USE OF FIBERS TO IMPROVE THE PERFORMANCE OF CONCRETE

By

MICHAEL DICKEY

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Thesis Approved:

Tyler Ley

Thesis Adviser

Norb Delatte

Robert Emerson

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Name: MICHAEL DICKEY

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Abstract: This work creates a simple test method to determine the effectiveness of macro synthetic fibers and steel fibers inside concrete by analyzing data from laboratory mixtures with a series of different fiber types and dosages. Comparisons are made between the different fibers for different concrete properties. The goal of this research was to develop a simple test method, called the Split Beam Test, to test the effectiveness of different fibers in comparison to one another. The performance of the fibers is based on how well the fibers can control the crack width before ultimate failure. The research also looks into the effect that each of these fibers has on the ability to finish the surface of the concrete, the slump, and the compressive strength. The Split Beam Test showed to produce consistent results within mixtures and provides a simple way to compare fiber types and dosages to one another. Promising results were also shown by The Split Beam test to show that the use of fibers in concrete can be used to decrease the crack width of a beam.

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CHAPTER I

INTRODUCTION TO FIBER REINFORCED CONCRETE

1.0 INTRODUCTION

Throughout the world, concrete is a widely used material, from large structural elements and bridge decks to driveways and sidewalks. This composite material is easy to make and can be molded into nearly any shape desired. Concrete is made by mixing rock, sand, cement, and water. Today, the science behind concrete mixtures is more complex due to increased emphasis on long-term durability and performance, which has led to the widespread use of various admixtures. However, the overall concept of designing, producing, and constructing long-lasting concrete infrastructure remains.

Cracks are one of the major causes of many of the durability issues inside of concrete. When concrete cracks, it can allow harmful chemicals to easily penetrate the concrete. This chemical penetration can cause durability mechanisms such as corrosion of steel reinforcement, freeze-thaw damage, alkali-silica reaction, and others. These durability mechanisms can cause damage that can harm structures and put them out of service. Understanding how to keep these cracks small can help to slow these durability mechanisms and keep structures lasting longer and having better performance.

Cracks also cause serviceability issues in practice. Warehouse equipment often uses hard wheels to carry high loads. These wheels will catch small cracks and cause them to grow over time. As these cracks open, this makes it harder for the equipment to travel over the cracks and it causes them to decrease the loads that they carry [1]. Owners are also unhappy with the aesthetics of surface cracks. For all of these reasons, it is advantageous to keep cracks small.

One way to help keep cracks small is with the use of fibers. Fibers are made out of many different things, dating back to when early Egyptian builders used straw “fibers” in an attempt to provide durability to their structures [2]. Today, both synthetic and steel fibers are growing in popularity for their ability to minimize cracking, improve performance, and add long-term durability to structures [3,4].

Using fiber reinforcement to minimize the crack size inside of concrete could help slow several different durability issues. However, these fibers will have a potential effect on the strength, workability, and finishability of the concrete. While the goal is to keep the cracks small, other properties such as the impact on the workability of the concrete should not be ignored. Yet, an effective tool to measure the performance of fibers to keep these cracks small and evaluate the workability of the concrete has not been developed.

This work presents a simple method, called the Split Beam Test, to quantify how different types and dosages of synthetic and steel fibers can decrease the crack size of reinforced concrete structures. The work also quantifies how the fibers impact the finishability and workability of the concrete mixtures while also looking at the compressive strength for each fiber type. Testing is presented from 11 different types of fibers at 3 different dosages.

CHAPTER II

QUANTIFYING THE CRACK REDUCTION AND FINISHABILITY OF FIBER REINFORCED CONCRETE

2.1 INTRODUCTION

10 million cubic yards of concrete are produced worldwide placed each year [5]. Yet, a significant issue of concrete remains to be cracking. Cracks can allow water and other chemicals to penetrate the concrete and cause durability issues. The larger the crack is, the easier the chemicals can penetrate [6]. Past research has been done to show the effect of different reinforcement ratios and placement on crack propagation using different modeling techniques [7,8,9]. In one study, three different size beams were made with depths (D) of 3, 6, and 12 inches and a length of 4.5D. Steel was used at 5 different ratios with different orientations, either placed as longitudinal steel in the bottom of the beam or inclined steel placed at a 45-degree angle directly above where the crack was intentionally started. The crack was initiated using a saw blade at D from the support with a depth of .33D. The goal was to determine how the reinforcement ratio and placement affected how the crack formed. It was found that with certain reinforcement ratios and placement, the crack could be more dispersed throughout the beam, therefore increasing the toughness of the beam. When reinforcement was placed in a way in which it was perpendicular to the crack size, the cracks would spread out over the entire beam rather than just fail in one spot. Even when lower reinforcement ratios were used, there was an

improvement in performance if the rebar were placed in strategic places. This was found to be true for all sizes of beams tested [7].

Additionally, research has also been done to show that when using fiber reinforcing, the crack growth can be slowed, which then slows these durability issues and provides longer-lasting structures [6,10]. Previous research has been done on crack opening load and the crack opening displacement to find whether fibers help to keep cracks smaller. For this method, fibers were specifically placed during the casting process perpendicular to the direction of the crack growth. The beam was then loaded and the crack opening load and width to determine how these fibers affected the cracking load and width [10].

Previous research on fibers includes the withdrawn standard, ASTM C1018 [11]. This test evaluated the post-fracture flexural toughness of fiber reinforced concrete. The test provided insight on finding the first-crack strength and basing the toughness of the concrete on that number. The test would find the 3 different "toughness indices" based on areas under the moment-deflection graph. The toughness indices found would then be correlated into a "residual strength factor" that was used to determine the effectiveness of a given fiber [11].

The ASTM standard C1609 [12] aims to provide a test method that provides insight into fiber performance by using a third-point loading system to find the flexural toughness and the post crack residual strength, similarly to the withdrawn standard ASTM C1018. ASTM C1609 uses either a 4x4x14 inch or a 6x6x20 inch beam and uses different points on the load vs. deflection graph to find residual strengths and toughness [12]. While both ASTM C1018 and ASTM C1609 are valuable, they only provide insight into the residual strength provided at very large crack sizes. This does not provide any information about how the fibers perform when the cracks are small.

Aim of research

A simple test was needed to determine the effectiveness of both synthetic fibers or steel fibers inside of concrete. The goal of this test is to be able to quantify the impacts of fiber reinforcing in combination with steel rebar inside of the concrete. The Split Beam Test uses a simple hydraulic press to load the beam in tension and measure the crack size as the load is increased. The main difference between the Split Beam Test and the previous methods is that the Split Beam Test focuses on early loading on the beams while methods such as ASTM C1609 focuses on later loading and residual strength. Also, the Split Beam Test contains both rebar and fibers while the ASTM C1609 test only tests fibers. The Split Beam Test allows the performance of different fiber dosages and fiber types to be quantified to compare them to one another. A finishability test known as the Float Test was used to determine how the use of fibers affects the finishability of the concrete. This work shows the results of a concrete mixture with 3 different dosages of fibers and 11 different fiber types.

2.2 EXPERIMENTAL METHOD

2.2.1 Materials

All of the concrete mixtures that were investigated were prepared using a Type I Portland cement that met the requirements of ASTM C150 [13]. Both the oxide analysis and the Bogue calculations for the cement used are shown in Table 2-1. The aggregates were locally available crushed limestone and natural sand. The nominal maximum coarse aggregate size of the crushed limestone was 1”. Both aggregates met ASTM C33 [14] specifications. The mixture designs that were used are shown in Table 2-2. The dosages of the fibers are also shown in Table 2-2, the volumes were chosen based on the dosage rate for typical fiber reinforced concrete. An asterisk (*) denotes that steel fibers were used rather than macro synthetic fibers. The fiber volumes of 0.25%, 0.33%, and 0.50% of the mixture volume were investigated for steel fibers and 0.25%, 0.50%, and 0.75% of the mixture volume for synthetic fibers. Comparisons between fibers were only made at equal volumes unless noted otherwise. Since the macro synthetic and steel fibers have different densities, their mass is different. Macro synthetic fibers at 4 lbs./cy corresponded to a steel fiber dosage of 33 lbs./cy. Reports will be shown using lbs./cy because that is most typically used in the industry. Typically, the yield of the mixture would be adjusted for different dosages of fibers. However, since the fiber volume is so low, no adjustments were made.

Table 2-1. Oxide Analysis for Type I Portland cement and Class C fly ash

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	P_2O_5	C_3S	C_2S	C3A	C_4AF
Cement (%)	21.1	4.7	2.6	62.1	2.4	3.2	0.2	0.3	-	48	24	8.1	7.9
Fly Ash (%)	25.32	19	5.2	33	7.8	2.6	3.4	0.6	1.9	-	-	-	-

Table 2-2. Concrete Mixture Designs per 1 cyd

Dosage Rate of Fiber	W/cm	Cement (lbs.)	Fly ash (lbs.)	Coarse (lbs.)	Fine (lbs.)	Water (lbs.)	Fibers (lbs.)
0 lbs.	0.45	488	122	1835	1195	275	0
4 lbs.	0.45	488	122	1835	1195	275	4
8 lbs.	0.45	488	122	1835	1195	275	8
12 lbs.	0.45	488	122	1835	1195	275	12
***33 lbs.**	0.45	488	122	1835	1195	275	33
***44 lbs.**	0.45	488	122	1835	1195	275	44
***66 lbs.**	0.45	488	122	1835	1195	275	66

* Note: that steel fibers were used rather than macro synthetic fibers.

Table 2-3 shows the properties for each fiber tested. Names denoted with an "M" refer to the use of macro synthetic fibers. Names denoted with an "S" refer to the use of steel fibers. The number after the letter denotes which fiber was used. The "E" refers to a fiber that is embossed. If there is more than one type of embossing, it will be denoted as E1 and E2. For example, M3 means that macro synthetic fiber number 3 was used. S1 means that steel fiber number 1 was used. M6-E means that it is an embossed version of M6. The C following M4 indicates that it was cut to be 1-inch in length. S2 is the same fiber with 2 different lengths. S2-1 is 1-inch long and S2-1.5 is 1.5-inches long. Images of these fibers can be found in Figure 2-1 below.

Table 2-3. Fiber Properties

Fiber Name	Material	Embossed	Tensile Strength (ksi)	Length (in)	Specific Gravity	Aspect Ratio	Modulus (ksi)
M1	Copolymer/ Polypropylene	Yes	85-90	2	0.91	85	800
M2	Polyolefin	No	85-90	2	0.91	100	1,600
M3	Polypropylene/ Polyethylene	No	85-90	2	0.92	79	-
M3-E1	Polypropylene/ Polyethylene	Yes	85-90	2	0.92	79	-
M3-E2	Polypropylene/ Polyethylene	Yes	85-90	2	0.92	79	-
M4	Polypropylene /Polyethylene	No	85-90	2	0.92	74	1,380
M4-E	Polypropylene/ Polyethylene	Yes	85-90	2	0.92	74	1,380
M5	Polypropylene/ Polyethylene	No	85-90	1	0.92	37	1,380
S1	Steel	No	30	2	7.86	67	30,500
S2	Steel	No	50	1.0	7.86	41	30,500
S3	Steel	No	50	1.5	7.86	41	30,500

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

(i)

(j)

Figure 2-1 Shows an image (a) M1, (b) M2, (c) M3, (d) M3-E1, (e) M3-E2, (f) M4, (g) M4-E, (h) S1, (i) S2-1.5, (j) S2-1

2.2.2 Concrete batching and mixing

Aggregates were collected from outside storage piles and brought into a temperature-controlled room at 23°C for at least 24 hours before mixing. Aggregates were placed in the mixer and spun and a representative sample was taken for a moisture correction. At the time of mixing, all aggregate was loaded into the mixer along with approximately two-thirds of the mixing water. This combination was mixed for three minutes to allow the aggregates to approach the saturated surface dry (SSD) condition. Next, the cement, fly ash, and the remaining water was added and mixed for three minutes. After the mixing, the mixture rested for three minutes while the inside of the mixing drum was scraped. After the resting period, the fibers were slowly added to the mixture. The goal of slowly adding the fibers was to attempt to mitigate any fiber balling and get an even distribution of the fibers. After the fibers were thoroughly mixed, the WR was added until the desired slump was reached.

2.2.3 Concrete testing

The slump was first tested before any fibers or admixtures were included according to ASTM C143 [15]. After the initial slump was measured, the fibers were slowly added into the concrete and mixed for an additional 3 minutes. The slump was again measured to determine if it met the desired slump of 3 +/- 0.25 inches. If the slump met the target, the concrete was transferred to a wheelbarrow. If the slump did not achieve the target, then a water reducer was added until the desired slump was achieved.

After the concrete was transferred into the wheelbarrow, the concrete was tested for finishability using the float test, along with unit weight and air content according to ASTM C138 and ASTM C231, respectively [16,17].

Samples were made for the Split Beam Test and compressive strength testing according to ASTM C192 [18]. There were three 6x6x20 inch beams made for split beam testing at 3 days and three 4x8 compressive strength cylinders to be tested each day after 3, 7, 28, and 56 days, according to ASTM C39 [19]. More details for the Float Test and Split Beam Test are given in the following sections.

2.2.4 Float Test

The Float Test was developed to measure the finishing process. It consists of a sample form with dimensions of 2 ft. by 3 ft. and a depth of 3.5 in., a modified bull-float, a template with three standard holes, 1 in. in diameter and height, and a strike-off board. The sample form is filled with concrete and three standard holes were created. Next, the modified bull-float was placed on one end and moved forward and backward as described in Figure 2-2. The number of passes to close the holes were counted. Also, the number of passes to achieve a smooth surface was counted. The Float Test procedure is summarized in the appendix and more details can be found in Cook (2015), [20]. Figure 2-2 shows a brief description of the Float Test method.

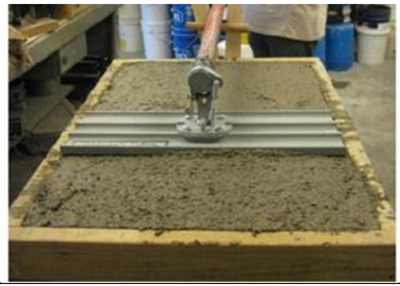
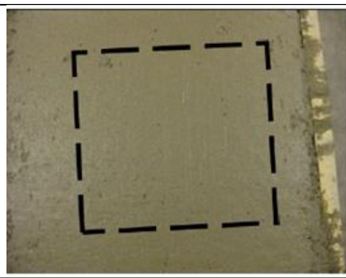
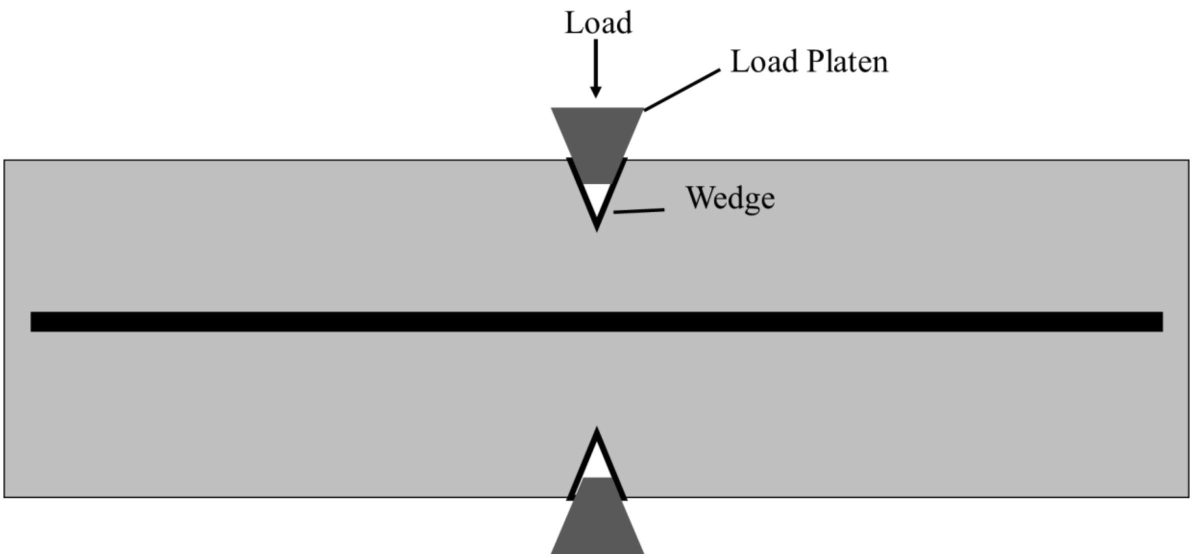
	
Step 1	Step 2
After placing and leveling the concrete with a strike-off board, place the template on the form and insert the 1” diameter dowel into the concrete to create a hole	Place bull float on the surface. With a fixed upward tilt of 2 degrees, move the bull float at a constant forward motion of 0.5ft/sec until it reaches the form. (This is one pass.)
	
Step 3	Step 4
Using only the middle 1.5 ft^2 area, determine the texture scale and closing of the holes.	If the texture was a 3 or greater or the hole was not removed, the bull float passed back and forth until the texture was 2 or smaller and the hole closed.

Figure 2-2 provides the Float Test procedure steps. (acquired from Cook 2015)

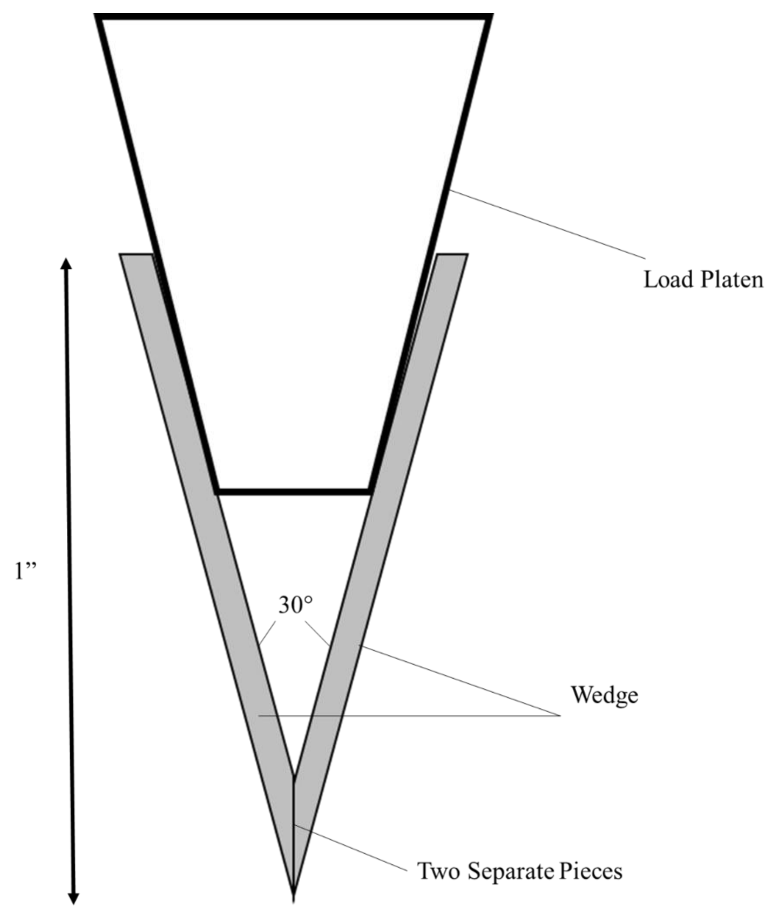
2.2.5 Split Beam Test Method

2.2.5.1 Sample Preparation

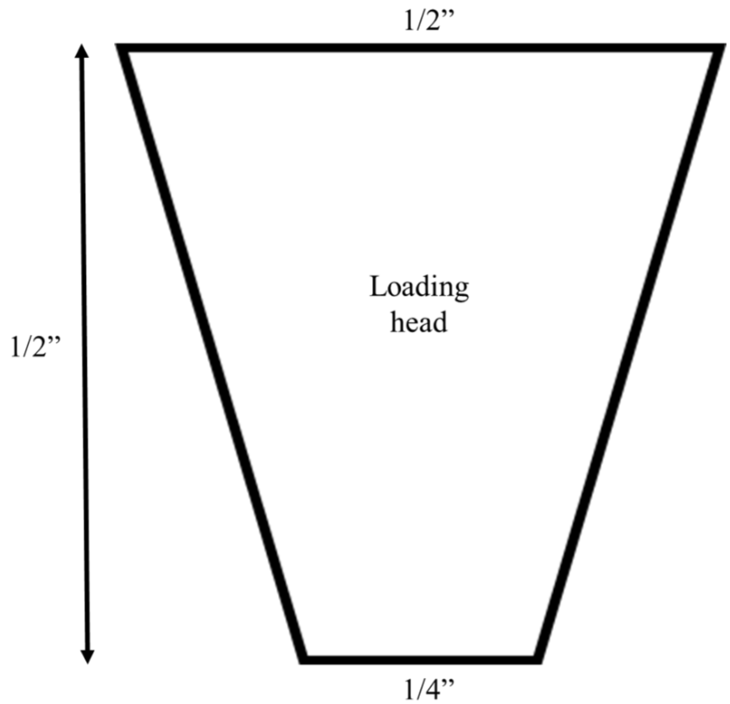
The Split Beam test uses 6x6x20 inch molds that have a #3 rebar placed in the middle and two wedges that are cast in the same location at the top and bottom of the concrete. These wedges and load platen are created to have the same geometry. An overview of this is shown in Figure 2-3. The wedges are made of two pieces of ¼” thick mild steel that make up a “V” shape. The wedge is split at the bottom of the V. This causes the wedge to spread once loaded with the platen. This will cause a crack at a known location. The wedges are held together by glue while casting the fresh concrete.


