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Compressive and Flexural Properties of Hemp Fiber Reinforced Concrete

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Abstract: The compressive and flexural properties of hemp fiber reinforced concretes (FRC) were examined in this paper. Natural hemp fiber was mixed using dry and wet mixing methods to fabricate the FRC. Mechanical properties of the FRC were investigated. The main factors affecting compressive and flexural properties of the FRC materials were evaluated with an orthogonal test design. Fiber content by weight has the largest effect. The method for casting hemp FRC has been optimised. Under the optimum conditions, compressive strength increased by 4 %, flexural strength increased by 9 %, flexural toughness increased by 144 %, and flexural toughness index increased by 214 %.

Keywords: Hemp, Fiber reinforced concrete (FRC), Mixing methods, Compressive and flexural properties

Introduction

Fiber reinforced concrete (FRC) is a composite concrete material consisting of a hydraulic cement matrix reinforced with discontinuous discrete fibers (metal, glass, or other synthetic or natural fiber material). The modern development of fiber reinforced cement composites dates back to the 1960s [1]. Since then, fibers used as reinforcement materials have diversified. More and more research now focuses on the natural fiber reinforcement. A unique aspect of these fibers is the low amount of energy required to extract these fibers [2]. Only a low degree of industrialization is required for their processing [3]. Therefore, the applications of natural fibers in concrete have provided an exciting prospect to the construction industry.

To utilize natural fibers as reinforcement in concrete, it is important that the fiber reinforced concrete has appropriate physical and mechanical properties for an application. Nagaraja [4] investigated the strength properties of concrete cube specimens reinforced with short random fibers of nylon and bamboo, and found that only bamboo reinforcement led to improvement in the concrete compressive strain energy. Another research by Shimizu [5] reported that 8 to 12 % of improvement in flexural and tensile strengths occurred on the coir fiber reinforced concrete. Lin [6] showed in his research that sisal fiber contributed to a reasonable increase in toughness of FRC.

Work on the behaviour of concretes reinforced with jute fiber [7], rice straw, sugar cane fiber [8], wood fiber [9] and san fiber [10] has also been reported. From those results, it can be concluded that the addition of these natural fibers does not improve FRC's compressive strength distinctly compared to plain concrete. However, both the flexural load and energy absorption capacity of the FRC are increased over those of plain concrete.

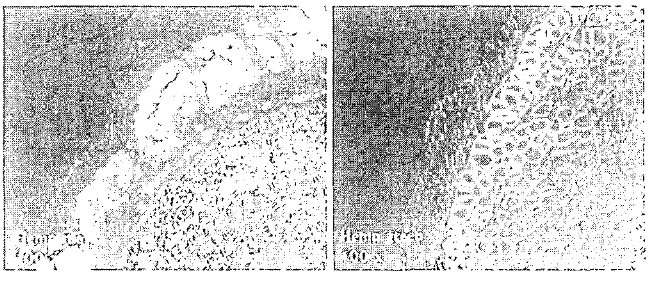
Up to date, little has been reported on the compressive and flexural properties of concrete reinforced with Australian grown hemp fibers. Hemp is a type of natural bast fiber. It is extracted from the bast of hemp plants. Figure 1 shows the cross-sections of mature and green hemp stems. Hemp belongs to the family Mulberry, genus Cannabis. The fiber-producing species is called Cannabis sativa [11]. Unlike other natural fibers such as wool and cotton, hemp fiber needs to be extracted from the bast before it can be utilized. The quality of hemp fiber is dependent on both the bast quality and the processing methods [12].

From 1995, hemp has been allowed to be cultivated in trials in parts of Australia and now it is mainly planted in winter rainfall zone (West Australia, Victoria, Tasmania) of Australia [13]. The specific tensile strength of hemp is 75 cN/tex, and specific modulus of elasticity is up to 60 N/tex [14]. These properties make the hemp fiber a candidate as reinforcement fibre for FRC.

Fiber factor (FF), introduced by the American Concrete Institute (ACI) [16], is a simple way to evaluate the effect of fiber content and fiber length on the mechanical properties of the fiber reinforced materials. The fiber factor used in this research is defined in equation (1),

$$FF = V_f \times \frac{L}{d} \tag{1}$$

Where V_f is the fiber content by weight (in percentage), L is



Mature hemp fiber Green hemp fiber

Figure 1. Cross-section view of the hemp fibers in the stem [15].

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*Corresponding author: xwang@deakin.edu.au the length of fiber in millimetres and *d* is diameter of fiber also in millimetres.

Unlike steel and carbon fibers, natural fibers have not been used in commercial FRC, probably due to the inconsistence in fiber supply and in the quality of resultant concrete, plus a lack of proper mixing method and mature prediction tools for estimating the mechanical performances of the concrete.

In this paper, hemp fiber reinforced concrete is examined. The effects of aggregate size, fiber content (by weight), fiber length and fiber-concrete mixing methods on the concrete's compressive and flexural strength, post-cracking properties, which included flexural toughness and toughness index, were evaluated. A method of optimising the mechanical properties of hemp FRC, mainly based on flexural toughness and toughness index, was also reported.

Experimental

Materials

Hemp Fiber

The hemp used in this research was grown in Australia. The decorticated hemp was retted in a Thies Eco Bloc LFA pressure dye kier together with NaOH solution. The retting was carried out at 120 °C for 40 minutes and was followed by a fresh bath rinse. The fiber was removed from the carrier and squeezed using a Rapid Laboratory Pad Mangle at 3.0 bar pressure. The fiber was then dried using a Stray field 25T RF Dryer. The dried fiber was then opened using a pinned Fearnaught opener. The opened fiber was weighed under dry conditions and cut into different lengths on a Fiber Trimmer manually before mixing.

After retting and opening, hemp fiber width was measured using an Optical Fiber Diameter Analyser (OFDA 100) according to Australia Standard 4492.5-2000. Two thousand fiber snippets were measured on each slide and the results of five slides were recorded. The mean value of the five measurements was taken as the fiber diameter (approximated and referred to as fiber 'width' in this paper). The 'width' distribution of hemp fibers is shown in Figure 2.

