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Optimization of Hemp Fiber Reinforced Concrete for Mix Design Method

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Abstract**—**The purpose of this study is to evaluate the incorporation of hemp fibers (HF) in concrete. Hemp fiber reinforced concrete (HFRC) is becoming more popular as an alternative for regular mix designs. This study was done to evaluate the compressive strength of HFRC regarding mix procedure. HF were obtained from the manufacturer and hand processed to ensure uniformity in width and length. The fibers were added to concrete as both wet and dry mix to investigate and optimize the mix design process. Results indicated that the dry mix had a compressive strength of 1157 psi compared to the wet mix of 985 psi. This dry mix compressive strength was within range of the standard mix compressive strength of 1533 psi. The statistical analysis revealed that the mix design process needs further optimization and uniformity concerning the addition of HF. Regression analysis revealed that the standard mix design had a coefficient of 0.9 as compared to the dry mix of 0.375 indicating a variation in the mixing process. While completing the dry mix, the addition of plain HF caused them to intertwine creating lumps and inconsistency. However, during the wet mixing process, combining water and HF before incorporation allows the fibers to uniformly disperse within the mix hence the regression analysis indicated a better coefficient of 0.55. This study concludes that HRFC is a viable alternative to regular mixes however more research surrounding its characteristics needs to be conducted.

Keywords**—**Hemp fibers, hemp reinforced concrete, wet and dry, freeze thaw testing, compressive strength.

I. Introduction

CONCRETE is a mixture of water, aggregate and cement that has been used for thousands of years. It is the most used man-material today with over an estimated 4100 million tons of cement created worldwide in 2019 to make it [5]. The main component in concrete is the binder, cement, which sets and hardens. Various materials such as calcium oxide and crushed volcanic rock have been used throughout history to create cement. Portland cement is widely used today, however dating back to 1824 the creation process entails heating a mixture of limestone, clay, and sand up to 1450 °C in a rotating kiln [4].

Using natural fibers in mix designs has been done with HFRC as an expansion into more green based concrete mix designs to create more sustainable structures. Hemp belongs to the Cannabaceae family and has one of the quickest grow times of approximately 15 weeks [7]. The durable fibers have a variety of uses in both commercial and manufacturing trade creating a 4.7 billion USD industry globally. Data have shown that HF with a mean width of 60 μm has an average tensile strength of approximately 310 MPa while the strength at 40 μm is recorded to be closer to 610 MPa [2]. The inverse correlation creates a unique phenomenon which is ideal for incorporating as a strengthening agent in various materials. HF 23.15 ± 17.6 μm wide used to create reinforced concrete have been proven to increase compressive strength by 4%, flexural strength by 9% and flexural toughness by 144% depending on percentage [3].

Hemp reinforced fiber mix is incorporated into two different ways referred to as dry and wet. The proportions of aggregate, cement and hemp are kept constant while the order of materials added is changed to determine potential effects on samples. This is compared to data from concrete mixes made similarly but without hemp referred to as standard or base mixes.

The objectives of the research are as follows:

1. Evaluating the impact of HFRC and comparing the compressive strength to standard concrete mixes without HF.
2. Evaluating the HRFC in regards to wet and dry conditions in comparison to standard concrete mixes without HF.
3. Identifying the potential leaching of heavy metals such as cadmium and chromium from standard concrete mixes in comparison to similar leaching potential to HRC mixes.
4. Researching the impact of HF in concrete mix design and how it relates to standard mixes to identify a correlation with compressive strength.
5. Incorporating statistical analysis to determine efficacy of the HF mix design process.

II. Materials

Hemp

Raw natural HF are initially used for this experiment (Fig. 1). The remaining processing is done by hand as the husk from the stem of the hemp plant is stripped leaving only fibers. The fiber widths initially range from approximately 2000 μm to 23 μm. The fibers are combed through with a quadruple row hackling comb to reduce the width to 50 μm (Fig. 3). Hackling combs are traditionally a metal plate with rows of needles used to prepare other natural fibers such as flax for spinning. Three variations of the hackles are created with smaller nails that are closer together. This ensures no fiber is larger than 200 μm in width to capitalized on the inverse correlation between strength and size.

Research has shown that hemp measuring 23.15 ± 17.60 μm has the properties listed in Table I with in a 95% confidence range [3].