Load
Load Platen
Wedge

(a)


Load Platen
1”
30°
Wedge
Two Separate Pieces

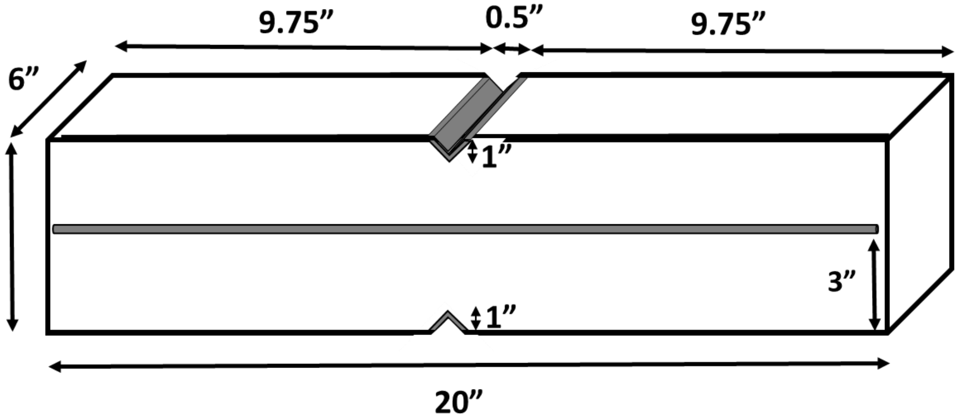
(b)



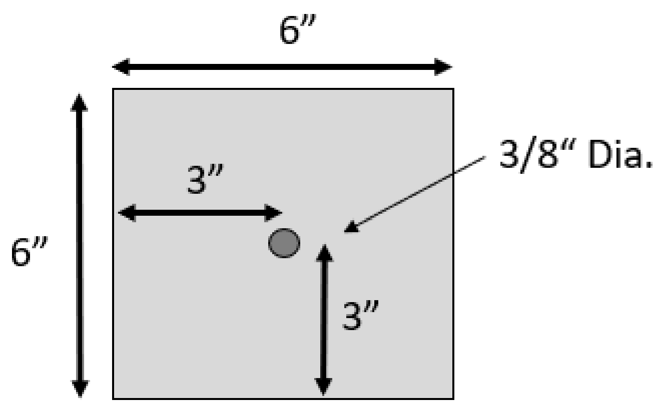
(c)

Figure 2-3 shows the schematic of the split beam and notch with (a) being an overall view and (b) being a close-up image of the notch and (c) being a dimensioned image of the loading head.

The layout of the beam, notches, and rebar is shown in Figure 2-4. On each end, a 3-inch tall plastic chair is used to hold the rebar in place while the concrete is cast. The notches are glued together to keep them in place until loading. To assure that the notches do not move from the middle of the beam, the notch is taped to the sides of the beam so no movement can happen.



(a)



(b)

(c)

Figure 2-4 shows the schematic of the split beam showing the (a) front view, (b) side view, and (c) real image of the split beam.

2.2.5.2 Consolidation of sample beams

The beams were consolidated using an external vibrating table. The table ensures that neither the rebar nor the notches move during the consolidation process. The vibration duration was 5 +/- 1 second for each layer of the two layers and the vibrations per minute were approximately 3600 vpm, per ASTM C192 [19]. The beams were then finished with a wood float until a flat surface was achieved, according to ASTM C192.

2.2.5.3 Curing conditions of sample beams

After the beams have been cast and finished, they are covered with wet burlap and a tarp for 48 hours. The beams are demolded and then stored in an environmentally controlled chamber that is held at 73° F with a relative humidity of 100% for an additional 24 hours. The beams are then tested after a total of 72 hours. All curing met the standards of ASTM C192 [18].

2.2.5.4 Placement of reinforcement steel

The rebar is included to hold the concrete together after a crack has formed. Tests were done using one bar, two bars, and no rebar. When using no rebar, the sample would very quickly fail after the initial crack of the concrete. This quick failure did not allow time to measure the crack size. Two pieces of rebar were sufficient but there was no advantage over using a single piece of rebar. For this reason, the beams use a single #3 rebar Grade 60 which is placed directly in the middle of the beam. To determine the length of the reinforcement, the development length calculations were completed using the ACI 318 equations for development length in tension as shown in equation 1. For the equation shown below, the following values were used:

Fy = 60 ksi

F'c = 4 ksi (strength of mix with no fibers at 3 days)

Ψ_t = 1.0 for normal bars

Ψ_e = 1.0 for non-epoxy coated rebar

Ψ_s = 0.8 for #6 or smaller

λ = 1 for normal weight concrete

$C_b + K_{tr} / d_b = 2.5$

$$\ell_d = \left(\frac{3}{40} \frac{f_y}{\lambda \sqrt{f'_c}} \frac{\Psi_t \Psi_e \Psi_s}{\left(\frac{c_b + K_{tr}}{d_b} \right)} \right) d_b \qquad \text{Equation 1}$$

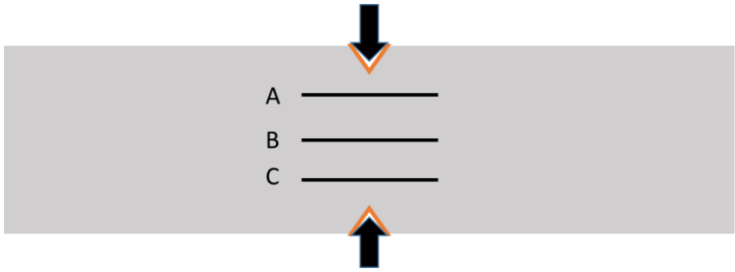
This showed a development length of at least 8.5 inches was needed. A length of 19 inches was chosen to allow the rebar chairs to sit away from where the crack would form. All calculations are shown in the appendix.

2.2.5.5 Loading of sample beams onto hydraulic supports

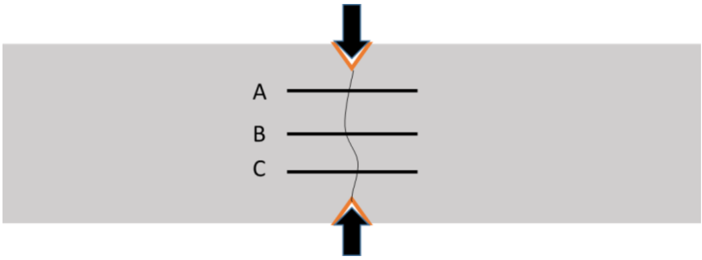
The main goal of the test is to test fiber performance; the goal of the loading is to put the beam in tension. The notches at the top and bottom are intended to load the beam in a way to propagate a crack down the middle of the beam as shown in Figure 2-5. The beam is loaded at 1,500 lbs./min until a load of 2,500 lbs. is reached, this is because the beams with this mixture design will not crack before a load of 2,500 lbs. is reached. Therefore, it is loaded quickly until 2,500 lbs. to shorten the overall length of the test. The beam is then loaded in 250 lbs. steps at 450 lbs./min to slow the rate of loading so that the crack size can be measured. The loading heads also served as the supports for the beam. The Split Beam Test has a typical length of 25 minutes per beam. With a typical test requiring 3 beams to be tested, the overall length is between 70-90 minutes.

2.2.5.6 Testing Procedure

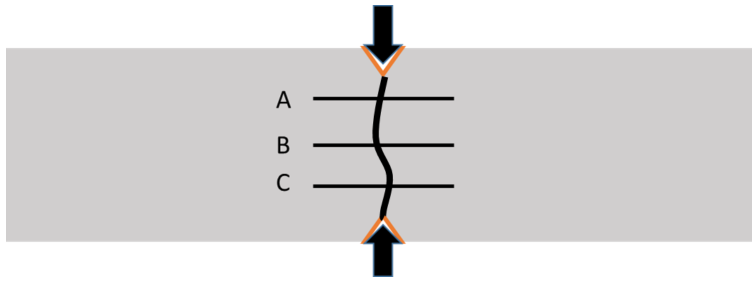
The beams are marked at 1.5, 3, and 4.5 inches from the top as shown in Figure 2-5. The hydraulic press loads the sample in 250 lbs. steps, and then the crack size is recorded using a calibrated crack card at each step. The deflection, crack size, and load are recorded at each step. The deflection was not used in the analysis and could be neglected in future testing. The figure below shows how the crack size of the beam increases as the load increases. A detailed test method for the split beam test can be found in the Appendix.



(A)



(B)



(c)

Figure 2-5 shows the schematic of the split beam loading steps (a) before cracking, (b) after some load is applied, and (c) after more load is applied.

The load that was put onto the beam was converted into stress using methods from previous work [19]. As shown in Figure 2-6 below, the friction force and normal force were considered. 50% of the load was assumed to go onto each side of the wedge. For the friction force, a 0.7 friction factor was assumed for the steel on steel friction [20]. The modulus of elasticity of the concrete was found using the average compressive strength of all of the mixtures tested at an age of 3-days. The steel and rebar were considered two different components of the test and were calculated separately from each other. To do this, the area and modulus of each component were found so that the percentage of the load in both the concrete and the steel could be found. After the percentage of each was found, the stress was found in both the concrete and the steel and then added together to find the total stress in the beam. To find the stress in the steel, the total effective load was found and multiplied by the percentage of the force in the steel. That value was then divided by the total area of rebar to find the stress in the rebar in psi. The same method was used to find the stress in the concrete. The total stress in the beam was found by adding the stress in the steel to the stress in the concrete. It was found that for every 1,000 pounds, there was stress of 606 psi. This conversion factor is what will be used for this paper. The detailed calculations and all assumptions can be found in the appendix.

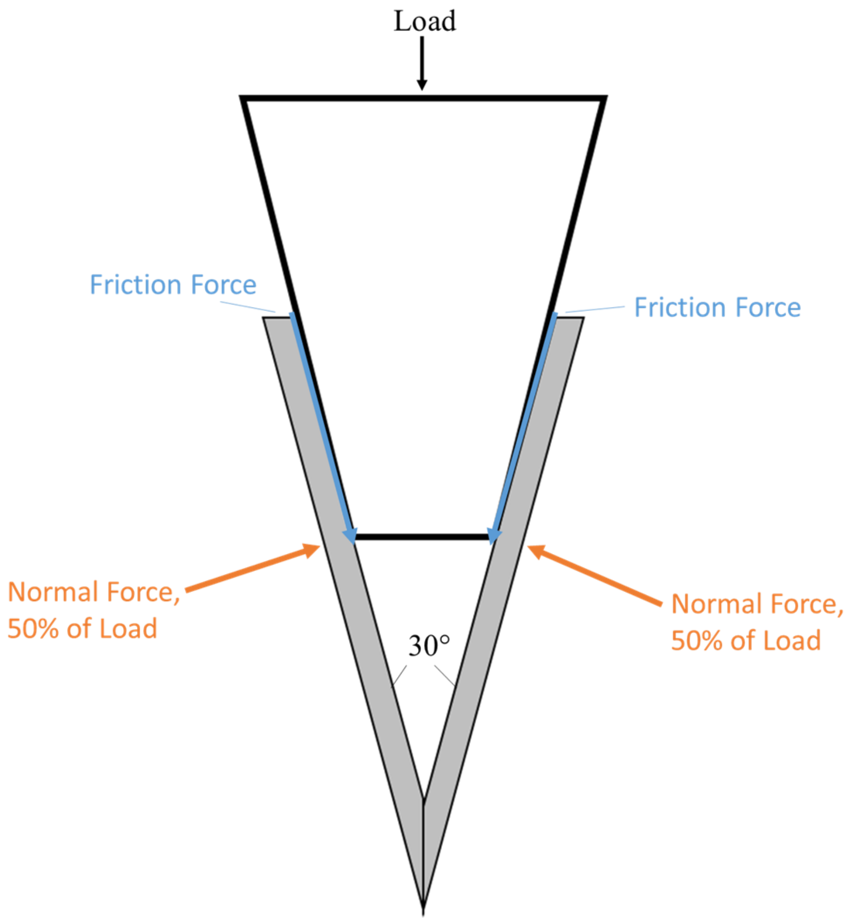


Figure 2-6 shows the free body diagram of the top wedge.

2.3 RESULTS AND DISCUSSION

2.3.1 Number of samples

To determine the consistency of the Split Beam Test, a T-test was performed to determine how many samples were necessary to be made for each of the different fiber dosages. After finding the average crack size and standard deviation, the T-test was run to determine any statistical differences in the samples. A 95% confidence interval was used for each combination of 7 different samples with the same mix design and fiber dosage. The test showed that there was no significant statistical difference between any of the samples when at least 3 samples were used. This was found to be true for every fiber dosage that was used.

2.3.2 Slump measurement of the fresh concrete

The slump test was used to measure the consistency between mixtures. Table 2-4 shows the changes in slump based on incremental dosages of fiber reinforcement content and the different fiber types. As more fibers are added to the concrete, the slump of the concrete decreases, and the amount of water reducer needed to reach the desired slump increases.

Table 2-4. Slump Change from Fiber Reinforcement for All Mixtures

	Initial Slump (in)	Slump after fibers (in)	Slump after WR (in)	WR required for final slump (oz/cwt)
0 lbs./cy	4.5	4.5	4.5	0
M1 at 4 lbs./cy	4.5	2.75	2.75	0
M1 at 8 lbs./cy	4.5	1.5	3.25	1.5
M1 at 12 lbs./cy	3.75	0.5	3.25	1.75
M2 at 4 lbs./cy	3	2.25	2.75	0.56
M2 at 8 lbs./cy	3	1	2.75	1.05
M2 at 12 lbs./cy	3.25	0.25	2.75	1.45
M3-E1 at 4 lbs./cy	3.5	1.5	3	0.45
M3-E1 at 8 lbs./cy	3.25	1.5	3	0.75
M3-E1 at 12 lbs./cy	3.5	0.5	2.75	1.3
M3 at 4 lbs./cy	4.5	3.25	3.25	0
M3 at 8 lbs./cy	3.75	1.5	2.75	1.07
M3 at 12 lbs./cy	4	0.25	3	1.95
M3-E2 at 4 lbs./cy	3.75	3.25	3.25	0
M3-E2 at 8 lbs./cy	4.5	1	2.75	1.2
M3-E2 at 12 lbs./cy	3.75	0.25	2.75	2.05
M4 at 4 lbs./cy	3.75	2.25	3	0.74
M4 at 8 lbs./cy	4.5	1.5	3.25	1.42
M4 at 12 lbs./cy	4	0.5	3	2.72
M4-E at 4 lbs./cy	4	3.25	3.25	0
M4-E at 8 lbs./cy	3.5	1.25	3.25	1.69
M4-E at 12 lbs./cy	5	0.5	3.25	2.66
M4-C at 4 lbs./cy	5	3.25	3.25	0
M4-C at 8 lbs./cy	5	3	3	0
M4-C at 12 lbs./cy	5	0.75	3.25	1.44
S1 at 33 lbs./cy	4.5	3.25	3.25	0
S1 at 44 lbs./cy	4.25	3.25	3.25	0
S1 at 66 lbs./cy	4.25	3	3	0
S2-1 at 33 lbs./cy	5	4.5	4.5	0
S2-1 at 44 lbs./cy	5	4	4	0
S2-1 at 66 lbs/cy	5	3.75	3.75	0
S2-1.5 at 33 lbs./cy	5	3.75	3.75	0
S2-1.5 at 44 lbs./cy	5	4	4	0
S2-1.5 at 66 lbs./cy	5	3.5	3.5	0

Table 2-4 shows that the use of synthetic fibers decreases the slump more than steel fibers. When equal volumes of steel and synthetic fibers were used, the mixtures with steel fibers did not require any WR to achieve a 3 +/- 0.25-inch slump while the synthetic fibers did require WR in many of the cases. For example, M1 4 lbs./cy and S2-1 33 lbs./cy have the same volume of fibers in the mixture and start with nearly the same initial slump. However, M1 4 lbs./cy lost 1.75 inches of slump after fibers were added and S2-1 33 lbs./cy only lost 0.50 inches of the slump.

As more synthetic fibers are added to the mixture, the greater the decrease in slump and the more WR required to achieve the desired slump. This could be due to the high fiber count for the macro synthetic fibers in the higher dose mixtures. With more fibers, the fibers are more likely to impede the flow of the concrete, lowering the slump and workability, causing more WR to be needed. The important thing to note is that all mixtures tested had a very similar slump. This consistency allows the Float Test to compare the performance of the fibers without having to consider how the slump affects the results.

2.3.3 Float Test Data

The following graphs show the results of the float test for all mixtures that were tested. All testing of the Float Test was done according to the work done in Cook, 2015 [13]. In the graph, the darkest color refers to the lowest dosage of fibers (4 lbs./cy and 33 lbs./cy) while the lightest color refers to the highest dosage of fibers (12 lbs./cy and 66 lbs./cy). The dosages are also distinguished by pattern, as shown in the legend. The full table of values can be found in the Appendix. There are two horizontal lines drawn on the graph, if the number of passes meets or is underneath the green line, the finishing is desirable. If the number of passes falls between the green and red line, the finishing is moderate. If the number of passes is above the red line, the finishing is poor

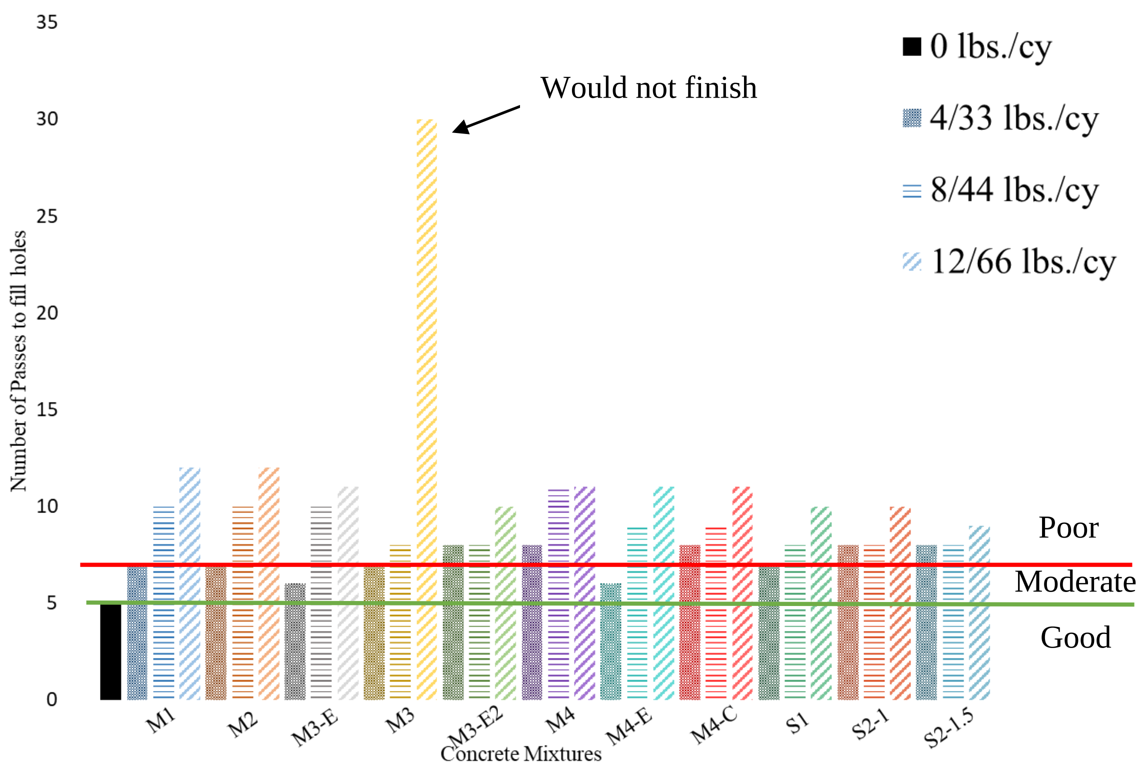


Figure 2-7 shows the number of passes to fill holes in the Float Test for all mixtures

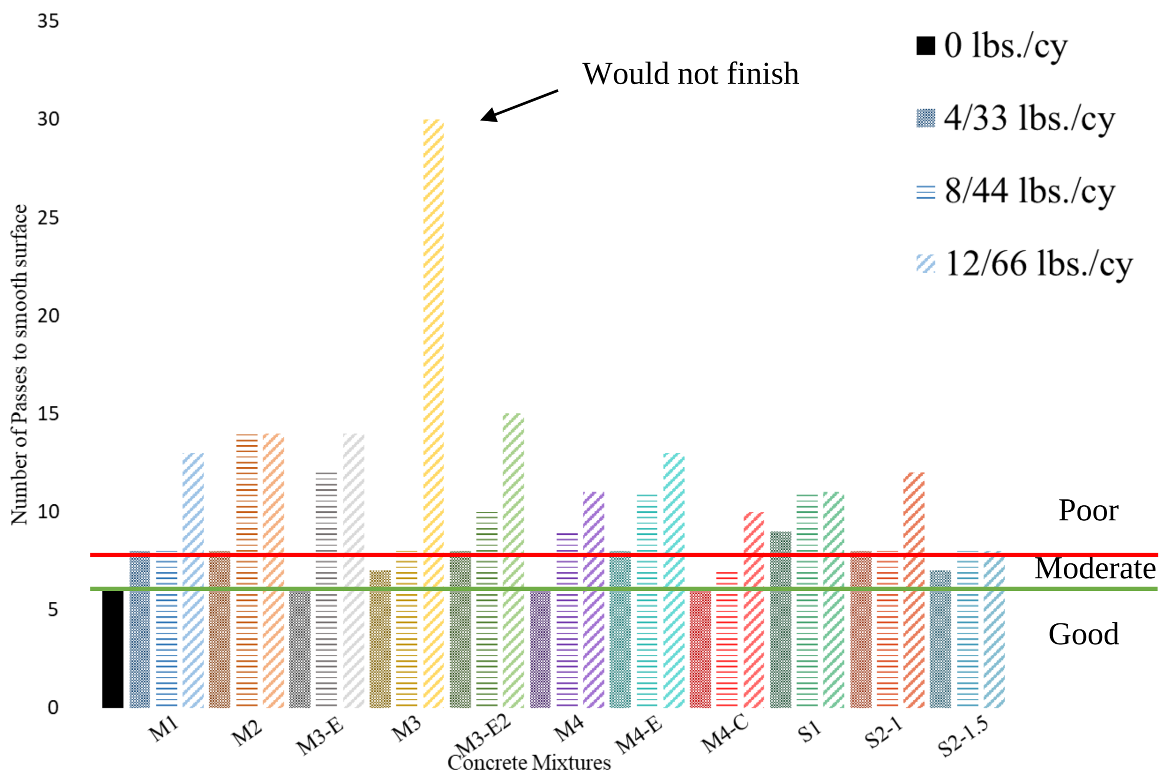


Figure 2-8 shows the number of passes to smooth the surface in the Float Test for all mixtures.

