Experimental Investigation of Shear-Critical Reactive Powder Concrete Beams without Web Reinforcement

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ABSTRACT

An experimental investigation was conducted on the behavior of ultra-high strength reactive powder concrete (RPC) beams. Fifteen singly reinforced beams were cast without web reinforcement. The main variables were the steel fiber content, longitudinal steel ratio, shear span to effective depth (a/d) ratio and silica fume content. The maximum concrete matrix compressive strength f'_{cf} was 110 MPa, containing one type of fiber. An empirical expression is proposed to predict the shear stress resistance of RPC beams without web reinforcement. The proposed expressions gave good prediction for shear strength.

Keywords: Fibers, Reactive powder concrete, Silica Fume, Shear Strength of Beams.

الاستقصاء العملي لعتبات خرسانة المساحيق الفعالة الخالية من تسليح القص

الخلاصة

جرت عملية استقصاء عملي على سلوك عتبات خرسانية عالية المقاومة مصنوعة من المساحيق الفعالة. خمسة عشرة عتبة تحوي حديد تسليح طولي تم صبها وخالية من تسليح القص. المتغيرات الرئيسية التي تم دراستها هي محتوى الالياف الفولاذية, نسبة حديد التسليح الطولي, نسبة فضاء القص الى العمق الفعال ومحتوى السليكا الفعالة. اعلى قيمه لمقاومة الانضغاط كانت 110 ميكاباسكال باستعمال نوع واحد من الالياف الفولاذية. تم اقتراح علاقات للتنبؤ بمقاومة اجهاد القص لعتبات خرسانة المساحيق الفعالة الخالية من تسليح القص. العلاقات االمقترحة اظهرت تطابقاً جيداً لمقاومة اجهاد القص بالمقارنة مع النتائج العملية.

INTRODUCTION

Reactive Powder Concrete (RPC) is an ultra-high strength, low porosity material with high cement and silica fume contents and steel fibers. RPC uses low water-binder ratios and new generation superplasticizers with eliminating the coarse aggregates, and in brief all optimized particle size less than 600 micrometers. In laboratories across the world, RPC was developed in the 1990's of the last century. RPC can be readily used in a wide variety of structural

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applications, including situations where the concrete is required to carry substantial tensile stresses due to shear and bursting forces.

RPC is recognized as a revolutionary material that provides a combination of ductility, durability and high strength. The high strength means that RPC structures can be built with less structural weight, greater structural spans, and have good anti-seismic characteristics compared to conventional concrete structures. The superior ductility and energy absorption of RPC provides greater structural reliability. The superior corrosion resistance of RPC provides the ability to withstand the rigors of corrosive environments.[1]

RESEARCH SIGNIFICANT

Design of structures with new materials, such as RPC, cannot be carried out with normal design recommendations that do not cope well with nontraditional materials. In many countries, concrete with a compressive strength of more than 80MPa cannot be used because current codes restrict the extra strength. Therefore, much work on setting up new design of standards and codes for RPC structures must be done to make use of the material's potential. So, it is necessary to study the mechanical properties of RPC beams. The main aim of the present research is to derive the Empirical expressions to predict shear resistance of RPC beams based on experimental data.

LITERATURE REVIEW

Ashour et al. [2] studied the shear behavior of high strength steel fiber concrete (HSFRC) beams without stirrups under the action of flexure and shear. Based on their test results two empirical equations were modified. The first one which is a modification of the ACI Building Code method, has been developed to predict the shear strength of singly reinforced HSFRC beams without stirrups and as follows:

$$v = (0.7\sqrt{f'_{cf}} + 7F)\, d/a + 17.2\, \rho_w d/a,\ \text{MPa} \qquad \text{.... (1)}$$

Where:
ρ_w=flexural reinforcement ratio
a=shear span, mm
d=depth of tension steel in section, mm
f'_{cf} =the cylinder compressive strength of fibrous concrete
F = fiber factor expressed as:

$$F=(L_f/D_f)V_f\, B_f \qquad \text{...(2)}$$

D_f=fiber diameter, mm
L_f= fiber length, mm
V_f=volume fraction of steel fibers
B_f=bond factor =0.5for round fibers [3]
The second which is a modification of Zsutty's equation[4], has been developed to predict the shear strength of reinforced HSFRC beams without stirrups and as follows:

For a/d ≥2.5

$$v= [2.11(f'_c)\ 0.33+7F]\ (\rho_w\ d/a)^{0.333} \quad ,MPa \qquad ....(3)$$

For a/d <2.5

$$v= [Eq.\ (3)](2.5/a/d)+ v_b(2.5\text{-}a/d) \quad ,MPa \qquad ....(4)$$

where:

$$v_b=0.41\tau F \quad ,MPa \qquad .....(5)$$

τ = average fiber-matrix interfacial bond stress=4.15 MPa
F = fiber factor
The ultimate shear strength of HSFRC beams has been studied by Shin, et al.[5], who proposed the following empirical equations, [Eq.(6)and Eq.(7)], for determining the shear stress of HSFRC beams.

$$v=0.22\ f_{sp} +217\rho_w\ d/a +0.34\ \tau F \quad \text{for } a/d < 3 \ ,MPa \qquad ......(6)$$

$$v=0.19\ f_{sp} +93\rho_w\ d/a +0.34\ \tau F \quad \text{for } a/d \geq 3 \ ,MPa \qquad ....(7)$$

Where
f_{sp} = the splitting tensile strength of fibrous concrete
Bunni[6] proposed an expression to predict the shear strength of HSFRC beams as:
For a/d ≥2.5

$$V= [2.3(f'_{cf}\ \rho_w\ d/a)^{0.333} + 3.11(F\ d/a)^{0.735}]b_w\ d \ ,N \qquad .....(8)$$

For a/d < 2.5

$$V=[2.3(f'_{cf}\ \rho_w\ d/a)^{0.333} + 2.5/(a/d) + 3.11(F\ d/a)^{0.735}]b_w\ d\ ,N \qquad ....(9)$$

Khuntia, et al. [7] made an attempt to present a rational and unified procedure for predicting the shear strength of normal and HSFRC beams. A design equation [Eq.(10)] is suggested for evaluating the ultimate shear strength of HSFRC beams based on the basic shear transfer mechanisms and numerous published experimental data on concrete strength up to 100 MPa (14,500 psi).

$$v= (0.167\alpha+0.25F)\ \sqrt{f'_{cf}} \quad ,MPa \qquad ....(10)$$

Where
α = the arch action factor
= 1 for $a/d \geq 2.5$
=2.5 $d/a \leq 3$ for $a/d < 2.5$

Kwak, et al. [8] developed a new equation [Eq.(11)] for shear strength. The results of 139 tests of fiber-reinforced concrete beams without stirrups were used to evaluate existing and proposed empirical equations for estimating shear strength.

$$\nu = 3.7 f_{sp}^{2/3} (\rho_w \, d/a)^{1/3} + 0.8\nu_b \quad ,\text{MPa} \qquad \text{….(11)}$$

where:
f_{sp} = the splitting tensile strength of concrete
$\nu_b = 0.41\tau F$
τ = average fiber-matrix interfacial bond stress=4.15 MPa
F = fiber factor

EXPERIMENTAL PROGRAM

Specimens dimensions and variables

In this paper fifteen shear tests of RPC beams without steel stirrups are reported. The beams were designed to have extra strength in flexure to ensure shear failure. The beams are presented in Fig (1) and Table (1).

