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Li, Zhijian, Wang, Xungai and Wang, Lijing 2006-03, Properties of hemp fibre reinforced concrete composites, *Composites part A: applied science and manufacturing*, vol. 37, no. 3, pp. 497-505.

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Properties of Hemp Fibre Reinforced Concrete Composites

Zhijian Li, Xungai Wang* and Lijing Wang

School of Engineering and Technology, Deakin University, VIC 3217, Australia

Abstract: This research is concerned with the mechanical and physical properties of hemp fibre reinforced concrete (HFRC). An experimental program was developed based on the statistical method of fractional factors design. The variables for the experimental study were: 1) mixing method; 2) fibre content by weight; 3) aggregate size; and 4) fibre length. Their effects on the compressive and flexural performance of HFRC composites were investigated. The specific gravity and water absorption ratio of HFRC were also studied. The results indicate that the compressive and flexural properties can be modelled using a simple empirical linear expression based on statistical analysis and regression, and that hemp fibre content (by weight) is the critical factor affecting the compressive and flexural properties of HFRC.

Keywords: hemp fibre reinforced concrete (HFRC), dry and wet mix, statistical analysis, compressive and flexural properties

* Corresponding author:

Professor Xungai Wang

School of Engineering and Technology

Deakin University

VIC 3217, Australia

Telephone: 0061-3 5227 2894

Fax : 0061-3 5227 2539

E-mail : xwang@deakin.edu.au

1. Introduction

Natural fibres like jute, coir, bamboo and sisal have already been used as reinforcement materials in cement matrices for many years, especially in developing countries [1-3]. However, there are several drawbacks in using natural fibres as concrete reinforcement materials. For instance, the fibres vary in properties more than steel or glass fibres, which may result in variations in concrete quality. There is also a lack of proper mixing methods and prediction tools for estimating the mechanical performance of the resultant concretes. Previous research [4] has indicated that variations in the ultimate mechanical properties of the concrete, where natural fibres were used as the reinforcing materials, were of such a scale that it was impracticable to predict their mechanical properties with any degree of accuracy. Until the sources of this unpredictability are found, it is difficult to make any design improvements to the performance of such composites.

Many factors affect the properties of natural fibre reinforced concrete (NFRC). They include fibre type, fibre geometry, fibre form, surface, matrix properties, mix design, mixing method, placing method and curing method, etc. [5]. Many studies on NFRC used only a few significant parameters (fibre content, fibre length, fibre type) for the performance predictions of NFRC[6, 7].

Hemp fibre has high tensile strength and strong tolerance for an alkali environment [8, 9]. These properties make hemp fibre a good reinforcement material. In this paper, hemp fibre reinforced concrete (HFRC) is examined. An experimental program was developed to evaluate the properties of HFRC, and data analysis was based on the statistical method of the fractional factors design. The variables of the experimental study were: 1) mixing methods; 2) fibre content by weight; 3) aggregate size: and 4) fibre length. The main factors influencing the mechanical properties of HFRC have been assessed and the combination effects of major fibre reinforcing parameters with different matrix qualities on the compressive and flexural properties of HFRC have been discussed and summarized in simple empirical expressions.

2. Experimental

2.1 Materials

2.1.1 Hemp fibre

Table 1 gives some of the physical and mechanical properties of hemp fibre used in this research. The range of value is at 95% Confidence Level.

Table 1. Properties of hemp fibre

Properties	Values
Specific gravity (g/mm^3)	1.5
Width (μm)	23.15±17.60
Moisture absorption (%)	9.40±0.53
Water absorption (%)	85～105
Tensile strength (Mpa)	900 [10]
Modulus of elasticity (GPa)	34 [10]

2.1.2 Binders and aggregates

The aggregates of three grades used in the experiments were local Blue Metal Screenings gravels. The maximum sizes of the grades were 20mm, 14mm, and 7mm 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 according to Australian Standard 1141.5-2000).

Local washed Granetic sand was used in the experiment. 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 is suitable for concrete design requiring 28 days compressive strength ranged between 20～40Mpa.

2.2 HFRC Samples preparation

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

The mixing method is critical to the properties of HFRC. To simplify the procedure and reduce the cost of HFRC products, both wet mix and dry mix were used. They are described in Tables 2 and 3 respectively. The sample was cast in a cylinder of 200mm height and Φ100mm cross-section.

