Direct Shear Behavior of Carbon Fiber Reinforced Self-Compacting Concrete

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Received on: 14/1/2013 & Accepted on: 5/12/2013

ABSTRACT

This paperrepresents an experimental and statistical investigation for the behavior of connectionpoints produced by using self-compacting concrete and subjected to direct shear. The investigation also includes the effect of carbon fiber inclusion as reinforcement on self-compacting concrete (SCC) behavior in direct shear.

This study gives results of sixteen push-off or direct shear specimens in four groups. Variations include volume fraction for carbon fiber (V_f = 0.00, 0.50, 0.75 and 1.00) % for every percentage change in the steel reinforcement. The steel reinforcement parameter $\rho_{vf}f_y$ values are (0.00, 2.66, 5.33 and 7.99) MPa(where ρ_{vf} varies from 0.00 to 0.0173 and f_y=585.7MPa) . The main material properties studied include compressive strength, splitting tensile strength and modulus of rupture. Measurements of deformations were made throughout testing of shear specimens.

The dimension of the shear plane in the push-off specimenswas 170x185 mm. The shear reinforcement was normal to the shear plane. Specimens were cast by using SCC which is a type of high performance concreteand reinforced with carbon fiber.

This work aims to investigate the direct shear behavior of SCC with or without carbon fiber at constant water to cementitious materials ratio of 0.3 by weight. It is found that using carbon fiber increased the direct shear strength. However, carbon fiber alone (without reinforcement) leads to brittle failure. In contrast, adding rebars leads to higher strain and more ductile behavior−increased shear capacity is obtained when higher steel quantity is used. The aim of adding carbon fibers was the increase of the horizontal strain (displacement). It was found that the optimum percentage of volume fraction was 0.75 % for fresh and hardened concrete.

In addition, the effects of carbon fiber on compressive strength of SCC lead to a drop in compressive strength (f'_c) compared with reference specimens. This drop in f'_c was 2.39, 8.38 and 13.58% for V_f =0.50, 0.75 and 1.00%, respectively. In contrast, the splitting tensile strength increased by 3.34, 31.2 and 18.2 as compared with the cylinder strength without carbon fibers atV_f equal to0.50, 0.75 and 1.00% respectively. The

https://doi.org/10.30684/etj.32.10A.13
2412-0758/University of Technology-Iraq, Baghdad, Iraq

modulus of rupture increased by [11.9, 21.99 and 13.83%] as compared with SCC without carbon fibers at V_f equal to 0.50, 0.75 and 1.00% respectively.
Based on push-off tests results for this work and those available in the literature, two statisticalmodels have been established using regression analysis. Four variables f'_c,f_{ct},$\rho_{vf}f_y$ and V_f, were included in these models. Both models showed good representation according to their coefficients of variation (COV)values. Verification of the models were done by using 273 observations from literature and the present work.

Keywords: Direct shear, Self-compacting concrete, Carbon fiber, reinforced concrete.

القص المباشر للخرسانة ذاتية الرص المدعمة بالياف الكاربون

الخلاصة

يقدم هذا العمل دراسة تجريبية و أحصائية لسلوك مناطق الاتصال باستخدام خرسانة ذاتية الرص, وايضا تم التحري تأثير ادخال الياف الكاربون لخرسانة ذاتية الرص على سلوك القص المباشر. تقدم هذه الدراسة نتائج الفحص لستة عشر نموذج للقص المباشر موزعة في اربعة مجاميع. تضمنت المتغيرات المدروسة النسبة الحجميةلالياف الكاربون والتي تراوحت من صفر الى 1 % مقابل تغير العامل ($\rho_{vf}f_y$) من صفر الى 7.99 ميكا باسكال. كانت الخواص المدروسة هي: مقاومة الانضغاط و مقاومة الشد بالانشطار مع قياس الانفعالات الافقية و الشاقولية للنموذج المفحوص .أن ابعاد مستوي القص للنموذج المفحوص كانت 185x170 ملم و تم توزيع حديد التسليح ليكون عموديا على مستوي القص.و استخدام خرسانة الذاتية الرص (عالية الاداء) في صب هذه النماذج مع تدعيمها بالياف الكاربون.
من خلال نتائج البحث وجد ان استخدام الياف الكاربون قد ادت الى زيادة في مقاومة القص المباشر للخرسانة ولكنها لم تمنع حدوث الفشل الفجائي في حالة عدم وجود حديد التسليح الرئيسي. في حين ان وجود حديد التسليح الرئيسي بقي هو المسيطر على الانفعالات (التشوهات) القصحيث زادت مقاومة القص دائما بزيادة نسبة حديد التسليح. برز دور الياف الكاربون جليا في تقييد انفعالات (تشوهات) الافقية. كما وجد من خلال البحث بان النسبة الحجمية (0.75 %) لالياف الكاربون كانت هي المثالية في حالتي الخرسانة الطرية و المتصلبة.

