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Predicting the Strength of Fiber Reinforced High Performance Concrete Based on Push-Off Tests

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ABSTRACT

This paper reports the results of an investigation into the strength of fiber reinforced high-performance concrete (FRHPC)based on push-off tests. Both experimental and analytical studies were performed. In the experimental study, eight FRHPC push-off specimens were tested. Two types of fibers, straight and hooked-end, in conjunction with percentage of volume fraction of steel fibers,0.5%, 1.0%, 1.5% and 2.0% were used. In the analytical study, a new proposed expression was derived based on experimental data in this research and available data from the literature. These include high strength concrete (HSC) with compressive strength of $40 < f'_c < 107$ MPa. The investigated variables were, fibers factor (F), area of reinforcement perpendicular to shear plane ($\rho_v f_y$), and concrete compressive strength (f'_c). The proposed expression gave good prediction for the direct shear strength of the tested specimens-the proposed expression predicted the direct shear stress resistance of tested/calculated values with a coefficient of variation (COV) of 12.88 percent.

Keywords: direct shear, high performance concrete, push-off test, steel fibers.

التنبؤ بمقاومة الخرسانة العالية الاداء المسلحة بالالياف بالاستناد لفحص القص المباشر

الخلاصة

في هذا البحث تم دراسة مقاومة الخرسانة العالية الاداء المسلحة بالالياف الحديدية تحت القص المباشر. تم اجراء دراسة عملية وتحليلية، في الدراسة العملية تم فحص ثمانية نماذج من الخرسانه العالية الاداء المسلحة بالالياف الفولاذية تحت القص المباشر وتم استعمال نوعين من الالياف : المستقيمة والمعقوفة النهايات، وكانت نسبة حجوم الالياف(0.5 و1.0 و1.5 و2.0)%.
اما في الدراسة التحليلية فتم اشتقاق معادلة لايجاد مقاومة القص المباشر بالاعتماد على النتائج العملية لهذا البحث وبحوث سابقة ولمقاومة انضغاط تتراوح بين (40 الى 107)

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ميكاباسكال. المتغيرات التي تم اعتمادها بالمعادلة كانت معامل الالياف (F) ومساحة حديد التسليح العمودي على مقطع القص ($\rho_v f_y$) ومقاومة الانضغاط للخرسانة (f'_c).
المعادلة المقترحة اعطت تنبؤ جيد عن مقاومة القص المباشر للخرسانة العالية الاداء المسلحة بالالياف الحديدية حيث كانت نسبة معامل التباين حوالي 12,88%.

INTRODUCTION

Short concrete members like brackets, corbels and ledger beams may fail by direct shear. Such failure in (HSC) may be brittle and catastrophic. Steel fibers restrain cracking, increase tensile strength, and enhance ductility and energy absorption characteristics. Therefore, it is possible to use steel fibers as shear reinforcement to reduce deformation, increase ductility and the ultimate capacity of connections[1].

If steel fiber reinforced concrete has such important characteristics, a logical question would be based on why it is nearly not used for a safer structural design. This is explained considering the total lack of standards contemplating steel fiber reinforced concrete structural design.

Based on push–off failure tests from this work and available in the literature, a new expression for evaluating the ultimate direct shear stress resistance of FRHPC specimens was predicting.

LITERATURE REVIEW

Al-Obidi [1] studied the direct shear strength of high strength concrete with fibers (HSFRC). Based on test results an empirical equation was developed for direct shear strength for normal and high strength concrete with and without fibers.

$$v_u=\varphi\,(0.7\sqrt{f'c}+0.86\,\rho_v f_y+8.8\,F) \qquad \text{.......(1)}$$

Where φ=0.85 ;

$$\rho_v=A_{vf}/bh \qquad \text{......(2)}$$

$$\text{and } F=(L_f/D_f)\,V_f\,B_f \qquad \text{......(3)}$$

Where A_{vf} =area of shear-friction reinforcement,mm^2
bh=area of shear-friction plane, mm^2
B_f = the bond factor that accounts for bond characteristics of the fibers. Based on a large series of pullout tests by Narayanan and Kareem-Palanjian(2) B_f was assigned a relative value of 0.5 for round fibers, 0.75 for crimped fibers, and 1.0 for indented fibers.