Table 2. Wet mix procedures

The water required for mixing was weighed, including the extra water to allow for hemp fibre absorption (saturated surface-dry condition, SSD);
The water and hemp fibre were added into a water container and stirred slowly;
The aggregate, sand, and cement were added into a mixer;
The mixer started and stirred the mixture for 3 minutes;
All the water and fibres were slowly poured into the matrix;

The mix was stirred for 4 minutes;
Mixing was stopped for 2 minutes;
The mix was then stirred for another 3 minutes before being poured and cast into oiled steel moulds.

Table 3. Dry mix procedures

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

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

2.3 Outline of experiment

A systematic experimental program was carried out to evaluate the hemp fibre reinforcement parameters. Sizes of the aggregate, fibre content by weight and fibre length were the selected factors. Compressive and flexural strength, flexural toughness, and toughness indices were dependent variables. Only early age (7 days) specimens were used in the experiments. All the specimens were surface dried before testing. The experimental details are shown in Table 4. Each mix series is coded. For example, the code 20D106L30 refers to 20mm aggregate size, dry mix method (D, and W for wet mix method, R for reference series), 1.06% fibre content by weight and 30mm fibre length (L).

Table 4. Experiment details

Mix Code Series	Aggregate Size (mm)	Fibre Content (%)	Fibre Length (mm)	Fibre Factors
20R000L00	20	0	0	0.00
14R000L00	14	0	0	0.00
07R000L00	07	0	0	0.00
20W018L10	20	0.18	10	0.78
14W018L10	14	0.18	10	0.78
07W018L10	07	0.18	10	0.78
20W018L20	20	0.18	20	1.57
14W018L20	14	0.18	20	1.57

07W018L20	07	0.18	20	1.57
20W036L20	20	0.36	20	3.13
14W036L20	14	0.36	20	3.13
07W036L20	07	0.36	20	3.13
20W060L20	20	0.60	20	5.22
14W060L20	14	0.60	20	5.22
07W060L20	07	0.60	20	5.22
20W106L30	20	1.06	30	13.83
14W084L30	14	0.84	30	10.96
07W084L30	07	0.84	30	10.96
20D036L10	20	0.36	10	1.57
20D054L20	20	0.54	20	4.70
20D072L30	20	0.72	30	9.39
14D036L20	14	0.36	20	3.13
14D054L30	14	0.54	30	7.04
14D072L10	14	0.72	10	3.13
07D036L30	7	0.36	30	4.70
07D054L10	7	0.54	10	2.35
07D072L20	7	0.72	20	6.26
20D060L10	20	0.60	10	2.61
14D060L10	14	0.60	10	2.61
07D060L10	7	0.60	10	2.61

Introduced in the ACI (American Concrete Institute) report, 1982, the fibre factor is a simple way to evaluate the effect of fibre content and length on a matrix's mechanical properties after the fibres have been introduced into the matrix. The fibre factor FF (or fibre reinforcing parameters [11]) is defined as,

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

Where V_f is the fibre content by weight in percentage, L is the length of fibre and d is diameter/width of fibre, both in millimetres.

Fibre factors (fibre content and fibre aspect-ratio) have a significant relationship with the mechanical and physical properties of cementitious materials[12, 13]. However, the interaction between fibre and matrix becomes complicated when fibres are introduced into the concrete rather than the mortar matrix, because they are not separated by a fine grained material which can move easily between them, but by particles which will often be of a larger size than the average fibre spacing if the fibres are uniformly distributed [14]. This promotes fibre clustering and interaction between fibres and large aggregates, making the concrete more porous as the fibre content and maximum size of aggregate increase. So in this paper, fibre, matrix and aggregate parameters have also been studied.

To indicate the relationship of aggregate and fibre, the aggregate parameter Q is introduced, which is related to fibre factors (FF), and defined as follows in this paper,

$$Q = \alpha A_g \tag{2}$$

Where α is a constant which depends on fibre type and fibre surface properties, varied as maximum aggregate size is changed, A_g is defined as aggregate content [14], which is the weight of aggregate greater than 5mm divided by the total weight of concrete. Compared to the other materials in concrete, the weight of hemp fibre can be negated, so A_g is the same in all mixing series. In this paper, Q was set as 2.0, 1.5, and 1.0 for 20mm, 14mm and 7mm aggregate size HFRC separately.