بالاضافة الى ذلك تمت دراسة تاثير الياف الكاربون على مقاومة الانضغاط للخرسانة ذاتية الرص حيث انخفضت مقاومة الانضغاطمقارنة الحالة V_fتساوي 0.00 %. ذلك النقصان في مقاومة الانضغاط كان 2.39, 8.38 و 13.58 %, على التوالي عندما كانت 0.50, 0.75, 1.00 %. بينما زادت مقاومة الشد بالانشطار بمقدار 3.34, 31.2 و 18.2 % لنسبة الياف الكاربون 0.50, 0.75, 1.00 %, على التوالي. ولقد زادت قيمة معامل الكسر بمقدار 11.9 , 21.9 و 13.8 % اذا ما قورنت بالعتبة ذات نسب الياف الكاربون 0.50, 0.75و 1.00 %, على التوالي.

استند تحليل النتائج لهذه الدراسة و دراسات سابقة (لفحص القص المباشر)وقدم مقترحين للتصميم . باستخدام تحليل الانحدار. تعتمد على اربعة متغيرات هي f'_cf_{ct}, $\rho_{vf}f_y$وV_f. عند مقارنة المقترحين مع الطرق الاخرى وجد بــانهما يعطيان افضل نتائج لــ 273نتيجه اختبار لفحص القص المباشر.

INTRODUCTION

A shear force which is transmitted across a specific shear plane is denoted as shear-transfer. This force may be of high importance in many types of reinforced concrete members, e.g. such situations include precast concrete connections, brackets, corbels, members with shear span less than the effective depth where pure or direct shear is more likely to occur and column footing connections subjected to high shear forces.[1,2,3] In some cases a crack exists in the shear plane before any shear force is applied due to either temperature deformation or due to the existence of tension forces caused by restrainedshrinkage.[4**]**

Self-compacting concrete (SCC) is a new class of high performance concrete that can spread readily into place under its own weight and fill restricted sections as well-even with congested reinforcement in structures without the need of mechanical consolidation and without undergoing any significant separation of material constituents. The use of SCC can improve productivity in structural applications such as repairand facilitate the filling of restricted sections. Such concrete has been widely used to facilitate construction operations, especially in sections presenting special difficulties to casting and vibration such as bottom sides of beams and girders[5].

The SCC possesses high compressive strength, stiffness, low thermal and electrical conductivity, low combustibility and toxicity.Two characteristics, have limited its use, it is brittle and weak in tension. However the developments of fiber-reinforced composites(FRC)have provided a technical basis for improving these deficiencies. **[6]** Fibers are small pieces of reinforcing material added to a concrete mix which normally contains cement, water and fine and coarse aggregate. Among the more common fibers used are steel, glass, asbestos, carbon and polypropylene. When the load imposed on concrete approaches that for failure, cracks will propagate, sometimes rapidly, fibers in concrete provide a means of arresting the crack growthIf the modulus of elasticity of the fiber is high with respect to the modulus of elasticity of the concrete or mortar binder, the fibers help to carry the load, thereby increasing the tensile strength of the material. Fibers are improved the toughness and the flexural strength. They also reduce creep strain and shrinkage of concrete.**[7]**

Experimental work

Materials

Cement

Ordinary Portland cement was used in all mixes throughout this investigation. It conforms to the Iraqi specification No.5/1984 (Type I)[(8)], Tables (1) and (2) show the physical and chemical properties of this cement.

Carbon fiber

The carbon fibers used in this study are a product of SikaWrap Company. The length of fiber is (10mm) and the physical properties are shown in Table (3).

Fine aggregate

Natural sand from Al-Ukhaider, Karabala, Iraq,regionwas used for concrete mixes in this work. The fine aggregate has 4.75 mm maximum size. The grading of the fine aggregate is shown in Table (4),Table (5) shows thephysical properties of the fine aggregate. The obtained results indicate that the fine aggregate grading & the sulfate contend are within the limits of Iraqi specification No.45/1984.[(9)]

Coarse aggregate

Natural gravel from Al-Niba'ee region was used .The tested characteristics of this gravel are given in Table (6). Table (7) shows the physical properties of the coarse aggregate. Results indicate that the used coarse aggregate was within the requirements of the Iraqi standard specification No.45/1984**[9]**.

