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Natural Fibers for Sustainability in Shotcrete Applications

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INTRODUCTION

The global construction industry consumes millions of tons of non-renewable resources every year. Conventional construction materials are known to be produced from sources that require an extremely high energy demand and, therefore, produce a large carbon footprint. The use of renewable, natural fiber resources plays a significant role in the development of eco-friendly building practices.

Natural fibers, derived from sustainable plant sources, have been shown to perform as well as synthetic fibers composed of polypropylene and fiberglass. This reduces the environmental impact of the raw materials, as well as creates a high-performing, robust shotcrete formulation that is resistant to microcracking and physical stress.

BACKGROUND

Microcracking and drying shrinkage present major challenges to the construction industry. When natural fibers are included in the concrete matrix, they can help reduce internal microcracking and contribute to both increased compressive and flexural strength, as well as cement hydration.

Natural fibers have been found in building and construction materials since the dawn of time. These fibers can be from both plant and animal-based sources. History teaches us that the Egyptians used straw and horsehair to produce bricks and other construction materials several thousand years ago. Throughout history, many different types of natural fibers have been used in construction, such as flax, straw, jute, hemp, kenaf, bamboo, cane, horsehair, and wool.

Shotcrete ASTM C 1480	No Fibers	PP 6 mm	PP 12 mm	Fiberglass 13 mm	Hemp 6 mm	Flax 6 mm	Banana 6 mm	Kenaf 6 mm	Kenaf 6 mm-m	Kenaf 12 mm-m	Fique 6 mm	Fique 6 mm-m	Fique 12 mm
Ingredients	%	%	%	%	%	%	%	%	%	%	%	%	%
Cement (Type I/II)	28	28	28	28	28	28	28	28	28	28	28	28	28
Sand	66.922	66.622	66.622	66.622	66.8095	66.772	66.82825	66.847	66.622	66.622	66.7907	66.622	66.7907
Red Microsilica	5	5	5	5	5	5	5	5	5	5	5	5	5
BASF PCE superplasticizer	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
Air entrainer	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
Fiberglass – 13mm				0.3									
Polypropylene – 6 mm		0.3											
Polypropylene – 12 mm			0.3										
Hemp – 6 mm					0.1125								
Flax – 6 mm						0.15							
Kenaf – 6 mm								0.075	0.3				
Kenaf – 12 mm										0.3			
Fique – 6 mm											0.1313	0.3	
Fique – 12 mm													0.1313
Banana – 6 mm							0.09375						
Total	100	100	100	100	100	100	100	100	100	100	100	100	100
Water (Q 12.4-14.6%)	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2

Table 1: Basic shotcrete formulations with respective dosages of fibers

The fiber source of choice was heavily influenced by local availability.

Plant-based fibers consist of two categories: bast and leaf. Bast fibers come from the core of the stalk or stem and are made up of several groups of fiber cells that are extracted from the core. Examples of bast fiber include flax, jute, hemp, and kenaf. Leaf fibers, as expected, come from the leaf of the plant. Examples of leaf fibers include banana, pineapple, and sisal. In recent years, several advances have been made in treating natural fibers to further enhance their physical and mechanical properties, and their benefits in construction.

TESTING

Azelis, a global distributor of specialty chemicals and additives, including MiniFIBERS, had their Construction Solutions Lab investigate using natural fibers in shotcrete. The objective was to understand if the natural fibers could provide comparable properties relative to synthetic fibers when used in shotcrete. If the natural fibers perform similarly, there is a sustainable benefit to using them. Five types of natural fiber (hemp, flax, banana, kenaf, and fique), were evaluated against synthetic fibers of a similar length, which were made of polypropylene and fiberglass. These were also evaluated against a control group, containing no fibers.

Historically, ancient mortars containing natural fibers made of animal hair and plant fibers withstood the environment of mortars over hundreds of years. However, to start the investigation, the potential for the material to degrade in the basic environment of concrete was tested. The natural fibers were subjected to a solution of calcium hydroxide at a pH of 11.5 to determine if they would degrade in the highly alkaline concrete environment. This was done by rinsing the fibers with water over a 325 μm sieve, then drying and weighing them. The fibers were then soaked in the calcium hydroxide solution for 24 hours, and then once again rinsed with water over a 325 μm sieve. Finally, they were dried and weighed. The resulting mass change was only 0.1%, showing that the natural fibers would likely not degrade in the alkaline environment of concrete.

