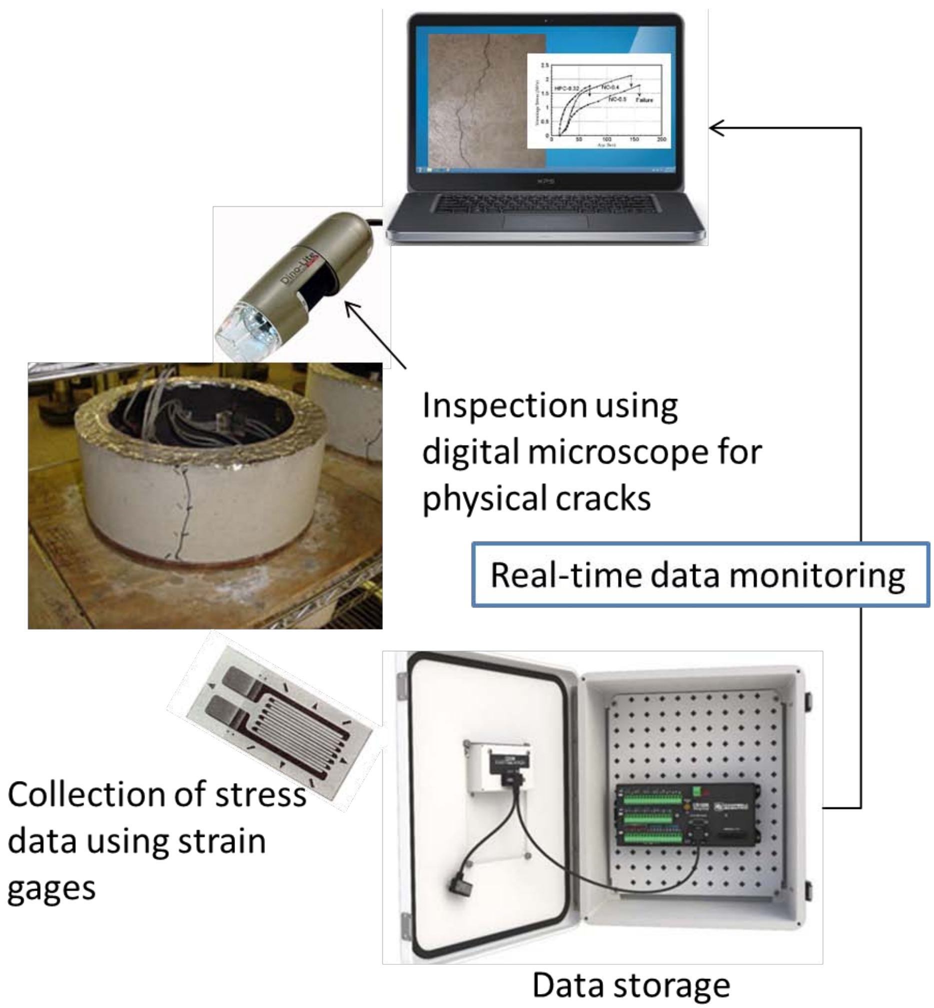


Figure 3.13 - Schematic of restrained shrinkage test

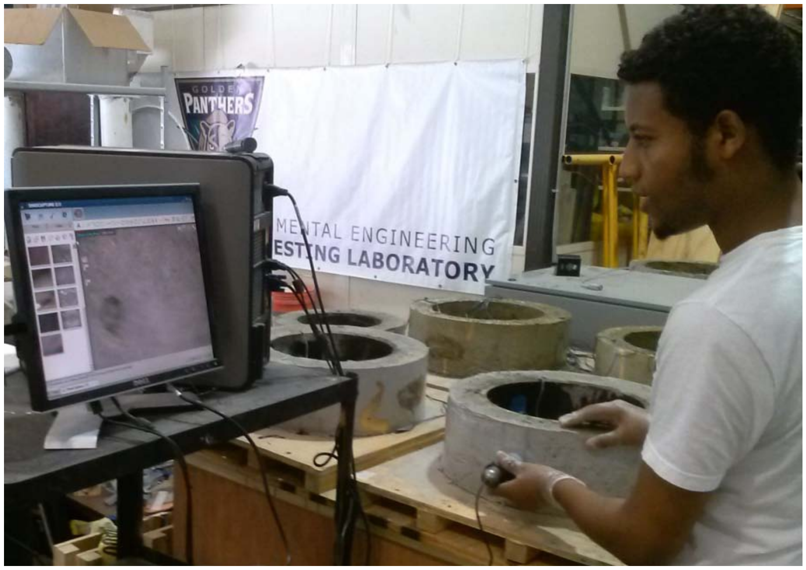


Figure 3.14 - Inspection of physical cracks

3.5 Data Collection and Analysis

Data collection was done with the help of two separate systems. A Vishay data acquisition system was used to collect and process the load and deflection data from the LVDTs and the universal testing machine. The load-cell and the LVDTs were first calibrated and the scan rate was set to 5 seconds. Smartstrain software was used to interface the instruments with the data acquisition system. The strain reading from the strain gages was collected and processed with the help of a data-logger from Campbell Scientific Inc. The data-logger was assembled and programmed for this purpose. Multiplexers were added to the system to expand the data-logger capacity to read from 48 strain gages, which was sufficient for this project. The scan rate was set to 5 minutes and every 30 minutes the data-logger averaged the data and recorded the mean value. Data was programmed to be constantly transferred to a computer on a daily basis. The collected data was then plotted and the strain was monitored to detect cracks. Figure 3.15 shows the data acquisition and data-logger used in this project. In addition an environmental logger was also used to collect ambient temperature and humidity of the testing environment.

3.6 Testing Environment

Shrinkage measurements are sensitive to environmental parameters such as temperature and humidity. Hence, it is crucial to maintain the temperature and humidity of the testing room. The testing room was equipped with an air conditioning unit, which was adjustable with a combined thermostat-humidistat control mounted inside the room. The thermostat was set 73^{o}F and humidity of 50%. An environmental logger was used to collect the environmental parameters so as to avoid any change in temperature and humidity. Figure 3.16 illustrates the variation in temperature and humidity in the room.

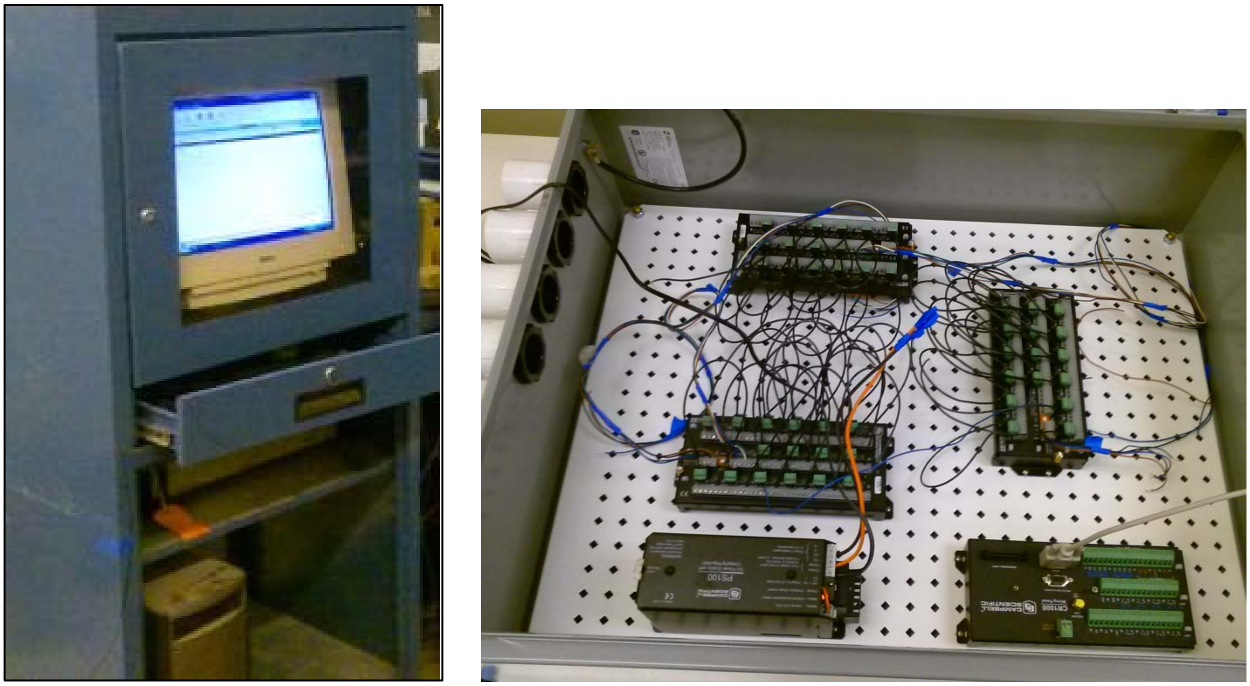


Figure 3.15 - Data collection and analysis (a) Data acquisition (b) Data-logger

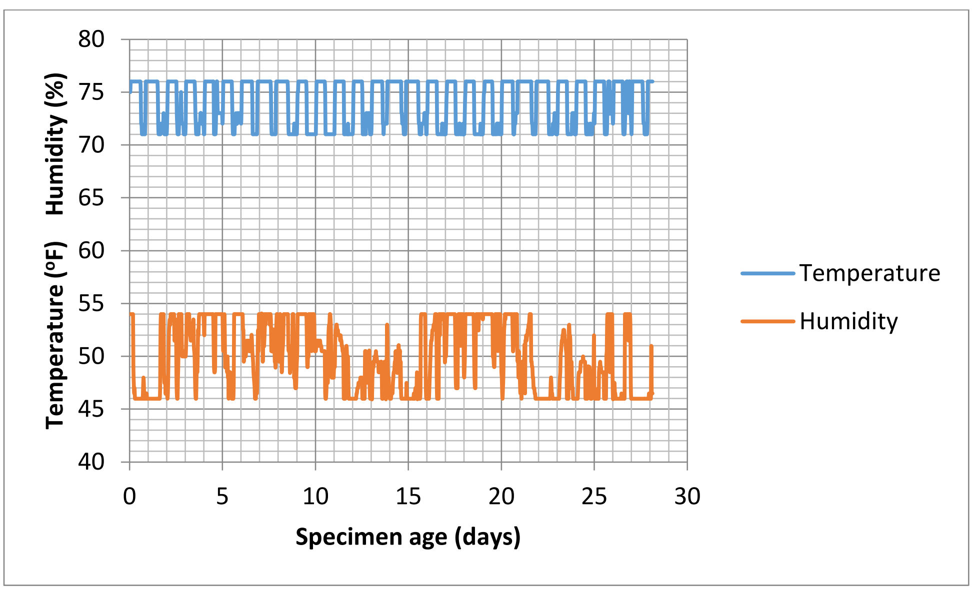


Figure 3.16 - Temperature and humidity plot for the test period

3.7 Summary

This chapter focuses on the laboratory experiments that were conducted to understand the behavior of high-early strength FRC for concrete pavement slab replacement. A total of ten concrete mixtures were investigated to determine their plastic properties, mechanical properties, and shrinkage performance. The plastic properties included visual observations of fiber balling, determination of the unit weight, and workability measurements. Several mechanical properties were investigated for each mixture, which consisted of the compressive strength, flexure toughness, modulus of rupture, and residual strength. A restrained shrinkage test was used in the evaluation of the shrinkage performance of all ten mixtures. The ten mixtures consisted of one controlled mixture adopted from actual replacement slab mixture. Different fiber types and amounts were added to the controlled mixture to form the remaining nine mixtures being investigated.

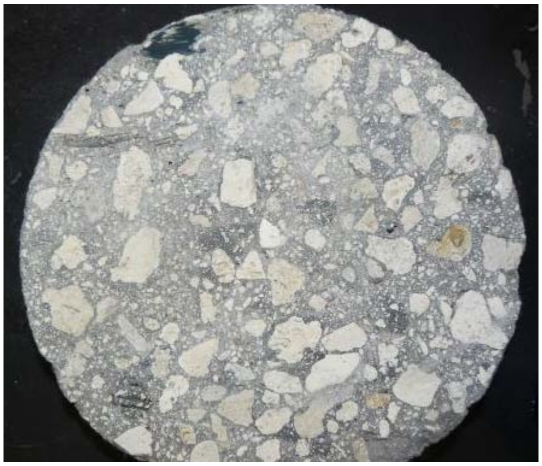
CHAPTER 4
RESULTS AND DISCUSSIONS

This chapter describes the results of the laboratory experiments detailed in Chapter 3. Plastic properties, mechanical properties and cracking performance as well as any observations made during mixing are discussed here. The chapter first discusses the observed balling of fiber followed by a discussion on the plastic properties. The mechanical properties and cracking performance are discussed next.

4.1 Mixing Observation

The first task carried out was to determine the best method in distributing the fibers into concrete. The mixing method was crucial in determining a uniform fiber distribution and in preventing the formation of fiber clumps and balls. A preliminary investigation was made using trial batches to select the best mixing technique for making FRC. The main difference in the mixing techniques was in the mechanism in which the fiber was added. Two different techniques of adding the fiber were tested to compare the distribution of fibers and their susceptibility to fiber balling. The first technique, T01, was mixed by adding the fibers in dry state along with the coarse and fine aggregates prior to the addition of water. In the second technique, T02, the fibers were added in the wet state after the addition of water. The fibers were dumped into the mixer in small bowls to simulate the field condition. Visual inspection of the concrete in plastic state was carried out to check for instances of fiber balling. The hardened specimens from both techniques were cut and visually inspected for uniformity of the fiber distribution along the concrete matrix. The 24-hour compressive strength specimen was also tested to compare and check for the presence of defects due to improper mixing and fiber balling.

Figure 4.1 illustrates the cut surface of both techniques. Their 24-hour compressive strengths are summarized in Table 4.1. Based on the visual inspection and compressive strength results, both techniques provided good distribution of fiber in concrete. However, the second technique provided better matrix consistency for nylon fiber where balling was encountered. The nylon fibers get wet easily when water is added to the dried mixture when using the mixing procedure developed for the first technique. As the nylon fiber becomes wet, it tends to clamp together forming fiber balls as shown in Figure 4.2. These fiber balls produced corner pockets and prevented proper consolidation as can be seen in the casted prism specimen shown in Figure 4.2. Regardless of the technique used in mixing, the nylon fibers would stick and accumulate along the mixing blades of the mixer, which means not all added fibers are incorporated into the mixture. For these reasons, it is recommended that only experienced contractors be allow to use nylon fiber.



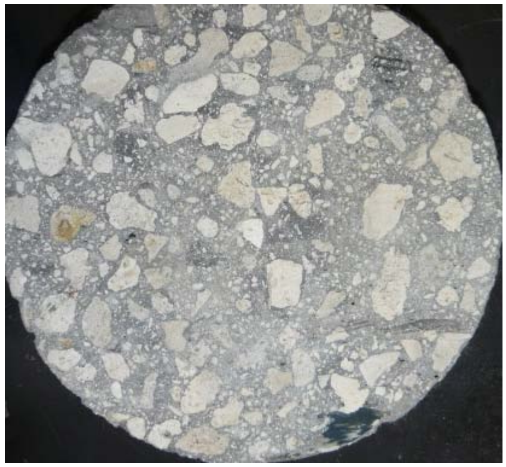
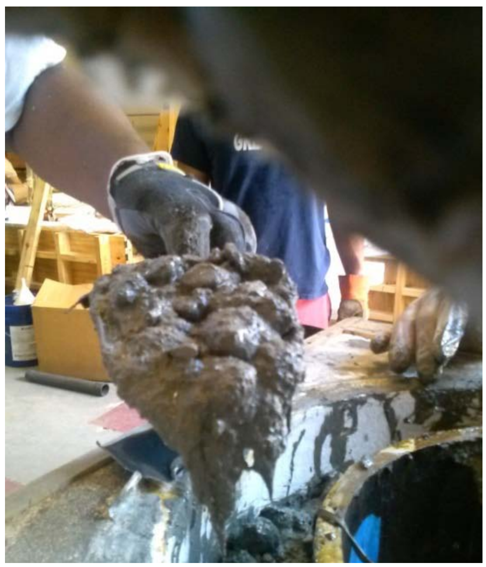


Figure 4.1 - Visual inspection of fiber distribution T01 and T02

Table 4.1 - Results of the trial mix

Mix	Fiber type	Fiber added in	Fiber distribution	24hr Compressive strength (psi)	Slump (sec)
T01	Polypropylene, 0.5"	dry state	well	6210	22
T02	Polypropylene, 0.5"	wet state	well	6190	21

(a) pockets due to fiber balling



(b) fiber balls during casting

Figure 4.2 - Fiber balling in M06 and M09

4.2 Plastic Properties

Two plastic properties were of concern in this project: 1) the unit weight and 2) the workability of the concrete. The workability of the concrete was tested using the inverted slump cone method shown in Figure 4.3. The time of flow of the concrete through an inverted cone was measured. The results of the unit weight and time of flow through an inverted cone are given in Table 4.2 for the different mixtures. According to the test results there was no notable reduction in workability due to the addition of fibers. There was a slight reduction in the time of flow in the case of stiff fibers, i.e., steel, glass and long (1.5-in) polypropylene fibers. However, the reduction was insignificant with only about 2 to 3 seconds increase. It should be noted that a 15 second time of flow is equivalent to a 1-in slump, which was the targeted slump for this particular control mixture used in this study. Therefore, unlike FRC with high-dosage (>1%) fiber content that has lower workability reported in the literatures, the workability of FRC with low-dosage (<0.5%) fiber content is not affected. The mixture can further be optimized to increase the workability of the concrete by using superplasticizer but the Research Team decided to stick to the targeted slump of the control mixture obtained from FDOT. Table 4.2 also reports the unit weight, which was relatively constant for all mixture.