Vinayagam [3] studied the shear transfer in high strength concrete with fibers (HSFRC). Based on his test results an empirical equation was proposed to predict of direct shear strength for (HSFRC).

$$v_u = 0.575\left(\frac{rvfy + stu}{f'c}\right)^{0.5} * f'c \qquad \text{........(4)}$$

Where stu = the post-cracking tensile strength of fiber concrete which can be estimated from the fiber properties per [Eq.(5)],[5].

$$stu = h_l h_o V_f \frac{l_f}{2r} t_u h \qquad \text{.......(5)}$$

Where h_l = length efficiency factor; h_o = fiber orientation factor; V_f = volume fraction of fiber ; l_f = fiber length; r = ratio of fiber cross section to its perimeter; and t_u = ultimate bond strength of fiber

The factor h_l depends on the critical fiber length, l_c. If $l_c > l_f$, then failure occurs by fiber pullout and h_l = 0.5. The value of h_o depends on the distribution of fibers. For three-dimensional random orientation, Romualdi and Mandel (1964) (5) had analytically shown that h_o = 0.405. However, this factor has been found to vary between 0.33 and 0.5.

For a given volume fraction of fibers, stu can be determined from [Eq.(5)] provided that the value of t u is known. Lim et al(4) have generated test data for the same type and brand of fibers employed in this study. An average value of t_u = 6.64 MPa was reported, and this has been adopted in the present study.

RESEARCH SIGNIFICANCE

This paper studies the effect of FRHPC under direct shear. Based on regression analysis of 108 experimental test results from this research and those available in the literature[1,3,6,7,8,9], a new expression will be used to predict the direct shear strength of FRHPC and will be compared with the previously proposed expressions [Eq.(1), and (4)] and three codes formulas (ACI(A1), CAN(A2), and BS(A3))

TEST PROGRAM

Test Specimen and Materials

The direct shear transfer behavior of FRHPC was investigated through testing of initially uncracked push-off specimens shown in [Fig.(1)]. The specimens had dimensions of 267x152x133 mm, with a shear plane area of 89x133 mm^2. These dimensions were determined on the basis established through previous research[10].

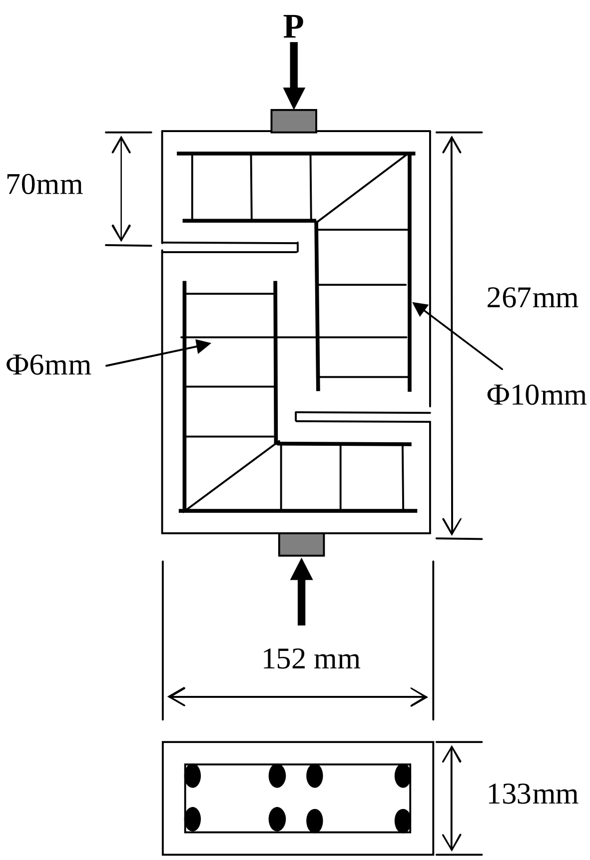


Figure (1) Direct Shear Dimensions for Double L-Shaped Specimens.

The two parameters of the investigation were: (1) type of fiber-straight and hooked-end fiber; and (2) the volume fraction of steel fiber. By combining these variables, 8 types of specimens, classified by the type of steel fiber and volume fraction of steel fiber used, were obtained, as outlined in [Table (1)]. In this table the steel fiber types are identified as: straight steel fiber (S), hooked-end steel fiber (H), and the volume fraction of steel fiber are identified by a number from 0.5 to 2.0 (i.e., S2.0 stands for straight steel fiber with 2.0% percentage of steel fiber). The test program included 2 specimens for each type of specimen used.

In manufacturing the test specimens, the following materials were used: cement (ASTM Type I) manufactured in Iraq**.** Densified silica fume(11) from Sika Materials Company in Baghdad has been used as a mineral admixture added to the mixtures of the research. The used percentage is 10% of cement weight (as an addition, not as replacement of cement).