2.4 Mechanical Testing

2.4.1 Compressive Strength

Compressive tests were carried out on a 385KN MTS Servo Hydraulic Universal Testing machine. All the specimens were surface dried before testing. The preload was 10KN and the loading rate was 2.5KN/Sec (about 20Mpa/min with reference to AS 1012.9-2000). The tests were ended when the displacement reached 10 mm.

2.4.2 Flexural Strength (modulus of rupture)

The flexural tests were carried out on the same testing system using a four point bending configuration, with a loading rate of 0.13KN/Sec acting on two upper points (AS 1012.11-2000). The tests ended when the displacement at mid-span reached 5mm. Specimens were 350mm in length and 100mm×100mm in cross-section.

2.4.3 Flexural Toughness and Index

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.

According to the American Concrete Institute (ACI) Committee 544 method of characterizing toughness [15], the toughness is defined as the whole area under a flexural load-deflection curve up to a mid-span deflection of 1.9mm divided by the area of broken section. This definition was adopted in this paper for calculating the toughness.

Toughness indices are defined as the whole area under the flexural load-deflection curve divided by the area under the curve up to the deflection at first crack (the first-crack toughness). Normally, the difference between first-crack strength and maximum strength of composite samples is very small. For convenience in calculation, the area under the deflection of maximum load was used in this study instead (peak-load toughness indices).

To find the main effect factor and interaction among the three factors (aggregate size, fibre content and fibre length) in the wet mix method, the SPSS® statistical analysis package (release 11.5) was used to analyse the compressive and flexural strength, toughness and toughness index results from the experiments.

3. Results and Discussion

The results of the physical and mechanical properties of HFRC are shown in Table 5. Over 300 specimens were tested and each result in Table 5 represents the mean of at least 3 specimens). The confidence level of the results is 95%.

Table 5. Mechanical and physical properties of HFRC

Mix Code Series	Compressive Stress (MPa)	Flexural Stress (MPa)	Flexural Toughness (KJ/m^2)	Toughness Index	Specific Gravity (g/mm^3)	Water Absorption Ratio (%)
20R000L00	30.81±0.35	4.77±0.26	0.78	1.38	2.43	0.50
14R000L00	33.45±2.45	5.09±0.09	1.19	1.87	2.43	0.52
07R000L00	30.57±2.91	5.08±0.24	1.01	1.94	2.38	0.67
20W018L10	23.82±0.23	4.52±0.24	1.34	3.33	2.34	0.74
14W018L10	35.22±1.06	4.78±0.12	1.08	2.45	2.41	0.73
07W018L10	32.73±5.89	5.04±0.36	1.37	3.72	2.33	0.80
20W018L20	32.65±2.09	4.62±0.50	0.73	1.86	2.39	0.41
14W018L20	34.30±3.55	5.10±0.36	0.89	2.01	2.39	0.50
07W018L20	24.70±2.80	4.69±0.20	0.95	2.83	2.32	0.57
20W036L20	32.09±0.82	5.18±0.24	1.90	4.34	2.39	0.61
14W036L20	26.41±2.44	4.96±0.25	1.28	3.03	2.36	0.65
07W036L20	24.23±3.40	4.56±0.32	1.42	3.64	2.31	0.58
20W060L20	26.76±0.29	4.11±0.24	1.25	3.72	2.33	0.78
14W060L20	25.52±1.93	4.41±0.22	1.39	4.13	2.35	0.70
07W060L20	20.08±3.71	4.49±0.13	1.51	4.92	2.33	0.67
20W106L30	13.88±0.44	3.10±0.08	1.04	2.89	2.20	0.75
14W084L30	21.73±1.18	4.07±0.14	1.33	3.75	2.32	0.83
07W084L30	20.11±0.58	4.10±0.05	1.38	4.45	/ *	/ *
20D036L10	30.81±0.35	4.77±0.26	0.78	1.38	2.34	0.71
20D054L20	33.45±2.45	5.09±0.09	1.19	1.87	2.34	0.73
20D072L30	30.57±2.91	5.08±0.24	1.01	1.94	2.31	0.62
14D036L20	25.41±1.58	4.43±0.04	1.09	3.39	2.34	0.76
14D054L30	25.31±0.65	4.20±0.16	1.55	3.58	2.33	0.77
14D072L10	20.72±1.20	3.72±0.15	0.83	2.46	2.25	0.74