Table 4.2 - Plastic properties of the different mixes

Mix	Time of flow (sec)	Unit weight (lb/ft^3)
M01	14	141.0
M02	14	141.0
M03	17	141.3
M04	15	141.1
M05	14	141.1
M06	13	141.1
M07	16	141.1
M08	15	141.1
M09	15	141.1
M10	14	141.1

(a) (b)

Figure 4.3 - Plastic property measurements (a) unit weight (b) time of flow

4.3 Mechanical Properties

The mechanical properties that were investigated in this study were compressive strength, modulus of rupture, flexure toughness, and residual strength. This section discusses their results and observations made for all mixtures.

4.3.1 Compressive Strength Test

The results of the compressive strength tests at three different specimen ages (6 hours, 24 hours and 28 days) are listed and depicted in Table 4.3 and Figure 4.4, respectively. As can be seen from the test results, in general FRC had higher compressive strength at early-age but then there was little effect on the compressive strength when comparing to ordinary concrete. Higher effects could be achieved at higher volume fractions, but at a low-dosage of 0.1% and 0.3% used in this project, there was no significant increase in the compressive strength. One noticeable difference was the 24-hour compressive strength of FRC was in general higher (could be as much 1000 psi) in comparison to ordinary concrete (control mixture). This could be attributed to the fiber confining the concrete at early-age. As shown in Figure 4.5, the specimens with fiber showed higher shutter resistance as compared to the control specimens. Unlike the fiber reinforced concrete, the plain concrete specimens were shattered, while the former stayed in one piece after been subjected to ultimate load. All mixtures had an initial setting time of approximately 5 hours. Another observation that was made was the mixture containing nylon fiber had a strength reduction at 28 days, which could be attributed to fiber balling encountered for these mixtures that prevented proper consolidation and fiber distribution.

Table 4.3 - Compressive strength of the mixes at different ages

Mix	Compressive Strength (psi)			Fiber Type	Fiber Volume fraction (%)
	6 hours	24 hours	28 days		
M01	3350	6340	9720	None	0
M02	3380	6200	10030	Polypropylene 0.5" multifilament	0.1
M03	3610	7590	9920	Steel 0.5" monofilament	0.1
M04	3940	7270	9630	Glass 0.5" monofilament	0.1
M05	3370	6600	9470	Basalt 0.5" monofilament	0.1
M06	3400	6310	9370	Nylon 0.5" monofilament	0.1
M07	4210	7370	10770	Polypropylene 1.5" macro synthetic	0.1
M08	4990	7250	9750	Polypropylene 3/4" fibrillated	0.1
M09	3570	6510	9780	Nylon 0.5" monofilament	0.3
M10	5010	7390	9810	Polypropylene 3/4" fibrillated	0.3

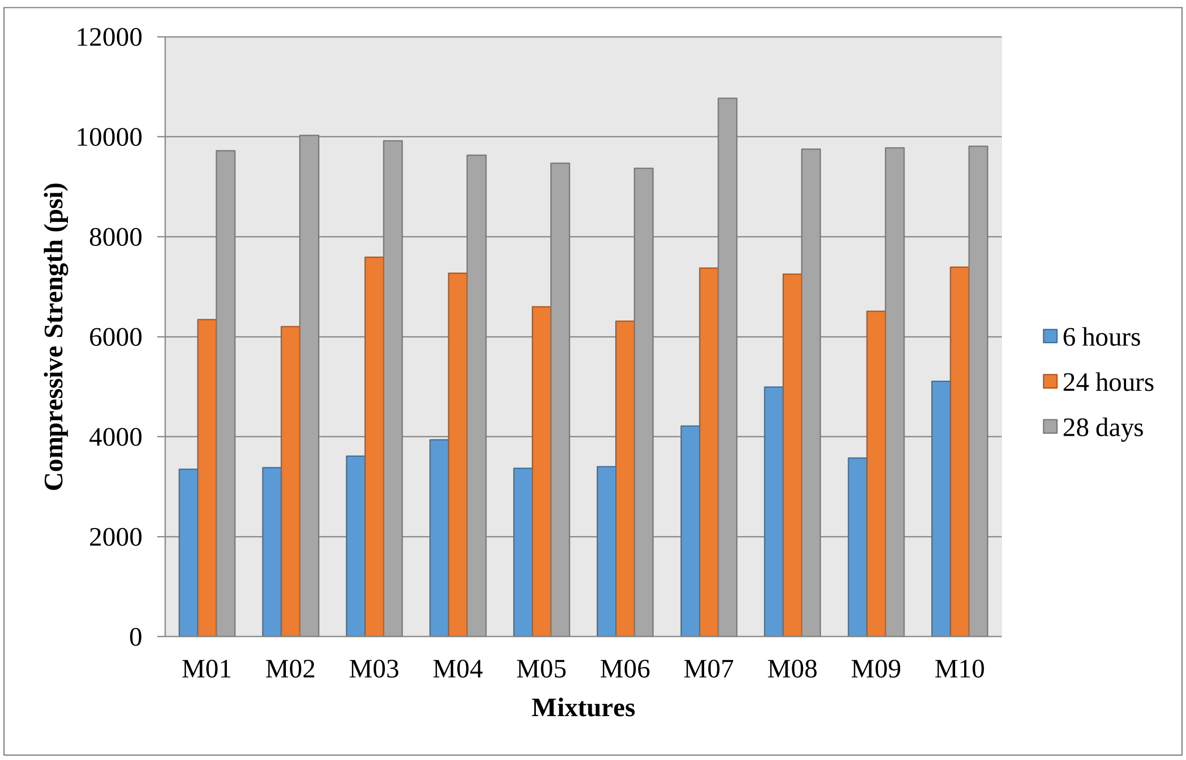


Figure 4.4 - Compressive strength of the mixes at different ages

(a) Plain concrete (M01)

(b) Fiber reinforced concrete (M08)

Figure 4.5 - Shutter resistance analysis of fractured specimens

4.3.2 Modulus of Rupture

The modulus of rupture is a measure of flexural strength. The behavior of the FRC was expected to be superior as compared to ordinary concrete. However, the fiber volume fraction chosen was intended to improve the early age cracking resistance, not the flexural strength. As a result, only a small increase in capacity was observed. It is also observed that fibers with higher stiffness had the highest modulus of rupture. The results of the modulus of rupture test are given and depicted in Table 4.4 and Figure 4.6, respectively.

As can be seen from the test results, almost all mixtures had low modulus of rupture. This is typical of an ordinary concrete which had low flexural strength. By introducing a fiber in to the mixture, the modulus of rupture was increased only to a small degree. To attain significant improvements the fiber volume fraction should be much higher. In addition, the tensile and bond strengths of the fiber should be higher. In this test fibers with higher tensile strength performed better than those with lower tensile strengths. Steel and 1.5" monofilament polypropylene fibers increased the modulus of rupture by 21% and 31%, respectively. Although the percentages showed good improvements, in reality it is not as high as the percentages. Two modes of failure were identified in this test. For fibers with lower tensile strength, the mode was tensile failure in concrete immediately followed by tensile failure of the fibers. For fibers with higher tensile strength the mode was tensile failure of concrete followed by a delayed pull out of the fibers. Unlike in the first mode of failure discussed above, in the second mode of failure the specimen stayed intact after the onset of tensile cracking. Figures 4.7 and 4.8 show pull out of steel fibers and failure modes. Another factor was the fiber length. The longer the fiber, the better the bond strength. An ideal fiber to boost the modulus of rupture would be one that has higher tensile and bond strengths and are long.

Table 4.4 - Modulus of rupture of the different mixes

Mix	Modulus of rupture (psi)	Fiber type	Fiber volume fraction (%)
M01	515	None	0
M02	520	Polypropylene 0.5" multifilament	0.1
M03	625	Steel 0.5" monofilament	0.1
M04	555	Glass 0.5" monofilament	0.1
M05	615	Basalt 0.5" monofilament	0.1
M06	575	Nylon 0.5" monofilament	0.1
M07	675	Polypropylene 1.5" macro synthetic	0.1
M08	615	Polypropylene 3/4" fibrillated	0.1
M09	590	Nylon 0.5" monofilament	0.3
M10	620	Polypropylene 3/4" fibrillated	0.3

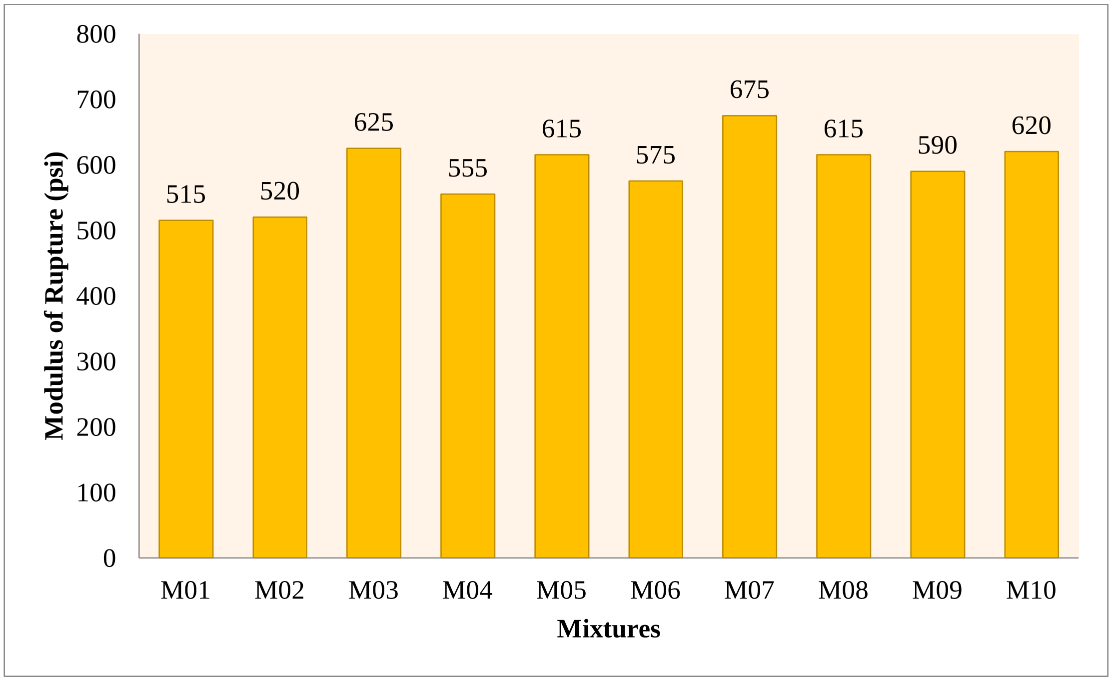


Figure 4.6 - Modulus of rupture of the different mixes

Figure 4.7 - Pull out of steel fibers. The holes on the right indicate pull out locations

Figure 4.8 - Modes of failure

4.3.3 Residual Strength

The residual strength test was conducted to compare the post cracking strength of different mixtures. The result of the residual strength test is summarized and depicted in Table 4.5 and Figures 4.9. As expected, the ordinary concrete mixture had no post-cracking residual strength. The analysis of the test results clearly showed that most of the mixtures had no post-cracking strength due to the lower fiber volume fraction used. Fibers with higher tensile strength have showed some post cracking residual strength. For example, mixture containing steel fiber (M03) showed the highest post-cracking residual strength. Mixtures containing nylon and polypropylene fibers (M06-M10) also showed some residual strength as well. The rest of the mixtures could not be reloaded after cracking as the specimen shattered into two pieces. Hence the reloading load was taken as 0lb.

Table 4.5 - Average residual strength of the different mixes

Mix	Average Residual Strength ARS (psi)	Fiber Type	Fiber Volume Fraction (%)
M01	0	None	0
M02	0	Polypropylene 0.5" multifilament	0.1
M03	110	Steel 0.5" monofilament	0.1
M04	0	Glass 0.5" monofilament	0.1
M05	0	Basalt 0.5" monofilament	0.1
M06	45	Nylon 0.5" monofilament	0.1
M07	90	Polypropylene 1.5" macro synthetic	0.1
M08	50	Polypropylene 3/4" fibrillated	0.1
M09	60	Nylon 0.5" monofilament	0.3
M10	70	Polypropylene 3/4" fibrillated	0.3

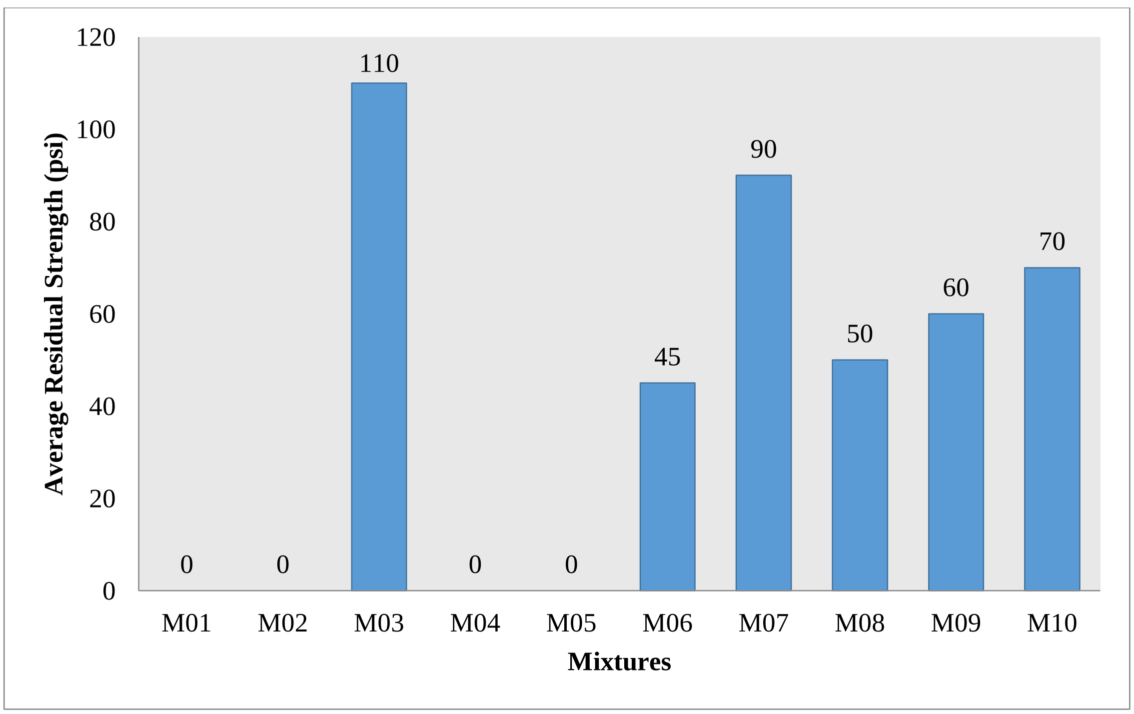


Figure 4.9 - Average residual strength of the different mixes

4.3.4 Flexural Toughness

Flexural toughness is one means of measuring the post-crack strength of FRC. An attempt was made to find the flexural toughness parameters of the different mixtures used in this project. However, the flexural toughness parameters could not be computed for most of the mixtures. This was because most of the specimens split in two at first crack, hence it was not possible to measure further. The results of the flexural toughness test are given and depicted in Table 4.6 and Figures C1 and C2. As can be seen from Table 4.6, flexural toughness indices were computed for mixtures M03 and M07 only, which stayed intact after the first crack. Comparing the residual strength factor $R_{5,10}$ M03 proves to be superior to the rest of the mixtures.