Al-Ukhaidher fine sand grading and limits of ASTM C33[12] is used. Well-graded coarse aggregate with a maximum size of 12 mm is used. The steel fibers used in this test program were straight and hooked-end steel fibers manufactured by Bekaert Corporation. The fibers have the properties described in [Table (2)] which is brought from China, a new generation of modified superplasticizer, Sika® Viscocrete® PC20[13], is used. The mix design of SFHPC using local constituent is 1**:** 0.95 **:**1.4 (cement **:**sand **:**aggregate)[3] with water cement ratio 0.25 plus 2.0% by weight of binder of Sika® Viscocrete® PC20 admixture.

Table (1) Details of the tested specimens and results*

Specimens	f'_{cu} (MPa)	$\rho_v f_y$ (MPa)	F	v_u (MPa)
S0.5	79	2.87	0.163	11.5
S1.0	88	2.87	0.325	13.1
S1.5	98	2.87	0.488	14.5
S2.0	103	2.87	0.650	15.4
H0.5	74	2.87	0.296	11.9
H1.0	80	2.87	0.592	13.5
H1.5	87	2.87	0.880	15.2
H2.0	95	2.87	1.185	16.1

*See Appendix B for existing test results

Table (2) Properties of the Steel Fibers*

Description	Hooked-end	straight
Length	30	13 mm
Diameter	0.38	0.2 mm
Density	7800 kg/m^3	7800 kg/m^3
Tensile Strength	2300 MPa	2600 MPa
Aspect Ratio	79	65

*Supplied by the manufacturer

Mild steel deformed bars Ø10 and Ø6 mm. Yield strengths of the 10, and 6 mm bars were 570, and 600 MPa, respectively.

The mixing procedure was as follows:

1-Mix dry components (cement, sand, gravel, and silica fume) for 2 to 3 min.

2-Add superplasticizer to the water before pouring it into the mixer.

3-The fresh concrete was then mixed for 5 min.

4-Add the fibers slowly and sprinkling them into the mixer to avoid balling. After all the fibers were added, then the fresh concrete with fibers was mixed for 2 min.

The specimens were cast with the wide face of 267x152 mm [Fig.(1)] placed horizontally. Also, control cubs of 100x100 mm were cast for compressive strength test of steel fiber reinforced concrete. All the specimens were compacted using a table vibrator at a frequency of 5.5 cycles/sec for two min. immediately after the placement of concrete. The hardened pushoff specimens and control cubs were demolded after 24 hours, and Steam cured at 90°C for 48 hours in water bath, by raising the temperature at 15°C/hr. After that the samples were left until their temperature is equal to the ambient temperature, and then kept in the 95% R.H.

moist curing at laboratory temperature. After removed from water curing, all specimens had a drying period of preparation of about 15 days.

LOADING SETUP AND MEASUREMENTS

All the push-off specimens were loaded along the shear plane for direct type of shear loading. The vertical displacement along the shear plane and horizontal displacement across it were measured using dial gauge and demec points devices respectively, as shown in Fig.(2-a). The horizontal displacement was made to indicate the cracking load as well as to measure the crack width across the shear plane. Fig.(2-b) shows typical specimens after failure in different fiber types.

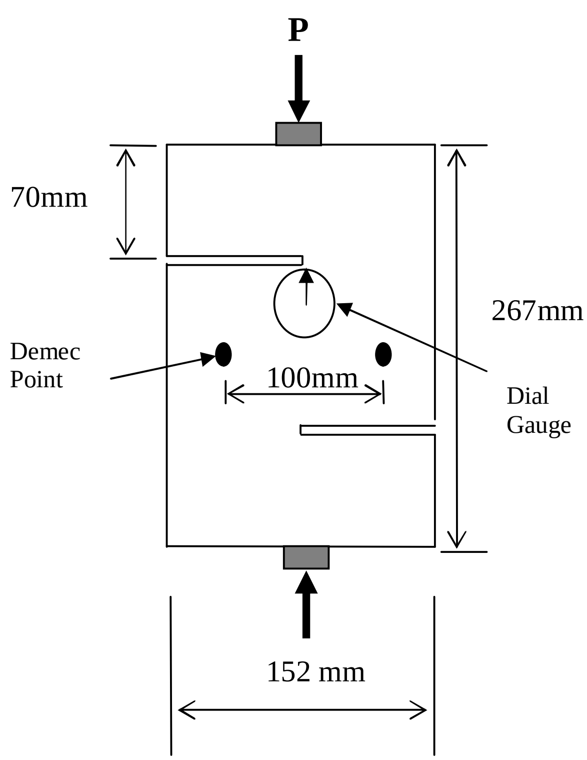


Figure (2-a) Location of Demec Point and Dial Gauge for Double L-Shaped Specimens.

