SOUTHERN PLAINS
TRANSPORTATION CENTER

Cotton-Derived Composite Materials for Climate Resilient Transportation Infrastructure

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16.ABSTRACT

This report summarizes the results of completed project entitled “Cotton- Derived Composite Materials for Climate Resilient Transportation Infrastructure”. Here, we aimed to develop high performance and economically facile natural fiber-reinforced transportation infrastructure.The main three tasks of this project include: (1) preparation of cotton cellulose-based concrete; (2) characterization of cotton cellulose-based concrete for strength and durability; and (3) investigation of possible enhancement of other pavement materials through the use of cotton fiber and its derivatives.

The results showed that the tensile strength and modulus values of cotton-derived concrete composites after 28 days are comparable with the control specimens without added cotton. The composite materials prepared from cotton and its derivatives also showed high load endurance properties with high ductility values as compared to control samples, which are extremely crucial in climate resiliency. The data collected in this research also demonstrated the high load resistance and elastic deformation properties of other cotton cellulose-derived particulate composites such as flowable fluids, and geopolymers. Moreover, the addition of raw cotton to highly plastic swelling clay significantly reduced the swell potential.

Overall, using renewable natural fibers mainly cotton and its derivatives, we demonstrated that the properties of conventional construction infrastructure can be adapted to climate change. Therefore, the results of this project are extremely promising. Importantly, the simplicity of the preparation method, relative abundance, and low cost of cotton fibers, make this technology an attractive approach worthy of being further investigated.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised March 2003)

Acknowledgements

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Cotton-Derived Composite Materials for Climate Resilient Transportation Infrastructure

Final Report

August 2018

by

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INTRODUCTION

PROBLEM STATEMENT

The intensity and the frequency of extreme climate events are projected to increase over the next 50 to 100 years [1]. Specifically, in the southern plains region of the United States, long durations of heat waves, floods, hurricanes, poor soil conditions and freezing winters have created detrimental effects on the transportation infrastructure. Transportation infrastructure is already vulnerable to the prevailing climate change. The future climate variability will increase these vulnerabilities; hence, maintaining safe and efficient infrastructure is likely to become more challenging. Disruptions to civil infrastructure cause significant impacts to land-based transportation including increased wear and tear on roadways and bridges, delays caused by increased traffic congestion, property damage from accidents, fatalities and injuries that impact the productivity of the U.S. economy, energy usage and public safety. Furthermore, increased traffic congestion and funding constraints experienced in transportation agencies for construction, maintenance, rehabilitation, and preservation of infrastructure aggravate these weather-related impacts on transportation infrastructure. Therefore, development of novel road construction materials including concrete with high strength and toughness to withstand local weather and climate change is of significant interest.

Cellulose and its derivatives have been extensively used for diverse applications. Especially, the low molecular weight (MW) acid hydrolyzed derivatives of cellulose including microcrystalline cellulose (MCC) and nanocrystalline cellulose (NCC) have been recently investigated for developing composite materials with enhanced properties. In this project, we tested both long-chain cotton cellulose fibers with high MW and short-chain cotton-derived MCC with low MW as reinforcing materials to enhance the mechanical properties of cementitious materials including tensile strength, load resistance capacity, and crack resistance. These cotton fiber-cementitious composites have the potential to effectively serve as an alternative to conventional construction materials while significantly enhancing the construction, maintenance, rehabilitation, preservation, and sustainability of infrastructure.

Materials prepared from natural polymers such as cellulose are gaining considerable attention for construction, energy, biomedical and many other applications where biocompatibility and biodegradability are of paramount importance. Therefore, the overall goal of this project was to prepare economically feasible and environmentally benign cotton fiber derived concrete composites with enhanced mechanical and structural properties. Furthermore, we investigated possible applications of cotton derived products in the pavement construction. The results reported in this project provide valuable insights into future research initiatives in preparing various natural polymer-based concrete composite materials that are resilient to extreme weather conditions.

BACKGROUND

In this section, an overview of the effect of extreme climate events on transportation infrastructure, concrete materials, cellulose and its derivatives are discussed.

The effect of climate change on transportation infrastructure:
Climate change is predicted to increase over the next 50 years with increases in summer temperatures, rising sea levels, changing rainfall patterns, more frequent extreme weather events such as droughts, floods, hurricanes, poor soils and freezing winters. These drastic temperature variabilities, severe precipitations, and flash flooding may result in damage to rail systems, roads, bridges, and vehicles that use them, and may consequently impact the productivity of the U.S. economy, energy usage, and public safety. The U.S. economy relies on the personal and freight mobility provided by the country’s wide transportation networks. For example, the estimated value of U.S. expenditures including construction, maintenance and preservation of transportation infrastructure in 2010 was over $4 trillion. States of Texas and Oklahoma also spend approximately $9 billion annually to maintain transportation infrastructure due to recent severe weather changes.

Concrete materials:
Concrete is one of the world’s most widely used construction materials; it is a particulate composite comprised of coarse and fine aggregate held together by a binder of cementitious paste. Cements are mostly lime-based such as Portland cement and calcium aluminate cements. Asphalt is also a type of cement frequently utilized in road constructions. Concrete possesses very low tensile strength, limited ductility, and little resistance to cracking, and therefore may undergo internal micro-cracks. These micro-cracks result in the brittle failure of concrete. Moreover, concrete is also vulnerable to climate changes and extreme temperature fluctuations, which may impair the performance of major infrastructure systems such as bridges, highways, or buildings. Temperature fluctuations cause curling, warping, and thermal-expansion stresses within concrete, resulting in the formation of cracks. The deterioration rate of concrete depends on material composition, construction processes, and also is influenced by climate change. Therefore, reinforcing materials are added to concrete in order to improve the mechanical and structural properties. Fibers such as carbon, steel, and fiberglass are commonly added as reinforcing materials to enhance the mechanical properties of concrete. These fibers provide a desirable balance between the mechanical, physical, and durability characteristics when mixed with concrete. While the primary thrust in this project was to investigate the potential enhancement of Portland cement concrete through incorporation of cotton cellulose derived products, we also studied the improvements of other construction materials such as flowable mixtures, asphalt concrete, and stabilized soil subgrade through incorporation of cotton cellulose and its derivatives.

Cellulose-derived MCC:
Cellulose is the most ubiquitous and abundant natural polymer on earth and is widespread in plants, bacteria, marine algae and other biomasses. It is the main constituent of the plant cell wall. Cellulose is structurally similar to starch and has a basic molecular formula of $C_6H_{10}O_5$ as determined by elemental analysis [2]. The main sources of cellulose include wood, cotton, flax, hemp, jute, ramie, and bacteria.

Cellulose incorporates excellent properties such as biocompatibility, biodegradability, nontoxicity, low cost, low density, high stiffness, thermal and mechanical stability and good sorption properties. These properties make cellulose a good choice for preparing high-performance materials with desirable functionalities in structures.