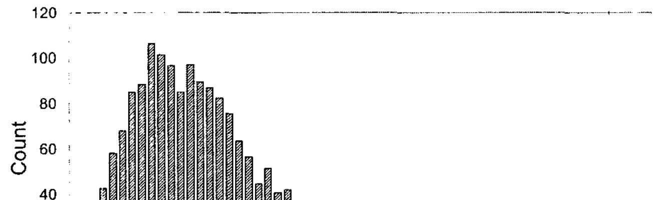

Figure 2. The width distribution of hemp fibers.

Table 1. Physical properties of hemp fiber

Properties	Values
Specific gravity (g/mm^3)	1.5
Width (micrometer)	23.15 ± 17.60
Moisture absorption (%)	9.40 ± 0.53
Water absorption (%)	85~105
Tensile strength (MPa)	900 [17]
Elastic modulus (GPa)	34 [17]

Table 1 gives some of the hemp fiber physical properties measured and reference mechanical properties used in this paper. The range of values is at the 95 % Confidence Level.

Binders and Aggregates

Three grades of aggregate (local Blue Metal Screenings gravels) were used in the experiment. Their maximum sizes were 20 mm, 14 mm, and 7 mm respectively. Their apparent particle densities were 2.36, 2.43, and 2.60×10^3 kg/m^3 respectively, and their water absorption ratios were 3.52, 3.80, and 4.12 % (measured with reference to Australian Standard 1141.5-2000), respectively.

The sand used in the experiment was local Washed Granetic sand. Its apparent particle density was 2.48×10^3 kg/m^3, and water absorption ratio was 0.40 %.

The cement was supplied by Australian Tradesman GP Cement (Manufactured by Australian Cement Limited), and the designed 28 days compressive strength of concrete was expected in the range of 20-40 MPa.

Experimental Design

Many factors can affect the properties of natural fiber reinforced concrete. They include fiber type, fiber geometry, fiber form, surface and matrix properties, mixture fraction design, mixing, placing and curing methods, and many others [18]. Each factor also contains different constituents that can affect the FRC properties. Therefore design of experiments is very important in research into FRC materials.

In this paper, it was assumed in advance that the chief function of hemp fiber was to inhibit the propagation of cracks passing through the matrix and to enable stress to be transferred across the cracking area. From this, it would be expected that hemp FRC should have an improved compressive and flexural properties. Therefore, aggregate sizes, fiber content by weight and fiber length were selected as the main factors, and compressive and flexural strength, flexural toughness, and toughness index were chosen as the dependent variables. Early aged (7 days) FRC specimens were used in the experiment.

In a flexural test, specimens' width and depth should equal, or exceed, three times both the fiber length and the nominal dimension of the maximum size aggregate [19]. Otherwise, the long fibers not only add difficulty to the mixing procedure, they also tend to increase the measured flexural strength which is atypical of short random fiber composite. Therefore, the

Table 2. First group in experimental design

No.	Max. aggregate size (mm)	Fiber content by weight (%)	Fiber length (mm)	Fiber factor
1	20	0	0	0.00
2	14	0	0	0.00
3	07	0	0	0.00
4	20	0.18	10	0.78
5	14	0.18	10	0.78
6	07	0.18	10	0.78
7	20	0.18	20	1.57
8	14	0.18	20	1.57
9	07	0.18	20	1.57
10	20	0.36	20	3.13
11	14	0.36	20	3.13
12	07	0.36	20	3.13
13	20	0.60	20	5.22
14	14	0.60	20	5.22
15	07	0.60	20	5.22
16	20	1.06	30	13.83
17	14	0.84	30	10.96
18	07	0.84	30	10.96

Table 3. Orthogonal test design of the second group

Factors	A: Max. aggregate size (mm)	B: Fiber content by weight (%)	C: Fiber length (mm)
Level I	20	0.36	10
Level II	14	0.54	20
Level III	07	0.72	30

Table 4. Orthogonal test design table

No.	A: Aggregate size (mm)	B: Fiber content (%)	C: Fiber length (mm)	Result
19	A1: 20	B1: 0.36	C1: 10	F1
20	A1: 20	B2: 0.54	C2: 20	F2
21	A1: 20	B3: 0.72	C3: 30	F3
22	A2: 14	B1: 0.36	C2: 20	F4
23	A2: 14	B2: 0.54	C3: 30	F5
24	A2: 14	B3: 0.72	C1: 10	F6
25	A3: 07	B1: 0.36	C3: 30	F7
26	A3: 07	B2: 0.54	C1: 10	F8
27	A3: 07	B3: 0.72	C2: 20	F9
I	I1=F1+F2+F3	I2=F1+F4+F7	I3=F1+F6+F8	
II	II1=F4+F5+F6	II2=F2+F5+F8	II3=F2+F4+F9	
III	III1=F7+F8+F9	III2=F3+F6+F9	III3=F3+F5+F7	
T	T1= max(I1,II1,III1) − min(I1, II1,III1)	T2= max(I2,II2,III2) − min(I2,II2,III2)	T3= max(I3,II3,III3) − min(I3,II3,III3)	

maximum fiber length in the experiment is limited to 30 mm.

Two groups of experiments were carried out. The wet mixing method was used for the first group of experiments and the experimental material factors are shown in Table 2.

For the second group of experiments, the dry mixing method was used to carry out the mixing procedure. To cover more data range and to reduce the number of experiments required, the Taguchi method (orthogonal test method) [20] and an orthogonal test table were used in the test design. Table 3 shows the main factors and their levels for this group of experiments.

The experiment arrangement is shown in Table 4, where I, II, III are the sum of the result (F) of different factors, II3 is the sum of all the results in level II factor 3 (F2+F4+F9), and T is the difference between these factors, with a higher T value representing a stronger influence of this factor on the FRC result.

Within each group in this research, any specimens within the group with an exceptional test result were cast again in the same component fraction and tested to confirm the data obtained. If variation between the two results was above 10 %, the average value was used as the new result, and if variation was less than 10 %, then the former test result was accepted.

FRC Sample Preparation

In this research, over 300 cylinder and beam specimens were cast and tested. The concrete mix design of cement: sand: aggregate is 1:1.5:2.5 by weight, with water cement ratio of 0.5 in both groups. This water ratio allowed for a 6-10 cm slump medium workability used for mixing the concrete specimens. Each test result represents the mean of at least 3 tests.