Figure (2-b) Typical Specimens After Failure in Different Fiber Types.

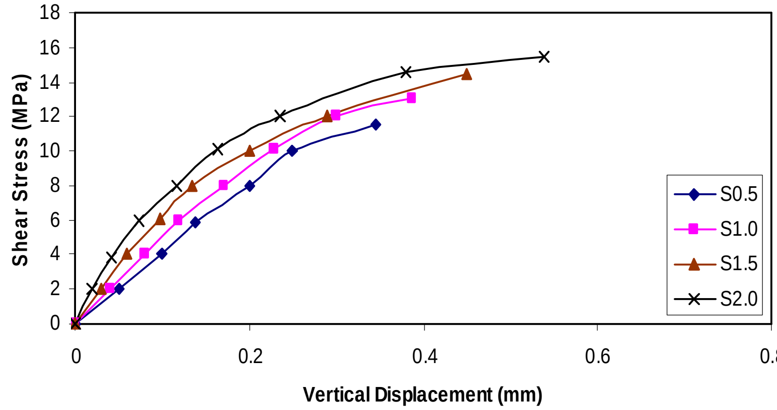
TEST RESULTS AND DISCUSSION

Strength and Deformation Behavior

The results obtained from the eight tests are summarized in [Table (1)]. The maximum shear stress was obtained by dividing the applied shear load by the area of the shear plane.

The shear stress versus vertical displacement relationships of the FRHPC specimens are shown in Fig.(3). For the specimens reinforced with fibers, S0.5, S1.0, S1.5, S2.0, H0.5, H1.0, H1.5 and H2.0, the behavior of shear stress versus vertical deformation was linear up to first cracking. After cracking, the specimens with higher percentage of fibers carried a higher load due to the steel fibers in the concrete mix, resulting in a strength increase up to 26 percent for specimens containing 2.0% steel fibers compared to the specimens with 0.5% steel fibers. After reaching the maximum shear stress level, the specimens with steel fiber failed in a ductile manner, showing a softening behavior due to the pullout of the steel fibers from the matrix.

In comparison to the straight fibers, the larger aspect ratio L_f/D_f available for the hooked-ended fibers which exhibit greater pull-out strengths in combination with similar tensile strength have the potential to achieve higher load capacities for a given fiber quantity.



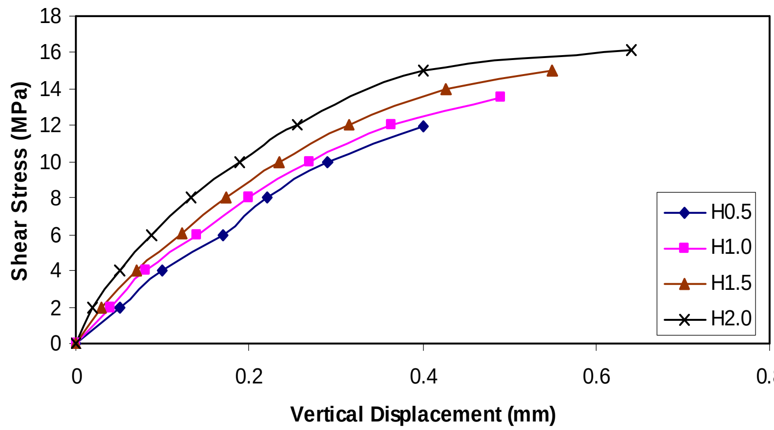


Figure (3) Shear stress versus vertical displacement.

EVALUATION OF EXPERIMENTAL RESULTS

Proposed Expression

Al-Obidi formula is modified in this work to predict the direct shear strength of FRHPC (40< f'_c <107 MPa) with and without shear reinforcement $\rho_v f_y$ by using regression analysis on the 108 push-off test results from this research and those available in the literature [1,3,6,7,8,9] (Appendix B). The main significant variation parameters are concrete compressive strength f'_c , fiber factor F and ratio of reinforcement perpendicular to shear plane $\rho_v f_y$.

$$v_u=\varphi(0.1f'_c+2\rho_v f_y^{0.66}+5F^{0.43}) \quad ,MPa \qquad \text{…….(6)}$$

Where φ=0.85 and F= $(L_f/D_f)\ V_f\ B_f$

COMPARISON OF DESIGN METHODS

[Table (3)] compares the proposed expression [Eq.(6)] with five design methods: Eq.(1), Eq.(4), Eq.(A1), Eq.(A2) and Eq.(A3). To test these expressions, the total of 108 test results failing in direct shear were applied, then the mean (μ), standard deviation (SD), and coefficient of variation (COV), were calculated for these expressions as shown in [Table (3)]. It is obvious that the proposed expression has the lowest value of COV of 12.88% and values of μ and SD of 0.986483 and 0.127112, respectively. While the other expressions give much higher COV values- between (30.74%-31.34%).

