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Performance of Hemp Micro- and Macrofiber in Cement Mortar

by Brian Giltner, Seamus Freyne, and Anthony J. Lamanna

*The focus of this study is to determine the optimum length of micro (average diameter less than 0.3 mm) and macro (average diameter greater than or equal to 0.3 mm) hemp fibers subjected to tensile loading in a cement paste mixture. Optimizing the length of the fibers to carry tensile loading for concrete members is important to minimize waste of hemp material and to provide the best performance. This study evaluated three water-cement ratios (*w/c*): 0.66, 0.49, and 0.42 (f_c' = 17.2, 24.1, and 27.6 MPa [2500, 3500, and 4000 psi], respectively). Because of the high cost of cement, replacement of cement with fly ash was also part of the program to determine if the addition of fly ash would have a negative impact on the performance of the hemp fibers. The results show that hemp micro- and macrofibers bonded to the cement matrix and carry higher tensile loads at higher* w/c*. Statistical analysis (regression modeling) shows that the optimum length for hemp macrofibers is 30 and 20 mm (1.18 and 0.79 in.) for microfibers.*

Keywords: bonding; fibers; hemp; tensile capacity; twine; water-cement ratio.

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, the Marihuana Tax Act of 1937, that forbade the growing and harvesting of hemp.[1] This was reversed with the 2014 and 2018 Farm Bills,[2,3] which allows the legalized growing of hemp in the United States if the individual states also pass legislation allowing its growth. The 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.

The tensile performance of hemp fibers in cement paste or concrete has not been extensively studied. In this study, multiple hemp fiber lengths were assessed in increments of 10 mm (0.39 in.), ranging from 20 to 60 mm (0.79 to 2.36 in.). Without using partial cement substitution, each fiber length was cast into three distinct water-cement ratios (*w/c*): 0.66, 0.49, and 0.42. Similar fiber lengths and *w/c* were used in the casting of additional samples, but fly ash was added as a partial cement substitute. This fills a gap in earlier research by offering an overall range for determining the ideal hemp fiber length.

RESEARCH SIGNIFICANCE

Limited studies have been conducted on the use of short-length hemp fibers as reinforcement in structural concrete.[4-8] Each study looked at a limited number of fiber lengths (usually two or three lengths) and only one *w/c*, usually above 0.5. Other studies have looked at natural fibers, but not hemp.[9-12] The previous studies never provided justification for the selection of the fiber lengths. These studies provide limited background information on how natural fibers behave when cast into cement mortar or concrete mixtures.

This study examined five different lengths of hemp micro- and macrofibers with three different *w/c* (low, medium, and high) to determine how the fibers would behave to tensile testing. In this research, fly ash is also added to the mixture to see what impact it will have on the tensile performance of the fibers. A greater knowledge of the performance of hemp fibers in a concrete matrix will come from the investigation of various fiber lengths, *w/c*, and the addition of fly ash. Using the proper size of fibers in concrete can maximize its performance while reducing construction costs, increasing its tensile capacity, and improving its ductility.[4]

EXPERIMENTAL INVESTIGATION

Cement paste combinations were used to cast specimens containing both micro and macro hemp fibers, varying in length for each casting. The same mixing ratios that are used for each concrete mixture are also used for the cement paste. The bonding between the fiber and the cement mixture—which would be comparable in a concrete mixture—was the main focus of this work. To observe effects on the tensile performance, a number of variables were changed, including the length and size of the fibers, the *w/c*, and the inclusion of fly ash.

Materials and specimens

Hemp micro- and macrofibers (refer to Fig. 1) were acquired from suppliers in the United States. The microfibers are raw hemp fibers extracted from the stalk of hemp plants, while the macrofibers are twine that is machined from the microfibers. Based on the fibers' diameter, concrete fibers are categorized as either micro or macro. As was previously said, macrofibers have a diameter of at least 0.3 mm, whereas microfibers have a diameter of 0.3 mm or less. These dimensions have been adopted by the fiber production sector to separate fibers into micro and macro categories. The twine (macrofiber) was given in neatly wound balls, and the microfibers were bundled into a mass. To test different embedment

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Table 1—Experimental program

Concrete strength, MPa (psi)	w/c	Cementitious material	Number of samples				
			Length, mm (in.)				
			20 (0.79)	30 (1.18)	40 (1.57)	50 (1.97)	60 (2.36)
27.6 (4000)	0.42	Cement only	5	5	5	5	5
		Cement with fly ash	5	5	5	5	5
24.1 (3500)	0.49	Cement only	5	5	5	5	5
		Cement with fly ash	5	5	5	5	5
17.2 (2500)	0.66	Cement only	5	5	5	5	5
		Cement with fly ash	5	5	5	5	5

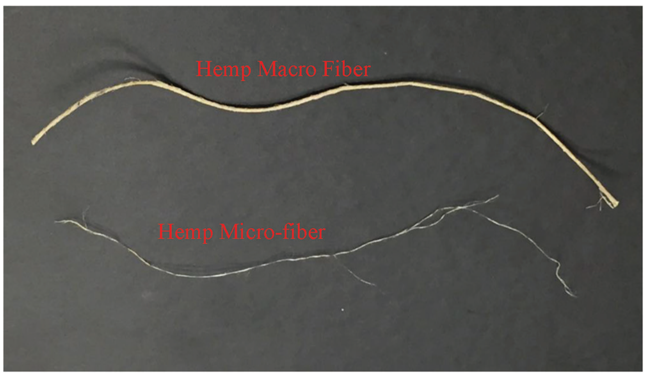

Fig. 1—Hemp macrofiber and hemp microfiber.

