CONCRETE BREAKOUT STRENGTH OF POST-INSTALLED ANCHORS WITHIN FIBER REINFORCED CONCRETE

by

TRAVIS MICHAEL PECHACEK

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-Travis Pechacek

Abstract

CONCRETE ANCHORS EMBEDDED WITHIN FIBER REINFORCED CONCRETE

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Supervising Professor: Dr. Azzawi

This study investigates the effects of Polypropylene fibers on the concrete breakout of post-installed screw anchor bolts. Concrete anchors were installed within concrete specimens of differing amounts of Polypropylene fibers. Four differing mixtures were produced using, 0, 0.5, 1, and 1.5% fibers by volume of the mixture. Their physical properties were calculated through testing at the Civil Engineering Laboratory Building (CELB). In total, 16 cylindrical specimens, 4” in diameter and 8” in height, and 6 beam specimens, 6”x6”x20” were produced and tested. After 28 days of curing, the specimens were tested for their compressive and tensile strengths, as well as their modulus of rupture. Additionally, twenty screw anchors were installed and tested in the varying mixture types. The results of the tests were then analyzed. It was discovered that as the fiber reinforcement approached 1% and over, the compressive strength of the concrete decreased which was attributed to reduced workability and increasing air voids from poor consolidation. Although the compressive strengths of the 1% and 1.5% were reduced, there was a linear trend between the addition of fiber reinforcement and tensile breakout capacity, however the results also showed a relationship between the compressive strength of the concrete and the tensile breakout capacity. Regression analysis was performed and the CCD method modified in order to predict the breakout capacity of a post-installed anchor. In conclusion, the addition of fiber reinforcement will lead to an increase in the breakout capacity of an anchor, while the reduction in compressive strength of a specimen will lead to a decrease in the breakout

capacity of an anchor. Due to loss in workability the addition of fibers can also lead to poor consolidation which can lead to a reduction in the compressive strength, and thus a reduction in the breakout capacity of the anchor.

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1 INTRODUCTION

Concrete is important. Concrete foundations carry the loads of a structure and distribute them to the soil beneath. Concrete pavements carry the loads of vehicles and pedestrians and distribute their loads to the soil below. Additionally, concrete columns and beams can be used to construct entire buildings. Whether a steel column, an architectural panel, or a traffic barrier, attaching different elements to concrete is typical in the design of different concrete systems. Anchorage is vital. Therefore, it is important to understand how these anchors function, and what can be done to make these anchors more efficient.

All concrete anchors are not alike. Some anchors are CIP anchors, meaning that the anchor is placed within the concrete pour, locking it in place as the concrete cures. Other anchors are post-installed, meaning that the anchor is installed into concrete that has already cured. Many anchors have a small washer and nut that is tack welded to the end of the anchor rod to prevent the anchor from simply being pulled up. Others are adhesive, where the bond created between steel and concrete holds the anchor in place. The principle of all these anchors is essentially the same. The anchor has a volume of concrete, otherwise known as a “cone of influence”, that holds the anchor in place. This influenced concrete resists forces, such as tension and shear that threaten to tear the anchor away from the concrete. Concrete breakout occurs when the force resisted by the cone of influence is too high and the anchor breaks out of the concrete. Sometimes the anchor itself, or even the adhesive bond can fail before concrete breakout occurs. Often times, an anchor design may be controlled by the concrete breakout strength of an anchor. If so, how can the concrete breakout strength of an anchor be increased?

Concrete breakout is controlled by many different factors, such as the spacing, the embedment, or the edge distance of the anchors. These factors are directly related to the cone of influence. As the anchors become spaced further apart, when the embedment becomes deeper, or as the edge distance becomes further, the cone increases. As the cone of influence increases, so does the breakout strength. Another seemingly obvious factor includes the compressive strength of the concrete. As the compressive strength of the concrete increases, so does the concrete breakout strength. Sometimes these factors may play a pivotal role in a structure's design. Can another factor be added that may help increase the concrete breakout strength of an anchor?

The tensile strength of concrete in design is considered negligible. However, when fibers are introduced to the mixture, these fibers drastically increase the tensile strength of the concrete. Is it possible that increasing the tensile strength of the concrete would lead to an increase in concrete breakout strength of an anchor? Could this new mixture change the angle of the cone of influence thereby increasing or decreasing the influential volume of concrete? Would changing the mixture design be a cost-effective way to increase anchorage efficiency?

A sizable amount of past research has be dedicated to fiber-reinforced concrete (FRC) due to its potential to enhance existing concrete design methods and practices. In particular, propylene fibers are corrosion resistant making them more beneficial than other steel fiber products. Additionally, FRC is known to both provide ease in construction and, more importantly, allow the shrinkage of cracks developed throughout the design life of a concrete member. If FRC can stay uncracked throughout its design life and increase the mixture's tensile strength, then the benefits of using fibrous concrete for anchorage could be unrivaled.

1.1 Objectives

The main objective of this study was to investigate the concrete breakout strengths of post-installed screw anchors installed within concrete mixtures of varying polypropylene fiber dosages. To meet this objective, four concrete mixture designs were created using varying amounts of fibers. Specimens of all four design mixtures were tested for their physical properties. Post-installed anchors were then installed within the specimens of differing mixtures and then tested.

1.2 Research Contribution

Research into the design of post-installed anchorage into fibrous concrete appears limited, however research into macro-synthetic polypropylene fibers has numerous sources, as does experimentation of concrete anchors. Currently, many producers of post-installed anchors, such as DEWALT, Powers Fasteners, Simpson, etc, do not appear to have any published research on the effects of their anchors in fibrous concrete. This research will provide a foundation for future anchorage research and code adoption (ACI, AASHTO, etc.). The benefits of this research include the possible reduced costs and increased anchor strength by the simple addition of fibers in lieu of special concrete reinforcement, designs changes or specialty anchors. For applications such as anchorage to fiber reinforced pavement for guardrails, this research will allow designers to consider the additional strength provided by the fiber reinforcement. The additional strength provided by the fibers will allow cheaper anchors to be used while still maintaining the necessary strength requirements.

1.3 Outline for Dissertation

This thesis is organized into the six following chapters respectively:

Chapter 1 – Introduction: This chapter explains the nature of concrete in tension and why fibers have been introduced to the concrete mixture.

Chapter 2 – Literature Review: This chapter presents the background of anchors, fiber reinforcement concrete and previous studies on concrete within steel fiber reinforced concrete.

Chapter 3 – Experimental Program: This chapter presents the concrete mixture design, and the fabrication, curing, and testing set-up of all specimens

Chapter 4 – Experimental Results and Discussion: This chapter presents compressive and tensile strength of cylinder specimens, the modulus of rupture of the beam specimens, and the ultimate tensile strengths of the screw anchors installed.

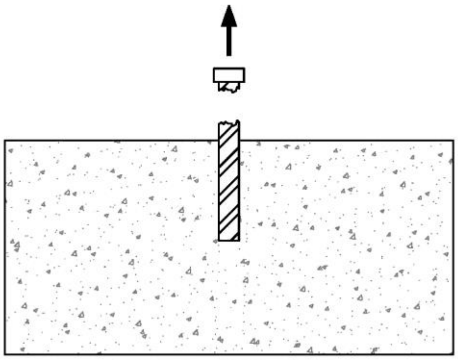
Chapter 5 – Summary and Conclusions: The findings of this research are summarized and the conclusions are presented.

2 LITERATURE REVIEW

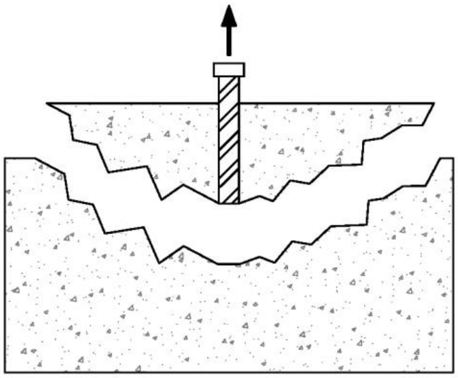
2.1 Previous Research and Accepted Design Practices

2.1.1 Concrete Anchors

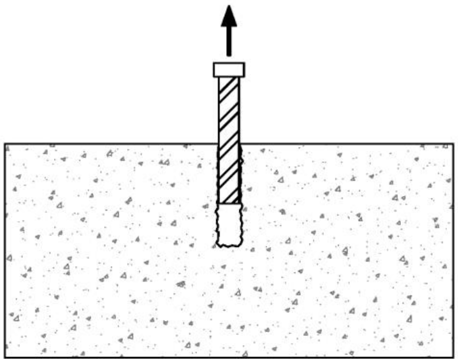
Anchorage to concrete is not a new subject, however there are only two main branches of concrete anchors: cast-in-place and post-installed. Like the name implies, cast-in-place anchors, such as hex head bolts or J bolts, are set in place as the concrete is poured. Once the concrete cures, the anchors are already in place and can be used. Cast-in-place anchors are common in applications such as steel frame design and can be used in groups of anchors connected via steel base plate. Post-installed anchors are installed after the concrete has cured. These anchors are installed via drilling into the concrete and then applying adhesive to the anchor bolt, torqueing into place, etc, depending on the type of post-installed anchor bolt used. Post-installed anchors are much more versatile than cast-in-place bolts since they can be installed after the concrete has cured. The ACI code allows the designs of both types of bolts and provides guidance in calculating the three different types of anchorage failures: steel failure, concrete breakout, and pullout failure.



STEEL FAILURE



CONCRETE BREAKOUT



PULLOUT

Figure 1: Anchor failure modes

Steel failure is the fracture of the shank of the anchor. As the tensile load increases on the anchor and anchor may begin to yield, and the cross sectional area will begin to pinch together and decrease. If the tensile load continues to increase and surpass the ultimate tensile strength of the anchor, the anchor will fracture. The ACI code currently prescribes an equation utilizing the ultimate strength of the steel, as oppose to the yielding strength. Equation 1 is the accepted equation for steel strength in anchor design, where Ns is the ultimate strength of the steel, As is the effective area of the steel in tension, and fult is the ultimate strength of the material:

$$Ns = As * fult$$

Equation 1: Steel strength in anchor design (ACI 17.4.1.2)

Pullout failure is described as the localized crushing of concrete around the bearing of the anchor, such as a cast-in-place hex head anchor. In the case of localized crushing, the pullout failure of an anchor is controlled by the compressive strength of the concrete. Equation 2 can be used to calculate the pullout strength of a cast-in-place anchor, where Np is the ultimate pullout strength, Ab is the area of bearing and f'c is the compressive strength of the concrete:

$$Np = 8 * Ab * f'c$$

Equation 2: Pullout strength of cast-in-place anchor (ACI 17.4.3.4)

Pullout failure can also occur when the frictional component is surpassed and the anchor simply slips out of the concrete. For instance, if an expansion bolt is deeply embedded, the breakout strength of the anchor may be higher than the friction holding the anchor in place. The anchor bolt would then simply slip out of the concrete as opposed to breaking out. Due to the diversity in mechanical properties of post-installed anchors, the ACI does not provide a means to calculate the pullout load of an anchor. Instead the ACI code specifies the pullout strength of all post-installed anchors to “be based on the 5 percent fractile of result of tests performed and evaluated” (ACI). There is a method that can be used to estimate an anchor’s pullout capacity (Eligehausen), however it relies on the quality of the drilled hole and the pre-tensioning of the anchor which is challenging to evaluate. Therefore, testing is considered the most reliable source when estimating pullout capacities for mechanical anchors.