The weight of sand and aggregate count in this mix design was measured at their saturated surface-dry (SSD) condition weight. With reference to Australian Standard 1141.5-2000, the sand and aggregate apparent particle density and SSD base particle density were calculated prior to the test in order to modify the water content in concrete component. This gave a constant water/cement ratio for specimens in each batch. The mixing was done with a 2.2 cubic feet rotary drum mixer. At least six specimens were made in each batch; three for compression and three for flexural test.

In the sample preparation procedure, the slump test is a quick and effective guide line to measure workability of FRC. After introducing hemp fibers into the FRC, the water absorption ability of the fiber will reduce water quantity used in cement action and decrease the slump of concrete, which means less workability. The SSD condition for hemp fiber was uniformly attained using the centrifugal method, i.e., dry spinning for 5 minutes. The SSD weight of hemp fiber is approximately 2.15 times of an air-dried weight [21]. In this experiment, the SSD water absorption ratio was set as 100 %.

Another factor during this procedure, mixing method, is

Table 5. Wet mix procedures

1) The water required for mixing was weighed, including the extra water to allow for hemp fiber absorption (SSD);
2) The hemp fiber was added into the water container and stirred slowly;
3) The aggregate, sand, and cement were added into mixer;
4) The mixer was started and run for 3 minutes;
5) All the water and fibers were slowly poured into the matrix;
6) The mix was stirred for 4 minutes;
7) Mixing was stopped for 2 minutes;
8) The mix was then stirred for a further 3 minutes before being poured and cast into oiled steel moulds.

Table 6. Dry mix procedures

1) Half amount of aggregate was poured into the mixer, the mixer was started and then half amount of hemp fiber was added;
2) All the aggregate was added into the mixer;
3) The rest of hemp fiber was slowly put in the aggregate;
4) Extra water for hemp fiber absorption (SSD) was added and stirred with mixer for a further 5 minutes;
5) Sand was added into the mix and stirred for 3 minutes; then cement was added together with half amount of water;
6) The mixer was stirred for 3 minutes and the remaining water was added;
7) Mixing was stopped for 2 minutes;
8) The mix was then stirred for 3 minutes before being poured and cast into oiled steel moulds.

critical to the hemp FRC. Hardly any published papers on short fiber reinforced concretes revealed the method of fiber dispersion during mixing, with the exception of a paper by Chen [22] who used a dispersant and a deformer in mixing short carbon fiber in matrix and found that the wet mix method was a more effective method only if a dispersant and a defoamer were used.

To identify a convenient procedure and reduce the cost of the hemp FRC product, the following two approaches (wet mix and dry mix) were used in this research. They are described in Tables 5 and 6.

When pouring the mix into a mould, compacting by rodding operation was continued, as recommended by AS 1012.8.1-2000 and 1012.8.2-2000. After that, the specimens were allowed to settle over night inside of covered moulds in a room with a temperature of around 22-24 °C. After 24 hours, the specimens were removed from the moulds and placed in 22-24 °C water tank to cure for 6 days. Then, they were removed from the tank, air-dried, and tested at the requested date.

Mechanical Testing

Compressive Strength

Compressive tests were carried out on a 385 KN MTS Servo Hydraulic Universal Testing Machine. The experimental set-up is shown in Figure 3.

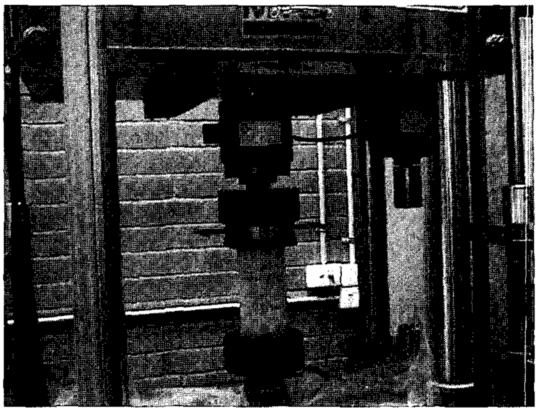

Figure 3. Compressive test configuration.

The sample was a cylinder of 200 mm height and Φ100 mm cross-section. All the specimens were surface dried before testing. The preload was 10 kN and the loading rate was 2.5 kN/sec (about 20 MPa/min according to AS 1012.9-2000). The tests ended when the displacement reached 10 mm. Load was measured directly from the MTS load cell and the vertical displacement at the loaded cross-head was obtained from the MTS actuator stroke. Due to the proximity of the grips to the FRC specimens' surface, additional LVDTs were not needed to measure the vertical displacement. This considerably reduced the time to test a specimen. Load and displacement data were taken continuously by a computer-controlled data acquisition system. Top loads and corresponding deflections were continuously recorded automatically by computer in two readings per second.

The compression stress is calculated using equation (2):

$$\sigma_c = \frac{4P(1000)}{\pi D^2} \tag{2}$$

Where σ_c is the compression stress, in MPa, P is the maximum applied force indicated by the testing machine, in kN, and D is the average diameter of specimen, in millimetres.

Flexural Strength (modulus of rupture)

The bending tests were carried out on a 350 kN MTS testing system using a four point configuration (Figure 4), with 300 mm span and 100 mm × 100 mm cross-section, at a loading rate of 0.13 kN/sec (reference to AS 1012.11-2000). The tests ended when the displacement at mid-span reached 5 mm. All the specimens were surface dried before testing. Top loads and corresponding mid-span deflections were continuously recorded automatically during the test with two readings per second.

When the fracture occurs within the middle third of the specimen, the modulus of rupture (flexure) is calculated using equation (3).