Table 2—Mortar mixture ratios

Concrete strength, MPa (psi)	w/c	Cementitious material	Fly ash/cement ratio	Sand/cement ratio
27.6 (4000)	0.42	Cement only	0	1.90
		Cement with fly ash	0.33	2.53
24.1 (3500)	0.49	Cement only	0	2.09
		Cement with fly ash	0.33	2.78
17.2 (2500)	0.66	Cement only	0	2.64
		Cement with fly ash	0.33	3.53

lengths, micro- and macrofibers were cut to length. Cement Type I/II, ASTM C150, was used in the cement mortar. Fly ash that met ASTM C618 standards was used for the samples that had some of their cement replaced. Potable water, river sand that was dredged from the Ohio River in Paducah, KY, and fine aggregate—crushed limestone from a nearby supplier in Western Kentucky—were the remaining components. Three *w/c* of 0.42, 0.49, and 0.66 were based on the requirements established by the Kentucky Transportation Cabinet[13] for the 28-day compressive strength of concrete (f_c' = 17.2, 24.1, and 27.6 MPa [2500, 3000, and 4000 psi], respectively). ACI 318-14 Table 19.2.1.1 allows f_c' = 17.2 MPa (3000 psi) 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 *w/c* above 0.5.[5-7]

Tables 1 and 2 provide a summary of the various mixture designs. In total, six mixture designs were cast with five different embedment lengths per design and five samples per embedment length for micro- and macrofibers.

Five specimens were cast for each mixture design with either hemp micro- or macrofibers. The specimen's cross-sectional dimensions measured 12 x 20 mm (0.47 x 0.78 in.) with fiber[14] embedment lengths varying from 20 to 60 mm (0.79 to 2.36 in.) in increments of 10 mm (0.39 in.). Figure 2 shows the mold setup for the 40 mm (1.57 in.) embedment length. The molds are made from closed-cell polyvinyl chloride (PVC) material. The closed-cell PVC material does not react or bond with cement paste.

The samples were able to be removed from the mold without any harm because the middle areas of the mold are designed to be removed. The mold with the fibers placed and prepared for cement paste application is depicted in Fig. 3. The molds' long sides are constructed in two sections, with a hole in the middle of each mold bay. One long side is installed from the lower half, and the fiber is then inserted through the mold bay and across it. Tape holds the end of the fiber that is resting across the bottom part in place. Next, the fiber is put over the lower part on the other side after it has been installed. The fiber's longer end allows it to be linked to the universal testing machine. The two upper portions are fastened in place after being positioned above the bottom sections. Before casting, the long free end of the fibers was gently pulled to straighten them. Tape was used to secure the fibers in place (refer to Fig. 3). This prevents the fiber from warping or deflecting as it is being cast. Twenty-four hours after casting, the samples were taken out of the mold and allowed to cure indoors for a total of 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 3 mm (0.12 in.) diameter tube and the cement paste packed around the fiber.[9] After curing, the fiber and cement configuration were subjected to a tensile loading similar to what was used in this study.

Tensile tests

The samples were subjected to tensile loading after they had air-cured for 28 days. Figure 4 shows the testing setup for the macro and micro hemp fibers. The hemp macrofiber

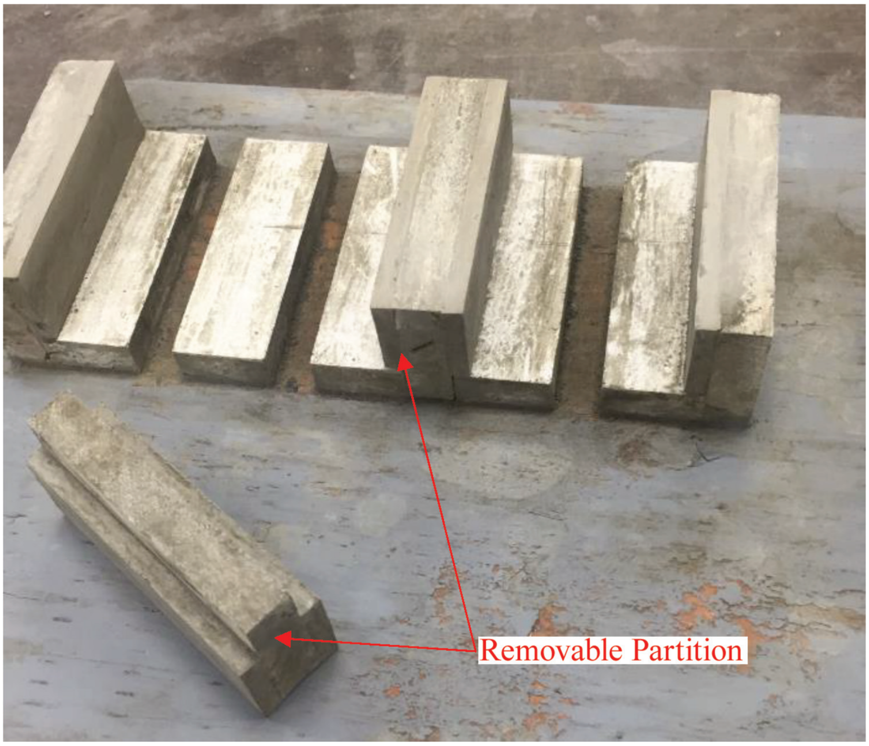

Fig. 2—Five 40 mm (1.57 in.) long mold-cast specimens.