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TABLE I
HF PROPERTIES [2]

Properties	Values
Specific Gravity (g/mm^2)	1.5
Moisture Absorption (%)	9.40 ± 0.53
Water Absorption (%)	85~105
Tensile Strength (MPa)	900
Elastic Modulus (Gpa)	34

Next, the dried fibers are placed into 3 L solutions containing 2 wt.% Ca $(OH)_2$ [1] for three days (Fig. 2) and are then cut into 20 mm in preparation for the mix design (Fig. 4). Precipitation is considered and assumed it creates a margin of 0.5.

Binders and Aggregate

The coarse aggregate used is between 9 mm-5 mm and the sand is local and run through a 3 mm sieve. The cement is Iron Clad type I & II.

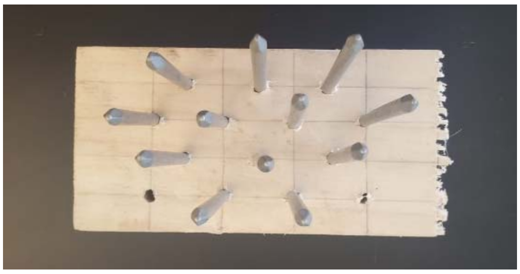

Fig. 1 First version of hackle

Fig. 2 Hemp before processing

Fig. 3 Rinsed hemp

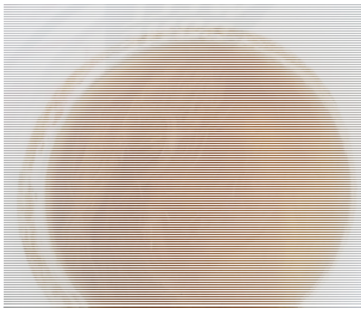

Fig. 4 Hemp soaking in $Ca(OH)_2$

III. MIX DESIGN

The concrete mixes are made to produce four 3x6 inches cylinders of each type. Two with HF and a one without which would be considered the control. The hemp mixes are broken down into a wet and dry which start with the same initial portions, but each is incorporated differently. The mix includes cement, sand, and aggregate which are calculated by weight with 1.5 kg sand and 2.5 kg aggregate for every 1 kg of cement used 1.5:2.5:1 for cement, sand and aggregate. Each mix has an initial water cement ratio of 1:2 with slump ranging between 6-10 cm and 4% HF. Each cylinder is filled, and every layer is tamped at least 25 times.

Dry

Initially, half of the aggregate is placed in the mixer with half of the HF. After three minutes mixing the remaining aggregate, hemp is then added concurrently with a quarter of the water and left to mix for five minutes. The sand is added to the mixer and allowed to mix for another five minutes followed by adding the cement and a partial amount of water. The remaining water required for the mix design is added three minutes later. The final mix was very stiff with no slump as per Fig. 5 and an additional 1/8th of the original water amount is added to achieve a slump of 7 cm.

Wet

First, the hemps combined with a quarter of the total water used are mixed in a separate container and set aside. The aggregate, sand, and cement are then added to a mixer for five minutes. The remaining water and all the fibers are poured into the mixer and left for five minutes. The mixer is stopped and inspected to ensure no lumps of HF are entangled before mixing for a final three minutes. The final slump is low at roughly 1 cm, more water is added to increase the slump to 8 cm.

Each cylinder is enclosed and left to cure for 21 days before the samples are removed. Minor imperfections are seen caused by air pockets (Fig. 6).

IV. DATA AND ANALYSIS

The data in Table II show all the information gathered about each specimen. It shows that the base mix has a greater density than the dry and wet hemp mix, as hemp is used to replace 4% of aggregate. Based on the schematics of typical fracture patterns according to ASTM C39 in Fig. 10 all cylinders created a Type 2 break. This indicates normal friction between plate and specimen [6]. The base case has the highest compressive strength with an average difference of 375.74 psi for the dry mix and 553 psi for the wet mix shown in Fig. 7. The results indicate that the dry mix performed significantly better than the wet mix, primarily because of the reduced variance in compressive strength.