The total annual worldwide production of cellulose is estimated to be between 10 to 100 billion tons and only about six billion tons of that is used by textile, paper, material and chemical industries [3-5]. By far, the most commercially exploited natural resources containing cellulose are wood and cotton [2, 4]. The cellulose content usually accounts for 40-45 percent of wood with a degree of polymerization (DP) values in the 300-1700 range, and almost 100 percent of cotton with DP values in the 8000-15000 range [2, 6, 7]. In recent years, the annual production of cotton has increased from 23 to 25.5 million tons per year, which is about one third of the global market of textile fibers [8, 9]. According to USDA Crop Production Summary 2017, the U.S. annual gross cotton production in year 2016 was approximately 4.1 million tons, and the state of Texas has produced approximately1.9 million tons of cotton last year, taking the lead in cotton production. In addition, Texas Tech University (TTU) is located in an area that is home to one of the greatest areas of concentrated cotton production in the world. During the various stages in the process of converting cotton fibers into yarn and then yarn into fabric, about 1/3 of cotton is discarded as waste due to fiber immaturity, short fiber length, lower fineness, and poor quality [8, 9]. Generally, used clothes and other cotton scraps from textile industries are either landfilled or incinerated without being further used [8, 9]. These disposing methods now have created a serious environmental concern mainly due to the contamination of soil and natural water sources [10]. Therefore, attempts have been made to recycle or to convert these waste materials into value-added products for both environmental and economic aspects [10-14]. Moreover, the main ingredient of cotton fiber is cellulose. One of the more effective ways for recycling waste cotton materials is extracting low MW cellulose fibers such as microcrystalline cellulose (MCC) and nanocrystalline cellulose (NCC) (also called as cellulose nanofibers (CNF) or cellulose nanocrystals (CNC)) from waste cotton materials [15]. Low MW cellulose fibers can be also derived from acid hydrolysis of long chain native cellulose, giving rise to highly crystalline and rigid nanoparticles [16]. Both MCCs and NCCs are typically rigid rod-like crystals with a degree of polymerization (DP) in the range of 10–20 nm and lengths in the range of 100-1000 nm [16]. Low MW derivatives of cellulose, including MCC and NCC, have attracted considerable attention in recent years due to their unique properties including high surface area-to-volume ratio, high Young's modulus, high tensile strength and low coefficient of thermal expansion. The high axial Young's modulus of NCC is close to the one derived from theoretical chemistry and potentially stronger than Kevlar [17]. There is scant information about the utilization of low MW MCC and NCC as reinforcing fibers to increase the toughness of brittle concrete materials [18, 19].

OBJECTIVES

In this project, we prepared cellulose-concrete composites derived from raw cotton and used them as reinforcing fiber materials to improve mechanical properties and durability of concrete. The testing related to the mechanical properties of the cotton fiber derived-concrete composites was conducted in the Department of Civil Engineering at Texas Tech University. The specific goals of this project were as follows:

Aim 1: Prepare particulate concrete composites with cotton cellulose and its derivatives.
Aim 2: Investigate the mechanical properties of composite materials prepared in Aim 1.
Aim 3: Investigate possible enhancement of particulate composite materials with the use of raw cotton cellulose and its derivatives.

SCOPE

While cellulose is considered the most abundant macromolecule on earth, it is only recently that attention has been devoted to explore the potential of this biopolymer to prepare various composite materials for advanced construction applications. Therefore, the main goal of this project was to prepare cotton fiber derived-concrete composites for potential construction applications.

The results obtained from this work pave the way for a renewable approach in preparing climate adaptive transportation and freight infrastructure. The use of natural fibers such as cellulose and its derivatives to reinforce conventional construction materials may significantly enhance the sustainability of infrastructure construction, maintenance, and rehabilitation.

1. EVALUATION OF THE EFFECT OF COTTON CELLULOSE FIBERS ON THE PROPERTIES OF VARIOUS PARTICULATE COMPOSITES

The compressive strength and the load resistance properties of mortar mixes, flowable fill mixes, concrete, geopolymers and clay in the presence and absence of waste raw cotton (RC) and treated cotton (TC) were investigated. Following is a detailed discussion of the results obtained**.**

1.1. Water Absorbency of Crushed Raw Waste and Crushed Treated Cotton

Both raw waste cotton (RC) and treated cotton (TC) were crushed using a Wiley mill, in order to achieve cotton fiber of 0.9 mm length. Due to the hydrophilicity of cotton, it was necessary to determine the amount of water absorbed by the cotton in water prior to the testing with concrete. RC and TC samples were previously dried in an oven at 80°C for 24 h, weighed and left suspended in a water beaker overnight and weighed again to determine the water adsorbed by each one (see Figure 1). Figure 1 shows the RC (left) and TC (right) in water. The colors of RC and TC are light brown and white, respectively. TC has a white color due to the removal of non-cellulosic materials including lignin, hemicellulose, wax, pectin, proteins, and oil during the scouring and bleaching treatment.

Figure 1. Water Absorbency of: Left-Crushed Row Cotton, Right-Crushed Treated Cotton

Our results indicated that raw crushed cotton has 727.5 percent and treated crushed cotton has 970 percent water absorbance with respect to the weight of cotton. Therefore, it is necessary to add extra water to the cement mixture to avoid reduction in cement hydration due to water absorbency of cotton. Figure 2 shows cotton mixed mortar specimens with no extra water. In the absence of extra water, cotton mixed mortar specimens show a large amount of voids and a less integrated structure due to the lack of adequate hydration of cement.

Figure 2. Cotton Mixed Mortar Specimens with No Extra Water

1.2 Mortar Mixes

All tests were conducted using two-inch by two-inch by two-inch mortar specimens made according to ASTM C109/C109M-16a, and three replicates were made for all mixes. A loading rate of 0.01 in/min was used in testing the specimens.

In order to test the water absorbency of cellulose, mortar specimens with crushed waste raw or crushed treated cotton (5 percent, with regard to the cement weight) and excess amounts of water (250 percent, 500 percent, 750 percent, 1000 percent and 1250 percent with regard to the weight of cotton) were prepared. The mixing proportions are shown in Table 1.

Table 1. Mortar Mixes with RC5 or TC5 (5percent, with regard to cement weight) with different excess water percent with regard to cotton weight)

Material	**Control**	**250%**	**500%**	**750%**	**1000%**	**1250%**
Cement (g)	237.50	237.50	237.50	237.50	237.50	237.50
River Sand (g)	653.13	653.13	653.13	653.13	653.13	653.13
Water (g)	115.19	146.44	177.69	208.94	240.19	271.44
Crushed cotton (g)	12.50	12.50	12.50	12.50	12.50	12.50

Note: 5% cotton w.r.t cement weight was added by replacing cement.

The compressive strength results showed that, for RC the optimum excess water content was around 500 percent and for TC it was around 250 percent with regard to the cotton weight. Figure 3 shows compressive strength of the mortar samples against various excess water percentages ranging from 0 to 1200percent.