Fig. 3—Forty mm (1.57 in.) mold with fibers installed.

had a length and diameter that is significantly larger than the hemp microfibers. The hemp macrofiber was able to be anchored into the jaws of the universal testing machine because the fiber had a large enough diameter to allow the jaws to engage it. The free end of the hemp microfiber was attached to heavy card stock (refer to Fig. 5) to allow the jaws to hold it in place during testing, as portrayed in Fig. 4.[15]

Each sample was loaded in tension per the requirements of ASTM D3822. The rate of extension of the universal testing machine is 10% of initial specimen length per minute. A tension test for macrofibers took 1.5 minutes, while the same test for the microfibers lasted 30 seconds or less.

EXPERIMENTAL RESULTS AND DISCUSSION

Fiber performance

A total of 258 tests consisted of 142 macrofiber samples and 116 microfiber samples. Originally, 300 samples were cast, but some were damaged, some had casting issues, and some were damaged while setting up the universal testing machine. Three modes of failure were observed: fiber slipping within the cement paste sample, partial breaking as depicted in Fig. 6, and complete tensile failure of the fiber as shown in Fig. 7. Only one macrofiber sample broke during the tension testing, while 78% of the microfibers broke or partially broke. Microfibers with an embedment length of 50 mm (1.97 in.) or greater had a breakage rate of 91%. The maximum tensile load for macrofibers is 79.1 N (17.79 lb) and the maximum for the microfibers is 26.1 N (5.87 lb).

Potential for ductility

The hemp macrofiber in 140 cases and microfibers in 19 instances slipped while the load was being applied. Figure 8 depicts load and displacement results that had 40 mm (1.57 in.) embedment length and were cast into the cement matrix without fly ash. The macrofiber failed by slipping but was still able to resist a noticeable load. The microfiber showed a similar trend but did not exhibit much slippage before breaking. The fiber slipping occurs when the tensile load applied to the fiber exceeds the shear strength that is created between the cement paste and fiber.

Figure 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 like the deformations of steel reinforcement in concrete. This allows the tensile load to be transferred to the concrete through shear.[16]

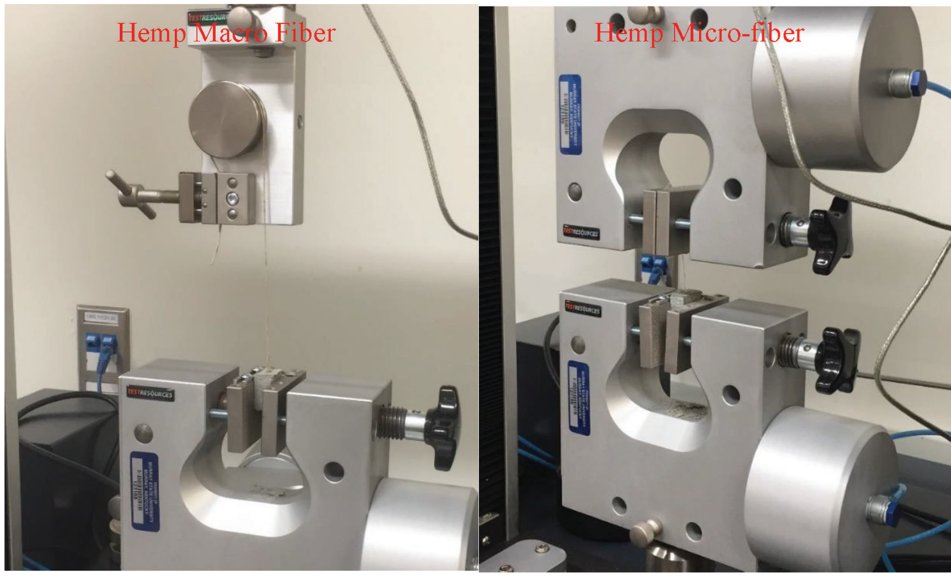

Fig. 4—Tension testing configuration.

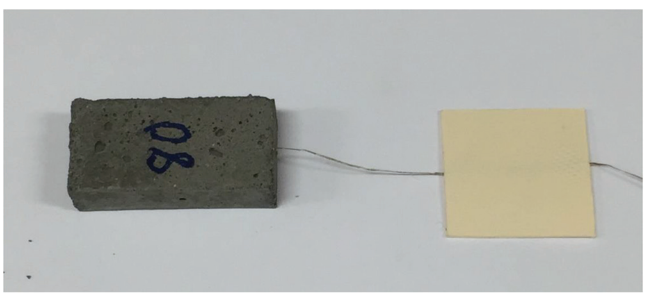

Fig. 5—Hemp fiber configuration for testing.

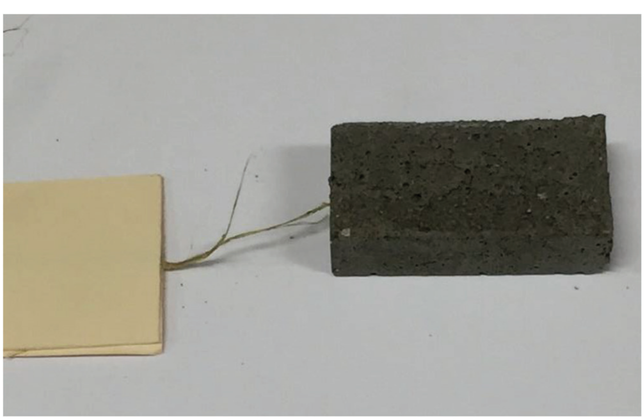

Fig. 6—Partial tensile break of fiber.