After the initial evaluation to determine the stability of the natural fibers, a formulation was created to test them in shotcreted concrete. This investigation was conducted to understand the impact of MiniFIBERS natural fibers on density, flow, setting time, dimensional stability, and hardened state strength (tensile, compressive, and flexure) properties.

TEST DESIGN

The test system used a basic concrete mortar formulation containing 28% Type I/II cement, 5% RED Industries microsilica, a small dose of BASF Melflux polycarboxylate ether superplasticizer, air entrainer, graded sand, and varying dosages of MiniFIBERS natural fibers, MiniFIBERS polypropylene fibers, and commercially obtained fiberglass fibers. Water was added at a rate of 13.2% based on total dry material weight.

Two additional studies were run to understand the impact of fiber quantity and length on the mortar. Since some fibers were lower in density than synthetic fibers, a set of tests were run to evaluate if the increased volume of fibers would influence the mortar by using a constant weight of fiber, effectively increasing the volume of fibers in the mortar. This could be beneficial to sustainability targets or to lightweight mortar targets. To evaluate the impact on length change, kenaf and fique were used at the lengths of 6 mm (0.25 in.) and 12 mm (0.5 in.). (Table 1)

PLASTIC STATE MORTAR TESTING

Azelis labs evaluated the plastic state properties of MiniFIBERs natural fibers in comparison to a mortar with no fibers, with synthetic fibers composed of fiberglass, and with synthetic fibers composed of polypropylene. Calorimetry, density, air content, and flow were tested.

Calorimetry was evaluated with thermocouples imbedded in insulated and covered mortar samples of equal volume. The calorimetry showed minimal impact on the cement heat of hydration. The peak heat output was very similar in duration and temperature for each type of fiber.

Mortar density testing was performed following ASTM C185 (modified). The results correlated with air measurements. Air content was targeted at 6-8%*. Air content was measured using a 0.026 ft^3 (0.75 liter) mortar air meter employing the same method as a standard 0.25 ft^3 (7.08 liter) air meter used in ASTM C 231. The air entraining admixture dosage was selected based on the mixture containing fiberglass fibers. This dosage was then held constant for all mixtures so the impact of the fibers on air content could be understood.