Fig.(4)shows that the predicted strength by proposed [Eq.(6)] is much closer to the actual direct shear strength than the other methods where the x-axis represents the design shear strength (v_uCalc.) while the y-axis represents the test shear strength (v_uTest).

Table (3) The Mean, Standard Deviation, and Coefficient of Variation Values of the FRHPC Values to Test Expressions.

No.	**Expressions**	v_uTest/v_uCalc		
		μ	**SD**	**COV(%)**
1	ACI-Code	1.907245	0.5956	31.34
2	CAN-Code	2.998085	0.948966	31.65
3	BS-Code	2.532678	0.800109	31.59
4	Vinaygam	1.48998	0.471476	31.64
5	Al-Obidi	1.260622	0.387589	30.74
6	Proposed	0.986483	0.127112	12.88

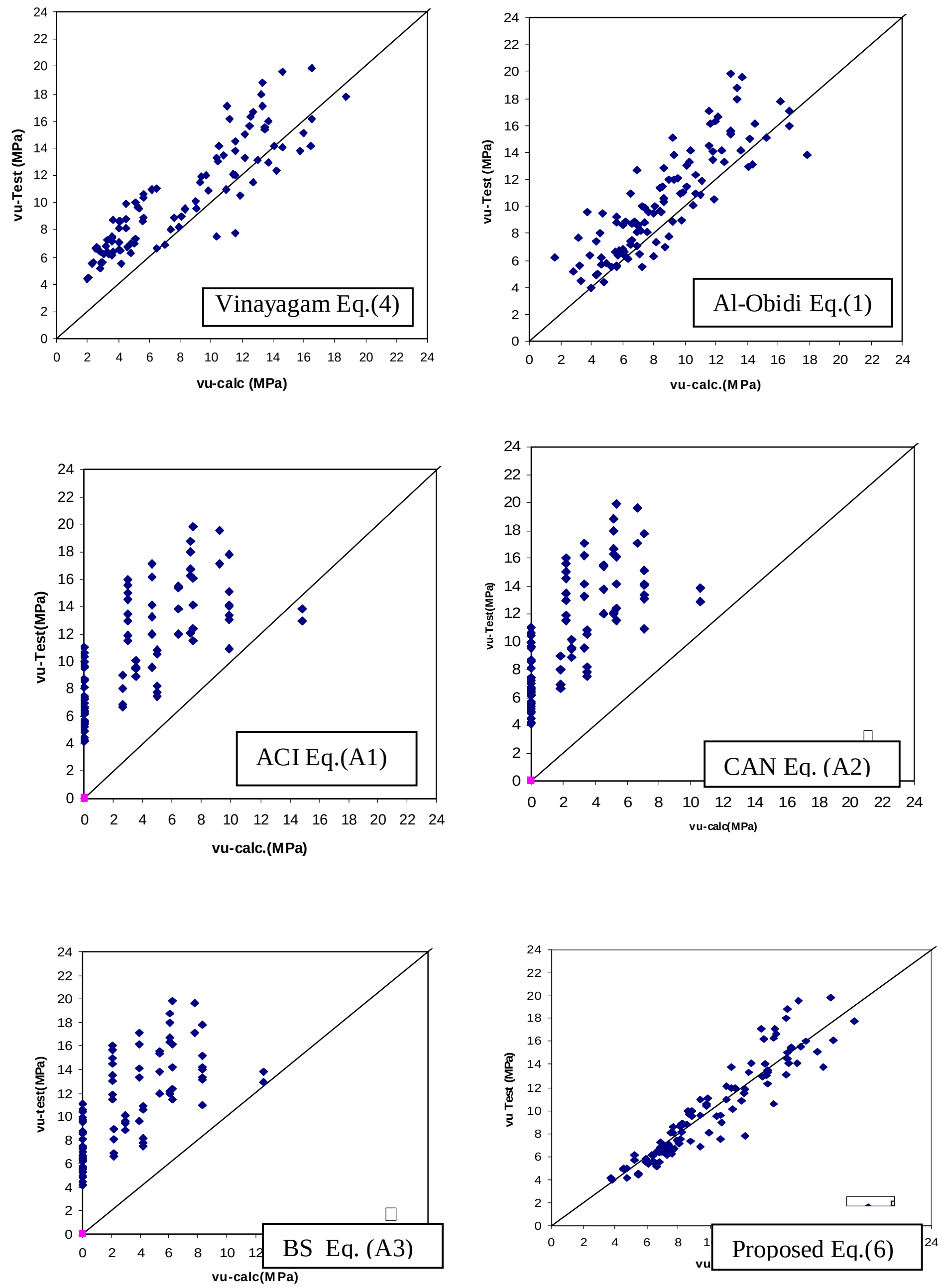


Figure (4) Comparison Between Experimental Data and Calculated.

INFLUENCE OF MAJOR PARAMETERS

The same previous specimens test results are applied to existing equations for shear-friction strength. As indicated in [Table (3)], the proposed expression which was proposed by Al-Obaidi (1) and modified in this research can give a reasonably low COV of 12.88 percent, [Eq.