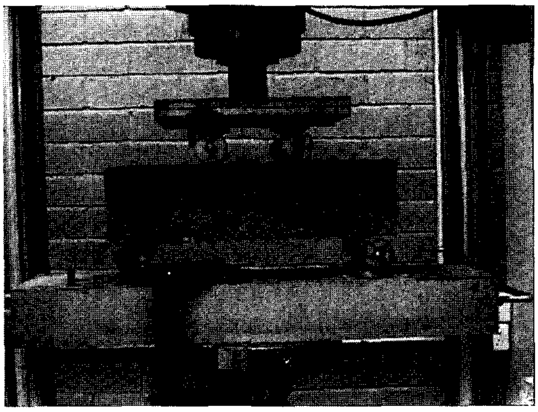

Figure 4. Flexural test configuration.

$$f_{cf} = \frac{PL(1000)}{BD^2} \tag{3}$$

Where f_{cf} is the modulus of rupture, in MPa, P is the maximum applied force indicated by the testing machine, in kN, L is span length, in millimetres, B is the average width of the specimen at the section of failure, in millimetres, and D is the average depth of specimen at the section of failure, in millimetres.

Flexural Toughness

Toughness, which is the concrete property represented by the area under a load-deflection curve, is a measure of the energy absorption capacity of a material and is used to characterize the material's ability to resist fracture when subjected to static strains or to dynamic or impact loads. Toughness may be specified to help define the performance requirements of FRC intended for use where post-cracking energy absorption or resistance to failure after cracking is important [23].

According to the American Concrete Institute (ACI) Committee 544 method of characterizing toughness, the toughness is defined as the area under the load-deflection curve up to mid-span deflection of 1.9 mm divided by the area of cross-section. Figure 5 shows a typical experimental load-deflection curve of FRC specimn.

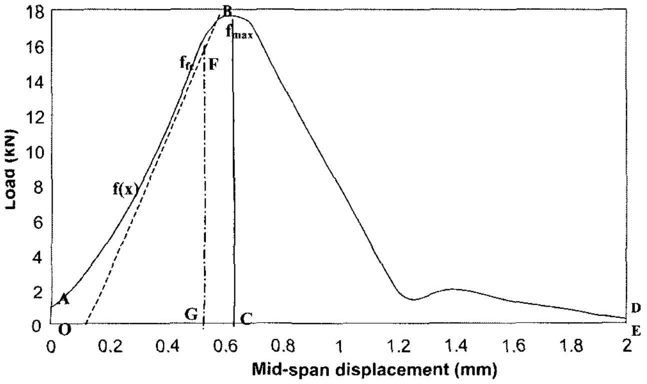

Figure 5. The flexural load and deflection curve of FRC.

The toughness can be worked out from equation (4) below,

$$T = \frac{\int_0^{1.9} f(x)dx}{S} = \frac{Area(OABDCO)}{S} \tag{4}$$

Where, T is the toughness, in kJ/m^2 (kN m/m^2), and S is the cross-section area of the broken beam, in m^2.

Since the vertical displacement at the loaded crosshead was obtained from the MTS in bending test, so the load-deflection curve contained a small crosshead displacement and centre point deflection measured from the bottom of the beam [2]. As the ultimate fracture load in flexural test was only below 20 kN, these deformations were within the tolerant limit and their effects on final test results could be ignored.

A toughness index is defined as the area above divided by the area under the curve up to the deflection at first crack (first-crack toughness). From Figure 5, one can notice that it's hard to determine the first-crack load f_{fc} exactly. For the convenience of calculation, the area (OABCO) under the deflection of maximum load f_{max} was used instead (Peak-load toughness index). Comparing peak-load toughness index to first-crack toughness index, the former will be much smaller.

After testing, samples were cut with an auto diamond saw and their cross sections were observed under an OLYMPUS BX51M microscope with a magnification of 125 times.

Results and Discussion

The uniform dispersion of hemp fibers inside the specimen acts like many micro-bars and is expected to help withstand the tensile and shear strength.

Wet Mix Group

Table 7 shows the results of this group. The ranges following each data are at the 95 % Confidence Level.

To compare the effect of aggregate and fiber, an improvement ratio (IR) was calculated using equation (5):

$$IR = \frac{FRC\ data - plain\ concrete\ data}{plain\ concrete\ data} \times 100 \tag{5}$$

Table 7 shows the effect of fiber factors on the FRC's mechanical properties. Compressive strength relationships of the different fiber factors are shown in Figure 6. From the compressive strength test results, it may be concluded that, for small aggregate size (7 mm and 14 mm) FRC, compressive strength improves slightly when the fiber factor is lower than 0.78, and continuously decreases when fiber factor is greater than this value. For the 20 mm aggregate size group, it reached the peak at a fiber factor around 1.57.

Flexural strength test results are shown in Figure 7. The value of the critical fiber factors for FRC is variable for different aggregate sizes. For the 20 mm aggregate size samples, the flexural strength reaches its peak at 3.13 FF value; for the

Table 7. Mechanical properties of hemp FRC in wet mix group

No.	Compressive strength (MPa) & (IR %)		Flexural strength (MPa) & (IR %)		Flexural toughness (kJ/m^2) & (IR %)		Toughness index & (IR %)	
1	30.8 ± 10.35	(0)	4.77 ± 0.26	(0)	0.78	(0)	1.38	(0)
2	33.45 ± 2.45	(0)	5.09 ± 0.09	(0)	1.19	(0)	1.87	(0)
3	30.57 ± 2.91	(0)	5.08 ± 0.24	(0)	1.01	(0)	1.94	(0)
4	23.82 ± 0.23	(−23)	4.52 ± 0.24	(−5)	1.34	(+72)	3.33	(+41)
5	35.22 ± 1.06	(+5)	4.78 ± 0.12	(−6)	1.08	(−9)	2.45	(+31)
6	32.73 ± 5.89	(+7)	5.04 ± 0.36	(−1)	1.37	(+36)	3.72	(+92)
7	32.65 ± 2.09	(+6)	4.62 ± 0.50	(−3)	0.73	(−6)	1.86	(+35)
8	34.30 ± 3.55	(+3)	5.10 ± 0.36	(0)	0.89	(−25)	2.01	(+7)
9	24.70 ± 2.80	(−19)	4.69 ± 0.20	(−8)	0.95	(−6)	2.83	(+46)
10	32.09 ± 0.82	(+4)	5.18 ± 0.24	(+9)	1.90	(+144)	4.34	(+214)
11	26.41 ± 2.44	(−21)	4.96 ± 0.25	(−3)	1.28	(+8)	3.03	(+62)
12	24.23 ± 3.40	(−21)	4.56 ± 0.32	(−10)	1.42	(+41)	3.64	(+88)
13	26.76 ± 0.29	(−13)	4.11 ± 0.24	(−14)	1.25	(+60)	3.72	(+170)
14	25.52 ± 1.93	(−24)	4.41 ± 0.22	(−13)	1.39	(+17)	4.13	(+121)
15	20.08 ± 3.71	(−34)	4.49 ± 0.13	(−12)	1.51	(+50)	4.92	(+154)
16	13.88 ± 0.44	(−55)	3.10 ± 0.08	(−35)	1.04	(+33)	2.89	(+109)
17	21.73 ± 1.18	(−35)	4.07 ± 0.14	(−20)	1.33	(+12)	3.75	(+101)
18	20.11 ± 0.58	(−34)	4.10 ± 0.05	(−19)	1.38	(+37)	4.45	(+129)