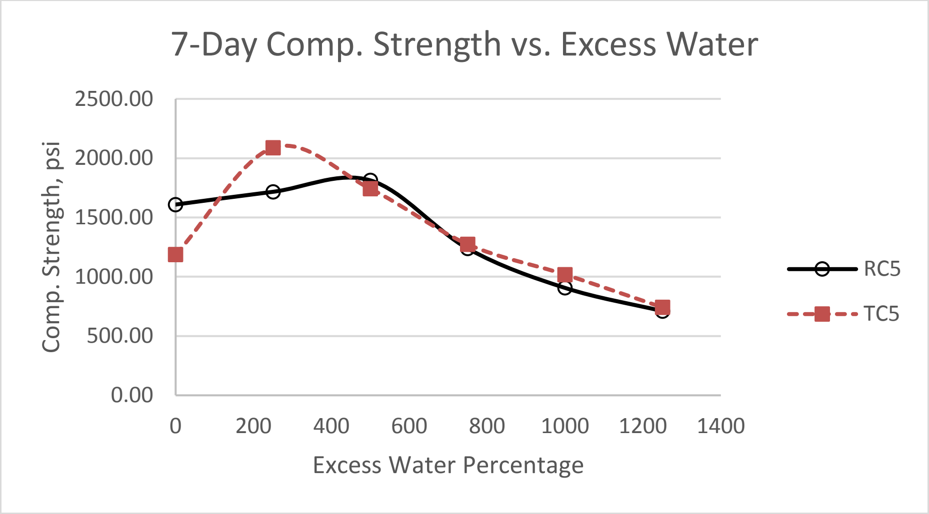

Figure 3. 7-Day Compressive Strength of Cotton (5%)-Mortar Specimens with Excess Water

Compressive strength tests were also conducted with varying cotton and excess water contents. Figure 4 exhibits the stress-strain curves for mortar samples prepared using three different percentages of cotton (2, 5 and 10 percent) and two different excess water contents (250 percent and 500 percent). The mortar sample (RC2-250) prepared from two percent crushed waste RC and 250 percent excess water showed the maximum compressive strength over other cotton added mortar specimens as shown in Figure 4. However, the control mortar sample without any added cotton showed the highest compressive strength after seven days (See Figure 4).

Figure 5 shows images of the control mortar sample and the mortar sample (RC2-250) prepared from two percent crushed waste RC and 250 percent excess water after failure. Even though the cotton added mortar samples showed lower strength values, they did not show an abrupt failure with increasing stress, indicating their ability to absorb high energy (See Figure 5). In contrast, the control mortar sample without any added cotton failed abruptly after reaching the peak strength (See Figure 5).

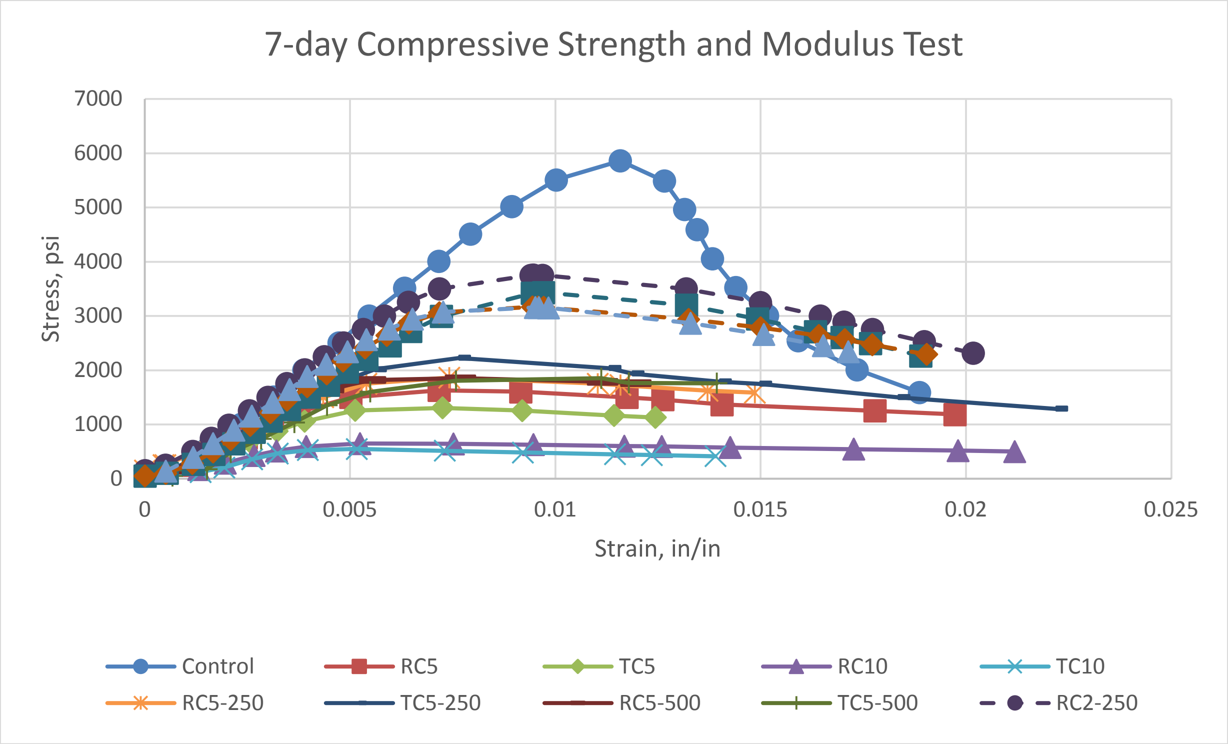

Figure 4. 7-Day Stress-Strain Curves for Different Mortar Mixes

Figure 5. Mortar Specimens after Failure; Left-Control, Right-With RC2%

Next, we tested the candidate mix of two percent crushed cotton (with regards to the cement weight) with 250 percent excess water, by replacing the sand with cement (see Table 2), and the results showed a slight increase in the average compressive strength. The mixing proportions for the mortar mixes when replacing sand by crushed RC and TC are shown in Table 2.

Table 2. Mortar Mixes with Replacing Sand by RC and TC with Excess Water

Material	TC2-250	RC2-250
Cement (g)	250.00	250.00
River Sand (g)	682.50	682.50
250 % Water (g)	133.75	133.75
2% Cotton (g)	5.00	5.00

Note: Two percent cotton with regards to cement weight was added by replacing sand.

Mortar mixes were also prepared by keeping the standard cement to sand ratio constant and adding excess water and two percent cotton (with regards to cement weight) separately to the mix as shown in Table 3. However, we did not see a significant increase in the compressive strength as compared to the cotton-mortar mixes prepared by replacing sand with cotton (data not shown).

Table 3. Mortar Mixes with RC and TC and Excess water (250 percent, with regards to cotton weight)

Material	TC2-250	RC2-250
Cement (g)	250.00	250.00
River Sand (g)	687.50	687.50
250% Water (g)	133.75	133.75
2% Cotton (g)	5.00	5.00

Note: Two percent cotton with regards to cement weight was added without replacing sand or cement.

We also tested the mortar mixes of two percent crushed cotton with 250 percent excess water, by adding crushed cotton separately to the control mix (see Table 4) with manufactured sand (MF). The results showed an increase in the average compressive strengths for both RC and TC and were comparable to the control mortar sample. The maximum compressive strengths for the two percent RC-mortar, two percent TC-mortar and control mortar samples are 4640, 4240 and 5642 psi, respectively. These results show that the compressive strength of the cotton-mortar specimens is greatly affected by the source of the sand.