The Float Test results show that in all fiber types and dosages that it becomes harder to fill the holes in every mixture. All of the middle and high dosages of fibers, regardless of type, show poor ability to fill the holes. M3-E2, M4, M4-C, S2, and S3 show poor finishing in all dosages. However, The Float Test results for the number of passes required to achieve a smooth surface showed more promising results than the number of passes required to fill the holes. Of the 33 fiber mixtures, 0 were good at filling the holes, but 3 were good at creating a smooth surface. 6 mixtures were moderate at filling the holes compared to 13 at smoothing the surface of the concrete. Finally, 29 mixtures performed poorly at filling the holes, but only 18 mixtures performed poorly at smoothing the surface. That is a change from 87% to 55% performing poorly. This could be from how the fibers interact with each other and the concrete. When finishing the surface, the fibers will lay down and allow a smooth surface to form. However, when trying to fill the holes, the fibers want to keep the integrity of the concrete shape and not allow the holes to be filled. Similar to how the fibers act in the slump test, the fibers want to hold the shape of the concrete together rather than letting it flow.

2.3.4 Compressive Strength Data

The following graph shows the results of the compressive strength testing of the different fiber dosages and fiber types at 3 and 28 days. The table for the compressive strength data and the standard deviation is shown in the appendix. As in the float test chart, the darkest of each color refers to the lowest dosage of fibers and the lightest color refers to the highest dosage of fibers. The black horizontal lines show the averages for the macro synthetic (MS) fibers and the steel (S) fibers at both 3 and 28 days. Three different types of hatching are shown to explain the dosage rate of each mix. Mixes with the lowest volume of each material have the same hatching.

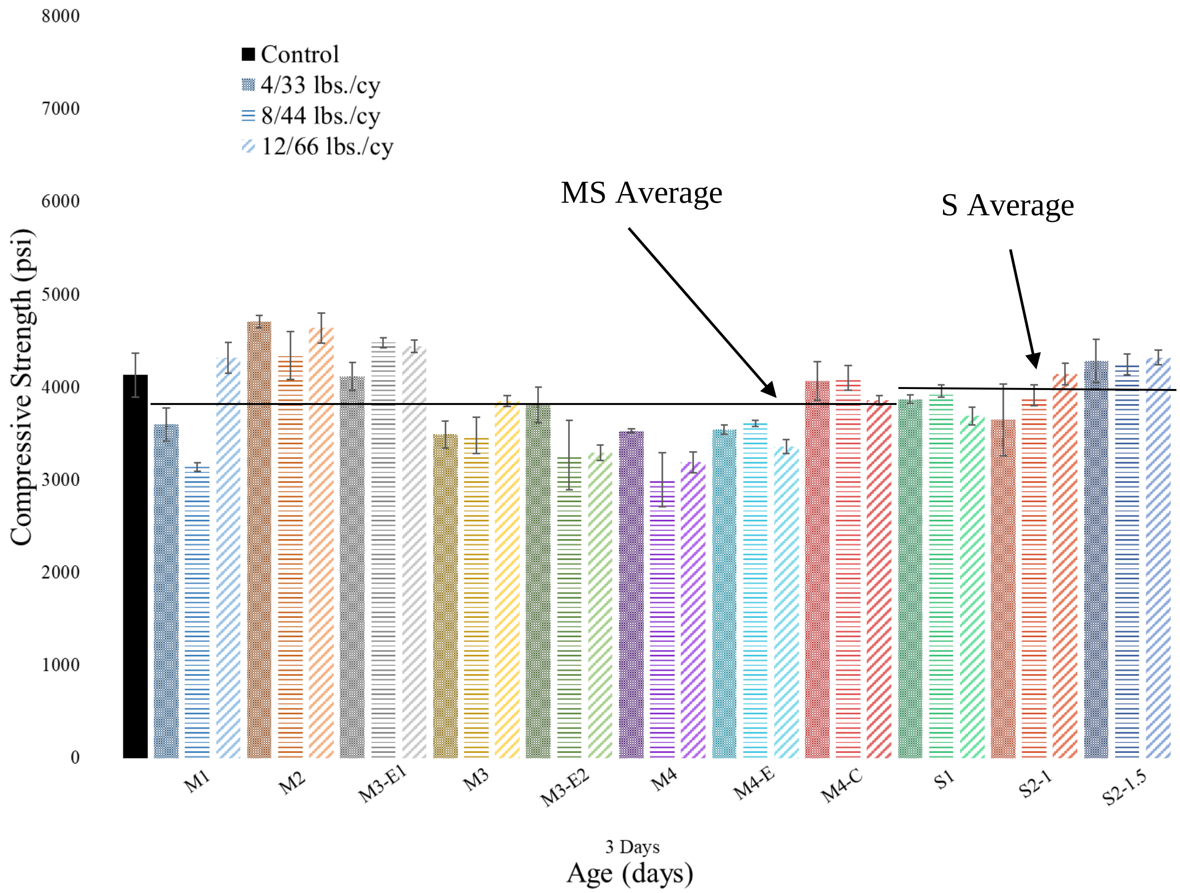


Figure 2-9 shows the compressive strength data results for all mixtures at 3 days.

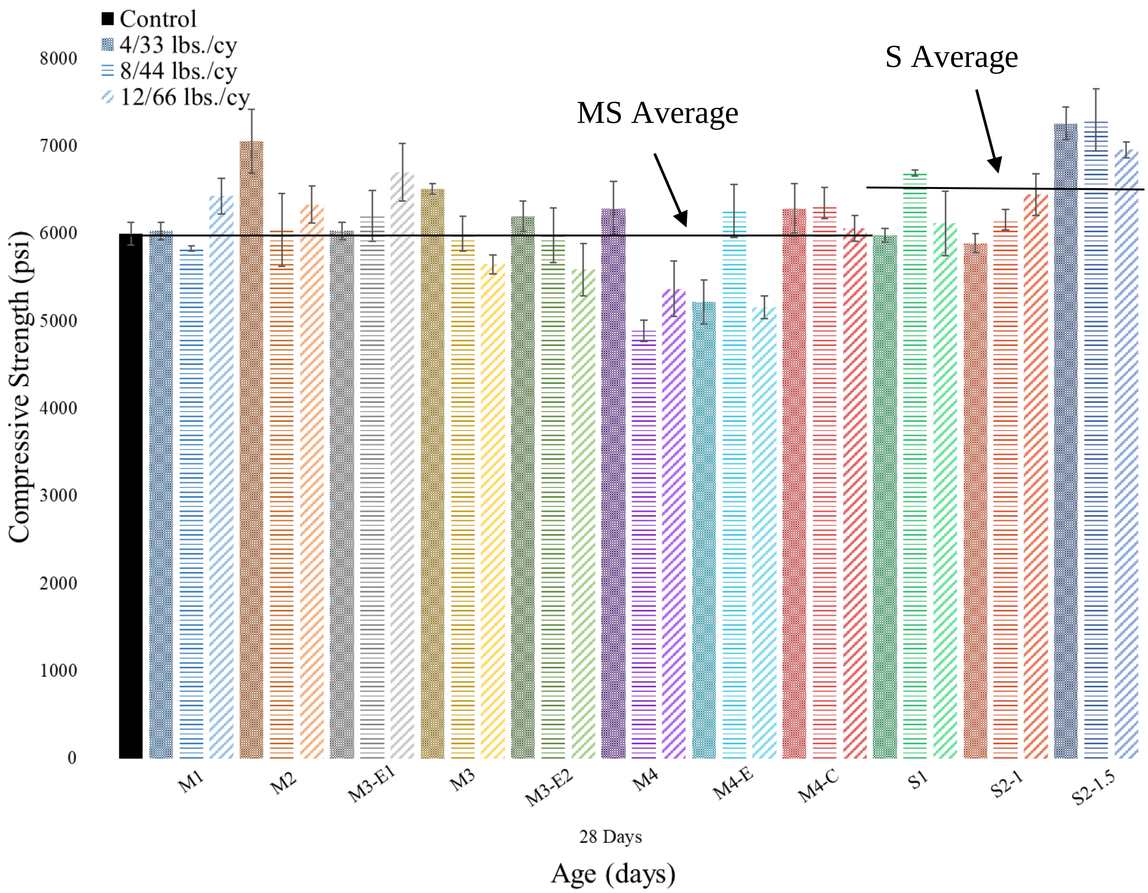


Figure 2-10 shows the compressive strength data results for all mixtures at 28 days.

A T-Test was done on the compressive strength data to determine which samples were statistically better or worse than the control at both 3 and 28 days. The black lines show the averages for both the steel and synthetic fibers at both 3 and 28 days. The results of the T-Test show that only 1 mixture showed a statistical increase from the control, S2-1.5 at 28-day strength. 5 of the mixtures showed a statistical decrease in strength and 4 of those 5 mixtures were made from polypropylene fibers. Polypropylene is the fiber that did well in the Split Beam Test. The decrease in strength for the 5 mixtures was an average of 800 psi at 3 days and 600 psi at 28 days. This is a 10% decrease from the average at 28 days.

2.3.5 Split Beam Testing

This section compares fibers at different dosages, different lengths, different surface finishes of the fiber, and different materials. The goal of this testing is to determine how each of these factors affects the crack propagation of the beam. The following table shows the overall results of the Split Beam Test. It shows the percent decrease from the control at 2,700, 3,300, and 3,900 psi. Any cell that is highlighted red showed an increase in crack size compared to the control. Figure 2-11 shows the performance of M1 at three different dosages and vertical lines showing the stress that was used to compare fibers. The stress of 2,700 psi was chosen as a comparison for early loading. At this stress, the crack size is still very small, and similar performance is shown between the mixtures. 3,300 was chosen as the middle stress as it is after the crack has started to grow but before any major failure of the beam. At this stress, the crack has grown and there is a difference in performance between fibers. 3,900 was chosen as the last stress because, at that point in loading, the crack size has grown and some fibers may be starting to pull out. It allows us to see which fibers perform better at higher stresses.

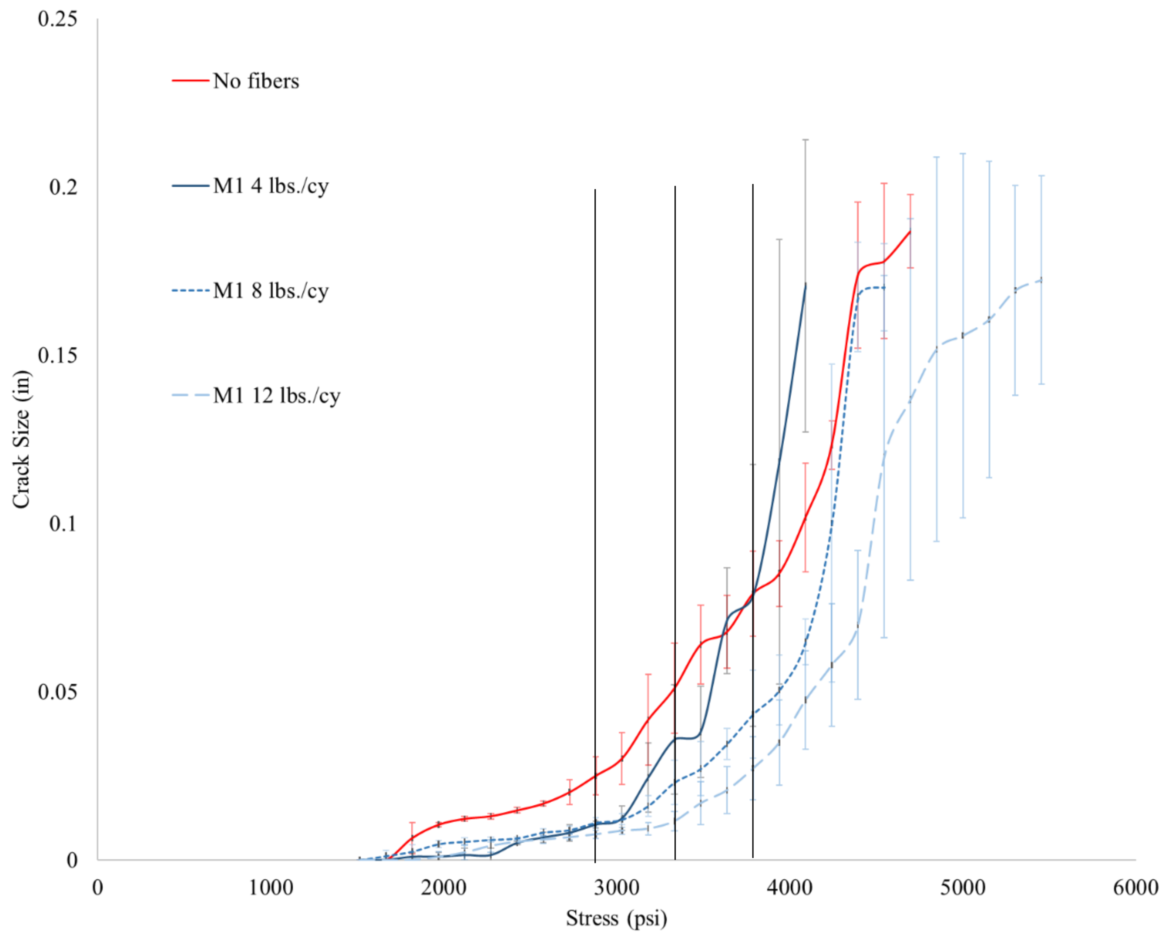


Figure 2-11 shows an example graph of three different dosages and the stresses that are being used to compare fibers to one another

This graph is shown below in a bar chart comparing the 4 different fiber dosages at the 3 different stresses that were considered. It shows the crack size on the x-axis and the different stress and mixtures on the y-axis. It shows that at the stress of 2,700 psi, the crack sizes are very similar to each regardless of fiber dosage and that all three show a smaller crack size than the control. This is likely due to there being less stress on each fiber at this lower overall stress. Because of this, fewer fibers are needed to keep the crack size small. At 3,300 psi, all three keep the crack smaller than the control, but the crack size is smallest when the higher dosages of fibers are used. This is because the stress is higher and so having more fibers allows for the stress to be more distributed between fibers. Finally, at 3,900 psi, the mixture with 4 lbs./cy shows an increase in crack size compared to the control. This is due to the fibers starting to pull out and is discussed more in the length section. The higher dosage of fibers is still keeping the crack smaller than the lower dosage of fibers.

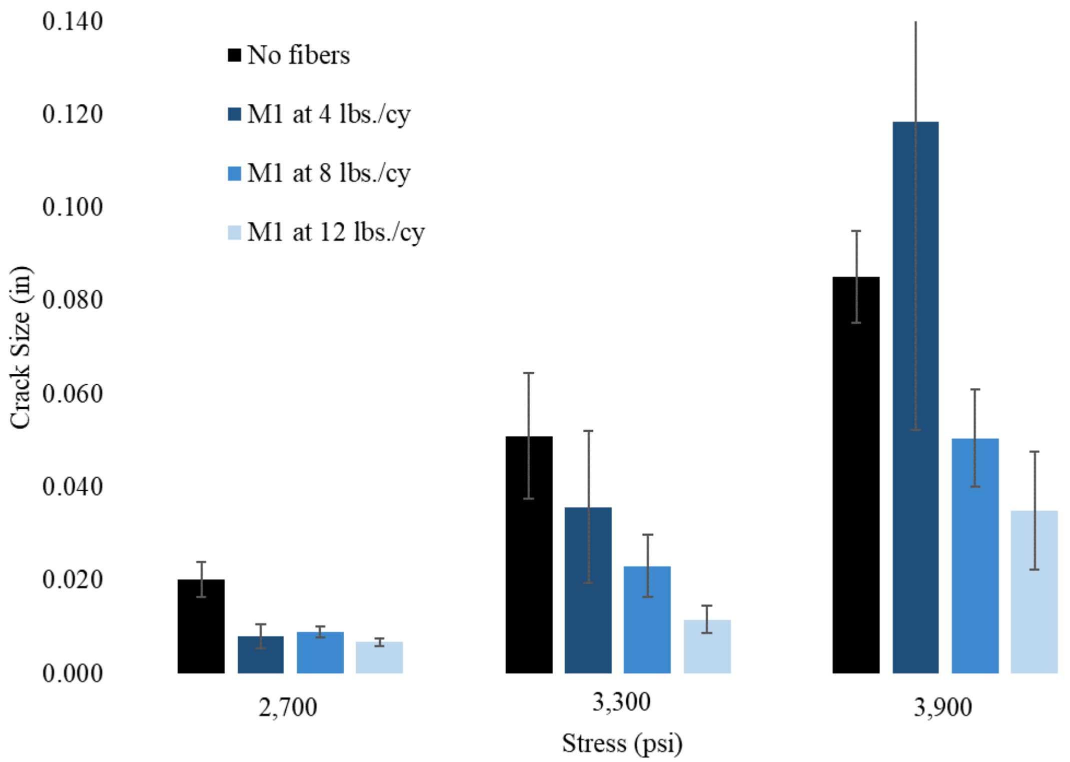


Figure 2-12 shows a bar chart comparing four different fiber dosages at three different stresses.

Table 2-5. Percent decrease in crack size at 3 different stresses

Mix ID	% decrease at 2,700 psi	% decrease at 3,300 psi	% decrease at 3,900 psi
0 lbs/cy	0	0	0
M1 4 lbs./cy	52	30	-39
M1 8 lbs./cy	50	55	59
M1 12 lbs./cy	56	77	65
M2 4 lbs./cy	26	33	14
M2 8 lbs./cy	38	57	22
M2 12 lbs./cy	89	81	64
M3-E1 4 lbs./cy	13	7	0
M3-E1 8 lbs./cy	47	53	0
M3-E1 12 lbs./cy	68	68	50
M3 4 lbs./cy	83	85	56
M3 8 lbs./cy	76	84	72
M3 12 lbs./cy	88	83	73
M3-E2 4 lbs./cy	85	30	17
M3-E2 8 lbs./cy	70	78	68
M3-E2 12 lbs./cy	65	78	69
M4 4 lbs./cy	89	83	73
M4 8 lbs./cy	73	78	76
M4 12 lbs./cy	72	80	66
M4-E 4 lbs./cy	73	39	-24
M4-E 8 lbs./cy	64	22	0
M4-E 12 lbs./cy	69	37	20
M4-C 4 lbs./cy	-44	-200	-140
M4-C 8 lbs./cy	63	-36	-96
M4-C 12 lbs./cy	58	-29	-128
S1 33 lbs./cy	91	86	85
S1 44 lbs./cy	91	86	82
S1 66 lbs./cy	87	86	78
S2-1 33 lbs./cy	32	-126	-159
S2-1 44 lbs./cy	55	-58	-100
S2-1 66 lbs/cy	40	-173	-140
S2-1.5 33 lbs./cy	38	-1	-104
S2-1.5 44 lbs./cy	68	18	-124
S2-1.5 66 lbs./cy	82	57	-61

*Note: That red indicates an increase in the crack size compared to the control

2.3.5.1 Varying Fiber Dosages

As shown in Table 2-5, comparisons were done for 11 different fiber types at 3 different dosages for each fiber. It was found that in almost every case, more fibers in the concrete contributed to reducing the crack size. This can be seen in the table above and the graphs that are shown in the appendix. The most likely reason for this happening is that if you have more fibers in the concrete, there is a higher chance that those fibers will come across the area that a crack is forming. If more fibers are working together to keep that crack small, the crack will not be able to open as easily. In the case that the crack propagated faster even though there were more fibers, such as M3-E2 at 3,700 psi, it could be attributed to how those fibers mixed into the concrete. More fibers in the mix mean that there is a higher chance of fiber balling and segregation. This balling could lead to an uneven distribution of the fibers, therefore not achieving the desired performance. The other problem with high fiber counts is that it can reduce the workability and finishing of the concrete, as shown previously. While there is a benefit to using more fibers in a mix, not all fibers performed well in the Split Beam Test. This will be discussed in the upcoming sections.

2.3.5.2 Varying Fiber Material

Tests were done to determine how different materials impact the ability to resist cracking. 5 mixtures were done with the same length and volume of fibers used. The materials tested were a copolymer, polyolefin, 2 different polypropylenes, and steel. The results of this test are shown in Table 2-6. It shows that at a stress of 2,700 psi, the copolymer and both of the polypropylene fibers slow the speed at which the crack grows. However, the polyolefin allows the crack to grow faster than those three by an average of 20%, and the steel keeps the crack smaller than those three types by an average of 13%. At 3,300 psi, the polypropylene and steel perform very similarly at all three dosages. Also, the copolymer and the polyolefin perform very similarly. With the first group keeping the crack smaller by an average of 28%. Finally, at the stress of 3,900 psi, there is a rapid growth in crack size for the low dosage of the copolymer but similar performance between the copolymer and the polyolefin at the middle and high dose. The steel and the polypropylene show very similar performance throughout. M4 does keep the crack smaller than M3 at this load when dosed at 4 lbs./cy, even though they are both made from polypropylene. However, it is important to note that the error bars for each of these two fibers still overlap, making them not statistically different from one another. M4 is also statistically the same as S1. However, M3 and S1 are statistically different at 3,900 psi. The T-test to show this can be found in the appendix. An example graph showing the middle dosage of fibers with equal volumes is shown in Figure 2-13. Note that the equal volumes equate to 4 and 33 lbs./cy and 8 and 66 lbs./cy. The other dosage rates are shown in the figures in the appendix.