07D036L30	25.93±2.11	4.59±0.13	1.29	3.28	2.36	0.55
07D054L10	23.69±1.42	3.88±0.04	1.21	4.03	2.31	0.74
07D072L20	18.49±1.20	3.71±0.11	0.96	3.28	2.21	0.83
20D060L10	22.94±2.11	4.02±0.22	1.21	4.39	2.33	0.59
14D060L10	21.59±0.85	4.31±0.25	1.52	4.21	2.33	0.63
07D060L10	15.40±1.12	4.69±0.27	1.59	4.40	2.31	0.75

* This result was unavailable.

3.1 Physical Properties

3.1.1 Specific gravity

Because the specific gravity of hemp fibre (1.5g/mm^3) is smaller than that of plain concrete (2.43g/mm^3), the addition of hemp fibre to the cementitious matrix reduces the specific gravity of the composite, as can be seen from Table 5. This agrees with previous research findings that fibre content has a statistically significant effect on the specific gravity of the composite [11].

Regression results in Figure 1, Equations 3 and 4 and show that the specific gravity D_c is linearly correlated with the matrix specific gravity D_m (which varies with aggregate sizes), aggregate size parameter Q and fibre factors. The correlation coefficient (R^2) is almost 100%.

Wet mix method:

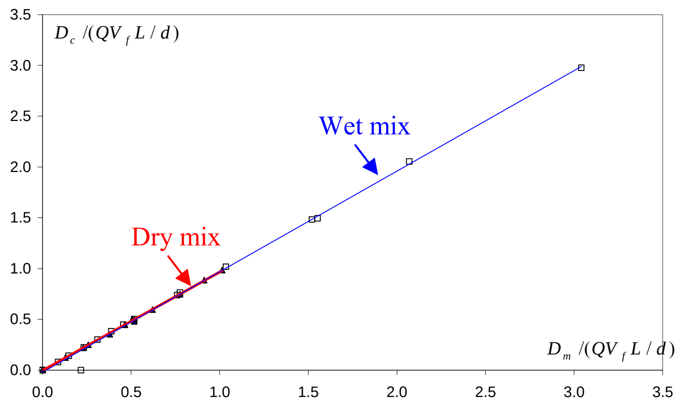
$$D_c = 0.99 \times D_m - 0.0212 \times (QV_f L / d) \quad (R^2=0.9964) \quad (3)$$

Dry mix method:

$$D_c = 0.9684 \times D_m - 0.003 \times (QV_f L / d) \quad (R^2=0.9994) \quad (4)$$

The subscripts "*c*" and "*m*" in the regression formulae (Equations 3 to 14) refer to the composite and matrix respectively. For both wet and dry mix methods, both aggregate size and fibre factors have a negative impact on the specific gravity D_c, and this impact is stronger for the wet mix method (-0.0212 in Equation 3) than for the dry one (-0.003 in Equation 4).

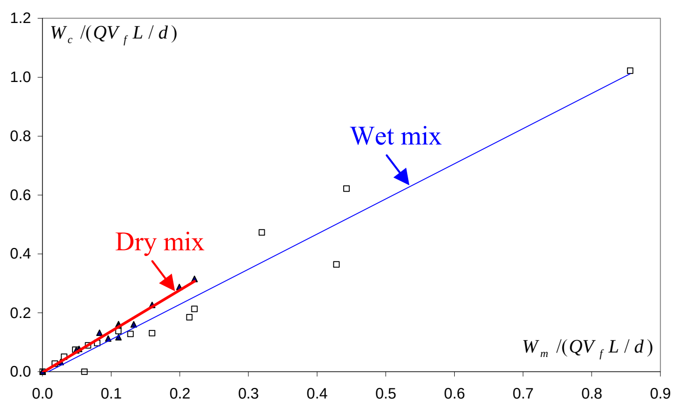
Figure 1. HFRC specific gravity correlation with fibre and matrix parameters



3.1.2 Water absorption ratio

As shown in Figure 2, aggregate size and fibre factors also have statistically significant effects on the water absorption ratio of HFRC composites. Their relationships are shown in regression Equations 5 and 6.