Fig. 5 Dry Mix without additional water

Fig. 6 Dry Mix Cylinder with imperfections

The decrease in compressive strength between the wet and dry mix is due to three major factors, (a) the size of the hand processed HF. Unlike most materials the width was too large on some of the fibers and Fig. 9 [2] shows linear relation and how inconsistent strength in each fiber can be inconsistent. (b) The hemp was still damp from soaking in $Ca(OH)_2$ and the distribution of the hemp was not even, when mixing in both the dry and wet mix the hemp formed clumps which had to be broken down by hand. (c) Since only 4% of fully dried HF was added to the mix and some of fibers were not completely dried, this compromised the strength of the mix instead of increasing the strength. Previous research conducted indicated that the lack of HF could potentially have adverse effects [3].

The dry mix was more promising in regard to strength. Regression analysis was conducted on the data set as shown in Fig. 8 and a T-test was shown in Tables IV and V.

TABLE II
DATA FOR ALL SAMPLES

Sample ID	Height (in)	Diameter (in)	Area (in^2)	Mass (g)	Density (pcf)	Strength (lbs)	Compressive Strength (psi)	Break Type
D1	6.06	3.01	7.10	1545.00	136.00	8249.00	1159.00	2
D2	6.10	3.01	7.10	1565.00	137.00	7782.00	1094.00	2
D3	6.02	3.02	7.20	1538.00	136.00	8320.00	1161.00	2
D4	6.00	3.02	7.20	1543.00	136.00	8701.00	1215.00	2
W1	6.19	3.02	7.20	1508.00	129.00	6799.00	949.00	2
W2	6.24	3.03	7.20	1523.00	129.00	7113.00	986.00	2
W3	6.09	3.03	7.20	1506.00	130.00	7203.00	999.00	2
W4	6.17	3.02	7.20	1520.00	131.00	7063.00	986.00	2
B1	6.01	3.04	7.30	1548.00	135.00	9129.00	1258.00	2
B2	5.99	3.02	7.20	1560.00	138.00	10147.00	1417.00	2
B3	5.96	3.02	7.20	1591.00	142.00	12292.00	1716.00	2
B4	5.68	3.02	7.20	1520.00	142.00	12472.00	1741.00	2

TABLE III
COMPARISON OF COMPRESSIVE STRENGTHS

Base Mix	Dry Mix	Wet Mix
1258	1,159	949
1417	1094	986
1716	1161	999
1741	1215	986

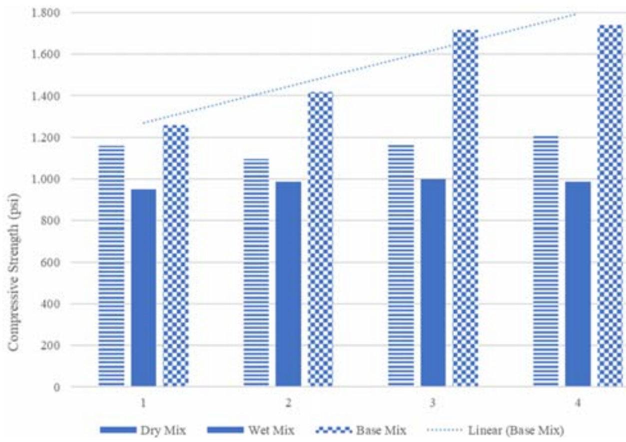

Fig. 7 Compressive strengths of all mix designs

TABLE IV
T-ANALYSIS OF BASE VS DRY MIX

t-Test: Two-Sample Assuming Equal Variances		
	Base Mix	Dry Mix
Mean	1533.00	1157.25
Variance	55278.00	2450.92
Observations	4.00	4.00
Pooled Variance	28864.46	
Hypothesized Mean Difference	0.00	
df	6.00	
t Stat	3.13	
P(T<=t) one-tail	0.01	
t Critical one-tail	1.94	
P(T<=t) two-tail	0.02	
t Critical two-tail	2.45	