Table 4.6 - Flexural toughness test result

Mix	First-crack Load (lbf)	First-crack Deflection (in)	First-crack Strength (psi)	First-crack Toughness (lbf-in)	I_5	I_{10}	$R_{5,10}$
M01	2720	0.0008	510	1.1	-	-	-
M02	2800	0.0009	525	1.3	-	-	-
M03	3281	0.001	615	2.0	4.1	7.7	72
M04	2933	0.0009	550	1.3	-	-	-
M05	3307	0.0009	620	1.5	-	-	-
M06	3067	0.0009	575	1.4	-	-	-
M07	3548	0.0011	665	2.3	4.2	6.7	50
M08	3253	0.001	610	1.6	-	-	-
M09	3120	0.0011	585	1.7	-	-	-
M10	3280	0.0012	615	2	-	-	-

4.4 Cracking Performance

The cracking performance was evaluated using the restrained shrinkage test. The restrained shrinkage test was carried out to compare the relative potential of different fiber reinforced mixtures in preventing and controlling early age shrinkage cracking. The results of the shrinkage test are summarized in Tables 4.7 and Figure 4.10. Two parameters were of interest in this test: 1) the age at cracking and 2) the crack width of a 28-day-old specimen. The age at cracking was determined from the strain-age graphs. A full depth crack was detected when there was a sudden drop in strain (more than 30 $\mu\varepsilon$) or a consistent drop of strain. Some cracks were superficial which do not penetrate to full depth of the specimen. Superficial cracks were noted by a localized drop in the strain-age graph. For comparative reasons the age at cracking was taken at the onset of cracking in case superficial cracks.

A closer look of the strain-age graphs for the first 8 mixtures (M01-M08) revealed that all but M02 and M08 had developed full depth cracks within the 28 days period after casting. This was clearly indicated by a sudden drop in strain. However, mixtures M02 and M08 had no indications of a superficial crack, which did not develop to full depth crack within the 28-day period. This result is further bolstered by the reduced crack width for these two mixes.

The crack width for all mixtures was measured at 28 days after casting. The measurement of the crack width also is in complete accord with the strain-age graphs. Mixtures M02, M07 and M08 had registered the smallest crack width as compared with the rest of the mixtures.

As far as age at cracking and crack width were concerned, polypropylene fibers have shown the best results. Mixtures M02 and M08 showed a combined effect of longer age at cracking and the smallest crack width without developing into a full depth crack within a 28-day period. The age at cracking increased by 62% (from 13 days for the ordinary concrete, M01, to 21 days for polypropylene FRC, M02 and M08). The crack width had also been reduced by 84% (0.4mm for M01 to 0.065mm for M02 and M08). The steel fiber reinforced concrete, M03, had also shown smaller crack width. This is due to the fact that two major cracks developed, hence the total crack width can safely be assumed to be twice as much as the value indicated in Table 4.7. The formation of more than one major crack in M03 is evident from the strain-age graph in Figure A3. In addition, the steel fibers had shown severe corrosion even in laboratory condition as shown in Figure 4.12. There were also multiple cases where the crack width was found to be greater than the crack in the control specimen. M03 and M07 had actually increased the crack width and lessened the age at cracking as compared to the control specimen. This can be related to the relatively higher flexural strength of the fibers used in these mixtures. M04 and M05 had highly scattered age at cracking (indicated by the standard deviation of the age at cracking) with an average age of slightly higher than the control specimen, however, with a wider crack. M06 had extended the age at cracking considerably, however, the crack width remained the same as the control specimen.

After assessing the results of the first eight mixtures, two mixtures (M09 and M10) were tested at a higher fiber dosage amount. The fiber volume fraction was increased to 0.3% to investigate the effect of increased fiber volume. Owing to their better performance in the first batch of tests nylon and polypropylene (0.75-in. long fibrillated) fibers were chosen for the second batch of tests. In both mixtures, no full depth crack was detected. Hence, it was required to increase the observation period to 40 days. Within this period both mixtures only developed superficial cracks, no full depth crack or a sudden drop in strain was recorded. Although M09 had a better performance in reducing the crack width and preventing a full depth crack, it developed the superficial cracks at a much earlier time as compared to M10. M10 on the other hand increased the age at cracking considerably as compared to the control mixture as well as all the other mixtures. With M10 mixture, it is possible to reduce the crack width by 84% (from 0.4mm for M01 to 0.065mm for M10) and extend the age at cracking by 138% (from 13 days for M01 to 31 days for M10).

Table 4.7 - Shrinkage test results

Mix	Full depth crack	Age at cracking (days)		Average Crack width in(mm)
		Average age at cracking (days)	standard deviation	
M01	Yes	13	0	0.016 (0.4)
M02	No	21	0	0.003 (0.065)
M03	Yes *	10	4.31	0.008 (0.2) *
M04	Yes	15	8.70	0.018 (0.45)
M05	Yes	12	4.17	0.018 (0.45)
M06	Yes	20	0.35	0.016 (0.4)
M07	Yes	11	1.56	0.024 (0.6)
M08	No	21	0	0.003 (0.065)
M09	No	19	0	0.004 (0.1)
M10	No	31	0	0.003 (0.065)

*Two major cracks were detected

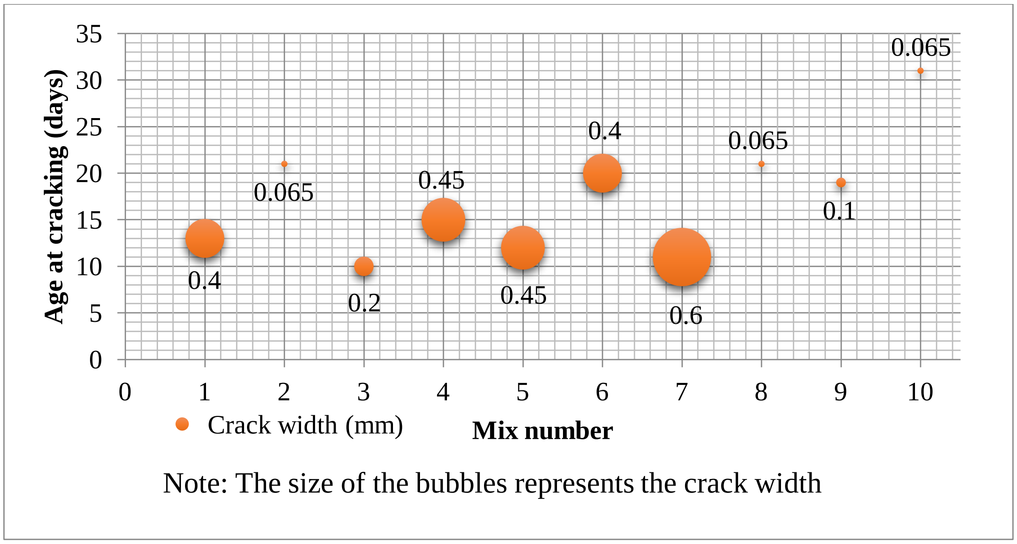
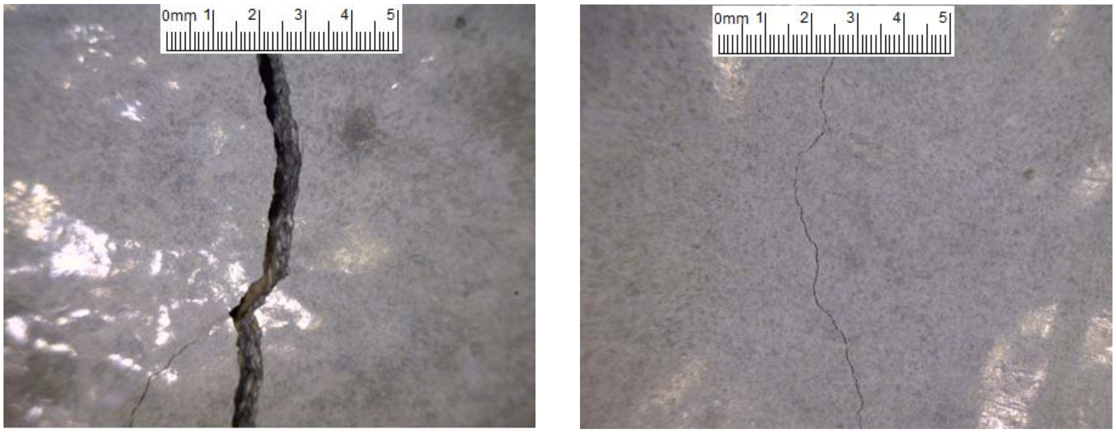


Figure 4.10 - Age at cracking and crack width for the different mixes



(a) M01 plain concrete (b) M10 Polypropylene fiber reinforced concrete

Figure 4.11 - Crack width at 40X magnification

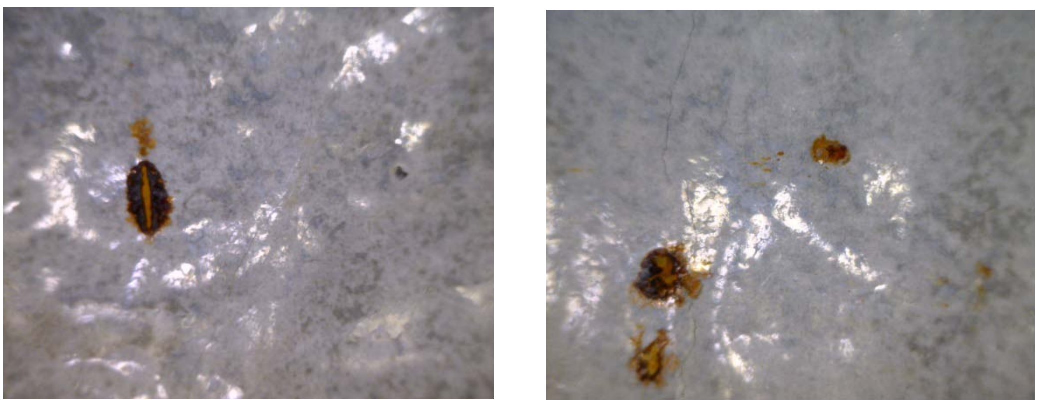


Figure 4.12 - Corrosion of steel fibers in the ring specimens

4.5 Summary

Ten mixtures were evaluated for their plastic properties, mechanical properties and cracking performance. The results reveled that for low-dosage (<0.5%) fiber content, there was little affect on workability and unit weight. Nylon fibers present challenges with clumps and balls and should not be used by inexperienced contractors. In general, the FRC had better mechanical properties than ordinary concrete but at low-dosage amounts, the increase in capacities was not significant. Overall, the short (<1-in) polyethylene fiber had the best performance in preventing early-age cracking and is recommended to be used for concrete pavement slab replacement. There was no direct relationship between the mechanical properties and cracking performance at the low dosage rate used in this study.

CHAPTER 5
DEMONSTRATION SLABS

This chapter discusses the second phase of this study. In this phase, five demonstration slabs: 1) control slab, 2) FRC slab with 0.1% of 0.5-in polyethylene fiber, 3) FRC slab with 0.3% of 0.5-in polyethylene fiber, 4) FRC slab with 0.1% of 0.75-in polyethylene fiber, and 5) FRC slab with 0.3% of 0.75-in polyethylene fiber were investigated for their early-age performance.

5.1 Demonstration Slab

A total of five full-scale slabs with a dimension of 6-ft × 6-ft × 6-in were constructed outdoors at FIU's outdoors testing facility to monitor their relative performance at early-age. The demonstration slabs were constructed by a general contractor that was approved by the FDOT. The five slabs consisted of one control slab with conventional concrete, two slabs with 0.1% and 0.3% volume fraction of 0.5-in. long polypropylene fibers, and two slabs with 0.1% and 0.3% volume fraction of 0.75-in. long polypropylene fibers. Table 5.1 summarizes the mixture proportions for the five slabs. During the construction, observations were made to determine any complications the contractor faces during the construction. The slabs were also instrumented with various sensors to monitor the shrinkage strains and temperature. Figure 5.1 illustrates the sensors locations on the slabs and Figure 5.2 illustrates the demonstration slab.

Table 5.1 – Demonstration Slab Concrete Mix Desing

	Slab #				
Materials (lb/cu. Yd.)	1	2	3	4	5
Type II Portland Cement			840		
Fine Aggregate (Silica Sand)			1200		
Coarse Aggregate (#57)			1500		
Water			274		
Admixture (oz)					
AEA (MB-AE 90)			2.1		
Type C (Pozzolith 122 HE)			672		
Type F (Glenium 3030 NS)			135		
Fibers (lb/cu. Yd.)					
Polypropylene 0.5" multifilament	N/A	1.5	4.5		
Polypropylene 3/4" fibrillated	N/A			1.5	4.5

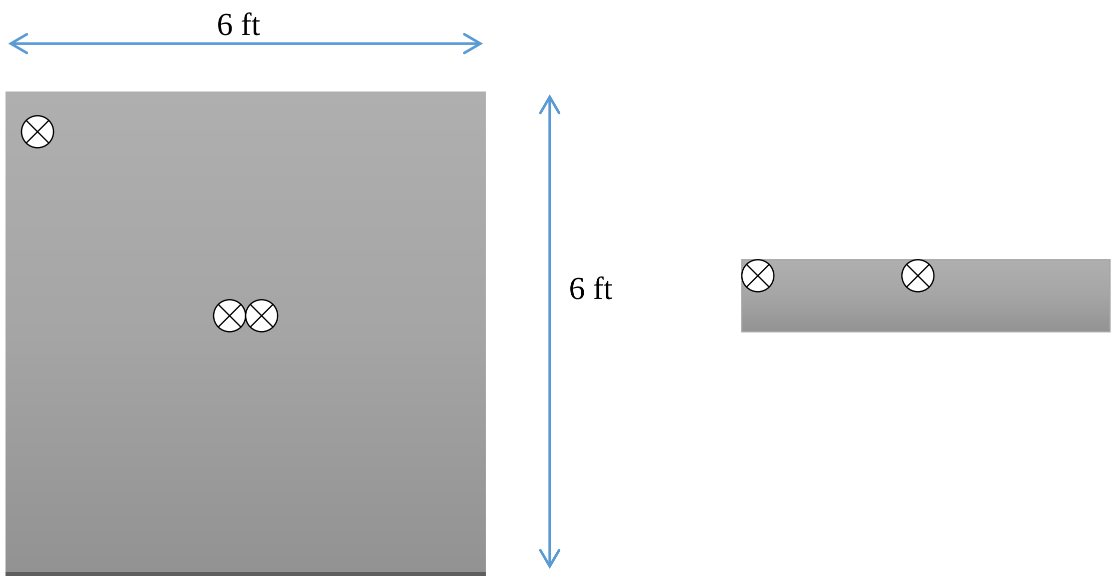


Figure 5.1 – Sensors locations

Figure 5.2 – Demonstration Slab

5.2 Instrumentation

The sensors used for monitoring the strains and temperature consisted of a vibrating wire strain gauges (VWSG). The VWSG (see Figure 5.2) was embedded in top portion of the concrete slab in the center and corner as shown in Figure 5.1. A total of three VWSG were installed in each slab. The cables were run out of the top of the slab, which will be connected to a data logger. The VWSGs were used to signal the crack location as well as the strain in concrete. The advantage of using VWSG was its ability to detect shrinkage strains while the concrete is still in a plastic stage. Furthermore, a thermistor was embedded inside the VWSG to record early age temperature histories. This information helps us in understanding the heat of hydration of the high-early concrete mixtures. The data was collected at 5 minutes intervals and every 30 minutes an average of strain was computed. Unfortunately, some sensors did not function properly and, as a result, the data is not reported here. Instead, visual inspection of the slab was made and based on the visual observation, no visible crack was found as of the writing of this report.