Breakout failure occurs when the tensile load imposed on the anchor surpasses the tensile strength of the concrete specimen and the anchor suddenly “breaks out” and shears out of the concrete in a cone. The ACI code estimates the typical break out angle to be approximately 35°, however there are studies that suggest the failure angle can be influenced by the embedment depth. As the embedment increases, so does the angle of failure. As the embedment decrease, the angle of failure can range from 21° to 28° (Yang). Additionally, there are a variety of methods to calculate the breakout capacity. ACI 318 prescribes the use of the concrete capacity design (CCD) method. The CCD also assumes a 35° failure angle and a rectangular breakout, as opposed to earlier methods that used an assumed 45° failure angle and a conical breakout. The CCD method predicts the breakout capacity with Equation 3, where Nb is the ultimate breakout capacity, kc is a constant based on the anchor type, f’c is the compressive strength of the concrete, λa is a constant based on the concrete type, and hef is the effective embedment depth of the anchor:

$$Nb = kc * \lambda a * \sqrt{f'c} * hef^{1.5}$$

Equation 3: CCD Method (ACI 318-14 Code) (ACI 17.4.2.2a)

The ACI 349 proposes another method which assumes a 45° failure angle and a conical breakout. The ACI 349 method uses equation 4, where P is the ultimate breakout capacity, L is the embedment length, d is the diameter of the anchor head, and f'c is the compressive strength of the concrete:

$$P = \pi * L * (L + d) * 4 * \sqrt{f'c}$$

Equation 4: ACI 349 breakout capacity equation (ACI 349 Appendix B)

One difference between the equations is the use of the diameter of the anchor head which is left out of the CCD method. Additionally, the ACI 349 method is more conservative for short embedded anchors while the CCD method is more conservative for the deep embedded anchors. There are numerous other methods for determining the breakout capacity of a concrete that consider other qualities such as tensile strength, changing failure angles, etc. This study will focus on the application of the CCD method in order to relative the results to previous studies.

2.1.2 Fiber Reinforced Concrete

Many studies have been conducted on the change in material properties in concrete with the addition of fiber reinforcement. Studies have shown that with the introduction of fiber reinforcement, the tensile and flexural strength subsequently increases (Ramli). The fibers embedded within the concrete further bind the aggregate together. The tensile strength of typical concrete is rather low. Regular concrete is bound together by chemical bonds created between cement and aggregate through hydration. The chemical bonds binding regular concrete together do not have a strong tensile strength and as regular concrete is pulled apart, the concrete cracks and fails easily. As fibers are introduced to the concrete mixture, the fibers further confine the concrete and bind it together. As a tensile force acts upon fiber reinforced concrete, both the chemical bonds and the fiber bind the concrete together, resulting in a higher tensile strength. Likewise, as the tensile strength of the concrete increases, so does the flexural strength. Since the fiber reinforced concrete can withstand higher tensile stresses, increasing flexure resulting in higher tensile stresses can also be resisted.

Furthermore, compressive strengths of fiber reinforced concrete have also been documented as slightly increasing, or no effects with the addition of fiber reinforcement (Ramli). This is due to the confining effects of the fiber on the concrete’s aggregate. However, as the dosage of fiber increases, the workability of the concrete typically decreases. Once enough fiber has been added to a concrete mixture the workability of the concrete may be too low to properly place, compact and consolidate. If the workability is too low and the concrete is not properly consolidated, small air voids may be present within the cured concrete. These air voids can lead to a reduction in compressive strength of the concrete.

There are several varieties of fiber reinforcement including steel and polypropylene fibers. Steel fibers are commonly used in the design of fiber reinforced pavement in order to reduce the cracking of the concrete due to exposure and service loading. Steel fibers however, are susceptible to rust. Polypropylene fibers are a synthetic fiber with similar effects to the mechanical properties of concrete, but cannot rust. Both steel and polypropylene fibers can be used to replace small reinforcing bars such as #3 or #4 rebar (MasterFiber MAC Matrix).

2.1.3 Fiber Reinforced Concrete Anchorage

There have been past studies focusing on the anchorage to fiber reinforced concrete. One study performed in Iraq focus on the use of cast-in-place anchor bolts embedded within steel fiber reinforced concrete (Al-Taan). The anchor bolts were embedded at varying depths in concrete with varying amounts of fiber reinforcement. It was discovered that the failure angle was influenced by the embedment depth, the amount of fiber reinforcement and the compressive strength of the concrete. As the embedment depth and fiber reinforcement increase, the angle of failure increased. As the concrete compressive strength decrease, the angle of failure decreased. Their results also showed an overall increase in the tensile strength of an anchor with increasing amounts of fiber reinforcement.

Many post-installed anchor manufacturers, such as DEWALT, Powers, Simpson, etc, test their own anchors and publish their findings. Currently DEWALT Screw-Bolt+ anchors have published data for installation into normal and lightweight concrete, masonry, brick and concrete on metal deck. There does not appear to be any published data for DEWALT Screw-Bolt+ anchors installed in fiber reinforced concrete.

3 EXPERIMENT PROGRAM

3.1 Fabrication of Test Specimens

3.1.1 Design of Test Specimen Formwork

Four different types of specimens were designed according to the test to be performed: compression, split, flexure and anchor pull tests. The compression tests performed utilized small 4”x8” cylinders. The split tests were also performed using 4”x8” cylinders. The flexure tests required 6”x6”x20” beams. The anchor pull tests required beams that would be large enough to ensure the anchors would have sufficient spacing and edge distance, and deep enough to ensure cracking proximity to rebar would not influence testing. For these reasons, a large 54”x24”x18” beam was chosen as the anchor specimens’ size. The large beam would allow multiple anchors to be sufficiently spaced with minimal possibility of breaking through another nearby anchor’s influence area. The large beam design would also be ideal for the placement of a supporting frame that could house the hydraulic ram and evenly distribute compression back into the beam outside of the anchor’s influence area.

3.1.2 Construction of Formwork

The smaller specimens utilized preexisting forms found at the UTA Civil Engineering lab. The cylinder specimens were all formed using typical 4”x8” plastic forms. The smaller beam specimens were all formed using assembled 6”x6”x20” steel forms. The large 54”x24”x18” specimens were formed using constructed wood forms. The design of the wood forms is shown in figures 2, 3 and 4:

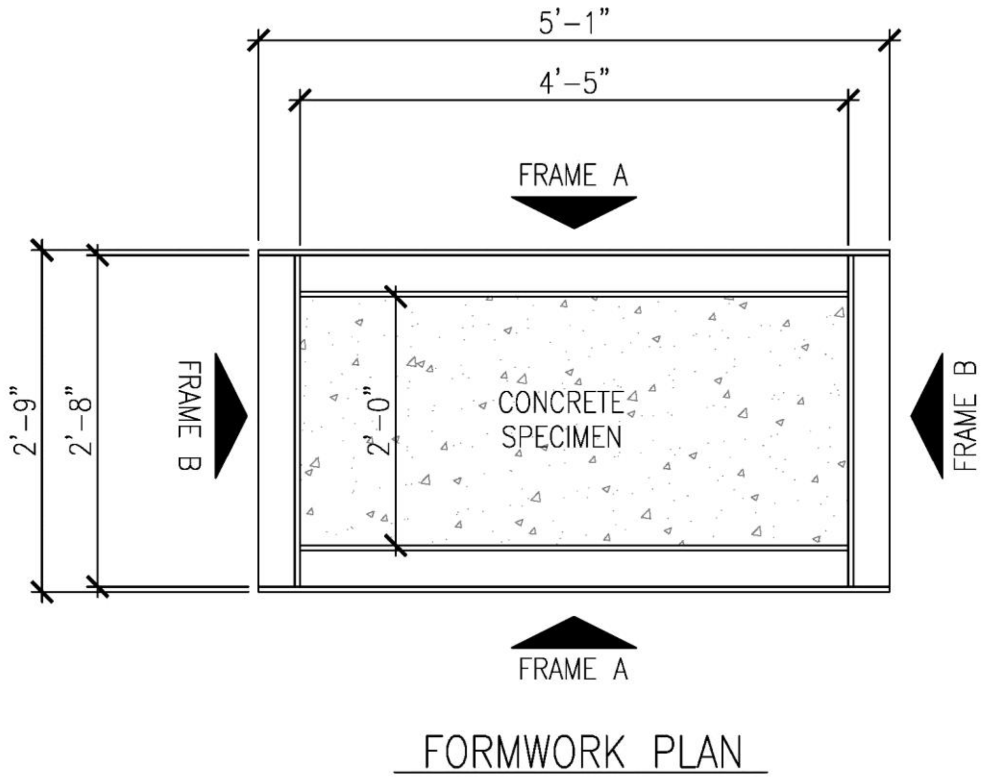
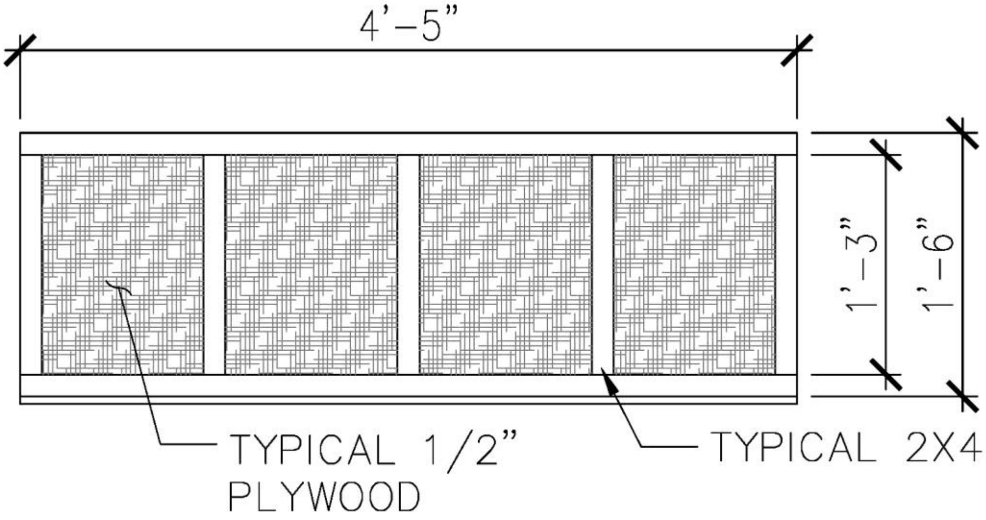
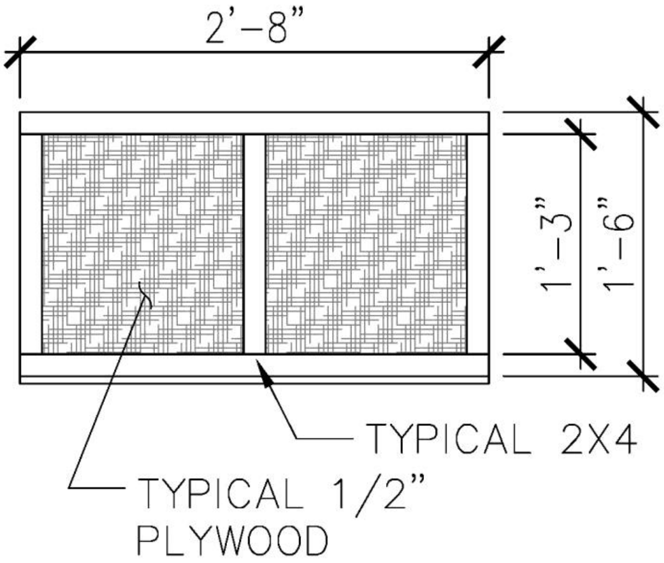


Figure 2: Wood Formwork - Plan View



FRAME A



FRAME B

Figure 3: Wood Formwork - Elevation Views

Figure 4: Wood Frames for Anchor Specimens

Using the formwork plans, typical 2x4's were nailed together to create the frame of the formwork. 7/16" plywood was nailed to the sides of all of the frame. Additional 7/16" plywood was nailed to the exterior of the "A" frames in order to connect the frame together, and ensure the pressures from the poured concrete could be resisted by the created diaphragm. An additional piece of 7/16" plywood was nailled to the bottom of the frames and along with several 2x4's in order to lift the framework as necessary. The figures below show the construction of the formworks:

3.1.3 Concrete Pouring

Prior to the pouring of concrete, all of the cylinder, small beam and large wooden forms were prepped by spraying the insides with WD-40. The WD-40 acts as a concrete releasing agent and stops the concrete from sticking to the forms as it cures. After the forms were sprayed, the rebar, for the large beams, was put in place using typical 3” chairs and tying the rebar down using typical rebar ties.