Figure 2. Water absorption ratio vs. fibre and matrix parameters



Wet mix method:

$$W_c = 1.1939 \times W_m - 0.0104 \times (QV_f L/d) \qquad (R^2=0.9554) \qquad (5)$$

Dry mix method:

$$W_c = 1.3988 \times W_m - 0.0025 \times (QV_f L/d) \qquad (R^2=0.9790) \qquad (6)$$

Unlike previous research findings that only those NFRC specimens made with 3% fibre content had a high water absorption ratio but there were no significant differences between those containing 0, 1, and 2% fibres [16], in this research, the water absorption ratio slightly decreases as the fibre factor increases. The smaller the aggregate size that was used in the concrete, i.e. the smaller the Q value, the higher the water absorption ratio.

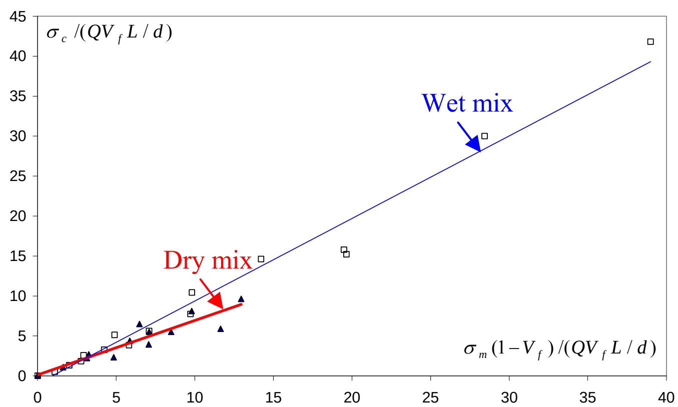
3.2 Mechanical Properties

The effects of the aggregate and fibre parameters on the mechanical properties of HFRC, i.e. compressive strength (σ_c), flexural strength (f_c), flexural toughness (T_c) and toughness indices (I_c), were analysed using composite methods under the conditions of fibre content $0.1 < V_f \le 1.0\%$ and fibre aspect ratio being larger than 400.

3.2.1 Compressive strength

Compressive strength is one of the most important properties of concrete materials. Both negative and positive results from the addition of fibres into the matrix have been reported [6, 17, 18]. Equations 7 and 8, and Figure 3 show the relationships between compressive strength and the aggregate size parameter and fibre factors.

Figure 3. Compressive strength correlation with fibre and matrix parameters



It has been observed from the regression equations that the compressive strength of composites has an increased coefficient (1.0332, larger than 1.0) in the wet mix method and a decreased coefficient (0.6824, smaller than 1.0) in the dry mix method. In the dry mix method, the addition of hemp fibre seems to weaken the performance of the composite, and the degree of weakening is quite obvious, but for the wet mix method (used by most former researchers), analysis becomes rather complex. In the wet mix method, compressive strength will increase with smaller aggregate size (small Q), shorter fibre length and a lower fibre content (small V_f and L/d). As V_f keeps on increasing, compressive strength tends to decrease.

Wet mix method :

$$\sigma_c = 1.0332 \times \sigma_m (1 - V_f) - 0.9579 \times (QV_f L / d) \qquad (R^2=0.9782) \qquad (7)$$

Dry mix method :

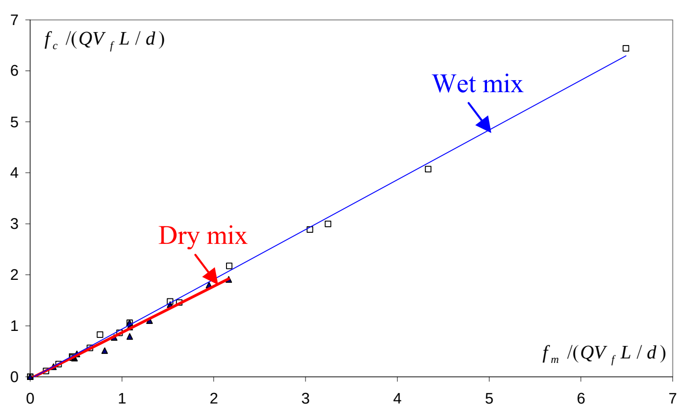
$$\sigma_c = 0.6824 \times \sigma_m (1 - V_f) + 0.1147 \times (QV_f L / d) \qquad (R^2=0.8927) \qquad (8)$$