For all beam specimens, the cross section was 100mm wide and 140mm in depth, the overall length was 1300mm, with clear span 1200mm.

The longitudinal reinforcement ratio (ρ_w), shear span-to-depth ratio (a/d), volume fraction of fibers (V_f), percentage of silica fume (SF), and compressive strength of concrete were varied. Table (1) illustrates all beams details.

Materials and Mix Design

The cement used in this research was AL-Sharqiya ordinary Portland cement (ASTM Type I) manufactured in the Kingdom of Saudi Arabia**.** Densified silica fume from Elkem Materials Company in Dubai has been used as a mineral admixture added to the mixtures of the research. The used percentage is 15% of cement weight (as an addition, not as replacement of cement).

Fine silica sand known as glass sand is used. This type of sand is by- produced in Al- Ramadi Glass factory. The fineness modulus is 2.32. The steel fibers used in this test program were straight steel fibers manufactured by Bekaert Corporation. The fibers have the properties described in Table (2) which is brought from United Arab Emirates.

Without the use of superplasticizer the production of RPC would not be possible. In this research, a new generation of modified superplasticizer, Sika® Viscocrete® 3110[9], is used. The mix design of RPC using local constituent is 1**:**1**:** 0.15 (cement **:**sand **:**silica fume) with water cement ratio 0.2 plus 1.7% by weight of binder of Sika® Viscocrete® 3110 admixture.

In this study, three steel reinforcement ratios were used (0.34, 0.49 and 0.59) as flexural reinforcement. Yield strengths of the 10, 12 and 16 mm bars were 658, 738 and 520, respectively. By using steel ratio of 0.34, two 16 mm bars were used while two 16 mm plus two10 mm bars were used in the case of 0.49 steel ratio and two 16 mm plus two12 mm bars were used in the case of 0.59 steel ratio.

Mixing, Curing And Fabrication

All the constituents were batched by an electronic balance and mixed in a horizontal pan mixer for about 10 minutes. Water and superplasticizer is added to the rotary mixer and the whole mix ingredients were mixed for a sufficient time**.**

Fibers were uniformly distributed into the mix slowly in 3 minutes during mixing process, and then the mixing process continued for additional 3 minutes. Although fibrous mixes are less workable than plain concrete, the mix procedures proved satisfactory in that the dispersion of fibers was found to be uniform and there was no significant fiber balling. Seven 200mm high by 100 mm diameter cylinders and three 100mm x 100mm x 400mm prisms were prepared from each batch and used for determining the compressive strength (f'_{cf}), splitting tensile strength(f_{tf}), modulus of elasticity(E_c) and modulus of rupture(f_{rf}) of RPC at the age of 28 days. Table (3) shows the Properties of hardened concrete. The letter M denotes specimens; the first number indicates the percentage of fiber content (V_f) and the second number indicates the percentage of silica fume (SF).

The hardened specimens were demolded after 24 hours. They were steam cured at about 70^{o}C for 48 hours in water bath. After that the samples were left to be cooled at room temperature, then placed in water and left until the end of water curing at 28 days.

Test procedure

The beams were simply supported and subjected to a two point load, as shown in Fig.(2). The distance between the two point loads was varied at (640, 528, 416, 304, and 192) mm according to a/d ratio (2.5, 3.0, 3.5, 4.0 and 4.5)respectively. Special bearing assemblies (roller, guide plates,etc.) were designed to facilitate applying loads to the test specimens.

Three dial gages were used to measure the deflections of the beams at every load stage on midspan and supports. Only the dial gage placed directly under the center line of the beam was necessary to calculate the midspan deflection. However, the other gages were used to check the support displacement reading.
Load was applied using a 1250 kN capacity calibrated electrohydraulic testing machine (Avery) in 5 kN increment up to failure. At the end of each increment, midspan deflection, crack development and propagation on the beam surface were recorded.

EXPERIMENTAL RESULTS

Test results from the 15 RPC beams are presented in Table (1), which include details of cracking and ultimate shear strength for test beams**.**

ANALYSIS OF RESULTS

Mode of failure

All the beams tested in this work failed in shear although the mode of failure differed from one a/d ratio to another. All the beams with a/d ratio of 3.0-4.5 failed in diagonal tension, with the exception of B9, B12 and B13 which had shear-flexure failure. All beams with a/d ratio of 2.5 failed in shear-compression as shown in Figures (3) to (5).

In nonfibrous beam B1, the development of shear cracks was sudden and immediately followed by a violent and completely destructive shear failure as shown in Figure (3). It was observed that when steel fibers were used, the shear crack propagation became slower and more gradual so that it showed significant post-cracking load capacity before the complete failure of the RPC beams was achieved.

Load-midspan deflection of RPC beams

Figures (6) to (9) present the effect of volume fraction of steel fibers (V_f), shear span to effective depth ratio (a/d), longitudinal reinforcement ratio (ρ_w) and adding different percentages of (SF) powder on the load-midspan deflection curve.

Proposed Expressions for Shear Capacity of RPC Beams

In the present work, two methods were considered to propose expressions for shear capacity of RPC beams. The first method depends on the well known Codes provisions for shear capacity with adding the effect of steel fibers to the proposed expressions.

The second method is conducted by modifying the expressions of shear capacity of HSFRC beams which are proposed by some of researchers as outlined in literature review.

The proposed expressions for shear capacity of RPC beams by the two proposed methods were, only based on the results of the fifteen beams tested in this investigation, because there is no other data on RPC beams failing in shear.

Method one

To formulate the requirements for the loaded RPC beams, it is necessary to identify all external and internal actions that may be present. The free body diagram of a part of a shear span of a simply supported RPC beam without stirrups, subjected to concentrated loads, may be examined, as shown in Fig. (10). The shear force V may be resisted by (1) the shearing forces across the compression zone, which sum up to V_{cz}; (2)the transverse force induced in the main flexural reinforcement by dowel action V_d; (3) vertical component V_{fi} of the fiber pullout forces along the inclined crack.

The total shear force can be written as follows:

$$V= V_{cz}+ V_d + V_{fi} \qquad \text{…… (12)}$$

Since the individual contribution from each of the first two internal shear components are difficult to estimate, they are commonly lumped together and denoted by the term V_c, the contribution of the concrete thus;

$$V= V_c+ V_{fi} \qquad \text{…. (13)}$$

Depending on test results obtained from this investigation on RPC beams failing in shear and reinforced only with steel fibers as shear reinforcement, the contribution for steel fibers in carrying the shear force in beams with steel fibers was computed by subtracting the test results of the ultimate load of the nonfibrous beam from the test results of the ultimate load of the corresponding beam with steel fibers. For the test results of the fifteen beams considered in this research, the shear stress was obtained by dividing the shear strength by $b_w d$.

$$\nu_{fi}\ \text{test} = \nu_{u1}\ \text{test} - \nu_{u2}\ \text{test} \quad \text{,MPa} \qquad \text{….(14)}$$

Where:

ν_{fi} test :experimental test results of the shear stress carried by steel fiber reinforcement.