The concrete was delivered by Quick Mix Concrete LLC using a volumetric truck which carried all of the components required and mixed them on site using an auger. The concrete mixtures used are shown in Tables 1-4:

Table 1: 0% Fiber Concrete Design Mixture

0% Fiber Concrete Design Mixture				
Component	ASTM	Density (lbs/cf)	Weight (lbs)	Volume (cf)
Type I/II Cement	C150	196.6	541	2.75
#67 Size Coarse Aggregate	C33	167.3	1885	11.27
Concrete Sand	C33	163.6	1458	8.91
Water		62.4	254	4.06
Polypropylene Fiber		59.06	0	0.00
Concrete		153.3	4138	27

Table 2: 0.5% Fiber Concrete Design Mixture

0.5% Fiber Concrete Design Mixture				
Component	ASTM	Density (lbs/cf)	Weight (lbs)	Volume (cf)
Type I/II Cement	C150	196.6	534.0	2.72
#67 Size Coarse Aggregate	C33	167.3	1880	11.24
Concrete Sand	C33	163.6	1452	8.88
Water		62.40	251.2	4.03
Polypropylene Fiber		59.06	7.973	0.14
Concrete		152.8	4125	27

Table 3: 1.0% Fiber Concrete Design Mixture

1.0% Fiber Concrete Design Mixture				
Component	ASTM	Density (lbs/cf)	Weight (lbs)	Volume (cf)
Type I/II Cement	C150	196.6	527.4	2.68
#67 Size Coarse Aggregate	C33	167.3	1874	11.20
Concrete Sand	C33	163.6	1447	8.84
Water		62.40	249.1	3.99
Polypropylene Fiber		59.06	15.95	0.27
Concrete		152.4	4113	27

Table 4: 1.5% Fiber Concrete Design Mixture

1.5% Fiber Concrete Design Mixture				
Component	ASTM	Density (lbs/cf)	Weight (lbs)	Volume (cf)
Type I/II Cement	C150	196.6	520.7	2.65
#67 Size Coarse Aggregate	C33	167.3	1869	11.17
Concrete Sand	C33	163.6	1441	8.81
Water		62.4	247.0	3.96
Polypropylene Fiber		59.1	23.92	0.41
Concrete		152.0	4101	27

MasterFiber MAC Matrix was used in the various mixtures. MasterFiber MAC Matrix is a macro-synthetic fiber with a specific gravity of 0.91 and with a recommended dosage range between 3 and 12 lbs per cubic yard. Fibers were added to the mixture in accordance to the manufacturer’s specifications. The concrete pour began with the 0% fiber specimens and ended with the 1.5% specimens. Fibers were added in stages. 0 lbs of fibers was added to the 0% mixtures, approximately 8 lbs to the 0.5% mixtures, 15 lbs to the 1.0% mixture, and 24 lbs to the 1.5% mixture. Once the concrete was poured into the frames, an internal vibrating device was used. The vibrating of the concrete was to properly consolidate the concrete and reach its full potential strength.

Figure 5: Concrete beam being vibrated and consolidated

Slump tests were performed in accordance to ASTM C143. These tests used a 8" base, 4" top 12" tall slump cone. Concretes from all four mix designs were poured into the cone, filling the cone in three lifts. After each lift the cone was rodded 25 times. Once the cone was filled and flush at the top, the cone was carefully lifted. The concrete crumbled downward or "slumped" and the slump was measured from the top of the cone using a tape measure. It was discovered that the slump would decrease as more fibers were added to the mixture. The workability of the mixtures was also seen to decrease as more fibers were introduced to the mixture. The slump test performed can be seen in Figure 6 and 7:

Figure 6: Filled Slump Cone

Figure 7: Slump Test

After the pours were complete, the large beams were left in place, covered with wetted towels and tarps to reduce dehydration of the beams and properly cure the specimens. The smaller specimens were taken and cured within the curing room at the CELB. Their forms would later be removed and the smaller specimens would once again be placed inside the curing room. The specimens were all left to cure for 28 days. He larger specimens would keep their forms on until after 28 days of curing to reduce the risk of moisture loss from exposure. After 28 days the large specimens were lifted by crane and their formwork simply slipped off and removed. The large specimens would then be turned onto their sides so the post-installed anchors could later be installed and tested.

Figure 8: Large concrete beams after pour

Figure 9: Small specimens placed inside curing room

3.2 Test Set-Up and Procedure

3.2.1 Compression, Tensile & Flexure Testing

After 28 days the smaller specimens were ready to begin testing. The tests performed were the compression, tensile and flexure tests. These tests all utilized the 60 kip compression machine found at the CELB. The 60 kip compression machine operated through the use of the loading table and the supported head. The head was rigidly supported and held the specimen in place. Different heads could be screwed onto the head allowing the different tests to take place. The specimen was placed onto the load table where the load would be applied. The table would be hydraulically lift with the specimen which would eventually make contact with the head and apply load.

The compression tests were performed in accordance with ASTM C39 using 4”x8” cylinders. The specimen was placed in the middle of the load table so the head would apply load to the top of the cylinder. The head had a simple, flat, round surface to applied load to the specimen. The specimen was loaded at an approximate rate of 400 lbs/sec and the ultimate load was recorded. The compressive strength of the concrete was measured using Equation 5, where fc is the compressive strength in psi, P is the applied ultimate load, and r is the radius of the cylinder:

$$fc = \frac{P}{\pi r^2}$$

Equation 5: Compressive strength of cylinder

The compression test setup can be seen in Figure 10:

Figure 10: Compression Test Setup

The tensile tests were performed in accordance with ASTM C496 using 4”x8” cylinders. The specimen was placed in the middle of the load table so the head would apply load across the length of the cylinder. The head had a long, pointed surface to applied load to the specimen. The specimen was loaded at an approximate rate of 100 lbs/sec and the ultimate load was recorded. The tensile strength of the concrete was measured using Equation 6, where ft is the tensile strength in psi, P is the applied ultimate load, L is the length of the cylinder, and D is the diameter of the cylinder:

$$ft = \frac{2P}{\pi LD}$$

Equation 6: Tensile strength of cylinder

The tensile test setup and results can be seen in Figure 11:

Figure 11: Split Test Setup

The flexure tests were performed in accordance with ASTM C78 using 6”x6”x20” beams. The specimen was placed in the middle of the load table and supported on both side 1” away from the each of the beam. The head had two long, pointed surfaces spaced 6” away from each other to applied load to the specimen. The specimen was placed on the load table so that the head would contacted the beam 6” away from its supports. The specimen was loaded at an approximate rate of 50 lbs/sec and the ultimate load was recorded. The flexure strength of the concrete was measured using Equation 7, where fr is the modulus of rupture in psi, P is the applied ultimate load, L is the span of the beam, B is the width of the beam and D is the depth of the beam:

$$fr = \frac{PL}{BD^2}$$

Equation 7: Modulus of rupture of cylinder

The modulus of rupture of the plain concrete (0% fiber) was estimated Equation 8:

$$fr = 7.5\sqrt{fc}$$

Equation 8: Modulus of rupture of normal concrete as prescribed by ACI

The tensile test setup and results can be seen in Figure 12:

Figure 12: Flexure Test Setup

3.2.2 Anchor Testing

The anchors tested were DEWALT Screw-Bolt+. The anchors were 2 ½” in length and embedded 2” into the sides of the large 54”x24”x18” specimens according to the manufacturer’s specifications. First, twenty holes were marked spaced 9” on center in the middle of the large specimen. Then, twenty holes were drilled using a concrete hammer drill with a 3/8” drill bit. Next, the surface of the holes was cleaned, and the individual holes were cleaned using forced air. With the anchor holes fully prep, adjustments to the design frame were needed to be made. Several 3/4” holes were drilled via drill press into 1/8” steel angles in order to fit 3/4” bolts and threaded rods. Figures 13 and 14show the steps taken prior to testing:

Figure 13: Holes are drilled into steel angles as needed for the testing setup

Figure 14: Holes are being drilled for the installation of the screw anchors

The anchors were all tested in accordance with ASTM E488. The anchors were all tested individually by placing 2-1/8" steel angles and 1-1/4" plate on top of each other so that the holes were flush and the screw anchor could be threaded through the holes. The anchor was then screwed into the concrete using an impact driver and driven until the screw anchor was fully in contact with the 1/4" plate. 2 additional angles were then bolted with a 3/4" bolt to the first 2 and a single 3/4" threaded rod was then threaded through the holes of the top angles and held in place with a nut. The threaded rod ran through a large steel plate, a hydraulic ram, a load cell, and 2 smaller steel plates and held in place at the top with 2 nuts. The hydraulic ram and large steel plate rested on the 12"x12" steel frame box which distributed the compressive force from the ram back into the concrete beam, outside of the anticipated breakout area of the anchor bolt. Once the frame was in place, the hydraulic ram was used to exert an upward tensile force on the anchor through the threaded rod. This force would be recorded by the load cell. The tensile force on the bolt would then be increase until the concrete failed and the anchor bolt broke out. Figures 15,16 17,18, & 19 detail the anchor pullout setup:

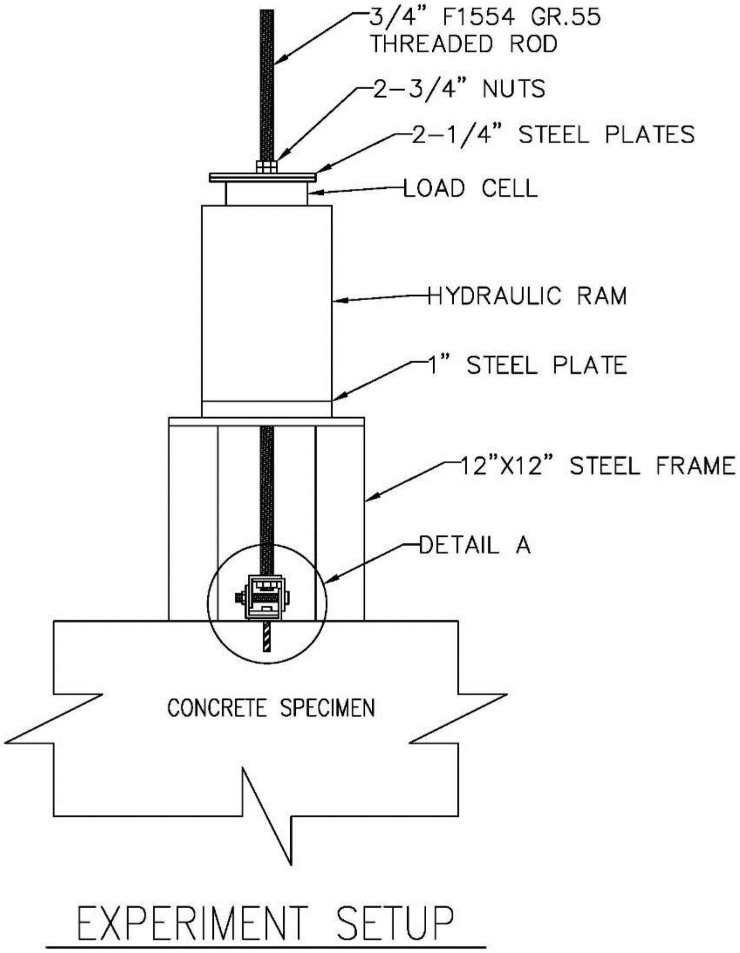


Figure 15: Anchor pullout test setup plan

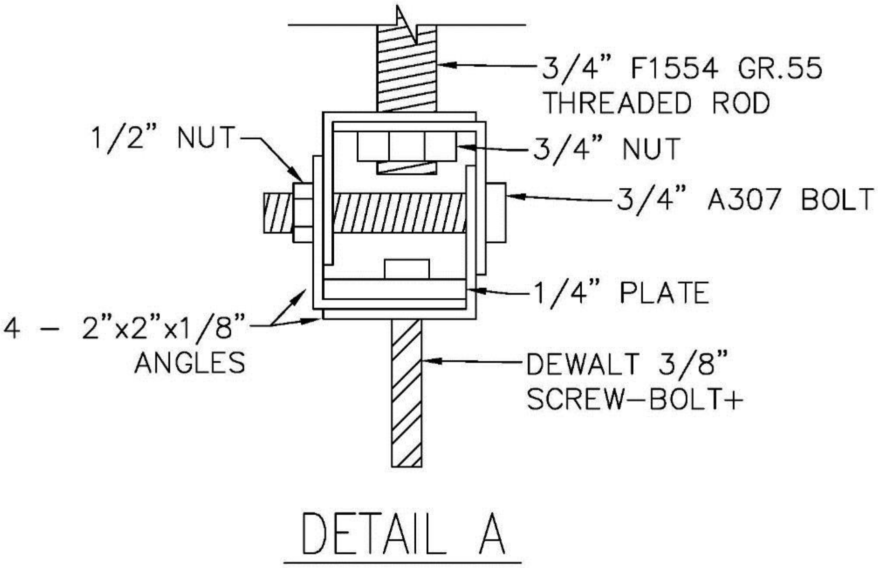


Figure 16: Anchor pullout test setup detail

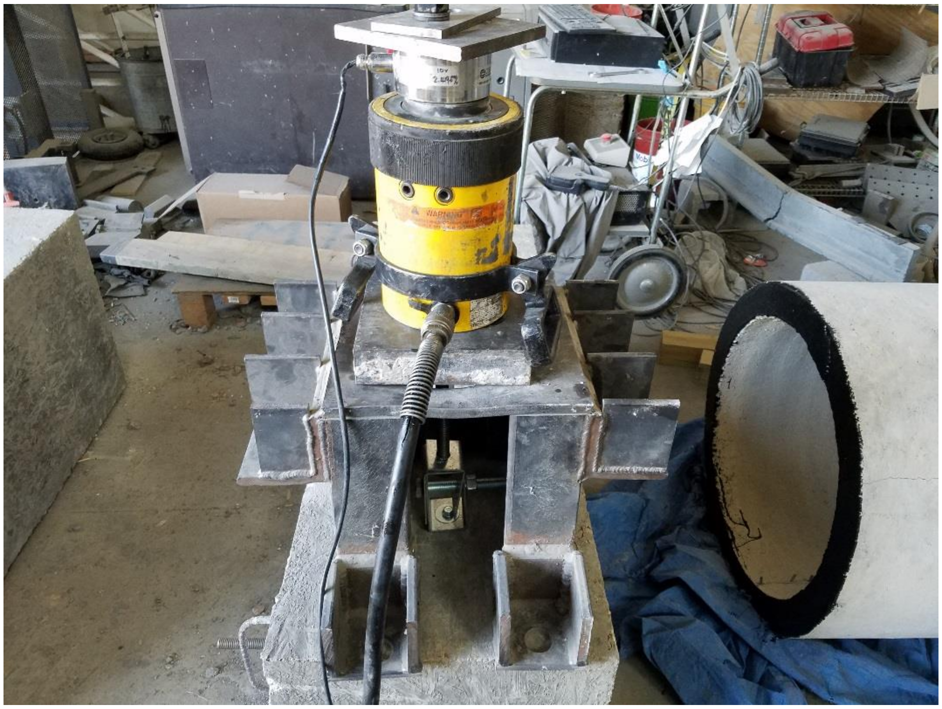


Figure 17: Anchor pullout test setup

Figure 18: Anchor pullout test closeup

Figure 19: Specimen 1 of the 0.0% fiber beam breaking out

After the anchor had been successfully tested, and broken or pulled out, the ultimate tensile load was recorded and the breakout/cracked area around the anchor was recorded. The failure angle was then recorded using Equation 9, where θ is the failure angle, D is the breakout diameter and Y is the embedment depth:

$$\theta = \arctan(\frac{Y}{D/2})$$

Equation 9: Failure angle of anchor

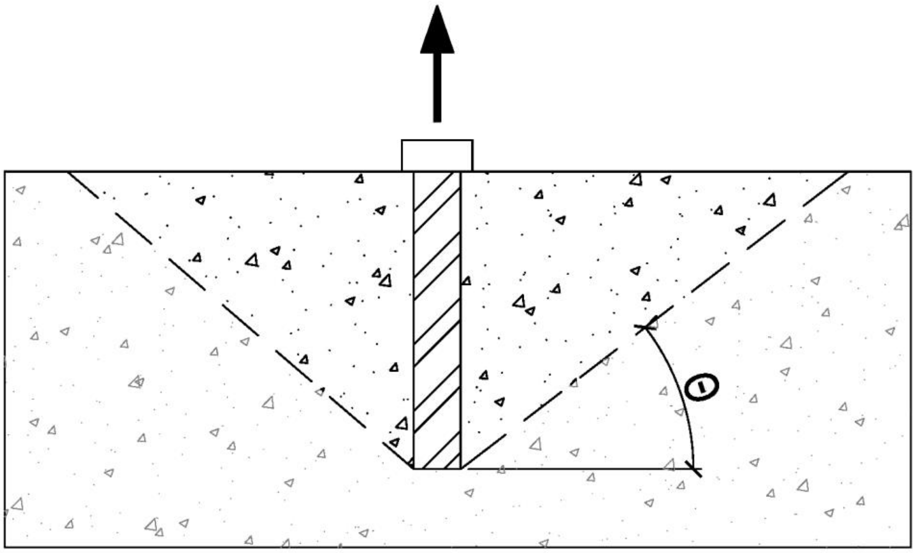


Figure 20: Failure Angle Diagram

4 EXPERIMENT RESULTS

4.1 Compression Test Results

4.1.1 Compression Test Results Data

Table 5: Compression Test Results

Compressive Strength (psi)				
Fiber Volume Fraction (%)	0.0%	0.5%	1.0%	1.5%
Specimen #				
1	2398	3245	2171	2026
2	3649	2729	2707	2658
Average	**3024**	**2987**	**2439**	**2342**

4.1.2 Compression Test Results Graph

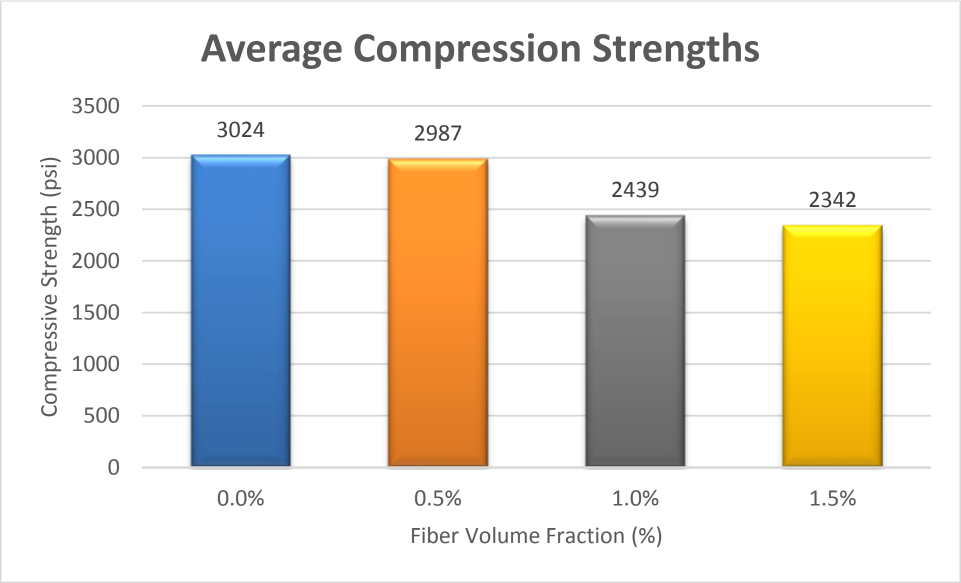


Figure 21: Compression Test Results

4.2 Split Test Results

4.2.1 Split Test Results Data

Table 6: Split Test Results

Tensile Strength (psi)				
Fiber Volume Fraction (%)	0.0%	0.5%	1.0%	1.5%
Specimen #				
1	201.2	142.1	290.1	252.4
2	69.4	185.5	100.0	175.6
Average	**135.3**	**163.8**	**195.1**	**214.0**

4.2.2 Split Test Results Graph

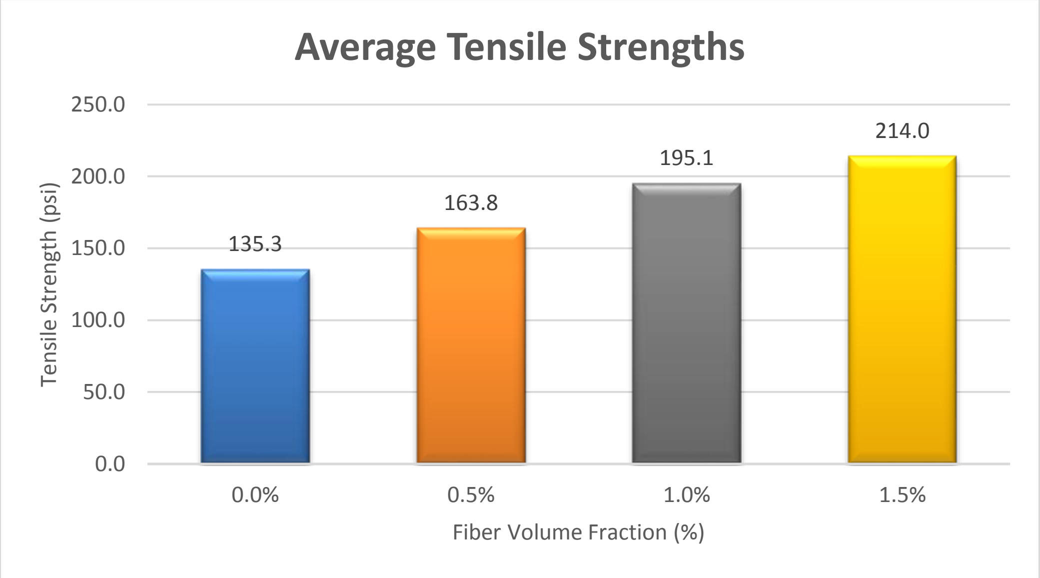


Figure 22: Tensile Test Results

4.3 Flexure Test Results

4.3.1 Flexure Test Results Data

Table 7: Flexure Test Results

Modulus of Rupture (psi)				
Fiber Volume Fraction (%)	0.0%	0.5%	1.0%	1.5%
Specimen #				
1		448.8	577.8	756.5
2		506.6	495.4	549.8
Average	**412.4**	**477.7**	**536.6**	**653.2**

4.3.2 Flexure Test Results Graph

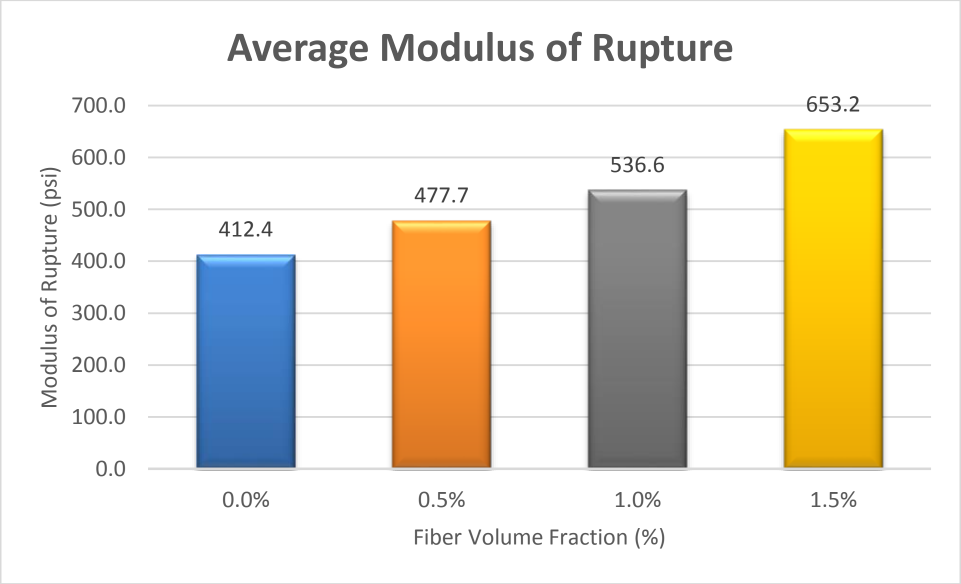


Figure 23: Flexure Test Results Comparison

4.4 Anchor Test Results

4.4.1 Ultimate Anchor Load Data

Table 8: Anchor Breakout Test Results

Fiber Volume Fraction (%)	Specimen	Max Load (lbs)
0.0%	1	3986
	2	3780
	3	3413
	4	4421
	5	3757
	Average	3871.4
0.5%	1	4856
	2	3528
	3	4559
	4	4055
	5	4925
	Average	4384.6
1.0%	1	4284
	2	3184
	3	3574
	4	3505
	5	3734
	Average	3656.2
1.5%	1	4604
	2	4719
	3	3894
	4	3528
	5	4421
	Average	4233.2