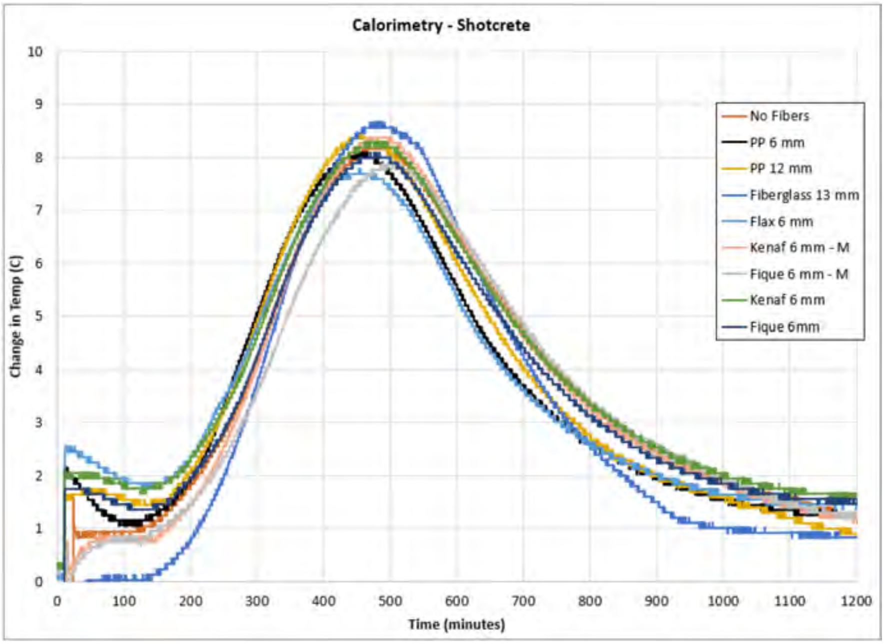

Table 2: Calorimetry - Shotcrete

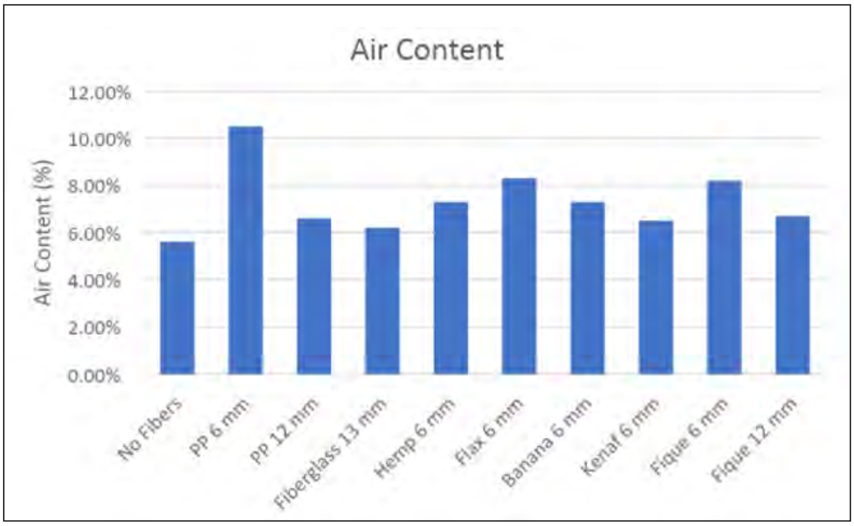

Table 3: Air Content

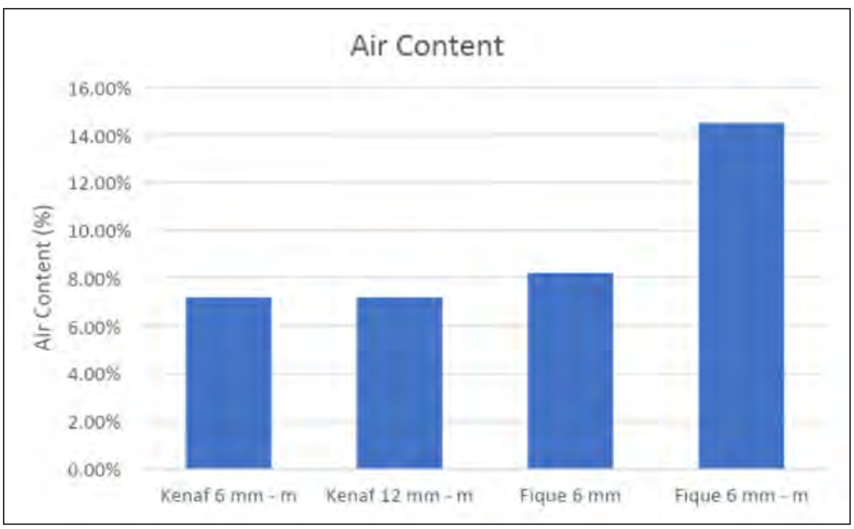

Table 4: Air Content

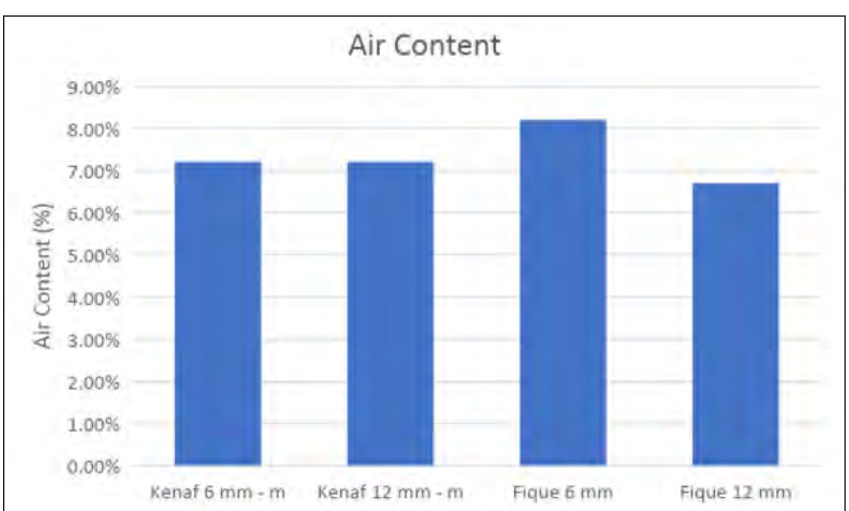

Table 5: Air Content

All the natural fibers maintained an air content at 6.2% - 8.2%, just above the synthetic 12 mm polypropylene and 13 mm fiberglass containing materials. All natural fibers caused less impact to entrained air content than 6mm polypropene fiber when the dosage of natural fibers was added based on density of the fiber.