Table 2-6. Percent decrease in crack size at 3 different stresses for 5 different fiber materials. (a) 2,700 psi, (b) 3,300 psi, and (c) 3,900 psi

Mix ID	Material	% decrease at 2,700 psi
M1 4 lbs./cy	Copolymer	52
M1 8 lbs./cy		50
M1 12 lbs./cy		56
M2 4 lbs./cy	Polyolefin	26
M2 8 lbs./cy		38
M2 12 lbs./cy		89
M3 4 lbs./cy	Polypropylene	83
M3 8 lbs./cy		76
M3 12 lbs./cy		88
M4 4 lbs./cy	Polypropylene	89
M4 8 lbs./cy		73
M4 12 lbs./cy		72
S1 33 lbs./cy	Steel	91
S1 44 lbs./cy		91
S1 66 lbs./cy		87

(a)

Mix ID	Material	% decrease at 3,300 psi
M1 4 lbs./cy	Copolymer	30
M1 8 lbs./cy		55
M1 12 lbs./cy		77
M2 4 lbs./cy	Polyolefin	33
M2 8 lbs./cy		57
M2 12 lbs./cy		81
M3 4 lbs./cy	Polypropylene	85
M3 8 lbs./cy		84
M3 12 lbs./cy		83
M4 4 lbs./cy	Polypropylene	83
M4 8 lbs./cy		78
M4 12 lbs./cy		80
S1 33 lbs./cy	Steel	86
S1 44 lbs./cy		86
S1 66 lbs./cy		86

(b)

Mix ID	Material	% decrease at 3,900 psi
M1 4 lbs./cy	Copolymer	-39
M1 8 lbs./cy		65
M1 12 lbs./cy		59
M2 4 lbs./cy	Polyolefin	14
M2 8 lbs./cy		22
M2 12 lbs./cy		64
M3 4 lbs./cy	Polypropylene	56
M3 8 lbs./cy		72
M3 12 lbs./cy		73
M4 4 lbs./cy	Polypropylene	73
M4 8 lbs./cy		76
M4 12 lbs./cy		66
S1 33 lbs./cy	Steel	85
S1 44 lbs./cy		82
S1 66 lbs./cy		78

(c)

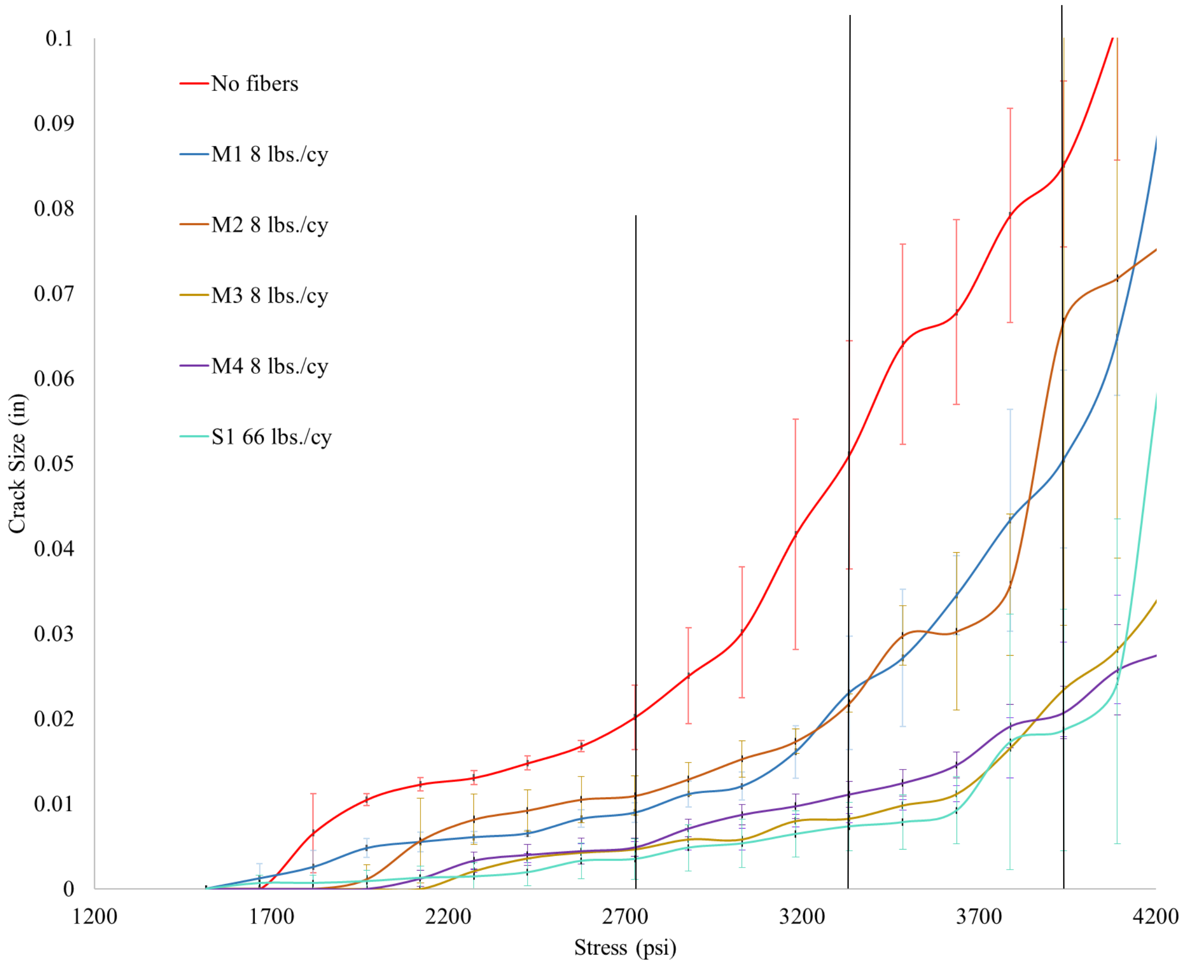


Figure 2-13 shows the Stress vs. Crack size graph for the middle dosage of five different fiber materials.

The following image shows a bar chart comparing the average crack size of the 5 different material types that were tested compared to the control. It compares them to one another at equal volumes of fibers in the mixture. The figure shows that the steel/polypropylene mixtures keep the crack size much smaller than the copolymer/polyolefin. It also shows the difference between the 2 is larger at the lower dosage compared to the higher dosage.

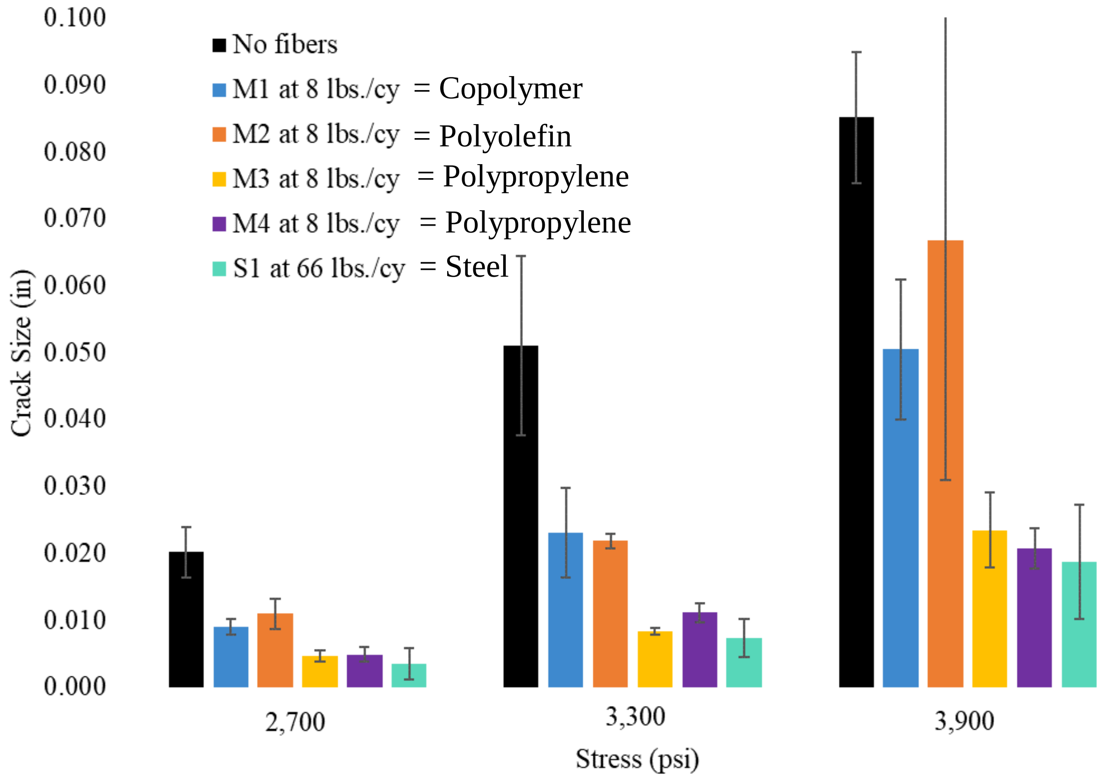


Figure 2-14 shows a bar chart comparing different material types to one another at equal volumes.

The following figure 2-15 shows the same figure as 2-14, except shows the lower dosage of fibers. It shows a similar trend, as the steel and polypropylene perform very similar, especially at low stress. The copolymer and the polyolefin also perform very similarly, but not as well as the steel and polypropylene. When looking at the highest stress, the steel keeps the crack the smallest, and M4 keeps the crack smaller than M3. However, as mentioned earlier, there is no statistical difference between those 2 fibers.

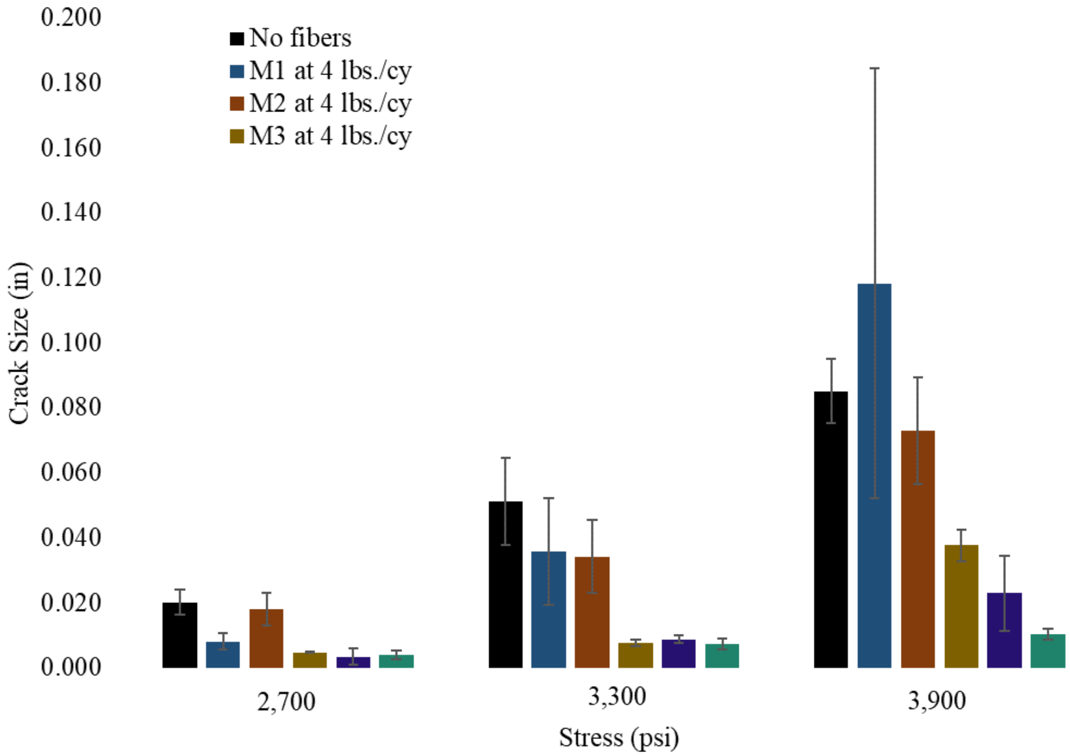


Figure 2-15 shows a bar chart comparing different material types to one another at equal volumes.

Many different things could lead to the difference in crack growth provided by these fiber types. The main difference is that the polypropylene and the steel perform very similarly and better than the copolymer and the polyolefin. One of the main contributors to the performance of the fibers may be the modulus. The steel fiber has a much higher modulus than the other fibers which could lead to it slowing the crack growth. However, the steel performs the same as polypropylene, so modulus cannot be the only thing that matters.

The tensile strength of the macro synthetic fibers is higher than steel. This could contribute to the M3 and M4 mixes performing the same as the steel, but M1 and M2 also have higher tensile strength and do not perform as well. Also, the main failure mechanism of the fibers appeared to be a pullout failure rather than a breaking failure. This would lead to the tensile strength not being as big of a contributor to the failure as the bond strength. The bond between the material and the concrete may affect the crack growth. It could be possible that the polypropylene bonds were better to the concrete than the polyolefin or copolymer.

The copolymer having a faster crack propagation could have to do with its surface texture. This will be discussed in more detail later in the paper. The surface texture of the fibers is likely important and needs to be studied in more detail. This could have been important to the polyolefin performing worse as well. To test this, mixtures would need to be completed with more copolymers and polyolefin as this data is not enough to show the true performance of this material.

Many things could be affecting the crack growth allowed by these fibers, but it is clear there is more than one important parameter that contributes to the performance. Additional research into material types needs to be done. The material is not the only thing that matters either, as we will look at in the coming sections.

2.3.5.3 Varying Fiber Lengths

Tests were done to determine how different lengths of fibers impact the ability to resist cracking. Two mixtures were done with the same type and amount of fibers but one mixture used 1” long fibers and the other mixture used 2” long fibers. The results are shown in Table 2-7. For these two mixtures, the crack size is very similar up to a stress of about 2,700 psi. After that, the 1” length fibers cause the crack to open more rapidly than if no fibers were used in the mixture. An example of this is shown in Figure 2-16 using the middle dosage of fibers. The rest of the dosages can be found in the appendix.

Table 2-7. Percent decrease in crack size at 3 different stresses for 2 different length fibers.

Mix ID	% decrease at 2,700 psi	% decrease at 3,300 psi	% decrease at 3,900 psi
M4 4 lbs./cy	89	83	73
M4 8 lbs./cy	73	78	76
M4 12 lbs./cy	72	80	66
M4-C 4 lbs./cy	-44	-200	-140
M4-C 8 lbs./cy	63	-36	-96
M4-C 12 lbs./cy	58	-29	-128

*Note: That red indicates an increase in the crack size compared to the control

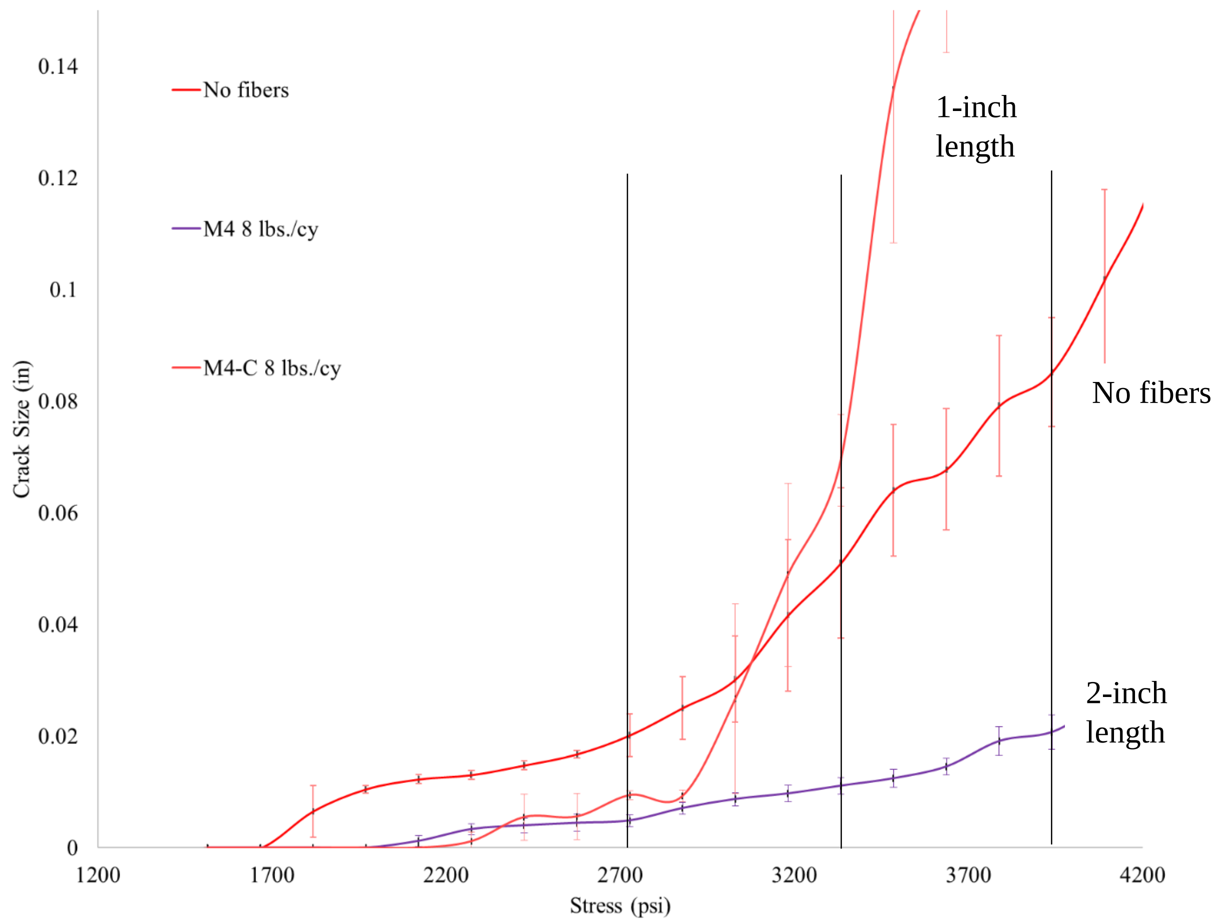


Figure 2-16 shows the Stress vs. Crack size graph for the middle dosage of two different length fibers.

The following image shows a bar chart comparing the average crack size of the 2 different length fibers that were tested compared to the control. It compares them to one another at equal volumes of fibers in the mixture. The figure shows that the longer fiber keeps the crack smaller than the control at all 3 stresses while the cut, 1-inch long fiber allows the crack to grow faster than the control at stresses of 3,300 and 3,900 psi.

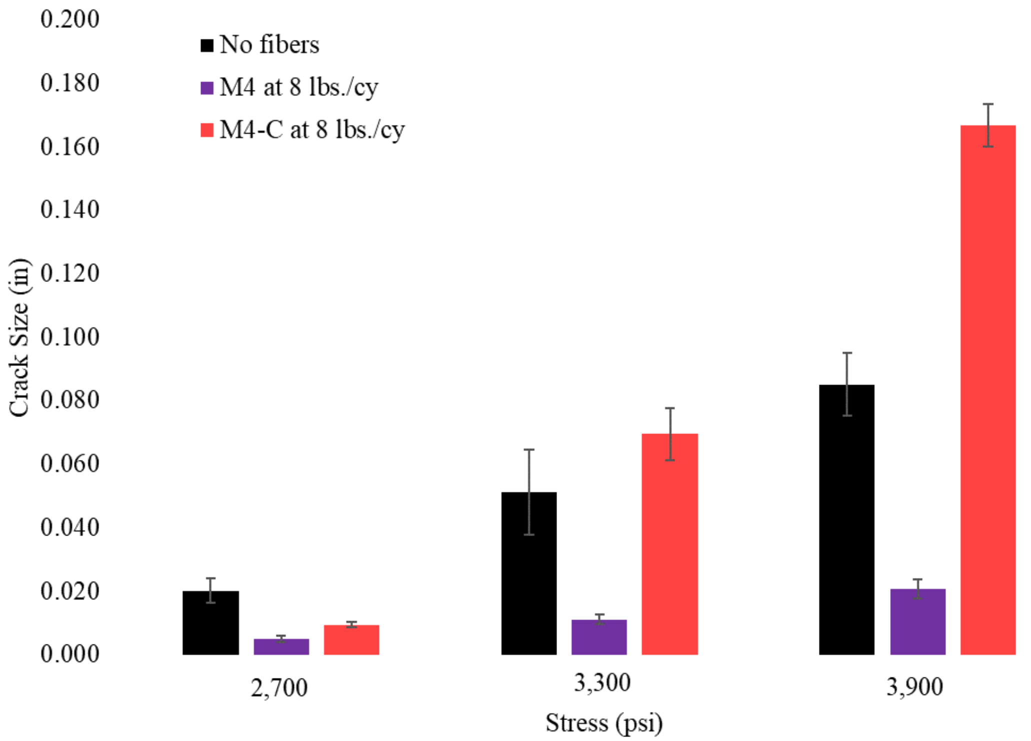


Figure 2-17 shows a bar chart comparing different fiber lengths to one another at equal volumes.

One possible reason for this happening is that there is a relationship between the aggregate size and the fiber length that requires a certain fiber length depending on the size of the aggregate. Further research would need to be done to help further this theory. If a 2-inch long fiber kept the crack size small when a 1-inch maximum size aggregate was used. A mixture using a ½-inch maximum-sized aggregate and the same 1-inch long fibers could prove this. Another possibility is that small impact loads are being put onto the beam when the anchorage fails for the short fibers. If the beam is trying to hold together and a fiber rips out, there could be a sudden transfer of load that causes the crack width to grow.

A test was also done on two different steel fibers that have the same properties but have different lengths. One mixture used 1-inch long fibers and the other used 1.5-inch long fibers. The results of this are shown in Table 2-8. The results show that at the low stress of 2,700 psi, all 6 mixtures, regardless of length or dosage rate, kept the crack smaller than the control. However, S3, the 1.5-inch long fiber, decreased the crack size more effectively. After 3,300 psi, the 1-inch fiber began to allow the crack to grow more rapidly than the control at all three dosages. The 1.5-inch long fiber still kept the crack smaller at the middle and high dosage, but not at the lowest dosage. Finally, at the stress of 3,900 psi, all 6 mixtures allowed the crack to grow much faster than the control. The middle dosage is shown in Figure 2-18 as an example, and the other dosages are shown in the appendix.

Table 2-8. Percent decrease in crack size at 3 different stresses for 2 different length steel fibers.