4.4.2 Ultimate Anchor Load Graphs

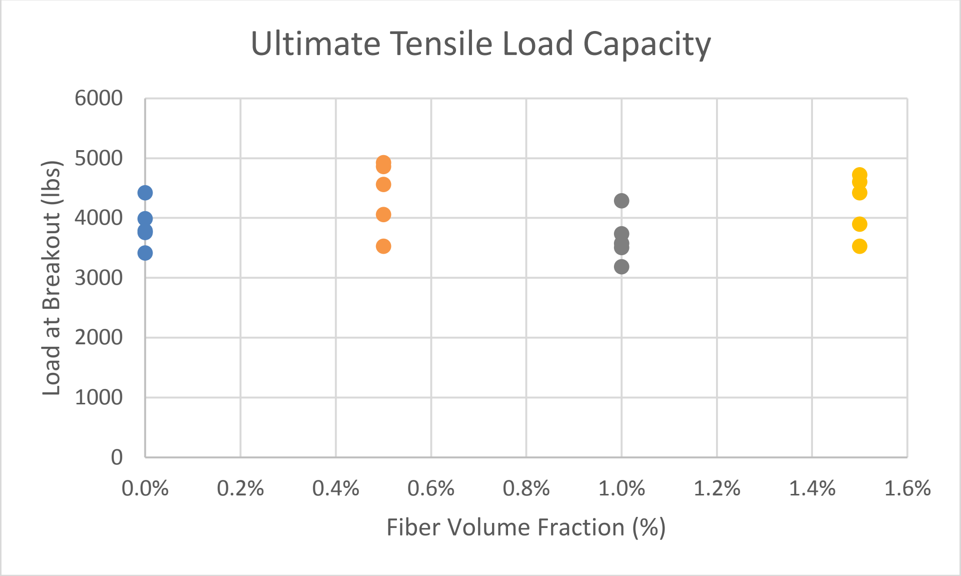


Figure 24: Ultimate load capacity of all tested anchors

4.4.3 Breakout Diameter and Failure Angle Data

Table 9: Breakout Diameters and Failure Angle Results

Fiber Volume Fraction (%)	Specimen	Diameter (in)	Failure Angle (°)
0.0%	1	11	20.0
	2	4	45.0
	3	8	26.6
	4	6.5	31.6
	5	9	24.0
	Average	7.7	27.5
0.5%	1	3	53.1
	2	3.75	46.8
	3	5.5	36.0
	4	3.5	48.8
	5	8.5	25.2
	Average	4.85	39.5
1.0%	1	7.5	28.1
	2	4	45.0
	3	3.5	48.8
	4	4.5	41.6
	5	6.5	31.6
	Average	5.2	37.6
1.5%	1	3.25	50.9
	2	2.5	58.0
	3	5	38.7
	4	4	45.0
	5	5.5	36.0
	Average	4.05	44.6

4.4.4 Breakout Diameter and Failure Angle Graphs

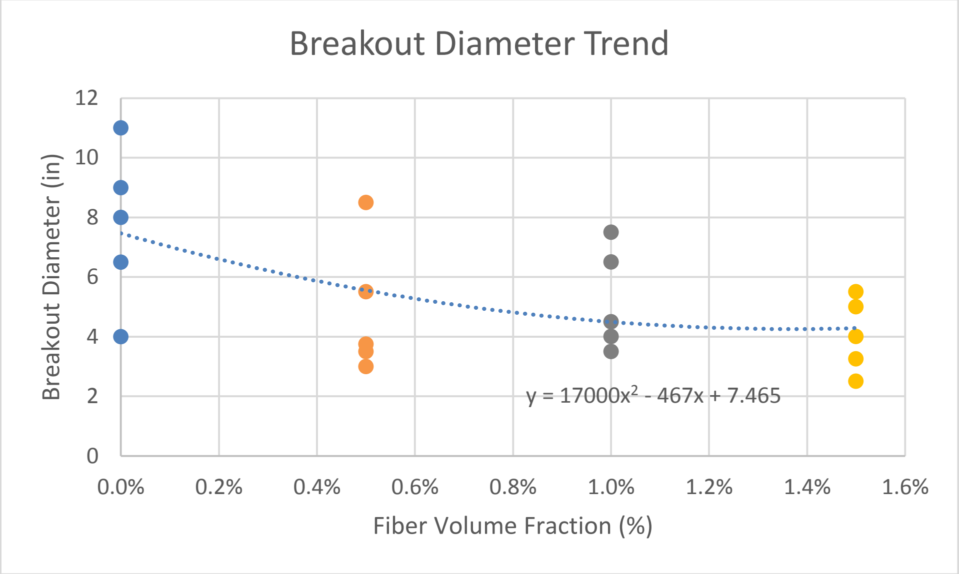


Figure 25: Breakout Diameter Comparison

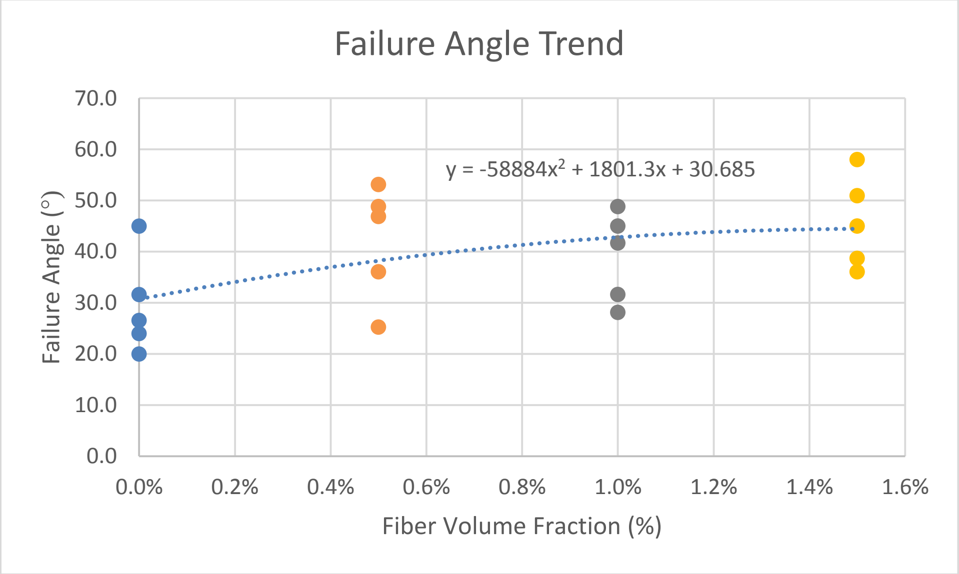


Figure 26: Failure Angle Comparison

4.5 Project Summary

4.5.1 Experiment and Results

A total of twenty-six concrete specimens were constructed during the experiment. Four large wooden frames were constructed prior to pouring in order to cast the large concrete beam specimens. Sixteen concrete cylinders were cast using plastic cylindrical forms. Six 6”x6”x20” beams were cast using metal frames. Four 54”x24”x18” beams were cast using the constructed wooden frames. Four separate concrete mixtures were used which differed by varying amounts of MasterFiber MAC Matrix, a macro synthetic fiber. The differing mixtures had 0%, 0.5%, 1.0% and 1.5% of fibers by volume. Once the concrete had been cast into all of the forms, the specimens were cured for 28 days. After the specimens had been cured, the smaller specimens were tested and the results recorded. Eight cylinders were tested in compression per ASTM C39. The compression test showed similar results in strength between the 0% and 0.5% fiber mix designs and a significant drop in strength in the 1.0% and 1.5% mix designs. Split tests were conducted on eight cylinders per ASTM C496. The split tests results demonstrated tensile strength growth as the amount of fibers increased. Flexure tests were conducted on the six 6”x6”x20” beams per ASTM C78. The results of the flexure tests displayed an increase in the modulus of rupture as the amount of fibers increased. The anchors were all tested in accordance with ASTM E488. The breakout diameter of the anchors was noticeably smaller. The largest ultimate load was recorded from the 0.5% mixture and the 0.5% mixture had the largest average ultimate load resisted. Several anchors from the 1.5% fiber mixtures were discovered to have cracks formed, but rather than break out, the anchors appeared to have failed locally near the threads and pulled out. Reference Appendix A, B, C, & D for all anchor failures.

4.6 Results Discussion

4.6.1 Small Specimen Deductions

Concrete is naturally very brittle and has very little tensile strength. The addition of fibers changes the structural properties of concrete. In the non-fiber reinforced concrete, the tensile strength came from the chemical bond between the aggregate and the cement. With the addition of fibers, the tensile stress applied to the concrete specimens was also resisted by the fiber embedded within the concrete. Thus, as the amount of fibers increase from one mixture to the next both the tensile and modulus of rupture increased. Also discovered was the linear trend between the measured tensile strength and moduli of rupture. As seen in the Split Test Graph, the tensile strength of the concrete increased by approximately 21.1% for every 0.5% of fiber by volume added to the concrete mixture. As seen in the Flexure Test Graph, the modulus of rupture increased by approximately 15.8% for every 0.5% of fiber by volume added to the concrete mixture. As more and more fiber is added to the mixture the flexural and tensile strengths of the concrete are increased linearly, which was as expect.

The compressive strength of the concrete was expected to be approximately 3000 psi. While the fiber was not expected to directly increase the compressive strength of the material, it was expected to passively increase the compressive strength. As more and more fiber was added to the material, the fibers were expected to further confine the concrete and thus lead to an increasing compressive strength. While the compressive strength of the 0.5% fiber mixture was similar to the mixture without fibers, the compressive strengths of both the 1.0% and 1.5% mixtures decreased significantly. It is believed that the increasing fibers led to a reduction in workability which then led to the reduction in compressive strength. As seen below, small air pockets, also known as bug holes, are visible near the surface of the concrete, indicating the probability of air voids being within the concrete specimen due to poor consolidation:

Figure 27: Bug holes seen on the surface of the 1.5% mixture specimen

As the fiber content of the mix designs increased and the workability of the concretes decreased, it appears that the fiber rich concretes contained more air voids. The increasing air voids reduced the compressive strength of the concrete, whereas it was expected to remain about the same or slightly increase. According to the manufacturer’s specifications the maximum recommended fiber dosage was 12 lbs per cubic yard. Since both the 1.0% and 1.5% fiber mixtures both exceeded the maximum recommended dosage and the 0% and 0.5% mixtures did not, this further explains why the workability may have decreased leading to a reduced compressive strength. While the fibers did not directly increase the compressive strength of the concrete, the fibers may have had an indirect effect due to the reduced workability. Reducing the amount of fibers or the maximum size of the aggregate may to avoid issues with consolidation in future experiments.

4.6.2 Anchorage Presumptions and Hypothesis

The initial presumption was that the concrete with the most fiber would yield the largest ultimate tensile load. However, it was also expected that the concrete compressive strength would either not change or subtlety increase with the introduction of fiber. Neither of these presumptions were accurate for this experiment. Instead, the compressive strength of the concrete substantially decreased as the fiber amounts exceeded the manufacturer's specified maximum dosage, and the largest average tensile load was recorded in the 0.5% fiber mixture. However trends did appear which seem to explain the behavior of the anchors.

In addition to the ultimate tensile loads, the diameters of the breakouts were also recorded. As fiber was introduced the breakout diameter approached 4" and the failure angle approached 45°. The only exception to an anchor installed in fiber reinforced concrete that did not appear to breakout with an angle of approximately 45° was specimen 1 of the 1% mix. The anchors that failed with breakout angles greater than 45° (specimens 1 & 2 of the 1.5% mix) appeared to have pulled out rather than broken out. The maximum failure angle for a breakout failure appeared to be approximately 45°.