Table 4. Mortar Mixes Adding RC and TC with Excess Water

Material	Control MFS	TC2+MFS-250	RC2+MFS-250
Cement (g)	250.00	250.00	250.00
MF Sand (g)	687.50	687.50	687.50
250 %Water (g)	121.25	133.75	133.75
2% Cotton (g)	0	5.00	5.00

Note: Two percent cotton w.r.t cement weight was added without replacing sand or cement.

1.3 Flowable Fill Mixes

All tests were conducted using three-inch by six-inch flowable fill specimens made according to ASTM standards, and three replicates were made for all mixes. A loading rate of 0.05 in/min was used in testing the specimens.

Flowable fill specimens with different percentages of RC (0.2, 0.5, 1, 2 and 5 percent) with regards to the cement weight was added to the control mix with 250 percent excess water with regards to the weight of cotton. The mixing proportions are shown in Table 5.

Table 5. Flowable Fill Mixes Adding RC with Excess Water

Material	RC5-250	RC2-250	RC1-250	RC0.5-250	RC0.2+-250
250 % Water (g)	1107	1033	1008	996	988
Cement (g)	247	247	247	247	247
Fly Ash class C (g)	743	743	743	743	743
River Sand (g)	3908	3908	3908	3908	3908
Cotton (g)	50	20	10	5	2

Figure 6 shows the plot of compressive strength of the flowable mixtures against added cotton percentage ranging from zero to five percent. Among all cotton added flowable mixes, the flowable mixture with two percent RC cotton showed the highest compressive strength. However, the control sample without any added cotton showed maximum compressive strength after seven days (see Figure 6).

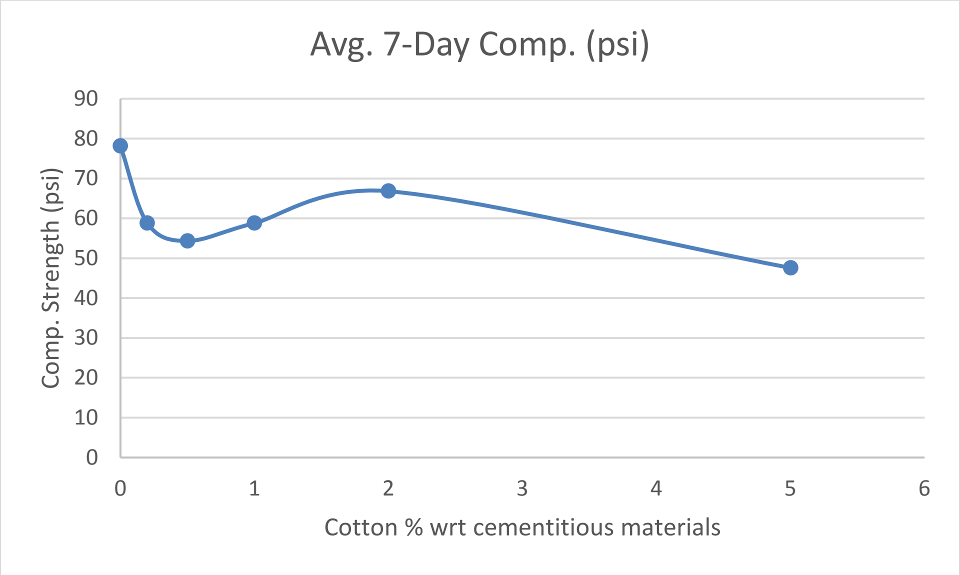

Figure 6. 7-Day Compressive Strength of Flowable Fill with Cotton Content

The effect of excess water on the flowable mixtures with two percent cotton was also investigated. The flowable fill specimens with two percent of RC with regards to the cement weight was added to the control mix with different percentages of excess water (0, 100, 200, 300 and 400 percentage) with regards to the weight of cotton. The mixing proportions are shown in Table 6.

Table 6. Flowable Fill Mixes adding RC with Excess Water

Material	**RC2**	**RC2-100**	**RC2-200**	**RC2-300**	**RC2-400**
Water (g)	983	1003	1023	1043	1063
Cement (g)	247	247	247	247	247
Fly Ash class C (g)	743	743	743	743	743
River Sand (g)	3908	3908	3908	3908	3908
2% Cotton (g)	20	20	20	20	20

Note: 2% cotton w.r.t cement weight was added without replacing sand or cement.

Figure 7 displays the plot of compressive strength versus excess water content for the flowable fill mixtures prepared from two percent RC. The compressive strength results showed that two percent RC with no excess water was the best candidate as shown in Figure 7, indicating that no extra water is required in the preparation of cotton-flowable fill mixtures.

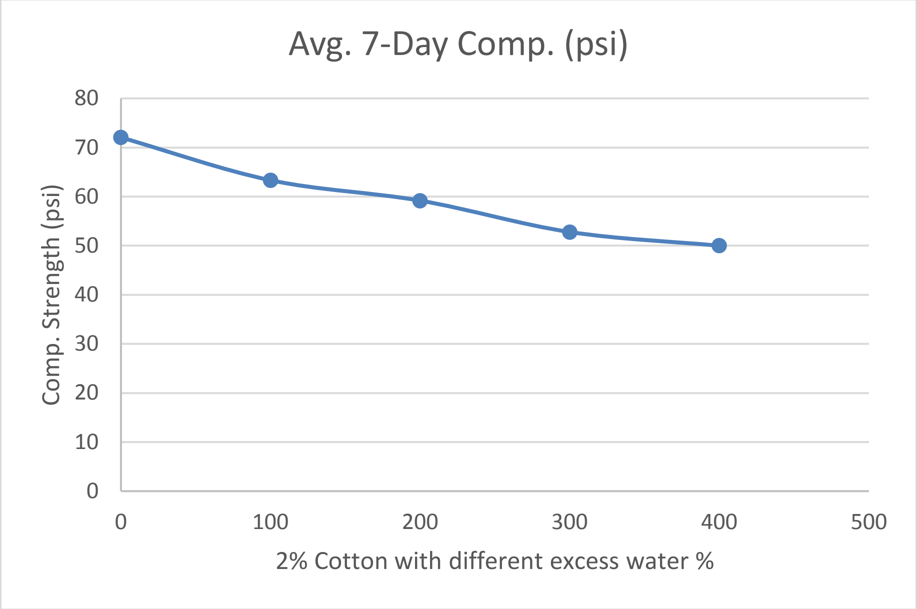

Figure 7. 7-Day Compressive Strength of Flowable Fill with Excess Water

The effect of the manufactured sand (MF) on the compressive strength was also tested using the flowable mix of two percent RC with no excess water. Our results showed a significant increase in the average compressive strength. The compressive strength of the flowable mixture with two percent raw cotton was 100 psi. Similar to the mortar mixes, the flowable fill specimens with cotton showed a higher load resistance and an elastic deformation as compared to the control specimens without added cotton.