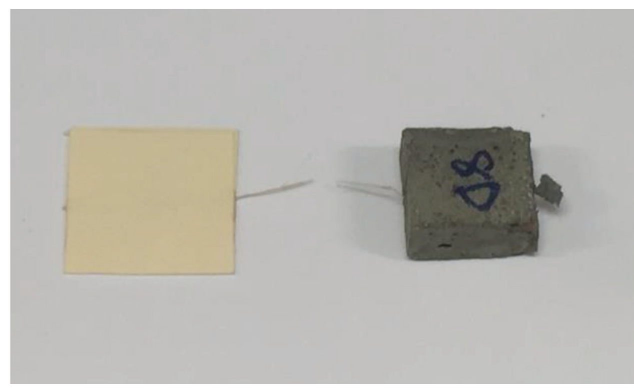

Fig. 7—Tensile failure of fiber.

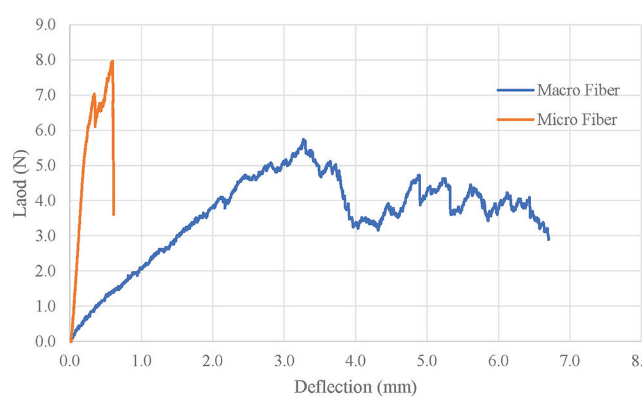

Fig. 8—Load versus displacement for macro- and microfibers—20 mm (0.79 in.) embedment, 0.42 w/c *with no fly ash. (Note: 1 mm = 0.0394 in.; 1 N = 0.2248 lb.)*

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 findings from Bažant and Desmorat when testing smooth steel fibers.[18] The maximum pullout stress decreases with the increase in diameter with the same length of embedment.

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 macro- and microfibers.

Each of the three mixture designs included batches that incorporated Class C fly ash at a maximum replacement rate of 25%.[13] The hemp micro- and macrofibers responded

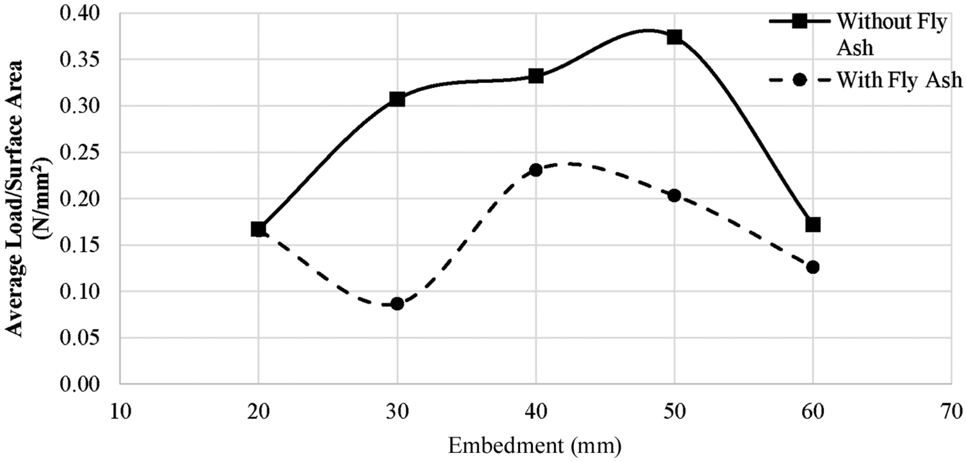

Fig. 9—Macrofiber: comparison of f_c' *= 27.6 MPa (4000 psi) mixture with and without fly ash. (Note: 1 mm = 0.0394 in.; 1 N/mm² = 145 psi.)*

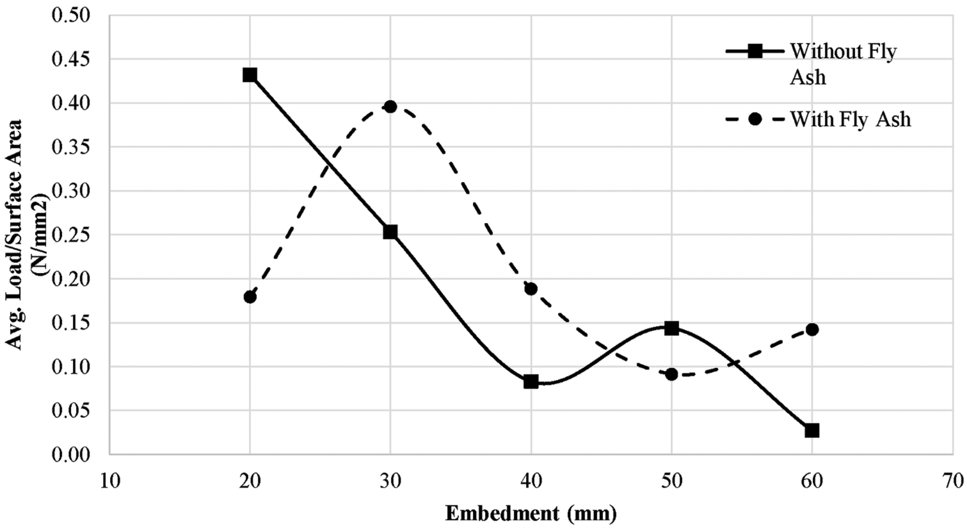

Fig. 10—Microfiber: comparison of f_c' *= 27.6 MPa (4000 psi) mixture with and without fly ash. (Note: 1 mm = 0.0394 in.; 1 N/mm² = 145 psi.)*