In Equation 7, although the coefficient of the matrix's initial compressive strength is slightly larger than 1, the coefficient of the fibre factor and aggregate parameter is also nearly 1 (-0.9579). As in the analysis above, once the fibre content passes a certain point, compressive strength begins to decrease. In Equation 8, because the coefficient of the matrix compressive strength is 0.68, it is too small for the final result to be larger than 1, regardless of how much the fibre content rises. So generally, the addition of hemp fibres into a cementitious matrix would reduce the compressive strength of the composite, regardless of the mixing method. The increased porosity of the composite material as a result of fibre addition is the major factor responsible for the reduction in compressive strength, which agrees with some previous findings [7, 19].

3.2.2 Flexural strength

Flexural strength of HFRC was closely related to the plain matrix bending strength, aggregate parameter and fibre factors. Figure 4 shows the correlation between flexural strength and the major parameters for the dry and wet mixing methods respectively.

Figure 4. Flexural strength correlation with fibre and matrix parameters



The regression in Equations 9 and 10 can be used to predict the flexural strength of HFRC when the fibre aspect ratio is larger than 400.

Wet mix method:

$$f_c = 0.9758 \times f_m - 0.0395 \times (QV_f L / d) \qquad (R^2=0.9980) \qquad (9)$$

Dry mix method:

$$f_c = 0.9058 \times f_m - 0.038 \times (QV_f L/d) \qquad (R^2=0.9832) \qquad (10)$$

These results also agree with some previous findings [20, 21]. The contribution of fibre introduced into concrete is negative (-0.0395 and -0.038), probably due to the large fibre aspect ratio used in this research. It has been shown that increasing the fibre content and aspect ratio more or less linearly increases the maximum flexural strength only up to the fibre aspect ratio of 150 [15].

In cases such as concrete beams and columns inside the building, where the compressive and flexural strengths are critical to performance, the regression equations above show that the addition of hemp fibre into the matrix has been detrimental to these properties. However, in some other applications like normal pavements, where its post-crack performance and properties over time is very important, the improvements in flexural toughness and toughness index would contribute to a longer service life of the composites.

3.2.3 Flexural toughness and index

Flexural toughness is an important property for concretes. Toughness not only reflects the impact ductility and fracture enhancements, but also is an assurance of the safety and integrity of a structural element prior to its complete failure.

Flexural toughness in plain concrete is related to crack growth. When the fibres were present in FRC, the cracks could not extend without stretching and debonding the fibres during the bending of a composite beam. As a result, considerable additional energy was necessary before the complete fracture of the material could occur [15]. The flexural toughness and toughness index of NFRC can be significantly improved by the addition of fibres [6]. Equations 11 to 14 and Figures 5 and 6 show the correlations between flexural toughness and toughness indices, with the major parameters for both mix methods.

Figure 5. Flexural toughness correlation with fibre and matrix parameters

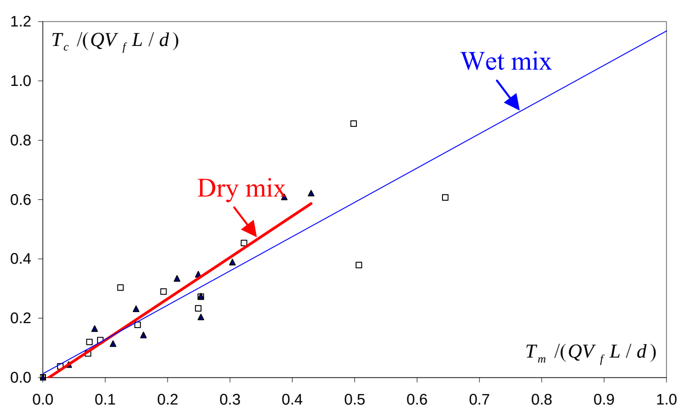
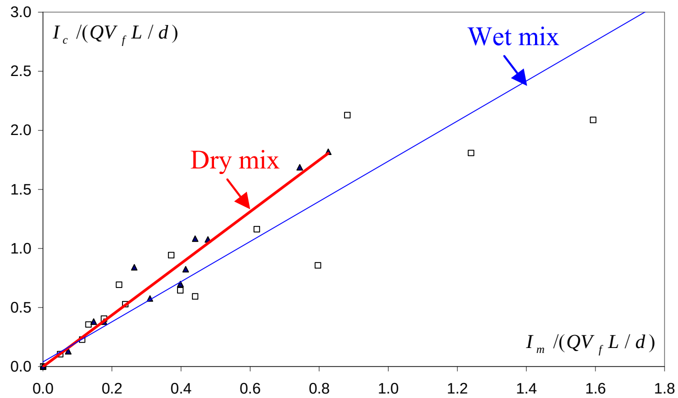