ν_{u1} test :experimental test results of the ultimate shear stress of fibrous RPC beam.
ν_{u2} test :experimental test results of the ultimate shear stress of nonfibrous beam.
Nonlinear multiple stepwise regression analysis by Data Fit software was adopted to relate the ν_{fi} in terms of the affecting parameters. The general expression can be written as:

$$\nu_{fi}=k_0\,(x)^{k1} \qquad \ldots\ldots(15)$$

where
ν_{fi} :predicted shear stress which is carried by steel fiber reinforcement MPa.
x :independent variables (f'_{cf} , a/d, F,…..,etc.)
k_o , k_1 :constants.
The proposed expressions for predicting the ultimate shear stress carried by steel fibers of RPC beams without stirrups are listed in Table (4).It is obvious that equation no.1, Eq. (16), has a value of COV of 8.778% and has higher correlation. This means that the power format gives the best representation for ν_{fi} prediction.

$$\nu_{fi}=15\, f'_{cf}\, \rho_w\, (a/d)^{-2}\, (F)^{0.24} \quad ,\mathrm{MPa} \qquad \ldots\ldots(16)$$

Where
ρ_w : longitudinal reinforcement ratio
a/d :shear span to effective depth ratio
After this stage, the proposed expression for predicting ν_{fi}, Eq.(16), will be added to the expressions of reinforced concrete beams given by the different Codes. These expressions :(1) ACI(10), equation, [Eq.(17)], (2) ACI, equation(10), [Eq.(18)], (3) CAN. (11) equation, [Eq.(19)], (4) NZ(12)equation,[Eq.(20)] and (5) BS(13) equation, [Eq.(21)].
Thus, five expressions will be examined as follows:

$$\nu_= 0.17\sqrt{f'_{cf}} +15\, f'_{cf}\, \rho_w\, (a/d)^{-2}\, (F)^{0.24} \qquad \ldots.\ (17)$$

$$\nu_= 0.16\sqrt{f'_{cf}} +17\, \rho_w\, d/a +15\, f'_{cf}\, \rho_w\, (a/d)^{-2}\, (F)^{0.24} \qquad \ldots.\ (18)$$

$$\nu_= 0.2\sqrt{f'_{cf}} +15f'_{cf}\rho_w(a/d)^{-2}(F)^{0.24} \qquad \ldots.(19)$$

$$\nu_= (0.07+10\, \rho_w)\sqrt{f'_{cf}} +15f'_{cf}\, \rho_w\, (a/d)^{-2}\, (F)^{0.24} \qquad \ldots.(20)$$

$$\nu_= 0.8(100\rho_w)^{1/3}(400/d)^{1/4}(f'_{cf}/20)^{1/3} +15\, f'_{cf}\, \rho_w\, (a/d)^{-2}\, (F)^{0.24} \qquad \ldots.(21)$$

In the above equations, it is important to notice that:

1. No reduction factors are used.
2. The term f'_c for nonfibrous concrete compressive strength of beams in the equations which are used to predict ν_c was replaced by f'_{cf} for fiber reinforced concrete compressive strength of beams.

3. [Eq.(21)] has not been modified from using f_{cu} (BS practice) to f'_{cf}. Research indicates that UHPFRC shows little difference between f_{cu} and f'_{cf} [14].
4. No upper limit for concrete compressive strength has been used –contrary to BS requirement.

To test these equations, the relative shear stress values RSSV(ν_{test}/ $\nu_{proposed}$) were found for the 15 beams tested in this research work using each of these equations, then the mean (μ), standard deviation (SD), and the coefficient of variation (COV) were calculated for these equations as shown in Table (5).

It is obvious from the table that equation no.5 [Eq.(21)] for ν_c proposed by BS Code, Eq.(B-5), has the lowest value of μ, SD, and COV of 1.057, 0.066, and 6.281%, respectively.

Method two

In this method, six expressions for shear strength of HSFRC beams are modified to represent the shear strength of RPC beams based on the result of the fifteen beams tested in this work by using nonlinear multiple regression analysis. Table (6) shows the comparison between the expressions of shear strength for HSFRC beams which were proposed by some of researchers and equations of shear strength for RPC beams which have been modified in this research work.

To test these modified expressions, the relative shear stress values RSSV (ν_{test}/ $\nu_{proposed}$) were found for the 15 beams tested in the present research work using each of these modified expressions, then the mean (μ), standard deviation (SD), and the coefficient of variation (COV) were calculated for these modified expressions as shown in Table (7).

It is obvious from the table that the modified expression of Bunni Eq. no.(3) for ν has the lowest value of μ, SD, and COV of 0.992, 0.081, and 8.130%, respectively. Thus, this expression was chosen for predicting the shear stress resistance of RPC beams with a/d equal to or greater than 2.5

$$\nu=4.56f'_{cf}\rho_w d/a+5.9\sqrt{(F)(d/a)} \quad \text{MPa} \qquad \text{.....(22)}$$

It is obvious that the proposed expression has a better value of COV at 8.135%. This means that the power format and constant gives the best representation for ν prediction.

Evaluation of the Proposed Expressions

Existing researches, so far, do not contain any beams, that can be applied to this work. Table (6) includes six existing proposals for shear stress resistance of HSFRC beams, based on test results of references 2, 5, 6, 7 and 8, respectively.
As indicated in Table (7), only one method which was proposed by Bunni[6] among existing researches can give a reasonably low COV of 8.13 percent, after the proposed modification given in this work, [Eq.(22)]. Figs.(11) to (14) indicate the influence of different factors on the value of RSSV based on the two proposed modifications- [Eq.(21) and Eq.(22)]. These figures show respectively the influence of f'_{cf}, ρ_w, a/d and F.

It can be seen from Figures (11) to (14) that the proposed modifications on the BS Code [13] and the Bunni proposal [6] give satisfactory predictions for RPC in shear. Figure (15) gives further comparison between the two expressions [(21) and (22)] and the application of [Eq. (1), (7), (10) and (11)] on a basis of RSSV versus the experimental shear stress at failure. Fig.(16) makes similar comparison between the six methods, where the proposed prediction is compared with the tested shear stress at failure.

From Figures (15) and (16), it can be seen that proposed [Eq. (21) and (22)] are the only ones that give satisfactory predictions for RPC. This contrasts with the applications from existing research, since references [2, 5, 6, 7 and 8], respectively on testing HSFRC in shear –not RPC. Further evidence of the applicability of proposed [Eq.(21) and (22)] for RPC can be seen in Fig.(18). While [Eq. (21) and (22)] give COV values of 6.3 and 8.1 percent, the HSFRC tests give much higher COV values- between 13.4%-23.9%.

CONCLUSIONS

1. Three modes of failure were observed for the tested RPC beams, these are: diagonal tension failure, shear-compression failure and shear-flexure failure. The shear-compression failure is observed when a/d is 2.5. All other RPC beams with an a/d ranging between 3.0 to 4.5 failed in diagonal tension except B9, B12 and B13which failed with shear-flexure mode.

2 When a/d ratio increases from 3.5 to 4.5 the mode of failure was in diagonal tension failure for V_f =1%, and changed to shear-flexure failure with V_f =2% as occurred in B13.

3. When SF content decreases from 15% to 5% with steel fiber content V_f =2% , the mode of failure changed from a diagonal tension failure to shear-flexure failure, as occurred in B9.

4. Based on test results obtained from this investigation, two expressions have been proposed to predict the shear stress resistance of reinforced RPC beams without web reinforcement, these are:

$$[\nu_{=}0.8(100\rho_w)^{1/3}(400/d)^{1/4}(f'_{cf}/20)^{1/3}+15\, f'_{cf}\, \rho_w(a/d)^{-2}(F)^{0.24}]$$

$$[\nu_{=}4.56\, f'_{cf}\, \rho_w\, d/a +5.9(F\, d/a)^{0.5}]$$

5. Comparisons with experimental data indicate that the proposed expressions properly estimate the effects of primary factors, such as concrete compressive strength, longitudinal steel ratio, shear span to effective depth ratio and fiber factor.