differently to the presence of fly ash. Figures 9 and 10 show average load/surface area versus the embedment length. The curves shown are polynomial trend lines of the average of the data for each embedment length.

Figure 9 is a plot of the macrofibers with and without fly ash. For all embedment lengths, the mixture without fly ash performs better than the mixture with fly ash. At the 20 and 60 mm (0.79 and 2.36 in.) embedment lengths, both mixtures' performance were almost equal to each other.

Figure 10 is a plot of the microfibers with and without fly ash in the cement mortar mixture. The performance of the microfiber is different than the performance of the macrofibers. Microfibers can carry a higher average load to surface area value than the macrofibers; however, the macrofibers will carry a higher average load because they have a larger surface area. The microfibers with 30, 40, and 60 mm (1.18, 1.57, and 2.36 in.) embedment had better performance with fly ash in the cement mortar mixture. This is the opposite of the macrofibers with the same embedment lengths.

Mixture designs

Three different mixture designs were used with the *w/c* varying from 0.42 to 0.66 (refer to Table 1). Figures 11 and 12 show the average load/surface area for each mixture design and each embedment length. The f_c' = 27.6 MPa (4000 psi) for macro hemp fibers performs better than the other mixture designs (refer to Fig. 11). The f_c' = 24.1 MPa (3000 psi) mixture is optimum for 20 mm (0.79 in.) embedment for microfibers, while f_c' = 27.6 MPa (4000 psi) mixture is best for the longer embedment lengths.

The average shear bond strength of the macro- and microfibers in cement mortar with and without fly ash is compared for each concrete strength (mixture design) in Fig. 13 and 14 (Fig. 13 shows the macrofibers and Fig. 14 shows the microfibers). Regarding each mixture design, the average load per surface area of the macrofibers falls within the same relative range. In the two lower-strength mixture designs, the microfibers follow the same pattern as the macrofibers; however, in the higher mixture design, the maximum limit without fly ash is significantly greater than with fly ash.

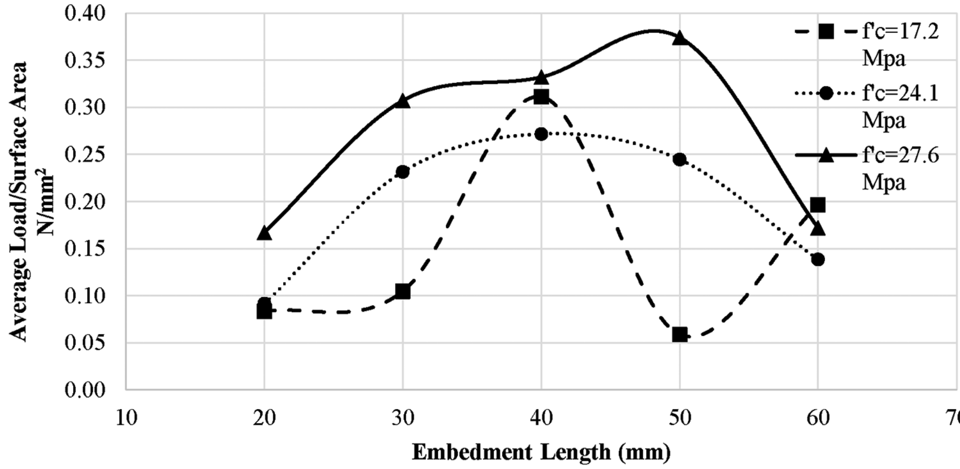

Fig. 11—Hemp macrofiber: comparison of mixture designs without fly ash. (Note: 1 mm = 0.0394 in.; 1 N/mm^2 = 1 MPa = 145 psi.)

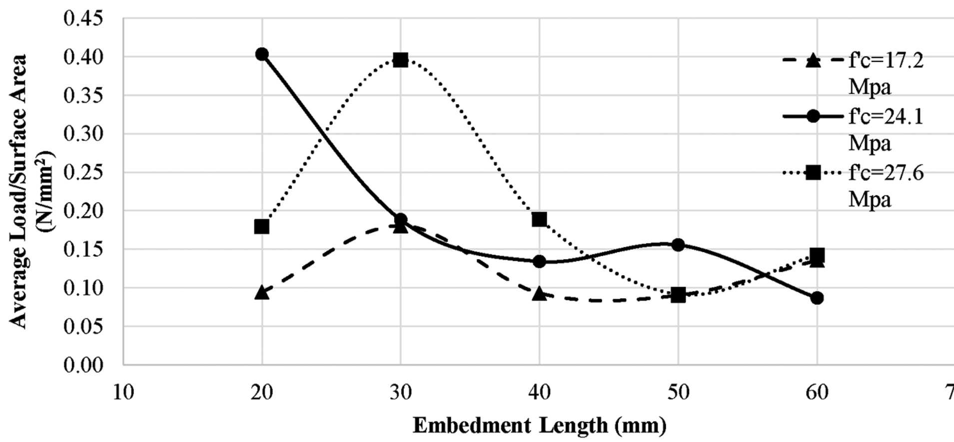

Fig. 12—Hemp microfiber: comparison of mixture designs with fly ash. (Note: 1 mm = 0.0394 in.; 1 N/mm^2 = 1 MPa = 145 psi.)