(6)]. [Figs.(5) to (7)] indicate the influence of different factors on the value of FRHPC based on the proposed modification-[Eq.(6)]. These figures are plotted using the factors affecting direct shear strength (f'_c, $\rho_v f_y$, and F)as x-axis and the value of ((v_uTest/v_uCalc.) as y-axis using the proposed expression. The solid line of (v_uTest/v_uCalc.)=1.0 which means safe prediction for direct shear strength.

It can be seen from [Figs.(5) to (7)] that the proposed expression give satisfactory predictions for FRHPC in direct shear.

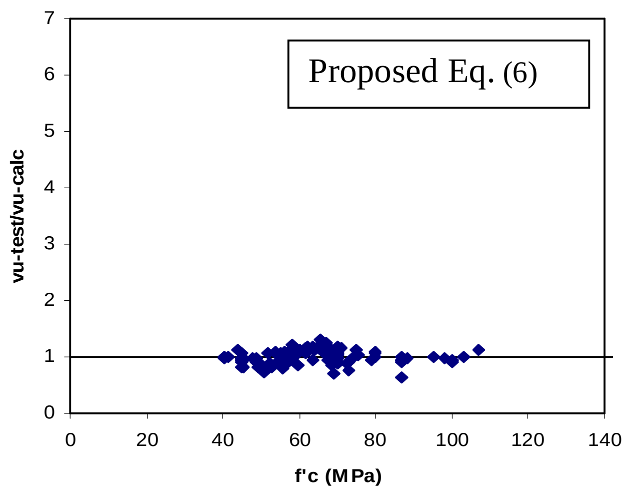


Figure (5) f'_c Versus the Relative Shear Stress Predictions.

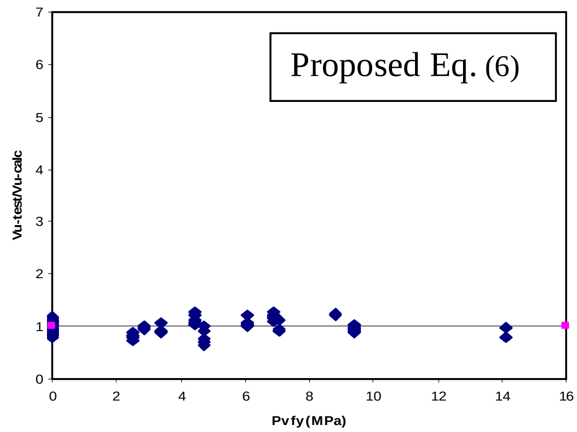


Figure (6) $\rho_v f_y$ Versus the Relative Shear Stress Predictions.

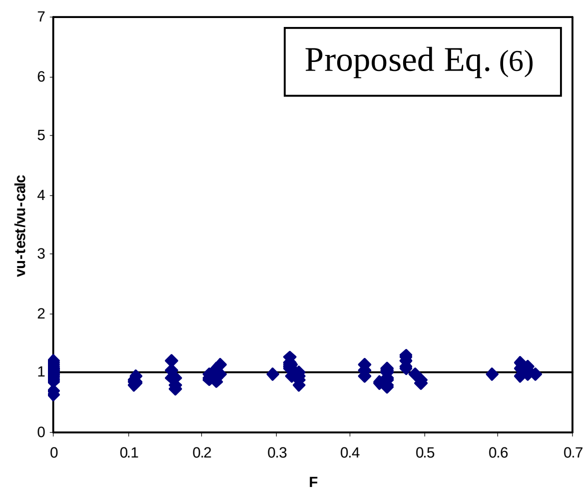


Figure (7) Fiber Factor Versus the Relative Shear Stress Predictions.