Silica fume

Silica fume which is also known as (SikaFume) is a byproduct of the reduction of high-purity quartz with coke in electric arc furnaces in the production of silicon and ferrosilicon alloys. Silica fume is also collected as a byproduct in the production of other silicon alloys. Because of its extreme fineness and high silica content, silica fume is a highly effective pozzolanic material. It has been found that silica fume improves compressive strength, bond strength and abrasion resistance. Table (8) gives properties of the used silica fume.

Limestone dust

Fine limestone dust was ground by blowing technique, to reach a specific surface of 3100 cm^2/g. The chemical composition of limestone is listed in Table (9).

Superplasticizer

For the production of high-performance concrete, a superplasticizer is used throughout this study. It is known commercially as "GLENIUM51". It is a new generation of modified polycarboxylic ether. It is suitable for the production of SCC. Also, it is free from chlorides and complies with ASTMC494 **[10]** Type F. It is compatible with all Portland cements that meet recognized international standards. Superplasticized concrete with "GLENIUM51" exhibits a large increase in slump without segregation. However, this effect is continued for about 45 minutes after concrete mixing. In the laboratory, 45 minutes are enough for casting and finishing the concrete surface. Therefore, no retarders are required. Table (10) shows the technical description of GLENIUM51.

Steel reinforcement

Deformed steel bars of diameters(9.54 and 15.82)mm are used in this study. The bars are tested to determine the yield stresses and the ultimate strength. The test has been carried out according to theASTM A615/A615M [11]. Properties of the steel bars and results obtained from the test are preset in Table (11).

Mix proportions:-

Mix proportions of SCC must satisfy the criteria of filling ability and segregation resistance. SCC mixes are designed to have a 28 day characteristic compressive strength more than **50** MPa in this study. The mix design method used in the present study is according to EFNARC **[12]**. The mix design has limited material proportion used in this study, Table (12).

Experimental programs

The 16 push-off specimens were constructed and tested, without cracking along the shear plane.key parameters investigated include the reinforcement parameter,$\rho_{vf} f_y$, the compressive strength of the concrete f_c' and volume fraction of carbon fiber V_f, The four series of test are detailed in Table (13).

Fabrication and Curing

The specimens were cast in a steel mold consisting of 2.5 mm thickness of steel plate.The dimensions and reinforcement details of the specimens are (500 x 260 x170) mm, as shown in Fig. (1). All bars had a 20 mm clear cover. Each SCC specimen was cast horizontally in one piece and one layer. The transverse reinforcement (parallel to the potential crack) consisted of (15.82 mm diameter deformed bars) and 9.54 mm diameter deformed bars were employed across the potential crack.

Each series had three cylinders with (100x200) mm, three cubes(100x1000x100) mm. Curing consisted of keeping the push-off specimens and the control specimens in a water bath for 60 days. Push-off specimens and their control specimens had at least 7 days of drying before test.

Results and Discussion

The uncracked specimens

The sixteen specimens were exposed to concentric axial load and the results are shown in Table (14). The values of the cracking shear strength V_{cr} indicated in Table (14) are defined according to Al-Obidi **[13]**. It was defined the shear stresses v_{cr} to be at the time when the dial gage reading, for horizontal displacement, began to show a rapid rise in values, Fig. (2). The cracking and ultimate shear strength was calculated by dividing V_{cr} and $V_{r\ Exp.}$ by the shear plane area which is 170x185 mm. The ductility is defined as the difference between the cracking shear strength and the ultimate shear strength as they were defined by Al-Obidi **[13]**.

From the test results indicated in Table (14), it could be concluded that:

1. Adding CF with $\rho_{vf} f_y$ equal to 0.00 MPa increased the shear strength $v_{r\ Exp.}$from (4.77 to 5.72 and 6.99) MPa forV_f equal to (0.00 , 0.50 and 0.75) %, respectively. Then a little reduction was noticed for V_f equal to 1.00 % where the shear strength $v_{r\ Exp.}$ equal to 6.36 MPa thus, the optimum percentage carbon fiber volume isV_f equal to 0.75 % .
2. Using reinforcement without CF (V_f equal to 0.00 %) leads to an improvement in shear strength by about (100, 167 and 207) %, for $\rho_{vf} f_y$equal to(2.66, 5.33 and 7.99) MPa, respectively, compared to the case of $\rho_{vf} f_y$ equal to 0.00 MPa.
3. For the same percentage of $\rho_{vf} f_y$, it is concluded that direct shear strength continues to increase with every percentage rise in CF, as well as an increase in ductility,the exception is again with $V_f$equal to 1.00 %.