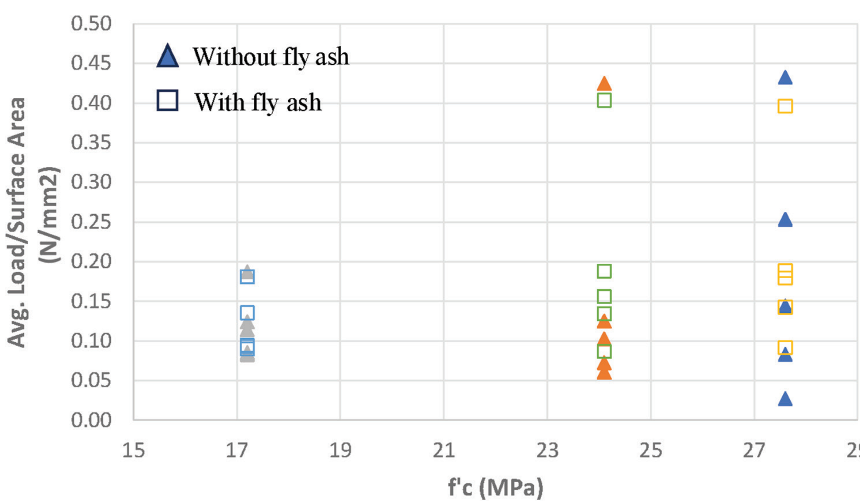

Fig. 13—Hemp macrofiber: comparison of mixture designs to shear bond stress. (Note: 1 mm = 0.0394 in.; 1 N/mm^2 = 145 psi.)

Embedment length

The length of macrofiber embedment can assist in determining the optimum macrofiber length for use as reinforcement in concrete. Figure 15 shows the average load/surface area per embedment length. Based on this chart, the 40 mm (1.57 in.) macrofiber embedment length had the highest tensile capacity. However, this may not be the optimum length to use because macrofibers tend to ball when added to a concrete mixture.

For microfibers, Fig. 16 shows that an embedment length of 20 or 30 mm (0.79 or 1.18 in.) would be preferable. The 20 mm (0.79 in.) length performed best with an f_c' = 17.2 MPa (2500 psi) mixture but the 30 mm (1.18 in.)

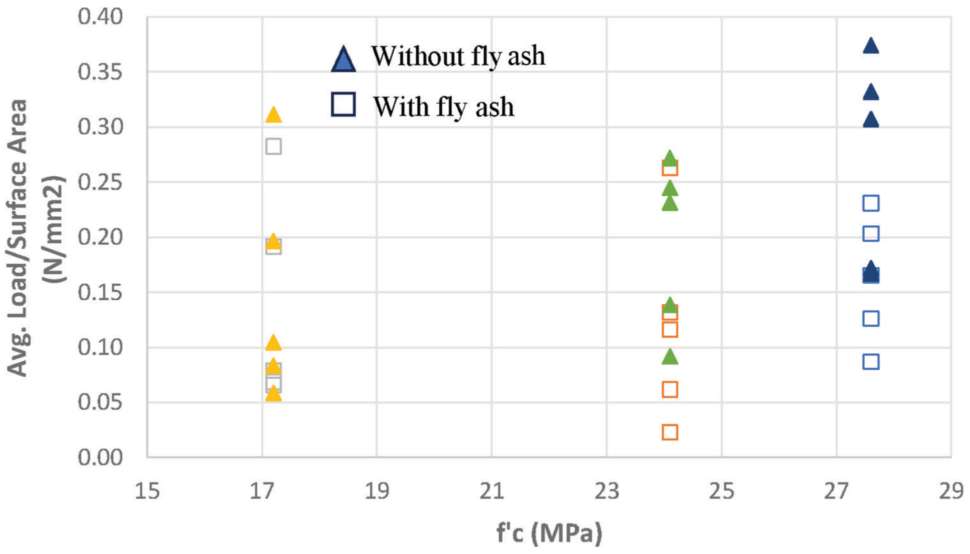

Fig. 14—Hemp microfiber: comparison of mixture designs to shear bond stress. (Note: 1 mm = 0.0394 in.; 1 N/mm² = 145 psi.)

