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Hemp fiber – an environmentally friendly fiber for concrete reinforcement

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The commercial use of hemp fiber in the construction industry within the United States is non-existent. This lack of use is because of State and Federal laws forbidding the growth of hemp in the United States, which has led to a lack of research. Not having an established supply chain for hemp and coupled with limited research has put the United States behind other countries in finding viable options for these renewable resources.

This is a study of the performance of raw hemp fibers and processed hemp twine in a cement past mixture subjected to tensile loading. Three water/cement ratios (0.66, 0.49, 0.42) were considered. Replacement of cement with fly ash is also part of the program to see if it affects the performance of the system. A detailed description of the method of applying the tensile load to the micro/macro fibers along with the fixture setup is part of this article. The results of this investigation show the hemp twine and fibers will bond to the cement matrix and they can carry higher tensile loads at higher w/c ratios. This study shows that 30 mm embedment length is best for hemp macro fibers and 20 mm embedment for hemp micro fibers.

This study also includes a comparative investigation of the performance of hemp fibers to synthetic and steel fibers added to a concrete mix. This investigation examined the compressive strength of the fiber-reinforced concrete mixes, flexural capacity, ductility, flexural toughness

and the effects the fibers have on Young's modulus of elasticity. All fibers were introduced to the same mix design (w/c = 0.49) with replacement of 25% of cement with fly ash. Hemp micro fibers at the same dosing rate a synthetic micro fibers has a slightly higher toughness and equivalent flexural strength. Hemp macro fibers at a higher dosing rate as compared to synthetic fibers will have similar toughness and equivalent flexural strength. Steel fibers performed better than the synthetic and natural fibers at 28-day compressive strength.

DEDICATION

To my wife, Kim, my son, Zachary and to my daughter Madison. You are the three great blessings that God has given me. Thank you for supporting me through this long journey.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION AND BACKGROUND

1.1 Introduction

Concrete is the most widely used construction material in the world[1]. Today, concrete is used for pavement, bridges, tanks, houses, skyscrapers, art, and many more. Skyscrapers (200 meters and taller) that have been built, 57% are made entirely of concrete while 32% are composite of concrete and steel[2]. Concrete is also used in developing nations, like Haiti, to build homes, schools, and clinics. Other common building materials, such as wood, are in limited supply in Haiti.

Concrete is one of the oldest construction materials. The Egyptians (around 3000 B.C.) used a crude form of cement, lime and gypsum, to make mortars[3]. Recent discoveries have noted that the exterior stones of the Egyptian Pyramids is a geopolymer concrete (doesn't contain Portland cement)[4]. The Minoan civilization in Crete (around 2000 B.C.) also developed a lime mortar that they used in construction[5]. This mortar was susceptible to moisture which caused it to dissolve over time[5]. The ancient Romans (300 B.C. to 476 A.D.) used a material that is very close to modern-day cement[3] that was used to build their massive structures. The Dome of the Pantheon in Rome, which was completed in 126 A.D., is an example of engineering and construction ingenuity that existed. The dome has a 44 meter span which was not surpassed until the nineteenth century[5].

Around 1800, John Smeaton (an English engineer) experimented with burning limestone and clay to create a cement that is moisture resistant (when cured) and will set up underwater (hydraulic cement)[5]. Smeaton was experimenting to find a mortar for the Eddystone Lighthouse that he was designing. Even though his experiments were successful, Smeaton chose to go with the proven techniques and materials of the Romans[5].

Modern-day cement was invented by Joseph Aspdin in 1824 in Leeds, U.K.[1,5]. Aspdin, like Smeaton, used limestone and clay and heated them to high temperatures. The major difference is Aspdin used limestone and clay from various quarries[5]. Aspdin was awarded a British patent in 1824 for which he named his new material Portland cement[1,3,5]. He gave it the name Portland since the cured concrete resembled stone that was quarried from the Isle of Portland[1,3,5]. His son William later refined the process to make a material that is very close to today's Portland cement1.

Adding reinforcement to concrete started shortly after the development of Portland cement. Joseph Monieer (1867 Paris, France), by most, is credited for the first particle use of reinforced concrete based on scientific methods[6]. Before this others had attempted reinforcing concrete for various uses. In 1848, Lambot developed a small reinforced concrete boat. He later patented the design and displayed the boat at the 1855 Worlds Fair[5]. W.B. Wilkinson created a reinforced slab that incorporated the use of hollow plaster domes as forms. The reinforcing used was discarded hoist ropes that had been used in mines[5].

The use of reinforced concrete in the United States was spearheaded by Thaddeus Hyatt in the 1850's. He was a lawyer and was appointed American consul at La Rochelle, France, where he served until 1865[7]. Hyatt is credited for building the first concrete house in London[7]. Hyatt's worked was not known until he published his findings in 1877[6].

During the late 1800s into the early 1900s, most of the knowledge and research associated with the design and construction of reinforced concrete was not widely known. Most engineers at the time kept the information to themselves because it was considered proprietary information[6]. One of the first reinforced concrete textbooks in English was published in 1907. Since that time, major developments in concrete design has occurred. Extensive research has been completed but there is still more to learn and new techniques to be developed.

1.2 Background

Reinforcement for concrete has changed over the years. In the mid-1800's iron square and round bars were used. Then steel (as it became more prevalent) was used instead of iron. The first specification for steel reinforcement was written in 1910[8]. The first ASTM for steel reinforcement for concrete (ASTM A15) was published in 1911[8]. An option to steel bar reinforcement is fiber reinforcement.

In 1898 the Hatschek process was developed which incorporated asbestos fibers in a cement mortar matrix[9]. In the 1960s and 1970s other fibers were used because of the health risks associated with asbestos. It wasn't until 1963 and 1964 that research papers on fiber reinforcement of concrete first appeared[10,11] In the 1960's, fiber reinforced concrete was limited to steel material normally obtained from tire manufaturers[11]. Glass fibers in concrete was first investigated in the late 1950s by USSR but was not successful because the glass fibers were attacked by the alkali of the cement paste. Later on, synthetic fibers such as nylon and polypropylene fibers were studied[9]. In 1973, the American Concrete Institute (ACI) Committee 544 released its first state-of-the-art report on fiber reinforced concrete[9]. Since the first report in 1973, there have been several updates to the original report and additional reports written exclusively on fiber reinforced concrete[9,12–15].

In the 1980s research started focusing on the use of natural fibers instead of steel, glass or synthetic fibers[16]. Some of the natural fibers that have been studied are coconut, sisal, hemp, wood, bamboo, elephant grass, etc.[17,18]

There are advantages to using natural fibers versus manufactured materials. The most obvious is natural fibers take less energy and money to process the natural fibers into a useable product while the manufactured materials will cost more and take a lot more energy[16]. Natural fibers also are a great way to reduce the environmental impact caused by construction. This will help reduce carbon emissions in the United States and other countries[19,20].

One promising natural fiber is hemp and it close relative marijuana[21]. Chapter 2 goes into detail on the difference between hemp and marijuana. The biggest issue that the United States had to deal with is that hemp was classified the same as marijuana since 1970[22]. This did not allow the growing of hemp in the United States from 1970 until 2014[23]. Now that growing of industrial hemp is legalized, additional research needs to be done to determine the uses for hemp and the fibers that the stalks produce.

This research investigated the use of hemp fibers to reinforce concrete as an alternative to steel reinforcement. The research first studied the viability of producing hemp fibers in the United States based on the current regulations, processing abilities, and market demand. Next optimizing fiber length to obtain the best performance while minimizing/controlling side effects was investigated. The third part of the research was to see how micro and macro fibers, at different dosing rates, performed as compared to commercially available micro and macro synthetic fibers and steel fibers.

1.3 References

1. February 2008, J. M. C. “The concrete conundrum.” Chemistry World. Available at: https://www.chemistryworld.com/features/the-concrete-conundrum/3004823.article. Accessed February 7, 2020.

2. “The Skyscraper Center.” Available at: http://www.skyscrapercenter.com/compare-data/submit?type%5B%5D=building&material%5B%5D=concrete&material%5B%5D=composite&base_region=0&base_country=0&base_city=0&base_height_range=4&base_company=All&base_min_year=0&base_max_year=9999&comp_region=0&comp_country=0&comp_city=0&comp_height_range=4&comp_company=All&comp_min_year=0&comp_max_year=9999&skip_comparison=on&output%5B%5D=list&output%5B%5D=material&dataSubmit=Show+Results. Accessed February 10, 2020.

3. “History of Concrete - Concrete and Cement History Timeline - The Concrete Network.” Available at: https://www.concretenetwork.com/concrete-history/. Accessed February 10, 2020.

4. “Geopolymer Concrete, Egyptian Pyramids, and a New Way Forward for Sustainable Masonry - Watershed Materials - Technology for New Concrete Blocks.” Available at: https://watershedmaterials.com/blog/2015/3/31/geopolymer-concrete-egyptian-pyramids-and-a-new-way-forward-for-sustainable-masonry. Accessed February 10, 2020.

5. Wight, J. K. “Reinforced Concrete - Mechanics and Design,” 7th edition, Pearson, 2016.

6. Wang, C.-K., and Salmon, C. G. “Reinforced Concrete Design,” Sixth, Addison-Wesley, 1998.

7. “Thaddeus Hyatt Papers 1843-1898 - Kansas Historical Society.” Available at: https://www.kshs.org/index.php?url=p/thaddeus-hyatt-papers-1843-1898/14047#description. Accessed February 11, 2020.

8. “CRSI: History of Reinforcing Steel.” Available at: https://www.crsi.org/index.cfm/basics/history-of-reinforcing-steel. Accessed February 12, 2020.

9. 544, A. C. “State-of-the-Art Report on Fiber Reinforced Concrete.” vol. 70. ACI, 1996.

10. Roumaldi, J. P., and Batson, G. B. “Mechanics of Crack Arrest in Concrete,” *Proceedings of the ASCE Journal of Engineering Mechanics*, V. 89, No. EM 3, 1963, pp. 147–68.

11. Zollo, R. F. “Fiber-reinforced Concrete: an Overview after 30 years of Development,” *Cement and Concrete Composites*, V. 19, 1997, pp. 107–22.

12. ACI Committee 544, and American Concrete Institute "Report on the physical properties and durability of fiber-reinforced concrete," Farmington Hills, MI, American Concrete Institute, 2010.

13. ACI 544 Committee. "Guide to Design with Fiber-Reinforced Concrete ACI 544.4." 2018. p. 4.

14. ACI 544 Committee. "Guide for Specifying, Proportioning, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete ACI 544.3." ACI Materials Journal, vol. 90. 1993.

15. Kong, F., and Evans, R. "Handbook of structural concrete," 1983.

16. Sethunarayanan, R., Chockalingam, S., and Ramanathan, R. "NATURAL FIBER REINFORCED CONCRETE." 1989.

17. Aziz, M., Paramasivam, P., and Lee, S. "Prospects for natural fibre reinforced concretes in construction," *International Journal of Cement Composites and Lightweight Concrete*, V. 3, No. 2, 1981, pp. 123–32.

18. Lewis, G., and Premalal, M. "Natural vegetable fibres as reinforcement in cement sheets," *Magazine of Concrete Research*, V. 31, No. 107, 1979, pp. 104–8.

19. Leung, J. "Decarbonizing U.S. Buildings," Center for Climate and Energy Solutions, 2018.

20. Paddock, L., and McCoy, C. "Deep Decarbonization of New Buildings," n.d., p. 20.

21. Kaiser, C., Cassady, C., and Ernst, M. "Industrial Hemp Production," *Center for Crop Diversification Crop Profile*, 2015.

22. "Section 811." Available at: https://www.deadiversion.usdoj.gov/21cfr/21usc/811.htm. Accessed June 3, 2018.

23. "7 U.S.C. 5940 - Legitimacy of industrial hemp research." Available at: https://www.gpo.gov/fdsys/granule/USCODE-2015-title7/USCODE-2015-title7-chap88-subchapVII-sec5940. Accessed November 19, 2017.

CHAPTER II

LIMITATION OF THE VIABILITY OF HEMP REINFORCED CONCRETE

Portions of this chapter has been submitted for publication in the Journal of Natural Fibers. Furthermore, the paper has been reformatted and replicated herein with minor modifications in order to fit the purposes of this dissertation.

2.1 Introduction

The use of natural fibers in construction is common. Natural fibers such as grass and straw have been used in adobe and cob[1]. In the 1870's these fibers were added to concrete[2]. . In recent years, hemp fiber has been used in a weak non-structural lime mix called hempcrete. Hempcrete has mainly been used as an infill material between studs to provide insulation for a structure[3]. Hemp has a thermal conductivity (λ) that varies from 0.040 to 0.060 W/mK[4] which is similar to rock wool values of 0.033-0.046 W/mK[5]. The thermal conductivity (λ) is not a common term used in construction in the United States. In the U.S. the R-value: the resistance of a material to heat flow. $R = l/\lambda$ where l, in meters, is the thickness of the insulating material. An additional benefit of natural fibers, unlike glass fibers, is they are not an irritant which makes the natural fibers more user friendly[5].

The use of natural fibers has been based on traditional methods more than scientific research[6]. Research results have shown that some natural fibers (coconut and jute) increase compressive and tensile strength of concrete[6], while other natural fibers (wood) show a reduction in compressive strength[7].

While hemp reinforced concrete is a new concept in the United States, weavers and artists have been using hemp fibers for years to make fabric, rope, and various forms of art work. The authors interviewed three local weavers and a master weaver at Colonial Williamsburg to learn about the process of extracting hemp fibers form the stalk.

The main advantage of natural fiber over steel fiber reinforcement is natural fibers do not rust or stain. Natural fibers can be produced at a lower cost as compared to polymer and steel fibers. Natural fibers also have:

- lower density than glass fibers (hemp 1.40 g/cm3 – E-glass 2.50-2.55 g/cm3),
- are a renewable resource,
- easily processed,
- and have good thermal (hemp 0.040 to 0.060 W/mK – E-glass 10.4 W/mk Carbon 121 W/mK) and acoustic insulating properties[8].

Hemp fiber also absorbs CO2 which cleans the air we breathe: this is something traditional reinforcement cannot do. This could make hemp reinforced concrete a potential carbon offset. The goal of carbon offsets is to reduce the emission of greenhouse gases.

2.2 Issues with producing hemp reinforced concrete

There are two major categories for cannabis: hemp and marijuana. Both forms of cannabis have the scientific name of Cannabis sativa L. Industrial hemp plants may be of the same species as marijuana and may have similar looking leaves; however, they have many differences. Industrial hemp normally reaches heights of 6 to 15 feet with few leave and branches[9]. Marijuana plants are short and are grown to produces many leaves and branches as well as buds.

The major difference between the two varieties of Cannabis sativa L. is marijuana contains 3% to 15% tetrahydrocannabinol (THC) while industrial hemp fiber contains less than 0.3% THC[10]. THC is the chemical that produces the euphoric feeling from smoking or ingesting marijuana. Concentrations of THC less than 1% cannot provide this effect when smoked or ingested[10,11].

The United State Congress in 1937 enacted legislation that made the growing, harvesting, and selling of marijuana illegal, but still allowed the production industrial hemp for fiber and oil[9,12]. However, Congress passed the Controlled Substance Act of 1970 which banned cannabis sativa L., including industrial hemp[13]. Since 1970, industrial hemp is considered a controlled substance by the Drug Enforcement Agency (DEA). The growing of hemp could carry the same criminal penalties as growing marijuana.

In 2014 Congress passed the Farm Bill[14] which allows some research institutions (i.e. universities) to grow industrial hemp[9]. These pilot programs allow universities to study the viability of hemp as a production crop, and examine possible uses for hemp. The states where the industrial hemp is grown must also have state statutes that allow the growing and cultivation of industrial hemp[15]. The 2018 Farm Bill allows the legalized growing of hemp by anyone in the United States[16]. The term "industrial hemp" includes the stalk, leaves and seeds of the plant (growing or not) that are used exclusively for industrial purposes, and the THC levels may not exceed 0.3 percent on a dry weight basis (weight of the THC divided by the dry weight of the total sample)[17].

The 2014 Act did not remove industrial hemp from the list of controlled substances; therefore, if the industrial hemp is not used or handled in accordance with the 2014 Act, then the use will be considered criminal and could be prosecuted at a state and/or federal level[18]. The

2018 Farm Bill removed industrial hemp form the list of controlled substances; therefore, it is a legal agricultural crop (if adopted by the states).

Another issue facing most universities and pilot farm programs is finding industrial hemp seed as opposed to marijuana seeds. China is one of the largest grower of hemp in the world[19]. China has provided seeds to university programs in the United States; however, it has been determined that some of the seeds produced plants with a THC much higher than 0.3 percent. A few states have developed seed certification programs to help reduce the potential of marijuana plants being grown[15]. For example, Maine requires that industrial hemp seed be from a certified source that is certified by the Association of Seed Certifying Agencies or other approved standards. The seed must be from plants that were tested while grown and found to have a THC content of 0.3% or less[20]. Other states, such as California and Oregon, only provide requirements for seed produced in their respective state[21]. These requirements establish clear zones to nocuous plants (weeds), to Cannabis, and other plants that may affect the pollination of the hemp.

If a university does not want to grow hemp for its fiber, the university may purchase hemp fibers (not regulated by state or federal law) from suppliers inside or outside the United States. Quality of purchased hemp fibers varies greatly. The fibers may not be pure hemp fibers when purchasing fibers from outside the United States. Fibers processed in other countries may be blended with other natural fibers such as sisal or jute and other plant fibers either intentionally or through cross contamination, as the facilities where the fibers are processed handle multiple fiber types[22].

2.3 Hemp production

Hemp is commercially grown in 23 countries[23]. Japan, the Netherlands and the United States are piloting or researching the viability of hemp for their industries. The United States is behind other nations in regards to hemp research and production. This is due to laws in the United States that forbid the growing of hemp while other countries never established such laws.

Thirty-eight states have passed legislation relating to industrial hemp (see Figure 2.1). Twenty-six of those states have specific legislation related to hemp pilot programs and research into the various uses[15]. Colorado, Kentucky and North Carolina are at the forefront with legislation that looks at specific research goals such as: use in animal feed, biofuel, agricultural improvements and soil conservation[15].

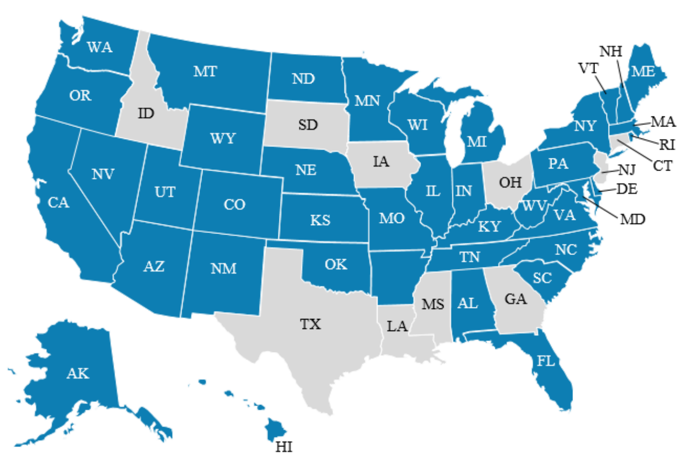

Figure 2.1 Map showing states that allow the growing of hemp (adapted by NCLS)

Blue states allow cultivation of hemp for commercial, research or pilot programs. Grey states do not allow cultivation of hemp.

Hemp fibers have many potential uses:

- Clothing
- Rope/twine/string
- Paper
- Plastic composites
- Bio-fuel
- Carpet
- Netting
- Reinforcement for concrete
- Insulation

One main issue that the must be addressed in the United States is the lack of infrastructure to support the processing of hemp fibers in the quantity and quality that will be required to produce fibers for reinforcing concrete.

2.4 Hemp fiber processing

Hemp plants contain fibers in the leaves, stems and stalks (see Figure 2.2). 1900 to 5700 lbs of fibers per acre can be harvested from hemp[1]. The estimated cost per acre to grow hemp fibers is $286.20[19]. Hemp bast fibers are the long strong fibers found in the stalk of the plant and provide structural strength the plant stalk[1,24]– see Figure 2.3 for typical cross-section of hemp stalk. These long fibers cut to a specific length may be replacement for synthetic fibers for use in concrete.

Figure 2.2 Dried hemp stalks

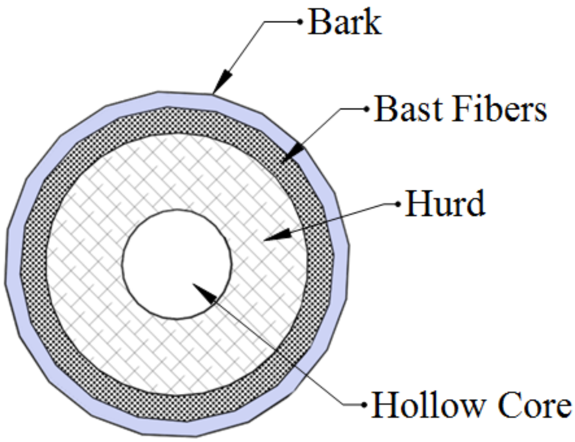

Figure 2.3 Typical hemp stalk cross-section.

Hemp fibers can be extracted from the stalk by mechanical, manual, biological, chemical methods or a combination of these methods. The most common method of extracting hemp fibers is a combination of mechanical/manual process along with a biological/chemical process (See Figure 2.4).

The mechanical process of extracting fibers is broken down into a few simple steps. The hemp plants are cut near the ground surface. The plant is allowed to lay in the field where the dew and rain start the retting process (the biological process of breaking down of the stalk material). Some farmers will bundle the hemp stalks together after harvesting, allow them to dry, then place them in a pond or body of water for the retting process. Placing the hemp stalks in the body of water speeds up the retting process [25] and produces longer fibers than dew retting [19].

After the retting process, the hemp stalks are baled and allowed to dry before being taken to a processing plant [19]. The bales are broken open and then the stalks are placed into a machine that crushes the stalks between rollers. This starts the process of breaking the fibers from the woody core, and fractures the core into smaller pieces [19].

The next step is to remove the remainder of the woody core (hurds) from the fibers through a process called decorting. In this process, the fiber/hurd bundle is beat by rods of a revolving drum. This process removes the hurds and short fibers from the long fibers also known as linen fibers [19].

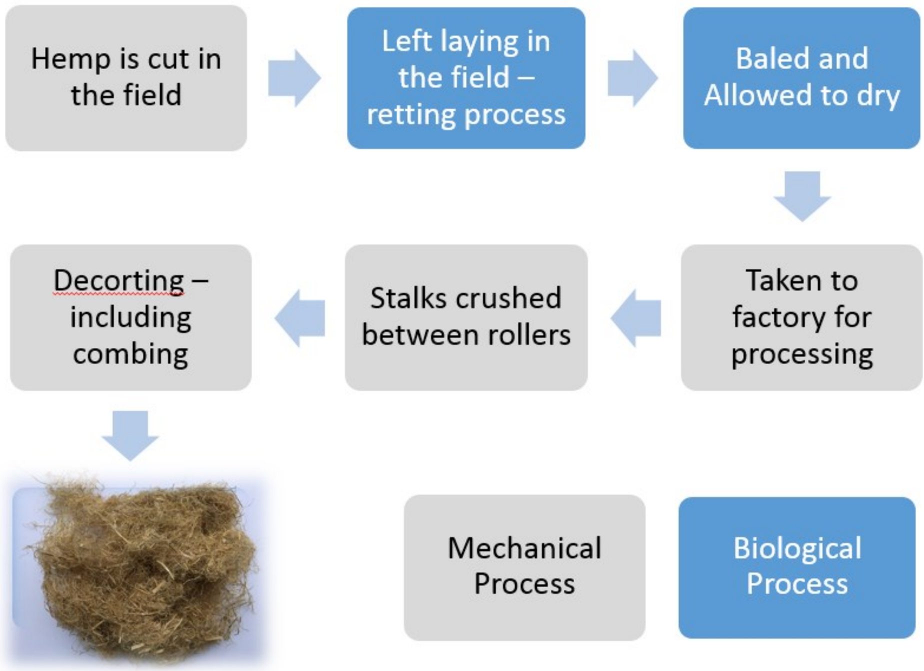

Figure 2.4 Typical hemp fiber processing

The manual processing of fibers is similar to the mechanical process described above but has a slightly different process after the retting process. After a period of time the stalks are beat against rocks or other solid objects to loosen the fibers and make them easily removed by hand. After the bales dry, they are removed from the field and will be processed indoors. The next process, skutching, is a process of hitting the retted stalks with a wood sword which crushes the hurds and starts the separation of the fibers. After skutching the bundle goes through a process called hackling. In this process the bundle is dragged across evenly spaced pins (similar to a comb) which helps remove the short fibers and hurd [25].

The authors of this article went through the process of skutching (see Figure 2.5 and Figure 2.6), hackling and combing (see Figure 2.7) with a drum carder. The results yielded fibers but it is very apparent that this is a very labor-intensive process that takes a noticeable amount of time for a small quantity of usable fibers. The long fibers that are produced approximately account for 3.5% of the original harvested weight [19] when processed by using either process. It was observed that the long fibers produced are not single strands but are actually two or three strands twisted together. The master weaver at Colonial Williamsburg confirmed that hemp fibers (as well as flax) when processed are not single fibers but twisted strands of two or three fibers) [26].

Figure 2.5 Combs Used for Skutching/Combing Fibers

Figure 2.6 Skutching/Combing By Hand

Figure 2.7 Drum Carding Machine

Biological method, also known as retting, is submerging the hemp stalks in water for up to 14 days. During the soaking period microorganisms removes pectic substances which frees the fibers and makes them easily removed by hand. Chemical retting is a form of retting which utilizes dilute alkali or dilute acids to breakdown the pectic [1]. There are issues with using chemicals: proper handling and disposal, cost of the chemicals and if the fibers are not properly rinsed after treatment then the acid could react with the concrete causing it to weaken.

2.5 Natural fibers as reinforcement in concrete

Previous research on natural fibers (some including hemp) have looked at development length, mixing issues, dosing rates, volumetric change and long-term effects.

A study of sisal fibers [27] established a methodology for determining the required minimum embedment length for sisal fiber in a cement matrix. Single sisal fibers were cast into varying length (10mm to 60mm) of cement paste cylinders approximately 3mm diameter. One end of the fiber extends past the top of the cylinder and was attached (by glue) to a heavy piece of cardboard. A distance of 10mm was maintained be the bottom of the cardboard and the top of the cement paste cylinder. The samples were secured in a universal testing machine and subjected to a tensile load. The length of development was determined to be the shortest length in which the fiber failed (broke within the 10mm distance between the cement paste cylinder and bottom of the cardboard) prior to pullout of the fiber from the cement paste cylinder [27]. Their study showed the critical length of embedment to be 30mm. The study defined critical length as the length where the local strong anchorage of the fiber is the highest [27].