The effect of fiber content on $v_{r\ Exp.}$of initially uncracked specimens is shown in Fig. (3). The value ofshear stress ($v_{r\ Exp.}$) is always significantly less withV_f equal to 1.00 % compared toV_f equal to 0.75 %, which could lead to the conclusion that V_f equal to 0.75 % is the optimum content. On the other hand, reinforcement for all percentages used was effective in increasing shear strength and could be more effective for higher ratios than those used in the present work.

Analysis of shear transfer

The properties of SCC with different V_f percentages are studied and control specimen results are recorded. The cylinder compressive strengthvalue ranged from 64.92 to 57.15 MPa. In all cases, increasing V_f leads to a drop in f_c'. The splitting tensile strength f_{ct} results range from 5.39 to 7.07 MPa. In all cases, increasing V_f raised the value of f_{ct}. As indicated earlier, f_{ct} is higher for $V_f = 0.75\%$ than for $V_f = 1.00$ % .The ultimate shear stress$v_{r\ Exp.}$ results range from 4.77 to 6.99 MPa, Table (15) shows details for $v_{r\ Exp.}$.

The proposed models

By using regression analysis method two models M1 and M2were developed. M1 depends on thevariables f'_c,$\rho_{vf}f_y$ and V_f , meanwhile M2 depends on variables f_{ct},$\rho_{vf}f_y$ and V_f :

$$v_{r\,M1} = 0.18{f'_c}^{0.7} + 0.70\rho_{vf}f_y + 2.50\,V_f \quad \dots (1)$$
$$v_{r\,M2} = 0.80f_{ct} + 0.65\,\rho_{vf}f_y + 1.50V_f \quad \dots (2)$$

Model (M1) and (M2) are based on 16 specimens from this work. In the above proposed models, it is important to notice that when (273 tests including 16 specimens from this study):

1. No reduction factors are used.
2. The value of concrete compressive strength isranged between (16.5 - 107.2) MPa.
3. The value of $\rho_{vf}f_y$for tests are ranged from(0 -16.32) MPa.

Accuracy of the proposed models

Table (17) gives a comparison for the values of $(v_{r\,Exp.}/v_{r\,Cal.})$ including all 273 tested push-off specimens. It can be seen that the best COV values are 15.15 and 16.67 % values by proposed M1 and M2 methods, respectively. The next best COV 23.91 % is by Hsu et al. **[18]**. The other COV values range between 23.93 and 42.94 % for the values of reference Loov and Patnaik **[19]** and PCI Handbook**[14]**, respectively. It is interesting to note that coverlet ACI Committee 318M-11 **[1]**,CAN StandardAssociation**[15]** and BS British Standard 8110 **[16]** COV values are exceedingly high (41.46 to 42.45)%, even compared to the best value ofHsu et al. **[18]**. Figs. (4) to (6) show the same relationship for all 273 specimens considered in this work. In these 273 tests only 3 methods lead to safe prediction of$(v_{r\,Cal.})$ for theCAN StandardAssociation **[15]**and M1 and M2. All others 8 methods lead to unsafe predictions for $v_{r\,Cal.}$. M1 and M2 give the least scatter in prediction, in contrastwith all 9 other methods.

Factors affecting the accuracy of prediction models

For the following discussion it should be kept in mind that the solid line $(v_{r\,Exp.}/v_{r\,Cal.})$ equal to one means 100 % agreement line for direct shear.

Effect of compressive strength of concrete (f'_c)

Figs. (7) to (9) show the influence of f'_c for all the tests 273 push-off. Again M1 and M2 show better predictions than the other 10 models. In these 273 tests only 3 models lead to safe prediction of $v_{r\,Cal.}$, CAN StandardAssociation model**[15]**, M1 and M2. All the others 8 models lead to unsafe predictions for $v_{r\,Cal.}$ .As before when $\rho_{vf}f_y$ equal to 0.00 MPa, all 273 results conform to M1, M2, Mattock and Hawkins **[17]** and Mattock **(21)**. Because other methods give zero resistance when $\rho_{vf}f_y$ equal to 0.00 MPa, only 200 tests may be used for them.

Effect of reinforcement parameter $(\rho_{vf}f_y)$

As expected, M1 and M2 gives the best relationship as shown in Figs. (10) to (12) showing much lesser scatter than all other 10 methods. In these 273 tests only 3 methods lead to safe and economic prediction of $v_{r\ Cal.}$CAN StandardAssociation **[15]** M1 and M2. All others 8 methods lead to unsafe predictions on $v_{r\ Cal.}$.As before when $\rho_{vf}f_y$ equal to 0.00 MPa, all 273 results apply to M1, M2, Mattock and Hawkins **[17]** and Mattock **[21]**. Because other methods give zero resistance when $\rho_{vf}f_y$ equal to 0.00 MPa, only 200 tests may be used for them.