6. The two proposed expressions, Eq.(21) and Eq.(22), have lower COVvalues of 6.3% and 8.1% respectively, but it is obvious that Eq.(22) is a more simple formula than Eq.(21) .

7. By testing the proposed shear stress expressions against the experimental results of this study, improvement in the overall prediction accuracy (COV value) is exhibited of 13.4% with respect to expression proposed by Ashour, 18.7%with respect to Shin formula, 23.9% and 18.6% with respect to Khuntia and Kwak equations respectively .

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Abbreviations **and Notations**

ACI	American Concrete Institute
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
BSI	British Standards Institution
CSA	Canadian Standards Association
COV	Coefficient of variation
HSFRC	High Strength Fiber Reinforced Concrete
NSC	Normal Strength Concrete
NZS	New Zealand Standards Association
RPC	Reactive Powder Concrete
RSSV	Relative Shear Stress Values
SF	Silica Fume
a	Shear Span,mm
B_f	Bond Factor
d	Depth of Tension Steel in Section, mm
D_f	Fiber Diameter, mm
F	Fiber Factor
f_{sp}	The Splitting Tensile Strength of Fibrous Concrete
L_f	Fiber Length, mm
V_f	Volume Fraction of Fiber
ρ_w	Flexural Reinforcement Ratio
τ	Average Fiber- Matrix Interfacial Bond Stress= 4.15 MPa

Table (1): Beam Details, Cracking Load, Ultimate Shear Strength and Mode of Failure for Test Beams.

Beams	b mm	a mm	V_f %	a/d	ρ_w %	SF %	f'_{cf} MPa	Diagonal Cracking Load V_{cr} kN	Ultimate Shear Strength V_u kN	$\frac{V_{u,test}}{V_{cr,test}}$	Mode of Failure *
B1	416	392	0	3.5	0.03	15	78	25	35.5	1.42	DT
B2	416	392	0.5	3.5	0.03	15	94	30	66.5	2.2	DT
B3	416	392	1.0	3.5	0.03	15	98	30	70	2.33	DT
B4	416	392	1.5	3.5	0.03	15	103	32.5	77.5	2.38	DT
B5	416	392	2.0	3.5	0.03	15	110	35	82.5	2.36	DT
B6	416	392	2.0	3.5	0.04	15	110	52.5	107.5	2.05	DT
B7	416	392	2.0	3.5	0.05	15	110	57.5	112.5	1.96	DT
B8	416	392	2.0	3.5	0.03	10	101	32.5	77.5	2.38	DT
B9	416	392	2.0	3.5	0.03	5	93.4	27.5	75	2.73	S+F
B10	640	280	2.0	2.5	0.03	15	110	37.5	125	3.33	SC
B11	528	336	2.0	3.0	0.03	15	110	35	97.5	2.79	DT
B12	304	448	2.0	4.0	0.03	15	110	25	62.5	2.5	S+F
B13	192	504	2.0	4.5	0.03	15	110	22.5	59.5	2.64	S+F
B14	640	280	1.0	2.5	0.03	15	98	32.5	100	3.08	SC
B15	192	504	1.0	4.5	0.03	15	98	20	55	2.75	DT

***** DT: diagonal tension failure, S+F: shear-flexure failure, SC: shear-compression failure.

Table (2): Properties of the Steel Fibers

Description	straight
Length	13 mm
Diameter	0.2 mm
Density	7800 kg/m^3
Tensile Strength	2600 MPa
Aspect Ratio	65

- Supplied by the manufacturer

Table (3): Properties of Hardened Concrete:

specimens Designation	Vf %	Silica Fume %	Compressive Strengthf'$_{cf}$ (MPa)	Splitting Tensile Strength f'$_{spf}$ (MPa)	Modulus of Rupture f'$_{rf}$ (MPa)	Modulus of Elastisity E_c (MPa)
M0.0-15	0.0	15	78	5.5	5.7	39.10
M0.5-15	0.5	15	94	9.2	10	42.25
M1.0-15	1.0	15	98	11	12	44.20
M1.5-15	1.5	15	103	14.5	15.05	46.80
M2.0-15	2.0	15	110	15.4	19	48.80
M2.0-10	2.0	10	101	14	17.6	47.50
M2.0-5	2.0	5	93.4	12.7	16	44.37

Table (4): Selection of the Basic Format for the Proposed Equations of ν_{fi}

No.	Proposed Equations of ν_{fi}	$\nu_{fi\ test}$ / $\nu_{fi\ proposed}$		
		μ	SD	COV(%)
1	$\nu_{fi} = 15\ f'_{cf}\ \rho_w\ (a/d)^{-2}\ F^{0.24}$	0.991	0.087	8.778
2	$\nu_{fi} = 29.36\ f'^{0.446}_{cf}\ (\rho_w\ F/\ a/d)^{0.777}$	0.953	0.231	24.27
3	$\nu_{fi} = 0.63\ f'^{1.047}_{cf}(\rho_w\ F)^{0.431}/(a/d)$	1.048	0.379	36.165
4	$\nu_{fi} = 0.002\ f'^{2.12}_{cf}\ (F)^{0.199}(a/d)^{-1.7}$	0.983	0.218	22.167
5	$\nu_{fi} = 0.04\ f'_{cf}\ (F/a/d)^{2.29*10\wedge10}$	0.991	0.415	41.880
6	$\nu_{fi} = 0.398\ (f'_{cf}\ F/a/d)^{0.847}$	1.059	0.417	39.336
7	$\nu_{fi} = 2.82\ (f'_{cf}\ F)^{0.418}/a/d$	0.948	0.269	28.401
8	$\nu_{fi} = 0.813\ (f'_{cf}\ F)^{0.416}$	1.003	0.405	40.397
9	$\nu_{fi} = 52.63\ (a/d)^{-1.8}(F)^{0.47}$	0.989	0.244	24.665
10	$\nu_{fi} = 23.6\ (F/a/d)^{2.29*10\wedge10}$	1.056	0.414	39.164

Table (5): Mean, Standard Deviation, and Coefficient of Variation Values of the Relative Shear Strength Values.

No.	Proposed Equations of ν	$\nu_{test} / \nu_{proposed}$		
		μ	SD	COV(%)
1	$\nu = \nu_c$, (ACI),$(0.17\sqrt{f'_{cf}}\,) + \nu_{fi}$, Eq.(16)	1.343	0.263	19.596
2	$\nu = \nu_c$, (ACI), $(0.16\sqrt{f'_{cf}} + 17\,\rho_w\, d/a\,) + \nu_{fi}$, Eq.(16)	1.324	0.248	18.75
3	$\nu = \nu_c$, (CAN),$(\,0.2\sqrt{f'_{cf}}\,) + \nu_{fi}$, Eq.(16)	1.231	0.173	14.068
4	$\nu = \nu_c$, (NZ), $[(0.07+10\,\rho_w)\,\sqrt{f'_{cf}}\,] + \nu_{fi}$, Eq.(16)	0.855	0.060	7.071
5	$\nu = \nu_c$, (BS), $[0.8(100\rho_w)^{1/3}(400/d)^{1/4}(f'_{cf}/20)^{1/3}]$ $+\nu_{fi}$, Eq.(16)	1.057	0.066	6.281

Table(6):Summary of Modified Shear Strength Equations Used by Different Investigators.