1.4 Concrete Mixes

All tests were conducted using three-inch by six-inch concrete specimens made according to ASTM standards, and three replicates were made for all mixes. A loading rate of 0.05 in/min was used in testing the specimens.

The effect of the amount of water added to the cotton-impregnated concrete specimens was also investigated. The concrete specimens with two percent RC cotton with regards to the cement weight was tested with different excess amounts of water (0, 100, 200, 300, 400, and 500 percent) levels with regards to the weight of RC. The mixing proportions are shown in Table 7.

Table 7. Concrete Mixes adding Two Percent RC with regards to cement with different excess levels of water

Material	RC2+-0	RC2+-100	RC2+-200	RC2+-300	RC2+-400	RC2+-500
Water (g)	484.70	508.29	531.88	555.47	579.05	602.64
Cement (g)	1179.47	1179.47	1179.47	1179.47	1179.47	1179.47
CA (g)	2526.24	2526.24	2526.24	2526.24	2526.24	2526.24
FA (g)	1803.38	1803.38	1803.38	1803.38	1803.38	1803.38
Cotton (g)	23.59	23.59	23.59	23.59	23.59	23.59

The concrete specimen with 300 percent excess water showed the highest compressive strength as shown in Figure 8.

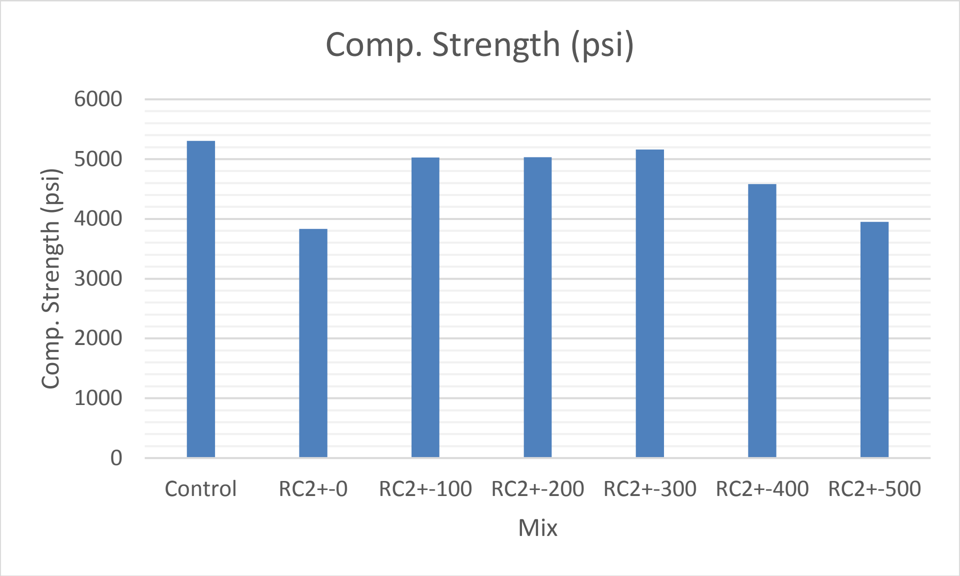

Figure 8. 7-Day Compressive Strength of Concrete with Different Water Levels

Figure 9 shows photographic images of the control concrete specimen and the concrete sample (RC2-300) prepared from two percent crushed waste RC and 300 percent excess water after failure. Similar to mortar and flowable fill mixtures, the concrete specimens with cotton showed elastic deformation with a higher load resistance as compared to the control specimens, as shown in Figure 9.

Figure 9. Concrete Specimens after Failure; Left-Control, Right-With RC2%

1.5 Geopolymer

We also investigated the effect of added cotton fibers on the compressive strength of geopolymers. Figure 10 shows the stress versus strain curves for geopolymer specimens in the presence and absence of cotton fibers. The geopolymer specimen tested with five percent RC showed higher load resistance properties and an elastic deformation compared to the control geopolymer without added cotton fibers (see Figure 10). However, the control sample showed a high compressive strength with an abrupt failure after a certain stress, as shown in Figure 10.

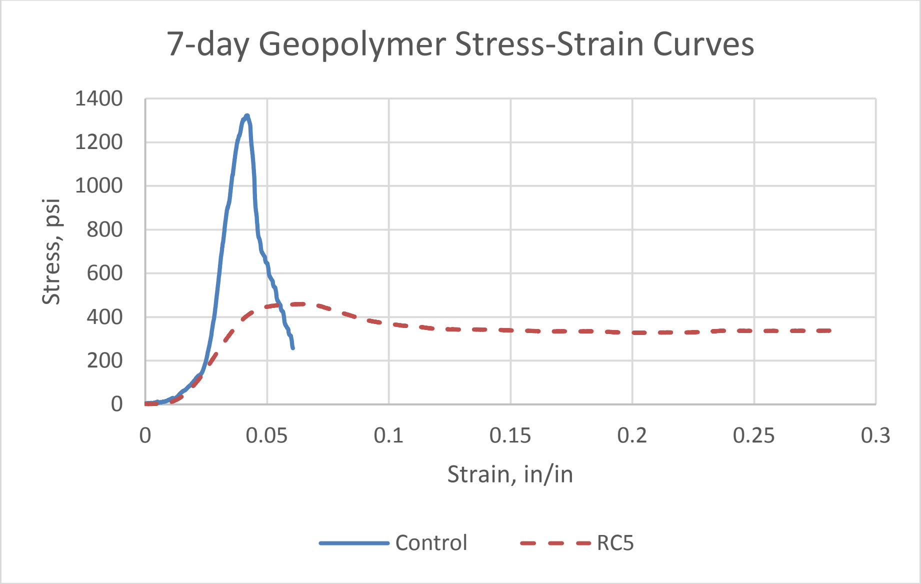

Figure 10. 7-Day Stress-Strain Curve for Geopolymer

1.6 Swelling Clay

Tests were also conducted to investigate the effect of fiber length on clay swelling. Figure 11 shows the percent swelling for plastic swelling clay (control) and RC-clay composite. Results showed that the addition of five percent RC to highly plastic swelling clay significantly reduced the swell potential from 15 percent to three percent (by a factor of five).