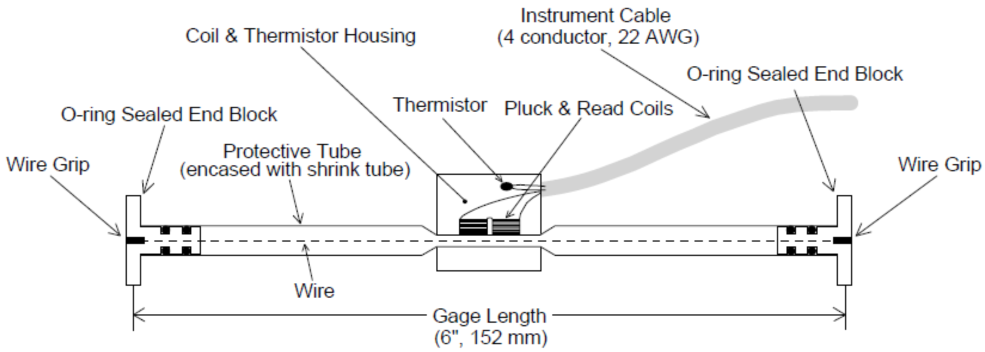


Figure 5.2-Vibrating wire strain gauge

5.3 Summary

Based on the observation of the five slabs, no construction related issue was found. The contractor did not have any construction issue with the FRC slabs since he had many years of experience, particularly in the commercial slab construction that uses FRC. The cost did not seem to be a problem considering that there is only $6.00 to $12.00 per cubic yard increases in material cost. Overall, the construction of the five slabs went well. However, one area that needs further investigation is the test method for evaluating the workability of FRC. Currently, there is no standard, with the exception of ASTM C995 that had been withdrawn and is no longer active, for evaluating the workability of FRC. Although the contractor did not need this information to construct the slab, the workability is needed to provide assurance to FDOT that no change has been made to the approved FRC mixture. Another area that needs further investigation is the use of FRC in real concrete pavement slab replacement project. Unlike real project where the slab is restrained by existing concrete pavement, the demonstration slabs were free to move and did not suffer any cracking.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

Ten mixes were tested to compare their potential use in restraining early age shrinkage cracking. Other strength tests were also conducted to see other parameters that would be affected by adding fibers to a concrete mix. In general, adding fibers to a concrete mixture was found to be beneficial in increasing the age at cracking and reducing the crack width. Comparing the shrinkage results, it was evident that stiff fibers (higher flexural strength) like steel, glass and 1.5-in long polypropylene fibers tend to provide good flexural strength, but are relatively poor in restrained shrinkage cracking. In most cases, these stiff fibers initiated cracking themselves. Hence, steel, glass, basalt and 1.5-in long polypropylene fibers are not recommended for restraining early age cracking as they were found to decrease the age at cracking and increase the crack width. Nylon fibers can be used to restrain early age cracking, however, care must be taken when mixing as fiber balling was encountered. Nylon fibers tend to get wet and once wet form fiber balls and prevent proper consolidation of the concrete especially around corners. Short (0.5-in and 1-in) polypropylene fibers can be used for restraining early age cracking. These fibers were found to be superior to other fibers in restraining early age cracking. Therefore, they are recommended for concrete pavement slab replacement. Some other conclusion include:

1. It can also be concluded that there will not be significant influence on workability and unit weight due to low volume fraction fiber addition to concrete.
2. Adding a fiber to concrete can increase the early age compressive strength by up to 48%. Furthermore the age at cracking can be more than doubled by just adding 0.3% volume of polypropylene fibers and the crack width is reduced to a fourth. Other fiber can also be used for intermediary effects. Steel fibers are found to provide residual strength, however they are also prone to deterioration due to corrosion. The steel fibers used were found to be rusted even under laboratory conditions.
3. When viewed holistically the use of fiber reinforced concrete for pavement slab replacement has an advantage of controlling early age cracking and increasing early age strength. Moreover the choice of fiber should be given due consideration as different types of fibers perform differently. A fiber with high tensile strength, higher pull out strength and lower flexural strength will be the best candidate to control early age shrinkage cracking. The ultimate choice of fiber type and volume fraction would depend on the desired effect or property. As far as controlling early age shrinkage cracking is concerned a mix with a combined effect of higher early age compressive strength, longer age at cracking and smallest crack width would be an ideal candidate.

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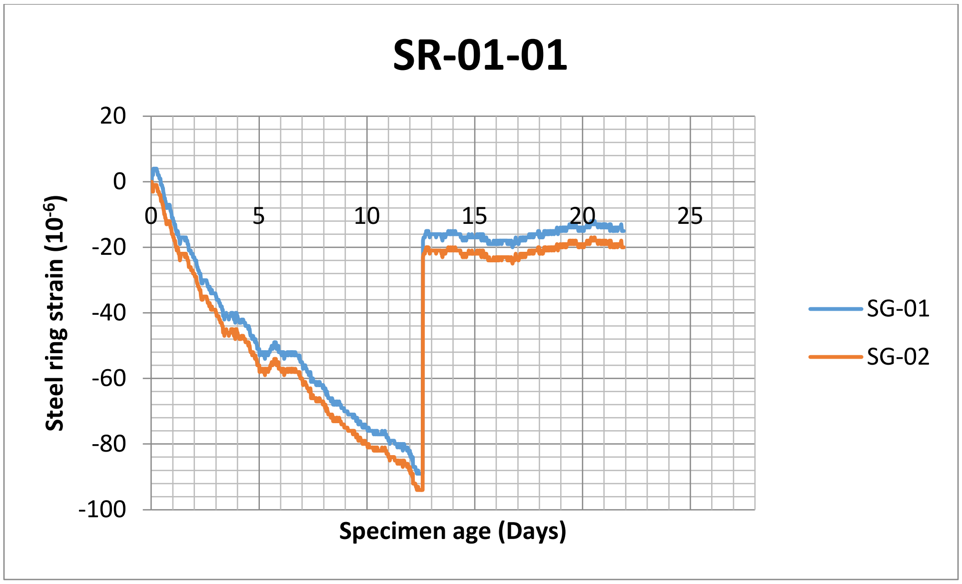
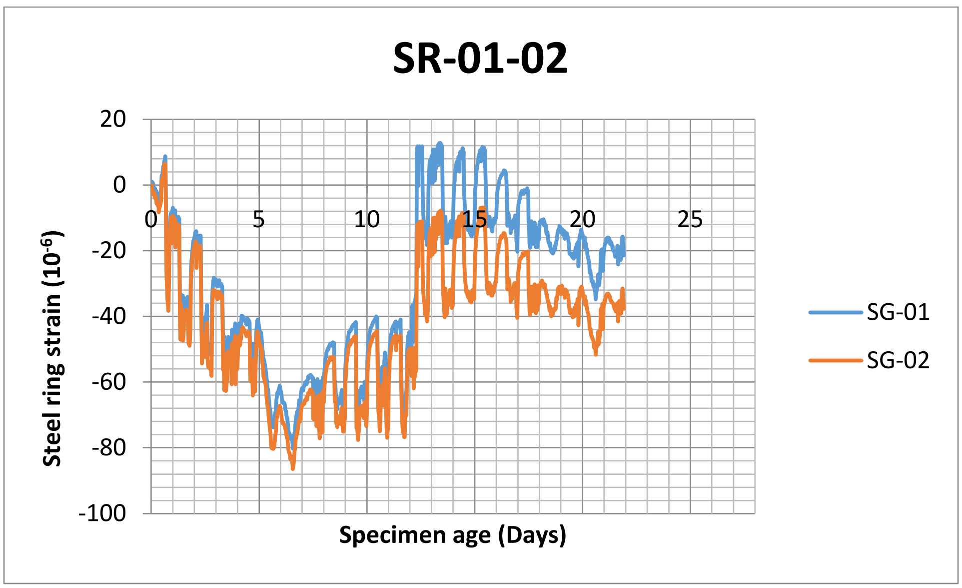
APPENDIX A:
RESTRAINED SHRINKAGE TEST RESULTS