Figure 6. Toughness indices correlation with fibre and matrix parameters



It can be seen that the aggregate size parameter and fibre factors together play a significant role in enhancing the toughness and toughness index of the composite for the wet mix method. However, for the dry mix method, their contributions are negative. This phenomenon is probably due to the difference in water absorption during mixing, which may have resulted in different bond strength between fibre and matrix. When this composite concrete was cast using the dry mix method with continuous drying, it was found that loss of water resulted in considerable matrix materials shrinkage, hence reducing the bonding strength between fibre and matrix. When the bonding strength between fibre and matrix decreases, the flexural toughness behaviour of the composite is poor [22].

Wet mix method (Toughness):

$$T_c = 1.155 \times T_m + 0.013 \times (QV_f L / d) \quad (R^2=0.9066) \qquad (11)$$

Dry mix method (Toughness):

$$T_c = 1.3947 \times T_m - 0.0134 \times (QV_f L / d) \quad (R^2=0.9209) \qquad (12)$$

Wet mix method (Toughness indices):

$$I_c = 1.6986 \times I_m + 0.0404 \times (QV_f L / d) \quad (R^2=0.9278) \qquad (13)$$

Dry mix method (Toughness indices):

$$I_c = 2.1867 \times I_m - 0.0009 \times (QV_f L / d) \quad (R^2=0.9686) \qquad (14)$$

3.3 Main parameter analysis

From the above analysis, the properties of matrix, aggregate size parameter and fibre factors have a very strong correlation with the physical and mechanical properties of HFRC. The initial matrix properties are related to different aggregate sizes, and the fibre factors can be separated to fibre content and fibre length. Aggregate size parameter Q depends on interaction between aggregate size and fibre factors.

In order to find out the major factor or the most important interaction factors, hypothesis-testing statistics [23] were employed to determine which factor among these three factors influenced the mechanical properties of HFRC the most. In the analysis results, statistically significant effect, p value, means that there is the probability or risk that a Type I error could be made during the hypothesis-testing. The smaller the p value is, the less likely that a false hypothesis will be accepted as true.

3.3.1 Wet mix method

To simplify the factors in the analysis, factor "A" represents the aggregate size parameter, "B" represents the fibre content and "C" represents the fibre length factor. A+B means putting A and B together for the analysis, and A*B means the interaction of A and B. The mechanical properties, including compressive strength, flexural strength, flexural toughness and toughness indices were set as dependent variables.

The statistically significant effect p and F-ratio [24] values for the wet mix method are listed in Table 6, excluding those for the insignificant interactions. It can be deduced that:

- Compressive strength is strongly related to the interaction of aggregate size and fibre length ($F = 10.505$, $p < 0.005$);
- Flexural strength, flexural toughness and toughness index are all correlated with fibre content ($p < 0.005$);

The interaction of aggregate size and fibre length is the chief factor that affects the compressive strength, and the hemp fibre content is the main factor that affects the flexural strength and flexural toughness. Toughness indices are dominated by the hemp fibre content (by weight). Based on the above analysis, A*C and B are singled out.

The results in Table 7 show that the p values of compressive strength and toughness index (marked as **) are all smaller than the corresponding values in Table 6 (marked as *). This confirms that B and A*C are the main factors in the wet mix method that influence the compressive strength and toughness indices. B is still the main factor for flexural strength and toughness. It not only interacts with A*C but also with A+C.