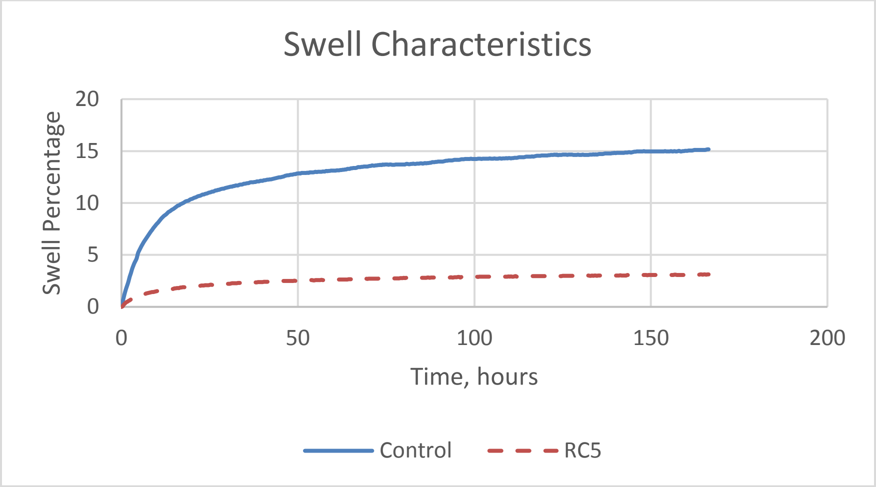

Figure 11. Swelling Characteristics of Clay

2. EVALUATION OF THE EFFECT OF COTTON CELLULOSE FIBER LENGTH ON THE PROPERTIES OF VARIOUS PARTICULATE COMPOSITES

The effect of the fiber length on the compressive strength and load resistance of different particulate composites was also first tested using the long chain cellulose fibers and microcrystalline cellulose (MCC). MCC is a short-chain fiber derived from acid hydrolysis of long-chain cellulose fibers. The typical length of MCC ranges from nanometers to a few hundred micrometers.

2.1 Mortar Mixes

All tests were conducted using two-inch by two-inch by two-inch mortar specimens made according to ASTM C109/C109M-16a, and three replicates were made for all mixes. A loading rate of 0.01 in/min was used in testing the specimens.

Mortar specimens with two different sizes of MCC (50 microns and 90 microns) were used. Mortar specimens were prepared using two percent MCC with regards to the cement weight with different excess amounts of water (250 and 500 percent, with regards to the weight of MCC). The mixing proportions are shown in Table 8.

Table 8. Mortar Mixes with 2% MCC with Excess Water

Material	Control	250%	500%
Cement (g)	245.00	245.00	245.00
River Sand (g)	673.75	673.75	673.75
Water (g)	118.83	131.33	143.33
2% MCC (g)	5.00	5.00	5.00

Note: Two percent MCC with regards to cement weight was added by replacing cement.

Amongst all cellulose-impregnated mortar specimens, the mortar specimen prepared from two percent MCC of 50 micron length with 250 percent excess water showed the highest compressive strength. A comparison of the average compressive strengths of all cellulose (two percent) impregnated mortar specimens tested are shown in Figure 12.

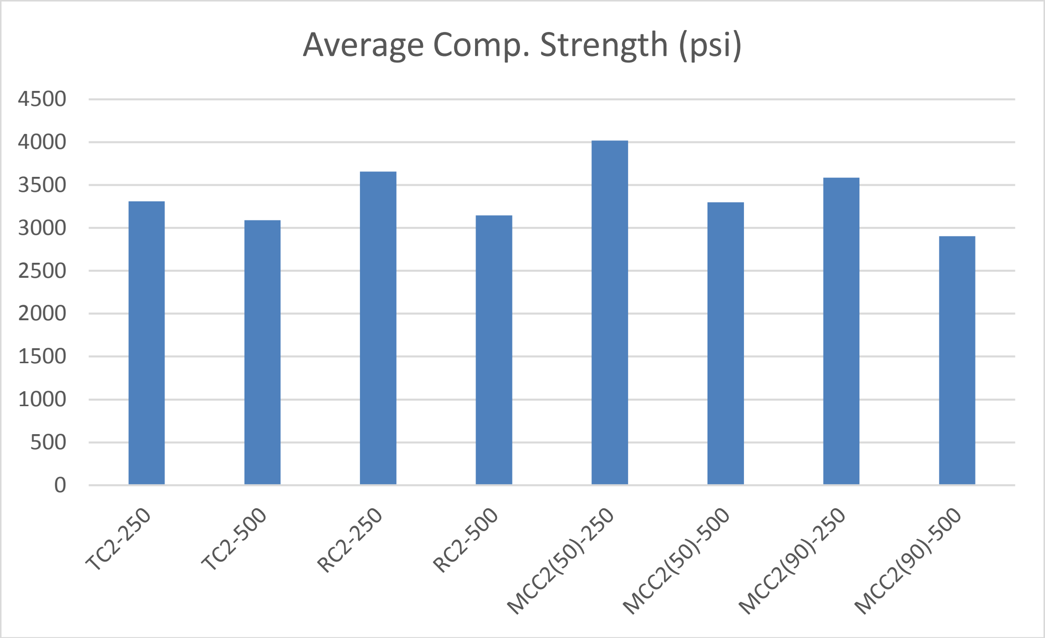

Figure 12. Average 7-Day Compressive Strength of Mortar

We also tested a mortar mix of two percent MCC (50 micron length) with 250 percent excess water, by replacing the sand with MCC instead of cement (see Table 9). The results showed an increase in the average compressive strength with this approach. The compressive strength of this mortar composite was 4209 psi.

Table 9. Mortar Mixes with 2% MCC and Excess Water

Material	MCC2 (50)	MCC2 (50)-250
Cement (g)	250.00	250.00
River Sand (g)	682.50	682.50
250 %Water (g)	121.25	133.75
2% MCC (g)	5.00	5.00

Note: two percent MCC with regard to cement weight was added by replacing sand.

We also tested the effect of manufactured (MF) sand over river sand on the compressive strengths of the MCC added mortar specimens. The mixing proportions are shown in Table 10. The mortar specimen prepared from two percent MCC (50 micron length) and 250 percent excess water along with MF sand showed higher average compressive strength of 4733 psi as compared to similar mortar specimen made of river sand.

Table 10. Mortar Mixes by Adding Two Percent MCC with Excess Water

Material	Control MFS	MCC2+ (50) MFS-250
Cement (g)	250.00	250.00
MF Sand (g)	687.50	687.50
250% Water (g)	121.25	133.75
2% MCC (g)	0	5.00

Note: Two percent MCC with regard to cement weight was added without replacing sand or cement.

Figure 13 shows a comparison of the average compressive strengths of all mortar mixes. The control mortar samples with river sand and manufactured sand showed the highest compressive strengths among all specimens tested. Amongst all fiber added mortar specimens, the mortar mix prepared from MF and two percent MCC (50 micron length) exhibited the highest compressive strength after seven days. Furthermore, our results suggest that the addition of fiber does not improve the compressive strength of the mortar specimens after seven days.