CONCLUSIONS

1. Increasing the volume fraction of steel fibers decreases the vertical displacement in the early stages of loading and increases the vertical displacement capacity prior to failure that leads to a more ductile mode of failure.
2. Using the hooked-end fibers leads to higher load capacities compared with straight fibers for a given fiber quantity.
3. The proposed equation simulates the strength provided by concrete itself, stirrup reinforcement, and fibers.

4. The proposed equation for the shear strength had low COV values of 12.88% and yields a reliable and conservative estimate of the shear strength of the tested samples in the present study.

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Appendix A

1-ACI 318M-11(14)

$v_u = \Phi A_s f_y \mu$ …….(A1)

where: $\Phi = 0.75$, $\mu = 1.4$

2-CAN-84(15)

$v_u = \Phi A_s f_y \mu$ …….(A2)

where: $\Phi = 0.6$, $\mu = 1.2$

3-BS-97(16)

$v_u = 0.6 F_b \mu$ …….(A3)

where: $\mu = 1.5$

Appendix B

Selected Data from other Literature

No.	Fiber Type	L_f/D_f	V_f (%)	B_f	f'_c	$\rho_v f_y$	F	v_uTest	Reference
1	Straight	63.5	0	0.5	56.4	0	0	4.13	(1)
2	Straight	65	0	0.5	56.4	4.42	0	9.6	
3	Straight	65	0	0.5	57.2	6.87	0	12.1	
4	Straight	65	0.5	0.5	58.2	0	0.158	6.36	
5	Straight	65	0.5	0.5	59.4	4.42	0.158	12	
6	Straight	65	0.5	0.5	58.2	8.84	0.158	17.12	
7	Straight	65	1.0	0.5	60.3	0	0.3175	8.59	
8	Straight	65	1.0	0.5	64	4.42	0.3175	14.12	
9	Straight	65	1.0	0.5	63.6	6.87	0.3175	16.7	
10	Straight	65	1.0	0.5	67.1	8.84	0.3175	19.58	
11	Straight	65	1.5	0.5	66.5	0	0.476	9.7	
12	Straight	65	1.5	0.5	67.1	4.42	0.476	16.17	
13	Straight	120	1.5	0.5	66.1	6.87	0.476	18.8	
14	Straight	120	1.0	0.5	59.7	0	0.3175	8.63	
15	Straight	65	1.0	0.5	61.7	4.42	0.3175	13.3	
16	Straight	65	1.0	0.5	61.7	6.87	0.3175	16.3	
17	Straight	65	1.5	0.5	67.8	0	0.476	9.54	
18	Straight	65	1.5	0.5	65.4	4.42	0.476	17.1	
19	Straight	72	1.5	0.5	65.4	6.87	0.476	18	
20	Hooked	0	0	0.75	44	0	0	4.21	(8)
21	Hooked	29	0.5	0.75	45.3	0	0.11	4.49	
22	Hooked	58	0.5	0.75	45.3	0	0.22	5.62	