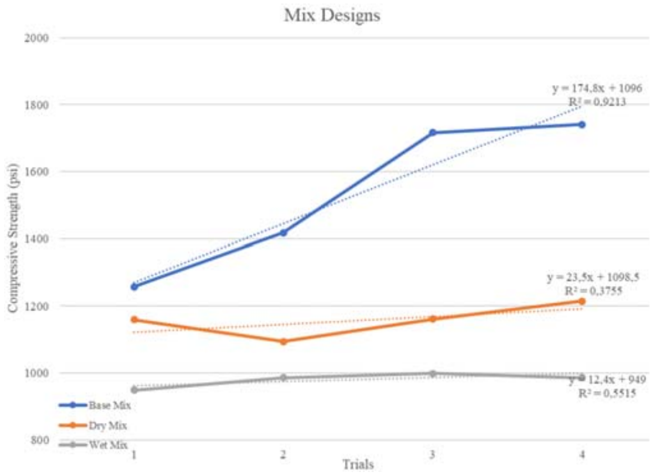

Fig. 8 Comparison of Compressive Strength between Wet and Base Mix

TABLE V
T-ANALYSIS OF BASE MIX VS WET MIX

t-Test: Two-Sample Assuming Equal Variances		
	Base Mix	Wet Mix
Mean	1533.00	980.00
Variance	55278.00	464.67
Observations	4.00	4.00
Pooled Variance	27871.33	
Hypothesized Mean Difference	0.00	
df	6.00	
t Stat	4.68	
P(T<=t) one-tail	0.00	
t Critical one-tail	1.94	
P(T<=t) two-tail	0.00	
t Critical two-tail	2.45	

TABLE VI
AVERAGE OF ALL CYLINDER DATA

Sample ID	Height (in)	Diameter (in)	Area (in^2)	Mass (g)	Density (pcf)	Strength (lbs)	Compressive Strength (psi)
D1	6.05	3.02	7.15	1547.75	136.25	8263.00	1157.25
D2							
D3							
D4							
W1	6.17	3.03	7.20	1514.25	129.75	7044.50	980.00
W2							
W3							
W4							
B1	5.91	3.03	7.23	1554.75	139.25	11010.00	1533.00
B2							
B3							
B4							

V. CONCLUSION

Initial testing indicated that the dry hemp mix had a significantly greater compressive strength than the wet hemp mix (dry mix 1,157 psi and wet mix 980 psi). The dry mix compressive strength was comparable to the base mix in regard to compressive strength only. However, regression analysis indicated variations in mix design for the dry mix with an R^2 value of 0.37 indicating the optimization of the mixing process. It can be concluded that the results are promising using hemp as an alternative for traditional aggregates however, further research is recommended. In the future hemp which has been machine processed and left untreated should be used. Hand processing is not effective enough and becomes more difficult as the fiber widths reduce. Fibers also needs to be entirely dried to ensure accurate weight is measured.

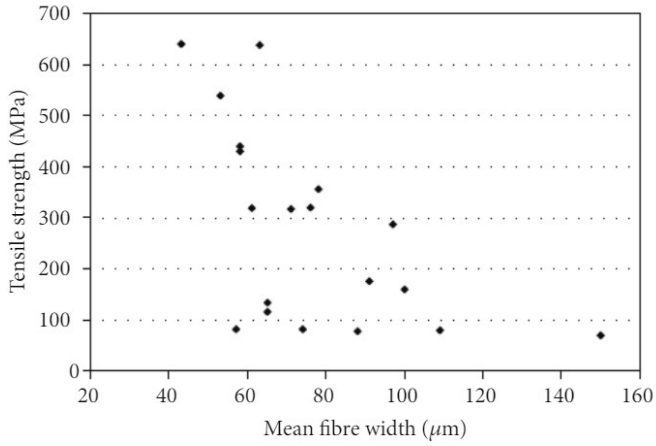

Fig. 9 Data on Hemp Strength

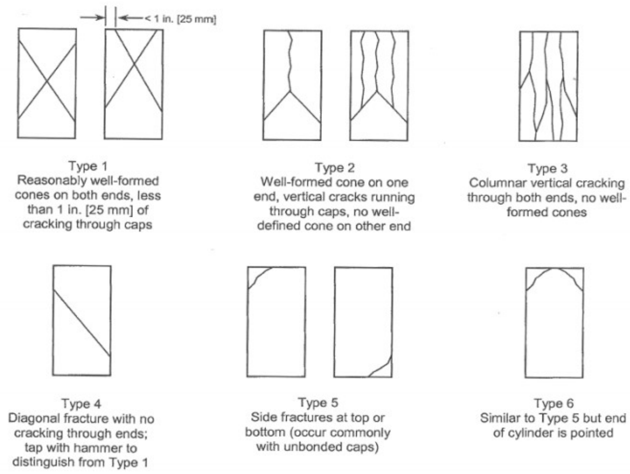

Fig. 10 Concrete Fracture Analysis

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