After analyzing the change in compressive strengths between the concrete mixes, the 0% and 0.5% fiber mixes were compared and the 1.0% & 1.5% mixes were compared. The comparisons can be seen in the graphs below:

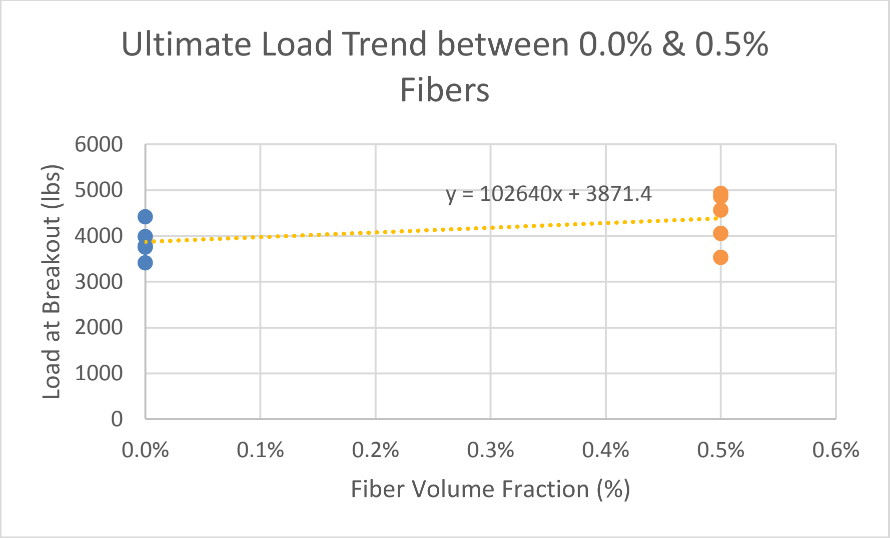


Figure 28: Anchors in 0.0% and 0.5% fiber reinforced concrete

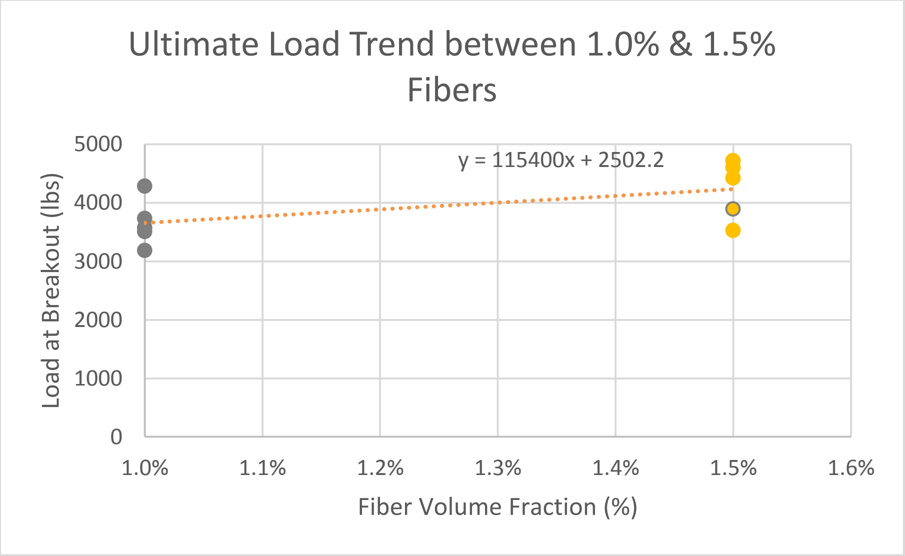


Figure 29: Anchors in 1.0% and 1.5% fiber reinforced concrete

These comparisons discovered that ultimate tensile strengths of these anchors increased by approximately 1090 lbs per 1% of fiber by volume. By modifying the CCD method prescribed by the ACI code, for polypropylene fibers, the ultimate tensile strength of the anchor can be computed, where Nb is the ultimate tensile load, kc is equal to 17 for post-installed anchors, λa is 1 for normal concrete and 0.75 for all poorly consolidated concrete, f’c is the compressive strength of the concrete, hef is the effective embedment depth of 2”, Lf is the length of the fiber in inches, Df is the diameter of the fiber in inches, and Vf is the amount of fiber by volume fraction (%):

$$Nb = \left(1.4 + \frac{Lf}{Df} * Vf\right) * \sqrt{f'c} * hef^{1.5} * \lambda a * kc$$

Equation 10: Modified CCD method

Using the Equation 10 and the average measured compressive strengths, the measured ultimate tensile loads were compared to the modified equation:

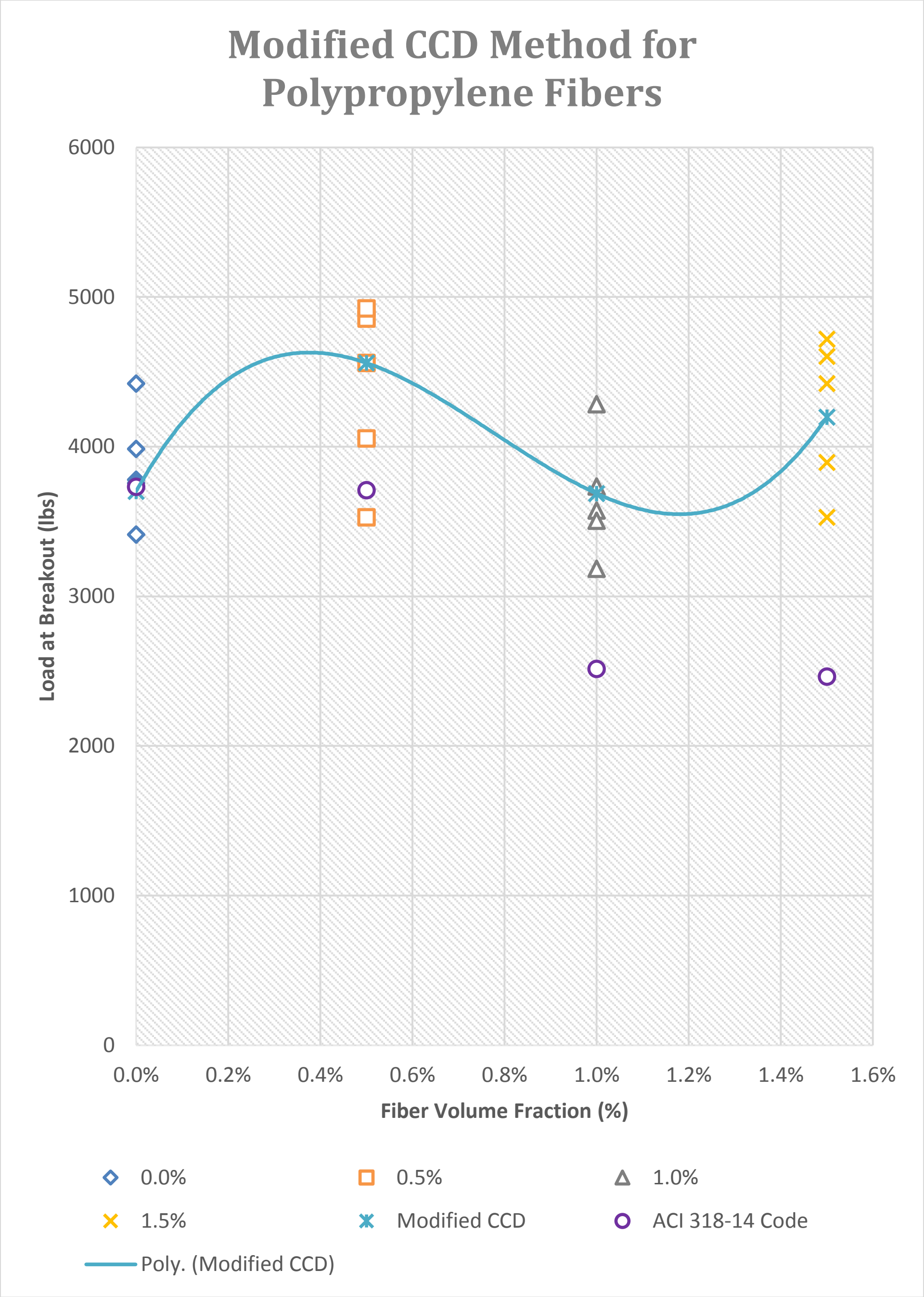


Figure 30: Modified CCD method compared to results

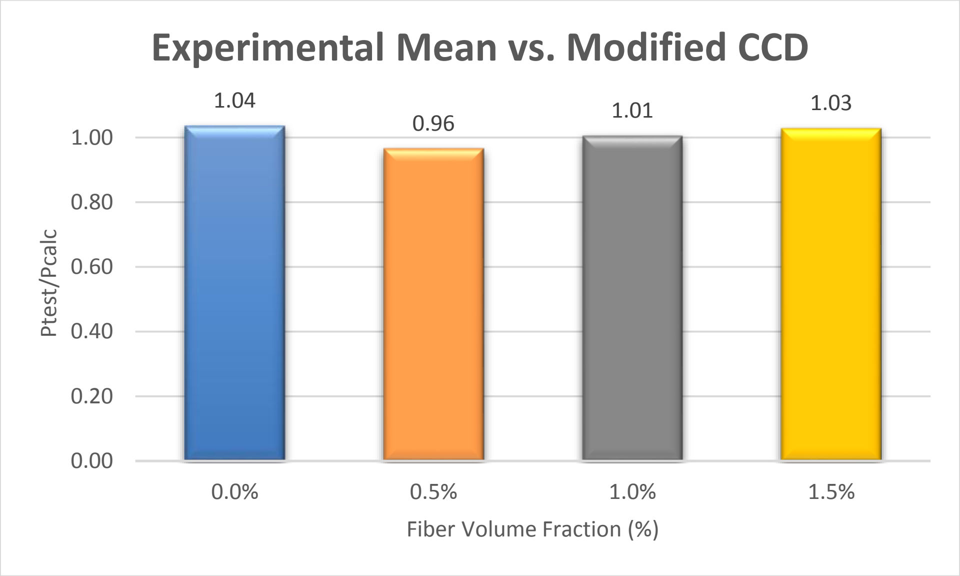


Figure 31: Comparison of Mean Values

The modified CCD method appears to accurately predict the failure of the post-installed screw anchors. Additionally, the test data concludes that the addition of fibers in these post-installed short embedment anchors will yield in an approximate 45° failure angle. Using mechanics of material theory, for a material in uniaxial tension the plane of maximum shear stress occurs 45° from the principal plane. Therefore, anchors are possibly breaking out as the shear stress occurring exceeds the shear strength of the material, resulting in a ductile fraction. As the failure angle approaches 45° the linear trend between the ultimate tensile anchor load and the amount of fibers may change as the rate of increasing tensile strength and shear strength differs.

The experiment also revealed insights into the pullout strength of the DEWALT screw bolts. The 3/8” diameter Screw-Bolt+ does not have a pullout strength published because the breakout of the concrete control the design of the anchors. Specimens 1 & 2 of the 1.5% fiber mix design both failed in pullout. The fiber is not believed to have influenced the pullout strength of the anchor, but that cannot be concluded without more testing. However, if the fiber does not influence the pullout strength of an anchor, anchors normally controlled by concrete breakout may fail in pullout with the addition of fibers in the concrete design. Consequently, the publication of pullout strength for all post-installed anchors is required for thorough design.

In summary, the ultimate tensile strength showed growth as additional fibers were introduced. The addition of fibers did not appear to influence the ultimate pullout strength of the anchors. Aside from the tensile strength, the shear strength of the concrete may also be an influencing factor, seen as the tensile strength increased while both the compressive and ultimate anchor loads decreased. Finally, the anchor breakout diameters all decreased with the addition of fibers.

5 CONCLUSION

5.1 Project Results

5.1.1 Summarized Conclusions

- The addition of fiber reinforcement increased the tensile capacity of the anchors by approximately 29.2% for every 1% of polypropylene fiber added.
- The concrete mixtures became more ductile as the fiber dosage increased.
- The failure angle approached 45° as the fiber dosage increased.
- The workability of the concrete decreased as the fiber dosage increased.
- The tensile and flexural strength of the concrete increased with the addition of fibers while the compressive strength decreased.

- Since the tensile strength of the concrete consistently increased with the addition of fibers but the compressive strength decrease, the shear strength of the concrete may limit the tensile capacity of anchors within fiber reinforced concrete.
- Decreasing the compressive strength of the concrete led to a decrease in the tensile capacity of the anchors.

5.2 Research Contribution & Continuation

5.2.1 Research Impact

Although fibers are not the most economically solution for all concrete construction, plenty of fibers have been used in the design of pavement. Pavement is subject to both intense use and exposure. The use of fibers in pavement can further confine the concrete, passively bolstering the compressive strength while simultaneously reducing the cracking from use, shrinkage, thermal expansion, etc. Traffic barriers, such as guardrails, can be anchored to the pavement. Anchorage to the fiber reinforced pavement can be done using post-installed anchor bolts, such as DEWALT Screw-Bolt+. Understanding the effects of fiber on the anchor will help designers with the planning of future traffic barriers. The increased strength of anchorage from fiber will allow designers to reduce the number of anchors used, thus reducing the cost of construction.

There does not appear to be any published research for the embedment of DEWALT Screw-Bolt+ installed in fiber reinforced concrete. These findings can be used for future research into the subject. Additional research and publication of the results will allow designers the ability to design with post-installed anchor bolts with the increased strength that the addition of fibers will allow. While cast-in-place anchors may provide more strength than the typical post-installed anchor, damaged post-installed anchors used in the anchorage of traffic barriers could simply be replaced.