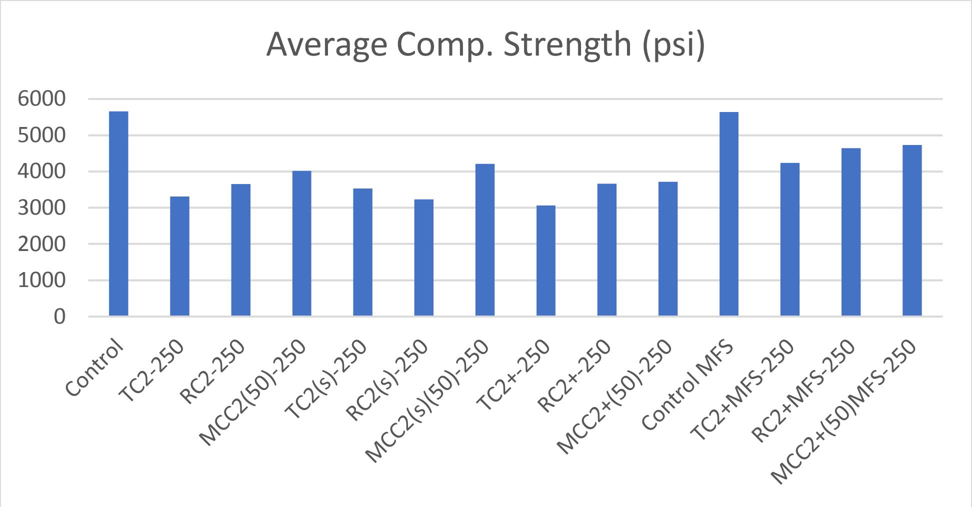

Figure 13. Average 7-Day Compressive Strength of Mortar with MFS

Although mortar specimens with MCC have higher compressive strength values than TC and RC added mortar specimens, they did not show high load resistance and elastic deformation properties. Those specimens showed a brittle failure similar to control specimens. These results suggest that both load resistance and elastic deformation properties are dependent on the fiber length. Therefore, tests were conducted using long-chain cotton cellulose fibers.

2.2 Concrete Mixes

2.2.1 Concrete Mixes with One-Inch Long Raw Cotton (RC) Fibers

The compressive strength of the concrete mixtures with one-inch long waste cotton fibers was investigated. All tests were conducted using three-inch by six-inch concrete specimens made according to ASTM standards, and three replicates were made for all mixes. A loading rate of 0.05 in/min was used in testing the specimens.

Concrete specimens with one percent one-inch waste raw cotton fiber with regards to the cement weight was added on the top of the mix and tested with different excess water (0, 100, 200, 300, 400 and 500 percent with regards to the weight of the fiber). The mixing proportions are shown in Table 11.

Table 11. Concrete Mixes adding 1% 1-inch long RC with Excess Water

Material	**1”1+-0**	**1”1+-100**	**1”1+-200**	**1”1+-300**	**1”1+-400**	**1”1+-500**
Water (g)	484.70	496.49	508.29	520.08	531.88	543.67
Cement (g)	1179.47	1179.47	1179.47	1179.47	1179.47	1179.47
CA (g)	2526.24	2526.24	2526.24	2526.24	2526.24	2526.24
FA (g)	1803.38	1803.38	1803.38	1803.38	1803.38	1803.38
1% 1-inch RC (g)	11.79	11.79	11.79	11.79	11.79	11.79

Figure 14 exhibits compressive strength data for concrete samples with one percent one-inch cotton fiber and varying excess water contents. As can be seen in Figure 14, the concrete sample with one percent one-inch cotton fiber and 100 percent excess water showed the highest compressive strength after seven days.

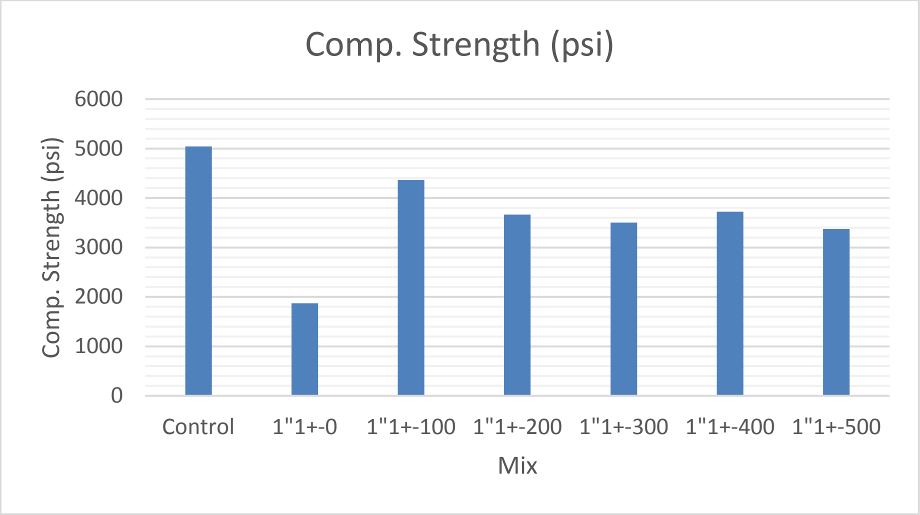

Figure 14. 7-Day Compressive Strength of Concrete with 1-inch fiber with Different Water Levels

Figure 15 shows photographic images of the control concrete specimen and the concrete sample (RC2-300) prepared from two percent crushed waste RC and 300 percent excess water after failure. The fiber-added concrete specimens followed a similar load resistance and elastic deformation properties as discussed earlier (see Figure 15).

Figure 15. Concrete Specimens after Failure; Left-Control, Right-With 1% 1-inch Cotton Fibers

2.2.2 Concrete Mixes with One-Inch Long Twisted Raw Cotton (RC) Fibers

Morphological studies of the concrete samples with one-inch long fibers showed that one-inch long fibers tend to agglomerate in the middle of the mixture and become entangled during the mixing. Therefore, we manually twisted the one-inch long fibers to disperse homogenously and prevent them from subsequent agglomeration and entanglement during the mixing. Figure 16 shows digital images of the manual process of making twisted-cotton fibers.

Figure 16. Process of Making Twisted Cotton Fibers; Left-cotton fibers, Middle-manually twisted fibers, Right-twisted bundle of fibers

All tests were conducted using three-inch by six-inch concrete specimens made according to ASTM standards, and nine replicates were made for this mix. A loading rate of 0.05 in/min was used in testing the specimens.

Concrete specimens with one percent one-inch twisted RC fiber with regards to the cement weight was added on the top of the mix and tested with 100 percent excess water level with regards to the weight of cotton fiber. The mixing proportions are shown in Table 12. The volume of the added cotton with regards to the total volume is 0.25 percent.

Table 12. Concrete Mixes adding One Percent Twisted One-inch RC with excess water

Material	**RCT0.25+-100**
100%Water (g)	1420.84
Cement (g)	3255.34
CA (g)	6972.43
FA (g)	4977.32
1% 1-inch twisted RC (g)	27.69

The average strength results showed an average seven-day compressive strength of 3,907 psi, 28-day compressive strength of 4,308 psi, and 28-day indirect tensile strength of 446 psi. As can be seen in Table 13, the indirect tensile strength values of the control concrete mixes varied significantly from sample to sample. Interestingly, the concrete mixes with cotton showed consistent indirect tensile strength values (see Table 13).

Table 13. 28-Day Indirect Tensile Strength of Concrete Mixes

Specimen	IDT (psi)	Average IDT (psi)
Control-1	320.00	**432.33**
Control-2	452.00	
Control-3	525.00	
RCT0.25+-100-1	443.00	**445.67**
RCT0.25+-100-2	466.00	
RCT0.25+-100-3	428.00	

Figure 17 shows the control concrete specimen and the concrete sample prepared from one percent one-inch twisted RC fiber and 100 percent excess water after failure. The concrete specimens with one percent cotton showed less brittle failure compared to the control specimens as shown in Figure 17.