No.	Investigator	Predictive Expression for Shear Stress Resistance for HSFRC Beams	Modified Predictive Expression for Shear Stress Resistance for RPC Beams
1	**Ashour et al.[10] (1)**	$\nu=[0.7\sqrt{f'_{cf}}+7F]d/a+17.2\rho_w d/a$	$\nu=[0.34\sqrt{f'_{cf}}+15F+374.4\rho_w]d/a$
2	**Ashour et al.[10] (3)**	$\nu=[2.11(f'_{cf})^{0.33}+7F](\rho_w\, d/a)^{0.33}$	$\nu=[2.4f'_{cf}+52.4F](\rho_w\, d/a)^{0.8}$
3	**Bunni [49] (8)**	$\nu=2.3(f'_{cf}\rho_w d/a)^{0.333}+3.11(Fd/a)^{0.735}$	$\nu=4.6f'_{cf}\rho_w d/a+5.9\sqrt{(F)(d/a)}$
4	**Shin et al.[48] (7)**	$\nu=0.22\,f'_{sp}+217\rho_w\, d/a+0.34\,\tau F$ for $a/d<3$ $\nu=0.19\,f'_{sp}+93\rho_w\, d/a+0.34\,\tau F$ for $a/d\geq 3$	$\nu=-0.045f'_{sp}+534.4\rho_w d/a+\tau F$ for $a/d\geq 2.5$
5	**Khuntia et al.[50] (10)**	$\nu=(0.167\alpha+0.25F)\sqrt{f'_{cf}}$ $\alpha=1$ for $a/d\geq 2.5$	$\nu=(0.0058\alpha+0.0036F^{0.196})(f'_{cf})^{1.45}$ $\alpha=1$ for $a/d\geq 2.5$
6	**Kwak et al.[51] (11)**	$\nu=3.7f_{sp}^{2/3}(\rho_w\, d/a)^{1/3}+0.8\nu_b$ $\nu_b=0.41\tau F$ $\tau=4.15$	$\nu=227.5f_{sp}^{0.38}(\rho_w\, d/a)+0.8\nu_b$ $\nu_b=0.41\tau F$ $\tau=4.15$

Table (7): The Mean, Standard Deviation, and Coefficient of Variation Values of the Relative Shear Strength Values to Test the Modified Expressions.

No.	modified Expressions	µ	SD	COV(%)
1	Ashour et al.(modified)	0.984	0.106	10.770
2	Ashour et al.(modified)	0.982	0.116	11.847
3	Bunni (modified)	0.992	0.081	8.130
4	Shin et al. (modified)	0.983	0.134	13.580
5	Khuntia et al.(modified)	1.000	0.215	21.486
6	Kwak et al. (modified)	0.988	0.108	10.790

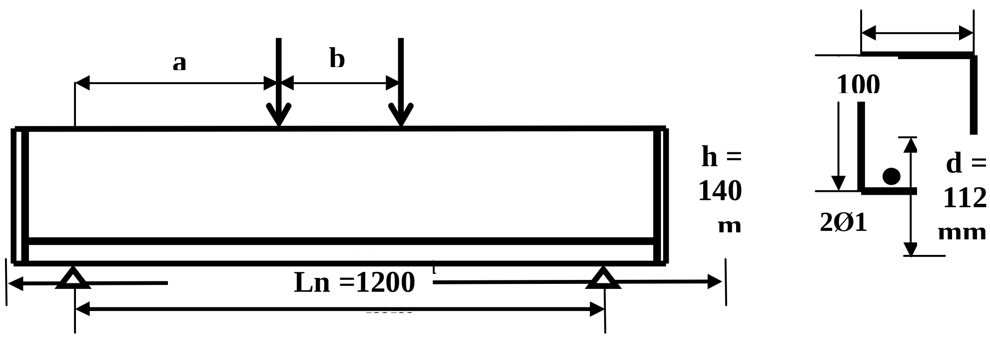

Figure (1): Details of Typical tested Beam Designed to Fail in Shear

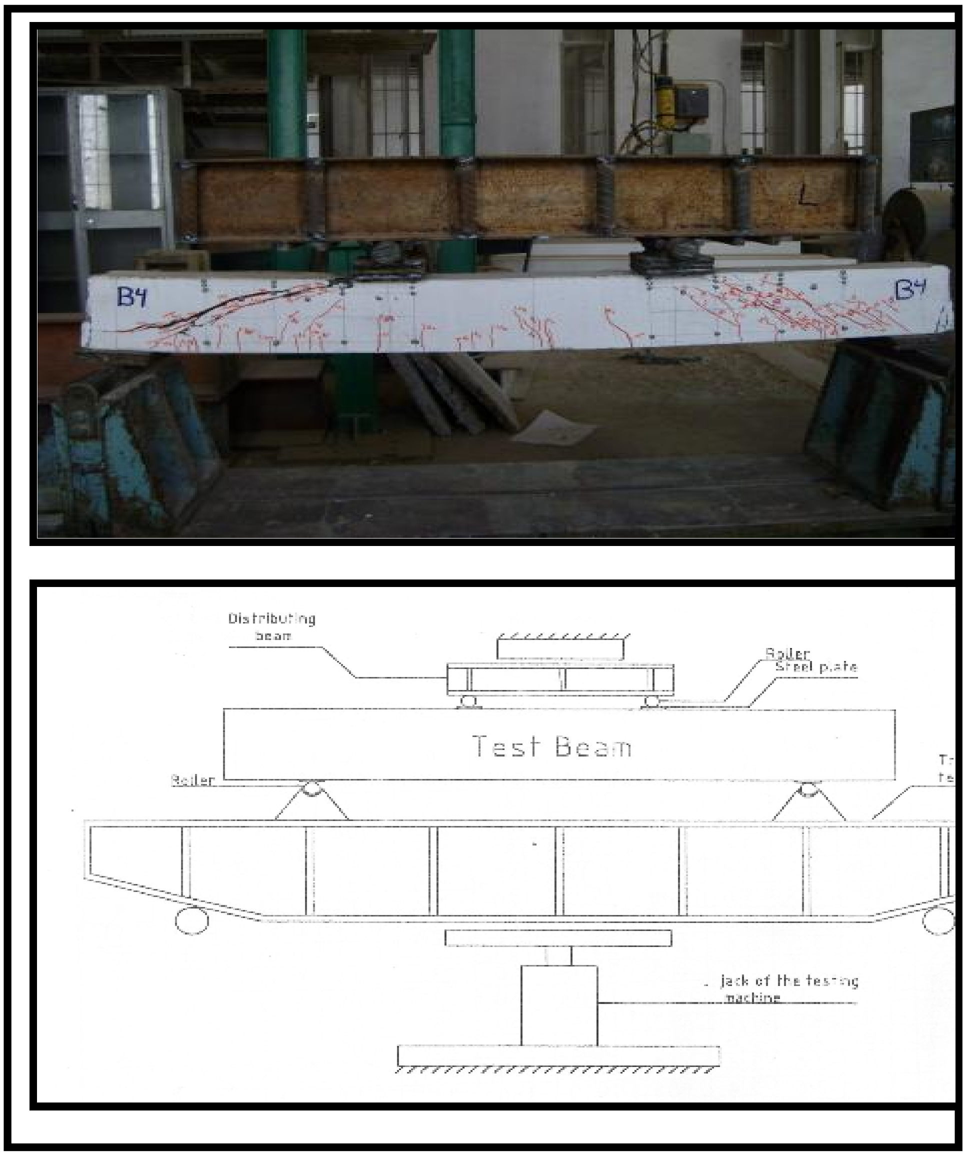

Figure (2): Beams Testing Machine Details

Figure (3): Crack Patterns for Nonfibrous Beam B1.