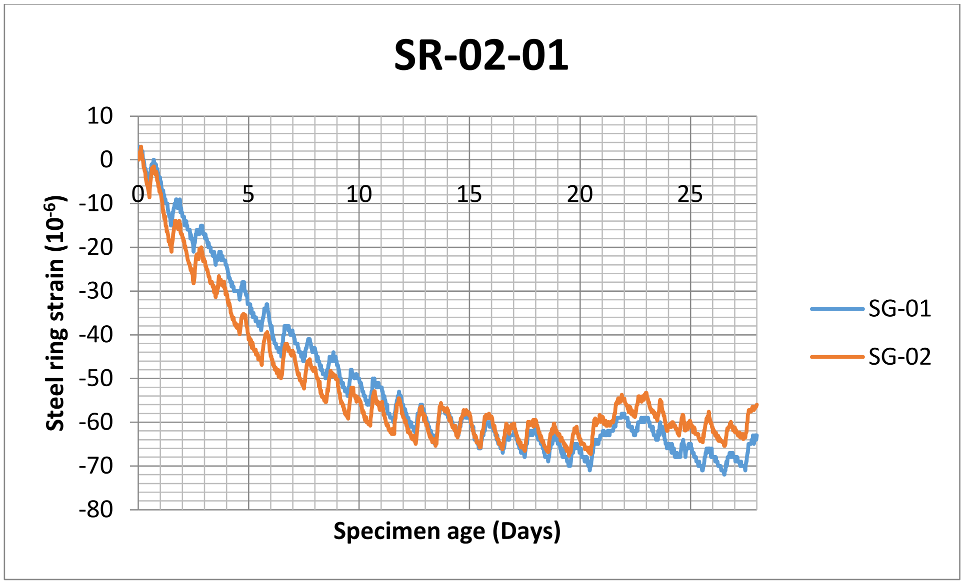


(A) Specimen 1

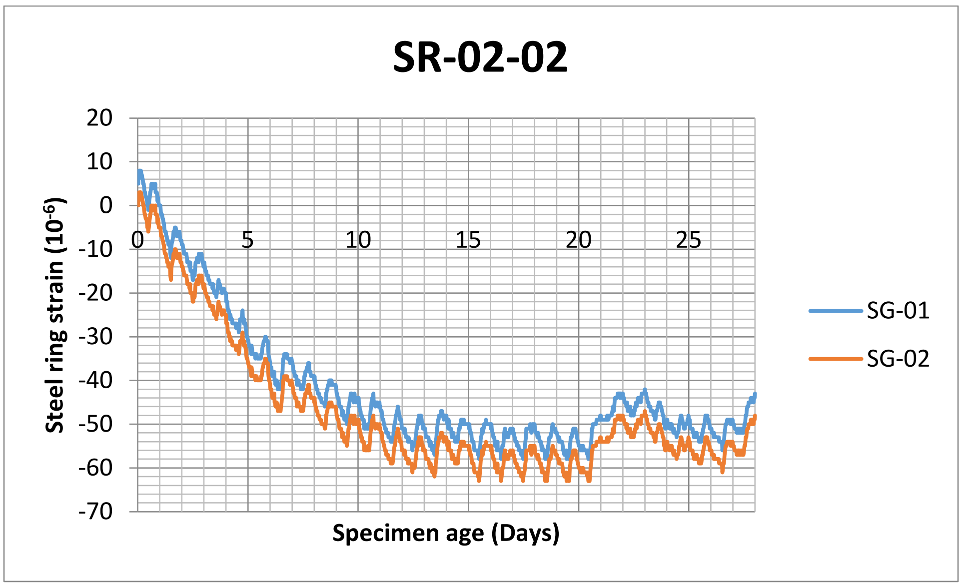


(B) Specimen 2

Figure A1. Mix M01: Plain Control specimen without fiber

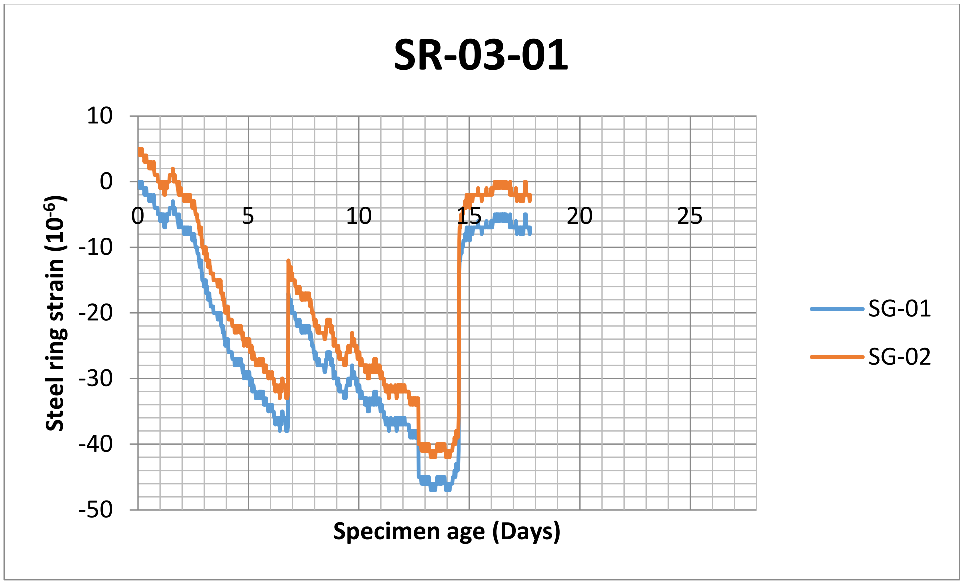


(A) Specimen 1

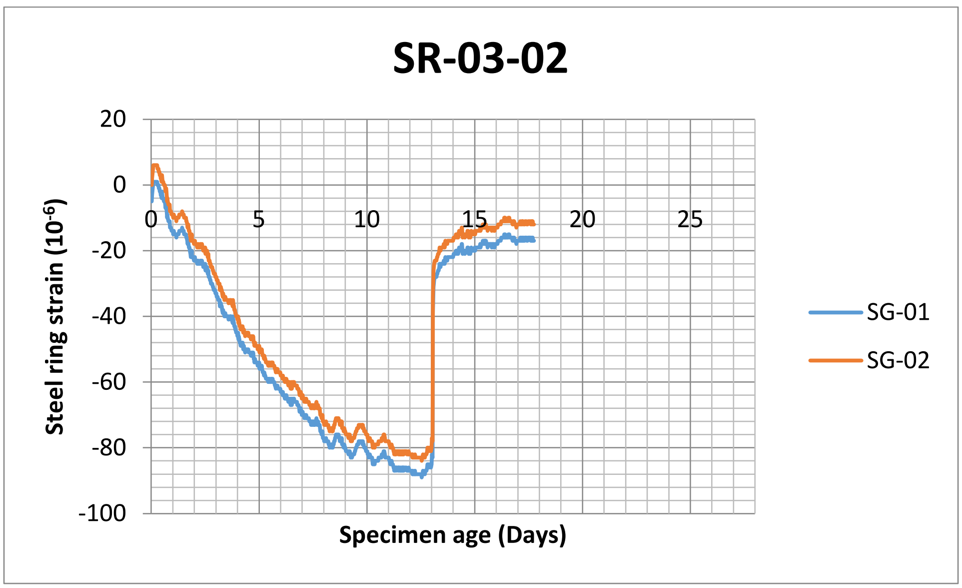


(B) Specimen 2

Figure A2. Mix M02: Concrete with 0.5” Polypropylene fibers

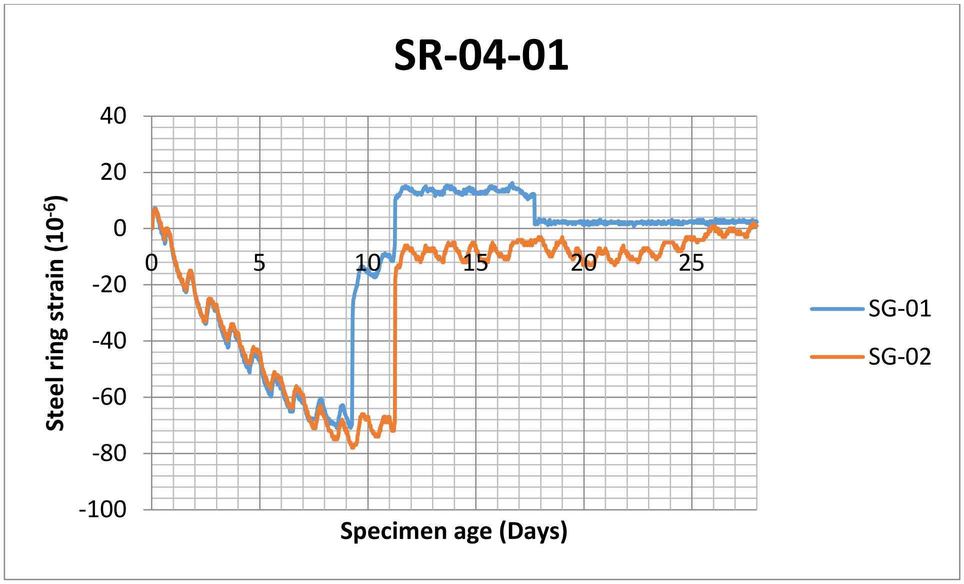


(A) Specimen 1

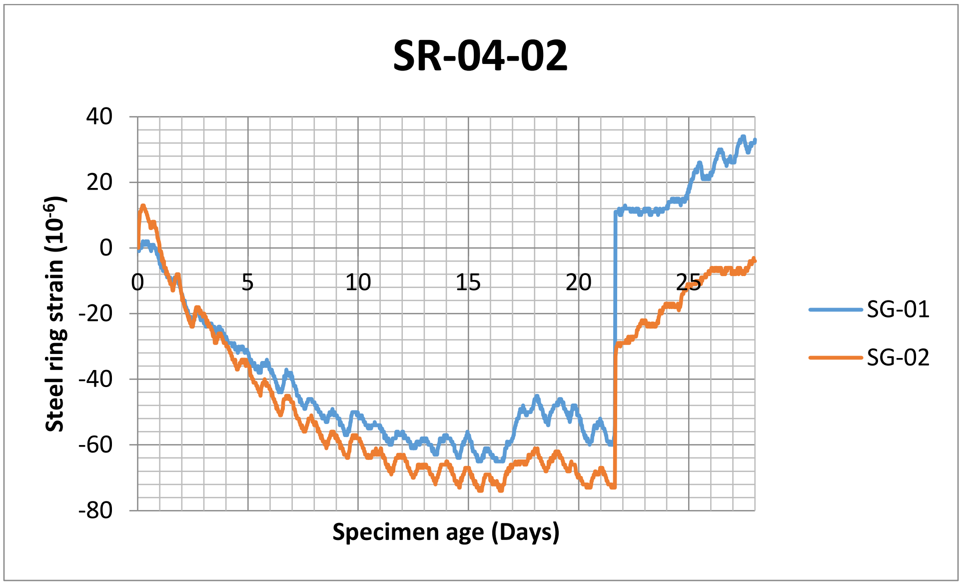


(B) Specimen 2

Figure A3. Mix M03: Concrete with steel fibers

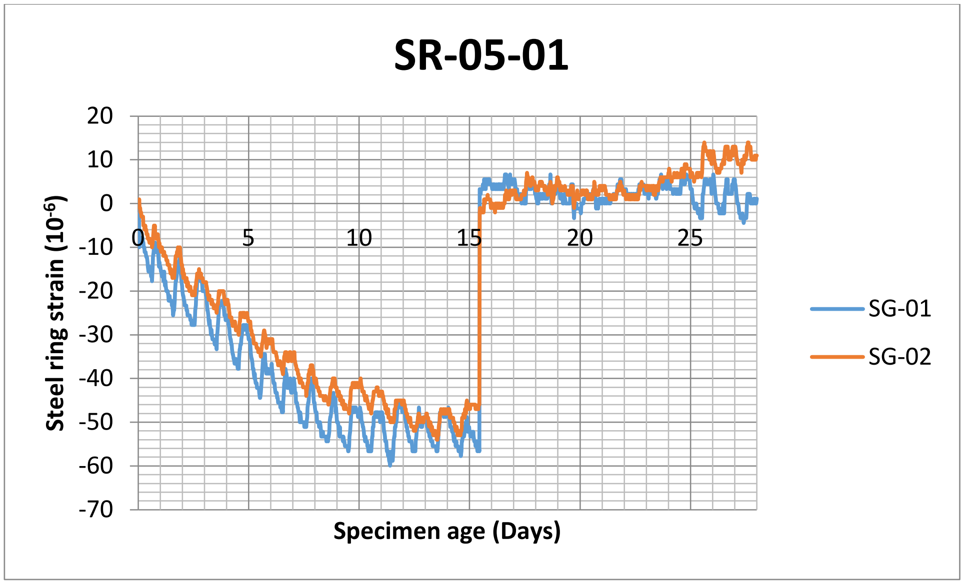


(A) Specimen 1

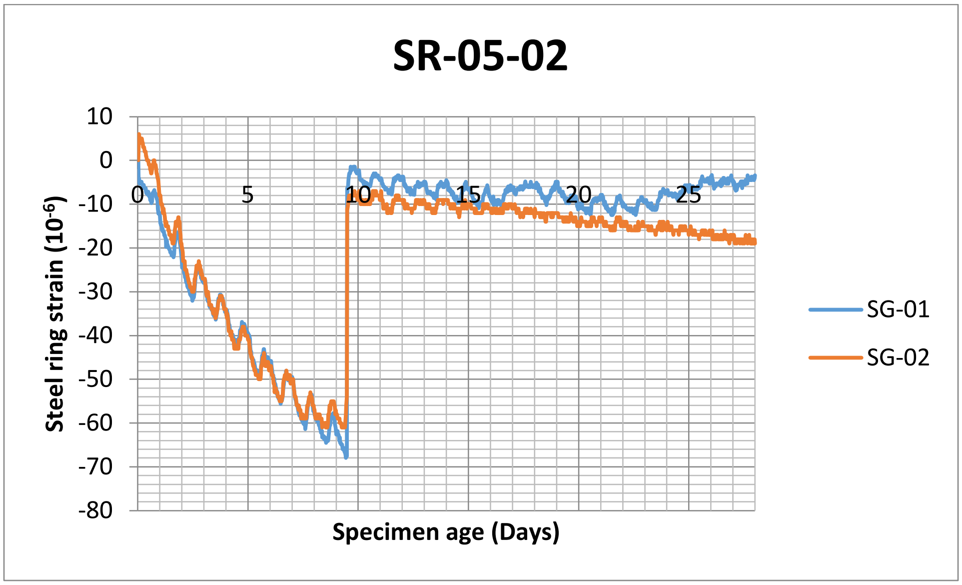


(B) Specimen 2

Figure A4. Mix M04: Concrete with glass fibers

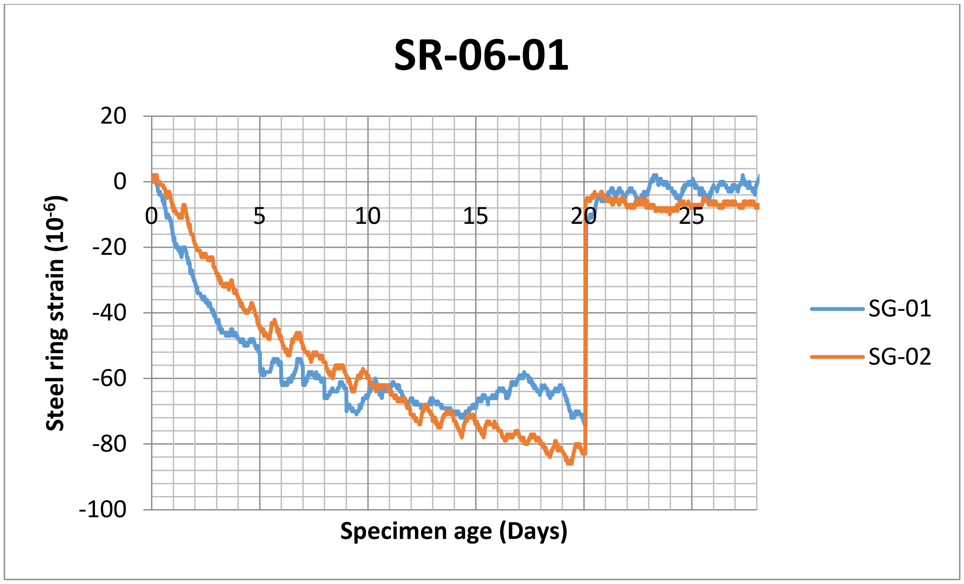


(A) Specimen 1

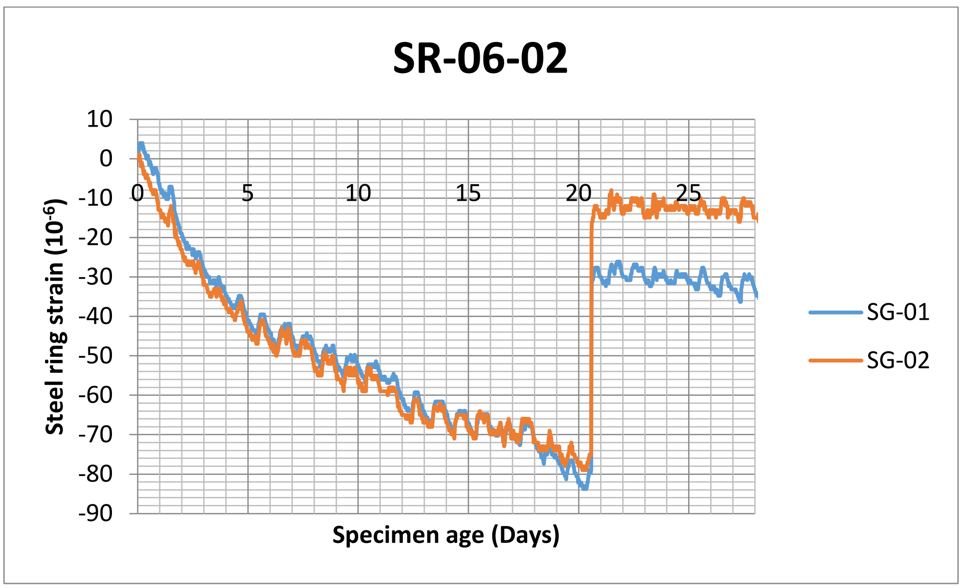


(B) Specimen 2

Figure A5. Mix M05: Concrete with Basalt fibers

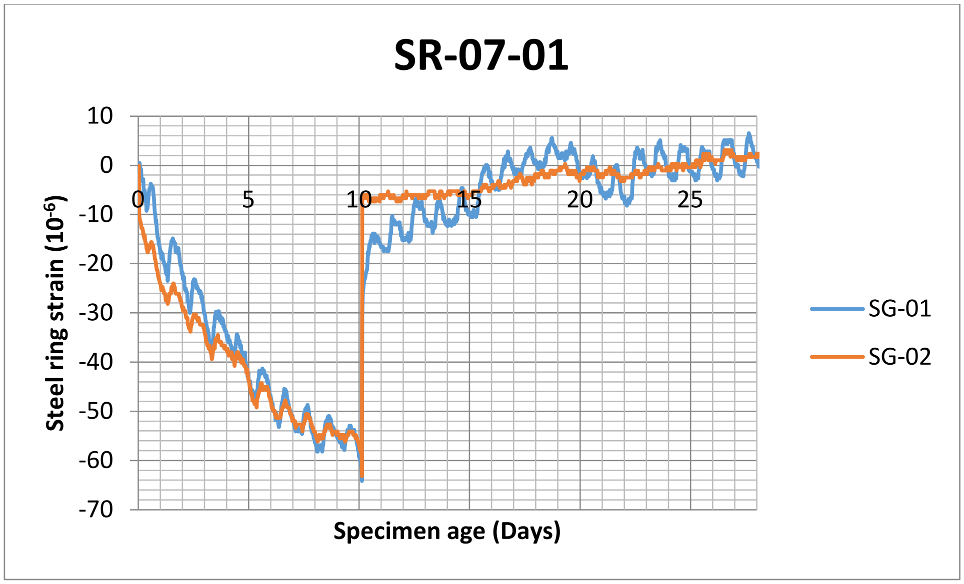


(A) Specimen 1

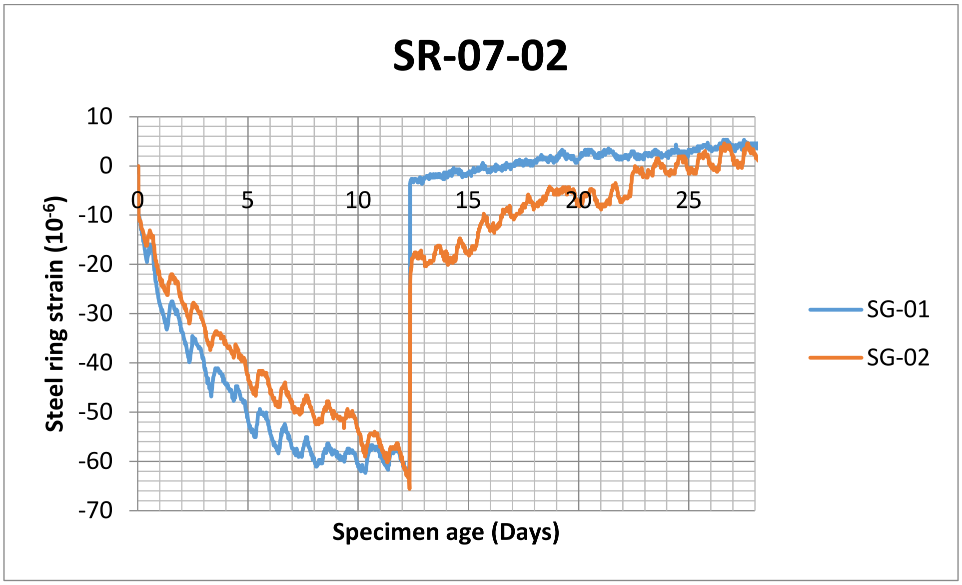