Another study looked at the development length or anchorage of natural fibers in concrete [28]. This study tested water reed, elephant grass, plantain, and musamba. The length of anchorage, to cause fiber failure, varied from 20mm to 30mm. The test method used to determine the anchorage length was similar to Morrissey, Coutts and Grossman but instead of the fiber embedded in a cylindrical shape, it was embedded in a cube of cement paste. Lewis and Premealal do not report the composition of the cement matrix.

The sisal fiber study [27] did not follow ACI, ASTM or other standardized testing methodology. Industry is lacking an ACI, ASTM, or other standards that provide guidance on how to determine the development length for organic fibers. For future research, ASTM D3822 *Standard Test Method for Tensile Properties of Single Textile Fibers* should be used in conjunction with the methods established by Morrissey, Coutts and Grossman to look at processed hemp fiber in the multiple strand configuration (natural) instead of a single strand (highly processed).

Natural fibers are known to ball (clump together) during mixing. Different methods of mixing (wet and dry) have been proposed to resolve this issue. One study found that the use of a superplasticizer with sisal fibers performed well [29]. The use of superplasticizers with hemp fibers has not been studied. The use of a superplasticizer should be investigated with the lower w/c ratios to see if this will help with reducing the balling of the fibers and with the overall workability of the concrete mixes [30]. The superplasticizer should not have any adverse effect on the compressive or flexural strength of the concrete.

Past research has looked at varying percentages of fiber dosing (based volume). The percentage of fiber has varied from as little as 0.5% to 20% of total volume[2,6,31,32]; however, a consistent approach to the evaluation of incremental increases in the percentage of hemp fibers to concrete has not been conducted.

A low percentage of fibers have shown not to provide much increase in flexural capacity of concrete [2]. Other studies conducted with hemp fibers have shown that maximum flexural capacity is achieved at 16% fiber volume [31].

Research on long-term use of with hemp fiber has not been completed. One study [28] notes, for the fibers they studied, that vegetable fibers are susceptible to rot. Their study of cement sheets reinforced with natural fibers noted that fibers exposed to a 1 month and 3-month wetting-drying cycle had a reduction in tensile strength: in one particular case the fibers only had 87% of their original strength. The Lew and Premalal study did not discuss if concrete cover or exposure to alkali pore solution made a difference to these effects.

Lew and Premalal also discuss the issues of organic fiber volumetric change when exposed to moisture or drying out [28]. As the fibers take on moisture (from pre-soaking the fibers or form the mixing water), they will swell (increase in volume) and then shrink when the concrete mixture cures (dries). This will create a void in the concrete where the fiber does not bond to the cement matrix, which could result in the fiber pulling out during tensile stress or initiate crack creation.

Previous studies have considered fiber treatment. Treatment has included: soaking the hemp fibers in a solution of NaOH (sodium hydroxide also known as caustic soda) for 24 to 48 hours, then removing and washing the fibers thoroughly before being added to the concrete mix[2,24,31,32]. Sodium hydroxide causes the smooth surface of the hemp fiber to become rough and thereby increase the bond between the fiber and concrete matrix. Some studies have shown that the use of NaOH treatment increased the tensile properties by 30% for flax fiber-epoxy composites [32]; however, the improvement in tensile capacity in concrete has not been established.

The use of chemicals, such as sodium hydroxide used in previous studies, can remove the natural oils in the fiber thereby increasing the bond strength with the concrete. The use of these chemical increases the cost of the fiber thereby increasing the cost of the concrete mix. The skill and the materials required for fiber treatment may not be available in developing countries and the proper disposal of these chemicals must be considered.

Recent research has considered other fiber treatments which include silane treatment, acetylation of natural fibers, benzoylation treatment [32] as well as fiber impregnation with water repellant agents [33]. Most of the chemicals that have been used for fiber treatment are very hazardous to the environment if not properly disposed of.

2.6 Future research

Previous research of hemp fibers integrated into concrete mixes was conducted in the Middle East and parts of Europe but additional research is needed in the following areas before we can definitively identify hemp as a viable product to be added to concrete:

Determination of development length for hemp fibers in concrete (optimum length of fiber). The hemp fibers need to be long enough to be able to carry the tensile forces generated when the concrete is subjected to pure tension or to flexure. If the fibers are too short they will allow the early onset of cracking in the concrete. Determining the proper fiber development length is crucial for providing a structurally adequate concrete section. Fibers that are too short will pullout and the concrete section will not benefit from the increased ductility that the fibers can provide. In the past limited research with hemp, an arbitrary length has been used in the research. Most of the articles on this subject matter do not provide background on how the fiber length has been established. Lengths from 10mm to 30mm have been used.

The Morrissey, Coutts and Grossman method used a cement and water mixture (paste); future research should include fine and coarse aggregate when studying fiber development length to see if the addition of aggregate has any effect on the development length.

Does the use of a superplasticizer improve the distribution of fiber in the mix and workability? Fiber length and the amount of fiber that is added to a concrete mixture has been shown to create a balling effect; that is, the fibers tend to clump together and create small fiber balls. This balling creates a concrete mixture that is difficult to work with [6]. Superplasticizers improve the "flow" of concrete, which may allow for better distribution of fibers and therefore better mechanical properties I the hardened concrete.

Investigate the %-volume of hemp fiber in a concrete mixture and how it affects compressive strength and tensile strength of the concrete. Past research has shown that compressive strength can be reduced when cellulose based fibers are added [7]. The Soroushian and Marikunte research did not specifically examine hemp fibers. Other research only used two percent by volume of fibers added to the concrete mixture [34]. Additional testing should look a multiple dosing rates of hemp fibers to see if an optimum percentage of hemp fibers exists.

Develop a rule-of-thumb formula for determining the proportioning requirements for hemp. Methods for proportioning concrete mixtures have been developed over the years. For example, the Kentucky Transportation Cabinet's Standard Specification for Road and Bridge Construction establishes water-cement ratios, ratio of fine aggregate to coarse aggregate based on concrete compressive strength. This part of the research would look at developing similar ratios for percentage of hemp fiber dosing based on the target compressive strength and workability of the concrete.

Are there long-term issues of organic fibers in concrete? Hemp is a natural fiber that over time if left on the ground will rot. Does a similar degradation occur if the fibers are encapsulated in concrete? If degradation occurs, will it only be at the surface of the concrete where it is exposed to the environment? This testing would also include freeze-thaw testing of hemp fiber reinforced concrete. Are their adverse effects on the fibers and the concrete mixture when exposed to several cycles of freezing and thawing?

Does hemp affect the permeability of concrete? Research has shown that the addition of steel fibers to concrete mix designs reduces the permeability and increases the load-carrying capacity of the concrete [35]. Similar research needs to be done for hemp to see if similar relationships exist.

CO_2 absorption – does hemp reinforced concrete have a higher CO_2 absorption when compared to plain concrete or concrete reinforced with traditional steel reinforcement? The built environment in the United Kingdom accounts for approximately 50% of the their total carbon emissions [5]. If the addition of hemp fibers to the concrete creates a CO_2 sink (carbon offset), cleaner air that could be achieved by creating buildings, bridges and roads with concrete containing hemp fibers.

Impact resistance – does hemp fibers added to concrete increase the impact resistance of concrete? Impact resistance of concrete containing sisal fibers (another organic fiber similar to hemp) has been shown that the absorbed energy increased and the sisal fiber concrete provided a more ductile behavior when compared AR glass fabric reinforced concrete [36]. Will hemp fiber concrete mixtures provide a similar performance? If so, the use of low cost hemp fibers in low strength, high impact applicatons such as highway barriers and anti-drive bollards is significant.

Care must be exercised when selecting cement and concrete admixtures. Some cements and admixtures may attack (or react) with the organic fibers (such as hemp) thereby reducing the strength of the concrete matrix.

2.7 Conclusion

There is much to learn from the use of hemp fibers in concrete. Research in this area is at the beginning of a long road of potential work. The information gained from researching hemp fibers will broaden our understanding for the use of these fibers in the design of thin concrete panels (for roofing or siding), slabs-on-grade, unreinforced foundations and walls. This will benefit areas, such as developing nations that have limited access to steel reinforcement or synthetic fibers. Industrial hemp can and does grow in almost all parts of the world and can be easily harvested and fibers extracted by local people without the use of expensive or complicated equipment.

Industrial hemp fiber can have a positive financial impact on the construction industry. Industrial hemp fiber is a renewable resource that has the potential for being an excellent reinforcement for concrete while providing sustainable benefits.

2.8 References

1. Pickering, K. L. “Properties and performance of natural-fibre composites,” Cambridge, Woodhead [u a], 2008, XVII, 557 S. pp.

2. Awwad, E., Mabsout, M., Hamad, B., et al. “Studies on fiber-reinforced concrete using industrial hemp fibers,” *Construction and Building Materials*, V. 35, 2012, pp. 710–7.

3. Pinkos, J., Dick, K., and Whitmore, E. “Load and moisture behaviour of Manitoba Hemp for use in hempcrete wall systems in a Northern Prairie Climate.” 2011. pp. 10–3.

4. Benfratello, S., Capitano, C., Peri, G., et al. “Thermal and structural properties of a hemp–lime biocomposite,” *Construction and Building Materials*, V. 48, 2013, pp. 745–54.

5. Lawrence, M. “The use of bio-based materials to reduce the environmental impact of construction,” *Civil and Environmental Research*, 2013, p. 6.

6. Aziz, M., Paramasivam, P., and Lee, S. “Prospects for natural fibre reinforced concretes in construction,” *International Journal of Cement Composites and Lightweight Concrete*, V. 3, No. 2, 1981, pp. 123–32.

7. Soroushian, P., and Marikunte, S. “Reinforcement of cement-based materials with cellulose fibers,” *ACI Special Publication*, V. 124, 1990.

8. Biagiotti, J., Puglia, D., and Kenny, J. M. “A review on natural fibre-based composites-part I: structure, processing and properties of vegetable fibres,” *Journal of Natural Fibers*, V. 1, No. 2, 2004, pp. 37–68.

9. Johnson, R. “Hemp as an agricultural commodity.” DTIC Document, 2014.

10. Kaiser, C., Cassady, C., and Ernst, M. “Industrial Hemp Production,” *Center for Crop Diversification Crop Profile*, 2015.

11. Chait, L. D., Evans, S. M., Grant, K. A., et al. “Discriminative stimulus and subjective effects of smoked marijuana in humans,” *Psychopharmacology*, V. 94, No. 2, 1988, pp. 206–12.

12. Musto, D. F. “The Marihuana Tax Act of 1937,” *Archives of General Psychiatry*, V. 26, No. 2, 1972, pp. 101–8.

13. “Section 811.” Available at: https://www.deadiversion.usdoj.gov/21cfr/21usc/811.htm. Accessed June 3, 2018.

14. “7 U.S.C. 5940 - Legitimacy of industrial hemp research.” Available at: https://www.gpo.gov/fdsys/granule/USCODE-2015-title7/USCODE-2015-title7-chap88-subchapVII-sec5940. Accessed November 19, 2017.

15. “State Industrial Hemp Statutes.” Available at: http://www.ncsl.org/research/agriculture-and-rural-development/state-industrial-hemp-statutes.aspx. Accessed May 7, 2019.

16. “2018 Farm Bill | The United States Senate Committee On Agriculture, Nutrition & Forestry.” Available at: https://www.agriculture.senate.gov/2018-farm-bill. Accessed May 10, 2019.

17. “Statement of Principles on Industrial Hemp.” Federal Register. Available at: https://www.federalregister.gov/documents/2016/08/12/2016-19146/statement-of-principles-on-industrial-hemp. Accessed November 11, 2017.

18. “DEA.gov / Headquarters News Releases, 08/11/16.” Available at: https://www.dea.gov/divisions/hq/2016/hq081116.shtml. Accessed November 19, 2017.

19. USDA. “Industrial Hemp in the United States: Status and Market Potential,” USDA, 2000.

20. “Industrial Hemp: Animal and Plant Health: Maine DACF.” Available at: http://www.maine.gov/dacf/php/hemp/index.shtml. Accessed June 4, 2018.

21. University of California, D. of A. and N. “Industrial Hemp Seed Certification Standards.” Available at: http://ccia.ucdavis.edu/Crop_Standards_pages/Industrial_Hemp. Accessed June 4, 2018.

22. Filipone, B. “Interview with Barbara Filipone,” 2017.

23. “What Countries Grow Hemp? | Hemp Growing Countries.” Ministry of Hemp. Available at: https://ministryofhemp.com/hemp/countries/. Accessed October 2, 2017.

24. Pickering, K., Beckermann, G., Alam, S., et al. “Optimising industrial hemp fibre for composites,” *Composites Part A: Applied Science and Manufacturing*, V. 38, No. 2, 2007, pp. 461–8.

25. Gaustad, S. “The Practical Spinner’s Guide - Cotton, Flax, Hemp,” Loveland, CO, Interweave, 2014, 160 pp.

26. Clancy, K. “Interview with Karen Clancy,” 2016.

27. Morrissey, F., Coutts, R., and Grossman, P. “Bond between cellulose fibres and cement,” *International Journal of Cement Composites and Lightweight Concrete*, V. 7, No. 2, 1985, pp. 73–80.

28. Lewis, G., and Premalal, M. “Natural vegetable fibres as reinforcement in cement sheets,” *Magazine of Concrete Research*, V. 31, No. 107, 1979, pp. 104–8.

29. Kong, F., and Evans, R. “Handbook of structural concrete,” 1983.

30. 544, A. C. “State-of-the-Art Report on Fiber Reinforced Concrete.” vol. 70. ACI, 1996.

31. Sedan, D., Pagnoux, C., Smith, A., et al. “Mechanical properties of hemp fibre reinforced cement: influence of the fibre/matrix interaction,” *Journal of the European Ceramic Society*, V. 28, No. 1, 2008, pp. 183–92.

32. Li, X., Tabil, L. G., and Panigrahi, S. “Chemical treatments of natural fiber for use in natural fiber-reinforced composites: a review,” *Journal of Polymers and the Environment*, V. 15, No. 1, 2007, pp. 25–33.

33. Toledo Filho, R. D., Ghavami, K., England, G. L., et al. “Development of vegetable fibre–mortar composites of improved durability,” *Cement and Concrete Composites*, V. 25, No. 2, 2003, pp. 185–96.

34. Awwad, E., Hamad, B., Mabsout, M., et al. “Structural Behavior of Simply Supported Beams Cast with Hemp-Reinforced Concrete,” *ACI Structural Journal*, V. 111, No. 6, 2014.

35. Hubert, M., Desmettre, C., and Charron, J.-P. “Influence of fiber content and reinforcement ratio on the water permeability of reinforced concrete,” *Materials and Structures*, V. 48, No. 9, 2015, pp. 2795–807.

36. Silva, F. de A., Zhu, D., Mobasher, B., et al. “Impact Behavior of Sisal Fiber Cement Composites under Flexural Load,” *Materials Journal*, V. 108, No. 2, 2011, pp. 168–77.

CHAPTER III

PERFORMANCE OF HEMP MICRO AND MACRO FIBERS IN CEMENT MORTAR

Portions of this chapter has been submitted for publication in the American Concrete Institute's Materials Journal. Furthermore, the paper has been reformatted and replicated herein with minor modifications in order to fit the purposes of this dissertation.

3.1 Introduction

Hemp is an emerging commodity in the United States. Just a few years ago this was a non-existent industry because of past legislation, Marihuana Tax Act of 1937, forbids the growing and harvesting of hemp[1]. This was reversed with the 2014 Farm Bill[2] and 2018 Farm Bill3 which allows the legalized growing of hemp in the United States if the individual states also pass legislation allowing its growth. United States now commercially grows and uses hemp, but remains behind other countries that have integrated hemp into commercial goods and products such as clothing, health products, and reinforced concrete roof panels.

Studies on the tensile performance of hemp fibers in cement paste or concrete have been limited. There are only two ACI Journal articles on the use of hemp fibers in concrete. This study provides additional information toward the development of requirements for the use of hemp in concrete.

3.2 Research significance

Limited studies have been conducted on the use of short length hemp fibers as reinforcement in structural concrete.[4–7] Each study looked at a limited number of fiber lengths (usually two or three lengths) and only one water/cement ratio, usually above 0.5. Other studies have looked at natural fibers but not hemp.[8–11] These other studies provide background information on how natural fibers behave.

This study examined five different lengths of hemp micro and macro fibers along with three different water/cement ratios (low, medium, and high) to determine the response of the fibers subjected to tensile testing. Macro fibers have an average diameter ≥ 0.3mm and micro fibers have an average diameter < 0.3mm. Properly sized fibers should be able to increase the tensile capacity of the concrete and enhance ductility.[4]

3.3 Experimental investigation

Specimens with micro and macro hemp fibers, of multiple lengths per casting, were cast in cement mortar mixtures. The cement mortar is based on the same mixing ratios as those used for their respective concrete mix. This investigation focused on the bonding between the fiber and the cement mixture, which would be similar in a concrete mix. Several components were varied such as water/cement ratio, length and size of fibers, and addition of fly ash to observe effects on the tensile performance.

3.3.1 Materials and Specimens

Hemp micro and macro fibers (see Figure 3.1) were acquired from suppliers in the United States. The micro fibers are raw hemp fibers extracted from the stalk of hemp plants while the macro fibers is twine that has been made from the micro fibers. The micro fibers comes as a packaged mass and the twine was supplied in balls (approximately 300 feet of twine). Micro and macro fibers were cut to length to test various embedment lengths. ASTM C150 Type I/II cement used with an ASTM C618 fly ash. The remaining materials included fine aggregate, river sand that was dredged from Ohio River in Paducah, KY, and potable water. Three water/cement ratios of 0.42, 0.49, 0.66 were based on the requirements established by the Kentucky Transportation Cabinet[12] for f'_c = 17.2, 24.1, 27.6 MPa concrete respectively. ACI 318-14 Table 19.2.1.1 allows f'_c = 17.2 MPa for structural concrete and developing areas of the world will probably use a lower f'_c because it will cost less. As stated earlier, other studies have only looked at one or two water cement ratios and the water cement ratios[5–7] above 0.5..

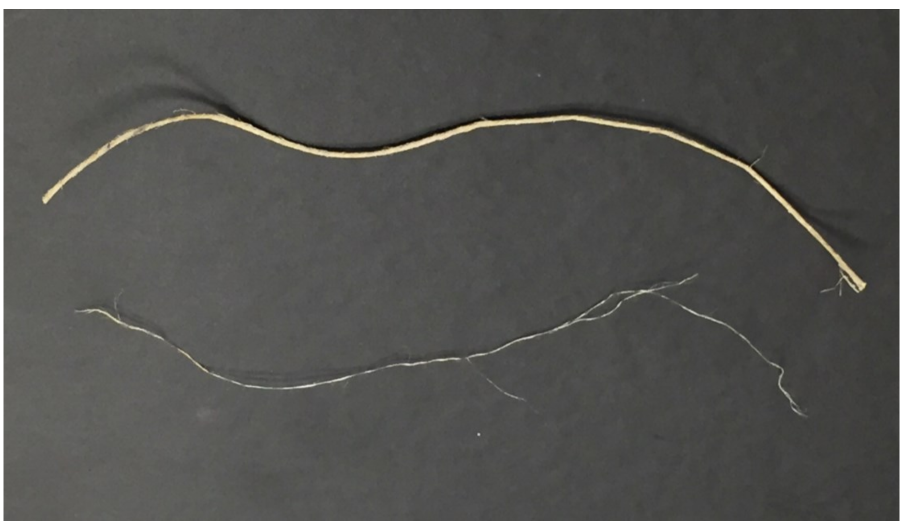

Figure 3.1 Hemp twine and hemp fiber

The top of the picture shows the larger diameter hemp macro fiber. The hemp micro fiber is in the lower portion of the picture.

Table 3.1 provides a summary of the various mix designs. In total six mix designs were cast with five different embedment length per mix design and five samples per embedment length for micro and macro fibers.

Table 3.1 Mix designs

Concrete Strength	**Water/ Cement Ratio**	**Cementitious Material**	**Number of Samples**				
			Length (mm)				
			20	**30**	**40**	**50**	**60**
27.6 MPa	0.42	Cement Only	5	5	5	5	5
		Cement with Fly Ash	5	5	5	5	5
24.1 MPa	0.49	Cement Only	5	5	5	5	5
		Cement with Fly Ash	5	5	5	5	5
17.2 MPa	0.66	Cement Only	5	5	5	5	5
		Cement with Fly Ash	5	5	5	5	5

This table provides a detail breakdown on the mix designs and length of embedment for the fiber.

Five specimens were cast for each mix design with either micro or macro hemp fibers. The specimen's cross-sectional dimensions measured 12 mm by 20 mm with fiber[13] embedment lengths varying from 20 mm to 60 mm in increments of 10 mm. Figure 3.2 shows the mold setup for the 40mm embedment length. The molds are made from closed-cell PVC material. The closed-cell PVC material does not react or bond with cement mortar.

The center sections of the mold are made to be removed which allowed the samples to be easily released from the form without damage. Figure 3.3 shows the mold with fibers installed and ready for the placement of cement mortar. The long sides of the molds are made in two pieces with a hole centered on each bay of the mold. The lower half of one long side is put in place, and then the fiber is placed across it and through the mold bay. The end of the fiber laying across the lower section is held in place by tape. The lower section on the opposite is then installed and the fiber laid across it. This end of the fiber is longer so that it can be connected to the universal testing machine. The both upper sections are placed on top of the lower sections and secured. The fibers were straightened prior to casting by lightly pulling on the long free end of the fiber. The samples were left in the molds for 24 hours after casting then removed to cure inside for 28 days.

Studies on steel, glass and polypropylene fibers used a vertical fiber configuration with multiple fibers in each mold.[14] Such a configuration is not possible for hemp because the hemp fibers lack enough stiffness to remain vertical. In another study, a single fiber was placed inside of a 3mm diameter tube and the cement paste packed around the fiber[8]. After curing, the fiber and cement configuration was subjected to a tensile loading similar to what has been used in this study.

Figure 3.2 40mm long mold

The molds are made of trim material made from PVC. Concrete does not bond to it and it leaves a smooth finish.

Figure 3.3 40m mold with fiber installed

The mold is fully assembled with the twin in place. The mold sides are held in place with masking tape.

3.3.2 Tensile Tests

The samples were subjected to tensile loading after they had air cured 28 days. Figure 3.4 shows the testing setup for the macro and micro hemp fibers. The hemp macro fiber had a length and diameter that is significantly larger than the hemp micro fibers. The hemp marco fiber was able to be anchored into the jaws of the universal machine because the fiber had a large enough diameter to allow the jaws to engage it. The free end of the hemp micro fiber was attached to heavy card stock to allow the jaws to hold it in place during testing as portrayed in Figure 3.5.[15]

Each sample was loaded in tension per the requirements of ASTM D3822, Standard Test Method for Tensile Properties of Single Textile Fibers. The rate of extension of the universal testing machine is 10% of initial specimen length per minute. A tension test for macro fibers took one and a half minutes while the same test for the micro fibers lasted 30 seconds or less.

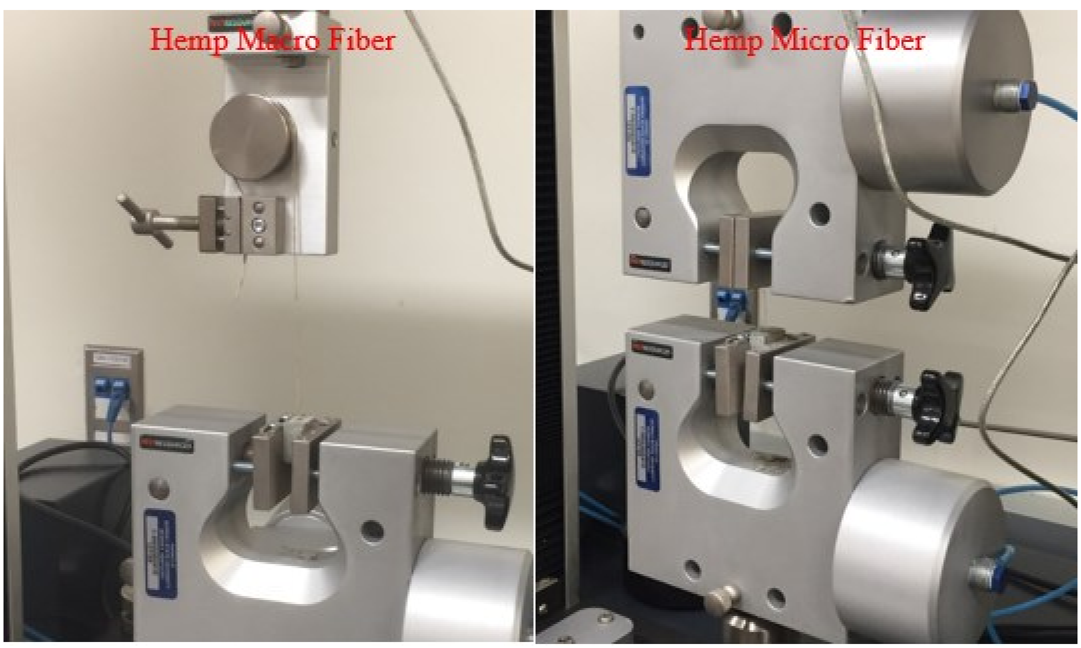

Figure 3.4 Tension testing configuration for hemp macro and micro fibers

Macro fibers setup is on the left and micro fiber setup is on the right.

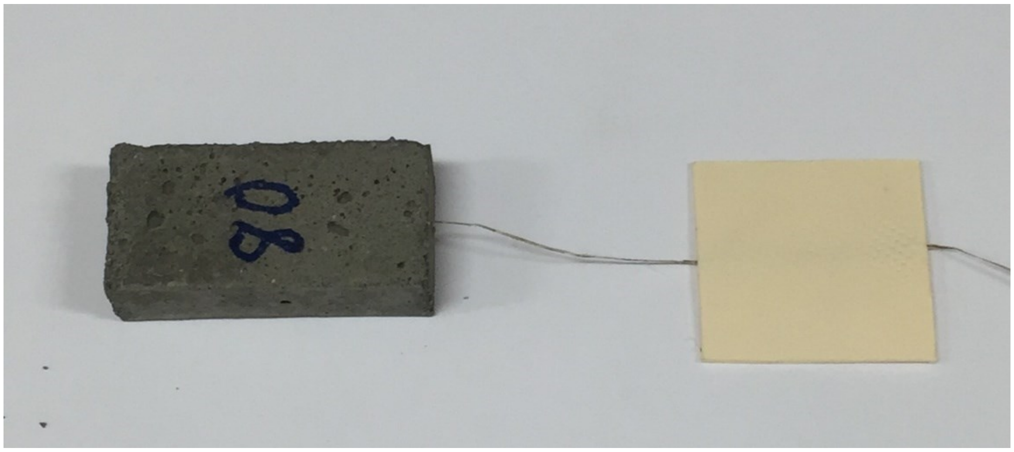

Figure 3.5 Hemp micro fiber configuration for testing

Additional information about setup and testing of the samples can be found in APPENDIX D.