Figure (4): Crack Patterns for Fibrous Beams B2, B3 and B4.

Figure (5): Crack Patterns for Fibrous Beams B5, B6 and B7.

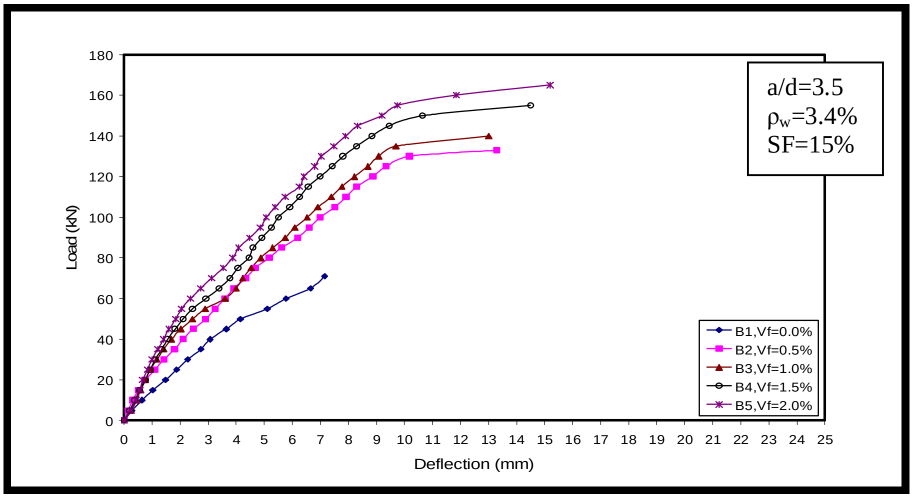

Figure (6): Effect of Fiber Content on the Load-Midspan Deflection Curves of RPC Beams.

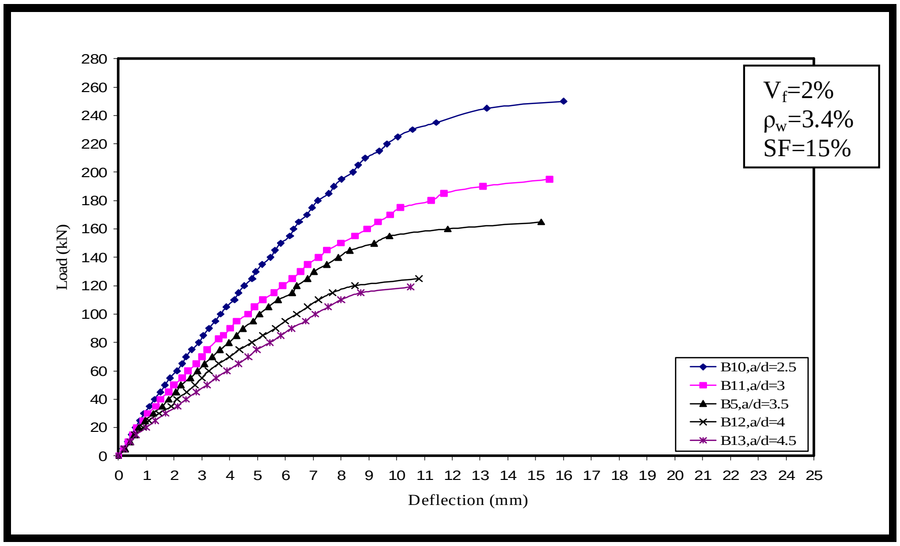

Figure (7): Effect of a/d Ratio on the Load-Midspan Deflection Curves of RPC Beams with V_f=2%.

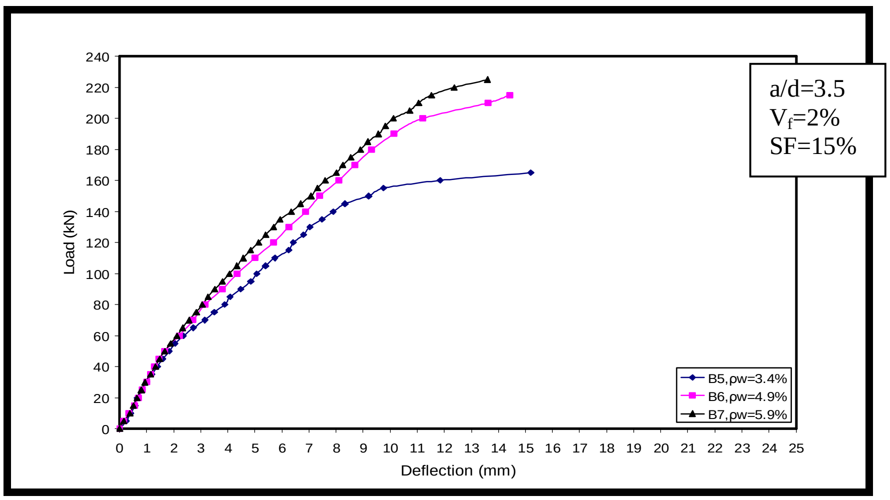

Figure (8): Effect of Steel Ratio ρ_w on the Load-Midspan Deflection Curves of RPC Beams.

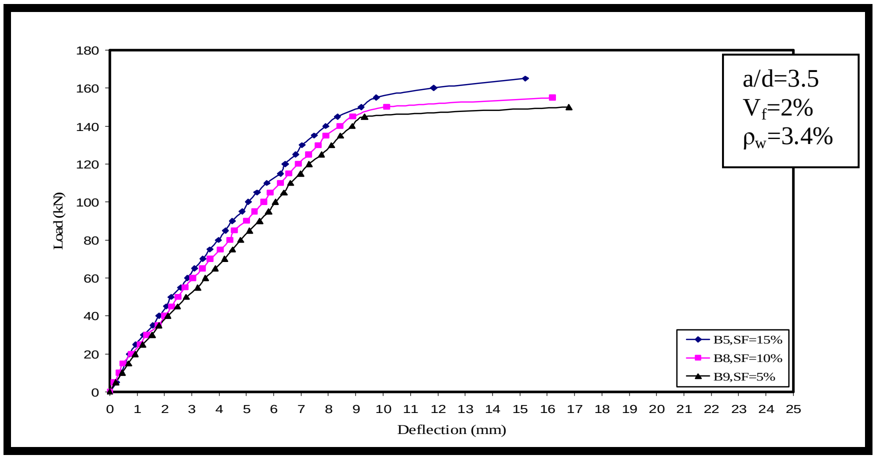

Figure (9): Effect of SF Content on the Load-Midspan Deflection Curves of RPC Beams.