(B) Specimen 2

Figure A6. Mix M06: Concrete with Nylon fibers

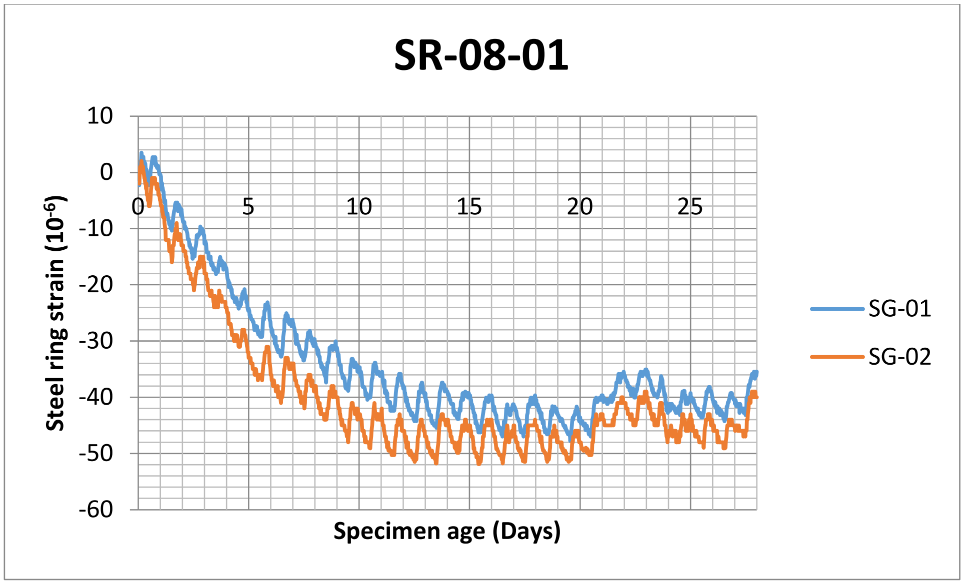


(A) Specimen 1

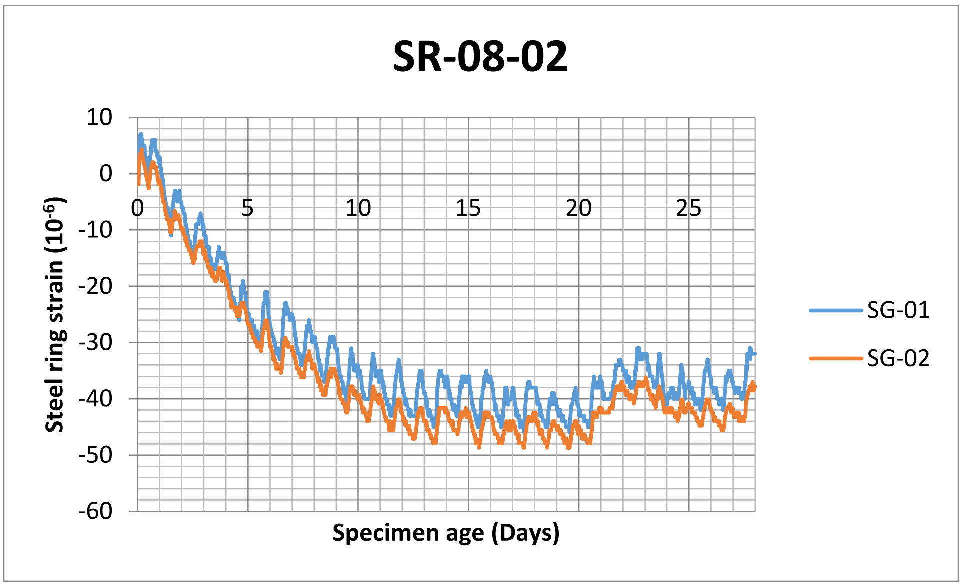


(B) Specimen 2

Figure A7. Mix M07: Concrete with 1.5” Polypropylene fibers

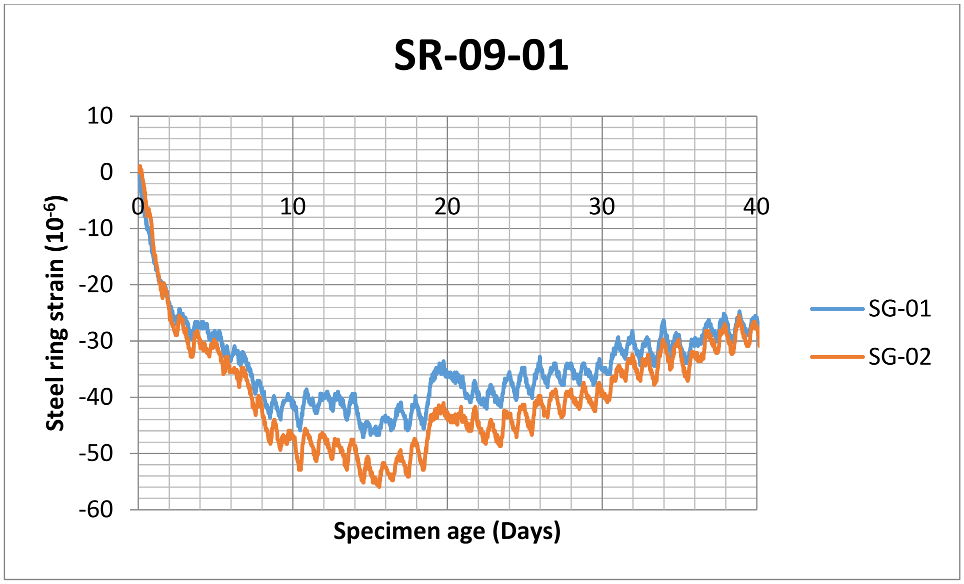


(A) Specimen 1

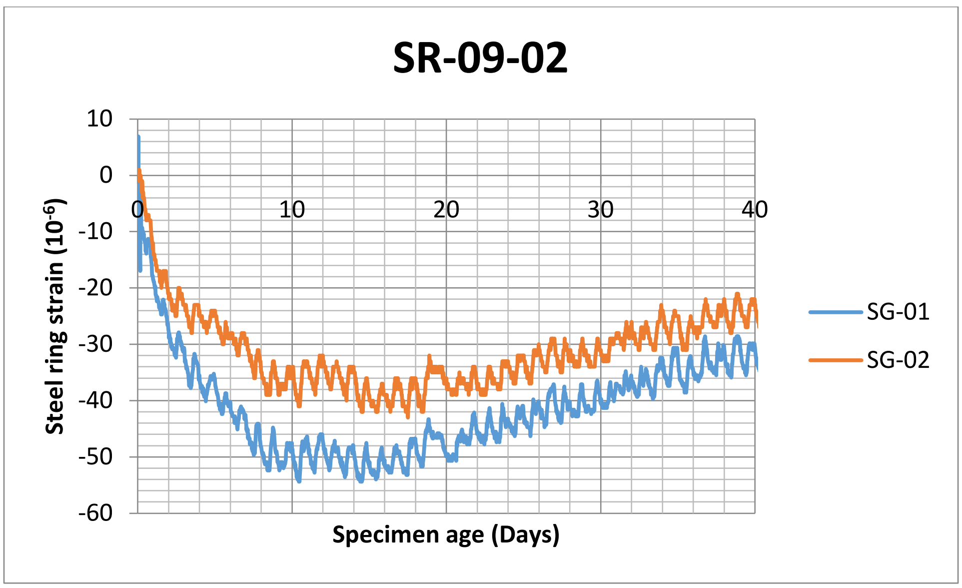


(B) Specimen 2

Figure A8. Mix M08: Concrete with 0.75” Polypropylene fibers

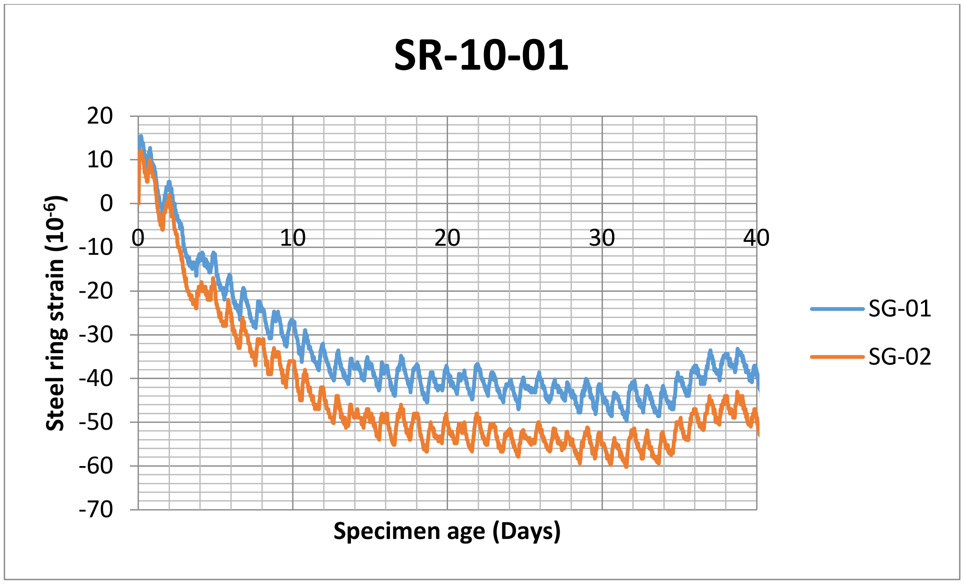


(A) Specimen 1

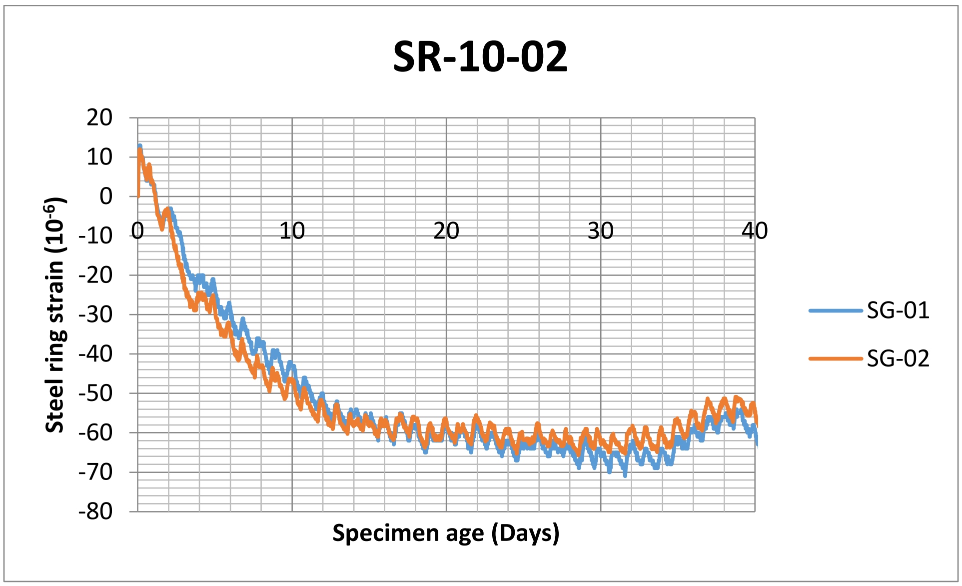


(B) Specimen 2

Figure A9. Mix M09: Concrete with Nylon fibers at 0.3% dosage



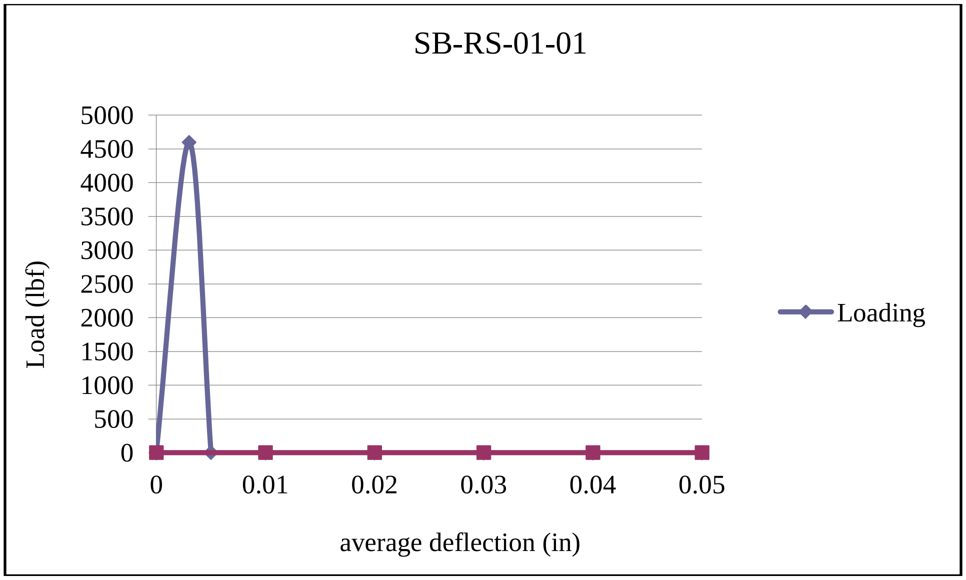
(a) Specimen 1



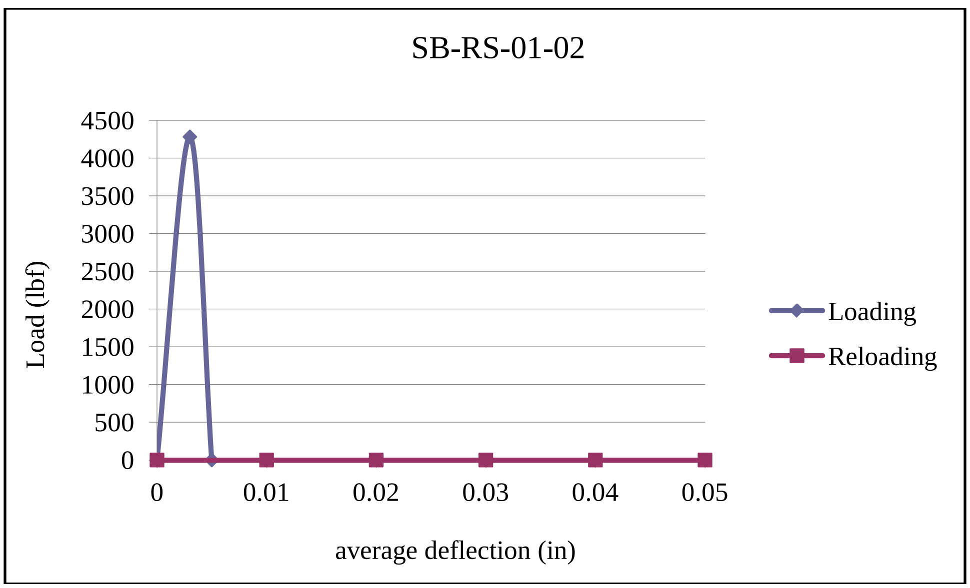
(b) Specimen 2

Figure A10. Mix M10: Concrete with 0.75" Polypropylene fibers at 0.3% dosage

APPENDIX B:
RESIDUAL STRENGTH TEST RESULTS

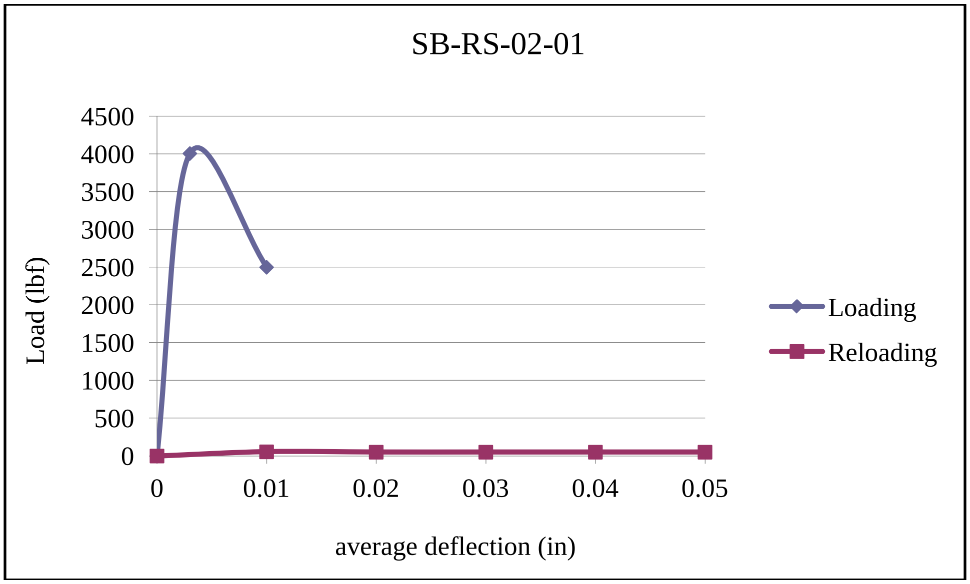


(a) Specimen 1

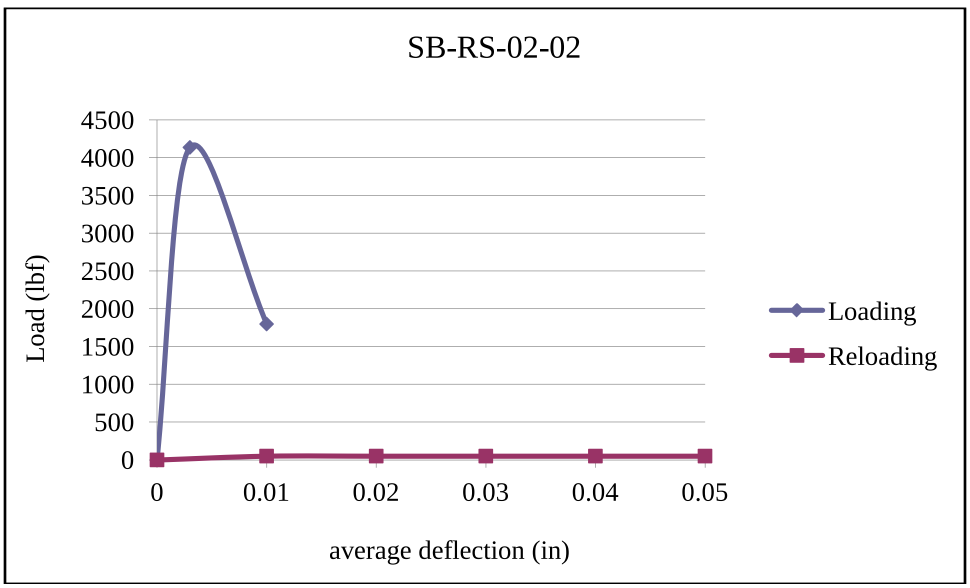


(b) Specimen 2