3.4 Experimental results and discussion

3.4.1 Fiber performance

A total of 258 tests consisted of: 142 macro fiber samples and 116 micro fiber samples. Originally 300 samples were cast but some samples were damaged, some had casting issues, and some were damaged during setting up the universal testing machine. All the tension test data can be found in APPENDIX A and APPENDIX B.

Three modes of failure were observed: fiber slipping within the cement mortar sample, partial breaking as depicted in Figure 3.6, and complete tensile failure of the fiber as shown in Figure 3.7. Only one macro fiber sample broke during the tension testing while 78% of the micro fibers broke or partially broke. Micro fibers with an embedment length of 50mm or greater had a breakage rate of 91%. The maximum tensile load for macro fibers is 79.1 N and the maximum for the micro fibers is 26.1 N.

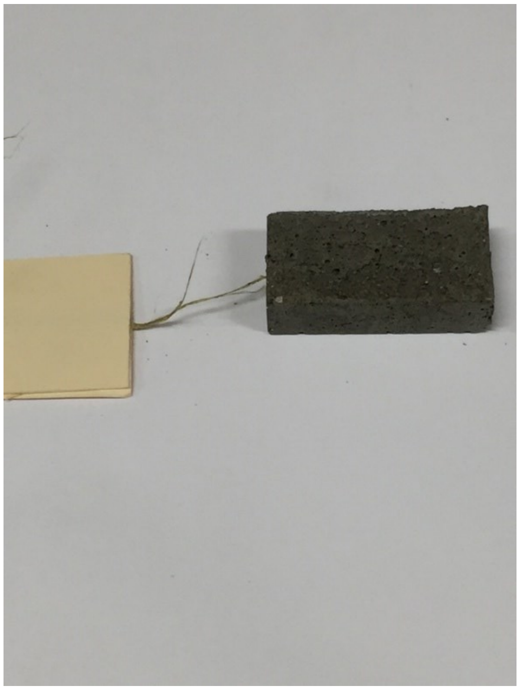

Figure 3.6 Partial tensile break of fiber.

Only part of the micro hemp fiber broke during tensile testing

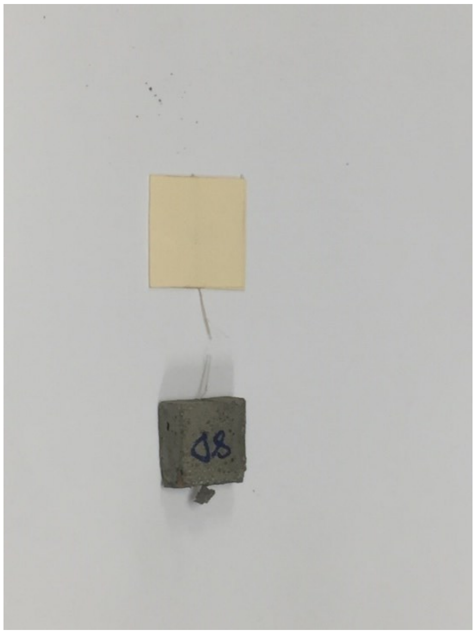

Figure 3.7 Tensile failure of micro fiber.

Fiber failed before fiber slipped.

3.4.2 Potential for ductility

The hemp macro fiber in 140 cases and micro fibers in 19 instances slipped while the load was being applied. Figure 8 depicts load and displacement results that had 40mm embedment length and were cast into the cement matrix with no fly ash. The macro fiber failed by slipping but was still able to resist a noticeable load. The micro fiber showed a similar trend but did not exhibit much slippage before breaking. The fiber slipping occurs when the tensile applied to the fiber exceeds the shear strength that is created between the cement mortar and fiber.

Figure 3.8 shows the reduction in the load beyond the peak as the deflection increases, and this characteristic is called residual strength. The fibers not being perfectly round or straight creates deformations that will act similar to the deformations of steel reinforcement in concrete. This allows the tensile load to be transferred to the concrete through shear[16].

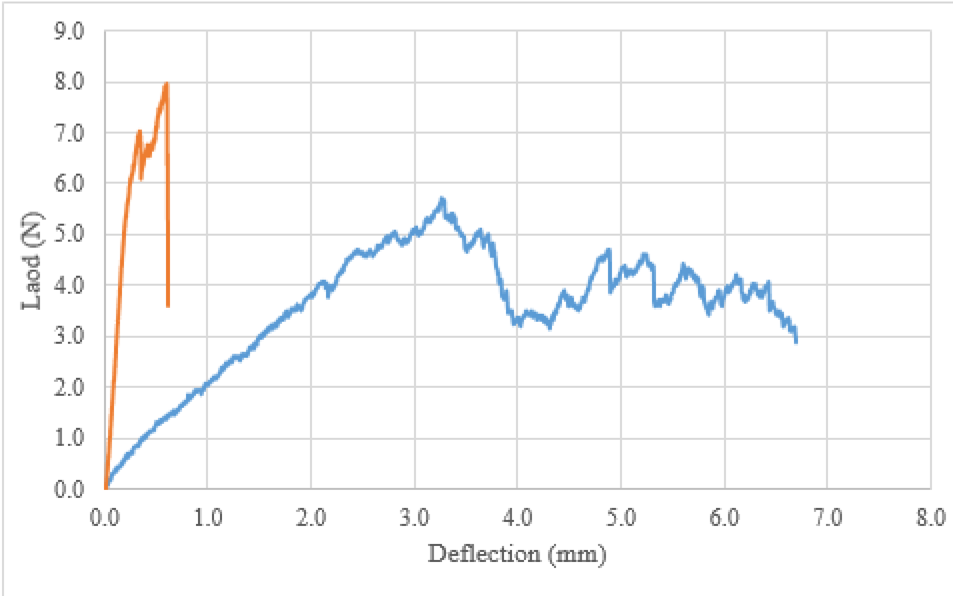

Figure 3.8 Load vs displacement for micro & macro fibers.

Blue line is the hemp macro fiber and the orange line is the hemp micro fiber. This graph is for 20 mm embedment with 0.42 w/c ratio without fly ash.

The average shear bond strength (τ_d) is the maximum load divided the average surface area embedded in the cement matrix.[17] This study found that the macro hemp fiber average shear bond strength is less than the micro hemp fiber. This is similar to findings that Bažant, et.al. found when testing smooth steel fibers. The maximum pullout stress decreases with the increase in diameter with the same length of embedment.[18]

3.4.3 Effect of fly ash

To remove the variability of the varying diameters of the micro and macro hemp fibers, the maximum load values have been normalized by dividing by the contact surface area. The contact surface is the length of embedment times the average circumference based on average diameter that were measured at multiple locations along the micro and micro fibers.

Each of the three mix designs included batches that incorporated Class C fly ash at a maximum replacement rate of 25%[12]. The micro and macro hemp fibers responded differently to presence of fly ash. Figure 3.9 and Figure 3.10 show average load/surface area versus the embedment length. The curves shown are polynomial trend lines of the average of the data. The macro fiber performed better when fly ash was not in the mix (see Figure 3.9) while the micro fiber can sustain a higher loading when fly ash is present (see Figure 3.10).

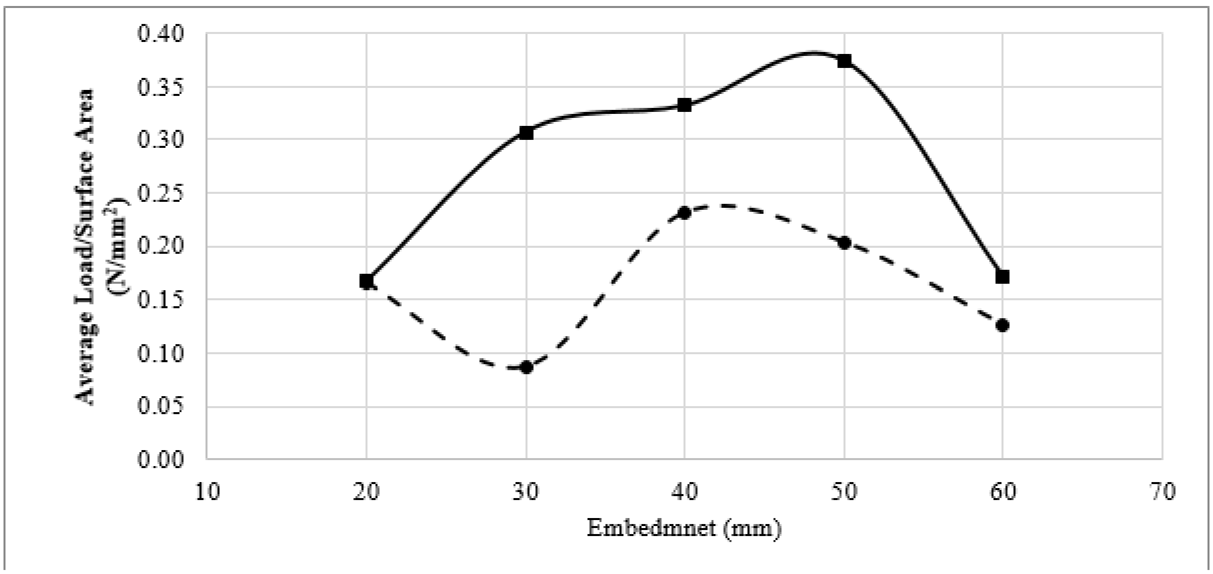

Figure 3.9 Hemp macro fiber

Comparison of f'_c=27.6 MPa mix with and without fly ash. Solid line is mix without fly ash and dashed line is with fly ash.

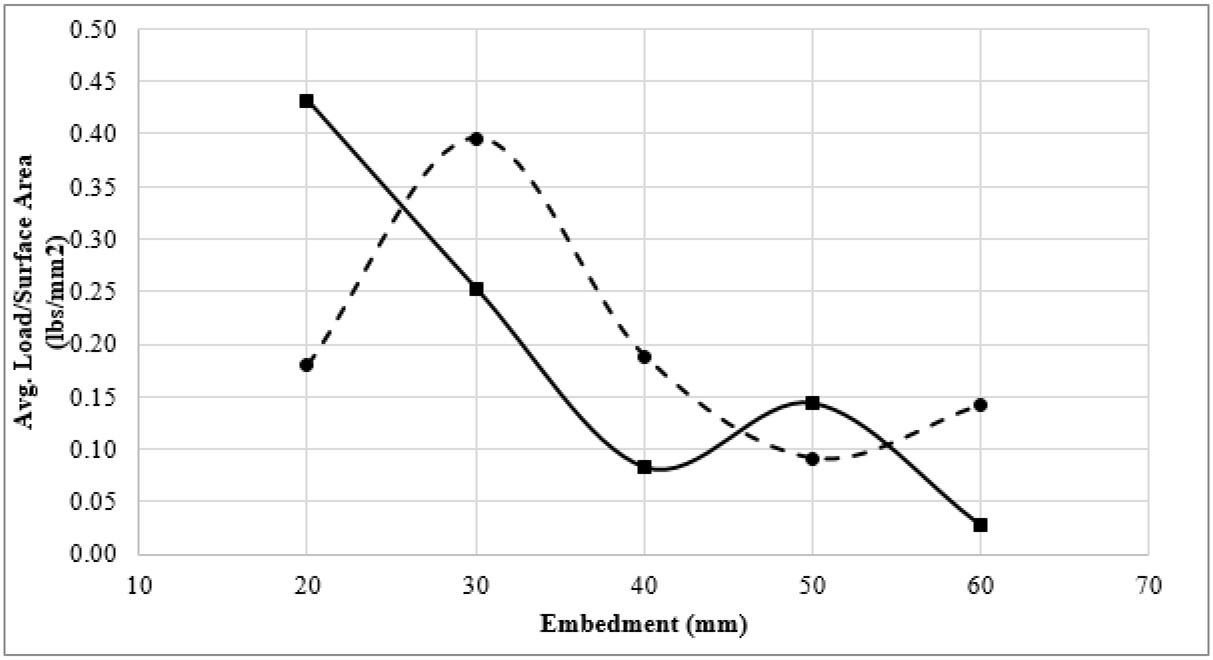

Figure 3.10 Hemp micro fiber

Comparison of f'$_c$=27.6 MPa mix with and without fly ash. Solid line is mix without fly ash and dashed line is with fly ash.

3.4.4 Mix Designs

Three different mix design were used with the water/cement ratios varying from 0.42 to 0.66 (see Table 3.1). Figure 3.11 and Figure 3.12 shows the average load/surface area for each mix design and each embedment length. F'$_c$ = 27.6 MPa for macro hemp fibers performs better than the other mix designs (see Figure 3.11). F'$_c$ = 24.1 MPa is optimum for 20mm embedment for micro fibers while F'$_c$ = 27.6 MPa mix is best for the longer embedment lengths. Figure 3.13 and Figure 3.14 compares the average shear bond strength, load divided by the surface area of the embedded fiber, as compared to the 28-day concrete compressive strength, f'$_c$.

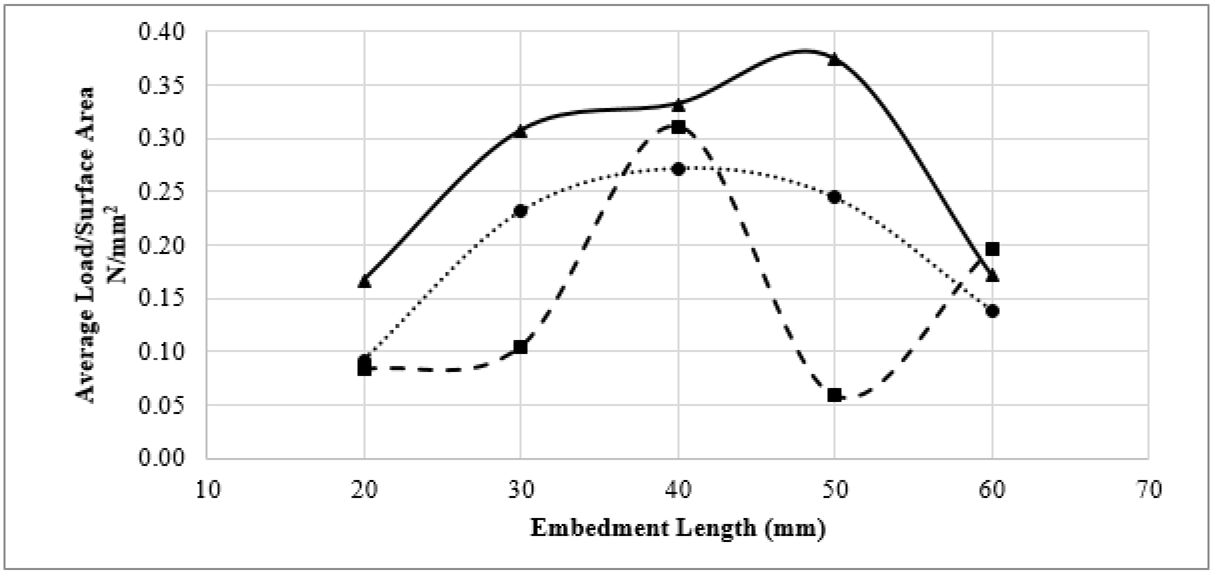

Figure 3.11 Hemp macro fiber mix comparison

Solid line f'$_c$ = 27.6 MPa , dashed line f'$_c$ = 24.1 MPa, and dotted line f'$_c$ = 17.2 MPa.

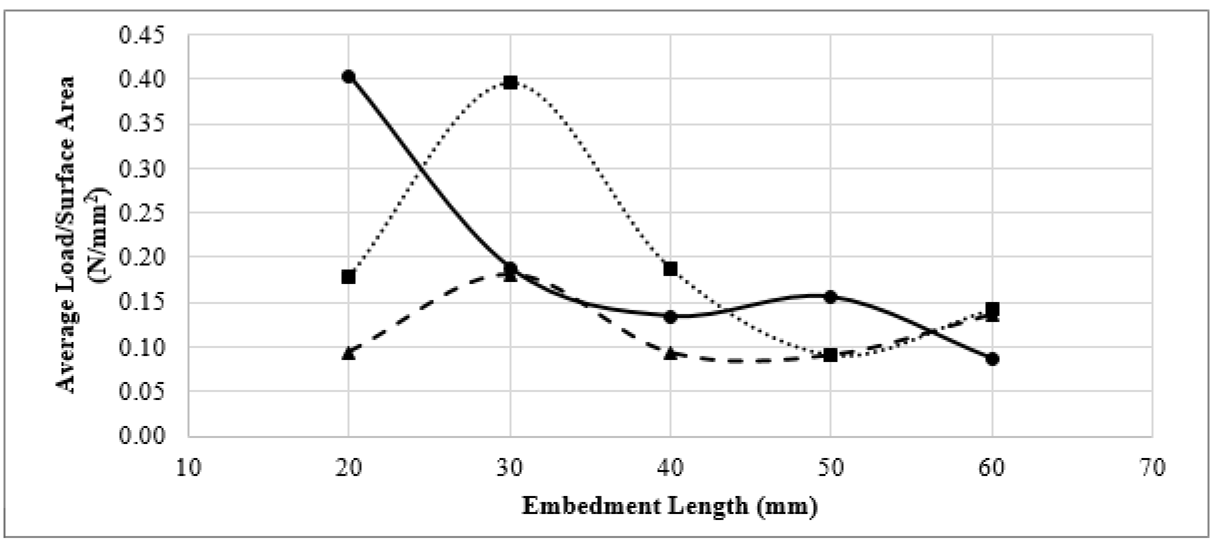

Figure 3.12 Hemp micro fiber mix comparison

Solid line f'$_c$ = 27.6 MPa , dashed line f'$_c$ = 24.1 MPa, and dotted line f'$_c$ = 17.2 MPa.

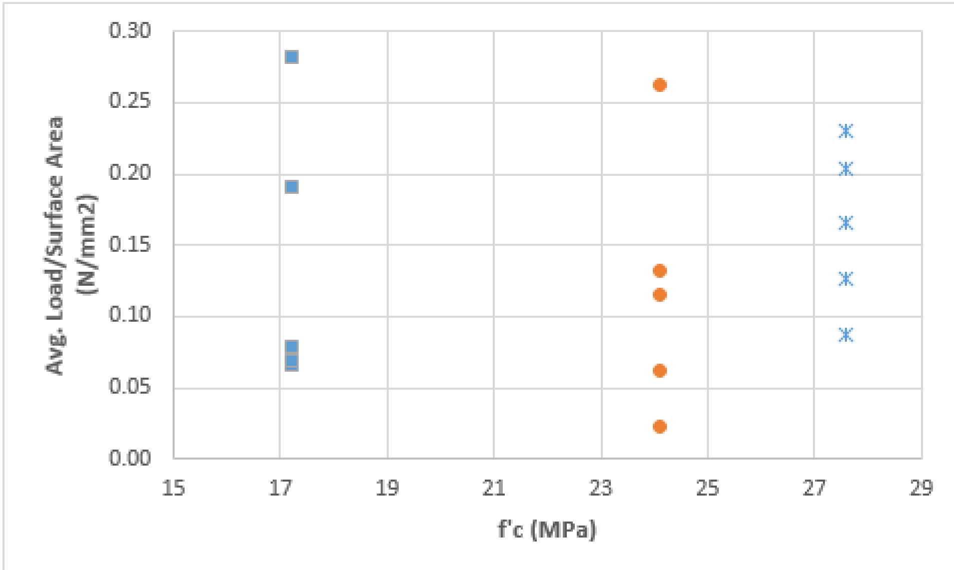

Figure 3.13 Hemp macro fiber – comparison of mix designs to shear bond strength

Three mix designs were evaluated $f'_c = 27.6$ MPa , $f'_c = 24.1$ MPa, and $f'_c = 17.2$ MPa.

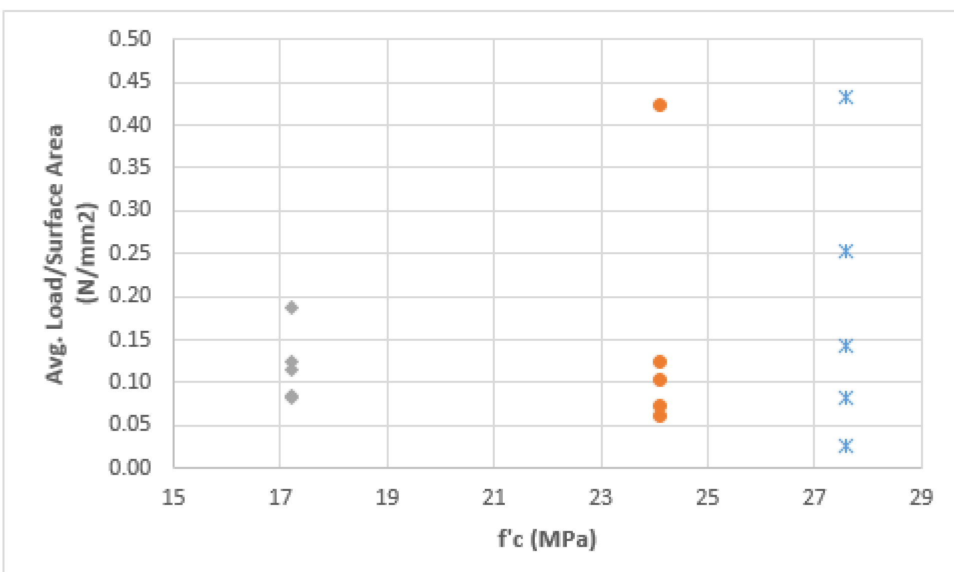

Figure 3.14 Hemp micro fiber – comparison of mix designs to shear bond strength

Three mix designs were evaluated $f'_c = 27.6$ MPa , $f'_c = 24.1$ MPa, and $f'_c = 17.2$ MPa.

3.4.5 Embedment length

The length of macro fiber embedment can assist in determining the optimum macro fiber length for use as reinforcement in concrete. Figure 3.15 shows the average load/surface area per embedment length. Based on this chart, the 40mm macro fiber embedment length had the highest tensile capacity. However, this may not be the optimum length to use because macro fibers tend to ball when added to a concrete mix.

Micro fibers, see Figure 3.16, shows that an embedment length of 20mm or 30mm would be preferable. The 20mm length performed best with a f'_c = 17.2 MPa mix but the 30mm length performed best in f'_c = 24.1 MPa and f'_c = 27.6 MPa mixes.

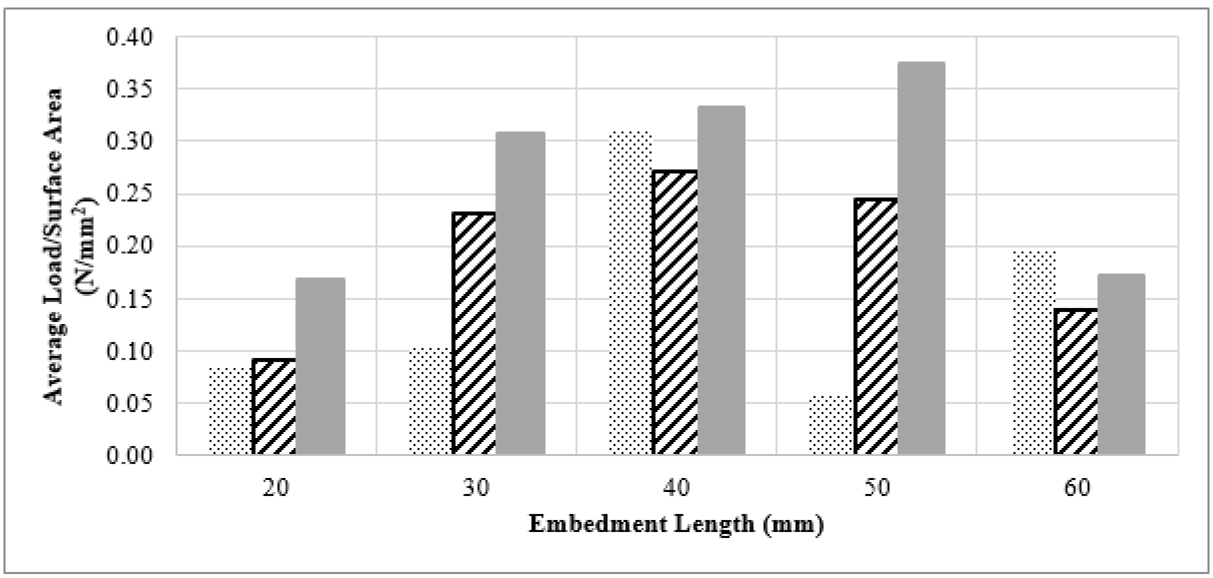

Figure 3.15 Hemp macro fiber – comparsion of embedment length and mix design

Grey colored bars are for f'_c = 27.6 MPa mix, angled hatching bars are for f'_c = 24.1 MPa mix and dotted bars are for f'_c = 17.2 MPa mix.

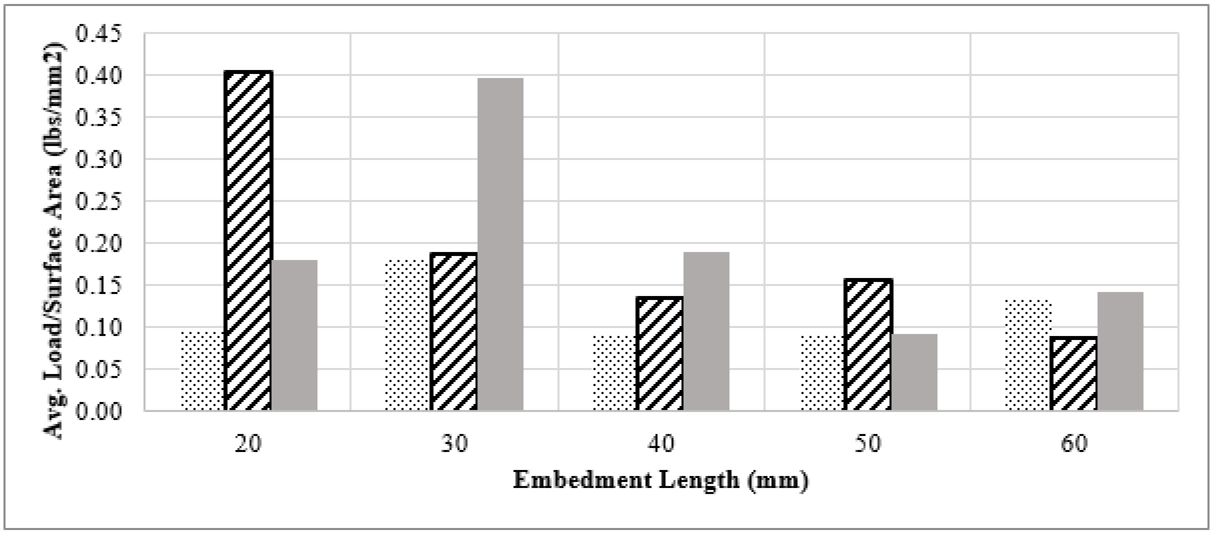

Figure 3.16 Hemp micro fiber – comparsion of embedment length and mix design

Grey colored bars are for f'_c = 27.6 MPa mix, angled hatching bars are for f'_c = 24.1 MPa mix and dotted bars are for f'_c = 17.2 MPa mix.