An additional test was run, increasing the amount of fibers to match the mass of the fiberglass fibers. In this case, there was higher measured air when using fique. This was an expected change based on the material's properties. The increased volume of kenaf maintained a constant air content.

Length of fiber did not have a consistent impact on the density of the mortar when volume of fiber addition was constant.

Flow can be a very important attribute to shotcrete since it must be reliably pumped and sprayed. Typically, the addition of fibers reduces the flow rate in cementitious mortar. Actual spray testing was not conducted, so flow was used as an indicator of the rheology. Flow was determined following ASTM C 1437 using a shocking table.

Fig. 1: Photo of unwound kenaf fiber in shotcrete mortar Hardened State Mortar Testing

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**Note: a targeted 6% air was chosen to better understand "as shot" hardened state properties. It is understood that high air content of 12% before shotcrete is placed would typically be targeted assuming 50% of the air is removed in the application process. Since the material could not be pumped and shot for hardened state tests, a typical "as shot" air content was targeted to avoid high air contents impacting hardened state properties.*

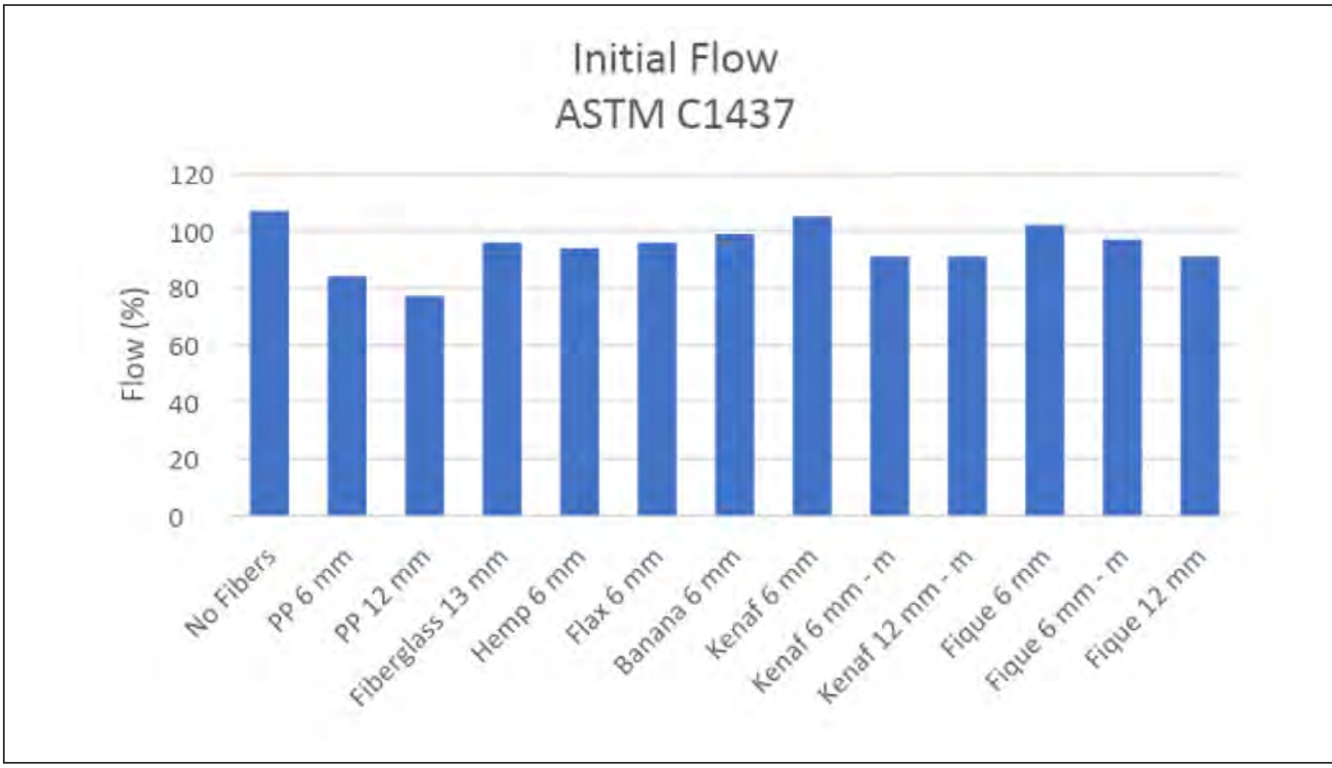

Table 6: Initial Flow ASTM C1437

The natural fibers had no negative impact to flow, and in all cases, they had equal or higher flow than the mortars containing synthetic, polypropylene fibers.