Mix ID	% decrease at 4,500 lbs	% decrease at 5,500 lbs	% decrease at 6,500 lbs
S2-1 33 lbs./cy	32	-126	-159
S2-1 44 lbs./cy	55	-58	-100
S2-1 66 lbs/cy	40	-173	-140
S2-1.5 33 lbs./cy	38	-1	-104
S2-1.5 44 lbs./cy	68	18	-124
S2-1.5 66 lbs./cy	82	57	-61

*Note: That red indicates an increase in the crack size compared to the control

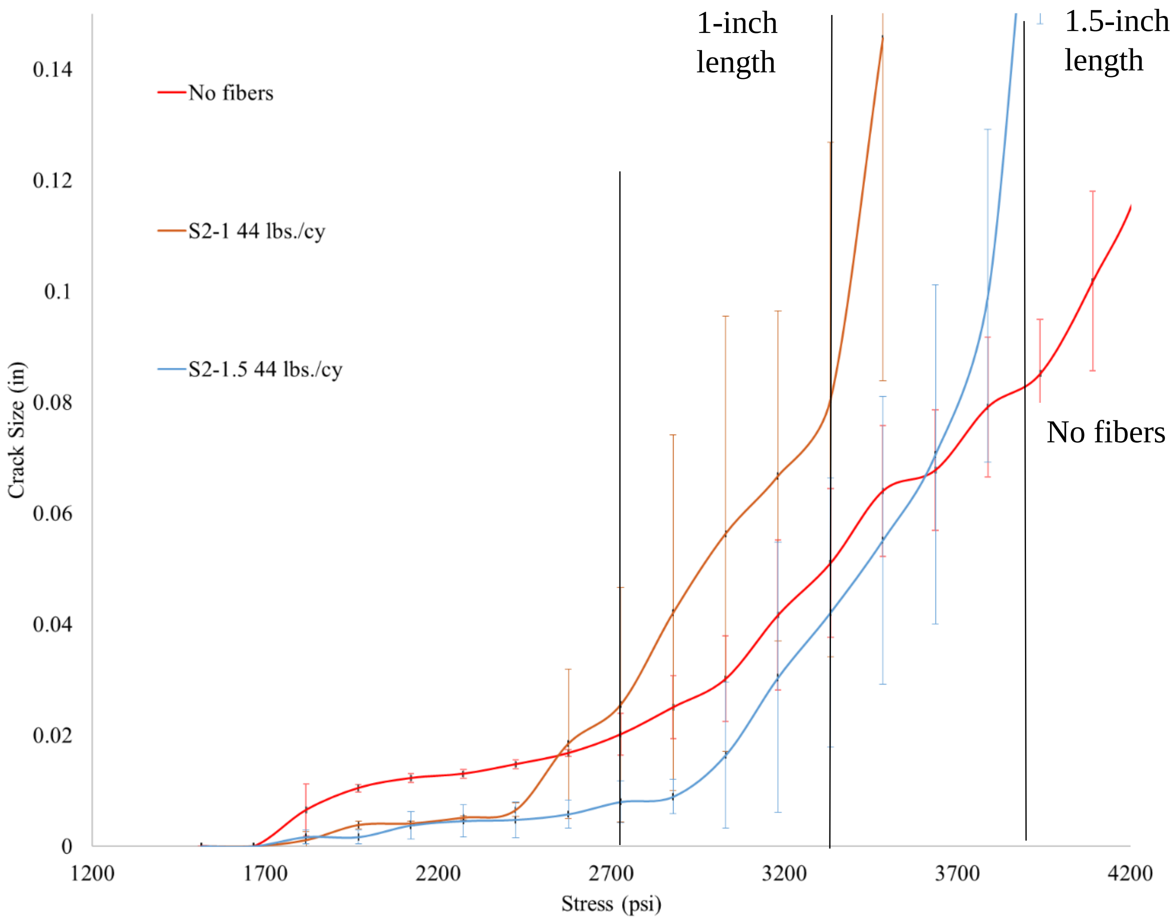


Figure 2-18 shows the Stress vs. Crack size graph for the middle dosage of two different length steel fibers.

The following image shows a bar chart comparing the average crack size of the 2 different length fibers that were tested compared to the control. It compares them to one another at equal volumes of fibers in the mixture. The figure shows that the 1.5-inch long fiber keeps the crack size smaller than both the 1-inch fiber and the no fiber mixtures at stresses of 2,700 and 3,300 psi. However, the 1.5-inch long fiber begins to allow the crack to grow faster than when no fibers were used at 3,900 psi. The 1-inch fiber again allows the crack to grow faster than the control at both 3,300 and 3,900 psi.

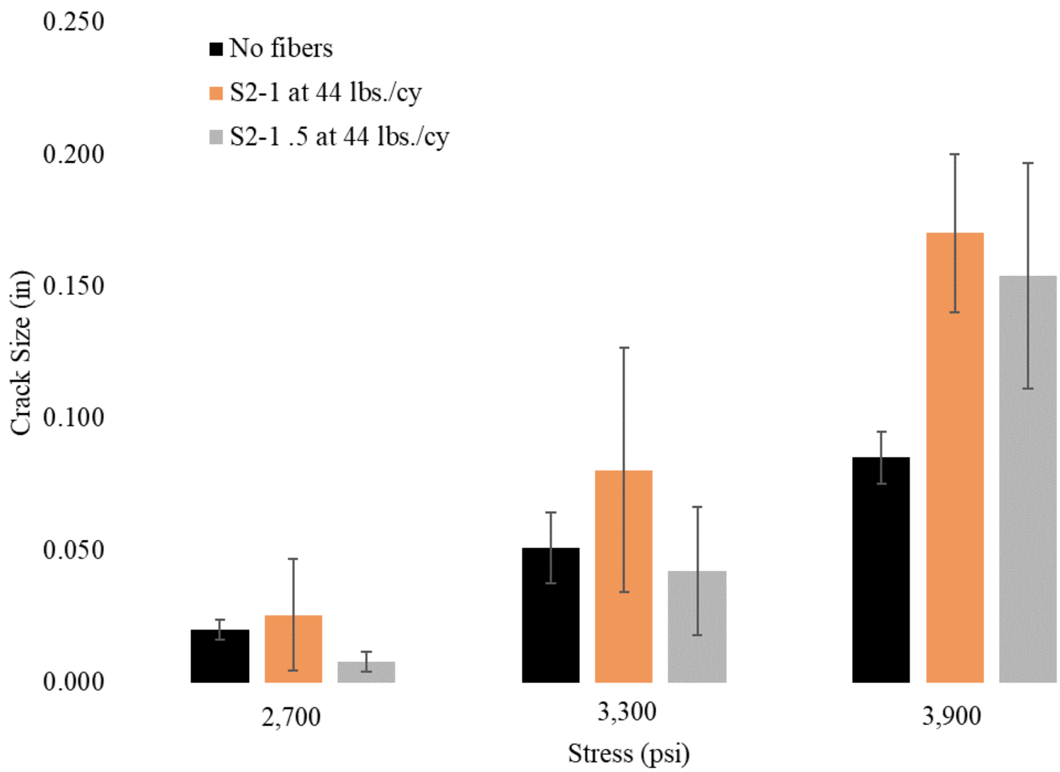


Figure 2-19 shows a bar chart comparing different fiber lengths to one another at equal volumes.

2.3.5.4 Varying Fiber Surfaces

Tests were done to determine how different surface textures impact the ability to resist cracking. 3 mixtures were done with the same type and amount of fibers used, but 1 fiber was considered to be smooth while the other 2 fibers had different types of embossment. The results are shown in Table 2-9. For these 3 mixes, the crack size was very similar up until stress of roughly 2,700 psi. After that, M3-E1 began to allow the crack to open at a faster rate than the other 2 mixes. Then, after the stress of about 3,300 psi, the M3-E2 began to allow the crack to propagate faster than the fiber with a smooth surface, especially at the lower dosage. At the middle and high dosages, the lower level of embossment performs only slightly worse than the smooth fiber. An example graph of this is shown in Figure 2-20, showing only the middle dosage of fibers. The other dosages can be found in the appendix. Overall on average, the crack growth for smooth fibers was 19, 27, and 37% more than embossed fibers at the stresses shown.

Table 2-9. Percent decrease in crack size at 3 different stresses for 3 different fiber surfaces.

Mix ID	% decrease at 2,700 psi	% decrease at 3,300 psi	% decrease at 3,900 psi
M3-E1 4 lbs./cy	13	7	0
M3-E1 8 lbs./cy	47	53	0
M3-E1 12 lbs./cy	68	68	50
M3 4 lbs./cy	83	85	56
M3 8 lbs./cy	76	84	72
M3 12 lbs./cy	88	83	73
M3-E2 4 lbs./cy	85	30	17
M3-E2 8 lbs./cy	70	78	68
M3-E2 12 lbs./cy	65	78	69

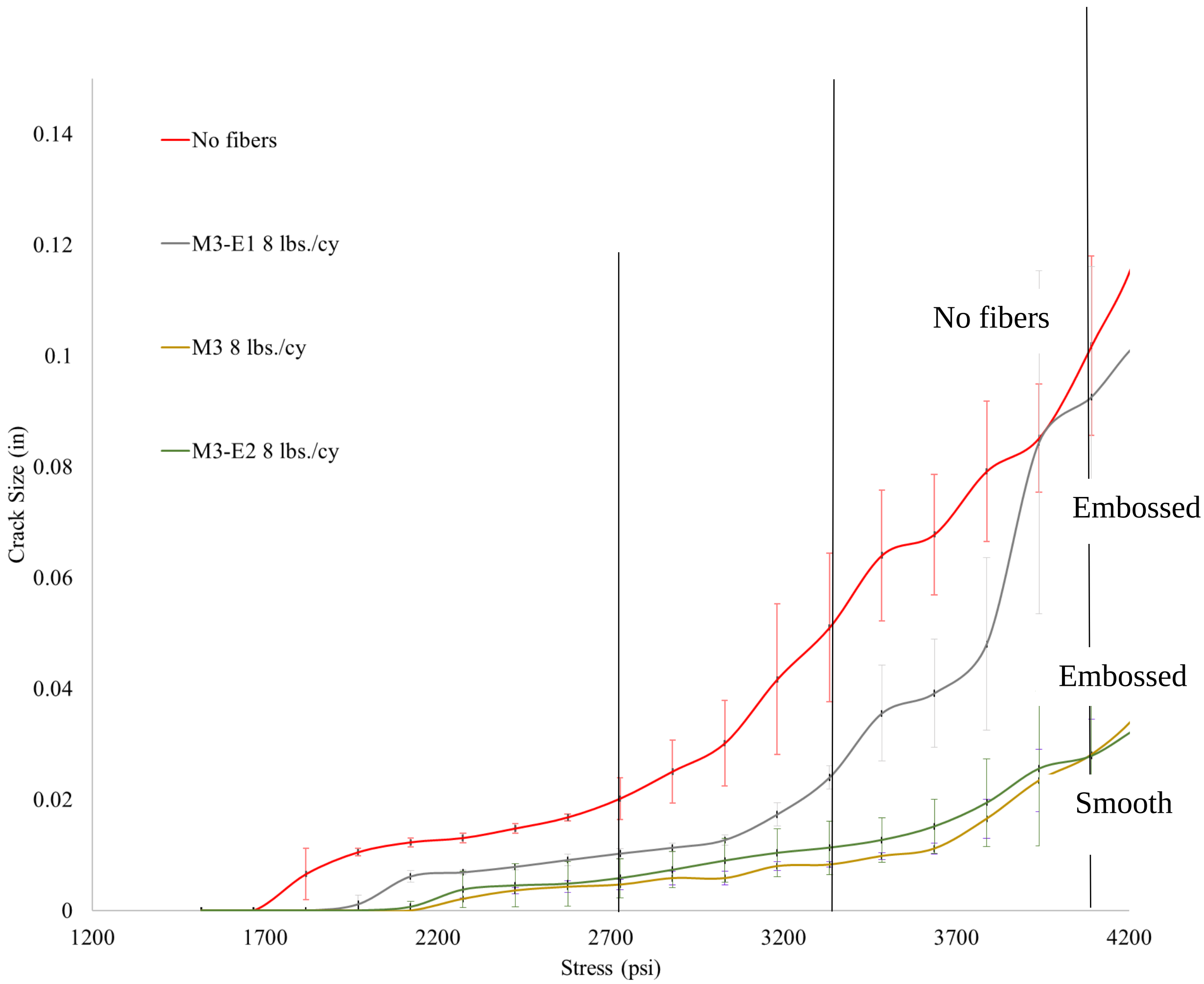


Figure 2-20 shows the Stress vs. Crack size graph for the middle dosage of three different embossed fibers.

This is shown again in a bar chart in Figure 2-21. It shows the crack size on the x-axis and the mixtures and dosages on the y-axis. It again shows that the crack size is much smaller for the smooth fiber compared to both embossed fibers at 4 lbs./cy. The mixtures become close to one another and keep the crack much smaller than the mix with no fibers at higher dosage rates.

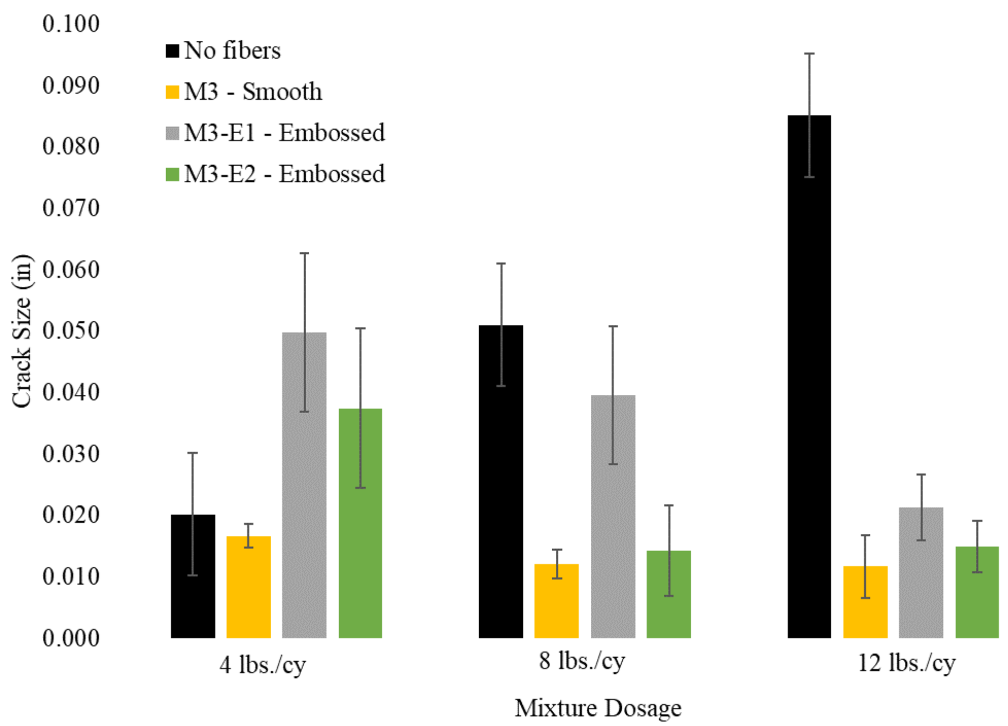


Figure 2-21 shows a bar chart comparing three different material surfaces to one another at different dosage rates.

Another example of this is shown with a different fiber. M4 and M4-E have the same properties, but one of them is embossed. The results for this are shown in Table 2-10, as well as an example with the middle dosage of fibers in Figure 2-22. The figures with the other dosages can be found in the appendix.

Table 2-10. Percent decrease in crack size at 3 different stresses for 2 different fiber surfaces.

Mix ID	% decrease at 2,700 psi	% decrease at 3,300 psi	% decrease at 3,900 psi
M4 4 lbs./cy	89	83	73
M4 8 lbs./cy	73	78	76
M4 12 lbs./cy	72	80	66
M4-E 4 lbs./cy	73	39	-24
M4-E 8 lbs./cy	64	22	0
M4-E 12 lbs./cy	69	37	20

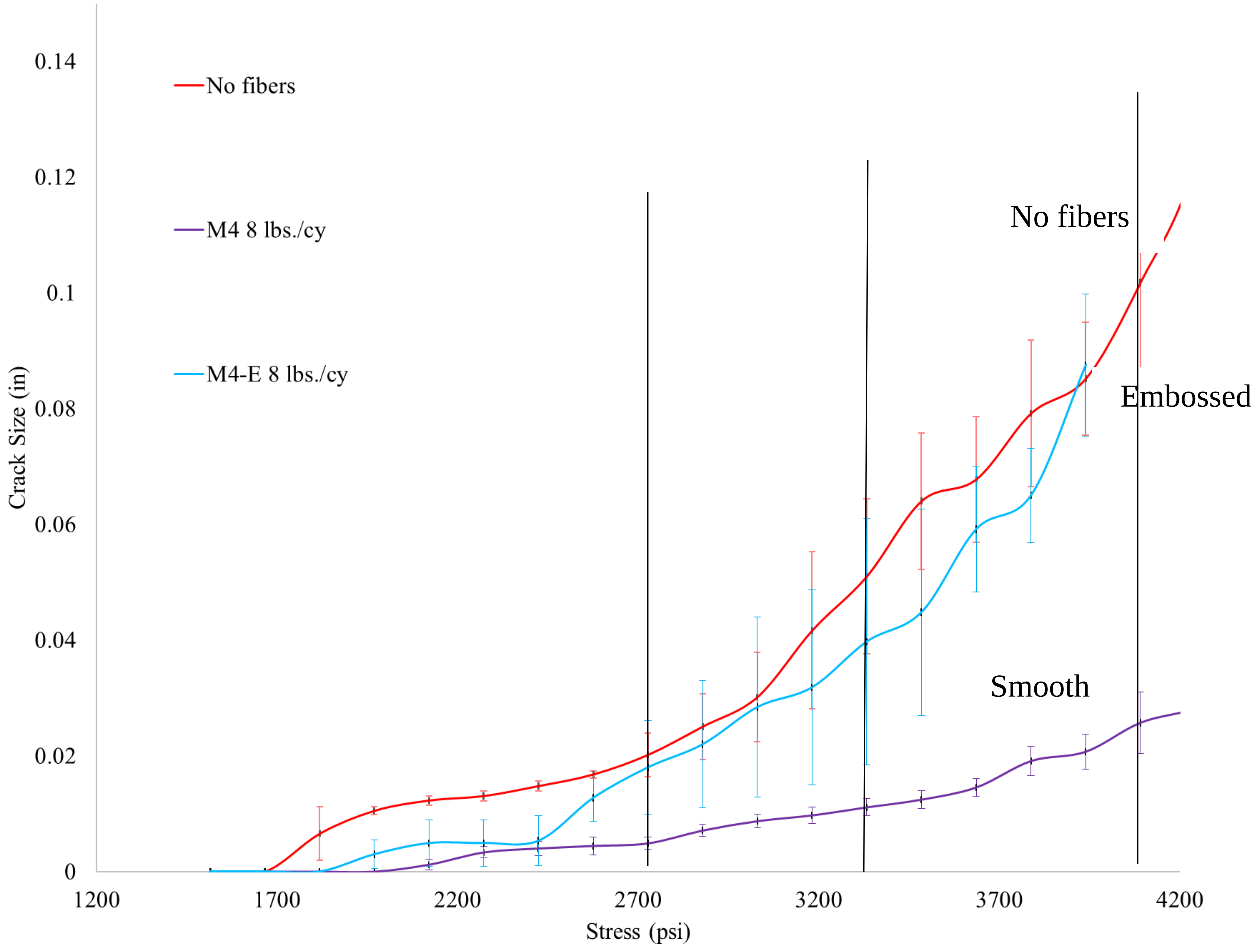


Figure 2-22 shows the Stress vs. Crack size graph for the middle dosage of two different embossed fibers.

This can be shown again in the bar chart in Figure 2-23. It shows the crack size of the 2 mixtures compared to the control. It once again shows that the crack size is much larger for the embossed fiber rather than the smooth fiber.

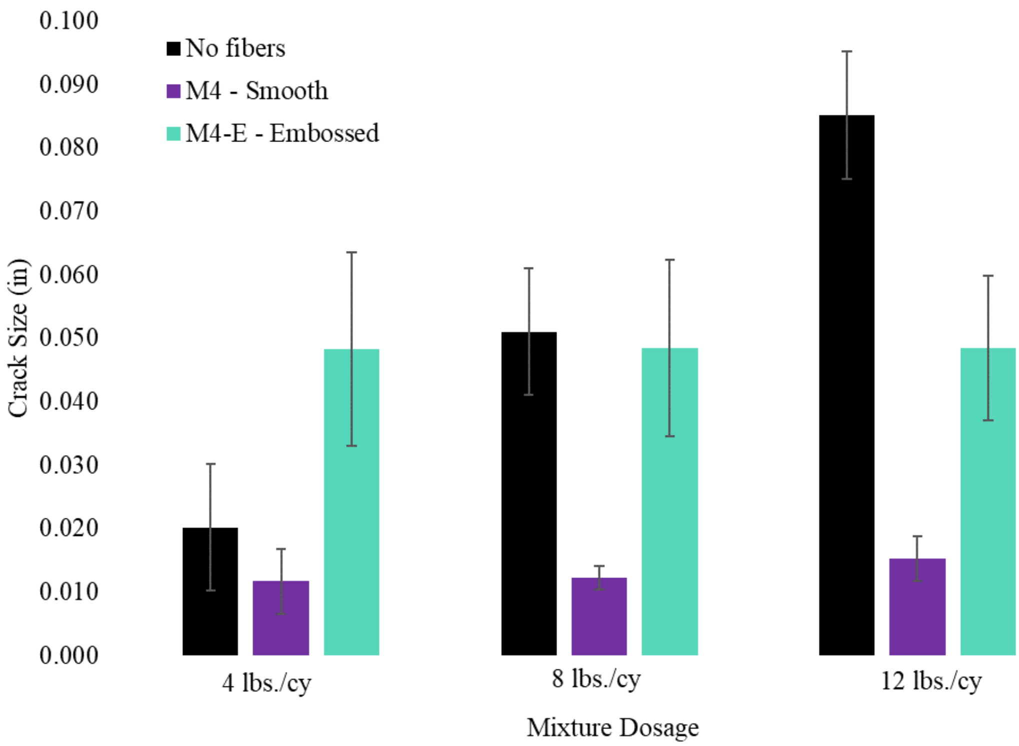


Figure 2-23 shows a bar chart comparing two different material surfaces to one another at different dosage rates.