Additional graphs of the tension testing can be found in APPENDIX F.

3.4.6 Statistical Analysis

The results were evaluated to detect statistical significance and build a regression model to fit the data. The dependent variable is maximum load for each sample tested. The independent variables were average fiber diameter, water/cement ratio, length of embedment, whether the mix contained fly ash, and fiber classified as micro or macro.

All the data was coded and evaluated to determine if a linear regression model would fit to the data, the significance of each main effect, and if there was interaction between the main effects. Below is the coding that was used for the regression analysis.

X_1 = average diameter of fiber

X_2 = 1 if it does not contain fly ash, 0 if it does

X_3 = 1 if it is a macro fiber, 0 if it is not

X_4 = 1 if is 20mm embedment, 0 if it is not

X_5 = 1 if is 30mm embedment, 0 if it is not

X_6 = 1 if is 40mm embedment, 0 if it is not

X_7 = 1 if is 50mm embedment, 0 if it is not

60 mm embedment will be when X_4, X_5, X_6, and X_7 are all equal to zero.

A linear regression model was built with the continuous variable only. Then subsequent models were built adding in the categorical variables and interactions. The significance of each independent variable and interaction was evaluated. This done through looking at the two-tail p-values that test the null hypothesis that each coefficient is equal zero. To reject the null hypothesis, p-value must be lower than 0.10 for a 90% confidence interval. If the p-values are lower than 0.10, then that variable is statistically significant in explaining the load.

The R2adj values are listed in Table 3.2. The models have been ranked in how the models were built. The two highest R^2_{adj} models, models 12 and 18, are then examined further. Model 18 is based on the natural log of the tensile load, the dependent variable while Model 12 is based tensile strength. Variable transformation of the dependent variable was done to see if a better model could be fit to the data and to more nearly satisfy that random errors are independent[19].

For Model 12 the independent variables having significance are fiber type, micro or macro; water/cement ratio 0.42; water/cement ratio 0.49; 20mm length of embedment; and 30mm length of embedment. Model 18 independent variables having significance are fly ash, fiber type, water/cement ratio 0.42, water/cement ratio 0.49, 20mm length of embedment, 30mm length of embedment, and the interaction between fiber type and fly ash. One way to visualize interaction effects is to do an interaction plot. An interaction plot with two parallel lines represents two independent variables that do not have interactions while non-parallel lines represent interaction. Figure 3.17 is a plot based on Model 18's fiber type and water/cement ratio 0.42 interaction. The two lines are parallel which shows there is no interaction between these two independent variables. Figure 3.18 clearly shows an interaction between fiber type and fly ash because the two lines cross. Figure 3.18 shows that for micro fiber in mixes containing fly ash will have a higher tensile load while macro fibers in the same mixes will have a lower tensile load.

For each of the models the residuals vs predicted is plotted as a histogram overlaid with normal distribution curve. The plot of dependent variable does not have to have a normal distribution plot; however, the plot of residual should be similar to a normal distribution plot. Figure 3.19 and Figure 3.20 shows the residuals plot for the two linear regression models. The plots for both models are close to a normal distribution. Model 18 has a higher adjusted R^2_{adj} which will make this a slightly better model at predicting the tensile load.

$$I \ln(Load) = 0.618X_2 + 0.401X_3 - 0.640X_4 - 0.606X_5 - 0.172X_6 - 0.136X_7 - 1.203X_2X_3 \qquad (3.1)$$

Table 3.2 Linear regression models with adjusted R^2 values

Model Number	Linear Regression Model Variables	Adj. R^2
18	regress ln_strength FlyAsh wc42 wc49 bed20 bed30 bed40 bed50 Fiber Fiber#FlyAsh Fiber#wc42	0.3361
17	regress ln_strength FlyAsh wc42 wc49 bed20 bed30 bed40 bed50 Fiber	0.2717
12	regress ln_strength dia FlyAsh wc42 wc49 bed20 bed30 bed40 bed50 Fiber	0.271
16	regress ln_strength FlyAsh ln_dia wc42 wc49 bed20 bed30 bed40 bed50 Fiber	0.2695
15	regress ln_strength FlyAsh ln_dia wc42 wc49 bed20 bed30 bed40 bed50	0.2331
7	regress StrengthN dia FlyAsh wc42 wc49 bed20 bed30 bed40 bed50 Fiber wc42##c.dia	0.2248
6	regress StrengthN dia FlyAsh wc42 wc49 bed20 bed30 bed40 bed50 Fiber wc42##bed20	0.2171
11	regress ln_strength dia FlyAsh wc42 wc49 bed20 bed30 bed40 bed50	0.2128
14	regress ln_strength FlyAsh ln_dia wc42 wc49	0.2097
13	regress ln_strength FlyAsh ln_dia	0.1789
10	regress ln_strength dia FlyAsh wc42 wc49	0.1721
8	regress ln_strength dia	0.1587
9	regress ln_strength dia FlyAsh	0.1556
4	regress StrengthN dia FlyAsh wc42 wc49 bed20 bed30 bed40 bed50	0.1509
3	regress StrengthN dia FlyAsh wc42 wc49	0.0965
5	regress StrengthN dia FlyAsh wc42 wc49 bed20 bed30 bed40 bed50 Fiber	0.0965
2	regress StrengthN dia FlyAsh	0.0849
1	regress StrengthN dia	0.0846

The models have been ranked highest to lowest based on their adjusted R^2 value.

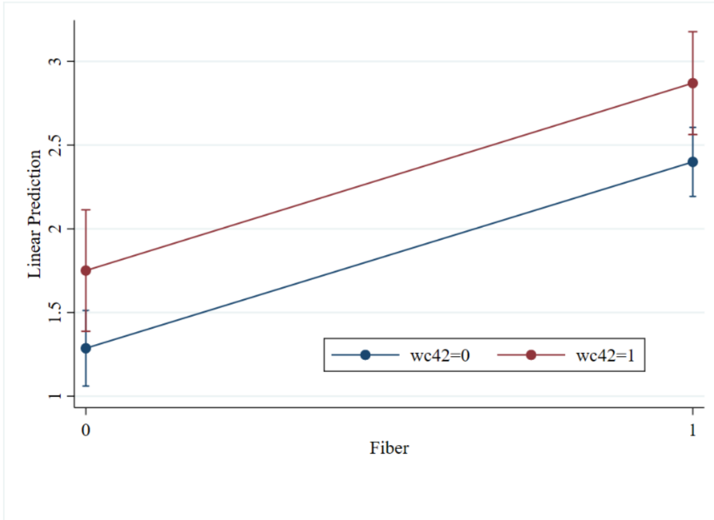

Figure 3.17 Interaction plot – fiber and w/c=0.42

Fiber = 0 is hemp micro fiber and Fiber = 1 is hemp macro fiber

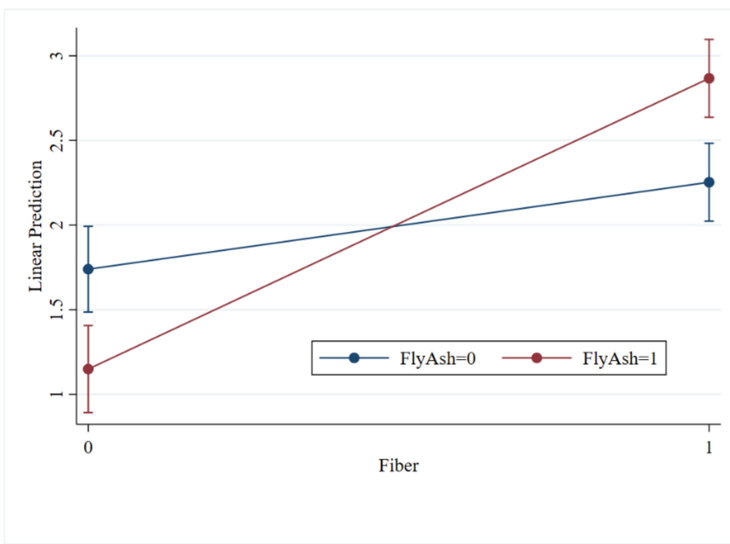

Figure 3.18 Interaction plot – fiber and fly ash

Fiber = 0 is hemp micro fiber and Fiber = 1 is hemp macro fiber

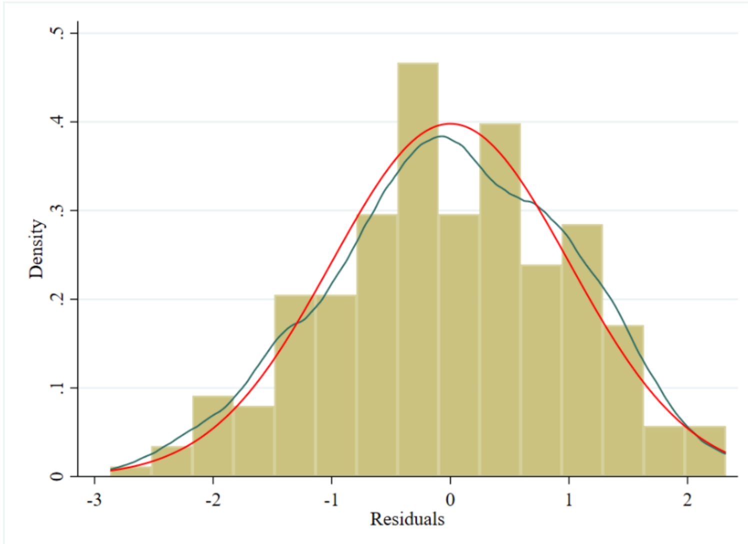

Figure 3.19   Residuals versus fitted model plot – Model 12

Red line = normal distribution, Blue line = residuals distribution

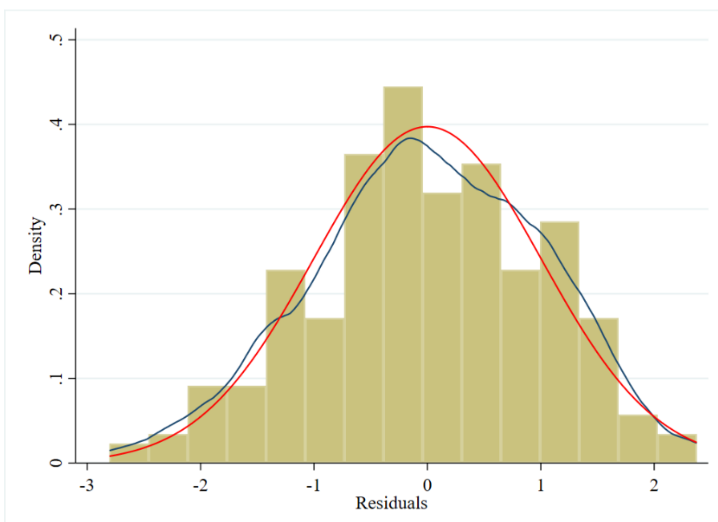

Figure 3.20   Residuals versus fitted model plot – Model 18

Red line = normal distribution, Blue line = residuals distribution

All the input data for STATA can be found in APPENDIX E along with additional information on the method of analysis.

3.5 Further research

Additional research is needed to standardize the requirements for hemp micro and macro lengths. Treating the fibers with a coating will improve bonding of fibers with the cement mortar. Such a study would include the stress-slip law and the size effect. This would be a study relationship of the interfacial shear stress to the interfacial slip with respect to the size of the fiber.[17] The use of water-based coating would be more environmentally friendly than the chemicals that are currently used to treat hemp fibers. It will also be necessary to determine the appropriate dosing rates for the hemp micro and macro fibers in different mix designs.

3.6 Conclusions

Based on the results of this experimental investigation, the following conclusions are drawn:

- Hemp micro and micro fibers will bond to cement mortar allowing the transfer of tensile forces into them. This will allow hemp fibers to be used as a form of fiber reinforcement; and
- Hemp micro and micro fibers have similar general characteristics but will perform differently depending on the concrete mix design and length of embedment; and

- Micro hemp fibers have a higher tensile carrying capacity with the $f'_c = 24.1$ MPa and macro hemp fibers at $f'_c = 27.6$ MPa. This means the lower water/cement ratio the higher the tensile capacity; and
- 30 mm embedment for hemp macro fibers performed the best in this study based on statistical analysis. Hemp micro fibers had the best performance with an embedment length of 30 mm for mixes without fly ash and 20 mm with mixes containing fly ash; and
- Working with natural fibers can be difficult because of the variability in the fibers (diameter, composition, etc.); therefore, testing with hemp micro and macro fibers in different concrete mix designs should be tested for flexure and compression capacities.

3.7 References

1. Musto, D. F. "The Marihuana Tax Act of 1937," Archives of General Psychiatry, V. 26, No. 2, 1972, pp. 101–8.

2. "7 U.S.C. 5940 - Legitimacy of industrial hemp research." Available at: https://www.gpo.gov/fdsys/granule/USCODE-2015-title7/USCODE-2015-title7-chap88-subchapVII-sec5940. Accessed November 19, 2017.

3. "2018 Farm Bill | The United States Senate Committee On Agriculture, Nutrition & Forestry." Available at: https://www.agriculture.senate.gov/2018-farm-bill. Accessed May 10, 2019.

4. Awwad, E., Hamad, B., Mabsout, M., et al. "Structural Behavior of Simply Supported Beams Cast with Hemp-Reinforced Concrete," ACI Structural Journal, V. 111, No. 6, 2014.

5. Awwad, E., Mabsout, M., Hamad, B., et al. "Studies on fiber-reinforced concrete using industrial hemp fibers," Construction and Building Materials, V. 35, 2012, pp. 710–7.

6. Li, Z., Wang, X., and Wang, L. "Properties of hemp fibre reinforced concrete composites," Composites part A: applied science and manufacturing, V. 37, No. 3, 2006, pp. 497–505.

7. Sedan, D., Pagnoux, C., Smith, A., et al. "Mechanical properties of hemp fibre reinforced cement: influence of the fibre/matrix interaction," Journal of the European Ceramic Society, V. 28, No. 1, 2008, pp. 183–92.

8. Morrissey, F., Coutts, R., and Grossman, P. "Bond between cellulose fibres and cement," International Journal of Cement Composites and Lightweight Concrete, V. 7, No. 2, 1985, pp. 73–80.

9. Toledo Filho, R. D., Ghavami, K., England, G. L., et al. "Development of vegetable fibre–mortar composites of improved durability," Cement and Concrete Composites, V. 25, No. 2, 2003, pp. 185–96.

10. Pickering, K., Beckermann, G., Alam, S., et al. "Optimising industrial hemp fibre for composites," Composites Part A: Applied Science and Manufacturing, V. 38, No. 2, 2007, pp. 461–8.

11. Ali, M., Liu, A., Sou, H., et al. "Mechanical and dynamic properties of coconut fibre reinforced concrete," Construction and Building Materials, V. 30, 2012, pp. 814–25.

12. Cabinet, K. T. "Standard Specifications for Roads and Bridge Construction," 2012.

13. Gokoz, U. N., and Naaman, A. E. "Effect of strain-rate on the pull-out behaviour of fibres in mortar," International Journal of Cement Composites and Lightweight Concrete, V. 3, No. 3, 1981, pp. 187–202.

14. Gokoz, U. N., and Naaman, A. E. "Effect of strain-rate on the pull-out behaviour of fibres in mortar," International Journal of Cement Composites and Lightweight Concrete, V. 3, No. 3, 1981, pp. 187–202.

15. D13 Committee "Test Method for Tensile Properties of Single Textile Fibers," ASTM International, n.d.

16. MacGregor, J. "Reinforced Concrete Mechanics and Design," Prentice Hall, 1988.

17. Bažant, Z. P., Li, Z., and Thoma, M. "Identification of Stress-Slip Law for Bar or Fiber Pullout by Size Effect Tests," Journal of Engineering Mechanics, V. 121, No. 5, 1995, pp. 620–5.

18. Bazant, Z., and Desmorat, R. "Size Effect in Fiber or Bar Pullout with Interface Softening Slip," Journal of Engineering Mechanics, V. 120, No. 9, 1994, pp. 1945–61.

19. Mendenhall, W., and Sincich, T. "A Second Course in Statistics - Regression Analysis," Prentice hall, 2012..

CHAPTER IV

COMPARISON OF NATURAL HEMP, SYNTHETIC AND STEEL FIBERS IN CONCRETE

Portions of this chapter has been submitted for publication in the American Concrete Institute's Materials Journal. Furthermore, the paper has been reformatted and replicated herein with minor modifications in order to fit the purposes of this dissertation.

4.1 Introduction

The hemp industry is growing rapidly in the United States. This former non-existent industry has transitioned into a prominent agricultural industry in several states. This growth has been made possible because of the 2014 Farm Bill[1] and the 2018 Farm Bill[2] which allow the legalized growing of hemp in the United States. Before these Farm Bills were passed, it was illegal to grow hemp because it was categorized with marijuana, which is a controlled substance[3]. The legal restrictions placed on growing hemp has caused the United States to fall behind other countries that have integrated into the commercial and industrial economy.

Previous studies on the use of hemp macro fibers are lacking in the areas of optimum fiber length, dosing rates, and the performance of concrete mixes that contain these fibers. Macro fibers have an average diameter $\geq$ 0.3mm and micro fibers have an average diameter < 0.3mm. In the past, studies on the use of hemp micro fibers have not included comparisons to synthetic micro fiber reinforced concrete.

4.2 Research significance

Hemp micro fiber reinforced concrete has been evaluated in other studies for compressive strength, flexural strength and modulus of elasticity.[4–10] This study compares the performance of synthetic micro and macro fibers, as well as steel macro fibers, to hemp micro and macro fibers. Comparison of the concrete mixes was made based on compressive strength, modulus of elasticity, equivalent flexural strength, and toughness. Previous studies have shown an increase in flexural strength when natural micro fibers, such as sisal, coconut, and similar materials, are added to a concrete mix.[11, 12]

4.3 Experimental investigation

Cylinder specimens examined in this investigation were 100 mm diameter by 200 mm height, beam specimens were 150mm by 150mm by 530 mm long. Cylinder and beam specimens with and without fiber reinforcement were evaluated. The variables were fiber type and the dosing rates of fibers. The specimens were air-cured with an air temperature of 23.9° C and a relative humidity of 40%. A total of eight cylinders and two beams were made using each mix.

At the age of 7 days and 28 days, concrete cylinders were tested for compressive strength per ASTM C39[13]. Additional concrete cylinders were tested at 28 days to determine the modulus of elasticity per ASTM C469.[14] Beams were tested for flexural strength per ASTM C78[15] and the flexural toughness and the equivalent flexural strength are calculated per ASTM C1609.[16]

4.3.1 Materials

The cement used for this investigation was Portland cement Type I/II meeting the requirements of ASTM C150. Class C fly ash meeting ASTM C618 requirements was used as cement replacement at a 25% maximum replacement rate. One study has shown that replacement of cement with cementitious materials, such as fly ash, helps prevent deterioration of plant fibers in concrete.[13] The fibers used in this investigation are synthetic micro fibers, synthetic macro fibers, steel macro fibers, hemp micro fibers, and hemp macro fibers. Table 4.1 lists the physical properties of the fibers. Figure 4.1 shows each fiber type side-by-side to show the size difference. Figure 4.1 through Figure 4.4 show close ups of each fiber type. The hemp micro and hemp macro fibers were not chemically treated. The remaining materials used were fine aggregate; river sand meeting the requirements of ASTM C33 from the Ohio River near Paducah, Kentucky, #67 stone per ASTM C33 and potable water. This investigation utilized one water-cement ratio: 0.49 based on the requirements established by the Kentucky Transportation Cabinet for Class A concrete mix.[17] Table 4.2 lists the concrete mix design parameters. The mix water quantity shown in Table 4.2 accounts for the aggregate and hemp fibers at a saturated surface dry condition. Table 4.3 lists the fiber dosing rates. The steel and synthetic fiber dosing rates are per manufacturer's recommendations.

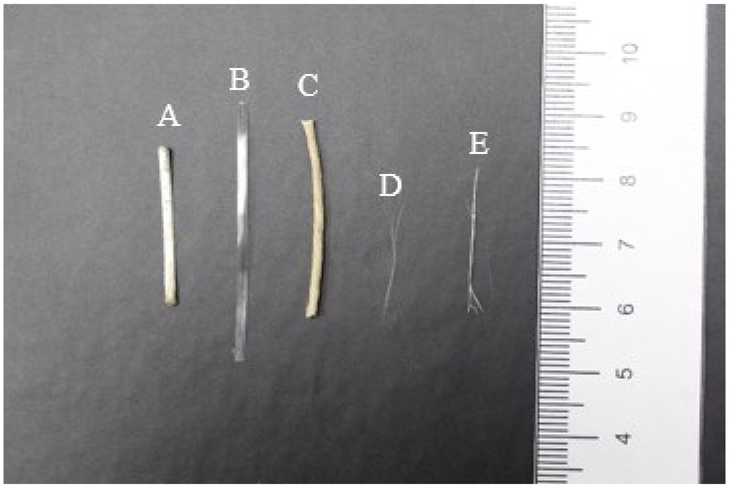

Figure 4.1 Fibers

A – Steel Fiber, B – Synthetic micro fiber, C – Hemp macro fiber, D – Synthetic micro fiber, E – Hemp micro fiber.

Figure 4.2 Hemp fibers

Macro hemp fibers on the left side of the figure and micro hemp fibers are on the right.

Figure 4.3 Synthetic fibers

Macro synthetic fibers on the left side of the figure and micro synthetic fibers are on the right.

Figure 4.4 Steel fibers

Table 4.1 Fiber characteristics

Fiber Type	Material	Specific Gravity
Synthetic Micro Fiber**	Modified Acrylic	1.17
Synthetic Macro Fiber**	Polypropylene	0.92
Steel Fiber	Low Carbon Steel	7.7*
Hemp Micro Fiber	Natural Hemp	1.5
Hemp Micro Fiber	Natural Hemp	1.5
Hemp Macro Fiber	Natural Hemp Twine	1.5
Hemp Macro Fiber	Natural Hemp Twine	1.5

**Provided by manufacturer

Table 4.2 Concrete mix design and properties

Item	Description	Amount (kg/m^3)
Cement	Type I/II	251
Fly Ash	Class C	84
Fine Aggregate	River Sand	761
Coarse Aggregate	Crushed Limestone	1177
Water	Potable Water	164
w/c ratio	0.49	---
f'_c @28-days	24.13 MPa (min)	---

Table 4.3 Fiber dosing rates and fiber factor

Fiber Type	Dosing Rate kg/m^3	Dosing Rate % of Volume	Aspect Ratio
Synthetic Micro Fiber	0.3**	0.025**	500
Synthetic Macro Fiber	3.26**	0.35**	90
Steel Macro Fiber	14.83**	0.19**	37
Hemp Micro Fiber Low	0.3	0.02	65
Hemp Micro Fiber High	7.50	0.50	65
Hemp Macro Fiber Low	3.26	0.22	29
Hemp Macro Fiber High	15.03	1.00	29

*Provided by manufacturer

4.3.2 Experimental procedure

All concrete mixes had the same method of mixing. The first items to add to the mixer are the coarse and fine aggregates, then approximately 40% of the water, and then all of the fibers. The mixer run time is five minutes. After this initial mix, add the cement and fly ash. The remaining water is slowly added as the mixer rotates. Continue mixing for five additional minutes to ensure thorough mixing of all constituents. Two batches for each concrete mix are required because of the mixer's capacity of 0.04 m^3.

The first batch of concrete was used to make two concrete beams and five cylinders. The beams were for flexural testing and the cylinders were for the determination of the 7-day and 28-

day compressive strengths. Each beam was tested per ATM C78[15] to measure the load and deflection of the simply supported beam with third-point loading.

The second batch of concrete, made on a different day, was for three additional cylinders and extra beams. The second batch of concrete cylinders were for determining the modulus of elasticity and used to compare to first batch's cylinder compressive strengths to ensure repeatability. One of the three cylinders, from the second batch, was used to determine the 28-day compressive strength by taking that cylinder to failure. The remaining two cylinders were used for determining the modulus of elasticity.

For one hemp macro fiber high mix, the fibers were not soaked in water prior to adding the fibers to the mixer. This allowed the dry fibers to absorb some of the mixing water creating a drier mix design. The other hemp micro and macro fibers mixes used fibers that had been soaked in water, then dried to saturated surface dry condition prior to adding to the mixer.

The dosing rates in Table 4.3 are the manufacturers' recommendations for synthetic and steel fibers. The dosing rates of the hemp micro fibers were the same as the dosing rate for the synthetic micro fibers. The dosing rates for the hemp macro fibers are based on the dosing rate for the synthetic macro fibers. A second, higher dosing rate was used for both the hemp micro and macro fibers in order to gauge the sensitivity of the mix performance to high doses of hemp fibers. Mixes containing fibers did not have the coarse aggregate reduced. Manufacturer's for synthetic and steel fibers market their fibers as to be added to a standard concrete mix without aggregate reduction; thereby, not requiring a special mix design to be created.

The dosing rates shown in Table 4.3 are in kg/m3 and percent by volume. Standards and research articles normally reference the dosing rate only as a percentage of the volume.

However, synthetic and steel fiber manufacturers provide dosing rates as kg/m^3. Conversion from kg/m3 to percent volume is calculated as follows:

$$\%Vol = \frac{{kg}/{m^3}}{S.G.\times 1000\,\frac{kg}{kg^3}} \times 100 \tag{4.1}$$

Table 4.3 also provides the aspect and the fiber factor.

$$Aspect = \frac{l}{d} \tag{4.2}$$

where l = length of the fiber and d = average diameter or equivalent diameter of the fiber.[18] The aspect ratio allows comparison of results from this investigation to other published work.

4.4 Experimental results and discussion

4.4.1 Compressive strength and modulus of elasticity

Figure 4.5, Figure 4.6 and Table 4.4 shows the measured compressive strengths at 7 days and 28 days. The plain, synthetic micro fiber, and steel macro fiber mixes show similar compressive strength at 28 days. The macro fiber mixes group together at 28-days but at noticeably lower strength than plain, micro fiber or steel macro fiber mixes. The hemp macro fiber high mix without pre-soaked fibers shows a very low 28-day compressive strength. The fibers absorbed the mixing water, thereby not allowing a complete chemical reaction to occur between the cement and water.