It was observed that the fibers are of a wound nature. During mixing, the fibers tended to uncoil and lengthen in the wet mortar. The mixed fiber was longer than the initial cut length and less rigid, signaling it had lengthened or uncoiled in the mixing process. It is hypothesized that this allowed for a higher flow in the mixture. (Fig. 1)

HARDENED STATE MORTAR TESTING

The mortar was cured for 28 days in 50% RH at 73°F (23°C), and the specimens were tested for compressive strength, split tensile strength, and flexural strength. Length change was also monitored over the curing period. Compressive strength was measured using 2 in. (50 mm) cubes following ASTM C 109. Split tensile samples were tested following ASTM C 496. Flexibility testing (following ASTM C 580) was run on specimens used for length change measures (following ASTM C 157).

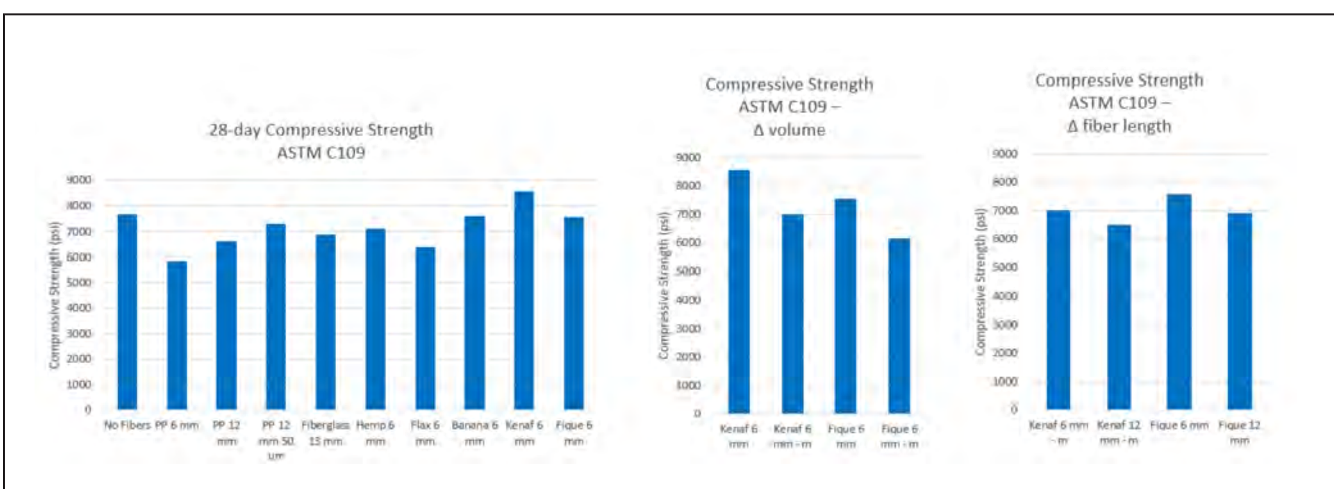

Table 7: Compressive Strength

All mortar containing natural fibers achieved compressive strength (Table 7) over 6000 psi (41 MPa) at 28 days, with the kenaf fiber mortar reaching over 8000 psi (55 MPa) and outperforming the synthetic fiber mortars. Increasing the volume of natural fibers of the same length led to a reduction in compressive strength. Mortar containing 6 mm length natural fibers had higher compressive strength than mortar containing equal amounts of 12 mm length fibers.