Figure B1. Mix M01: Concrete with 0.75" Polypropylene fibers at 0.3% dosage

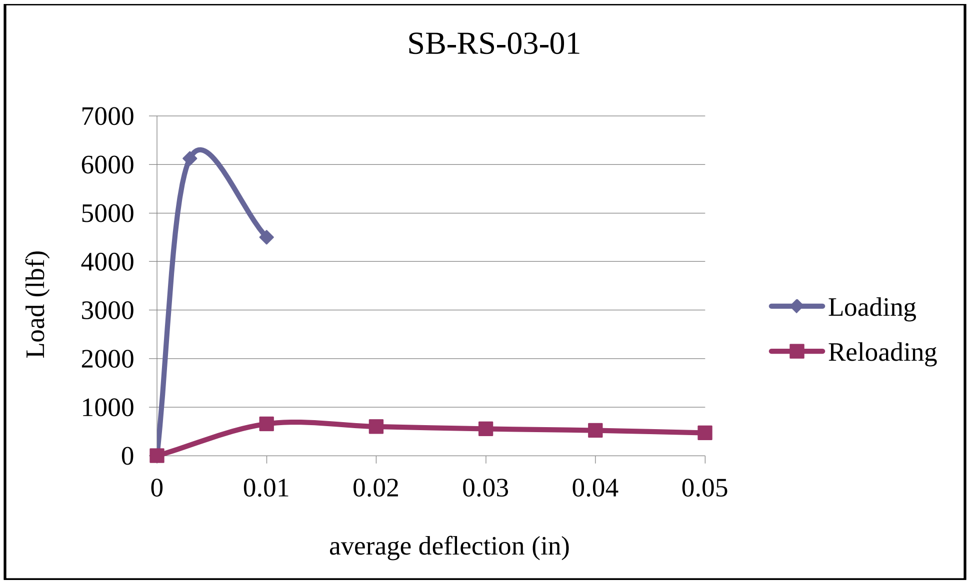


(a) Specimen 1

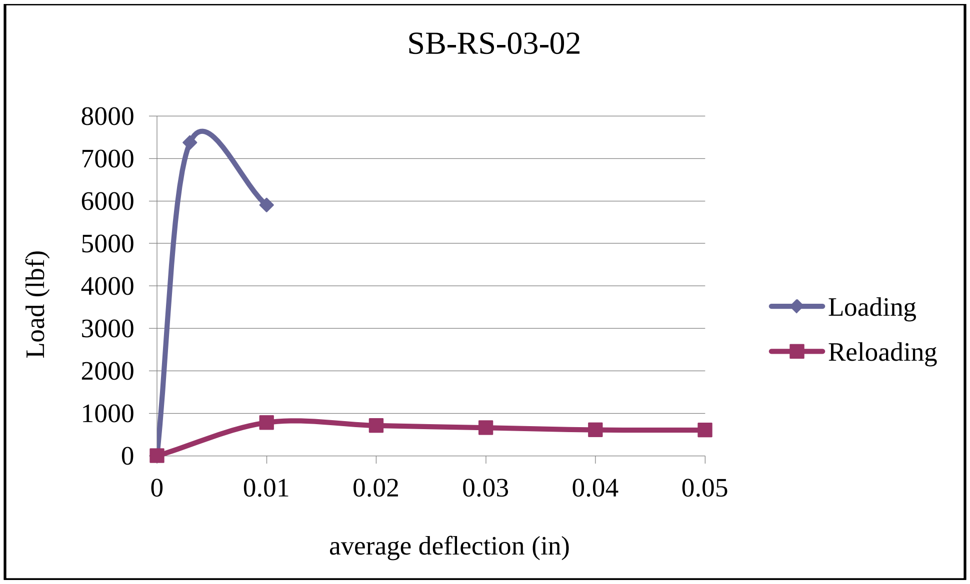


(b) Specimen 2

Figure B2. Mix M02: Concrete with 0.5” Polypropylene fibers at 0.1% dosage

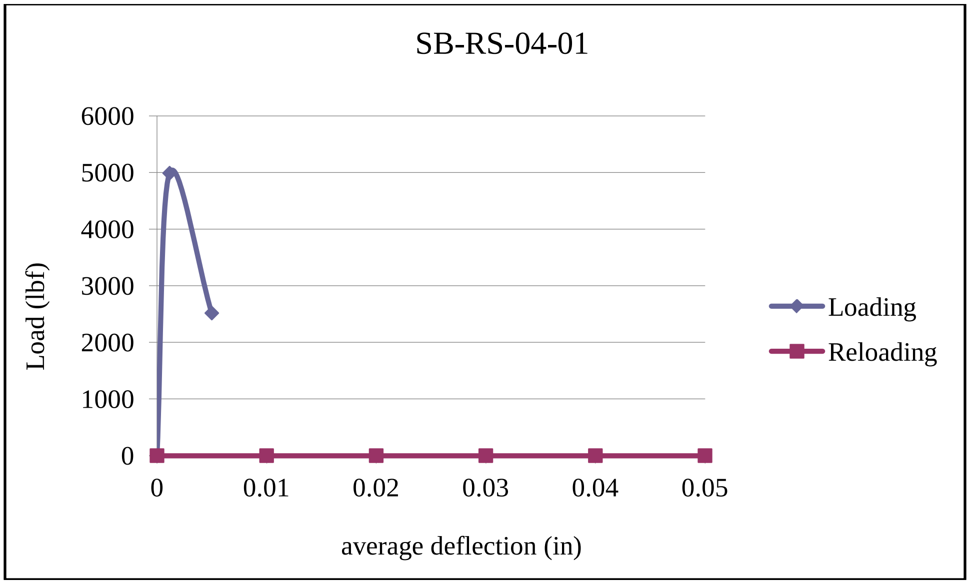


(a) Specimen 1

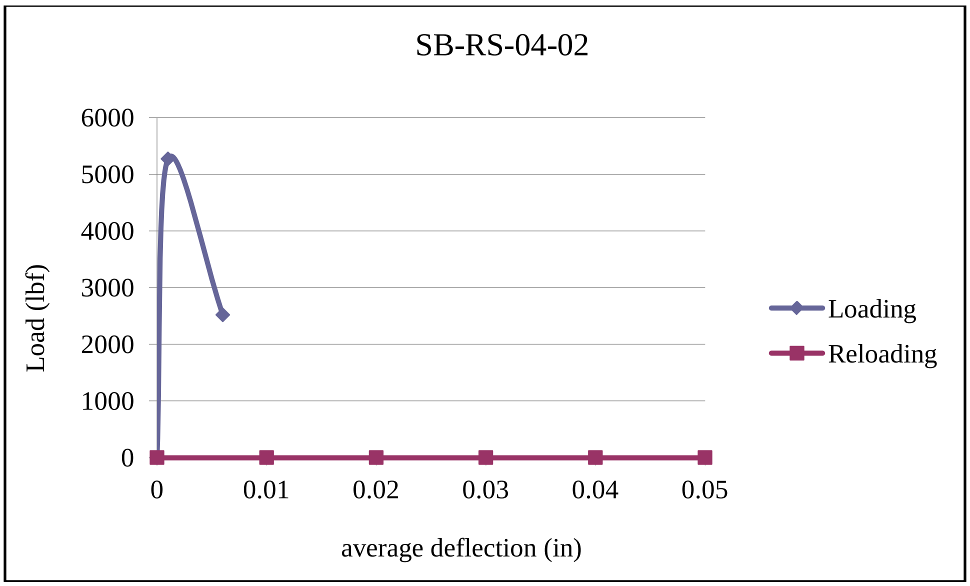


(b) Specimen 2

Figure B3. Mix M03: Concrete with 0.5” steel fibers at 0.1% dosage

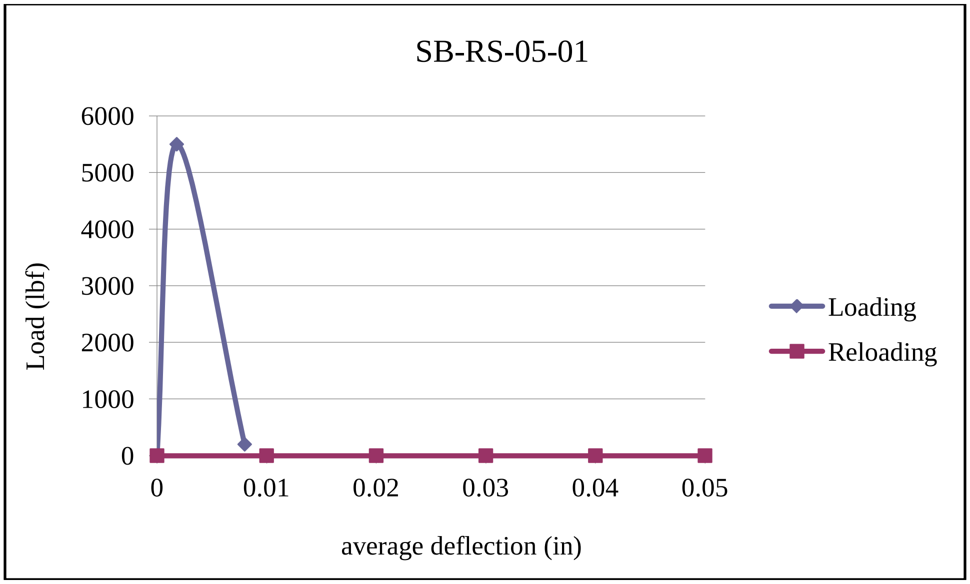


(a) Specimen 1

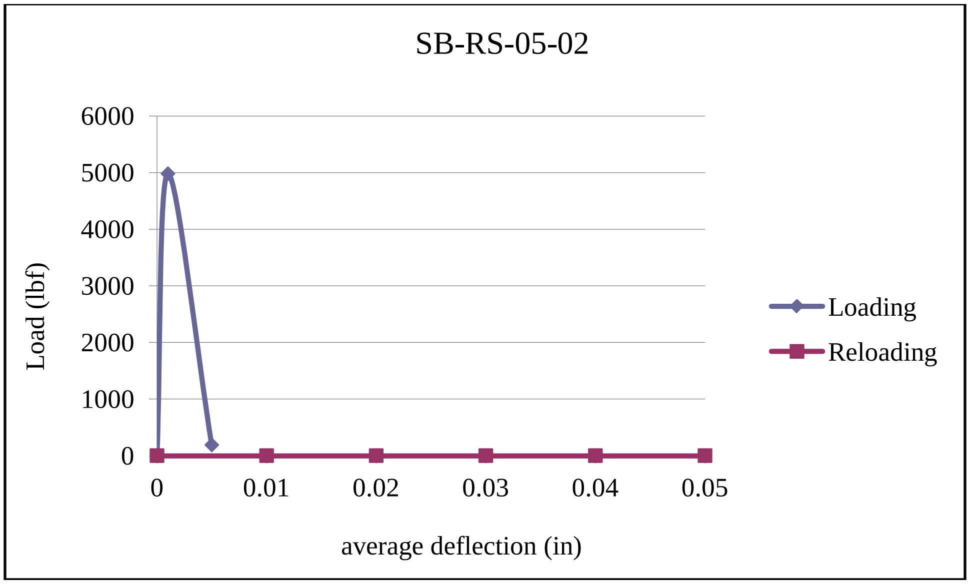


(b) Specimen 2

Figure B4. Mix M04: Concrete with 0.5” Glass fibers at 0.1% dosage

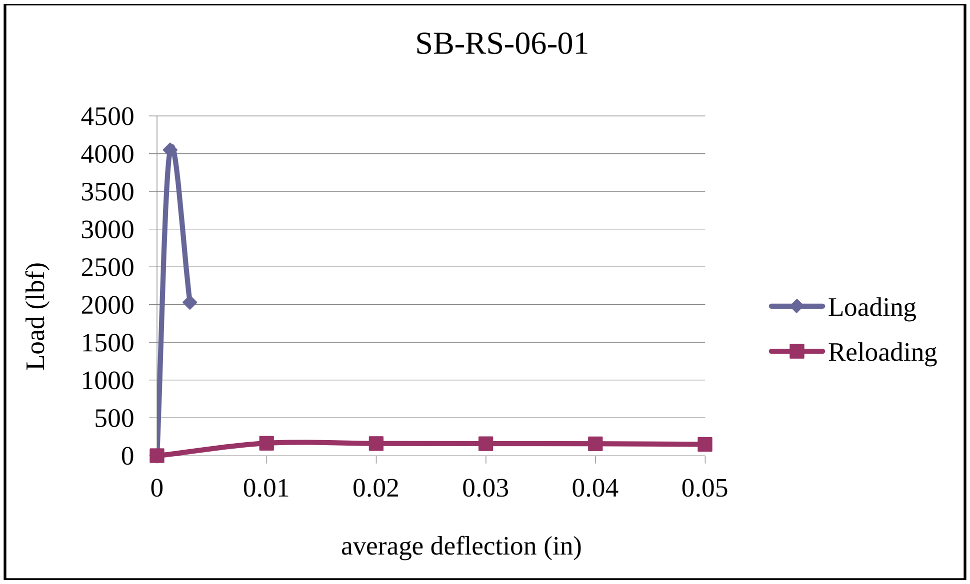


(a) Specimen 1

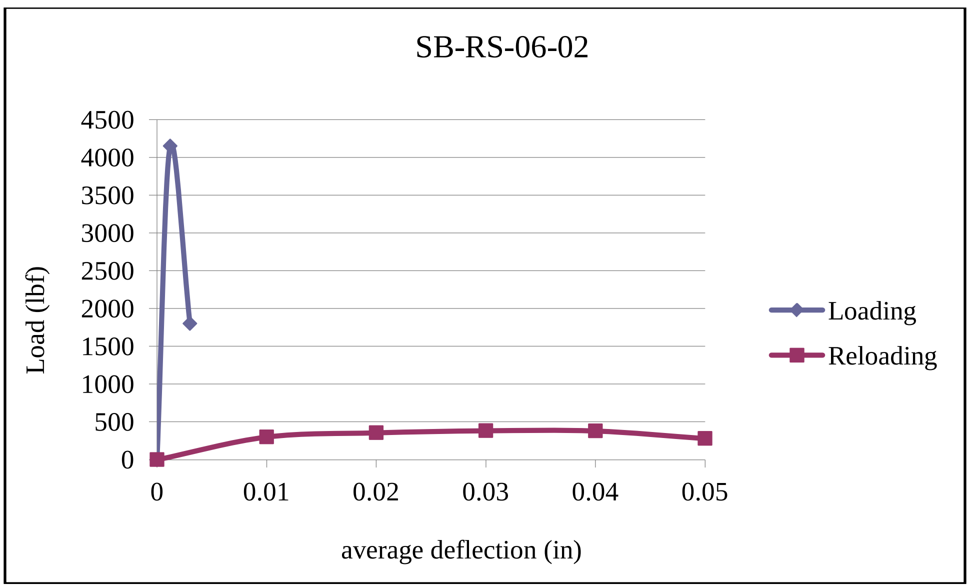


(b) Specimen 2

Figure B5. Mix M05: Concrete with 0.5” Basalt fibers at 0.1% dosage

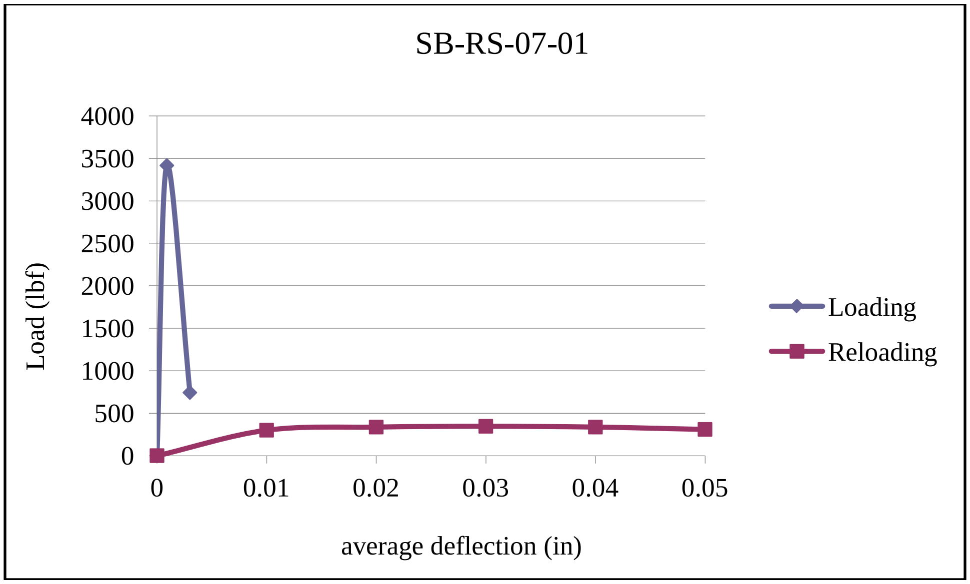


(a) Specimen 1

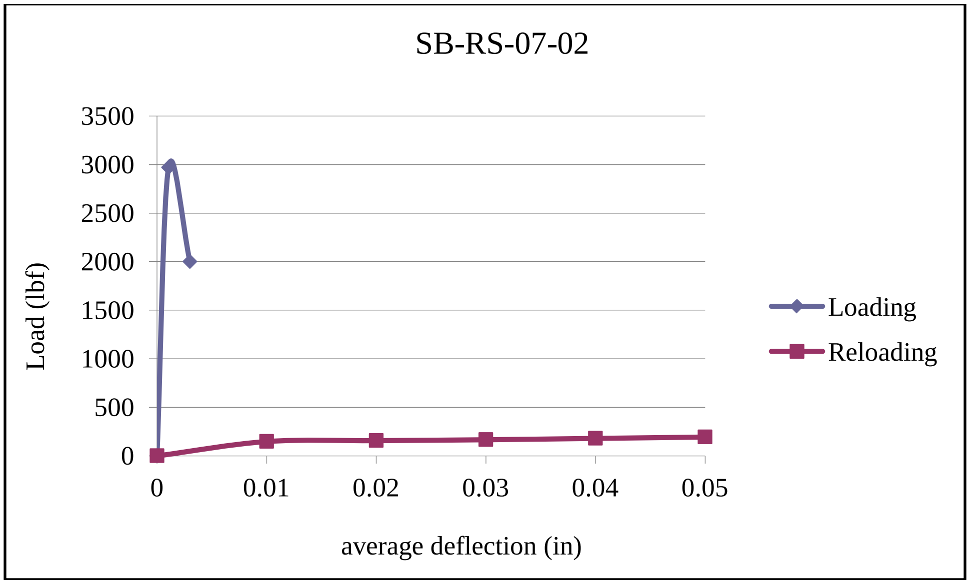


(b) Specimen 2