For this paper, percent change is calculated based on the following:

$$\%Change = \frac{(Fiber\ Mix\ Value - Plain\ Concrete\ Value)}{Plain\ Concrete\ Value} \times 100 \quad (4.3)$$

The synthetic micro fiber mixes saw a reduction of compressive strength of 10% at 7-days and an increase of 3% at 28-days when compared to the plain concrete sample. Synthetic macro fiber mixes saw a reduction of 34% and 32% at 7-days and 28-days respectively. Other research has confirmed that adding synthetic macro fibers reduces the 28-day compressive strength of the concrete.[19] Bolat showed that a dosing rate of 0.425% by volume reduced the 28-day compressive strength 6% when compared to the plain concrete control sample.[19] Our research supports that adding synthetic macro fibers at increasing volumes will lower the 28-day compressive strength.

The steel macro fibers reduced the 7-day compressive strength by 15%, but the 28-day compressive strength was 6% higher than the control sample. Hemp micro fiber mixes at the lower dosing rate showed a reduction of compressive strength at the 7-day and 28-day tests of 12% and 2%, respectively. The higher dosing rate of the hemp micro fibers yielded a mixt that saw a larger decrease in the compressive strength, 39% at both 7 days and 28 days. Similarly, Awwad, et. al.[5] found that a dosing rate of 0.5%, by volume, hemp micro fibers saw a reduction of compressive strength of 20% at 7 days and 28 days[5]. The differences in results can be attributed to the fibers in the Awwad study being treated with sodium hydroxide solution, while the hemp fibers in this study were not treated. Treatment with sodium hydroxide strips away the natural oils found on the surface of the hemp fibers thereby allowing a strong bond between the fiber and cement mortar. In addition, this investigation used a different concrete mix design without coarse aggregate reduction. Hemp macro fibers saw the largest decrease in the compressive strength. The lower dosing rate has 33% reduction at 7-day and the 28-day saw a 25% reduction. The higher dosing rate mix saw a larger reduction in the compressive strength, 42% at 7 days and 44% at 28 days.

Table 4 lists the modulus of elasticity of concrete for the text samples at 28 days per ASTM C469 using the following formula:

$$E = {(S_2 - S_1)}\Big/{(\varepsilon_2 - 0.000050)} \tag{4.4}$$

where E = modulus of elasticity, S_1 = stress corresponding to a longitudinal strain of 50 millionths, S_2 = stress corresponding to 40% of ultimate load, ε_2 = longitudinal strain produced by stress S_2. The micro fiber mixes had a slightly higher modulus of elasticity as compared to the control concrete mix, the plain concrete mix. Awwad, et.al., found that a 0.5% by volume hemp dosing rate resulted in a 7% reduction in the modulus of elasticity as compared to the control[5]. The difference in fiber preparation and the concrete mix design causes the reduction in the modulus of elasticity. The synthetic macro fiber and plain concrete mixes had similar moduli of elasticity values. The hemp macro and steel fibers have a much lower modulus of elasticity than the plain concrete control mix. Adding macro fibers produced mixes with a modulus of elasticity values that were much lower than micro fibers. Quantitatively, macro fibers reduced the modulus of elasticity by 2.5% to 35% compared to the control mix, while micro fibers increased it by 5% to 12.5%.

Table 4.4 Measured compressive stress, modulus of elasticity (E), peak flexural load

Fiber Type	Dosing Rate Kg/m^3	7-day (MPa)	28-day (MPa)	E (MPa)	Peak Flexural Load (kN)
Plain Concrete (Control)	0	29.6	34.1	13,800	5,200
Synthetic Micro Fiber	0.3	26.7	35.1	14,400	6,100
Synthetic Macro Fiber	3.26	19.4	23.2	13,600	5,900
Steel Macro Fiber	14.83	25.2	36.12	11,800	7,000
Hemp Micro Fiber Low	0.3	26.1	33.3	14,400	6,800
Hemp Micro Fiber High	7.50	18.2	21.0	15,400	5,200
Hemp Macro Fiber Low	3.26	19.9	25.7	11,400	6,800
Hemp Macro Fiber High	15.03	17.1	19.1	9,000	5,800

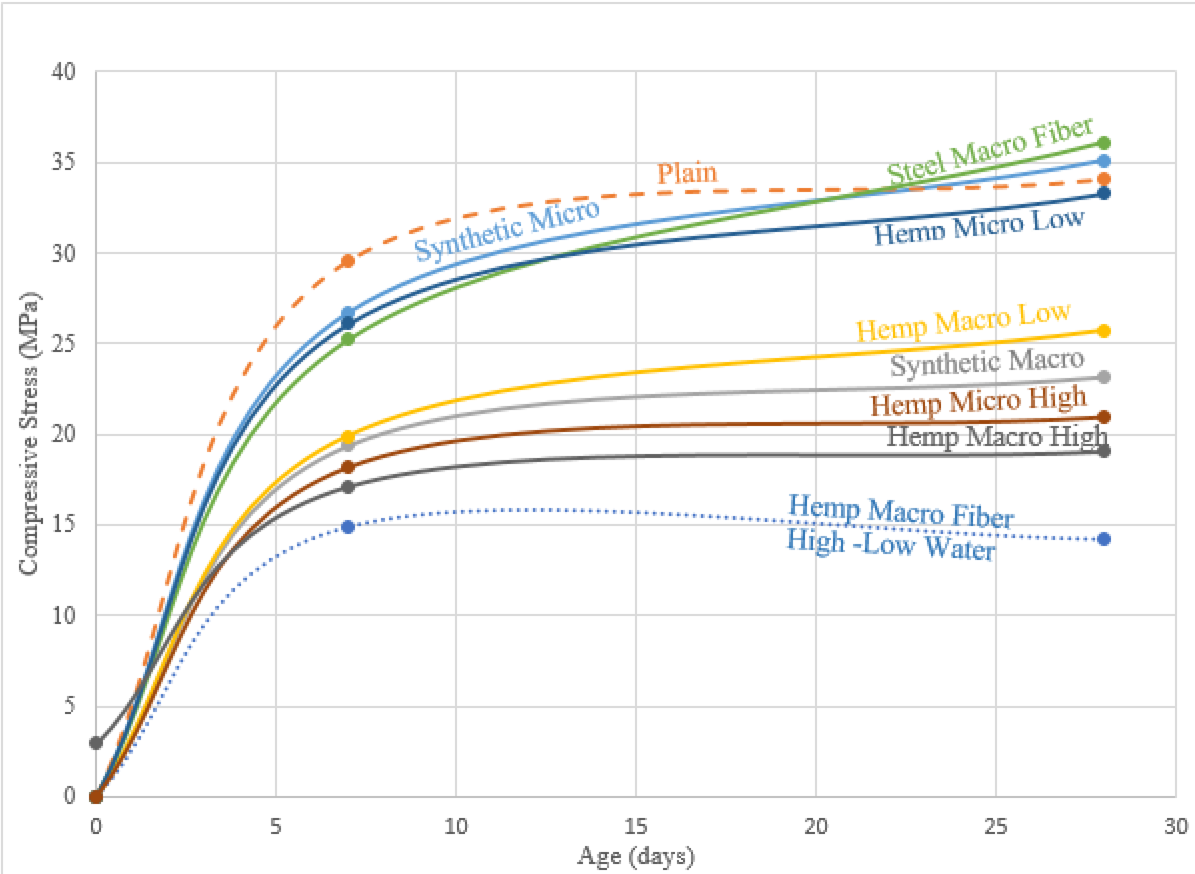

Figure 4.5 Measured compessive strength versus age

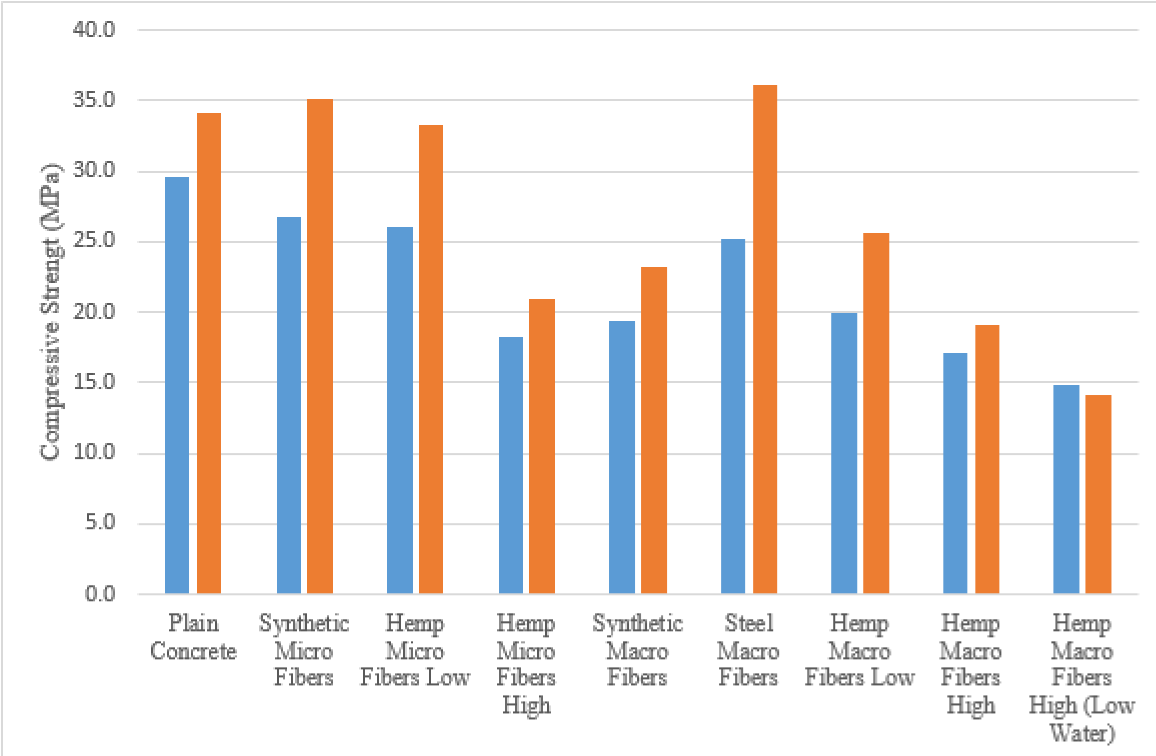

Figure 4.6 Measured compressive stress at 7 days and 28 days

Blue bars represent the compressive stress at 7 days and the orange bars represent the compressive stress at 28 days.

Additional compression test data can be found in APPENDIX C. APPENDIX D contains photographs of the experiment setup and close-up pictures of the cylinders and beams.

4.4.2 Flexural capacity and flexural toughness

Figure 4.7 and Figure 4.8 present the load/deflection curve for each mix. The plain or micro fiber reinforced beams do not exhibit ductility. As depicted in Figure 4.7, these beams reached their peak load, then exhibited brittle failure. Steel macro fibers and hemp macro fibers with low dosing rates showed similar failure, see Figure 4.8. Synthetic macro fibers; hemp macro fibers high dosing rate, and hemp macro fibers high dosing rate with low water showed ductility and exhibited resistance beyond the peak load, see Figure 4.8. The beam cracked, which reduced the loading but the beam continuing handling load by compensating through greater deflection. The test was stopped when the loading reached the initial setting of 2.7 kN, the beam failed, or deflection reached the limit of the digital dial gauge.

The area below the load/deflection curve is the flexural toughness, T^D_{150}, and is calculated per ASTM C1069[16], which supersedes ASTM C1018. The area to consider is from zero deflection to L/150 where L = distance between the supports. For this paper, L = 457.2 mm. L/150 for this test configuration was 3mm deflection. The toughness is also the energy that the beam can absorb. This is an important property for dynamic loadings, such as wind and seismic.[20]

The three beams that showed ductility had deflections that exceeded the L/150 limit. Toughness calculations, for this paper, used the limiting deflection of L/150. Figure 4.9 shows the toughness for each mix. The two mixes with the highest toughness values were the synthetic macro fibers mix and the hemp macro fibers high mix.

The equivalent flexural strength ($R^D_{T,150}$) is also calculated for each beam.

$$R^D_{T,150} = \frac{150 \cdot T^D_{150}}{f_1 \cdot b \cdot d^2} \times 100\% \qquad (4.5)$$

where f_1 = first-peak strength, b = average beam width at the fracture, d = average beam depth at the fracture, T^D_{150} = area under the load/deflection curve. The 150 subscript represents the L/150 deflection position. $R^D_{T,150}$ is the ratio of the flexural toughness to the first peak strength. Figure 4.9 shows the equivalent flexural strength for each mix design. As seen with the flexural toughness T^D_{150}, the two best performing mixes are the synthetic macro fibers and the hemp macro fibers high. These two mixes have similar toughness values and equivalent flexural strength.

Table 4.4 lists the maximum peak load for each beam. The concrete mix that contained steel fibers had the highest flexural load, and the plain concrete control sample and the hemp micro fiber high mix had the lowest. Increasing the hemp fiber volume reduced the peak load, but improved the ductility, as shown in Figure 4.10. Conversely, Sedan et.al. showed that increasing the volume of fiber increased the peak load, but the fibers in Sedan article were process differently than fibers used in this study.[6]

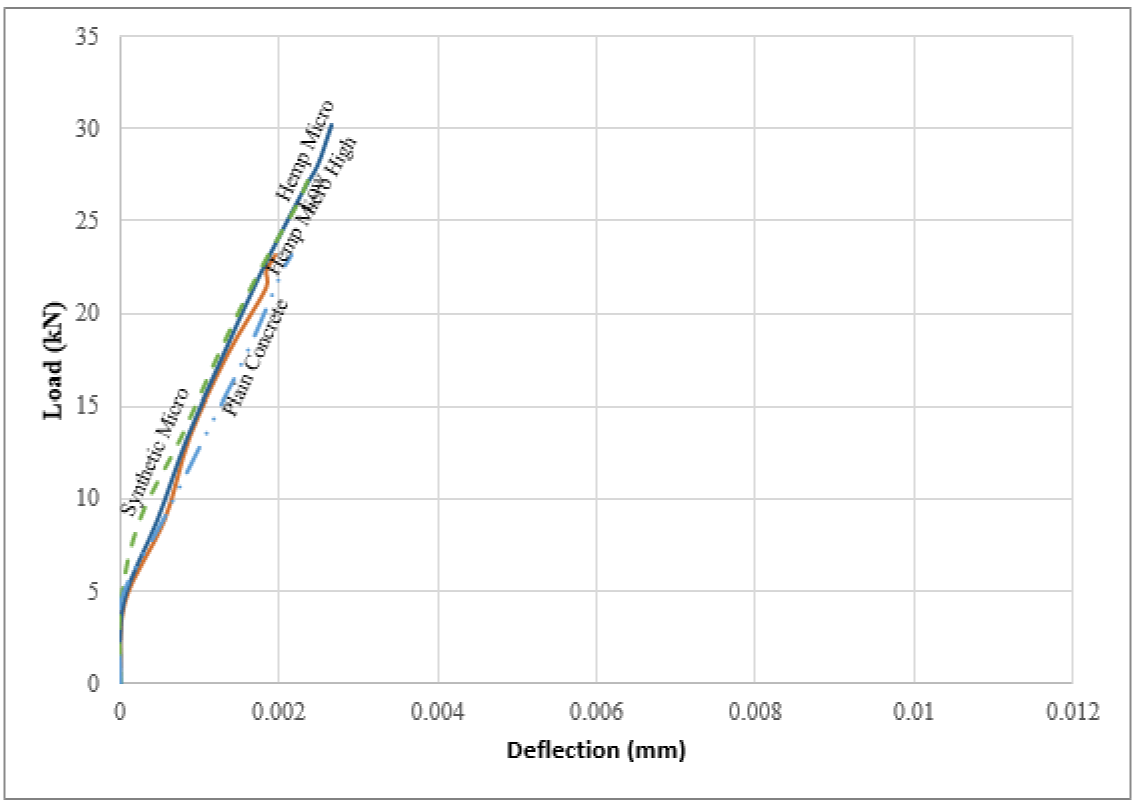

Figure 4.7	Beam flexure test - load vs deflection micro fibers

Load deflection curve for the different micro fibers.

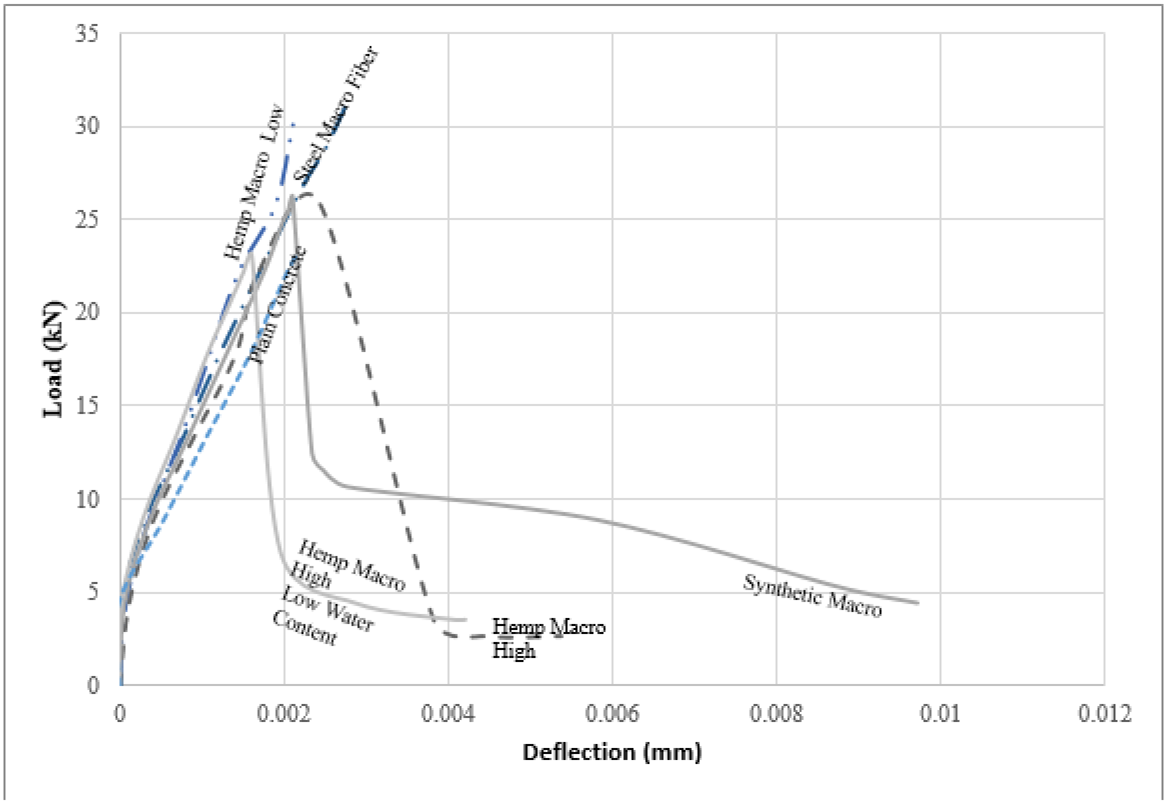

Figure 4.8 Beam flexure test - load vs deflection macro fibers

Load deflection curve for the different macro fibers

Figure 4.9 Toughness and equivalent flexural strength

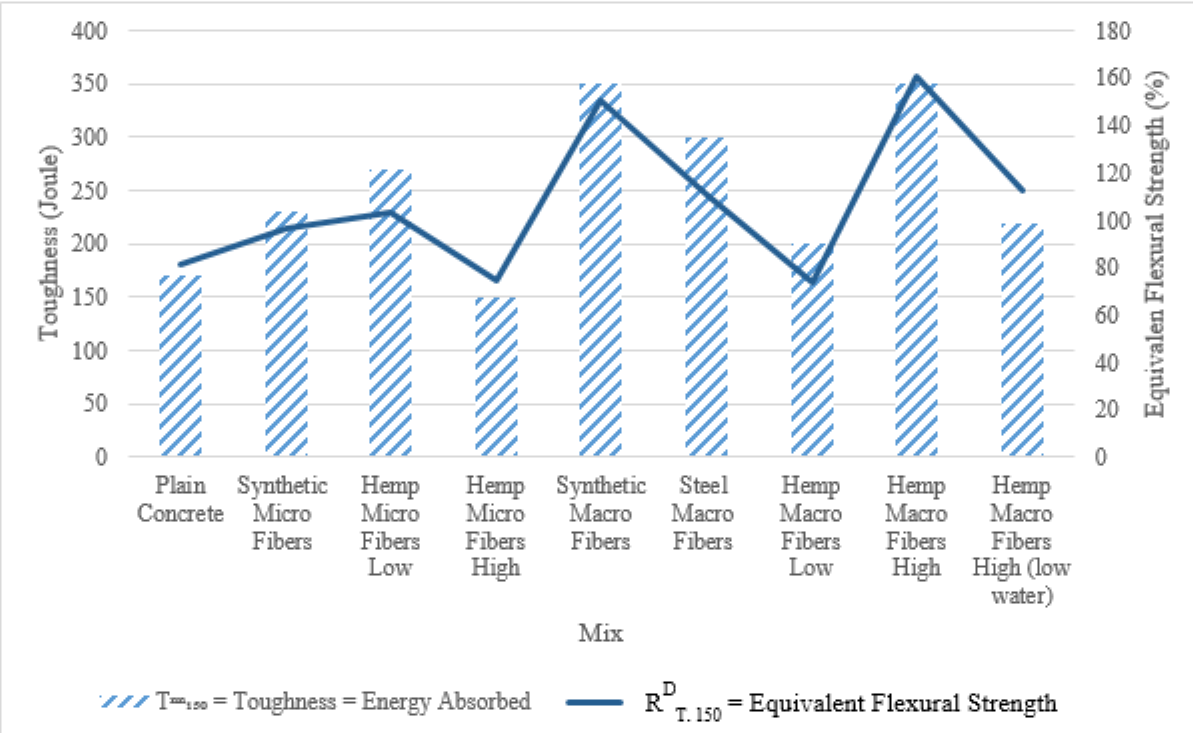

Figure 4.10 Toughness and equivalent flexural strength

Hatched bars represent toughness (T^{D}_{150}) and the solid line represents equivalent flexural strength ($R^{D}_{T,150}$)

4.4.3 Observations

One observation from batching the concrete beams and cylinders were the differences in workability. The mix that contained hemp macro fibers high exhibited especially harsh workability and remarkable stickiness. Pre-soaking the fibers or not made little difference. The micro hemp fibers tended to clump, see Figure 4.10, and this effect has been reported by other researchers.[21]

The concrete mix with steel fibers had more harsh workability than the plain concrete, but not as difficult as the 1% hemp macro fiber mixes. The “sticky” feeling was not as prominent as with the macro hemp fibers. There is a potential for steel fibers to cut because they can protrude from the concrete surface when removing the cylinder or beam from the mold.

The synthetic micro and macro fibers were just as workable as the plain concrete mix.

Figure 4.11 Micro hemp fiber bundles

4.5 Further research

Hemp fibers are a viable alternative to synthetic and steel fibers in concrete mixes. Different dosing rates for micro and macro hemp fibers need to be evaluated to determine optimum. Use of superplasticizers will likely improve the workability of the hemp reinforced concrete. Inexpensive and environmentally sustainable coatings for hemp fibers that could improve the bond and durability, is another topic for investigation. Mathematical models for synthetic and steel fiber reinforced concrete have been developed, and should be expanded to encompass natural fibers. [22]

4.6 Conclusions

The use of natural fibers is feasible, but requires different expertise and techniques as compared to synthetic or steel fibers. The natural fibers will need to be soaked in water and dried to a saturated surface dry condition. This treatment will prevent the fibers from absorbing the mixing water, which will adversely affect the hydration process and the compressive strength.

Based on the results of this experimental investigation, hemp fibers are a viable material for reinforcing concrete. Hemp can control micro cracking at doses of 0.5% for hemp micro fibers and at 1% for hemp macro fiber. Hemp macro fibers at higher dosing rates increase flexural toughness and equivalent flexural strength. Hemp is a renewable resource that has less of an impact on the environment than steel or synthetic materials, and can be a cost effective reinforcement when financial resources are limited. However, hemp can be detrimental to some concrete properties, namely the compressive strength and modulus of elasticity.

4.7 References

1. "7 U.S.C. 5940 - Legitimacy of industrial hemp research." Available at: https://www.gpo.gov/fdsys/granule/USCODE-2015-title7/USCODE-2015-title7-chap88-subchapVII-sec5940. Accessed November 19, 2017.

2. "2018 Farm Bill | The United States Senate Committee On Agriculture, Nutrition & Forestry." Available at: https://www.agriculture.senate.gov/2018-farm-bill. Accessed May 10, 2019.

3. "Controlled Substance Act - Title 21 Sction 811," 2018.

4. Li, Z., Wang, X., and Wang, L. "Properties of hemp fibre reinforced concrete composites," *Composites part A: applied science and manufacturing*, V. 37, No. 3, 2006, pp. 497–505.

5. Awwad, E., Mabsout, M., Hamad, B., et al. "Studies on fiber-reinforced concrete using industrial hemp fibers," *Construction and Building Materials*, V. 35, 2012, pp. 710–7.

6. Sedan, D., Pagnoux, C., Smith, A., et al. "Mechanical properties of hemp fibre reinforced cement: influence of the fibre/matrix interaction," *Journal of the European Ceramic Society*, V. 28, No. 1, 2008, pp. 183–92.

7. Awwad, E., Hamad, B., Mabsout, M., et al. "Structural Behavior of Simply Supported Beams Cast with Hemp-Reinforced Concrete," *ACI Structural Journal*, V. 111, No. 6, 2014.

8. Gopalaratnam, V. S., Shah, S. P., Batson, G., et al. "Fracture Toughness of Fiber Reinforced Concrete," *Materials Journal*, V. 88, No. 4, 1991, pp. 339–53.

9. Li, Z., Wang, L., and Wang, X. "Compressive and flexural properties of hemp fiber reinforced concrete," *Fibers and polymers*, V. 5, No. 3, 2004, pp. 187–197.

10. Asprone, D., Durante, M., Prota, A., et al. "Potential of structural pozzolanic matrix–hemp fiber grid composites," *Construction and Building Materials*, V. 25, No. 6, 2011, pp. 2867–74.

11. Swift, D., and Smith, R. "The flexural strength of cement-based composites using low modulus (sisal) fibres," *Composites*, V. 10, No. 3, 1979, pp. 145–8.

12. Ali, M., Liu, A., Sou, H., et al. "Mechanical and dynamic properties of coconut fibre reinforced concrete," *Construction and Building Materials*, V. 30, 2012, pp. 814–25.