Figure 17. Concrete Specimens after Failure; Left-Control, Right-With 1% 1-inch Twisted Cotton Fibers

3. ANALYSIS AND DISCUSSION

In this section, project test results are analyzed and discussed.

3.1 Mechanical Properties

Our results suggest that fiber length plays a significant role in determining the load resistance and ductile properties of the particulate composites. The concrete mixes with long fibers (one-inch) show high load resistance and elastic deformation improving the ductile properties. The mortar mixes with shorter fibers (MCC) show high compressive strengths compared to that of long fibers with slightly reduced load resistance and elastic deformation. However, the compressive strength of the particulate composites does not improve after the addition of fibers. The sand type also contributes to the strength of the fiber-added mortar and concrete samples. The samples with manufactured sand showed much higher compressive strengths as compared to the composites made of river sand. The tensile strength of the fiber added concrete samples is consistent compared to the control samples. The addition of fibers to highly plastic swelling clay significantly reduced the swell potential by a factor of 5. The unit weight of all cotton mixed particulate composites is lower than that of the control samples, as shown in Table 14.

Table 14. Unit Weight (lb/ft^3) of Different Composites

Composite	Control	With Cotton	
Mortar	139.12	2%	134.45
		5%	112.56
		10%	97.21
Concrete	148.19	1%	145.62
		2%	136.73
Flowable Fill	133.11	2%	128.73

3.2 Morphological Analysis

Figure 18 shows the morphological analysis for the three mortar samples, namely control sample without added cotton, mortar sample with two percent RC, and mortar sample with short-chain MCC. SEM images of mortar specimens with cotton fibers show that fibers are not dispersed in the cement mixture homogeneously.

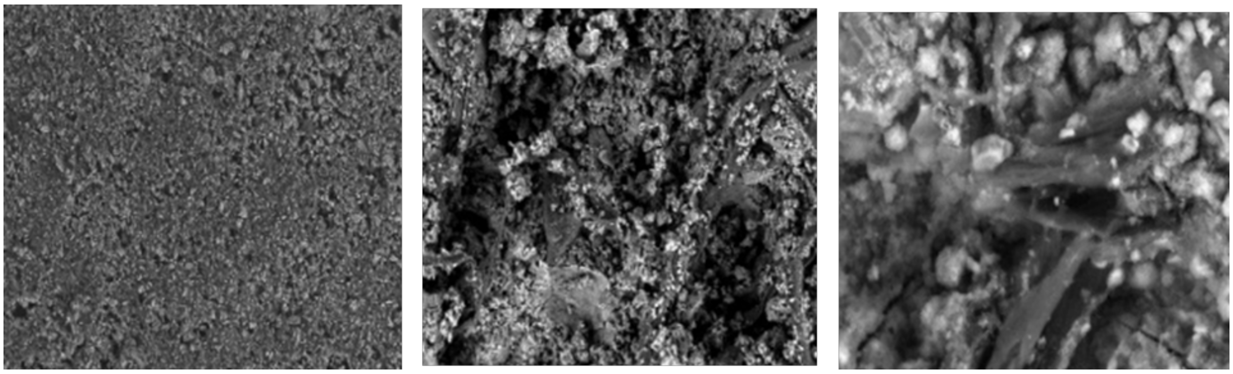

Figure 18. SEM Images of Mortar Specimens; Left-Control, Middle-With 2 % RC, Right-With 2% MCC.

Figure 19 shows SEM images of the cotton-concrete composites. SEM images of concrete with cotton fibers show the formation of cement hydrates on the fiber surface (see Figure 19). This indicates strong interaction between the fibers and cement. Fibers help to hold the composite mix together, which is an important aspect of fiber reinforcement.

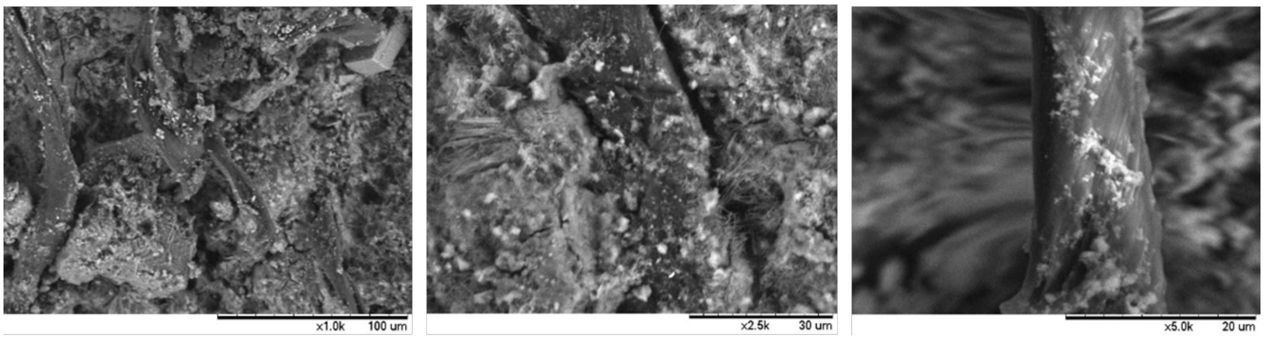

Figure 19. SEM Images of Concrete Specimens; Left-x1K, Middle-2.5K, Right-5K

4. CONCLUSIONS AND RECOMMENDATIONS

The results of this project clearly indicate the potential use of cotton-derived composites for climate resilient transportation infrastructures. The primary benefit in the cotton-derived composites is that it provides enhanced ductility and superior energy-absorbing properties while maintaining the strength and stiffness at acceptable levels. Natural fiber-based composites are also more sustainable environmentally and economically than conventional composites. The findings of this projects are promising and could open a new direction for the utilization of natural fibers in building climate resilient transportation infrastructures.

The recommendations of this project are:

1. One of the main drawbacks of cotton added composites stems from the difficulty to achieve homogenous mixing due to the hydrophilicity of cotton. This can be solved by modifying the fiber surface with a hydrophobic agent or using a homogenizer.
2. The results showed that the fiber length and size also play a major role in controlling the mechanical properties of these composites; therefore, more studies need to be conducted to investigate the effect of fiber properties on the mechanical properties of the composites.
3. The effects of water absorbed by the cotton on cement hydration during the aging process also need to be further investigated.
4. Biodegradation of natural fibers after exposing to outer environment may also needs to be investigated; therefore, longevity and stability of the cotton-added composites need to be examined under different weather conditions.

5. IMPLEMENTATION AND TECHNOLOGY TRANFER

The results indicate that this project could result in invention disclosure. Indeed, cotton and its derivatives (low MW weight fibers) have not been reported to improve the properties and durability of construction materials (concrete and asphalt). The improvements we observed in this project, compared to the conventional construction material is worth protecting. The results also indicate that this project will result in peer-review publication in high impact journals.

6. COST INFORMATION

Matching funds for project 15.3-03 have come primarily from faculty salary, research associate, and the corresponding F&A. A total of $58,985 in matching funds has been reported. Additional matching funds will be reported by Texas Tech’s Office of Accounting Services.

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