23	Hooked	29	1.0	0.75	48.7	0	0.22	6.18	
24	Hooked	58	1.0	0.75	45.2	0	0.44	5.53	
25	Hooked	29	1.5	0.75	47.8	0	0.32	6.43	
26	Hooked	58	1.5	0.75	41.5	0	0.64	7	
27	Hooked	0	0	0.75	53.5	0	0	4.89	
28	Hooked	29	0.5	0.75	56.4	0	0.11	5.57	
29	Hooked	58	0.5	0.75	59.5	0	0.22	6.19	
30	Hooked	29	1.0	0.75	55.6	0	0.22	7.24	
31	Hooked	58	1.0	0.75	56.4	0	0.44	6.71	
32	Hooked	29	1.5	0.75	58.3	0	0.32	8.1	
33	Hooked	58	1.5	0.75	55.1	0	0.64	8.59	
34	Hooked	0	0	0.75	72.4	0	0	5.38	
35	Hooked	29	0.5	0.75	63.6	0	0.11	6.68	
36	Hooked	58	0.5	0.75	67.3	0	0.22	7.44	
37	Hooked	29	1.0	0.75	70.2	0	0.22	8.72	
38	Hooked	58	1.0	0.75	68.5	0	0.44	7.38	
39	Hooked	29	1.5	0.75	71.2	0	0.32	9.92	
40	Hooked	58	1.5	0.75	74.8	0	0.64	11.05	
41	crimed	60	0	0.75	62	0	0	5.7	(7)
42	crimed	60	0	0.75	62	0	0	6.2	
43	crimed	60	1.0	0.75	80	0	0.45	10.4	
44	crimed	60	1.0	0.75	80	0	0.45	10.6	
45	crimed	60	0	0.75	66.7	6.1	0	12	
46	crimed	60	0	0.75	66.7	6.1	0	13.8	
47	crimed	60	1.0	0.75	75.4	6.1	0.45	15.5	
48	crimed	60	1.0	0.75	75.4	6.1	0.45	15.4	
49	shelled	33	0	1	53.6	0	0	4.95	(6)
50	shelled	33	0.5	1	55.6	0	0.165	5.2	
51	shelled	33	1.0	1	56.3	0	0.33	6.55	
52	shelled	33	1.5	1	52.9	0	0.495	6.27	
53	shelled	33	0	1	52.1	2.49	0	6.63	
54	shelled	33	0.5	1	50.9	2.49	0.165	6.9	
55	shelled	33	1.0	1	49.4	2.49	0.33	8.04	
56	shelled	33	1.5	1	52.3	2.49	0.495	8.96	
57	shelled	33	0	1	52	3.38	0	8.86	
58	shelled	33	0.5	1	54.2	3.38	0.165	9.47	
59	shelled	33	1.0	1	48.9	3.38	0.33	9.6	
60	shelled	33	1.5	1	52.2	3.38	0.495	10.1	
61	Hooked	60	0	0.75	40.2	4.71	0	8.18	(3)

62	Hooked	60	1.0	0.75	49.5	4.71	0.45	10.84	
63	Hooked	60	0	0.75	40.2	9.42	0	10.97	
64	Hooked	60	0.5	0.75	45.3	9.42	0.225	13.33	
65	Hooked	60	1.0	0.75	49.5	9.42	0.45	13.09	
66	Hooked	60	0	0.75	40.2	14.13	0	12.92	
67	Hooked	60	1.0	0.75	49.5	14.13	0.45	13.81	
68	Hooked	60	0	0.75	69	4.71	0	7.5	
69	Hooked	60	1.0	0.75	73	4.71	0.45	10.56	
70	Hooked	60	0	0.75	69	7.07	0	11.5	
71	Hooked	60	1.0	0.75	73	7.07	0.45	14.14	
72	Hooked	60	0	0.75	69	9.42	0	14.03	
73	Hooked	60	1.0	0.75	73	9.42	0.45	15.11	
74	Hooked	60	0	0.75	87	4.71	0	7.78	
75	Hooked	60	0	0.75	87	7.07	0	12.36	
76	Hooked	60	0.5	0.75	107	7.07	0.225	19.86	
77	Hooked	60	1.0	0.75	100	7.07	0.45	16.11	
78	Hooked	60	0	0.75	87	9.42	0	14.17	
79	Hooked	60	1.0	0.75	100	9.42	0.45	17.78	
80	Hooked	0	0	0.75	45	0	0	4	(9)
81	Hooked	29	0.5	0.75	45	0	0.109	4.4	
82	Hooked	29	1.0	0.75	45	0	0.217	5.6	
83	Hooked	29	1.5	0.75	45	0	0.33	6.1	
84	Hooked	58	0.5	0.75	45	0	0.21	5.5	
85	Hooked	58	1.0	0.75	45	0	0.42	6.5	
86	Hooked	58	1.5	0.75	45	0	0.63	7	
87	Hooked	0	0	0.75	56	0	0	5	
88	Hooked	29	0.5	0.75	56	0	0.109	5.5	
89	Hooked	29	1.0	0.75	56	0	0.217	6.4	
90	Hooked	29	1.5	0.75	56	0	0.33	7.1	
91	Hooked	58	0.5	0.75	56	0	0.21	6.8	
92	Hooked	58	1.0	0.75	56	0	0.42	8.1	
93	Hooked	58	1.5	0.75	56	0	0.63	8.9	
94	Hooked	0	0	0.75	70	0	0	5.8	
95	Hooked	29	0.5	0.75	70	0	0.109	6.7	
96	Hooked	29	1.0	0.75	70	0	0.217	7.5	
97	Hooked	29	1.5	0.75	70	0	0.33	8.8	
98	Hooked	58	0.5	0.75	70	0	0.21	7.2	
99	Hooked	58	1.0	0.75	70	0	0.42	10	
100	Hooked	58	1.5	0.75	70	0	0.63	11	