Table 6. Tests of between-subjects effects (Wet Mix: A+B+C)

Factors	Dependent Variable	F	*p*
A Aggregate Size	Compressive strength	4.321	0.02182
	Flexural strength	1.658	0.20639
	Toughness	0.180	0.83581
	Index	1.553	0.22709
B Fibre Content	Compressive strength	9.123	0.00073
	Flexural strength	8.308	0.00124*
	Toughness	10.144	0.00039*
	Index	9.689	0.00051*
C Fibre Length	Compressive strength	0.001	0.98132
	Flexural strength	0.027	0.86941
	Toughness	6.573	0.01525
	Index	3.856	0.05831
A*B	Compressive strength	1.369	0.26671
	Flexural strength	2.433	0.06756
	Toughness	1.674	0.18034
	Index	0.974	0.43540
A*C	Compressive strength	10.505	0.00031*
	Flexural strength	1.802	0.18126
	Toughness	0.569	0.57159
	Index	0.390	0.68024

* The effect was significant.

Table 7. Tests of between-subjects effects (Wet Mix: B+A*C)

Factors	Dependent Variable	F	*p*
A*C	Compressive strength	6.819	0.00004**
	Flexural strength	1.128	0.36745
	Toughness	1.442	0.21922
	Index	1.362	0.25088
B Fibre Content	Compressive strength	8.764	0.00079
	Flexural strength	7.166	0.00240**
	Toughness	9.438	0.00051**
	Index	9.717	0.00042**

** The effect was significant.

3.3.2 Dry mix method

The results for the dry mix method were analysed using the same procedure as above. Table 8 lists the analysis results. The interacting factors (A*B, B*C, C*A, and A*B*C) were insignificant and therefore omitted from the table. It is clear that the hemp fibre content (Factor B) is the major factor that affects the compressive strength, flexural strength and flexural toughness. Therefore, B and A*B are singled out for further analysis, and the results are given in Table 9. The statistically significant effects, p values, confirm that hemp fibre content (Factor B) is the main factor that affects the properties of the reinforced concrete materials.

Table 8. Tests of between-subjects effects (Dry Mix: A+B+C)

Factors	Dependent Variable	F	*p*
A	Compressive strength	3.470	0.04186
Aggregate	Flexural strength	3.302	0.04822
Size	Toughness	1.514	0.23365
	Index	1.575	0.22102
B	Compressive strength	21.657	0.00000*
Fibre	Flexural strength	21.958	0.00000*
Content	Toughness	4.137	0.01282*
	Index	1.696	0.18527*
C	Compressive strength	3.929	0.02861
Fibre	Flexural strength	1.386	0.26314
Length	Toughness	0.117	0.88960
	Index	0.108	0.89772

Table 9. Tests of between-subjects effects (Dry Mix: B+A*B)

Factors	Dependent Variable	F	*p*
A * B	Compressive strength	6.581	0.00003
	Flexural strength	5.412	0.00015
	Toughness	.988	0.47421
	Index	.566	0.82828
B	Compressive strength	78.685	0.00000**
Fibre	Flexural strength	56.603	0.00000**
Content	Toughness	4.058	0.00955**
	Index	8.892	0.00007**

4. Conclusions

The following conclusions can be drawn from this study:

The addition of hemp fibre into the concrete matrix results in a linear reduction in the specific gravity and the water absorption ratio of the HFRC.

The compressive strength, flexural strength, toughness and toughness indices, specific gravity, and water absorption ratio of HFRC are all correlated with aggregate size parameters, fibre factors and matrix initial mechanical properties. These relationships can be presented in simple empirical regression equations in the form of a composite mechanical approach.

Different mixing methods affect the mechanical and physical performance of the HFRC composites. Compressive strength of the HFRC is weaker when compared to the conventional concrete regardless of the mixing method used. Wet mix has a more positive influence on the composite's flexural properties (flexural strength, toughness and toughness index) than dry mix method, possibly due to the enhanced bonding between fibre and matrix. These properties make the HFRC more suitable for use in such applications as pavements.

Fibre content by weight is the main factor that affects compressive and flexural properties of HFRC, regardless of the mixing method used.

5. Acknowledgements

Assistance and suggestions from Mr. Chris Hurren, Dr. Huiming Wang, Dr. Tong Lin and Mr. Graeme Keating are gratefully acknowledged.

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