One possible reason for the smooth fiber slowing the cracks the most is that it was able to bond with the concrete better than the embossed fibers. If the embossment of the fibers was either too close together or not deep enough, it could potentially have hurt the bond of the fibers to the concrete. At high dosages, there is not as big of a difference between the low level of embossment and the smooth fiber. When looking at only the highest dosages, there was a 29% difference, however, when looking at the lowest dosage, the difference is 52%. This could be due to the fiber count, with more fibers, even though the embossment may hurt the bond, there are still enough of them to keep the stress on each fiber low enough to decrease the crack size. It is important to note that all 5 of these fibers decrease the crack size compared to the control at 2,700 and 3,300 psi. M4-E 4 lbs./cy shows an increase in crack size compared to the control at the highest stress. This could be due to the impact loads when the fibers fail which may increase the crack size. This is discussed in more detail in the fiber length section. Further testing on different types of embossment would give insight as to why some types perform better than others.

2.4 PRACTICAL SIGNIFICANCE

The Split Beam Test offers a new way to investigate fibers for durability. This test can also provide important insights into fiber design and fiber dosage level. From these findings, it can be said that fibers should be used when trying to keep the crack size small inside of concrete. Fibers with a smooth surface should be chosen over fibers with an embossed surface for optimal results. Polypropylene fibers or hooked end steel fibers showed good performance over the materials investigated. At the low dosages, the steel kept the crack the smallest, and M4 kept the crack smaller than M3. However, they were not statistically different from one another. Fibers of at least 2 inches performed well in the mixtures with a maximum nominal aggregate size of 1 inch. Fibers that are shorter than 2 inches showed crack growth that is faster than if no fibers were used at all. If finishing is a priority, such as flatwork, fibers should be used at a dosage rate of 4 lbs./cy or less when using macro synthetic fibers or 33 lbs./cy when using steel fibers.

2.5 CONCLUSIONS

A new testing procedure called the Split Beam Test was developed to test the ability of fibers to slow the crack growth in concrete. The test was able to see how both steel and synthetic fibers impact the crack size of concrete and can be used as a comparison between fibers. The following were found from this work:

- For 33 fiber mixtures, at filling holes in the float test, 0% performed well, 18% performed adequately, and 82% performed poorly.
- For 33 fiber mixtures, at smoothing the surface in the float test, 9% performed well, 39% performed adequately, and 52% performed poorly.
- Compressive strength showed some statistical difference between the fibers, with an average decrease of 600 psi, or 10%, at 28 days for the fibers that showed a statistical decrease.
- Steel and polypropylene fibers performed equally and they decreased the crack size by an average of 30% more than copolymers and polyolefin.
- Fibers that are shorter than 2 inches showed a decrease in crack size at a stress of 2,700 psi by an average of 44%. However, at stresses of 3,300 and 3,900 psi, the fibers shorter than 2 inches showed an increase in crack growth by 61% and 116%, respectively.
- Fibers that were 2 inches long showed an average decrease in the crack growth of 67%, 62%, and 44% at stresses of 2,700, 3,300, and 3,900 psi, respectively.
- On average, fibers with embossment decreased the crack growth by 19%, 37%, and 47% less than smooth fibers at 2,700, 3,300, and 3,900 psi, respectively.

CHAPTER III

SUMMARY

3.0 SUMMARY

This thesis has composed a study to create a simple test method to test the performance of fibers and compare 11 different fiber types at 3 different dosages to one another. The main focus was to first develop the method to test the fibers. The fibers were then tested for their performance in the Split Beam Test and Float Test.

The Split Beam Test was created to determine the performance of the different fiber types at different dosages. The test showed to produce consistent results within mixtures and provides a simple way to compare fiber types and dosages to one another.

Promising results were shown for the use of fibers inside of concrete. The use of fibers can decrease the crack size of concrete compared to a mixture with no fibers, while also still providing moderate to good results in the Float Test if used at the right dosage. This was found to be true for many different fiber types. The compressive strength of cylinders that included fibers showed that there can be some statistical difference, however, 97% of mixtures reached a compressive strength of 5,000 psi at 28 days.

3.1 FUTURE WORK

Future work should be considered on fibers to determine which fiber dosages, types, lengths, and surfaces are best for a given concrete mixture. One of the limitations of this study is that only one mixture design was studied, some fibers may perform better than others depending on things about the concrete mix design.

Fiber types are a component of this test that needs more research. Different materials with other properties that are consistent should be studied to determine what fibers are the best and why. Modulus, tensile strength, aspect ratio, material, and other parameters are sure to affect the performance of fibers at resisting crack growth.

The relationship between aggregate size and fiber length is another parameter that should be studied. Due to only one mixture design being tested, the relationship is not fully understood. Mixtures with larger aggregate and 2-inch length fibers as well as smaller aggregate and 1-inch length fibers would give much more insight into the relationship between the two.

Surface finishes could be investigated to determine if certain embossing could help the fibers perform well in the Split Beam Test. Different spacing and depths of the embossment may very well have an impact on the performance of the fibers. The information and types of embossment for this particular test were limited but showed conclusive results that every type of embossment performed worse than the smooth fibers, but not all embossments performed the same.

REFERENCES

[1] Holland, Jerry. Personal Communication, May 1, 2021

[2] Bledzki, Andrzej K., Volker E. Sperber, and Omar Faruk. *Natural and wood fibre reinforcement in polymers*. Vol. 13. iSmithers Rapra Publishing, 2002.

[3] Shah, Surendra P., and B. Vijaya Rangan. "Fiber reinforced concrete properties." *Journal Proceedings*. Vol. 68. No. 2. 1971.

[4] Sukontasukkul, Piti, and Pitthaya Jamsawang. "Use of steel and polypropylene fibers to improve flexural performance of deep soil–cement column." *Construction and Building Materials* 29 (2012): 201-205.

[5] Meyer, Christian. "Concrete materials and sustainable development in the USA." *Structural engineering international* 14.3 (2004): 203-207.

[6] Wang, Kejin, et al. "Permeability study of cracked concrete."Cement and concrete research 27.3 (1997): 381-393.

[7] Carmona, Jacinto R., Gonzalo Ruiz, and Javier R. del Viso. "Mixed-mode crack propagation through reinforced concrete." Engineering Fracture Mechanics 74.17 (2007): 2788-2809.

[8] Ingraffea, Anthony R., and Victor Saouma. "Numerical modeling of discrete crack propagation in reinforced and plain concrete." Fracture mechanics of concrete: Structural application and numerical calculation. Springer, Dordrecht, 1985. 171-225.

[9] Rena, C. Yu, and Gonzalo Ruiz. "Explicit finite element modeling of static crack propagation in reinforced concrete." International journal of fracture 141.3-4 (2006): 357-372.

[10] Banthia, Nandakumar, and N. Nandakumar. "Crack growth resistance of hybrid fiber reinforced cement composites." *Cement and Concrete Composites* 25.1 (2003): 3-9.

[11] ASTM C1018, 1997 (Withdrawn Version), "Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)," ASTM International, West Conshohocken, PA, 1997, www.ASTM.org.

[12] ASTM C1609, 2019, "Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete"(Using Beam With Third-Point Loading). ASTM International, West Conshohocken, PA, 1997, www.ASTM.org.

[13] ASTM C150, 2020, "Standard Specification for Portland Cement" ASTM International, West Conshohocken, PA, 2020, www.ASTM.org

[14] ASTM C33, 2018, "Specification for Concrete Aggregates," ASTM International, West Conshohocken, PA, 2003, www.ASTM.org.

[15] ASTM C143, 2020, "Standard Test Method for Slump of Hydraulic-Cement Concrete" ASTM International, West Conshohocken, PA, 2020, www.ASTM.org

[16] ASTM C138, 2017, "Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete" ASTM International Conshohocken, PA, 2017, www.ASTM.org

[17] ASTM C231, 2017, "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method" ASTM International Conshohocken, PA, 2017, www.ASTM.org

[18] ASTM C192, 2019, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory," ASTM International, West Conshohocken, PA, 2019, www.ASTM.org

[19] ASTM C39, 2020, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" ASTM International, West Conshohocken, PA, 2020, www.ASTM.org

[20] Cook. D. "Aggregate Proportioning for Slip Formed Pavements and Flowable Concrete", Oklahoma State University. Stillwater, OK; 2015.

[21] Aqib. S. "Analysis of Induced Crack Sizes in Reinforced Concrete Beams and Performance Evaluation of Silane in Concrete Bridge Decks", Oklahoma State University. Stillwater, OK; 2020.

[22] Engineering ToolBox, (2004). *Friction and Friction Coefficients*. [online] Available at: https://www.engineeringtoolbox.com/friction-coefficients-d_778.html

[23] ASTM C1116 / C1116M - 10a(2015). "Standard Specification for Fiber-Reinforced Concrete" ASTM International, West Conshokocken, PA, 2015, www.ASTM.org.

APPENDICES

Standard Method of Test for

The Split Beam Test for Fiber Reinforced Concrete

1. SCOPE

1.1 This test method describes a technique to compare different fiber types and amounts of fiber within a given concrete mixture to control cracking. This test uses wedges of a fixed geometry that are cast into the beam and then loaded with a low-capacity hydraulic press. The geometry of the wedges causes a crack to form that is manually measured.

1.2 *Unit* – the values stated in either SI units or inch-pound units are to be regarded separately as the standard. Within the text, the inch-pound units are shown in brackets. The values stated in each system are not exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in nonconformance with the standard.

1.3 *The standard does not purport to address all the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.*

2.0 REFERENCED DOCUMENTS

2.1 Robertson, B., McArtor, E., Dickey, M., Ley, MT., Cook, D. (2020) “Development of Concrete Mixtures to Mitigate Bridge Deck Cracking,” Oklahoma Department of Transportation (ODOT). ODOT SP&R Item Number 2274. Final Report. Oklahoma City, OK.

2.2 Dickey, M. (2021) “Additives to Improve the Performance of Concrete”, Thesis requirements for the degree of Master of Science, School of Civil and Environmental Engineering, Oklahoma State University at Stillwater, OK.

2.3 AASHTO R60, Practice for Sampling Freshly Mixed Concrete

2.4 ASTM C172, Practice for Sampling Freshly Mixed Concrete

2.5 ASTM C192 Practice for Making and Curing Concrete Strength Specimens in the Laboratory

3.0 SUMMARY OF TEST METHOD

3.1 This test method describes a simple test for the fiber type and dosage to control the amount of cracking in a concrete mixture. This is done by casting wedges that are aligned on the top and bottom of a concrete beam. The wedges are a fixed geometry and they are loaded with a platen with a matching geometry. A reinforcing bar is cast in the center of the beam to restrain the movement.

3.2 As load is applied to the wedges they form a crack. This crack is measured at different load increments and this is used to calculate the average size of the crack at a given tensile stress. The size of the crack can be determined by using a crack card.

4.0 SIGNIFICANCE AND USE

4.1 This test method provides a way to evaluate the tensile strength of the concrete mixture.

Additionally, if fiber reinforcement was incorporated into the concrete mixture, this test method can measure the decrease in crack size over using conventional rebar.

5.0 APPARATUS

5.1 Testing Machine – The testing machine shall have sufficient capacity and capability of meeting the rates of loading and keeping a constant load over time of 450 lb/min. The accuracy and calibration of this testing machine shall conform to the same requirements as AASHTO T97 and ASTM C78.

5.2 Wedges – Two mild steel plates with a fixed geometry are cast into the top and bottom of the concrete beam at midspan. The wedges are glued so that they hold together during casting and come apart when they are loaded. The dimensions are shown in Figure 1.

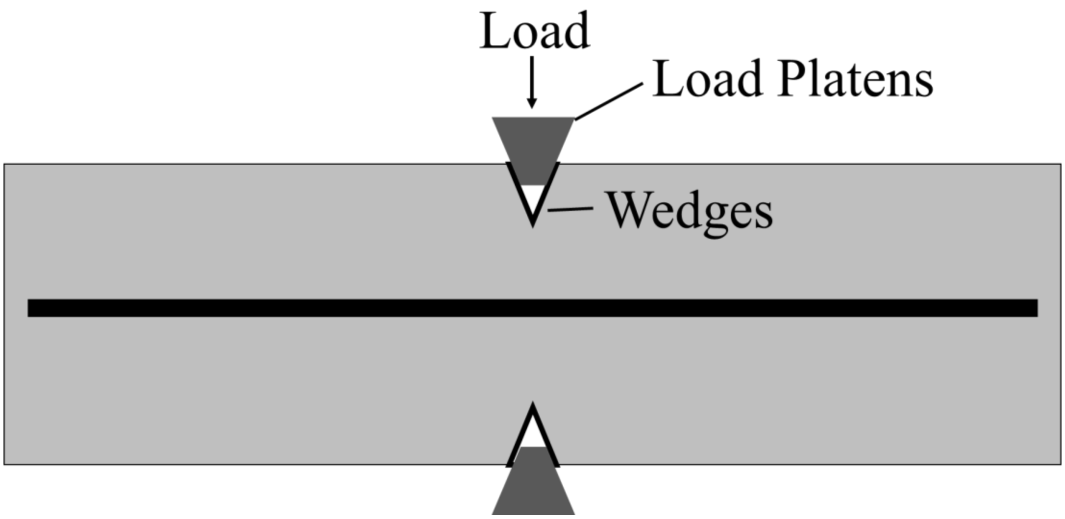
5.3 Length Measuring Device – A crack card, ruler, or other similar measuring devices on increments of 1/16" or smaller. The length of the measuring device must exceed 3 inches.

5.4 Split Beam Specimen Mold – The inter dimensions of the steel mold shall be 6 inches wide, 6 inches deep, and 20 inches long. Bearing notches shall also be able to be mounted onto the top and bottom mid-span of the beam.

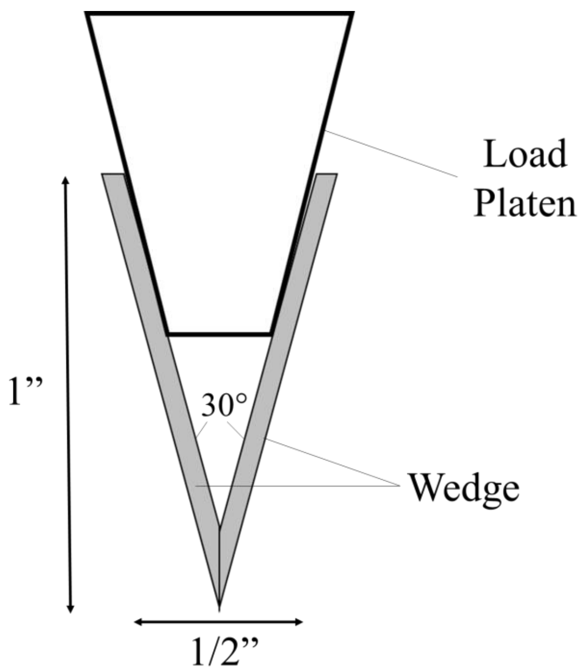
5.5 Longitudinal Steel Reinforcement – One #3 Grade 60 deformed steel reinforcement ASTM A615 was placed directly in the middle of the beam.

5.6 Plastic Chair – A 3-inch tall plastic chair is used to hold each end of the rebar in-place while the concrete is cast.

5.7 Load platen – Two metal load platens that are machined to fit the wedge geometry. Load is applied to the platens to apply loads to the wedges and cause the beam to crack in a controlled manner.



(a)



(b)

Figure 1 shows the schematic of the split beam and notch with (a) being an overall view and (b) being a close-up image of the notch.

6.0 SAMPLING, TEST SPECIMENS, AND TEST UNITS

6.1 Sample concrete in accordance with AASHTO R 60.

6.2 Assemble the beam molds, reinforcement steel, and mount wedges onto the molds. The bottom wedge should be placed in the center of the beam as shown below and taped onto the to secure it. The top-notch should be glued to a metal bar to help suspend it to the top of the beam as shown below. The layout of the beam, notches, rebar is shown in Figure 2.

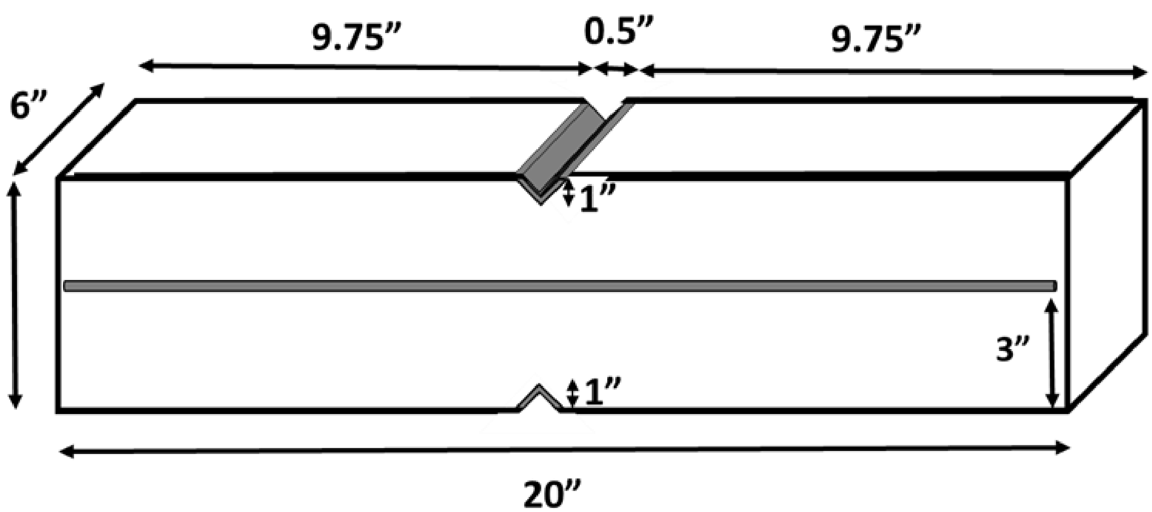
6.2.1 Placement of reinforcement – place a #3 steel reinforcement bar in the middle of the beam and held into place using a 3 inch plastic chair on each end of the reinforcement steel bar.

6.2.2. Mounting of wedges on mold– The notches are glued using DAP Rapid fuse all-purpose glue and taped into their respective positions to make sure there is no movement during consolidation.

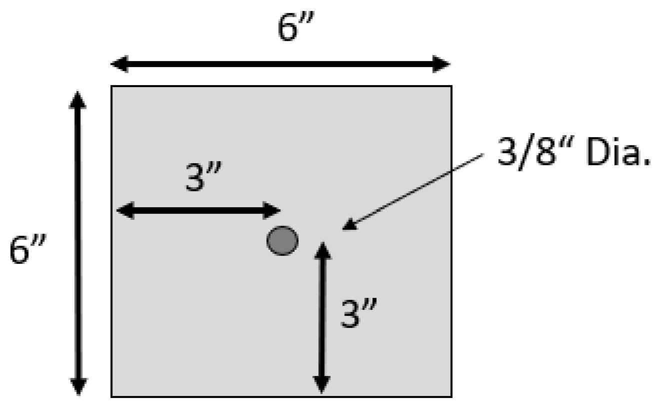
6.3 Consolidation of sample beams – The beams were consolidated using an external vibrating table. The table ensures that neither the rebar nor the notches move during the consolidation process. The vibration duration was 5 +/- 1 second for each layer and the vibrations per minute were at least 3600, per ASTM C192.

6.4 The beam must be surface finished with a wood float, magnesium float, or steel trowel, according to ASTM C192.

6.5 Curing conditions of sample beam – After the beam has been cast and finished, it is covered with wet burlap and a tarp for 48 h. The beam is demolded and then stored in an environmentally controlled room fog room that is held at 73° F for an additional 24 h. All curing met the standards of ASTM C192.



(a)



(b)

(c)

Figure 2 shows the schematic of the split beam showing the (a) front view, (b) side view, and (c) real image of the split beam.

7.0 PROCEDURE

7.1 The beams are then tested after 72 hours.

7.2 Before loading the specimen, the mid-span of the beam is marked at 1.5 inches, 3 inches, and 4.5 inches from the top.

7.3 The beam is loaded into the test machine using the notched wedges of the beam to be seated with the upper and lower bearding wedges as the supports for load distribution.

7.4 After the beam is properly seating into the machine, the beam is loaded at 1,500 lbs/min until a load of 2,500 lbs is reached.

7.5 Then the loading rate changes to incremental steps. The sample is loaded in incremental steps of 250 lbs. and this load is held constant for 30 seconds.

7.6 For each loading step the crack size and load are recorded.

8.0 CALCULATION AND REPORT

8.1 The crack size and load are recorded at each loading step. Record the deflection to the nearest 1/16 inch, crack size to the nearest 1/16 inch, and the load to the nearest 10 lbs.

9.0 KEYWORDS

10.1 Split Beam Test; Tensile Strength of Concrete; Concrete Strength; Fiber Reinforcement

Development Length Calculations

$$L_d = \left(\frac{3}{40} \frac{f_y}{\sqrt{f'_c}} \frac{\min(\psi_t \psi_e, 1.7)\psi_s \lambda}{\min\left(\left(\frac{c_b + K_{tr}}{d_b}\right), 2.5\right)} \right) d_b$$

(3/40) * (60,000/sqrt(4000)) * ((1*.8*1)/2.5) = 8.54 inches

Load to Stress Calculations

The modulus of elasticity was then found using:

Modulus of Elasticity = 57,000 * sqrt(f'c) = 3,513,716 in^4 Equation 2

Using a load of 1,000 pounds, the following was found:

Horizontal friction force = .7 * 1000/2 = 350 lbs. Equation 3

Because the loading head and wedges are made of steel, there is a frictional force that is generated. The friction force is parallel to the surface of the notch and because the steel is clean and dry, it is considered to be 0.7 [20]. This friction factor was multiplied by the load divided by 2 because two wedges have the friction acting on them.