13. C09 Committee "Test Method for Compressive Strength of Cylindrical Concrete Specimens," ASTM International, n.d.

14. C09 Committee "Test Method for Static Modulus of Elasticity and Poissons Ratio of Concrete in Compression," ASTM International, n.d.

15. C09 Committee "Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)," ASTM International, n.d.

16. C09 Committee "Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)," ASTM International, n.d.

17. Cabinet, K. T. "Standard Specifications for Roads and Bridge Construction," 2012.

18. 544, A. C. "State-of-the-Art Report on Fiber Reinforced Concrete." vol. 70. ACI, 1996.

19. Bolat, H., Şimşek, O., Çullu, M., et al. "The effects of macro synthetic fiber reinforcement use on physical and mechanical properties of concrete," *Composites Part B: Engineering*, V. 61, 2014, pp. 191–8.

20. Bazant, Z., and Planas, J. "Fracture and Size Effect in Concrete and Other Quasibrittle Materials," CRC Press LLC, 1998.

21. Merta, I., and Tschegg, E. K. "Fracture energy of natural fibre reinforced concrete," *Construction and Building Materials*, V. 40, 2013, pp. 991–7.

22. Caner, F. C., Bažant, Z. P., and Wendner, R. "Microplane model M7f for fiber reinforced concrete," *Engineering Fracture Mechanics*, V. 105, 2013, pp. 41–57.

CHAPTER V

CONCLUSIONS

5.1 Conclusions

This research was focused on the use of hemp, a natural fiber, as an alternate form of reinforcement for concrete. Hemp has great potential for use in structural concrete, whether to control temperature and shrinkage cracking or being used as primary reinforcement. This is beneficial for emerging nations that don't have the resources to make steel reinforcement or have the funds to import steel reinforcement. Hemp can grow in a wide variety of climates, from the tropics of Central America to the heartland of the United States. This is a fast-growing renewable resource that can also be used to make fabric for clothing, rope, and oils for medical purposes just to name a few.

The biggest issue for the United States is being able to set up processing facilities that can efficiently process the hemp plants. Most of the process plants in the United States are for CBD oil. Once the oil is extracted from the hemp plant, it is normally returned to the supplier of the plant (farmer) for disposal. The commercial processing of hemp fibers in the United States is almost nonexistent[19]. Research needs to be conducted to determine ways to stimulate the processing of hemp fibers in the United States which include how to automate the process to make it the most cost-effective.

The next item to address is the type of hemp fiber to use: micro (hemp fiber from the stalk) or macro (hemp twine). Each has is benefits as well as its issues. Hemp twine and raw fibers will bond to can transfer tensile forces within the concrete matrix. This shows that the fiber or twine is boding to the cement matrix. Hemp twine and hemp fibers have similar material characteristics but will perform differently depending on the cement mix design and length of the fiber. Hemp twine and hemp fibers at lower water-to-cement (w/c) ratios will carry higher tensile loads. Based on the research the optimum length for twin is 30 mm and for hemp fibers a length of 30 mm for mixes without fly ash and 20 mm with mixes containing fly ash.

The use of natural fibers as an alternative to steel reinforcement or manufactured fibers is feasible but needs to be handled differently than its manufactured counterparts. The hemp fibers or twine, like the coarse aggregate, will need to be at a saturated surface dry condition before being added to the mixer; otherwise, the hemp will absorb the mixing water which could adversely affect the hydration process.

The downside with using hemp is there is a 25% to 44% reduction in 28-day compressive strength and a 17% to 34% reduction in Young's modulus of elasticity for the dosing rates examined with the hemp twine. Hemp fiber, depending on dosing rate, can have an increase or a reduction in the 28-day compressive strength and a 13% increase in the Young's modulus of elasticity for the lower dosing rate and a 17% reduction in the Young's modulus for the higher dosing rate.

Working with natural fibers poses unique situations that will need to be addressed; such as, the variability in the fibers (diameter, composition, etc.). Finishing of concrete contains hemp behaves differently than plain concrete or synthetic fiber concrete. The finishing takes extra effort and a slightly different technique to obtain a nice finish.

Even with hemp's quirks, it can be used effectively in concrete for:

- control of micro cracking at doses of 0.5% (hemp micro fiber) and 1% (hemp macro fiber); and
- increasing flexural toughness and equivalent flexural strength; and
- an environmentally friendly alternative to man-made materials; and
- renewable resource that is probably available in areas that can't afford steel reinforcing.

5.2 Further Research

There is still more research that needs to be done to optimize how hemp fiber can be used to produce reinforced concrete that is commercially viable, economical and friendly to the environment. Additional research is needed to standardize the testing requirements for determining the optimum length of hemp twine and twine fiber lengths. Can fiber treatment with a coating improve fiber bonding with the cement mortar mix? This would need to include looking at the stress-slip law and the size effect. Water-based treatments should be considered as part of the research since they will be more environmentally friendly than chemicals that are currently being used. Dosing rates will need to be studied in further detail to determine optimum ranges of dosing for a particular concrete performance.

The use of admixtures, such as superplasticizers, still needs to be investigated to see if the admixtures can improve the performance of the concrete, improve finishing and workability of the concrete, and does it create any negative side effects. Long term durability studies need to be performed to see how the concrete performs through multiple freeze-thaw cycles, exposed to UV light, and how salts and other chemicals may affect the hemp. Further research is needed to develop mathematical models of the behavior of hemp fiber reinforced concrete. This has already been done for synthetic and steel fiber reinforced concrete.

Hemp has the potential to be a great way to reinforce concrete that will be environmentally friendly and cost-effective. This has such potential for countries that have limited financial resources to build buildings that will provide a better level of performance when subjected to various loading conditions.

APPENDIX A

TENSION TEST DATA FOR HEMP MACRO FIBERS IN

DIFFERENT CEMENT MORTAR MIXES

Appendix A contains all the raw data that was acquired during the tension testing of the hemp macro fibers in cement mortar which includes failure mode and ultimate load. The diameter of the twine was measured for each sample.

Table A.1 0.49 w/c ratio cement mortar mix without fly ash – tension test data

Sample	Length of Embedment (mm)	Avg. Dia. (μm)	Failure -Slip, Break, Partial Break	Strength (N)
a	20	0	0	0
b	20	1074.72	S	8.9445
c	20	0	0	0
d	20	981.55	S	2.9815
e	20	1056.555	S	6.23
f	30	867.655	S	4.895
g	30	907.45	S	73.336
h	30	704.815	S	11.926
i	30	1099.76	S	4.3165
j	30	1018.605	S	1.78
k	40	1041.65	S	49.395
l	40	930	S	9.879
m	40	1250.135	S	14.685
n	40	1067.78	S	35.2885
o	40	905.8	S	61.41
p	50	1052.44	S	72.09
q	50	877.24	S	33.108
r	50	971.82	S	23.0065
s	50	900.38	S	42.7645
t	50	1004.38	S	14.596
u	60	1130.695	S	14.9075
v	60	1601.795	S	34.6655
w	60	842.64	S	12.549
x	60	1066.315	S	58.1615
y	60	0	0	0

Tension test data without fly ash in the mix.

Table A.2 0.42 w/c ratio cement mortar mix without fly ash – tension test data

Sample	Length of Embedment (mm)	Avg. Dia. (µm)	Failure -Slip, Break, Partial Break	Strength (N)
a	20	1112.185	S	5.7405
b	20	1029.135	S	43.0315
c	20	1254.26	S	4.1385
d	20	1181.2	S	6.23
e	20	746.01	S	21.093
g	30	871.925	S	8.0545
h	30	673.755	B	44.7225
j	30	1243.53	S	13.973
k	40	1660.445	S	12.816
l	40	1070.69	S	62.8785
m	40	1049.82	S	51.3085
n	40	917.75	S	60.876
o	40	956.385	S	25.81
p	50	1156.785	S	27.9905
q	50	590.125	B	79.121
r	50	964.47	S	60.2975
s	50	770.12	S	15.13
t	50	1022.045	S	54.5125
u	60	1140.995	S	14.418
v	60	781.505	B	52.6435
w	60	814.825	S	38.7595
x	60	1144.18	S	20.1585
y	60	1214.115	S	20.381

Tension test data without fly ash in the mix.

Table A.3 0.66 w/c ratio cement mortar mix without fly ash - tension test data

Sample	Length of Embedment (mm)	Avg. Dia. (µm)	Failure -Slip, Break, Partial Break	Strength (N)
a	20	997.975	S	4.272
b	20	1312.98	S	9.701
c	20	1228.36	S	6.408
d	20	1104.305	S	4.3165
e	20	988.6	S	5.2955
f	30	1453.395	S	9.968
g	30	975.295	S	5.963
h	30	1528.87	S	15.575
i	30	821.21	S	9.2115
j	30	973.88	S	14.5515
k	40	884.195	S	7.6985
l	40	843.85	S	19.491
m	40	881.245	S	47.615
n	40	1052.705	S	53.1775
o	40	977.33	S	57.8055
p1	50	954.97	S	6.853
q1	50	770.885	S	10.858
r1	50	1081.265	S	4.272
s1	50	1079.02	S	5.607
t1	50	1124.37	S	17.6665
u	60	1154.535	S	16.5985
v	60	1003.695	S	63.368
w	60	924.865	S	44.411
x	60	1048.88	S	10.9915
y	60	941.35	S	46.28

Tension test data without fly ash in the mix.

Table A.4 0.49 w/c ratio cement mortar mix with fly ash – tension test data

Sample	Length of Embedment (mm)	Avg. Dia. (µm)	Failure -Slip, Break, Partial Break	Strength (N)
a	20	1325.87	S	5.5625
b	20	1312.725	S	21.538
c	20	1138.075	S	43.076
d	20	862.32	S	16.376
e	20	1400.715	S	7.12
f	30	1021.195	S	8.9445
g	30	982.2	S	3.471
h	30	1255.61	S	31.9065
i	30	1094.07	S	6.586
k1	40	856.24	S	5.34
l1	40	1566.19	S	1.335
n1	40	967.755	S	2.225
o1	40	1052.885	S	2.047
p	50	911.71	S	5.2065
q	50	993.91	S	10.057
r	50	984.105	S	28.035
s	50	1231.635	S	1.513
t	50	1337.425	S	4.0495
u	60	946.62	S	6.408
v	60	890.49	S	54.6015
w	60	977.745	S	37.9585
x	60	1112.81	S	7.6985
y	60	1372.64	S	13.9285

Tension test data with fly ash in the mix.

Table A.5 0.42 w/c ratio cement mortar mix with fly ash – tension test data

Sample	Length of Embedment (mm)	Avg. Dia. (µm)	Failure -Slip, Break, Partial Break	Strength (N)
a	20	1071.255	S	3.4265
b	20	1265.94	S	5.963
c	20	1279.69	S	13.439
d	20	1042.95	S	28.5245
e	20	1013.785	S	6.319
f	30	1283.04	S	7.12
g	30	1313.58	S	7.654
h	30	1132.95	S	6.7195
i	30	1178.55	S	2.225
j	30	1069.58	S	23.1845
k	40	955.795	S	68.886
l	40	1015.505	S	2.6255
m	40	1026.005	S	10.235
n	40	932.94	S	55.269
o	40	1444.325	S	1.691
p	50	893.14	S	15.5305
q	50	918.06	S	7.476
r	50	870.56	S	5.7405
s	50	1070.475	S	75.8725
t	50	1397.895	S	79.21
u	60	780.12	S	18.067
v	60	907.86	S	21.0485
w	60	1082.74	S	14.2845
x	60	910.695	S	5.9185
y	60	951.515	S	50.374

Tension test data with fly ash in the mix.

Table A.6 0.66 w/c ratio cement mortar mix with fly ash – tension test data

Sample	Length of Embedment (mm)	Avg. Dia. (μm)	Failure -Slip, Break, Partial Break	Strength (N)
a	20	818.925	S	17.3995
c	20	681.95	S	10.947
d	20	794.425	S	9.5675
e	20	817.52	S	17.6665
f	30	906.315	S	2.047
h	30	1096.19	S	4.628
i	30	1046.07	S	3.5155
j	30	813.59	S	12.1485
k	40	942.975	S	3.7825
l	40	1290.89	S	3.6935
m	40	884.335	S	25.988
n	40	800.23	S	3.8715
o	40	788.245	S	1.513
p	50	1065.895	S	11.036
q	50	968.5	S	38.181
r	50	804.18	S	63.0565
s	50	880.8	S	12.816
t	50	1174.95	S	9.078
u	60	1293.475	S	61.677
w	60	940.825	S	4.6725
x	60	1199.965	S	3.293
y	60	769.63	S	3.1595

Tension test data with fly ash in the mix.

APPENDIX B

TENSION TEST DATA FOR HEMP MICRO FIBER IN

DIFFERENT CEMENT MORTAR MIXES

Appendix B contains all the raw data that was acquired during the tension testing of the hemp fiber in cement mortar which includes failure mode and ultimate load. The diameter of the fiber was measured for each sample.

Table B.1 0.49 w/c ratio cement mortar mix without fly ash – tension test data

Sample	Length of Embedment (mm)	Avg. Dia. (µm)	Failure -Slip, Break, Partial Break	Strength (N)
b	20	198.37	B	2.3585
c	20	74.485	PB	2.0025
d	20	409.495	S	12.46
e	20	119.395	B	1.2905
f	30	440.855	B	1.157
h	30	602.915	B	0.801
i	30	138.175	PB	0.2225
j	30	198.06	B	8.2325
k	40	248.35	B	1.335
l	40	460.5	B	14.774
m	40	748.665	B	6.2745
o	40	290.12	B	1.6465
p	50	176.375	B	0.9345
q	50	556.6	B	0.5785
r	50	475.3887	B	8.8555
s	50	680.02	B	7.6985
t	50	646.175	B	13.3945
v	60	381.02	PB	4.6725
w	60	435.39	B	4.45
x	60	268.7	B	5.518
y	60	452.2436	B	1.2015

Tension test data without fly ash in the mix.

Table B.2 0.42 w/c ratio cement mortar mix without fly ash – tension test data

Sample	Length of Embedment (mm)	Avg. Dia. (µm)	Failure -Slip, Break, Partial Break	Strength (N)
c	20	554.995	B	7.9655
d	20	117.275	B	6.1855
e	20	173.625	B	2.492
f	30	238.585	B	2.9815
g	30	124.12	B	2.225
h	30	267.635	B	5.0285
i	30	412.395	B	4.183
j	30	119.425	PB	7.1645
k	40	724.96	B	13.3055
l	40	547.485	S	1.3795
p	50	275.43	S	3.827
q	50	383.045	B	8.8555
r	50	193.845	S	7.0755
s	50	171.355	B	5.6515
t	50	585.915	B	3.7825
v	60	246.595	B	1.424
y	60	292.325	B	1.2905

Tension test data without fly ash in the mix.

Table B.3 0.66 w/c ratio cement mortar mix without fly ash – tension test data

Sample	Length of Embedment (mm)	Avg. Dia. (µm)	Failure -Slip, Break, Partial Break	Strength (N)
b	20	336.485		1.2905
c	20	321.55	S	0.356
e	20	149.83	B	2.759
g	30	285.135	B	2.136
h	30	193.1	B	2.136
i	30	138.355	B	0.712
j	30	324.035	S	2.7145
k	40	323.295	B	7.387
l	40	364.895	B	1.068
m	40	772.795	B	11.8815
n	40	306.975	S	6.8085
o	40	428.3	B	3.6045
q	50	335.645	B	3.1595
r	50	234.27	B	3.8715
u	60	109.65	S	7.921
v	60	162.11	B	8.633
w	60	237.07	B	1.246
y	60	309.3151	PB	3.916

Tension test data without fly ash in the mix.

Table B.4 0.49 w/c ratio cement mortar mix with fly ash – tension test data

Sample	Length of Embedment (mm)	Avg. Dia. (µm)	Failure -Slip, Break, Partial Break	Strength (N)
a	20	194.845	B	6.8085
b	20	153.32	B	9.0335
c	20	234.04	PB	1.1125
d	20	407.245	S	1.1125
f	30	304.435	B	1.0235
h	30	242.15	B	2.136
i	30	407.87	PB	3.026
j	30	383.28	B	13.5725
k	40	178.86	B	1.2015
l	40	515.56	B	5.162
m	40	151.99	B	4.5835
o	40	197.595	B	4.0495
p	50	113.16	B	0.979
r	50	186.89	B	5.2065
s	50	282.165	B	12.2375
t	50	510.725	B	9.1225
u	60	429.645	B	2.848
v	60	175.51	PB	1.3795
w	60	488.1982	B	17.1325
x	60	405.045	B	5.4735
y	60	422.22	B	7.832

Tension test data with fly ash in the mix.

Table B.5 0.42 w/c ratio cement mortar mix with fly ash – tension test data

Sample	Length of Embedment (mm)	Avg. Dia. (µm)	Failure -Slip, Break, Partial Break	Strength (N)
c	20	232.83	B	1.1125
d	20	235.4085	B	4.183
g	30	261.2571	B	3.471
i	30	301.68	B	5.4735
j	30	323.8329	PB	26.077
l	40	208.48	S	9.5675
m	40	390.75	S	5.073
o	40	334.915	B	4.094
p	50	279.9	B	3.115
r	50	327.815	S	7.565
t	50	119.55	S	1.068
u	60	211.865	B	4.895
v	60	202.331	B	12.0595
w	60	258.19	B	2.0025
x	60	303.86	B	8.722
y	60	180.56	B	2.7145

Tension test data with fly ash in the mix.

Table B.6 0.66 w/c ratio cement mortar mix with fly ash – tension test data

Sample	Length of Embedment (mm)	Avg. Dia. (µm)	Failure -Slip, Break, Partial Break	Strength (N)
c	20	278.09	S	2.3585
d	20	513.88	B	1.7355
f	30	284.1449	B	11.481
g	30	246.7	B	1.157
h	30	308.725	B	7.7875
i	30	254.08	B	1.2015
j	30	332.605	S	3.3375
l	40	251.325	B	1.602
m	40	239.035	B	2.0025
n	40	317.41	S	1.9135
o	40	173.195	B	4.4945
p	50	169.275	PB	2.848
q	50	244.365	B	0.801
r	50	732.525	B	13.617
s	50	424.535	B	6.5415
t	50	207.415	B	3.471
u	60	259.78	S	1.2015
v	60	98.445	B	3.3375
w	60	366.03	B	6.8975
x	60	185.4233	B	10.7245
y	60	131.37	PB	1.6465

Tension test data with fly ash in the mix.

APPENDIX C

CONCRETE CYLINDER COMPRESSION TEST DATA

Appendix C contains the compression test data for the different concrete mixes based on the base mix of Class A concrete with fly ash.

Table C.1 Concrete mix design designations

Mix	Fiber type	Fiber Dosing Rate (kg/m^3)
2	Synthetic micro	0.3 = 0.01% by volume
3	Plain concrete	Not applicable
4	Synthetic macro	3.26 = 0.35% by volume
5	Hemp macro	3.26 = 0.22% by volume
6	Hemp macro	15.03 = 1.0% by volume
7	Steel Fibers	14.83 = 0.25% by volume
8	Hemp micro	0.3 = 0.02% by volume
9	Hemp micro	7.5 = 0.5% by volume
10	Hemp macro	15.03 = 1.0% by volume

Mix 6 did not pre-soak the hemp macro fibers to a saturated surface condition. Mix 5, 8, 9 and 10 pre-soaked the micro and macro fibers to a saturated surface dry condition.

Table C.2 Concrete cylinder compression test results

Sample	7-day Load (kN)	28-day Load (kN)
2A	209.8	
2E	223.9	
2B		292.9
2D		277.0
3C	244.1	
3B	236.2	
3E		276.4
3D		277.4
4A	166.6	
4E	148.3	
4C		198.6
4B		178.4
5A	155.8	
5C	167.3	
5E		208.6
5B		128.6
6B	108.5	
6A	133.3	
6C		109.2
6D		120.8
7C	202.1	
7E	207.0	
7B		296.5
7D		288.6
8B	215.2	
8D	207.5	
8E		272.7
8A		267.6
9A	155.2	
9C	139.9	
9B		164.6
9D		175.4
10C	139.0	
10E	109.5	
10D		150.3
10B		159.0

Table C.3 Concrete Young's modulus of elasticity data

Cylinder	Dia1 (mm)	Dia2 (mm)	Avg. Ult. Load (kN)	Δ_2 (mm)	P_1 (kN)
2I	100.7872	101.092	241.0	0.11303	3.7
2J	101.219	101.7778	241.4	0.1143	3.8
3I	101.3714	102.5398	202.9	0.09906	2.4
3J	102.4128	100.4316	198.8	0.09652	7.2
4H	100.9904	101.7778	214.4	0.10668	0.7
4I	100.7618	102.2858	217.3	0.10922	6.5
5H	101.0412	102.489	158.5	0.09144	4.5
5J	101.3206	101.346	162.7	0.09398	5.3
7H	101.346	101.4984	229.7	0.13208	1.0
7J	100.9904	101.7016	217.7	0.12954	0.9
8H	101.9048	101.5492	206.1	0.10414	6.4
8J	100.9142	101.8794	223.7	0.09906	0.8
9I	101.7016	101.346	230.4	0.10668	6.1
9J	102.2604	100.33	245.3	0.09906	5.4
10I	102.4128	102.7684	136.7	0.10922	1.1
10J	101.727	101.8794	132.7	0.08636	6.5

This table provides the results for testing the concrete cylinders for the modulus of elasticity.

APPENDIX D

PHOTOGRAPHS OF EXPERIMENT SETUP AND TEST RESULTS

Appendix D contains photographs of the setups for different experiments that were part of this study.

Figure D.1 Form setup for casting sample

This setup allows for casting multiple samples of various lengths at one time.

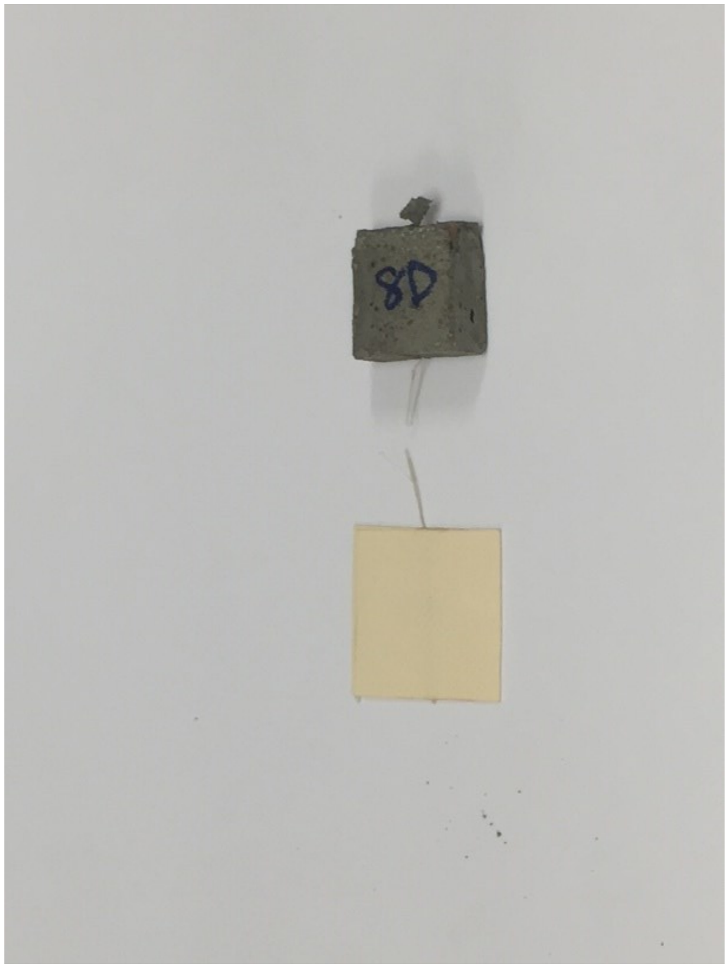

Figure D.2 Hemp micro fiber tension testing - break

The fiber of this sample broke during tension testing.

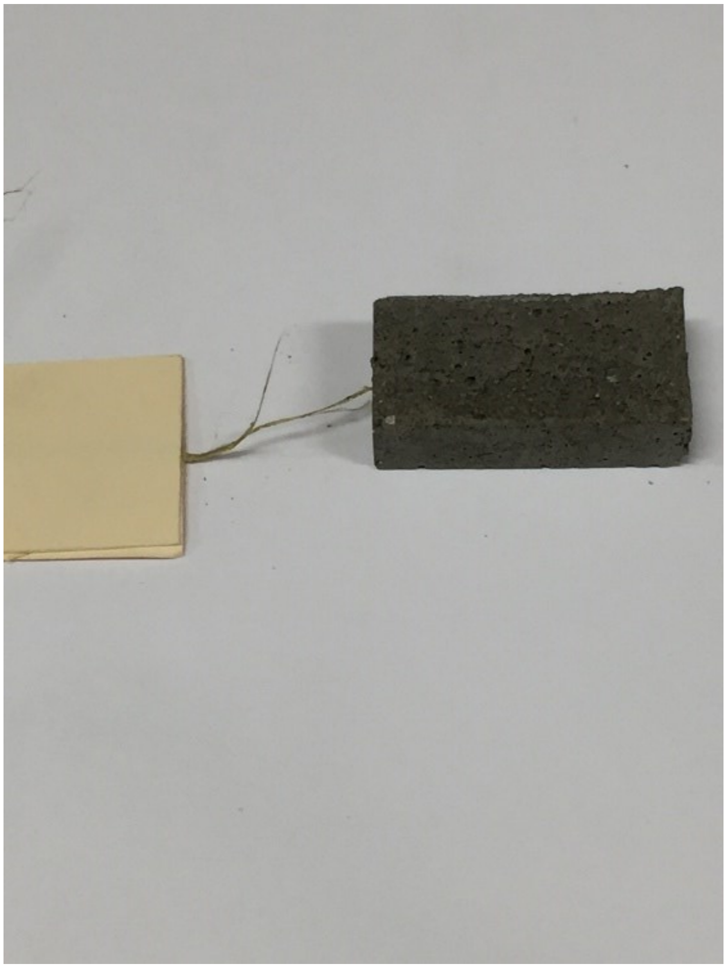

Figure D.3 Hemp micro fiber tension testing – partial break

The fiber of this sample had a partial break during tension testing.