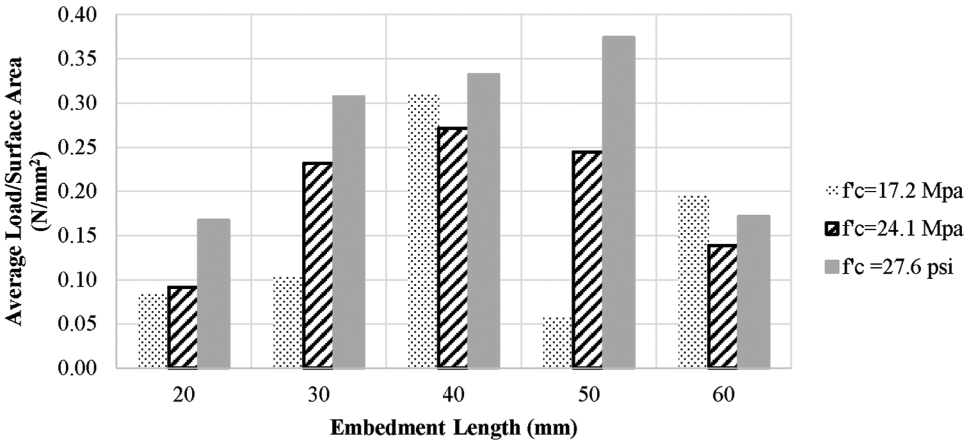

Fig. 15—Hemp macrofiber: comparison of embedment lengths. (Note: 1 mm = 0.0394 in.; 1 N/mm² = 1 MPa = 145 psi.)

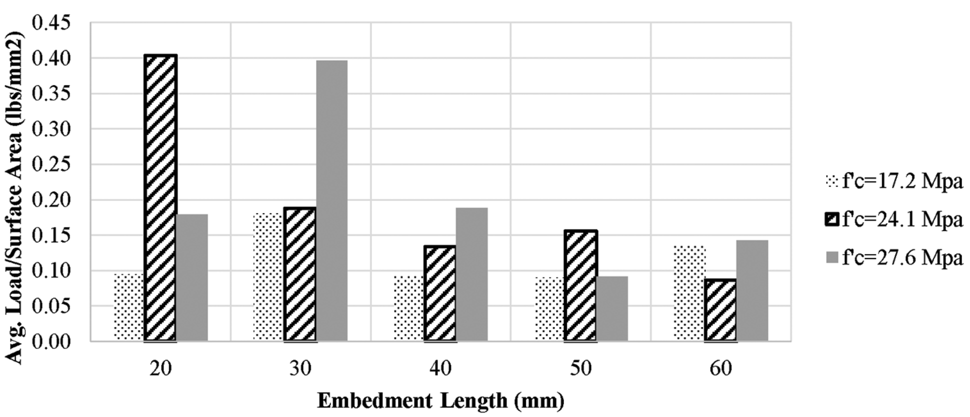

Fig. 16—Hemp microfiber: comparison of embedment lengths. (Note: 1 mm = 0.0394 in.; 1 N/mm² = 1 MPa = 145 psi.)

length performed best in f_c' = 24.1 and 27.6 MPa (3500 and 4000 psi) mixtures.

Statistical analysis

The results of 258 tests were evaluated to detect statistical significance and build a regression model to fit the data. The dependent variable is the maximum load for each sample tested. The independent variables were average fiber diameter, *w/c*, length of embedment, whether the mixture contained fly ash, and if the fibers were 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. The following is the coding that was used for the regression analysis:

Table 3—Adjusted R^2 values

Model number	Linear regression model variables	Adjusted 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

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 macrofiber, 0 if it is not

X_4 = 1 if is 20 mm (0.79 in.) embedment, 0 if it is not

X_5 = 1 if is 30 mm (1.18 in.) embedment, 0 if it is not

X_6 = 1 if is 40 mm (1.57 in.) embedment, 0 if it is not

X_7 = 1 if is 50 mm (1.97 in.) embedment, 0 if it is not

A 60 mm (2.36 in.) embedment will be when X_4, X_5, X_6, and X_7 are all equal to 0.

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 is done through looking at the two-tail p-values that test the null hypothesis that each coefficient is equal to 0. To reject the null hypothesis, the 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 R^2_{adj} values are listed in Table 3. The models have been ranked in how the models were built. The two highest R^2_{adj} models, models 12 and 18, were 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; *w/c* of 0.42; *w/c* of 0.49; 20 mm (0.79 in.) length of embedment; and 30 mm (1.18 in.) length of embedment. Model 18's independent variables having significance are fly ash, fiber type, *w/c* of 0.42, *w/c* of 0.49, 20 mm (0.79 in.) length of embedment, 30 mm (1.18 in.) 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 17 is a plot based on Model 18's fiber type and *w/c* of 0.42 interaction. The two lines are parallel, which shows there is no interaction between these two independent variables. Figure 18 clearly shows an interaction between fiber type and fly ash because the two lines cross. Figure 18 shows that microfibers in mixtures containing fly ash will have a higher tensile load, while macrofibers in the same mixtures will have a lower tensile load. (Note: The full-color version of this paper can be accessed at www.concrete.org.)

For each of the models, the residuals versus 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. Figures 19 and 20 show the residuals plot for the two linear regression models. The plots for both models are close to normal distribution. Model 18 has a higher adjusted R^2_{adj}, which will make this a slightly better model at predicting the tensile load.