Horizontal normal force = 2 * 1 * 1000 = 2000 lbs. Equation 4

The normal force is acting equally and opposite to the load applied. The load is multiplied by two because two wedges are taking the load of 1,000 lbs.

Effective horizontal force = 2,000 lbs. – 350 lbs. = 1,650 lbs. Equation 5

The effective normal force is the normal force applied minus the frictional losses from the friction force.

Effective beam depth = 6” – 1” – 1” = 4 inches Equation 6

The total depth of the beam is 6 inches. The depth of each notch, both the top and bottom, is 1 inch. The effective depth does not take into account the wedges, so they were subtracted to find the effective depth of the concrete to be 4 inches.

Cross sectional area of concrete (A_c) = 6” * 4” = 24 in^2 Equation 7

The 6 inches is the width of the beam and it is multiplied by the effective depth of the concrete.

Area of steel #3 bar (A_s) = .11 in^2

Concrete: E_c*A_c = (3,513,715 * 24)/1000 = 84,329 kips Equation 8

To find the load in the concrete, the modulus was multiplied by the area. It was then divided by 1,000 to put it into kips rather than pounds.

Steel: E_s*A_s = (29,000,000 * .11)/1000 = 3,190 kips Equation 9

The same was done for the steel, to find the load of 3,190 kips.

% force in steel = 3,190/(84,329 + 3,190) = 3.6% Equation 10

To find the percentage of the force in the steel, the force in the steel was divided by the total force in the beam.

% force in concrete = 96.4%

This is the rest of the load, 100% - 3.6% = 96.4%

Finally, from this, we can determine the stress in both the steel and the concrete so that the total stress for a 1,000-pound load can be found.

Stress in steel = (1,650 * .036)/.11 = 540 psi Equation 10

The stress in the steel should be the total effective load on the beam multiplied by the percentage of the force in the steel. They will give us the load in just the steel. To convert to psi, that load is divided by the area of the steel.

Stress in concrete = (1,650 * .964)/24 = 66.3 psi Equation 11

The same thing was done to find the stress in the concrete for a given load of 1,000 lbs.

Finally, the stress in the steel and the concrete were then added together to find the total stress in the beam for a 1,000-pound load.

Table A-1 Float Test Data

Mix Name	# of passes to close holes	# of passes to smooth surface
0 lbs./cy	6	6
M1 4 lbs./cy	8	8
M1 8 lbs./cy	8	8
M1 12 lbs./cy	13	13
M2 4 lbs./cy	8	8
M2 8 lbs./cy	14	14
M2 12 lbs./cy	14	14
M3-E1 4 lbs./cy	6	6
M3-E1 8 lbs./cy	12	12
M3-E1 12 lbs./cy	14	14
M3 lbs./cy	7	7
M3 8 lbs./cy	8	8
M3 12 lbs./cy	30	30
M3-E2 4 lbs./cy	8	8
M3-E2 8 lbs./cy	10	10
M3-E2 12 lbs./cy	15	15
M4 4 lbs./cy	6	6
M4 8 lbs./cy	9	9
M4 12 lbs./cy	11	11
M4-E 4 lbs./cy	8	8
M4-E 8 lbs./cy	11	11
M4-E 12 lbs./cy	13	13
M4-C 4 lbs./cy	6	6
M4-C 8 lbs./cy	7	7
M4-C 12 lbs./cy	10	10
S1 33 lbs./cy	9	9
S1 44 lbs./cy	11	11
S1 66 lbs./cy	11	11
S2-1 33 lbs./cy	8	8
S2-1 44 lbs./cy	8	8
S2-1 66 lbs/cy	12	12
S2-1.5 33 lbs./cy	7	7
S2-1.5 44 lbs./cy	8	8
S2-1.5 66 lbs./cy	8	8

Table A-2 Compressive Strength Table

Mixture	Age	Compressive Strength (psi)	Standard Deviation (psi)
Control	3 days	4130	239
	28 days	6000	130
M1 4 lb/cy	3 days	3600	180
	28 days	6030	98
M1 8 lb/cy	3 days	3140	44
	28 days	5830	32
M1 12 lb/cy	3 days	4320	167
	28 days	6430	205
M2 4 lb/cy	3 days	4710	68
	28 days	7060	366
M2 8 lb/cy	3 days	4340	257
	28 days	6040	416
M2 12 lb/cy	3 days	4640	162
	28 days	6330	213
M3-E1 4 lb/cy	3 days	4120	150
	28 days	6030	101
M3-E1 8 lb/cy	3 days	4480	56
	28 days	6200	290
M3-E1 12 lb/cy	3 days	4440	65
	28 days	6700	329
M3 4 lb/cy	3 days	3490	146
	28 days	6510	59
M3 8 lb/cy	3 days	3480	195
	28 days	6000	199
M3 12 lb/cy	3 days	3850	55
	28 days	5650	107
M3-E2 4 lb/cy	3 days	3810	190
	28 days	6200	175
M3-E2 8 lb/cy	3 days	3270	373
	28 days	5980	314
M3-E2 12 lb/cy	3 days	3290	84
	28 days	5590	300
M4 4 lb/cy	3 days	3530	24
	28 days	6290	306
M4 8 lb/cy	3 days	3000	291
	28 days	4890	121
M4 12 lb/cy	3 days	3190	110
	28 days	5370	313
M4-E 4 lb/cy	3 days	3540	50
	28 days	5220	252
M4-E 8 lb/cy	3 days	3610	35
	28 days	6260	304
M4-E 12 lb/cy	3 days	3360	75
	28 days	5160	130
M4-C 4 lb/cy	3 days	4070	207
	28 days		
M4-C 8 lb/cy	3 days	4100	132
	28 days		
M4-C 12 lb/cy	3 days	3860	51
	28 days		

S1 33 lb/cy	**3 days**	3870	47
	28 days	5980	77
S1 44 lb/cy	**3 days**	3960	64
	28 days	6690	35
S1 66 lb/cy	**3 days**	3690	98
	28 days	6120	368
S2-1 33 lb/cy	**3 days**	3650	387
	28 days	5890	107
S2-1 44 lb/cy	**3 days**	3910	112
	28 days	6160	119
S2-1 66 lb/cy	**3 days**	4140	116
	28 days	6450	239
S2-1.5 33 lb/cy	**3 days**	4280	233
	28 days	7260	184
S2-1.5 44 lb/cy	**3 days**	4250	112
	28 days	7300	355
S2-1.5 66 lb/cy	**3 days**	4320	80
	28 days	6960	90

Table A-3 Compressive Strength T-Test

3 day		M1 4	M1 8	M1 12	M2 4	M2 8	M2 12	M3 4	M3 8	M3 12	M4 4	M4 8	M4 12	M5 4	M5 8	M5 12	M6 4	M6 8	M6 12
	Control	0.069406	0.024386	0.396165	0.06596	0.443405	0.076387	0.943006	0.171903	0.207435	0.041703	0.042566	0.231281	0.212571	0.061423	0.026783	0.068815	0.014216	0.01718
28 day		M1 4	M1 8	M1 12	M2 4	M2 8	M2 12	M3 4	M3 8	M3 12	M4 4	M4 8	M4 12	M5 4	M5 8	M5 12	M6 4	M6 8	M6 12
	Control	0.777022	0.206404	0.158131	0.042345	0.897687	0.147298	0.801313	0.447115	0.079683	0.017941	0.991156	0.044861	0.265406	0.930467	0.18114	0.312284	0.000935	0.087589

M7 4	M7 8	M7 12	M8 4	M8 8	M8 12	S1 33	S1 44	S1 66	S2 33	S2 44	S2 66	S3 33	S3 44	S3 66
0.065572	0.086796	0.034991	0.777393	0.869598	0.242701	0.263002	0.411486	0.105475	0.222262	0.326747	0.981775	0.504625	0.592678	0.396326
M7 4	M7 8	M7 12	M8 4	M8 8	M8 12	S1 33	S1 44	S1 66	S2 33	S2 44	S2 66	S3 33	S3 44	S3 66
0.029925	0.361789	0.002884	#DIV/0!	#DIV/0!	#DIV/0!	0.878023	0.012361	0.701092	0.408091	0.271351	0.098122	0.002106	0.024317	0.001642

Table A-4 Fiber material T-Test at 3,900 psi

	M3	M4	S1
Control	0.009385	0.004686	0.006977
M3		0.205114	0.008275
M4			0.260567
S1			

If the cell is red, then the 2 mixtures are statistically different, if the cell is green, then the 2 mixtures are not statistically different. This shows that M3 and M4 are statistically the same, M4 and S1 are statistically the same. But M3 and S1 are not the same. All three are statistically better than the control mix with no fibers

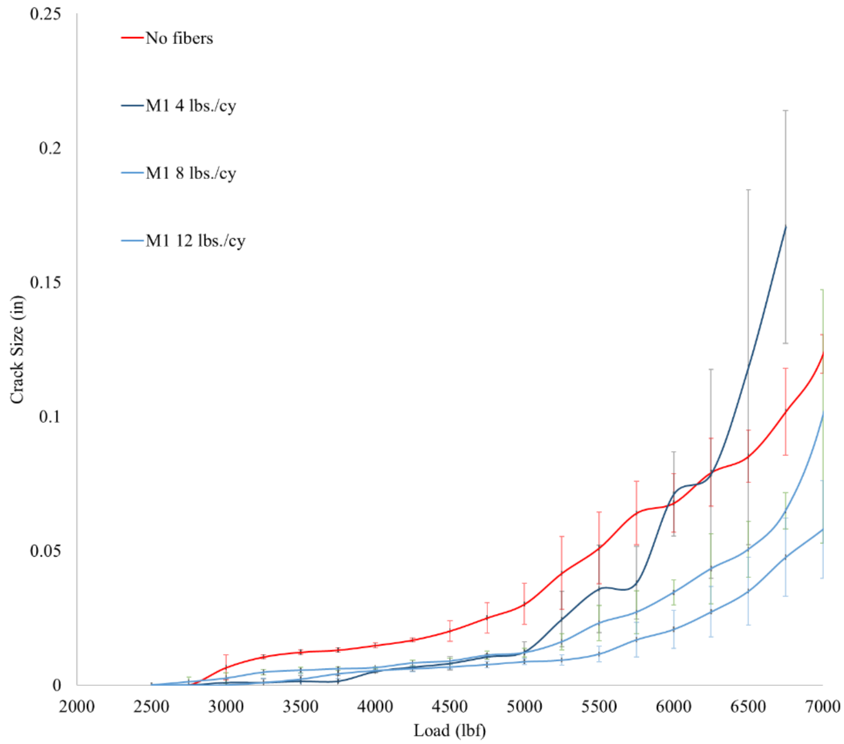


Figure A-1 shows the Stress vs. Crack size graph for the different dosages of fiber M1

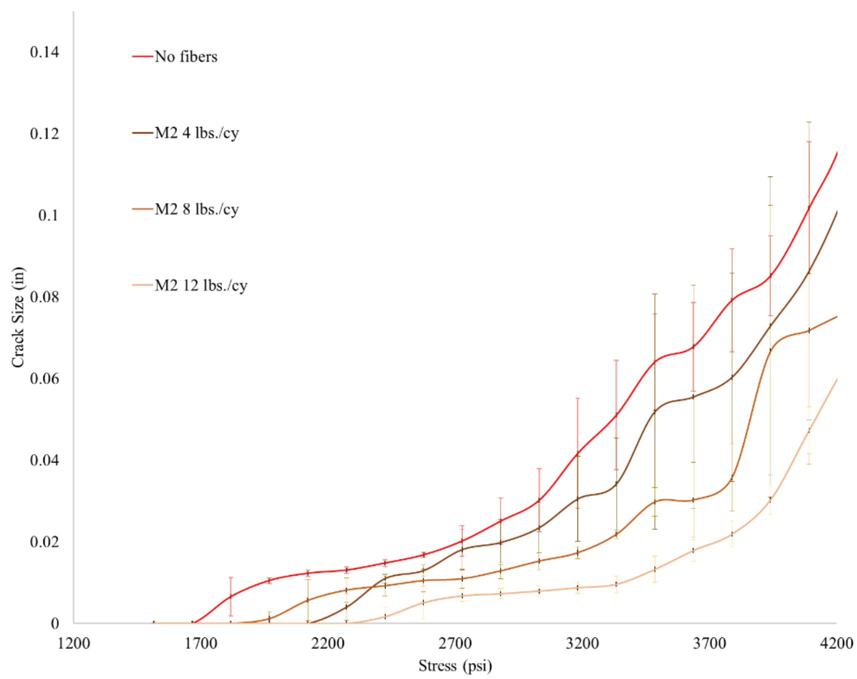


Figure A-2 shows the Stress vs. Crack size graph for the different dosages of fiber M2

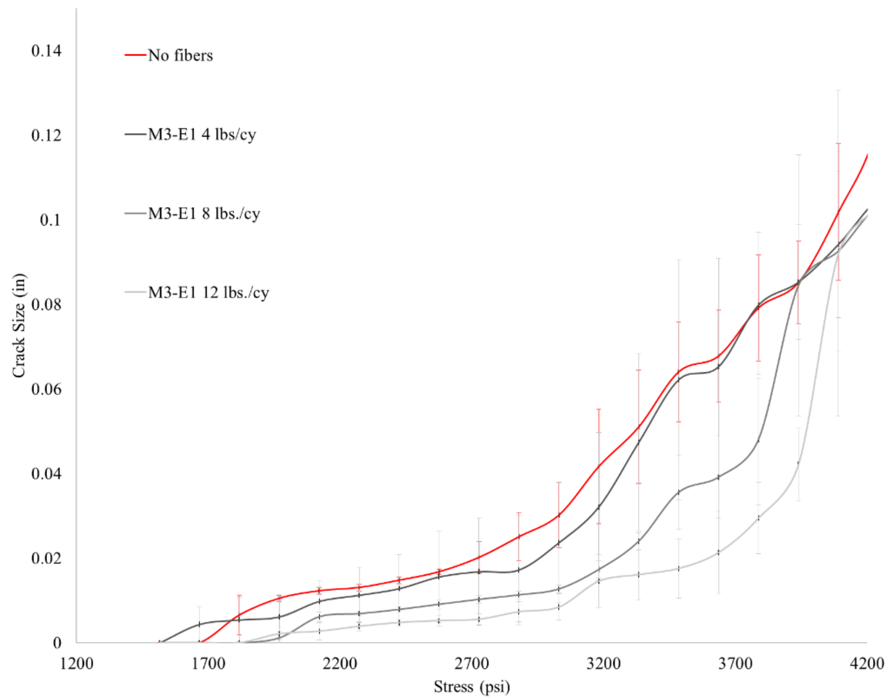


Figure A-3 shows the Stress vs. Crack size graph for the different dosages of fiber M3-E1

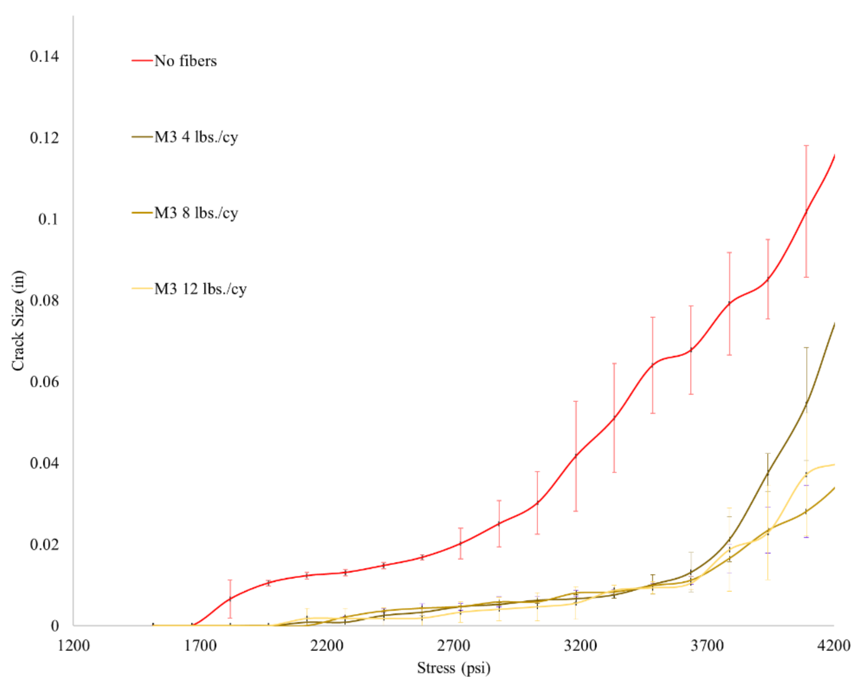


Figure A-4 shows the Stress vs. Crack size graph for the different dosages of fiber M3

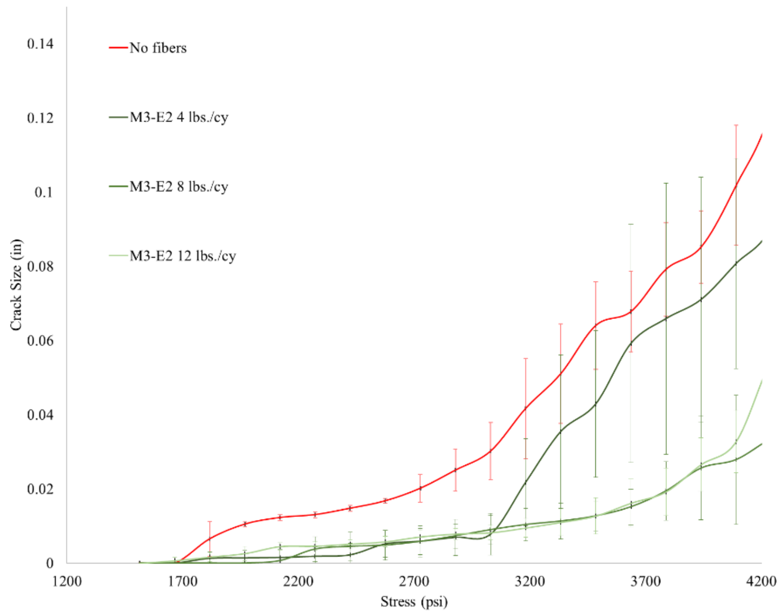


Figure A-5 shows the Stress vs. Crack size graph for the different dosages of fiber M3-E2

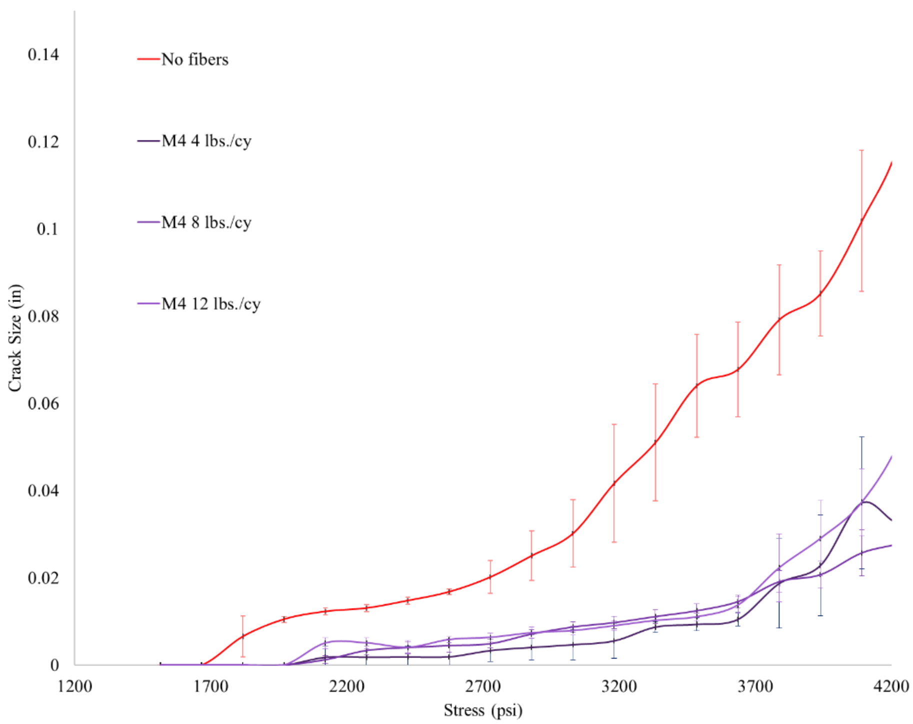


Figure A-6 shows the Stress vs. Crack size graph for the different dosages of fiber M4

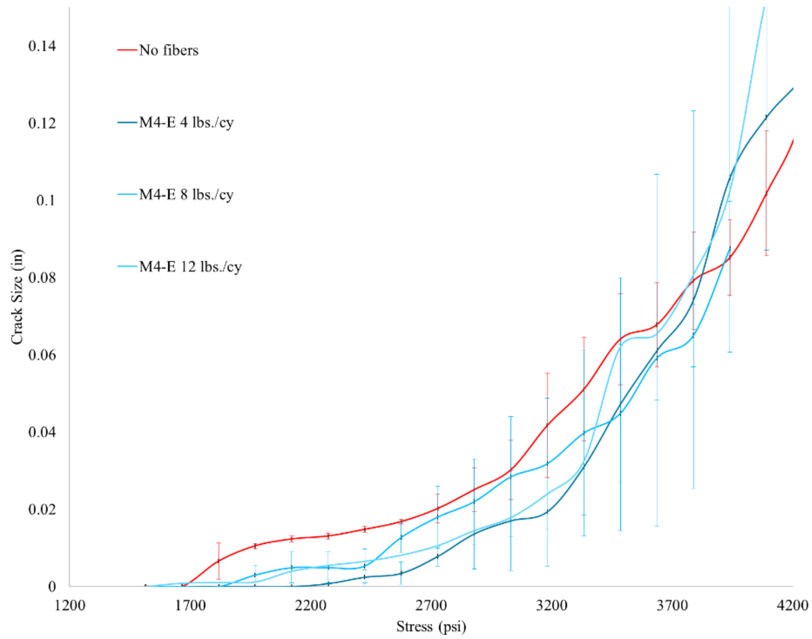


Figure A-7 shows the Stress vs. Crack size graph for the different dosages of fiber M4-E