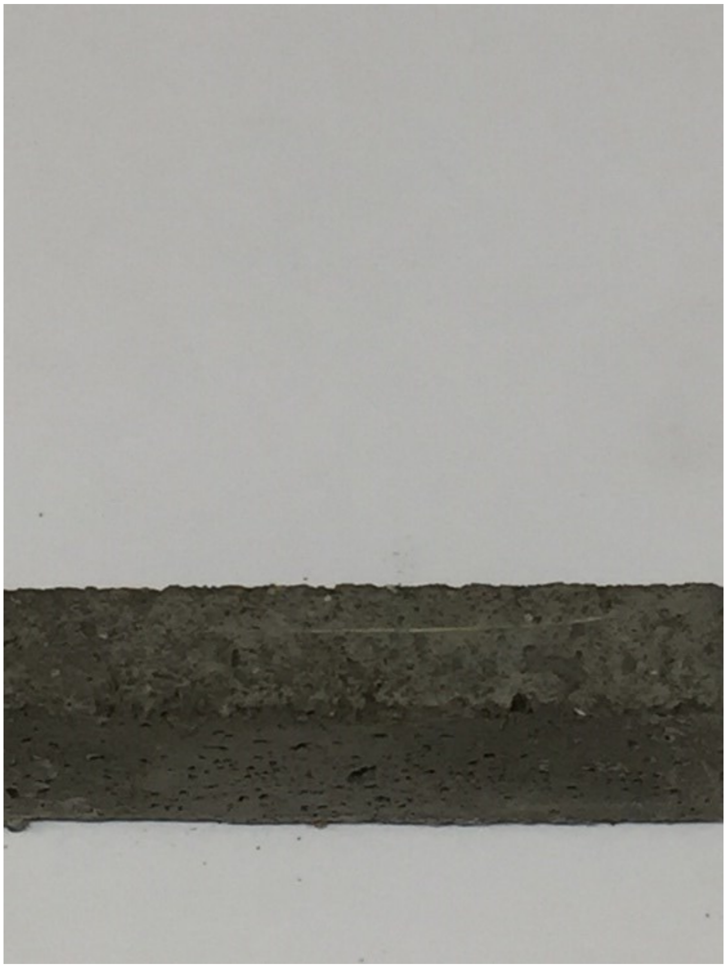

Figure D.4 Tension testing sample – casting issue

This sample has the fiber moved to the side of the form and is not surrounded by cement mortar. This sample was not tested.

Figure D.5 Microscope setup for measuring diameters

The microscope is connected to the computer which allows accurate measurement of fibers and to take quality photographs.

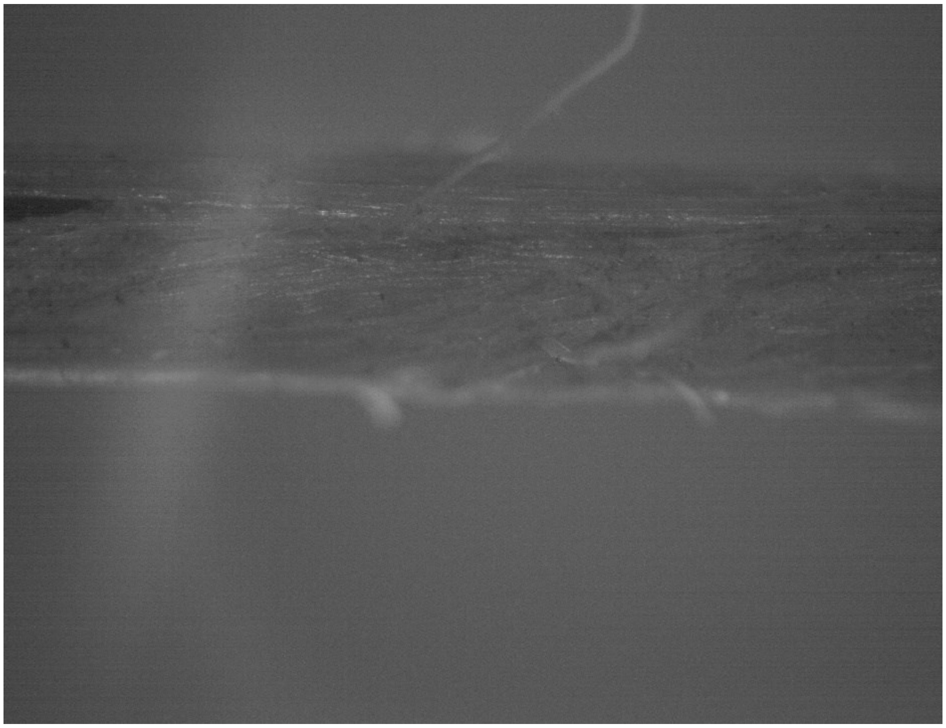

Figure D.6 Hemp macro fiber after tension testing

0.66 w/c ratio concrete mix without fly ash. No fraying of the fiber.

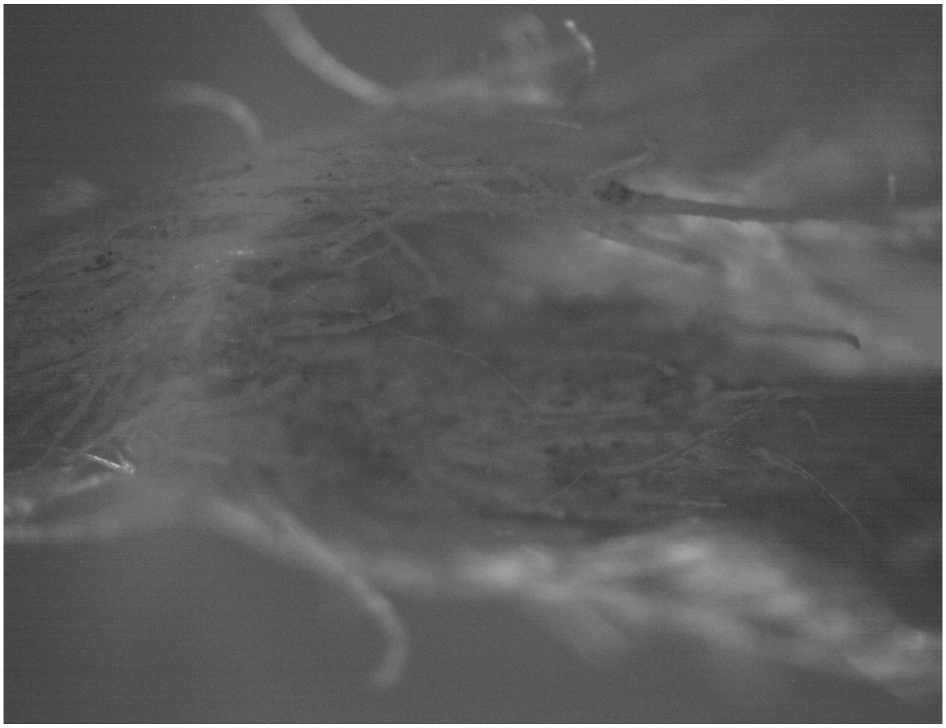

Figure D.7 Hemp macro fiber after tension testing

0.66 w/c ratio concrete mix without fly ash with fraying of the fiber.

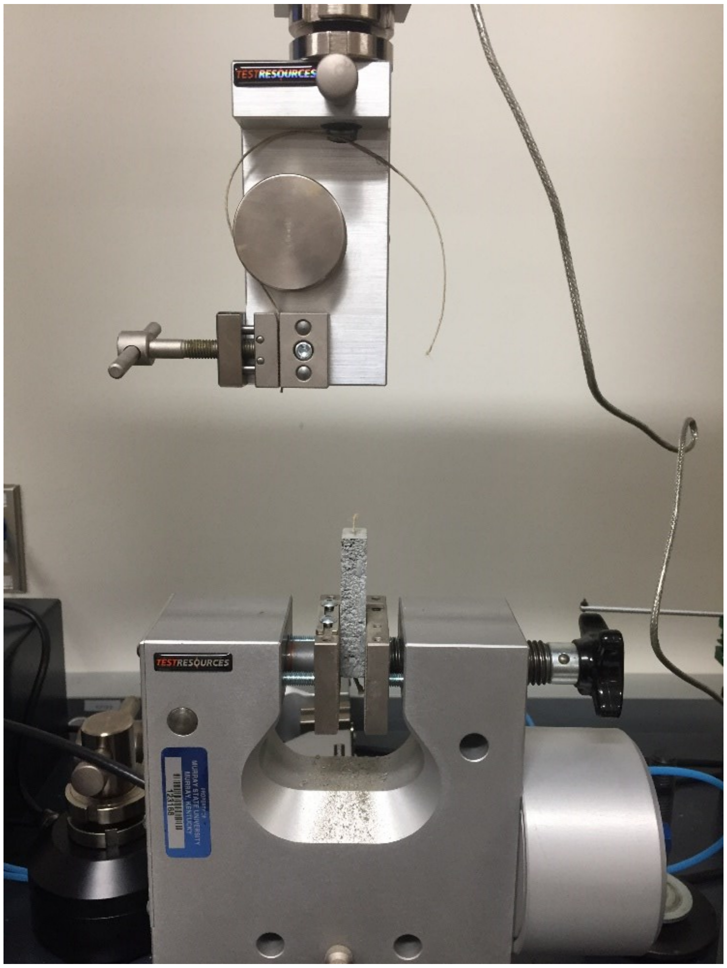

Figure D.8 Tension testing of hemp macro

This sample failed by the fiber breaking.

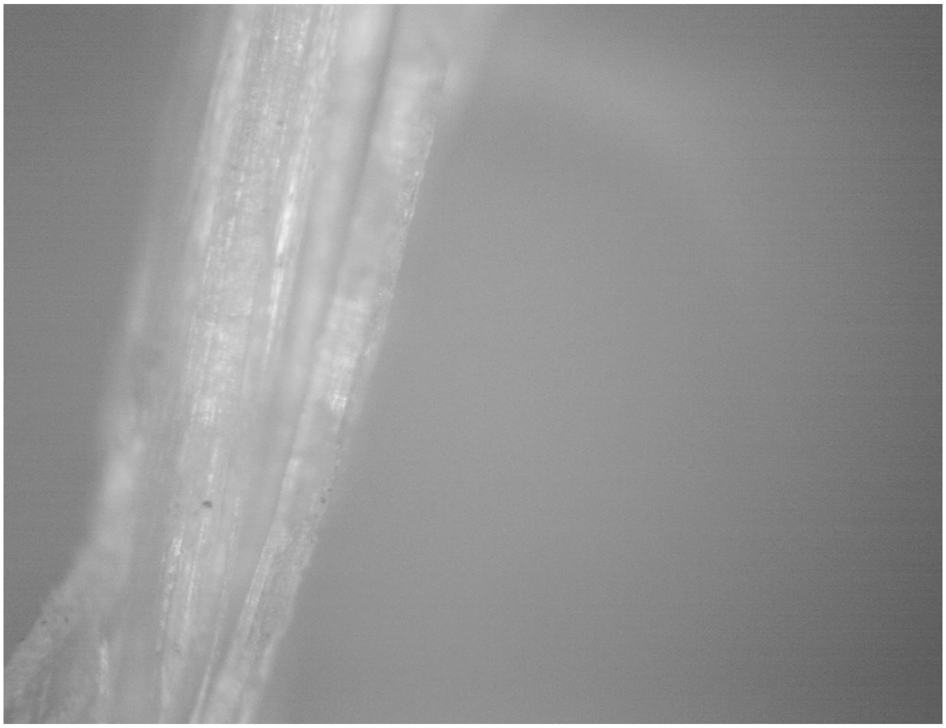

Figure D.9 Hemp micro fiber after tension testing.

0.66 w/c ratio concrete mix without fly ash.

Figure D.10 Compression testing machine setup

Compression testing machine setup for determining the 7-day and 28-day compressive strength of the concrete cylinders.

Figure D.11 Compression testing machine – Young’s modulus test

This setup shows the concrete cylinder with compressometer installed to allow measurement of deflection at different compressive loads.

Figure D.12 Beam flexural testing setup.

The hand lever is used to apply the initial load then the screw pump is used to apply a continuous loading per ACI requirements. Deflection of the load head is measured at the point where the load is applied.

Figure D.13 Cylinder without fibers after compression testing.

This is the control sample that doesn't contain fiber.

Figure D.14 Cylinder with synthetic micro fibers at end of compression testing

This is concrete cylinder that has synthetic micro fibers at a dosing rate of 0.3 kg/m^3.

Figure D.15 Cylinder with synthetic macro fibers at end of compression testing

This is a concrete cylinder that has synthetic micro fibers at a dosing rate of 3.26 kg/m^3.

Figure D.16 Cylinder with hemp micro fibers at end of compression testing

This is a concrete cylinder that has hemp micro fibers at a dosing rate of 0.3 kg/m^3.

Figure D.17 Another cylinder with hemp micro fibers at end of compression testing

This is concrete cylinder that has hemp micro fibers at a dosing rate of 0.3 kg/m^3.

Figure D.18 Cylinder with hemp micro fibers at end of compression testing

This is concrete cylinder that has hemp micro fibers at a dosing rate of 7.50 kg/m^3.

Figure D.19 Cylinder with hemp macro fibers at end of compression testing

This is concrete cylinder that has hemp macro fibers at a dosing rate of 3.26 kg/m^3.

Figure D.20 Cylinder with hemp macro fibers at end of compression testing

This is concrete cylinder that has hemp macro fibers at a dosing rate of 15.03 kg/m^3.

Figure D.21 Cylinder with steel macro fibers at end of compression testing

This is concrete cylinder that has steel macro fibers at a dosing rate of 14.83 kg/m^3.

Figure D.22 Cylinder with hemp macro fibers at end of compression testing

This is concrete cylinder that has hemp macro fibers (without pre-soaking) at a dosing rate of 15.03 kg/m^3.

Figure D.23 Concrete beam mold with fresh concrete.

This figure shows the reusable plastic beam mold with fresh concrete.

Figure D.24 Concrete beam without fiber reinforcement

This is the control beam mix which doesn’t contain any fibers.

Figure D.25 Concrete beam with synthetic micro fibers at end of flexural testing

This is concrete beam that has synthetic micro fibers at a dosing rate of 0.3 kg/m^3.

Figure D.26   Close-up of concrete beam with synthetic micro fibers at end of flexural testing

This is a close-up of the concrete beam that has synthetic micro fibers at a dosing rate of 0.3 kg/m^3.

Figure D.27 Concrete beam with synthetic macro fibers at end of flexural testing

This is concrete beam that has synthetic macro fibers at a dosing rate of 3.26 kg/m^3. Beam didn't separate.

Figure D.28 Close up of concrete beam with synthetic macro fibers at end of flexural testing

This is close-up of the crack in a concrete beam that has synthetic macro fibers at a dosing rate of 3.26 kg/m^3.

Figure D.29 Concrete beam with hemp micro fibers at end of flexural testing

This is concrete beam that has hemp micro fibers at a dosing rate of 0.3 kg/m^3.

Figure D.30 Close-up of concrete beam with hemp micro fibers at end of flexural testing

This is a close-up of a concrete beam that has hemp micro fibers at a dosing rate of 0.3 kg/m^3.

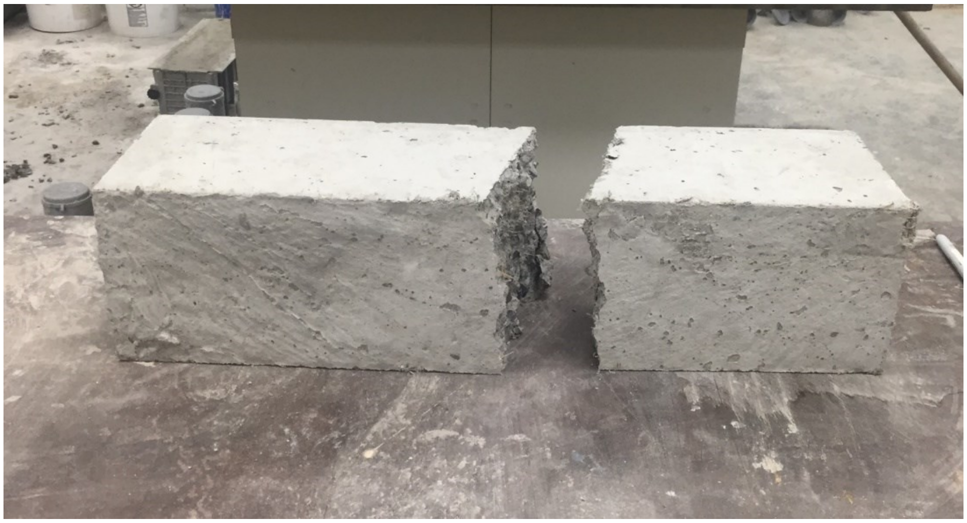

Figure D.31 Concrete beam with hemp micro fibers at end of flexural testing

This is concrete beam that has hemp micro fibers at a dosing rate of 7.5 kg/m^3.

Figure D.32 Close-up of concrete beam with hemp micro fibers at end of flexural testing

This is close-up of the crack in a concrete beam that has hemp micro fibers at a dosing rate of 7.50 kg/m^3.

Figure D.33   Concrete beam with hemp macro fibers at end of flexural testing

This is concrete beam that has hemp macro fibers at a dosing rate of 3.26 kg/m^3.

Figure D.34 Close-up of concrete beam with hemp macro fibers at end of flexural testing

This is a close-up of a concrete beam that has hemp macro fibers at a dosing rate of 3.26 kg/m^3.

Figure D.35 Concrete beam with hemp macro fibers at end of flexural testing

This is concrete beam that has hemp macro fibers at a dosing rate of 15.03 kg/m^3. Notice crack does not go all the way through the beam.

Figure D.36 Close-up of crack in beam with hemp macro fiber

This is a close-up of the crack in the beam with hemp macro fiber at a dosing rate of 15.03 kg/m^3.

Figure D.37 Top view of concrete beam with hemp macro fibers at end of flexural testing.

This is concrete beam that has hemp macro fibers at a dosing rate of 15.03 kg/m^3. Notice no crack on the top surface of the beam.

Figure D.38 Concrete beam with steel macro fibers at end of flexural testing

This is concrete beam that has steel macro fibers at a dosing rate of 14.83 kg/m^3.

Figure D.39 Close-up of concrete beam with steel macro fibers at end of flexural testing

This is a close-up of concrete beam that has steel macro fibers at a dosing rate of 14.83 kg/m^3. Note that the fibers are protruding from the fractured face. The steel fibers are sharp and can easily cut a person if they are not being careful.

Figure D.40 Concrete beam with hemp macro fibers at end of flexural testing

This is concrete beam that has hemp macro fibers (without pre-soaking) at a dosing rate of 15.03 kg/m^3

Figure D.41 Top view of concrete beam with hemp macro fibers at end of flexural testing

This is concrete beam that has hemp macro fibers (without pre-soaking) at a dosing rate of 15.03 kg/m^3.

APPENDIX E

LINEAR REGRESSION DATA

This appendix contains the raw data and code used to complete the linear regression in Chapter 2. STATA which is software for statistical analysis.

The following is the raw data for micro hemp fibers without fly ash in the mix. This data was taken directly from RStudio software. This data can be copied and pasted into the software and then be analyzed.

Sample No.	wc42	wc49	Fly Ash	bed20	bed30	bed40	bed50	Fiber	cddia	dia	Strength (N)
1 a	0	0	1	1	0	0	0	1	0.714769	997.975	4.272
1 b	0	0	1	1	0	0	0	1	1.495607	1312.98	9.701
1 c	0	0	1	1	0	0	0	1	1.28585	1228.36	6.408
1 d	0	0	1	1	0	0	0	1	0.978341	1104.305	4.3165
1 e	0	0	1	1	0	0	0	1	0.691531	988.6	5.2955
1 f	0	0	1	0	1	0	0	1	1.843669	1453.395	9.968
1 g	0	0	1	0	1	0	0	1	0.65855	975.295	5.963
1 h	0	0	1	0	1	0	0	1	2.030757	1528.87	15.575
1 i	0	0	1	0	1	0	0	1	0.276603	821.21	9.2115
1 j	0	0	1	0	1	0	0	1	0.655043	973.88	14.5515
1 k	0	0	1	0	0	1	0	1	0.432731	884.195	7.6985
1 l	0	0	1	0	0	1	0	1	0.332723	843.85	19.491
1 m	0	0	1	0	0	1	0	1	0.425418	881.245	47.615
1 n	0	0	1	0	0	1	0	1	0.850435	1052.705	53.1775
1 o	0	0	1	0	0	1	0	1	0.663594	977.33	57.8055
1 p1	0	0	1	0	0	0	1	1	0.608168	954.97	6.853

1 q1	0	0	1	0	0	0	1	1	0.151857	770.885	10.858
1 r1	0	0	1	0	0	0	1	1	0.921229	1081.265	4.272
1 s1	0	0	1	0	0	0	1	1	0.915665	1079.02	5.607
1 t1	0	0	1	0	0	0	1	1	1.028079	1124.37	17.6665
1 u	0	0	1	0	0	0	0	1	1.102852	1154.535	16.5985
1 v	0	0	1	0	0	0	0	1	0.728948	1003.695	63.368
1 w	0	0	1	0	0	0	0	1	0.533544	924.865	44.411
1 x	0	0	1	0	0	0	0	1	0.840953	1048.88	10.9915
1 y	0	0	1	0	0	0	0	1	0.574407	941.35	46.28
2 a	1	0	1	1	0	0	0	1	0.997874	1112.185	5.7405
2 b	1	0	1	1	0	0	0	1	0.792009	1029.135	43.0315
2 c	1	0	1	1	0	0	0	1	1.350051	1254.26	4.1385
2 d	1	0	1	1	0	0	0	1	1.168949	1181.2	6.23
2 e	1	0	1	1	0	0	0	1	0.090196	746.01	21.093
2 g	1	0	1	0	1	0	0	1	0.402316	871.925	8.0545
2 h	1	0	1	0	1	0	0	1	-0.08891	673.755	44.7225
2 j	1	0	1	0	1	0	0	1	1.323453	1243.53	13.973
2 k	1	0	1	0	0	1	0	1	2.356906	1660.445	12.816
2 l	1	0	1	0	0	1	0	1	0.895016	1070.69	62.8785
2 m	1	0	1	0	0	1	0	1	0.843283	1049.82	51.3085
2 n	1	0	1	0	0	1	0	1	0.515907	917.75	60.876
2 o	1	0	1	0	0	1	0	1	0.611676	956.385	25.81

2 p	1	0	1	0	0	0	1	1	1.108429	1156.785	27.9905
2 q	1	0	1	0	0	0	1	1	-0.29621	590.125	79.121
2 r	1	0	1	0	0	0	1	1	0.631717	964.47	60.2975
2 s	1	0	1	0	0	0	1	1	0.14996	770.12	15.13
2 t	1	0	1	0	0	0	1	1	0.774434	1022.045	54.5125
2 u	1	0	1	0	0	0	0	1	1.069289	1140.995	14.418
2 v	1	0	1	0	0	0	0	1	0.178182	781.505	52.6435
2 w	1	0	1	0	0	0	0	1	0.260776	814.825	38.7595
2 x	1	0	1	0	0	0	0	1	1.077184	1144.18	20.1585
2 y	1	0	1	0	0	0	0	1	1.250539	1214.115	20.381
3 b	0	1	1	1	0	0	0	1	0.905006	1074.72	8.9445
3 d	0	1	1	1	0	0	0	1	0.674055	981.55	2.9815
3 e	0	1	1	1	0	0	0	1	0.859978	1056.555	6.23
3 f	0	1	1	0	1	0	0	1	0.391731	867.655	4.895
3 g	0	1	1	0	1	0	0	1	0.490375	907.45	73.336
3 h	0	1	1	0	1	0	0	1	-0.01192	704.815	11.926
3 i	0	1	1	0	1	0	0	1	0.967075	1099.76	4.3165
3 j	0	1	1	0	1	0	0	1	0.765907	1018.605	1.78
3 k	0	1	1	0	0	1	0	1	0.823031	1041.65	49.395
3 l	0	1	1	0	0	1	0	1	0.546272	930	9.879
3 m	0	1	1	0	0	1	0	1	1.339826	1250.135	14.685
3 n	0	1	1	0	0	1	0	1	0.887803	1067.78	35.2885

3 o	0	1	1	0	0	1	0	1	0.486285	905.8	61.41
3 p	0	1	1	0	0	0	1	1	0.849778	1052.44	72.09
3 q	0	1	1	0	0	0	1	1	0.41549	877.24	33.108
3 r	0	1	1	0	0	0	1	1	0.649936	971.82	23.0065
3 s	0	1	1	0	0	0	1	1	0.47285	900.38	42.7645
3 t	0	1	1	0	0	0	1	1	0.730646	1004.38	14.596
3 u	0	1	1	0	0	0	0	1	1.043757	1130.695	14.9075
3 v	0	1	1	0	0	0	0	1	2.211524	1601.795	34.6655
3 w	0	1	1	0	0	0	0	1	0.329724	842.64	12.549
3 x	0	1	1	0	0	0	0	1	0.884171	1066.315	58.1615
4 a1	0	0	0	1	0	0	0	1	0.270939	818.925	17.3995
4 c1	0	0	0	1	0	0	0	1	-0.0686	681.95	10.947
4 d1	0	0	0	1	0	0	0	1	0.210208	794.425	9.5675
4 e1	0	0	0	1	0	0	0	1	0.267456	817.52	17.6665
4 f	0	0	0	0	1	0	0	1	0.487562	906.315	2.047
4 h	0	0	0	0	1	0	0	1	0.958226	1096.19	4.628
4 i	0	0	0	0	1	0	0	1	0.833988	1046.07	3.5155
4 j	0	0	0	0	1	0	0	1	0.257714	813.59	12.1485
4 k	0	0	0	0	0	1	0	1	0.578435	942.975	3.7825
4 l	0	0	0	0	0	1	0	1	1.44085	1290.89	3.6935
4 m	0	0	0	0	0	1	0	1	0.433078	884.335	25.988
4 n	0	0	0	0	0	1	0	1	0.224597	800.23	3.8715

4 o	0	0	0	0	0	1	0	1	0.194889	788.245	1.513
4 p	0	0	0	0	0	0	1	1	0.88313	1065.895	11.036
4 q	0	0	0	0	0	0	1	1	0.641707	968.5	38.181
4 r	0	0	0	0	0	0	1	1	0.234389	804.18	63.0565
4 s	0	0	0	0	0	0	1	1	0.424315	880.8	12.816
4 t	0	0	0	0	0	0	1	1	1.153457	1174.95	9.078
4 u	0	0	0	0	0	0	0	1	1.447258	1293.475	61.677
4 w	0	0	0	0	0	0	0	1	0.573106	940.825	4.6725
4 x	0	0	0	0	0	0	0	1	1.215464	1199.965	3.293
4 y	0	0	0	0	0	0	0	1	0.148746	769.63	3.1595
5 a	1	0	0	1	0	0	0	1	0.896417	1071.255	3.4265
5 b	1	0	0	1	0	0	0	1	1.379004	1265.94	5.963
5 c	1	0	0	1	0	0	0	1	1.413087	1279.69	13.439
5 d	1	0	0	1	0	0	0	1	0.826254	1042.95	28.5245
5 e	1	0	0	1	0	0	0	1	0.753959	1013.785	6.319
5 f	1	0	0	0	1	0	0	1	1.421391	1283.04	7.12
5 g	1	0	0	0	1	0	0	1	1.497094	1313.58	7.654
5 h	1	0	0	0	1	0	0	1	1.049347	1132.95	6.7195
5 i	1	0	0	0	1	0	0	1	1.16238	1178.55	2.225
5 j	1	0	0	0	1	0	0	1	0.892265	1069.58	23.1845
5 k	1	0	0	0	0	1	0	1	0.610213	955.795	68.886
5 l	1	0	0	0	0	1	0	1	0.758223	1015.505	2.6255