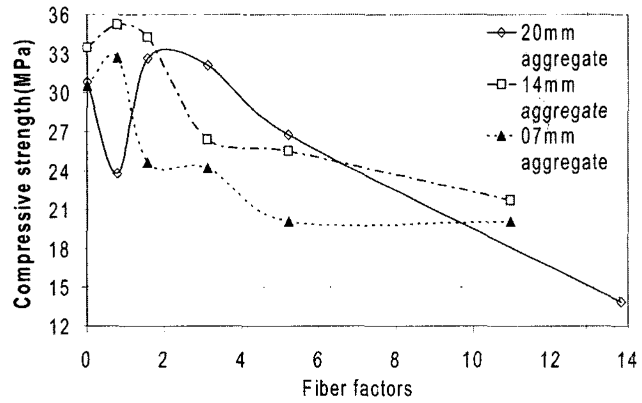

Figure 6. Compressive strength vs. different fiber factors.

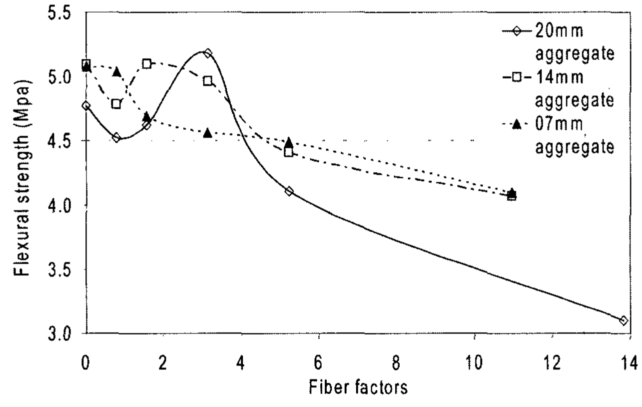

Figure 7. Flexural strength vs. different fiber factors.

14 mm aggregate size samples, the flexural strength reaches its peak at about 1.57 FF value; and for the 7 mm aggregate size samples, the peak flexural strength appears to occur when no fiber is added. This phenomenon indicates that the flexural strength of the FRC materials is affected by aggregates size, fiber factor, and their interactions.

The reason for reduction in compressive and flexural strength instead of an improvement with the addition of hemp fibers may be attributed to the air carried by hemp fiber during mixing, as air pockets may form many weak cavities inside the FRC. From experimental observation, the weakness can be summed up into three kinds: micro-structure cavity (Figure 8), gap along with fiber cluster (Figure 9) and fiber ball (Figure 10)

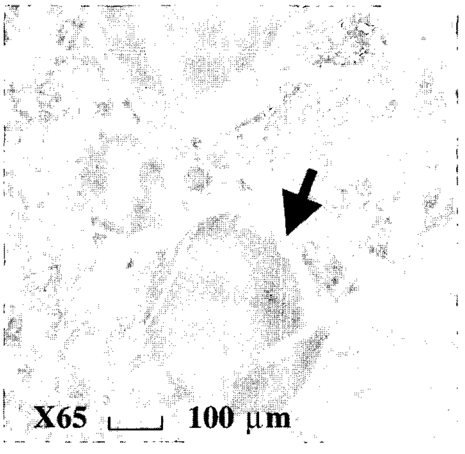

Figure 8. Cavity inside specimens.

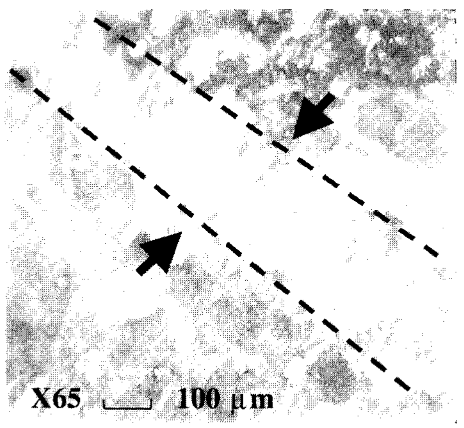

Figure 9. Gap along fiber inside specimens.

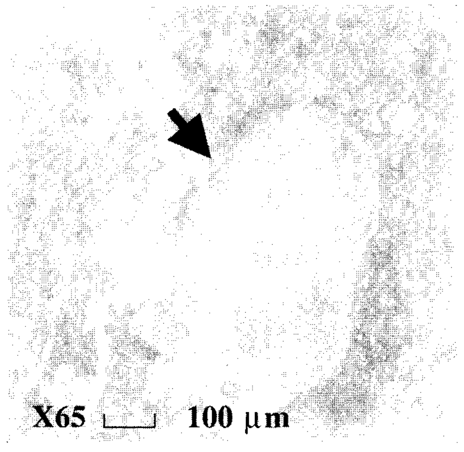

Figure 10. Fiber ball inside specimens.

inside the FRC. These three kinds of defects are primarily the results of insufficient dispersant during the casting procedure, especially results from the rodding operation (Hand vibration methods). Other reasons contributing to these weakness may include fiber length being too long, lack of control in dispersing fiber into matrix (too quick or too much at a time), and mix methods (they were more likely to appear in wet mix than in dry mix).