5.2.2 Recommendations for Future Research

- Investigation the behavior of cast-in-place anchors, including hex head & J-bolts, embedded within fiber reinforced concrete.
- Test the effects of using various types of fiber reinforcement.
- Test the effects of using various types of post installed anchors installed within fiber reinforced concrete.
- Investigate new methods for the consolidation of concrete with high amounts of fiber reinforcement.
- Investigate the effects of fatigue loads on anchors installed or embedded within fiber reinforced concrete.
- Investigate the effects of impact loads on anchors installed or embedded in fiber reinforced concrete.
- Test groups of anchors installed or embedded within fiber reinforced concrete.
- Study the behavior of anchors of different diameters and/or embedment lengths for anchors embedded within fiber reinforced concrete.
- Study the effects of environmental factors on anchors embedded within fiber reinforced concrete.
- Study the effects of concrete compressive strength with fibers using modified concrete designs utilizing different aggregate sizes.
- Investigate the effects of increasing shear & tensile strength of concrete on concrete anchorage via means other than fibers.
- Test the effects of anchor shear strength with the addition of fiber reinforcement.

Appendix A

Breakouts of 0.0% Fiber Specimens

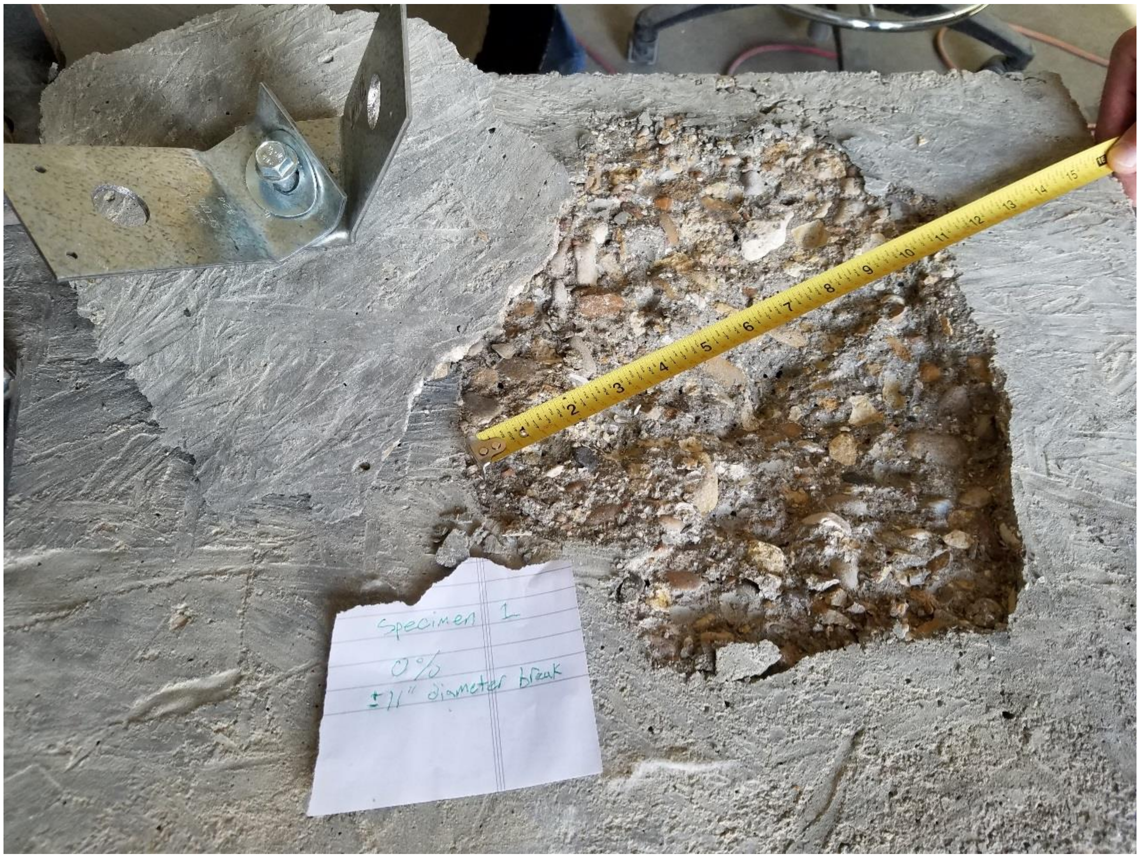


Figure 32: 0.0% Fiber - Specimen 1 Failure

Figure 33: 0.0% Fiber - Specimen 2 Failure

Figure 34: 0.0% Fiber - Specimen 3 Failure

Figure 35: 0.0% Fiber - Specimen 4 Failure

Figure 36: 0.0% Fiber - Specimen 5 Failure

Appendix B

Breakouts of 0.5% Fiber Specimens

Figure 37: 0.5% Fiber - Specimen 1 Failure

Figure 38: 0.5% Fiber - Specimen 2 Failure

Figure 39: 0.5% Fiber - Specimen 3 Failure

Figure 40: 0.5% Fiber - Specimen 4 Failure

Figure 41: 0.5% Fiber - Specimen 5 Failure

Appendix C

Breakouts of 1.0% Fiber Specimens

Figure 42: 1.0% Fiber - Specimen 1 Failure

Figure 43: 1.0% Fiber - Specimen 2 Failure

Figure 44: 1.0% Fiber - Specimen 3 Failure

Figure 45: 1.0% Fiber - Specimen 4 Failure

Figure 46: 1.0% Fiber - Specimen 5 Failure

Appendix D

Breakouts of 1.5% Fiber Specimens

Figure 47: 1.5% Fiber - Specimen 1 Failure

Figure 48: 1.5% Fiber - Specimen 2 Failure

Figure 49: 1.5% Fiber - Specimen 3 Failure

Figure 50: 1.5% Fiber - Specimen 4 Failure

Figure 51: 1.5% Fiber - Specimen 5 Failure

Appendix E

Flexure Tests – Loads v. Displacement

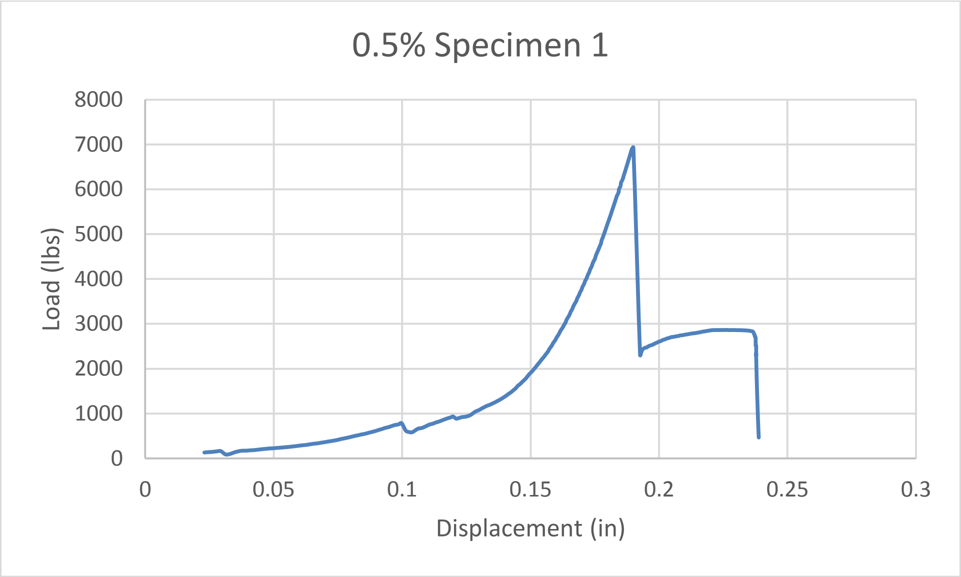


Figure 52: Flexure Test Results - 0.5% Fiber Mix, Specimen 1

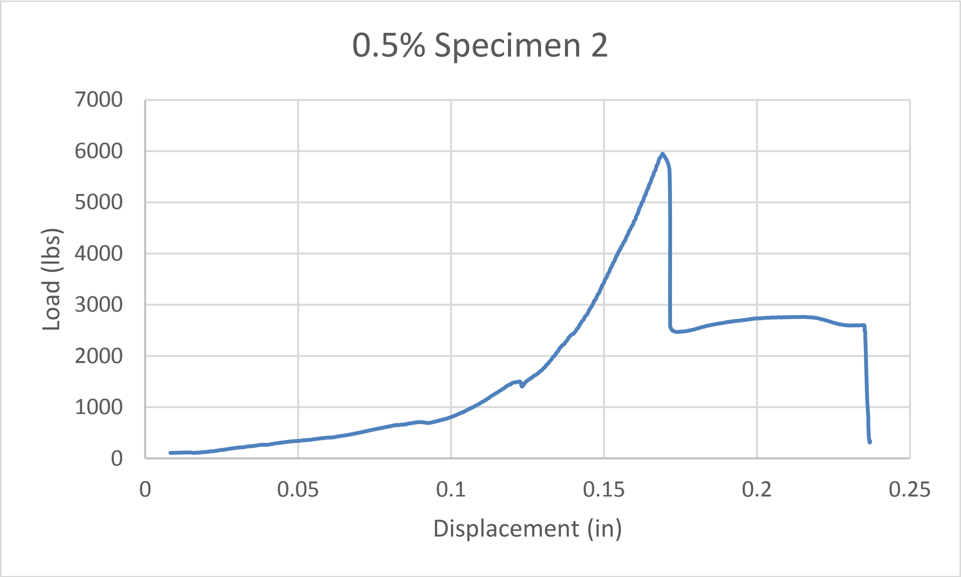


Figure 53: Flexure Test Results - 0.5% Fiber Mix, Specimen 2

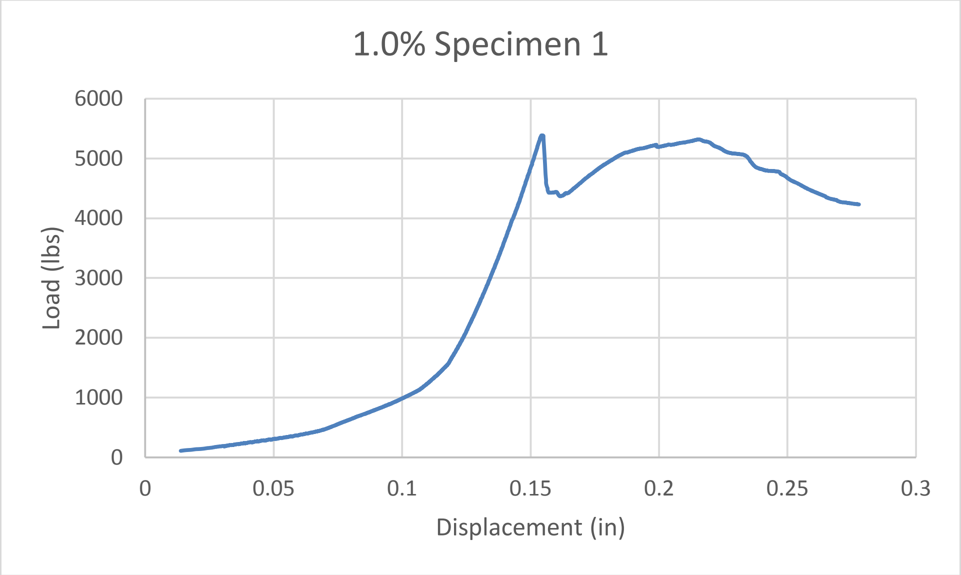


Figure 54: Flexure Test Results - 1.0% Fiber Mix, Specimen 1

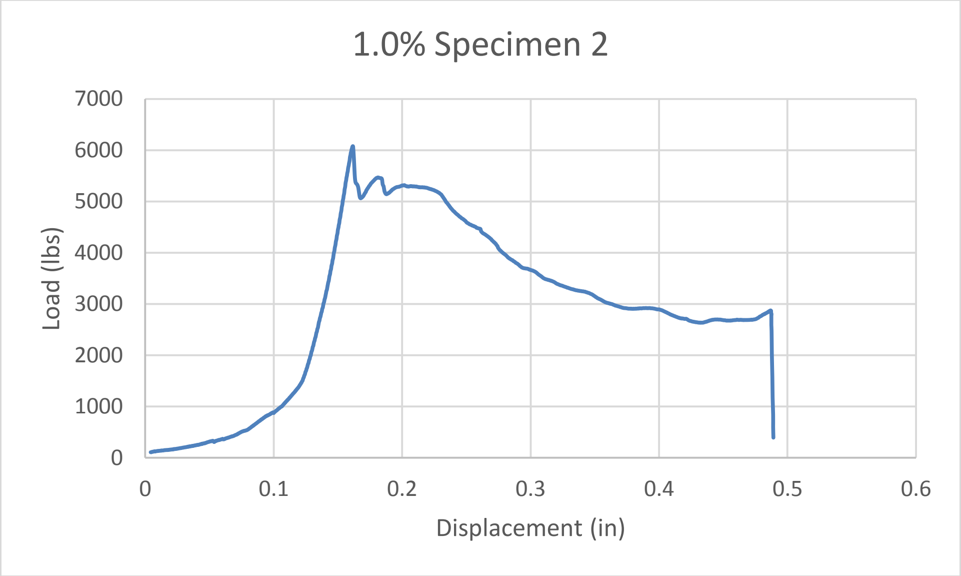