5 m	1	0	0	0	0	1	0	1	0.78425	1026.005	10.235
5 n	1	0	0	0	0	1	0	1	0.55356	932.94	55.269
5 o	1	0	0	0	0	1	0	1	1.821186	1444.325	1.691
5 p	1	0	0	0	0	0	1	1	0.454903	893.14	15.5305
5 q	1	0	0	0	0	0	1	1	0.516675	918.06	7.476
5 r	1	0	0	0	0	0	1	1	0.398932	870.56	5.7405
5 s	1	0	0	0	0	0	1	1	0.894483	1070.475	75.8725
5 t	1	0	0	0	0	0	1	1	1.706095	1397.895	79.21
5 u	1	0	0	0	0	0	0	1	0.174748	780.12	18.067
5 v	1	0	0	0	0	0	0	1	0.491392	907.86	21.0485
5 w	1	0	0	0	0	0	0	1	0.924886	1082.74	14.2845
5 x	1	0	0	0	0	0	0	1	0.498419	910.695	5.9185
5 y	1	0	0	0	0	0	0	1	0.599604	951.515	50.374
6 a	0	1	0	1	0	0	0	1	1.527559	1325.87	5.5625
6 b	0	1	0	1	0	0	0	1	1.494975	1312.725	21.538
6 c	0	1	0	1	0	0	0	1	1.062051	1138.075	43.076
6 d	0	1	0	1	0	0	0	1	0.378507	862.32	16.376
6 e	0	1	0	1	0	0	0	1	1.713085	1400.715	7.12
6 f	0	1	0	0	1	0	0	1	0.772327	1021.195	8.9445
6 g	0	1	0	0	1	0	0	1	0.675666	982.2	3.471
6 h	0	1	0	0	1	0	0	1	1.353398	1255.61	31.9065
6 i	0	1	0	0	1	0	0	1	0.952971	1094.07	6.586

6 k1	0	1	0	0	0	1	0	1	0.363435	856.24	5.34
6 l1	0	1	0	0	0	1	0	1	2.123266	1566.19	1.335
6 n1	0	1	0	0	0	1	0	1	0.63986	967.755	2.225
6 o1	0	1	0	0	0	1	0	1	0.850881	1052.885	2.047
6 p	0	1	0	0	0	0	1	1	0.500935	911.71	5.2065
6 q	0	1	0	0	0	0	1	1	0.704693	993.91	10.057
6 r	0	1	0	0	0	0	1	1	0.680388	984.105	28.035
6 s	0	1	0	0	0	0	1	1	1.293968	1231.635	1.513
6 t	0	1	0	0	0	0	1	1	1.556201	1337.425	4.0495
6 u	0	1	0	0	0	0	0	1	0.58747	946.62	6.408
6 v	0	1	0	0	0	0	0	1	0.447665	890.22	54.6015
6 w	0	1	0	0	0	0	0	1	0.664623	977.745	37.9585
6 x	0	1	0	0	0	0	0	1	0.999424	1112.81	7.6985
6 y	0	1	0	0	0	0	0	1	1.643493	1372.64	13.9285
8 c	1	0	1	1	0	0	0	0	-0.38329	554.995	7.9655
8 d	1	0	1	1	0	0	0	0	-1.46832	117.275	6.1855
8 e	1	0	1	1	0	0	0	0	-1.32864	173.625	2.492
8 f	1	0	1	0	1	0	0	0	-1.16761	238.585	2.9815
8 g	1	0	1	0	1	0	0	0	-1.45135	124.12	2.225
8 h	1	0	1	0	1	0	0	0	-1.0956	267.635	5.0285
8 i	1	0	1	0	1	0	0	0	-0.73677	412.395	4.183
8 j	1	0	1	0	1	0	0	0	-1.46299	119.425	7.1645

8 k	1	0	1	0	0	1	0	0	0.038017	724.96	13.3055
8 l	1	0	1	0	0	1	0	0	-0.40191	547.485	1.3795
8 p	1	0	1	0	0	0	1	0	-1.07628	275.43	3.827
8 q	1	0	1	0	0	0	1	0	-0.80952	383.045	8.8555
8 r	1	0	1	0	0	0	1	0	-1.27852	193.845	7.0755
8 s	1	0	1	0	0	0	1	0	-1.33426	171.355	5.6515
8 t	1	0	1	0	0	0	1	0	-0.30665	585.915	3.7825
8 v	1	0	1	0	0	0	0	0	-1.14776	246.595	1.424
8 y	1	0	1	0	0	0	0	0	-1.0344	292.325	1.2905
9 b	0	0	1	1	0	0	0	0	-0.92494	336.485	1.2905
9 c	0	0	1	1	0	0	0	0	-0.96196	321.55	0.356
9 e	0	0	1	1	0	0	0	0	-1.38762	149.83	2.759
9 g	0	0	1	0	1	0	0	0	-1.05222	285.135	2.136
9 h	0	0	1	0	1	0	0	0	-1.28036	193.1	2.136
9 i	0	0	1	0	1	0	0	0	-1.41606	138.355	0.712
9 j	0	0	1	0	1	0	0	0	-0.9558	324.035	2.7145
9 k	0	0	1	0	0	1	0	0	-0.95763	323.295	7.387
9 l	0	0	1	0	0	1	0	0	-0.85452	364.895	1.068
9 m	0	0	1	0	0	1	0	0	0.156591	772.795	11.8815
9 n	0	0	1	0	0	1	0	0	-0.99809	306.975	6.8085
9 o	0	0	1	0	0	1	0	0	-0.69735	428.3	3.6045
9 q	0	0	1	0	0	0	1	0	-0.92702	335.645	3.1595

9 r	0	0	1	0	0	0	1	0	-1.17831	234.27	3.8715
9 u	0	0	1	0	0	0	0	0	-1.48722	109.65	7.921
9 v	0	0	1	0	0	0	0	0	-1.35718	162.11	8.633
9 w	0	0	1	0	0	0	0	0	-1.17137	237.07	1.246
9 y	0	0	1	0	0	0	0	0	-0.99229	309.3151	3.916
10 b	0	1	1	1	0	0	0	0	-1.2673	198.37	2.3585
10 c	0	1	1	1	0	0	0	0	-1.57439	74.485	2.0025
10 d	0	1	1	1	0	0	0	0	-0.74396	409.495	12.46
10 e	0	1	1	1	0	0	0	0	-1.46306	119.395	1.2905
10 f	0	1	1	0	1	0	0	0	-0.66622	440.855	1.157
10 h	0	1	1	0	1	0	0	0	-0.26451	602.915	0.801
10 i	0	1	1	0	1	0	0	0	-1.41651	138.175	0.2225
10 j	0	1	1	0	1	0	0	0	-1.26807	198.06	8.2325
10 k	0	1	1	0	0	1	0	0	-1.14341	248.35	1.335
10 l	0	1	1	0	0	1	0	0	-0.61753	460.5	14.774
10 m	0	1	1	0	0	1	0	0	0.096778	748.665	6.2745
10 o	0	1	1	0	0	1	0	0	-1.03987	290.12	1.6465
10 p	0	1	1	0	0	0	1	0	-1.32182	176.375	0.9345
10 q	0	1	1	0	0	0	1	0	-0.37932	556.6	0.5785
10 r	0	1	1	0	0	0	1	0	-0.58062	475.3887	8.8555
10 s	0	1	1	0	0	0	1	0	-0.07338	680.02	7.6985
10 t	0	1	1	0	0	0	1	0	-0.15728	646.175	13.3945

10 v	0	1	1	0	0	0	0	0	-0.81454	381.02	4.6725
10 w	0	1	1	0	0	0	0	0	-0.67977	435.39	4.45
10 x	0	1	1	0	0	0	0	0	-1.09296	268.7	5.518
10 y	0	1	1	0	0	0	0	0	-0.63799	452.2436	1.2015
11 c	1	0	0	1	0	0	0	0	-1.18188	232.83	1.1125
11 d	1	0	0	1	0	0	0	0	-1.17549	235.4085	4.183
11 g	1	0	0	0	1	0	0	0	-1.11141	261.2571	3.471
11 i	1	0	0	0	1	0	0	0	-1.01121	301.68	5.4735
11 j	1	0	0	0	1	0	0	0	-0.9563	323.8329	26.077
11 l	1	0	0	0	0	1	0	0	-1.24224	208.48	9.5675
11 m	1	0	0	0	0	1	0	0	-0.79043	390.75	5.073
11 o	1	0	0	0	0	1	0	0	-0.92883	334.915	4.094
11 p	1	0	0	0	0	0	1	0	-1.0652	279.9	3.115
11 r	1	0	0	0	0	0	1	0	-0.94643	327.815	7.565
11 t	1	0	0	0	0	0	1	0	-1.46268	119.55	1.068
11 u	1	0	0	0	0	0	0	0	-1.23385	211.865	4.895
11 v	1	0	0	0	0	0	0	0	-1.25748	202.331	12.0595
11 w	1	0	0	0	0	0	0	0	-1.11902	258.19	2.0025
11 x	1	0	0	0	0	0	0	0	-1.00581	303.86	8.722
11 y	1	0	0	0	0	0	0	0	-1.31145	180.56	2.7145
12 c	0	0	0	1	0	0	0	0	-1.06969	278.09	2.3585
12 d	0	0	0	1	0	0	0	0	-0.48521	513.88	1.7355

12 g	0	0	0	0	1	0	0	0	-1.1475	246.7	1.157
12 h	0	0	0	0	1	0	0	0	-0.99375	308.725	7.7875
12 i	0	0	0	0	1	0	0	0	-1.1292	254.08	1.2015
12 j	0	0	0	0	1	0	0	0	-0.93456	332.605	3.3375
12 l	0	0	0	0	0	1	0	0	-1.13603	251.325	1.602
12 m	0	0	0	0	0	1	0	0	-1.1665	239.035	2.0025
12 n	0	0	0	0	0	1	0	0	-0.97222	317.41	1.9135
12 o	0	0	0	0	0	1	0	0	-1.3297	173.195	4.4945
12 p	0	0	0	0	0	0	1	0	-1.33942	169.275	2.848
12 q	0	0	0	0	0	0	1	0	-1.15329	244.365	0.801
12 r	0	0	0	0	0	0	1	0	0.05677	732.525	13.617
12 s	0	0	0	0	0	0	1	0	-0.70668	424.535	6.5415
12 t	0	0	0	0	0	0	1	0	-1.24488	207.415	3.471
12 u	0	0	0	0	0	0	0	0	-1.11508	259.78	1.2015
12 v	0	0	0	0	0	0	0	0	-1.51499	98.445	3.3375
12 w	0	0	0	0	0	0	0	0	-0.8517	366.03	6.8975
12 x	0	0	0	0	0	0	0	0	-1.29939	185.4233	10.7245
12 y	0	0	0	0	0	0	0	0	-1.43338	131.37	1.6465
13 a	0	1	0	1	0	0	0	0	-1.27604	194.845	4.272
13 b	0	1	0	1	0	0	0	0	-1.37897	153.32	9.701
13 c	0	1	0	1	0	0	0	0	-1.17888	234.04	6.408
13 d	0	1	0	1	0	0	0	0	-0.74954	407.245	4.3165

13 f	0	1	0	0	1	0	0	0	-1.00438	304.435	9.968
13 g	0	1	0	0	1	0	0	0	-1.32028	176.995	5.963
13 h	0	1	0	0	1	0	0	0	-1.15878	242.15	15.575
13 i	0	1	0	0	1	0	0	0	-0.74799	407.87	9.2115
13 j	0	1	0	0	1	0	0	0	-0.80894	383.28	14.5515
13 k	0	1	0	0	0	1	0	0	-1.31566	178.86	7.6985
13 l	0	1	0	0	0	1	0	0	-0.48105	515.56	19.491
13 m	0	1	0	0	0	1	0	0	-1.38227	151.99	47.615
13 o	0	1	0	0	0	1	0	0	-1.26922	197.595	57.8055
13 p	0	1	0	0	0	0	1	0	-1.47852	113.16	6.853
13 r	0	1	0	0	0	0	1	0	-1.29576	186.89	4.272
13 s	0	1	0	0	0	0	1	0	-1.05959	282.165	5.607
13 t	0	1	0	0	0	0	1	0	-0.49303	510.725	17.6665
13 u	0	1	0	0	0	0	0	0	-0.69401	429.645	16.5985
13 v	0	1	0	0	0	0	0	0	-1.32396	175.51	63.368
13 w	0	1	0	0	0	0	0	0	-0.54887	488.1982	44.411
13 x	0	1	0	0	0	0	0	0	-0.75499	405.045	10.9915
13 y	0	1	0	0	0	0	0	0	-0.71242	422.22	46.28

Linear regression was performed on each data set using STATA software.

regress StrengthN dia FlyAsh

The above line does a linear regression with StrengthN being the dependent variable and dia and FlyAsh being the independent variables. The command gives the output shown in Figure E.1.

Source	SS	df	MS			
				Number of obs	=	254
				F(2, 251)	=	12.74
Model	8077.53877	2	4038.76938	Prob > F	=	0.0000
Residual	79601.3857	251	317.136995	R-squared	=	0.0921
				Adj R-squared	=	0.0849
Total	87678.9245	253	346.557014	Root MSE	=	17.808

StrengthN	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
dia	.0136428	.002776	4.91	0.000	.0081755	.01911
FlyAsh	2.312096	2.235453	1.03	0.302	-2.09054	6.714732
_cons	4.460207	2.501628	1.78	0.076	-.4666494	9.387063

Figure E.1 STATA output two independent variable analysis

The number of independent variables was increased for subsequent models to find the best fit model. As the number of independent variables are increased, the effects of interactions was also evaluated to see how they impact the model.

Below is a regression input statement for a regression model considering interaction between Fiber and FlyAahs and interaction between Fiber and dia.

regress StrengthN FlyAsh wc42 bed20 bed30 bed40 bed50 Fiber Fiber##FlyAsh Fiber##c.dia

The ## tells Stata to evaluate the interactions between the two variables. For the case Fiber##FlyAsh, these two variables are categorical variables and are coded as such. The statement Fiber##c.dia is for checking the interaction between the categorical variable Fiber and the continuous variable dia. The c. must be added to the continuous variable name for Stata to properly perform.

The results of this linear regression are shown in Figure E.2.

Source	SS	df	MS			
Model	23555.5151	10	2355.55151	Number of obs	=	254
Residual	64123.4095	243	263.882343	F(10, 243)	=	8.93
				Prob > F	=	0.0000
Total	87678.9245	253	346.557014	R-squared	=	0.2687
				Adj R-squared	=	0.2386
				Root MSE	=	16.244

StrengthN	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
FlyAsh	-5.62586	3.096537	-1.82	0.070	-11.72534	.4736187
wc42	3.81805	2.196315	1.74	0.083	-.5081952	8.144294
bed20	-10.52188	3.307881	-3.18	0.002	-17.03765	-4.006096
bed30	-9.204602	3.192249	-2.88	0.004	-15.49261	-2.916591
bed40	-.4823539	3.214785	-0.15	0.881	-6.814755	5.850047
bed50	-1.959485	3.161726	-0.62	0.536	-8.187372	4.268403
Fiber	23.12891	8.503569	2.72	0.007	6.378799	39.87902
1.Fiber	0	(omitted)				
1.FlyAsh	0	(omitted)				
Fiber#FlyAsh						
1 1	14.56382	4.143888	3.51	0.001	6.401293	22.72634
dia	.0055356	.010242	0.54	0.589	-.0146387	.02571
Fiber#c.dia						
1	-.0198305	.0125415	-1.58	0.115	-.0445346	.0048735
_cons	11.71873	4.049866	2.89	0.004	3.741411	19.69606

Figure E.2 STATA output eight independent variable analysis with interactions

The regression model was taken one step further by using stepwise regression to help build a model.

stepwise, pe(0.1) forward: regress ln_strength FlyAsh dia Fiber

The above statement tells Stata to perform a forward stepwise linear regression with ln_strength being the dependent variable and FlyAsh, dia, and Fiber being the independent variables. Stata will automatically add variables that have a p-statistic < 0.1 which gives us a 90% confidence interval.   Figure E.3 shows the results for the stepwise regression.

```
p = 0.0000 <  0.1000  adding  Fiber

      Source |       SS           df       MS      Number of obs   =       254
-------------+----------------------------------   F(1, 252)       =     68.11
       Model |  76.9602186         1  76.9602186   Prob > F        =    0.0000
    Residual |  284.762151       252  1.13000854   R-squared       =    0.2128
-------------+----------------------------------   Adj R-squared   =    0.2096
       Total |   361.72237       253  1.42973269   Root MSE        =     1.063

------------------------------------------------------------------------------
 ln_strength |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       Fiber |   1.106709   .1341039     8.25   0.000     .8426022    1.370816
       _cons |   1.451515   .0995608    14.58   0.000     1.255438    1.647593
------------------------------------------------------------------------------
```

Figure A.1   STATA output for stepwise regression

Note that the only independent variable that was significant is Fiber.

The following code is used to run a linear regression model.

regress ln_strength FlyAsh wc42 wc49 bed20 bed30 bed40 bed50 Fiber Fiber##FlyAsh

The following code is used to visually display the interaction between the variables Fiber and FlyAsh.

margins r.Fiber@FlyAsh, plot

which the graph shown in Figure 3.18 that shows interaction between Fiber and FlyAsh.

The last point to consider is residuals. The plot of the residuals should be close to a normal distribution. To check this with Stata, the following commands were used.

Predict e, resid

This will generate the residuals for a given linear regression model and save the residuals to a variable called “e”. Any name can be used for the variable name.

After the residual variable is created the following command is used to plot the residuals.

histogram e, kdensity normal

The above command creates a histogram and smooth distribution curve for the residuals and overlays a normal distribution curve. This will the comparions of the residuals distribution to a normal distribution.

APPENDIX F

ADDITIONAL GRAPHS

Appendix F contains additional graphs based on the collected data. These graphs are provided to expand on the discussion found in the chapters.

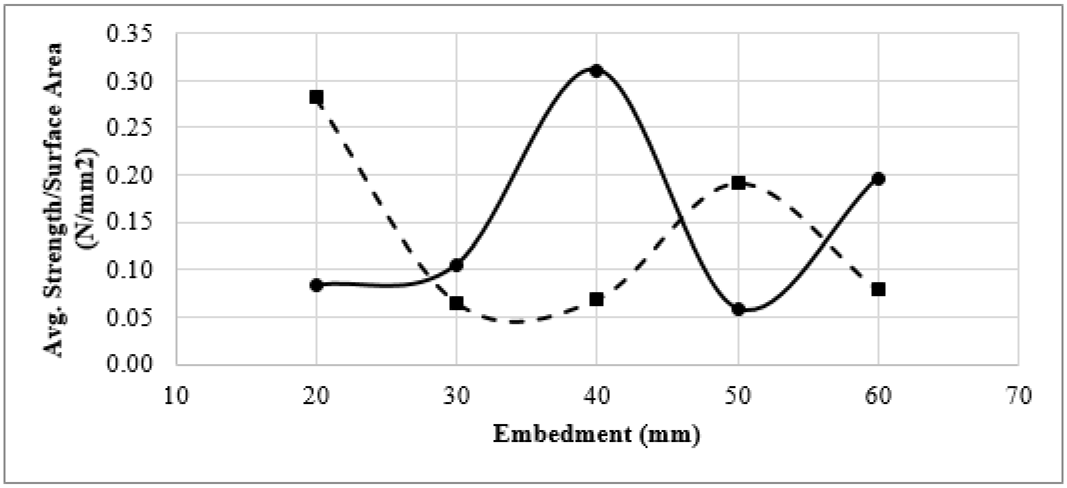

Figure F.1 Macro hemp fiber – 0.66 w/c ratio mix – load/surface area vs embedment length

Solid lines are mixes without fly ash. Dashed lines are mixes with fly ash.

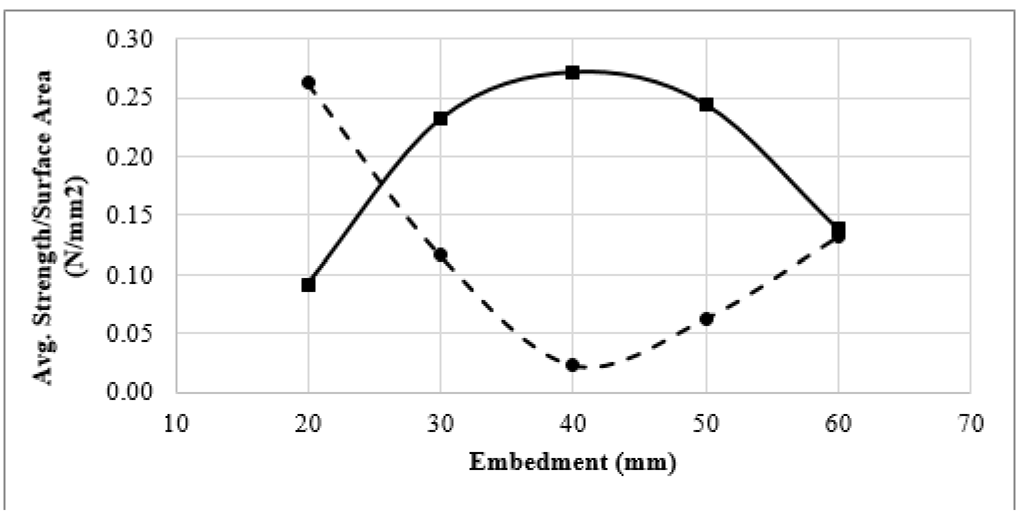

Figure F.2 Hemp macro fiber – 0.49 w/c ratio mix – load/surface area vs embedment length

Solid lines are mixes without fly ash. Dashed lines are mixes with fly ash.

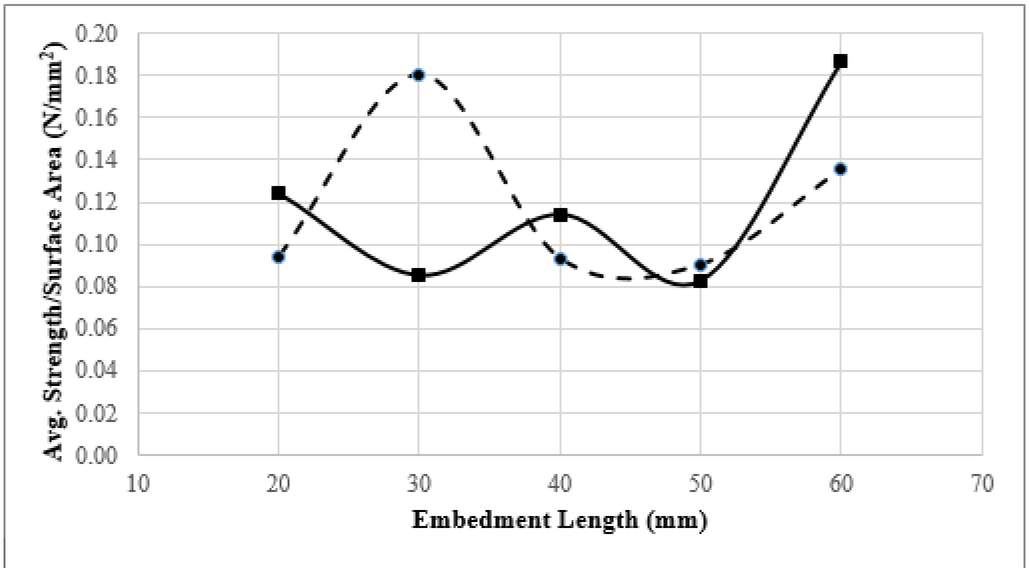

Figure F.3 Hemp micro fiber – 0.66 w/c mix – load/surface area vs embedment length

Solid lines are mixes without fly ash. Dashed lines are mixes with fly ash.

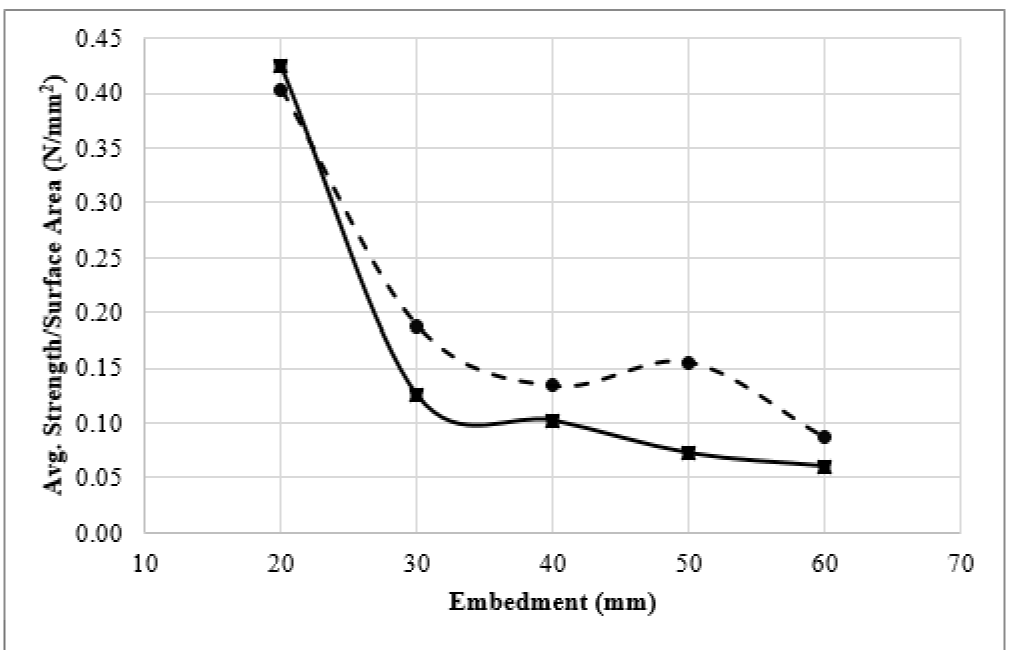

Figure F.4 Hemp micro fiber – 0.49 w/c ratio mix – load/surface area vs embedment length

Solid lines are mixes without fly ash. Dashed lines are mixes with fly ash.