Micro-structure cavity (Figure 8) is normal in plain concrete. However, it was more frequent with hemp fiber inside FRC. Gaps along with fiber cluster (Figure 9) and fiber balls (Figure 10) inside the specimens are fatal. These sudden changes in the cross-section will significantly increase the chances of stress concentration. The phenomenon of the fibrous matrices having higher air contents with increase in the fiber volume, and reduced flexural and compressive strength as a result has also been reported before [24]. These defects are called weakness factors.

It can be seen from Table 7 that at low fiber factors, compressive and flexural strength increases for some specimens. This is attributed to the possibility that the water which had been absorbed by the fibers, in significant quantities, is now available and utilised for further hydration of cement [7], which increases the bonding strength between the fiber and the matrix. Another reason for such favourable behaviour could be that fibers inhibited initial drying shrinkage of FRC and consequently also the inhibition of formation of shrinkage induced micro-cracking inside the specimens afterwards. These influences can be called positive factors. These positive factors and weakness factors act together on FRC to influence its properties.

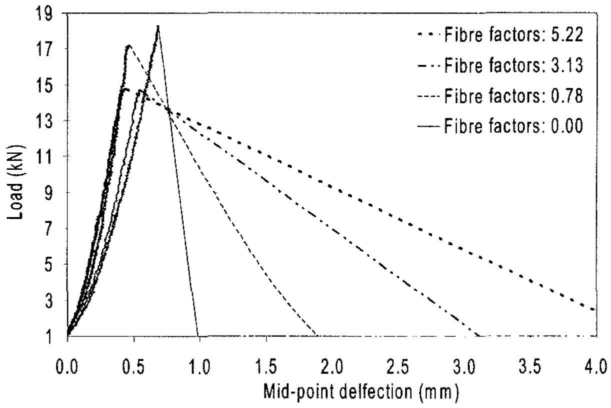

Figure 11. Flexural load-deflection curve of 7 mm aggregate size FRC.

The fiber is more effective in increasing the flexural toughness and toughness index than the compressive and flexural strength. Figure 11 shows the flexural load-deflection curves of 7 mm aggregate size FRC specimens for different fiber factors. Hemp FRC characteristics differ from that of plain concrete. The plain concrete sustains a load up to its ultimate (maximum) strength, when it fractures simultaneously as the first crack appears under the tensile force. Then, it loses the ability to sustain force any more. The load-deflection curve for the hemp FRC has a much smaller declining slope than that for plain concrete, and even under a quite reasonable crack width or deflection (1.9 mm in this research), the FRC specimens still has considerable residual strength. The maximum deflections at fracture of specimens increase with the increase in fiber factors. Thereafter, the hemp FRC is still able to sustain load under considerable deflection during the test as shown in Figure 12.

Flexural toughness relationships with different fiber factors of diverse aggregate size are shown in Figure 13. At around 0.78 fiber factor (FF), flexural toughness of all aggregate size reaches their secondary peak, and then drops sharply (slightly decreased compared with reference value at fiber factor equal to 0). The 20 mm aggregate size specimens peak at around 3.13 FF value, and the other two kinds of aggregate size specimens reach their peak at about 5.22 FF value. The reason for this occurrence could be explained from Figure 11; toughness is the area under flexural load-deflection curve, and as FF value keeps on increasing, the maximum flexural strength decreases. However the post-peak properties of load-deflection curve have been improved. So the toughness changing trend is non-linear

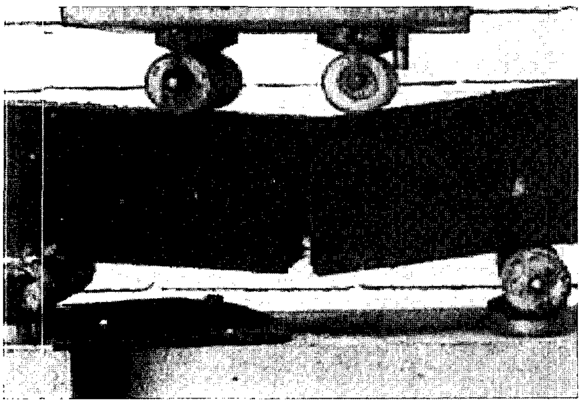

Figure 12. FRC specimen fracture in flexural test.

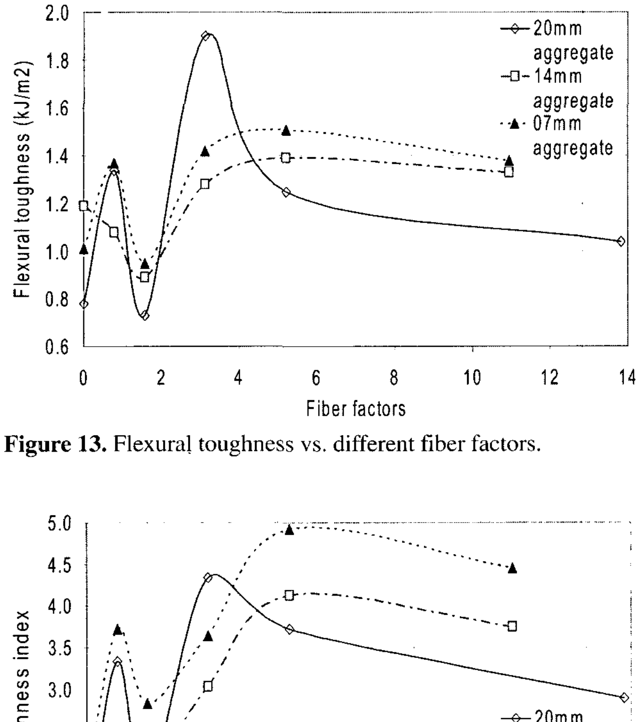

Figure 13. Flexural toughness vs. different fiber factors.