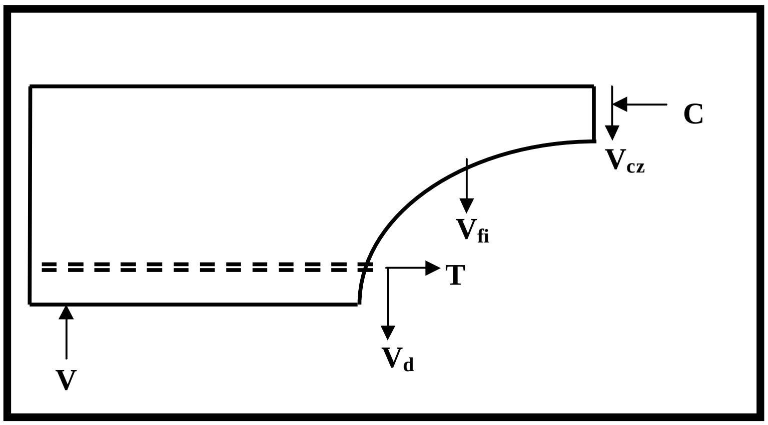

Figure (10): Free Body Diagram of Part of the Shear Span of a Simply Supported RPC.

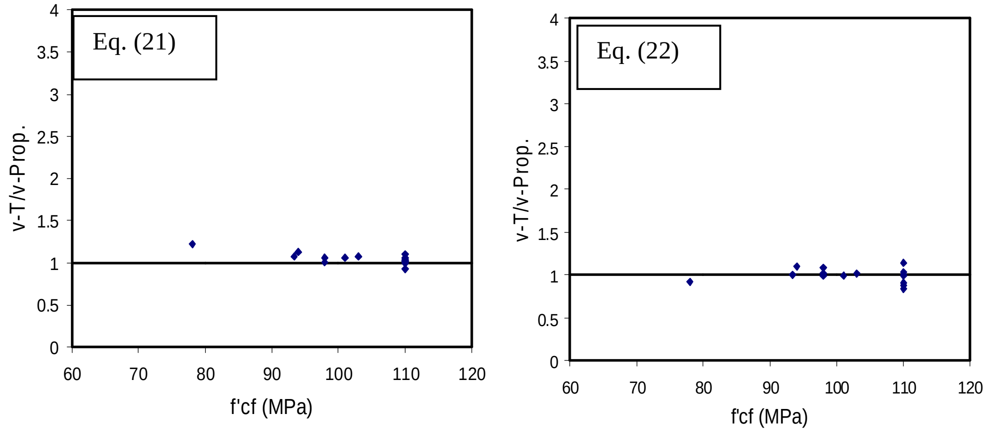

Figure (11): f'_{cf} Versus the Relative Shear Stress Predictions.

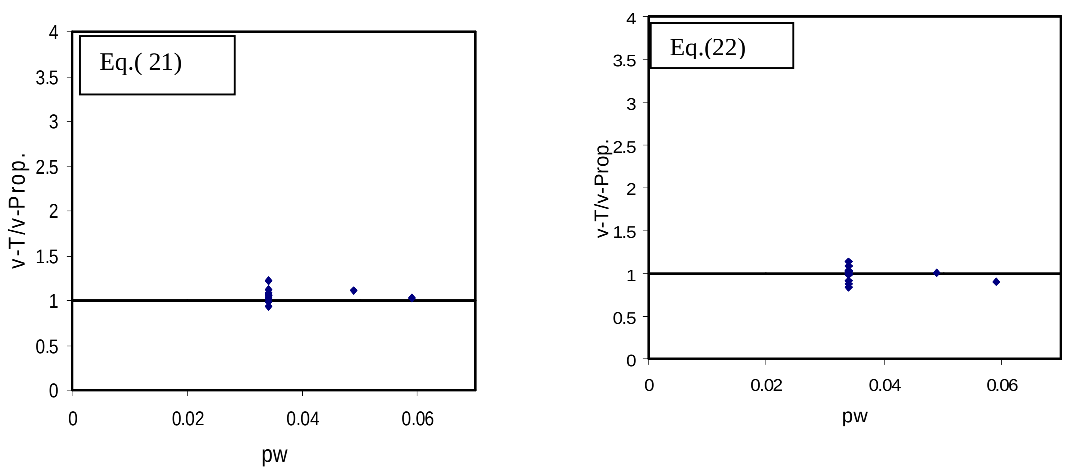

Figure (12): ρ_w Versus the Relative Shear Stress Predictions.

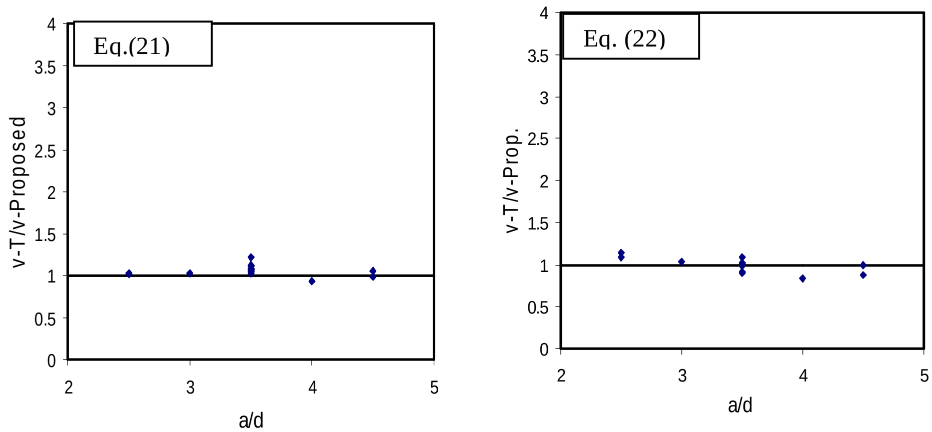

Figure (13): a/d Versus the Relative Shear Stress Predictions.

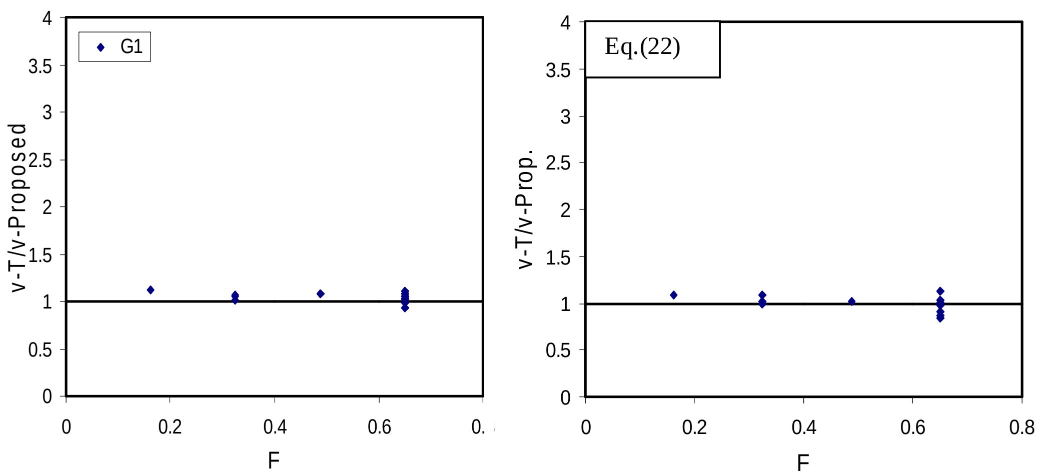

Figure (14): Fiber Factor versus the Relative Shear Stress Predictions.