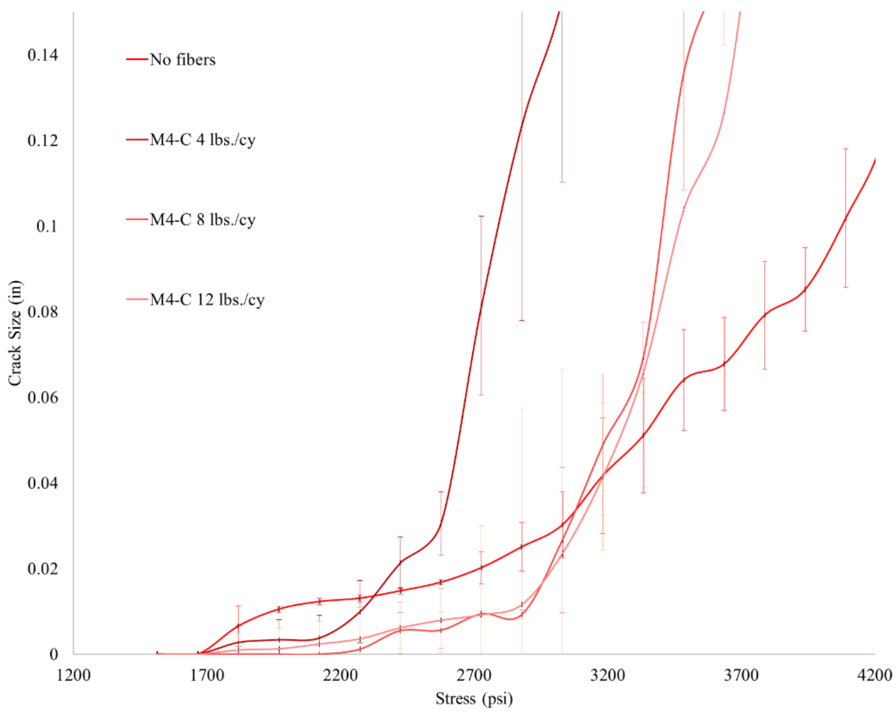


Figure A-8 shows the Stress vs. Crack size graph for the different dosages of fiber M4-C

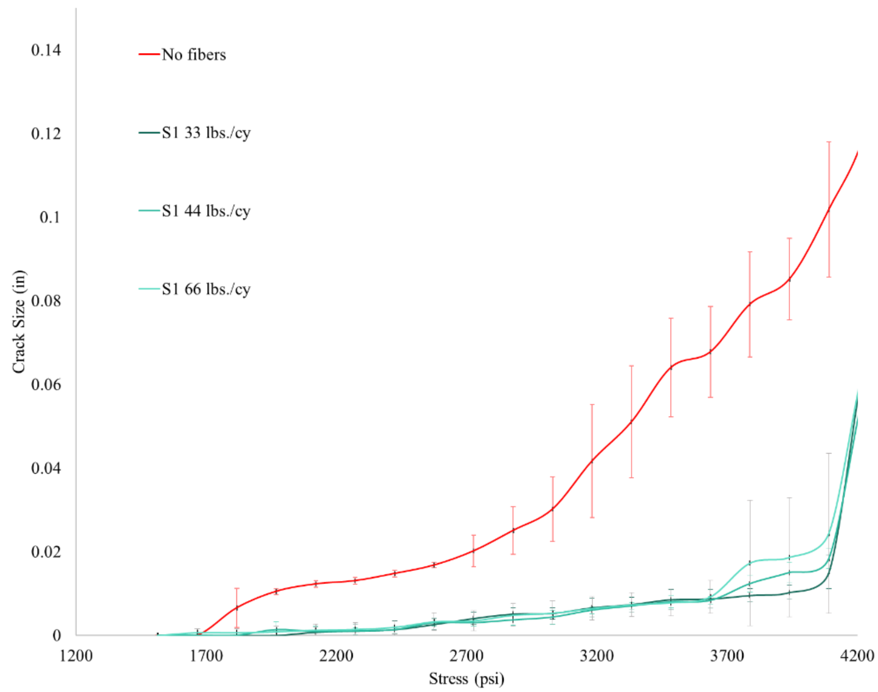


Figure A-9 shows the Stress vs. Crack size graph for the different dosages of fiber S1

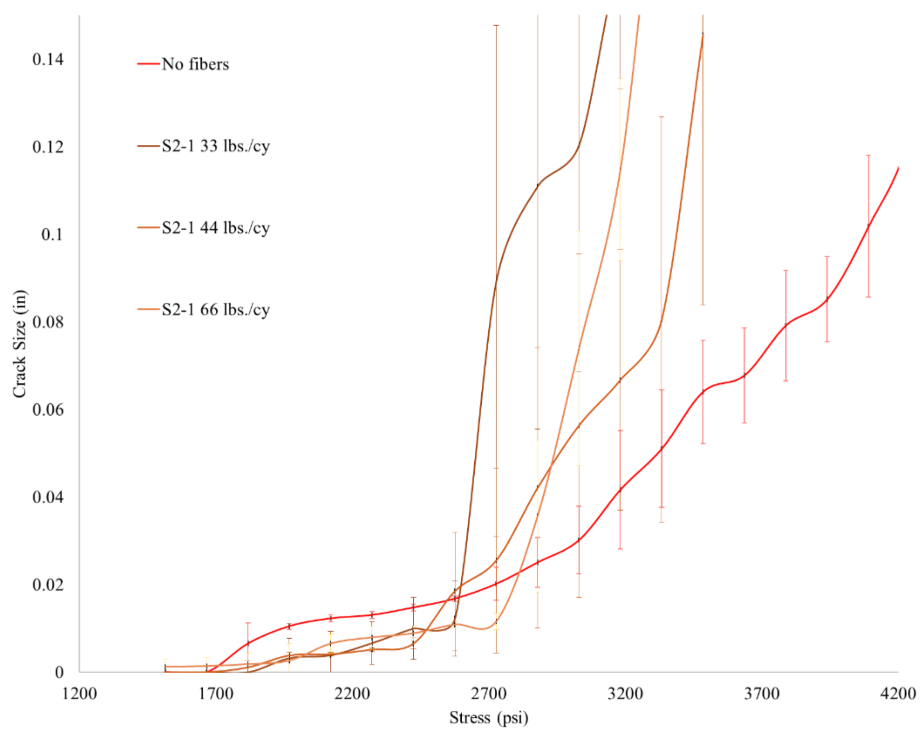


Figure A-10 shows the Stress vs. Crack size graph for the different dosages of fiber S2-1

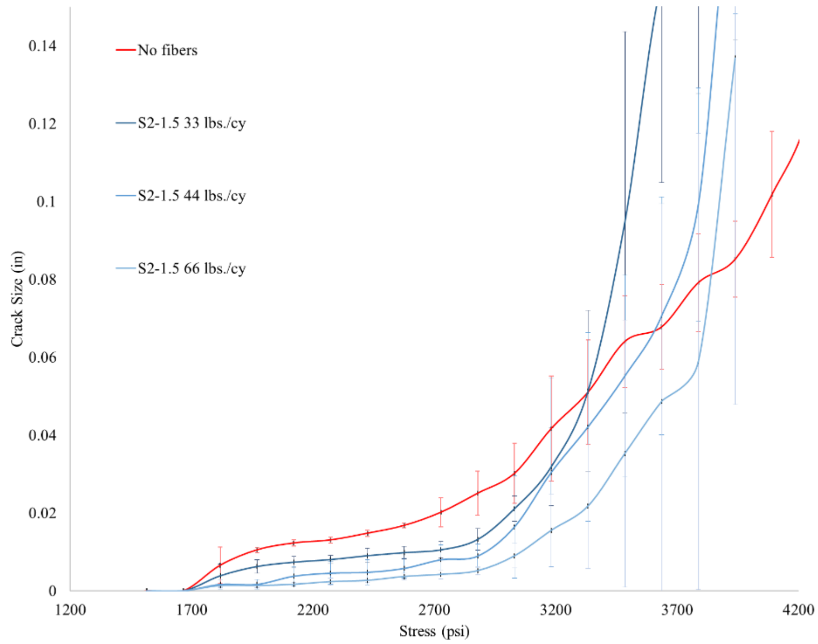


Figure A-11 shows the Stress vs. Crack size graph for the different dosages of fiber S2-1.5

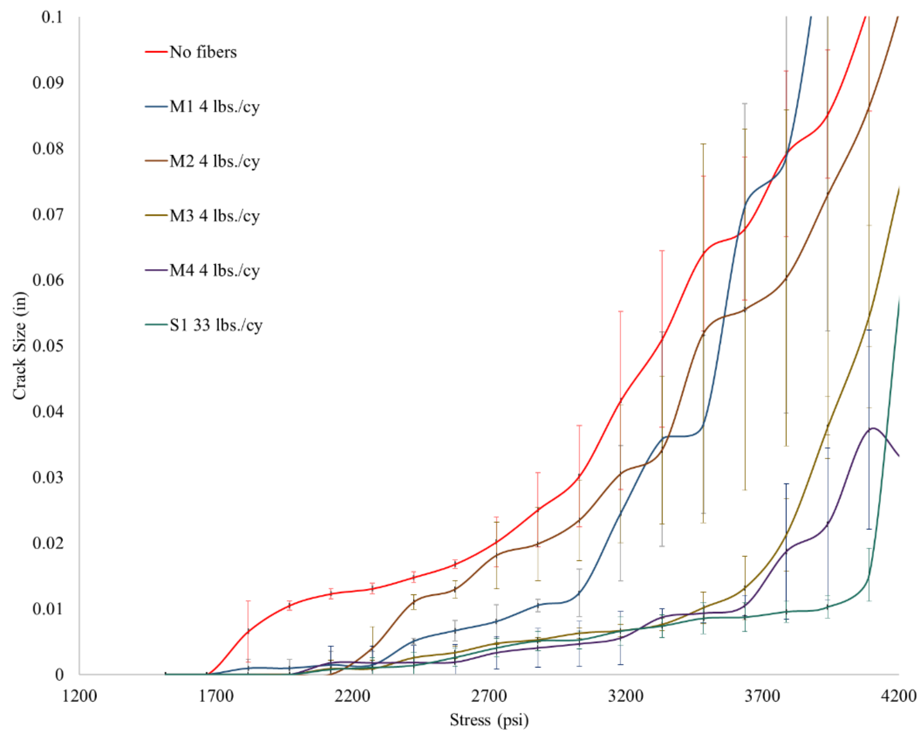


Figure A-12 shows the Stress vs. Crack size graph for the lowest dosage of 5 different materials

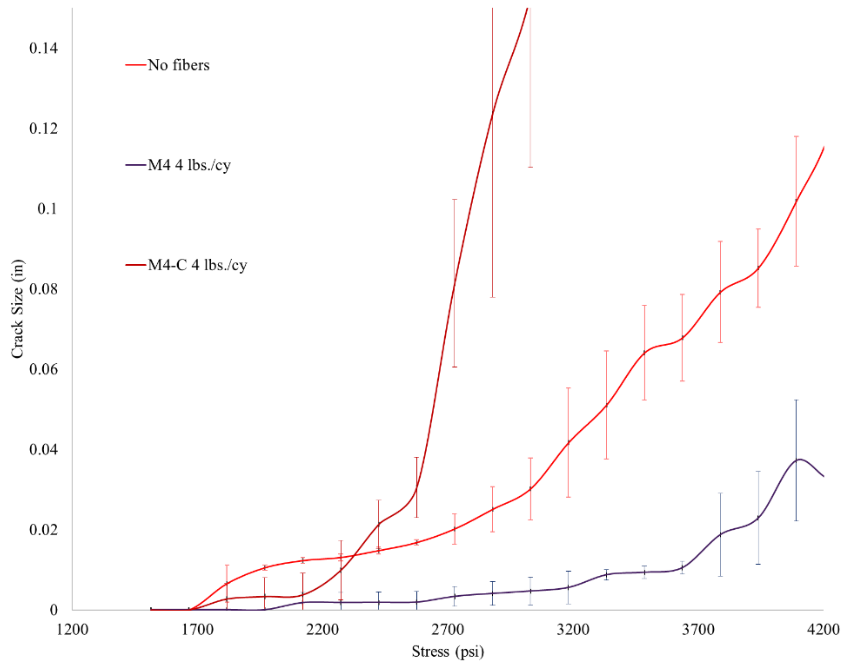


Figure A-14 shows the Stress vs. Crack size graph for the lowest dosage of different length fibers

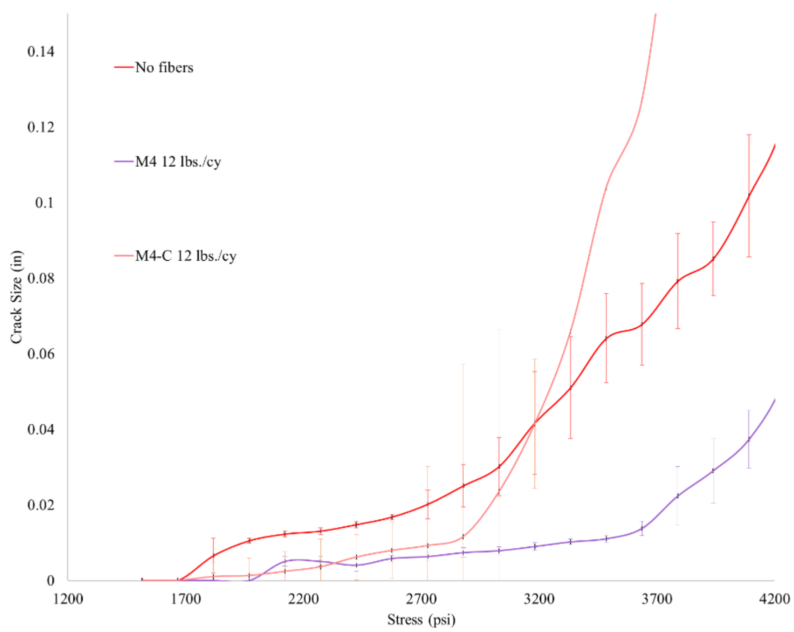


Figure A-15 shows the Stress vs. Crack size graph for the highest dosage of different length fibers

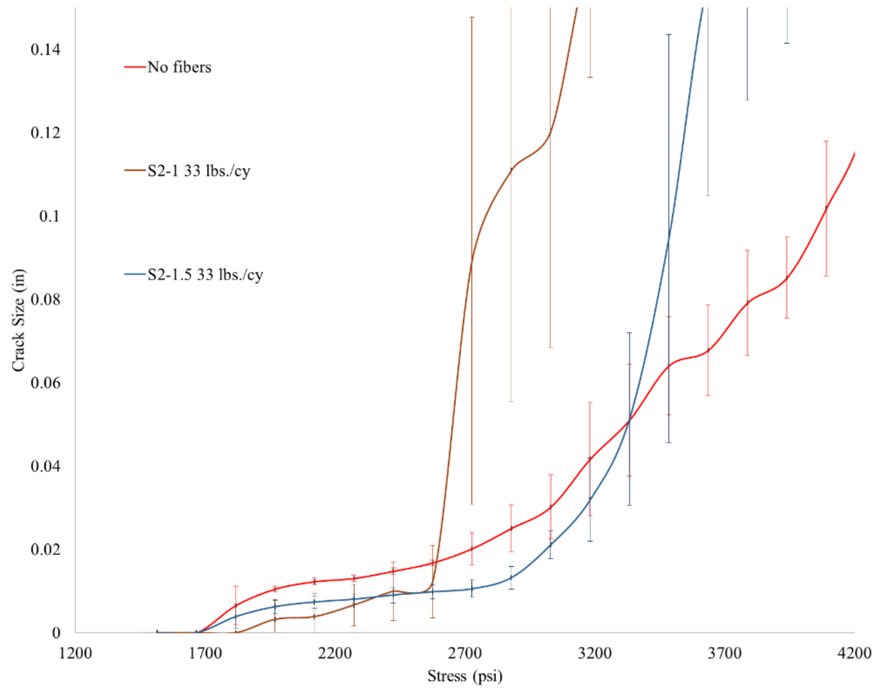


Figure A-16 shows the Stress vs. Crack size graph for the lowest dosage of different length steel fibers

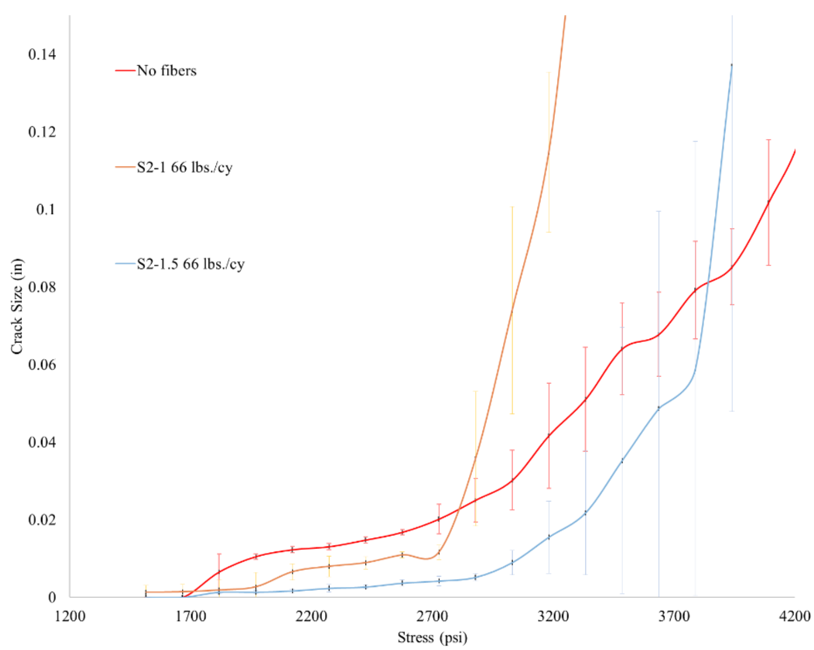


Figure A-17 shows the Stress vs. Crack size graph for the highest dosage of different length steel fibers

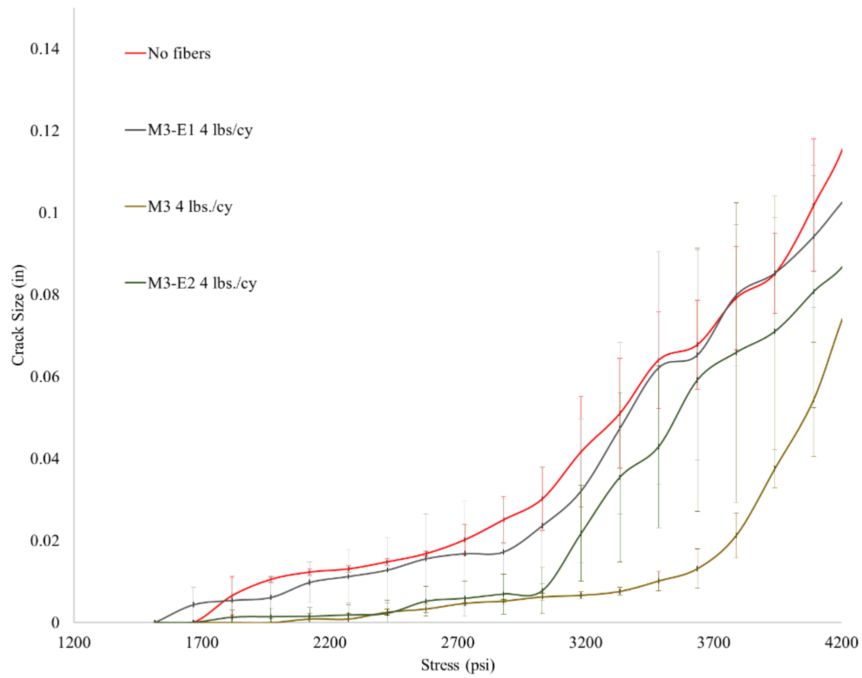


Figure A-18 shows the Stress vs. Crack size graph for the lowest dosage of fibers with different surfaces

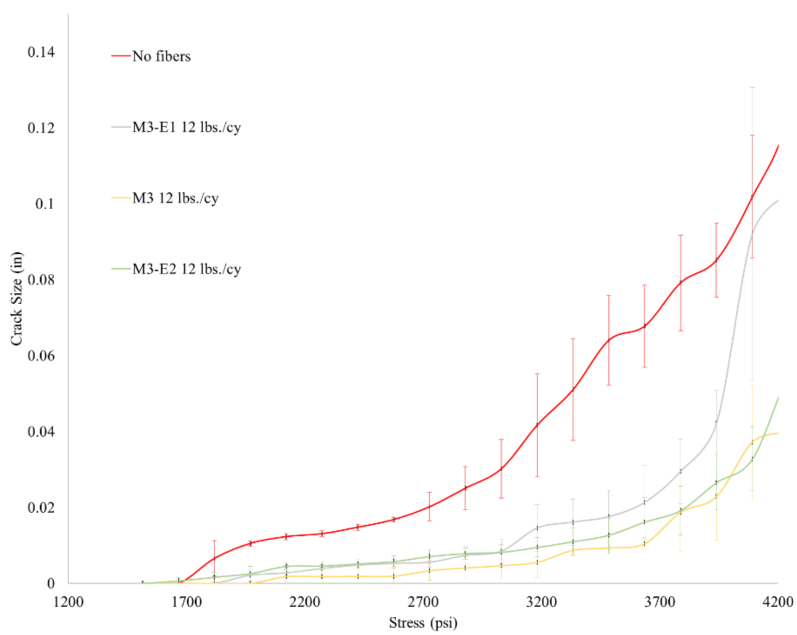


Figure A-19 shows the Stress vs. Crack size graph for the highest dosage of fibers with different surfaces

VITA

Michael Dickey

Candidate for the Degree of

Master of Science

Thesis: USE OF FIBERS TO IMPROVE THE PERFORMANCE OF CONCRETE

Major Field: Civil Engineering

Biographical:

Education:

Completed the requirements for the Master of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in May, 2021.

Completed the requirements for the Bachelor of Science in Civil Engineering at Oklahoma State University, Stillwater, Oklahoma in 2019.