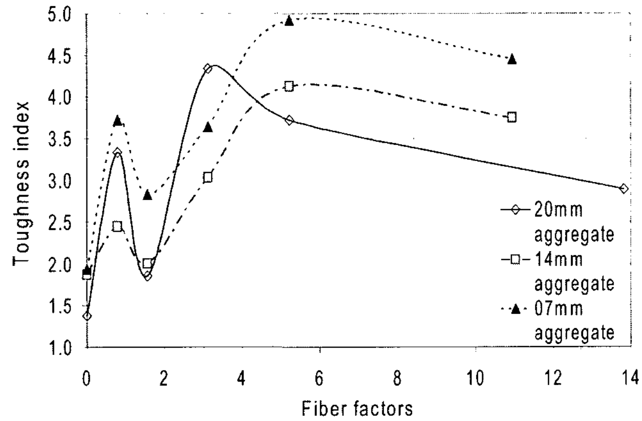

Figure 14. Toughness index vs. different fiber factors.

and toughness is influenced by peak load and post-peak roperties simultaneously.

Figure 14 shows the toughness index of a different aggregate size FRC in relation to fiber factors. Their trends are quite similar to the curves of flexural toughness. However, because toughness is related to the area of whole load-deflection curve, a slight decrease in maximum load will influence toughness greatly. As fiber content increases, more improvement in deflection will overcome the influence of maximum load loss to whole load-deflection area. So the change of toughness (whole area) is non-linear. There is a difference in toughness index, it's ratio of area of curve at post-peak load and area under load-deflection curve before peak load, so it rises at the same time as fiber is introduced (even at the bottom of toughness index vs. fiber factors, where FF value is nearly 2, the toughness index is still greater than the reference value at where FF equals 0).

As the FF value increases, the peak load of FRC will decrease, and the material becomes softer. Both the area of pre-peak load and the post-peak load increase. Flexural toughness index depends on the ratio of these two areas. These increases are also non-linear and related to fiber, matrix, and their interface properties. What we know is that there should be a balance point between them, therefore, when fiber factor passes 5.22 as shown in Figure 14, toughness index also decreases gently.

Compared to toughness, the toughness index shows the trend of fiber induced improvement in FRC more clearly. Though the peak point of the 20 mm aggregate size is still at 3.13 FF value and before the other specimens of different aggregate sizes reached their peaks at 5.22 FF value, the toughness index of 7 mm aggregate size is the largest compared with the other two sizes, meaning that 7 mm aggregate size contributed to the improvement in the FRC post-peak properties.

Another trend that needs to be noticed from Figures 13 and 14 is that after the point of 5.22 FF value, the toughness and toughness index become more stable, and the slope of decrease is very gentle as the FF value increases. This suggests that the loss of maximum flexural strength and the improvement in post-peak properties have more or less reached a balance point.

These results indicate that the fiber factor has an important effect on compressive and flexural properties of hemp FRC specimens, and the critical point of fiber factor here should be 5.22, which means 0.6 % fiber content by weight and 20 mm fiber length. Also, considering the result for toughness index, 7 mm aggregate size is recommended when wet mixing method is used.

Dry Mix Group

Table 8 shows the results, with the plain concrete (specimens No.1, 2 and 3) data used as reference for the FRC specimens in this group.

Table 9 shows the data computed following the calculation rule of orthogonal test method.

Compressive Strength

The orthogonal test results in Table 9, T_B (28.12) > T_C (9.16) > T_A (3.77) suggest that the factor B (fiber content) has significant influence on the compressive strength, followed by factor C (fiber length), and then factor A (aggregate size).

Table 8. Mechanical properties of hemp FRC in the dry mix group

No.	Compressive stress (MPa) & (IR %)		Flexural stress (MPa) & (IR %)		Flexural toughness (kJ/m^2) & (IR %)		Toughness index & (IR %)	
01	30.81 ± 0.35	(0)	4.77 ± 0.26	(0)	0.78	(0)	1.38	(0)
02	33.45 ± 2.45	(0)	5.09 ± 0.09	(0)	1.19	(0)	1.87	(0)
03	30.57 ± 2.91	(0)	5.08 ± 0.24	(0)	1.01	(0)	1.94	(0)
19	25.41 ± 1.58	(−18)	4.43 ± 0.04	(−7)	1.09	(+40)	3.39	(+146)
20	25.31 ± 0.65	(−18)	4.20 ± 0.16	(−12)	1.55	(+99)	3.58	(+159)
21	20.72 ± 1.20	(−33)	3.72 ± 0.15	(−22)	0.83	(+6)	2.46	(+78)
22	25.93 ± 2.11	(−22)	4.59 ± 0.13	(−10)	1.29	(+8)	3.28	(+75)
23	23.69 ± 1.42	(−29)	3.88 ± 0.04	(−24)	1.21	(+2)	4.03	(+116)
24	18.49 ± 1.20	(−45)	3.71 ± 0.11	(−27)	0.96	(−19)	3.28	(+75)
25	30.51 ± 0.93	(0)	4.98 ± 0.23	(−2)	1.57	(+55)	3.87	(+99)
26	22.63 ± 0.79	(−26)	4.48 ± 0.25	(−12)	1.46	(+45)	4.27	(+120)
27	14.53 ± 0.60	(−52)	3.21 ± 0.17	(−37)	0.90	(−11)	3.61	(+86)

Flexural Strength

Flexural strength is one of the main properties of plain concrete that fiber reinforcements can improve. Since T_B (3.34) > T_C (0.62) > T_A (0.49), the fiber content influences the flexural strength more than the other two factors.

Flexural Toughness

Again, it can be seen from Table 9 that T_B (1.54) > T_A (0.47) > T_C (0.24), suggesting that the fiber content has a greater influence than the other two factors.

Flexural Toughness Index (peak load)

Toughness index has a close relationship with toughness. However, because the ultimate compressive and flexural strength decrease as the fiber content increases, flexural toughness can't distinguish the relationship between total energy absorption and fiber content significantly.

Through Table 9, it can be seen that T_B (2.55) > T_A (2.33) > T_C (0.58). That means the fiber content also has a greater influence than the other two factors. From the data of each column, we can see in factor B, the toughness index reaches a peak at Level II (where fiber content is 0.54 %); in factor A, toughness index steps up from Level I to Level III (as the aggregate size decreases from 20 mm to 7 mm); in factor C, toughness index reduces slightly from Level I to Level III (as the fiber length increases from 10 mm to 30 mm).

So the recommended optimal mix design for this group should be around 0.54 % fiber content, 7 mm aggregate size and 10 mm fiber length. These results are in agreement with that for the wet mix group, confirming that fiber content by weight plays a dominant role in determining the compressive and flexural properties of hemp FRC.