Figure B6. Mix M06: Concrete with 0.5” Nylon fibers at 0.1% dosage

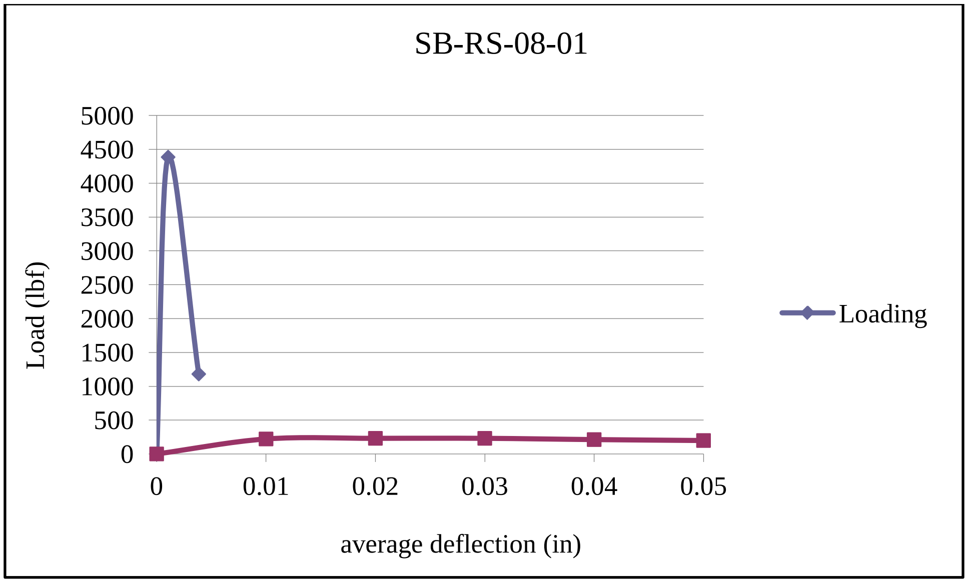


(a) Specimen 1

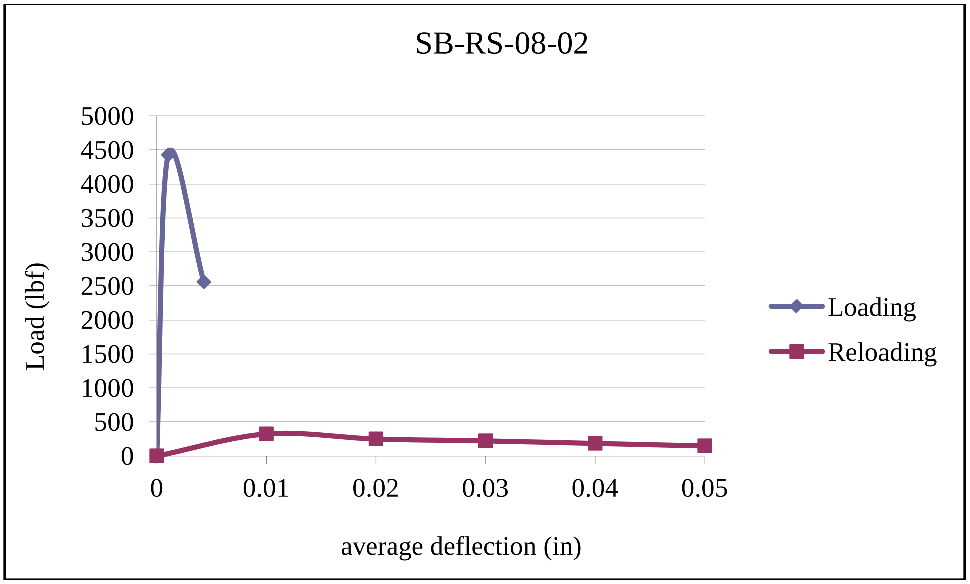


(b) Specimen 2

Figure B7. Mix M07: Concrete with 1.5” Polypropylene fibers at 0.1% dosage

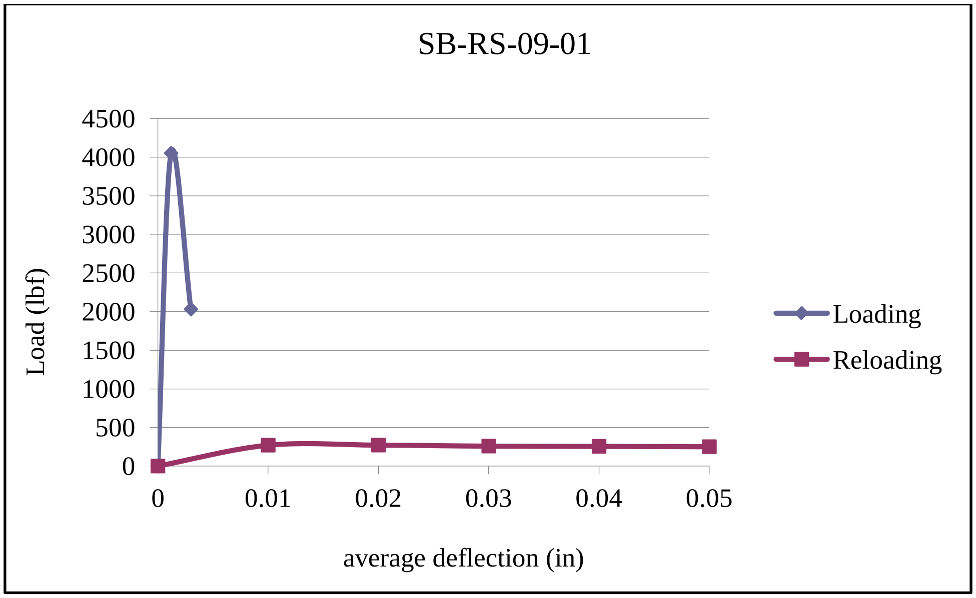


(a) Specimen 1

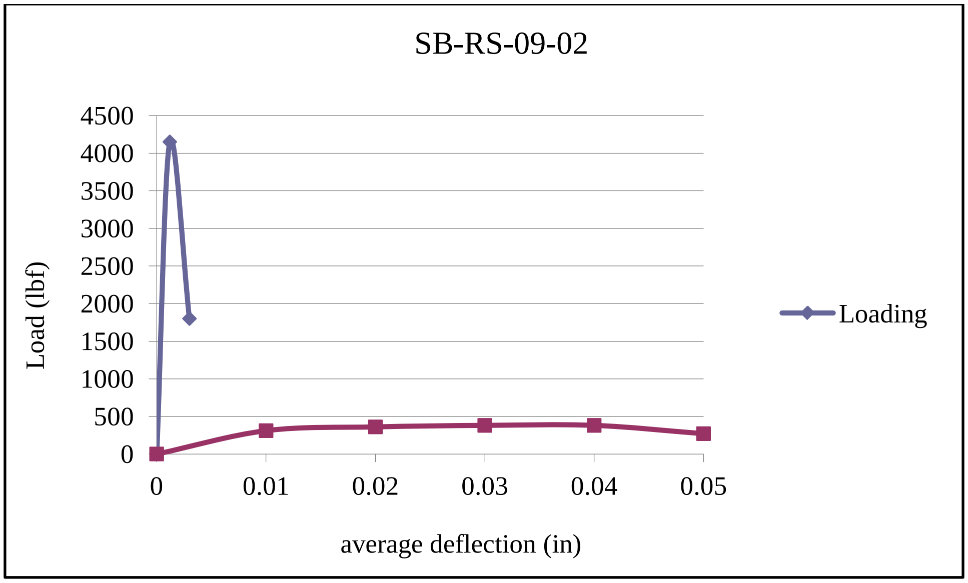


(b) Specimen 2

Figure B8. Mix M08: Concrete with 0.75" Polypropylene fibers at 0.1% dosage

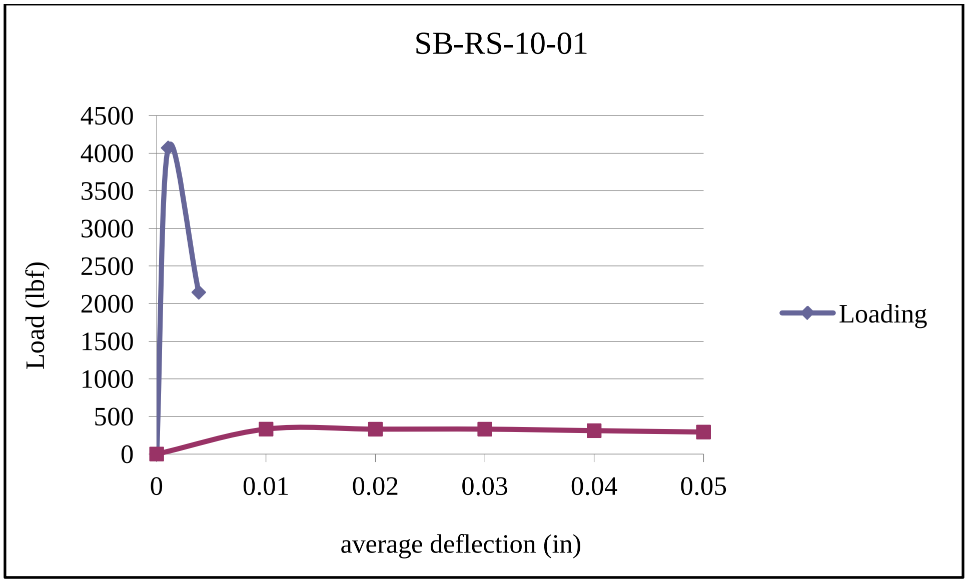


(a) Specimen 1

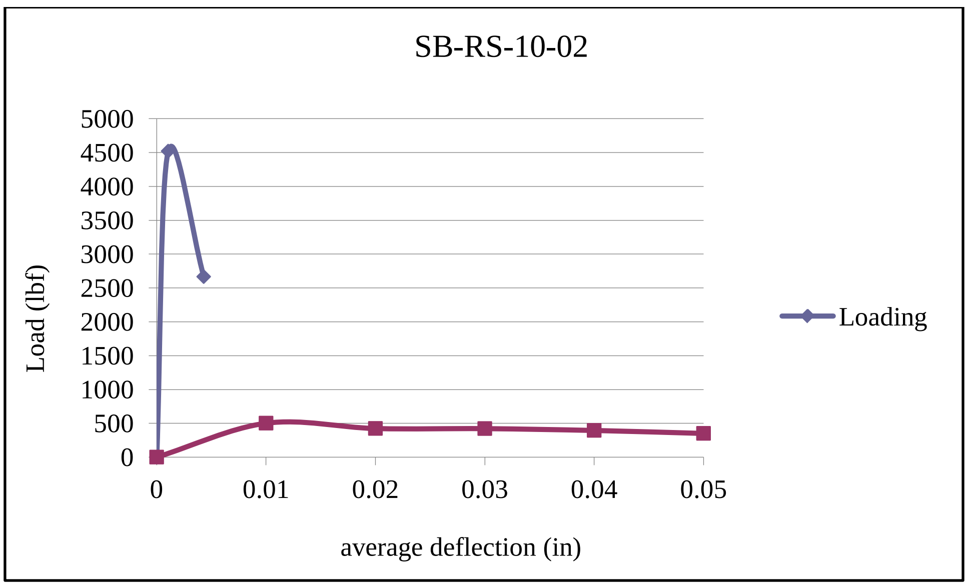


(b) Specimen 2

Figure B9. Mix M09: Concrete with 0.5" Nylon fibers at 0.3% dosage



(a) Specimen 1



(b) Specimen 2

Figure B10. Mix M10: Concrete with 0.75” Polypropylene fibers at 0.3% dosage

APPENDIX C:
FLEXURAL TOUGHNESS TEST RESULTS

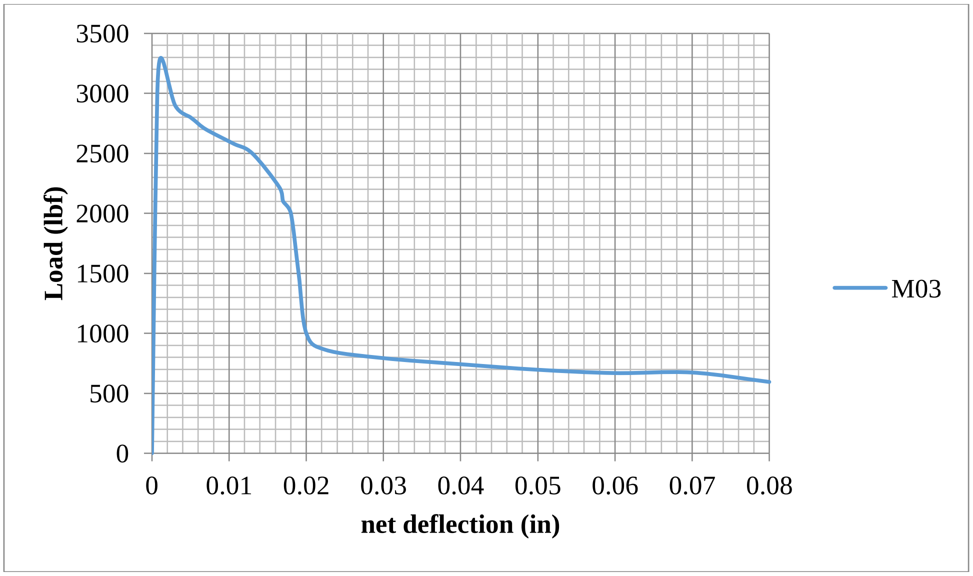


Figure C1. Load deflection curve for M03

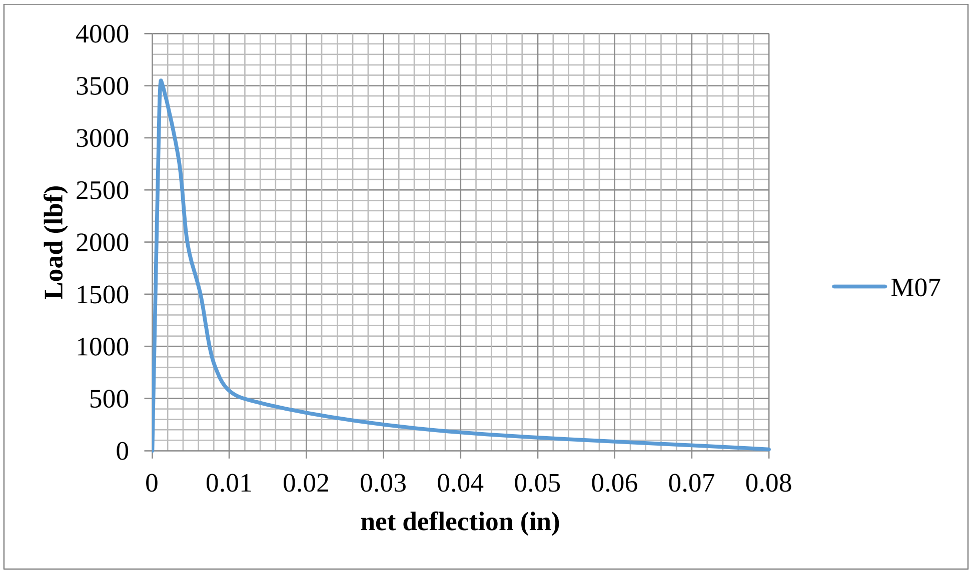


Figure C2. Load deflection curve for M07