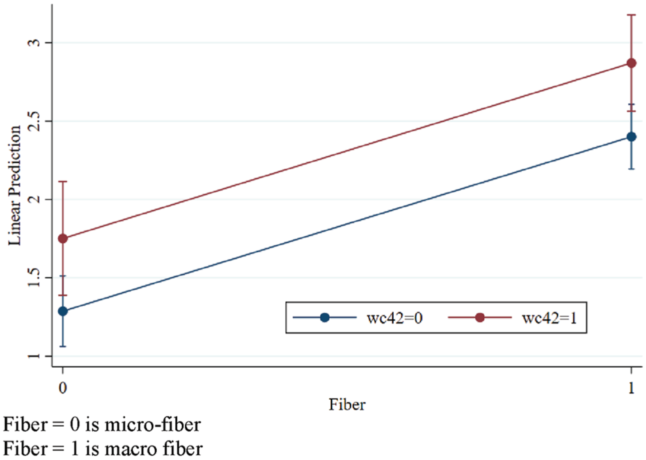

Fig. 17—Interaction plot: fiber and w/c *= 0.42.*

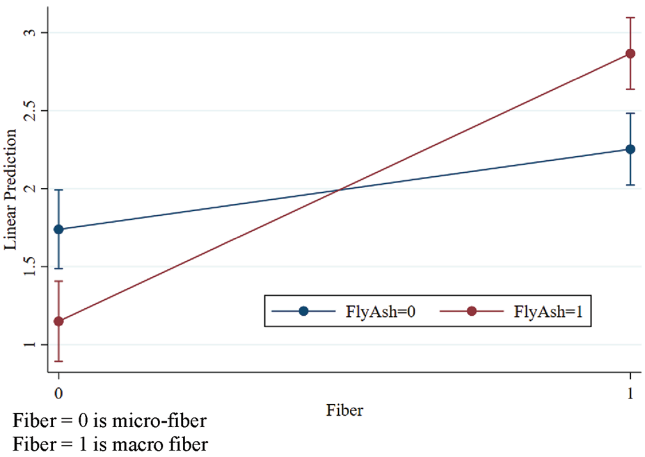

Fig. 18—Interaction plot: fiber and fly ash.

$$\ln(\text{Load}) = 0.618X_2 + 0.401X_3 - 0.640X_4 - 0.606X_5 - 0.172X_6 - 0.136X_7 - 1.203X_2X_3 \quad (1)$$

Small sample sizes may lead to overfitting of the data. Compared to earlier research, this one had 258 samples, which is a bigger sample size[4-8] and offers a sufficiently high sample size to prevent overfitting.

ADDITIONAL RESEARCH IDEAS

To standardize hemp micro- and macrofiber length requirements, more research is required. Applying a coating to the fibers will strengthen their bond with the cement mixture. The size effect and the stress-slip law would be covered in such a study. This would be an investigation of the link between the interfacial slip and shear stress in response to the fiber's size.[17] Using a water-based coating instead of the chemicals now used to treat hemp fibers would have a more positive environmental impact. Determining the proper dosage rates for the hemp micro- and macrofibers in various combination patterns will also be essential.

CONCLUSIONS

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

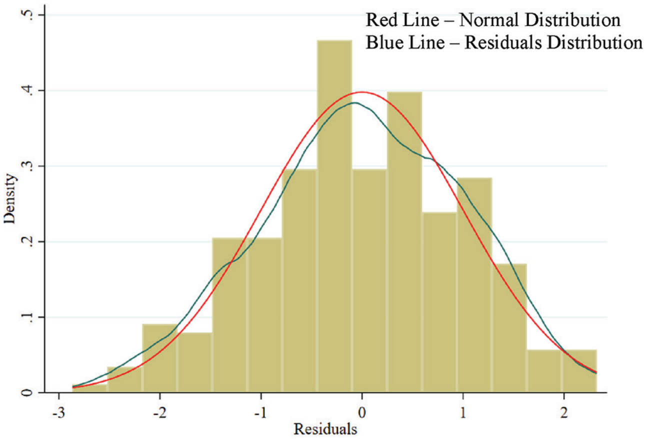

Fig. 19—Residuals versus fitted model plot: model 12.

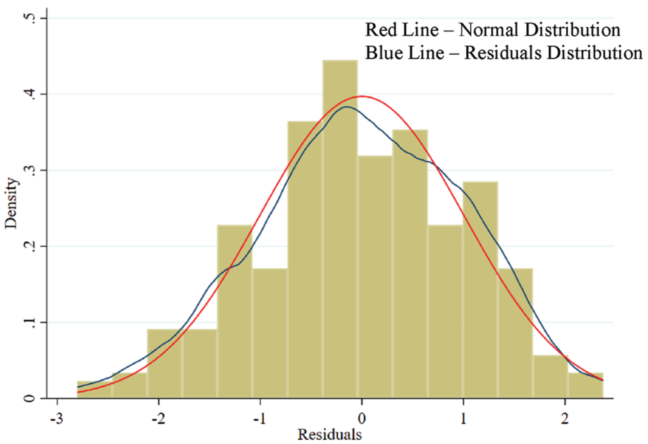

Fig. 20—Residuals versus fitted model plot: model 18.

1. Hemp macro- and microfibers will bond to cement paste allowing the transfer of tensile forces into them. This will allow hemp fibers to be used as a form of fiber reinforcement;
2. Hemp macro- and microfibers have similar general characteristics but will perform differently depending on the concrete mixture design and length of embedment;
3. Hemp microfibers have a higher tensile carrying capacity, with f_c' = 24.1 MPa (3500 psi), while hemp macrofibers have f_c' = 27.6 MPa (4000 psi). This means the lower the water-cement ratio (w/c), the higher the tensile capacity;
4. A 30 mm (1.18 mm) embedment for hemp macrofibers performed the best in this study based on statistical analysis. Hemp microfibers had the best performance with an embedment length of 30 mm (1.18 mm) for mixtures without fly ash and 20 mm (0.79 mm) for mixtures containing fly ash; and
5. Working with natural fibers can be difficult because of the variability in the fibers (diameter, composition, and so on); therefore, testing with hemp micro- and macrofibers in different concrete mixture designs should be tested for flexure and compression capacities.

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