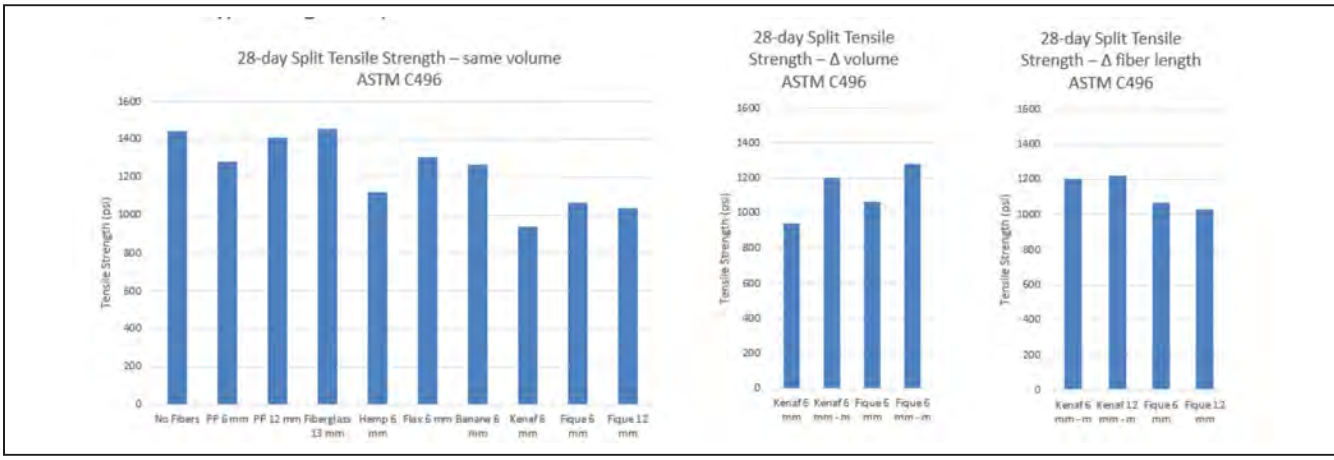

Table 8: Split Tensile Strength

Mortars containing natural fibers had lower split tensile strength (Table 8) than the control or synthetic fibers; however, with a typical target above 900 psi (6.2 MPa), all natural fibers exceeded this requirement. Increasing the volume of natural fibers increased the split tensile strength. This indicates there is an ability to further optimize a mixture design to achieve a higher tensile strength of the mortar if desired. Increasing the length of the fiber did not impact the tensile strength.

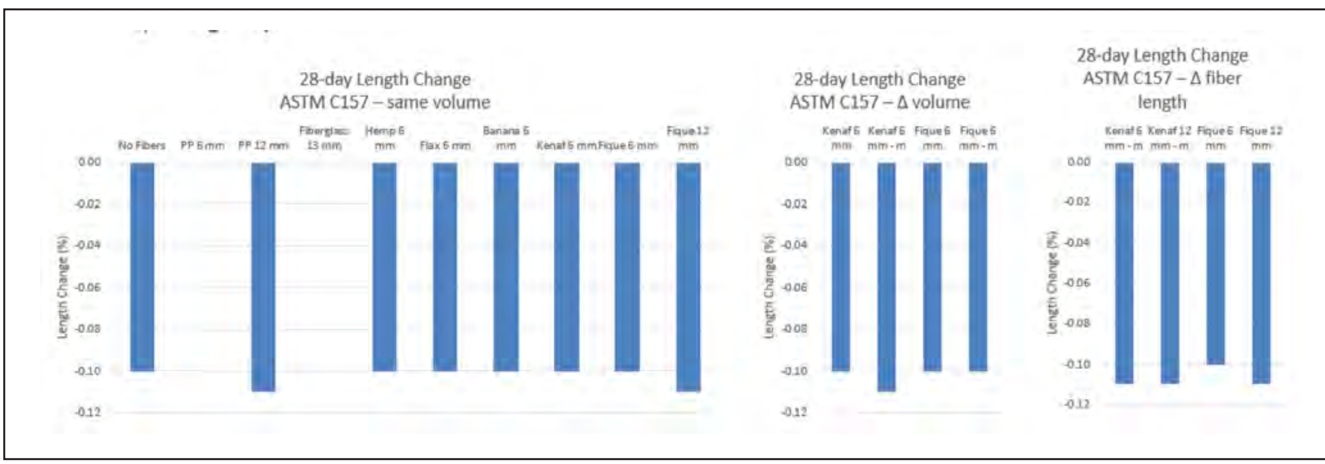

Table 9: Length Change

The dimensional stability was monitored for 28 days (Table 9) according to the ASTM C 157 method. None of the fibers had a great impact on length change. All were within 0.01% change in length.