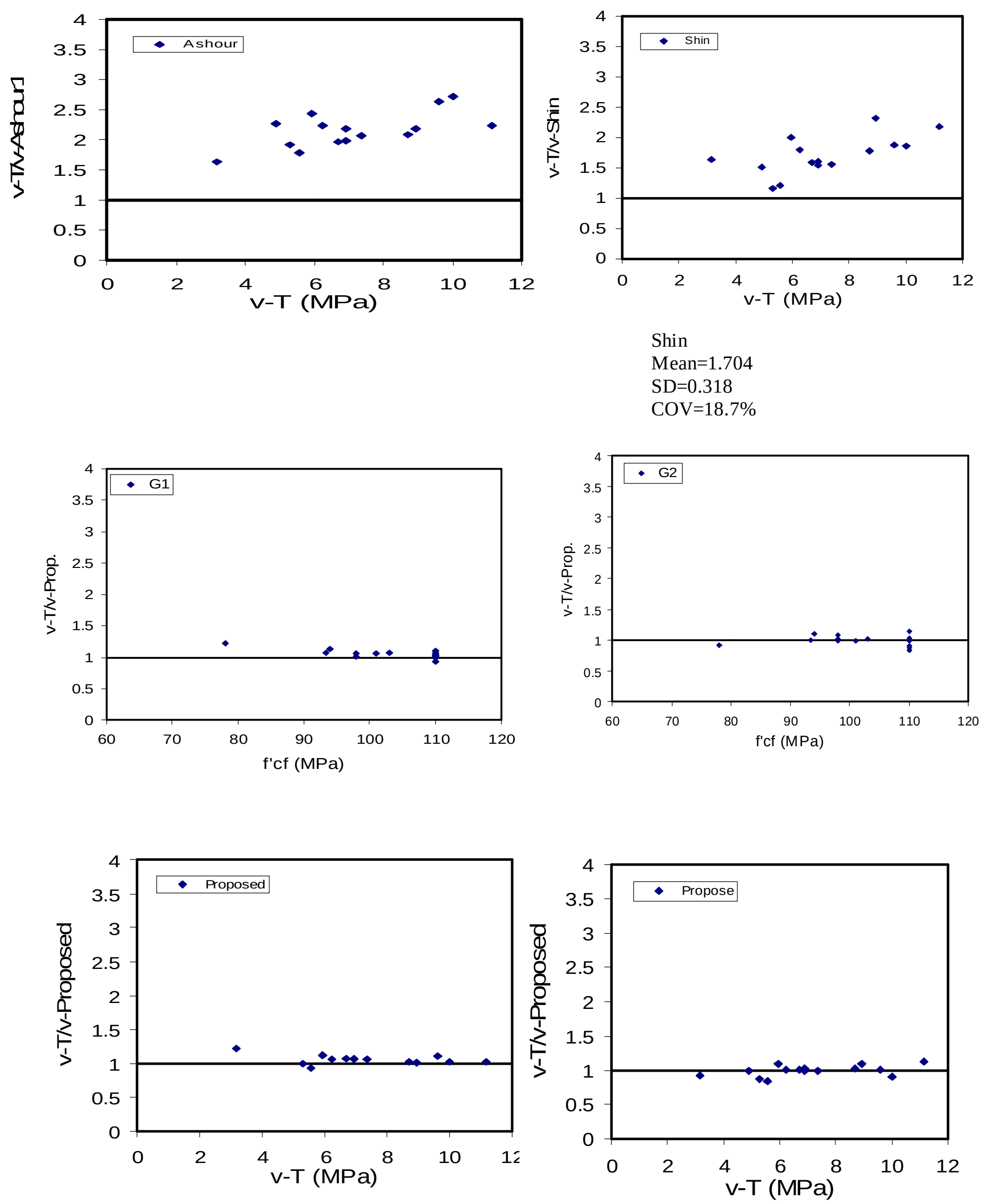

Figure.(15): Comparison of Various Equations with all Existing

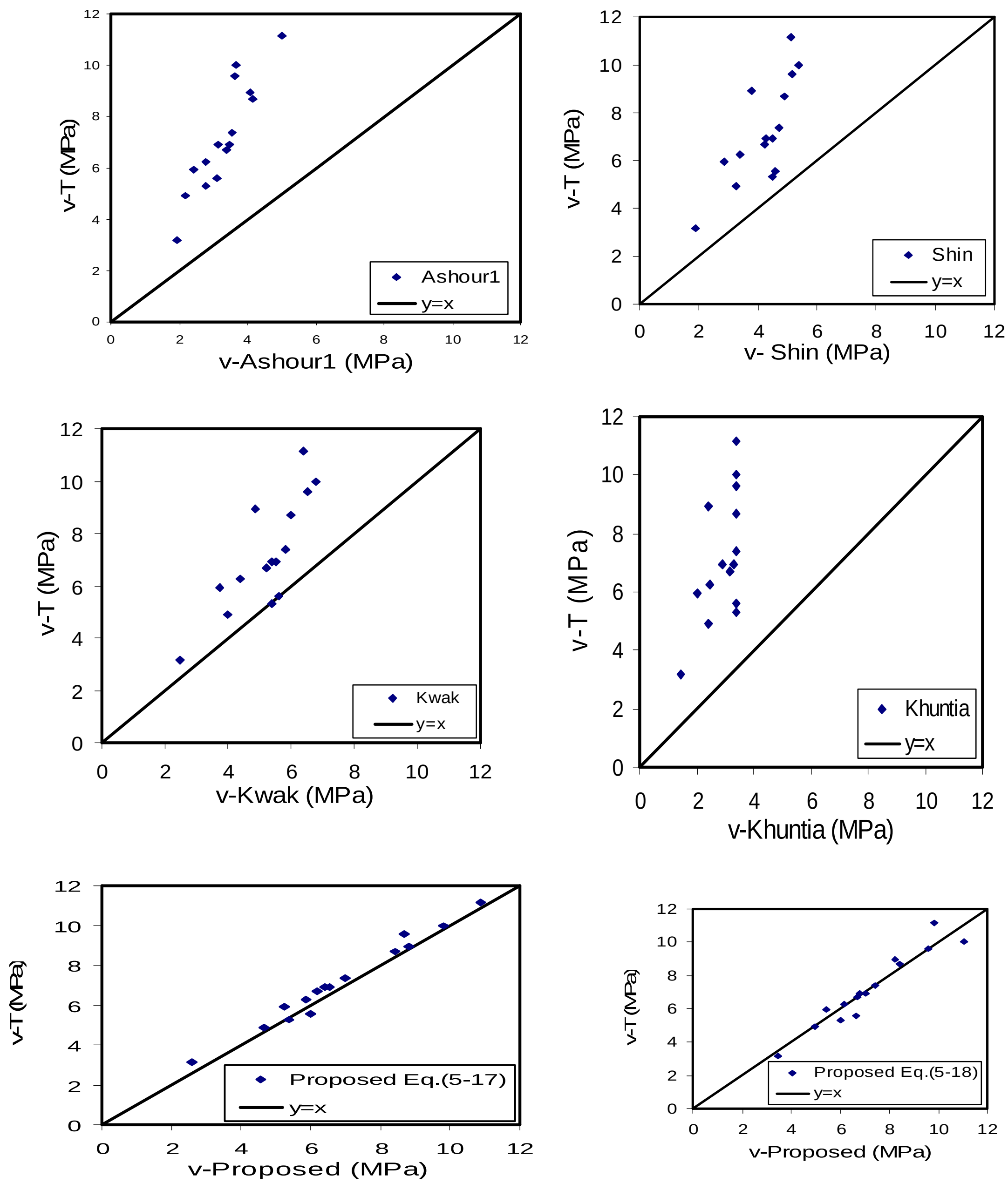

Figure (16) Comparison Between Experimental Data and Calculated.