Comparison of Mixing Methods

Using the result of 0.36 % by weight fiber content, 20 mm fiber length and 14 mm aggregate size specimen in the first group (No.11) and exactly the same component hemp FRC specimen in second group (No.22), a comparison is listed in Table 10. It can be seen that, in contrast with the report from Chen [22], wet mix method without any dispersant and defoamer agents was not markedly superior to dry mix method in hemp FRC.

Table 9. Calculated results from the orthogonal test

Property	Level	Factor		
		A	B	C
Compressive strength	I	71.44	81.85	66.53
	II	68.11	71.63	65.77
	III	67.67	53.73	74.93
	T	3.77	28.12*	9.16
Flexural strength	I	12.35	13.99	12.62
	II	12.18	12.57	12.01
	III	12.68	10.65	12.58
	T	0.49	3.34*	0.62
Flexural toughness	I	3.48	3.95	3.51
	II	3.46	4.23	3.75
	III	3.93	2.69	3.61
	T	0.47	1.54*	0.24
Flexural toughness index	I	9.42	10.54	10.93
	II	10.58	11.88	10.47
	III	11.75	9.33	10.35
	T	2.33	2.55*	0.58

*indicates the most significant results (T) for each property.

In the absence of dispersant and defoamer agent during mixing, there is not much difference between these two mix methods. However, dry mix method would be preferred for natural fibers like hemp, because natural fibers have strong ability in absorbing water and wet mix tends to increase fiber

Table 10. Mechanical properties hemp FRC prepared with different mix methods

Mix method	Compressive strength (MPa)	Flexural strength (MPa)	Flexural toughness (kJ/m^2)	Toughness index
Wet mix	26.41	4.96	1.28	3.03
Dry mix	25.93	4.59	1.29	3.28

Table 11. Statistical analysis for different mix methods

Mix method	Compressive strength SD	Flexural strength SD	Compression significance effect *p*
Wet mix	0.23-5.89	0.05-0.50	0.002
Dry mix	0.60-2.11	0.04-0.25	3.0E-7

entanglement or balling. Another reason to recommend dry mix method would be the stability of specimens' quality. Standard Deviation (SD) in wet mix group ranges from 0.23 to 5.89 in compressive strength and from 0.05 to 0.50 in flexural strength (Table 11). For the dry mix group, SD ranges from 0.60 to 2.11 in compressive strength and from 0.04 to 0.25 in flexural strength. Wet mix introduces the air into FRC more easily than dry mix, which causes large inconsistence in product quality even within the same batch.

Statistical analysis confirms the results. Analysis of variance (ANOVA) was performed on the collected data with SPSS® package (SPSS release 11.5). The SPSS general linear model procedures were used to evaluate correlation with the mechanical properties of hemp FRC specimens and main parameters. Only the most significant relationship between compressive strength and fiber content was discussed here.

Wet mix shows more significant influence on flexural toughness and toughness index, but accompanied by unstable quality caused by poor dispersion of fibers. On the contrary, samples from dry mix method have a relatively stable quality in compressive and flexural properties of hemp FRC and shown more direct relationship with the main factor, which is fiber content. In Table 11, p is the observed significance effect, and a smaller p value indicates more significant relationship between the dependant variables and the factors.

Optimal Mix Design

After the analysis of the dry mix and wet mix groups, the observed significance level for compressive and flexural properties was very low, which means interaction between them is clear enough and one can use the separate-variance t test and regression analysis continually in the statistical evaluation. However, the FRC specimens' data set is not large enough at this stage to carry on so many variable analyses. It can only be used to determine the general trend of hemp FRC.

As discussed before, under the wet mix condition, to achieve optimum flexural toughness index, the best mix design for hemp FRC will be about 0.6 % fiber content by weight, 7 mm aggregate size and 20 mm fiber length. Similarly, under the dry mix condition, the best design plan should be about 0.54 % by weight fiber content, 10-20 mm fiber length (or shorter fiber length) and 7 mm aggregate size. To verify the optimum design plan, a separate experiment was carried out under the dry mix condition, using 0.54 % by weight fiber content, 20 mm fiber length (or shorter fiber length) and 7 mm aggregate size. The results from the confirmation experiment agree well with the expected results, as indicated in Table 12.

Table 12. Comparison of validation results of optimal design versus maximum individual results in dry mix group

	Compressive strength (MPa)	Flexural strength (MPa)	Flexure toughness (kJ/m^2)	Toughness index
Validation	22.94	4.69	1.59	4.40
Prediction	20.80	4.55	1.51	4.65
Individual maximum	30.51	4.98	1.57	4.27

Conclusions

A method for casting hemp fiber-reinforced concrete (FRC) has been optimized. This method uses hemp fiber in the amount of 0.36 % fiber content by weight, 20 mm length fiber in the case of concrete with 20 mm aggregate size (wet mix method). Compared to plain concrete, this FRC improves the compressive strength by 4 %, flexural strength by 9 % and flexural toughness by 144 % and toughness index (peak load) by 214 %.

The FRC, cast with hemp fiber in the amount of about 0.60 % fiber content by weight, 10 mm fiber length (or shorter fiber length) and 7 mm aggregate size (dry mix method), yields a weak compressive strength and slightly decreased flexural strength but its overall flexural toughness increase is 57 % and toughness index increase is 127 %.

Fiber content by weight is the main factor that affects the compressive and flexural properties of hemp FRC, irrespective of the mix method used. Under the conditions reported in this paper, the minimum hemp fiber weight fraction for the fiber to be effective for increasing the flexural toughness is about 0.3 %, and the maximum fiber weight fraction for good flexural toughness is about 0.8 %, above this limit the rupture ductility of FRC will decrease.

From this research, hemp fiber shows good reinforcement properties in FRC. For stable material quality, dry mix method is recommended. The addition of hemp fibers into the matrix significantly increases the air content. As a consequence, the compressive strength and flexural strength decrease as the fiber content exceeds the optimal point (approximately 0.6 % in this research). Using dispersant and defoamer agent inside

RC may reduce this problem.

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