Figure 55: Flexure Test Results – 1.0% Fiber Mix, Specimen 2

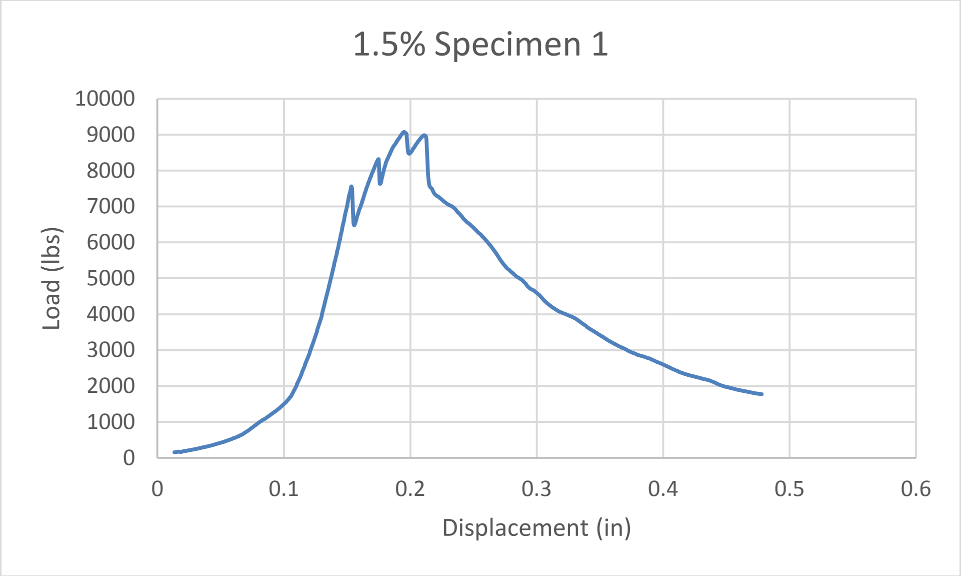


Figure 56: Flexure Test Results - 1.5% Fiber Mix, Specimen 1

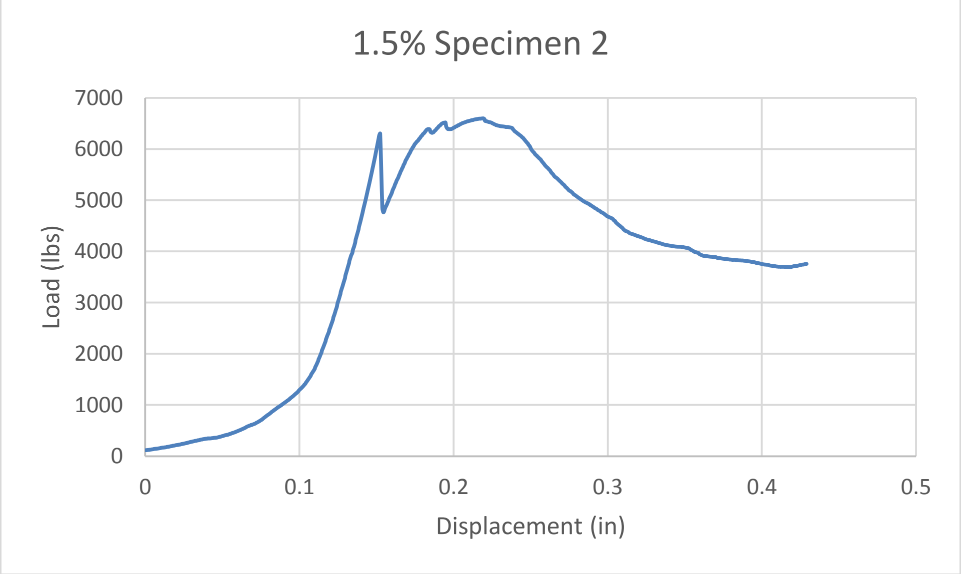


Figure 57: Flexure Test Results - 1.5% Fiber Mix, Specimen 2

Appendix F

Concrete Anchor Calculations

D = Breakout Diameter (in)
y = Embedment Depth (in)
Θ = Failure angle (°)

$$\tan\Theta = \frac{y}{D/2}$$

$$\Theta = \arctan\left(\frac{y}{D/2}\right)$$

0% fiber mixture)
Average D = 7.7"
y = 2"

$$\Theta = \arctan\left(\frac{2}{7.7/2}\right) = 27.5^\circ$$

0.5% fiber mixture)
Average D = 4.85"
y = 2"

$$\Theta = \arctan\left(\frac{2}{4.85/2}\right) = 39.5^\circ$$

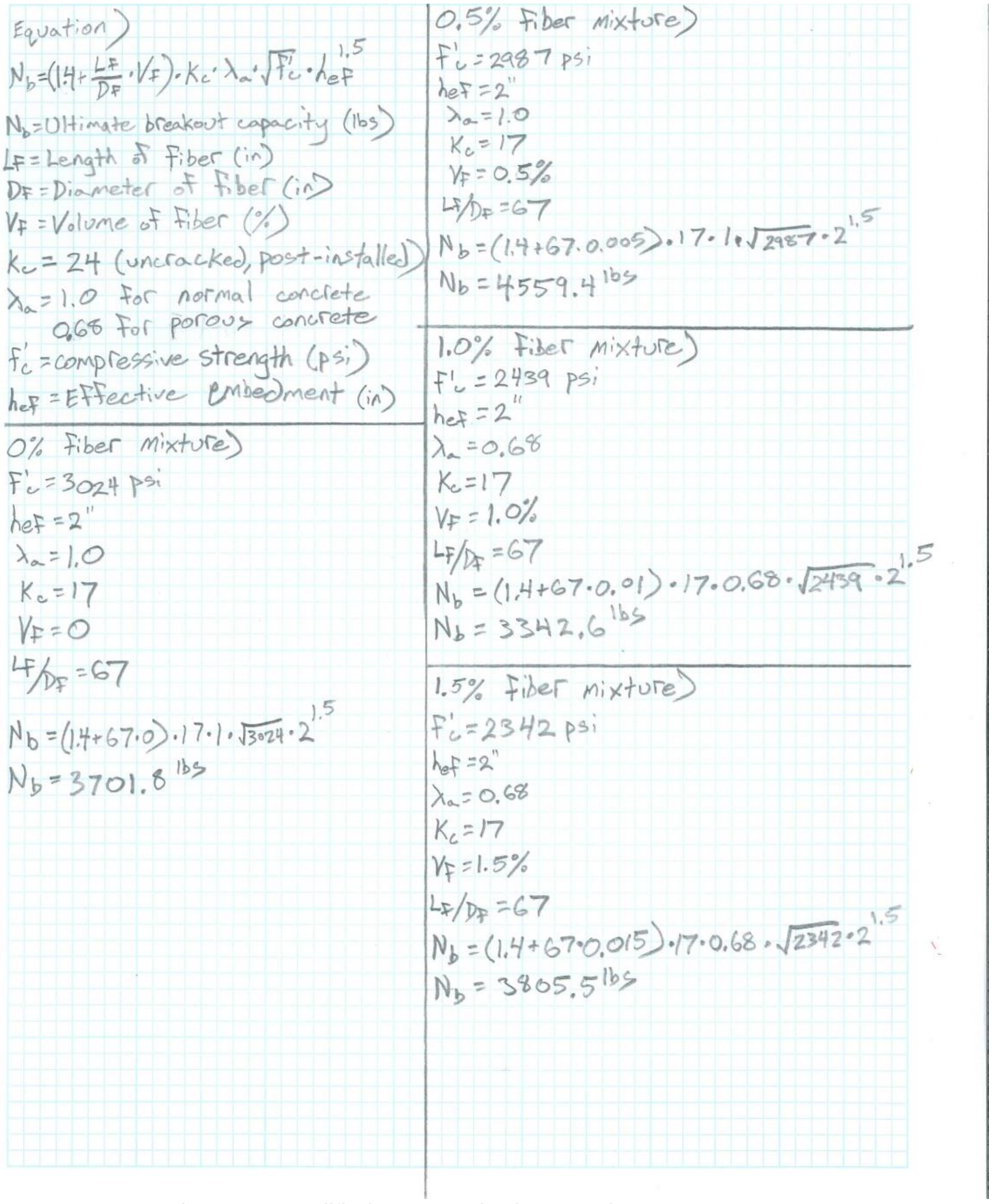
1.0% fiber mixture)
Average D = 5.2"

$$\Theta = \arctan\left(\frac{2}{5.2/2}\right) = 37.6^\circ$$

1.5% fiber mixture)
Average D = 4.05"

$$\Theta = \arctan\left(\frac{2}{4.05/2}\right) = 44.6^\circ$$

Figure 58: Failure angle calculations



Equation)

$N_b = \left(1.4 + \frac{L_F}{D_F} \cdot V_F\right) \cdot K_c \cdot \lambda_a \cdot \sqrt{f'_c} \cdot h_{ef}^{1.5}$

N_b = Ultimate breakout capacity (lbs)

L_F = Length of fiber (in)

D_F = Diameter of fiber (in)

V_F = Volume of fiber (%)

$k_c = 24$ (uncracked, post-installed)

$\lambda_a = 1.0$ for normal concrete
0.68 for porous concrete

f'_c = compressive strength (psi)

h_{ef} = Effective embedment (in)

0% fiber mixture)

$f'_c = 3024$ psi

$h_{ef} = 2''$

$\lambda_a = 1.0$

$K_c = 17$

$V_F = 0$

$L_F/D_F = 67$

$N_b = (1.4 + 67 \cdot 0) \cdot 17 \cdot 1 \cdot \sqrt{3024} \cdot 2^{1.5}$

$N_b = 3701.8$ lbs

0.5% fiber mixture)

$f'_c = 2987$ psi

$h_{ef} = 2''$

$\lambda_a = 1.0$

$K_c = 17$

$V_F = 0.5\%$

$L_F/D_F = 67$

$N_b = (1.4 + 67 \cdot 0.005) \cdot 17 \cdot 1 \cdot \sqrt{2987} \cdot 2^{1.5}$

$N_b = 4559.4$ lbs

1.0% fiber mixture)

$f'_c = 2439$ psi

$h_{ef} = 2''$

$\lambda_a = 0.68$

$K_c = 17$

$V_F = 1.0\%$

$L_F/D_F = 67$

$N_b = (1.4 + 67 \cdot 0.01) \cdot 17 \cdot 0.68 \cdot \sqrt{2439} \cdot 2^{1.5}$

$N_b = 3342.6$ lbs

1.5% fiber mixture)

$f'_c = 2342$ psi

$h_{ef} = 2''$

$\lambda_a = 0.68$

$K_c = 17$

$V_F = 1.5\%$

$L_F/D_F = 67$

$N_b = (1.4 + 67 \cdot 0.015) \cdot 17 \cdot 0.68 \cdot \sqrt{2342} \cdot 2^{1.5}$

$N_b = 3805.5$ lbs

Figure 59: Modified CCD method calculations

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Biographical Information

Travis Pechacek

Academic:

Bachelor of Science in Civil Engineering (August 2011 – May 2015)
University of Texas at Austin
Austin, Texas

Master of Science in Civil Engineering (January 2016 – Present)
University of Texas at Arlington
Arlington, Texas

Professional:

Civil – Graduate Engineer (June 2015 – January 2017)
Baird, Hampton, & Brown Inc.
Fort Worth, Texas

Structural – Design Engineer (January 2017 – Present)
Frank W. Neal & Associates, Inc.
Fort Worth, Texas