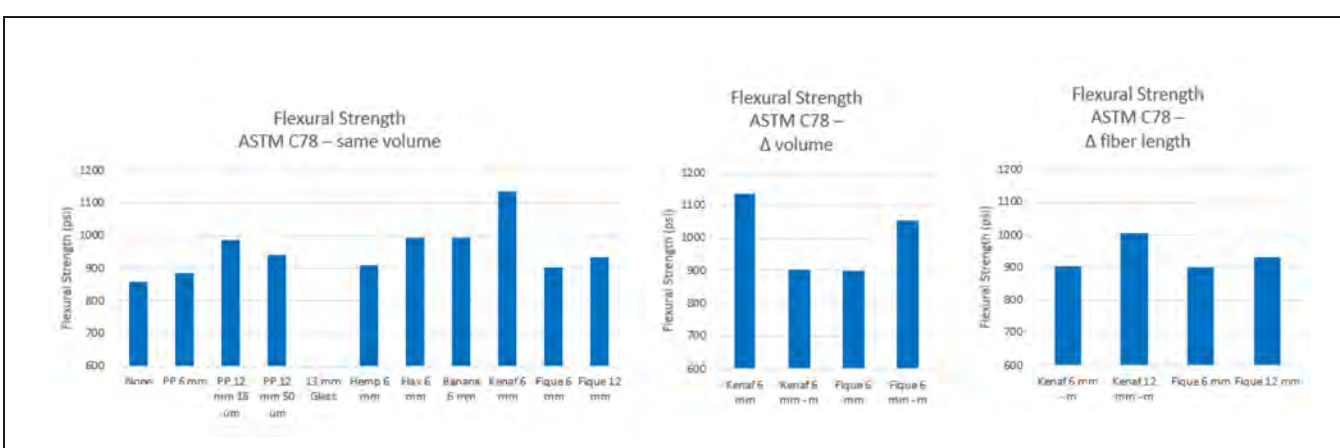

Table 10: Flexural Strength

All mortars containing fibers outperformed the control without fibers in flexural strength (Table 10). The fiber with the least impact was the 6 mm polypropylene fiber. Mortar containing 6 mm kenaf fiber showed the greatest increase in flexure strength. Longer fibers further increased the flexural strength of the mortar. Kenaf fibers contributed to the greatest increase in flexural strength in this regard as well.

Evaluation Summary
(Natural compared to polypropylene synthetic)

	flow	compression	tensile	shrinkage	flexural
Synthetic					
Fique	low				low
Flax		low	high		
Hemp	low				low
Banana					
Kenaf	highest	highest	low		highest
	lows are fine	lows are fine	*	All same	lows are fine

Table 11: Natural materials do not have high performance characteristics in tensile strength, but some match synthetic materials. Increased amounts of fibers improved the tensile strength.

Conclusion

The Azelis labs used a basic sand shotcrete mortar formulation to evaluate the impact of MiniFIBERS natural fibers. The typical performance requirements referenced were for "as-shot" mortar containing a targeted 6% air. The Azelis labs have concluded that utilizing natural fibers in mortar allowed the shotcrete formulation to perform to meet typical performance targets, while allowing for a lower carbon footprint due to the use of sustainable materials. The summary chart (Table 11) reviews the highest and lowest performing material; however, all natural fibers produced a material with sufficient properties.

Further analysis can be run to determine subjective properties such as workability, smoothing, and ease of use. "Shot" characteristics have not been evaluated in this study, but this could be done, and additional application testing could be conducted to further understand the natural fibers' impact on the mortar.

Processing natural fibers presents its own set of challenges. Due to their inherent nature, each fiber type has different cutting and processing characteristics. Currently, there are an extremely limited number of fiber processing companies that are capable of producing a consistent natural fiber cut that is less than 10 mm (.39 in.) in length. MiniFIBERS Inc. has state-of-the-art fiber cutting technology and is a world leader in fiber processing.

Joe McJunkins *is the Director of Technical Service & Product Management for MiniFIBERS Inc. located in Johnson City, Tennessee, USA. Mr. McJunkins is based in the Cleveland, Ohio area and is responsible for global activities related to CASE, Construction, and Industrial markets.*

Mr. McJunkins earned his BS in Chemistry in 1980. Joe possesses over 35 years of combined formulation and product development experience. His background covers a wide range of applications such as non-woven textiles, architectural polymers, coatings, adhesives, inks, and minerals. Mr. McJunkins holds a variety of patents for aqueous & non-aqueous coatings, polymers, inks, and functional fillers.

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