Effect of volume fraction of carbon fiber (V_f)

Figs. (13) to (15) show clearly that proposed methods of prediction (M1 and M2) lead to much better prediction for ratio ($v_{r\ Exp.}/v_{r\ Cal.}$).

Conclusions:

1. The dosage of superplasticizer (SPD) for (CFSCC) fiber reinforced concrete depends on the volume fraction of fiber. It increases with increasing percentage of volume fiber fraction. Also, it is found that using (0.50, 0.75, 1.00) % volume fraction for carbon fiber required higher percentages of SPD dosage by (30, 50, 80) %, respectively. Because of its absorption of some of mixing water, CF leads to lower workability than expected from the requirement of EFNARC **[13]**, as compared with the reference mix (without fiber) to keep the same workability of SCC.
2. The test results indicate that the value$V_f$equal to 0.75 % was the optimum limit for SCC.
3. For CFSCC the addition of carbon fiber at(0.50, 0.75 and 1.00) % lowers the compressive strength $f_c'$by (2.39, 8.38 and 13.58) %, respectively, as compared to the case of $V_f$equal to 0.00 %.
4. CFSCC shows significant improvement in splitting tensile strength compared with control mixes at the age of 60 days. The addition of carbon fiber at 0.50, 0.75 and 1.00 % increased the splitting tensile strength by (3.34, 31.20 and 18.20)%, respectively−as compared to 0.00 % of the fiber. For flexural tensile strength at the age of 60 days. CFSCC shows that the addition of carbon fiber at 0.50, 0.75 and 1.00% increased the flexural tensile strength by (11.90, 21.99 and 13.83) %, respectivelyas compared to 0.00 % fiber.
5. It is observed that an increase in volume fraction of fiber leads to an increase in the shear strength. However, there is a practical limit to the volume of fibers that can be added without causing loss in shear strength. Apparently, the higher fiber content V_f equal to 1.00 % leads to a greater demand in cement paste−i.e. lower fiber strengthening effect.
6. Cracking load and ultimate shear load increased with the increase of $\rho_{vf}f_y$. For example, increasing $\rho_{vf}f_y$ from 2.66 to 5.33 MPa for V_f equal to 0.00 % the rise in the cracking load was from 212 to 282 kN, respectively, while the ultimate shear load rise was from 300 to 400 kN, respectively.
7. For the case of ($\rho_{vf}f_y$ equal to 0.00 MPa) the cracking load was equal to the ultimate load with sudden failure. These values were 150, 180, 220 and 200 kN, for V_f equal to (0.00, 0.50, 0.75 and 1.00) %, respectively.
8. Specimens with steel reinforcement and fiber developed several small diagonal discontinuous cracks. At higher load these cracks formed a crack band along the shear plane. These specimens failed in less brittle manner, compared with specimens without steel reinforcement.

9. Direct shear tests have indicated a greater contribution of fibers to the strength than may be predicted from the influence of fibers on splitting cylinder strength of concrete. This may be due to the greater bond of the fibers which are under compressive stress in the case of direct shear testing.

10. Based on test results obtained from this investigation, two models, M1 and M2 have been developed to predict the direct shear of push-off tests with or without shear reinforcement or fibers.

11. Comparisons with experimental data indicate that the proposed models properly estimate the effects of primary factors, such as concrete compressive strength, steel reinforcement and fiber.

12. The two proposed models have low COV values of 12.41 and 15.24 % respectively for the experimental result of this study, while with the results added from the literature, the COV values are 15.15 and 16.67 %, respectively.

Table (1) Chemical composition of cement

Oxides	%	IOS 5:1984 requirements
CaO	61.27	-
SiO_2	21.27	-
Fe_2O_3	3.12	-
Al_2O_3	5.05	-
MgO	2.06	<5
SO_3	2.07	<2.8
Loss on ignition L.O.I%	3.21	<4
Insoluble residue I.R%	1.32	<1.5
Lime Saturation Factor, L.S.F	0.88	0.66 – 1.02
Main compounds (Bogue's equation)		
C_3S	43.42	-
C_2S	28.31	-
C_3A	8.11	-
C_4AF	9.48	-

The chemical and physical tests were made by the National Center for Construction Laboratories and Researches (NCCLR), Ministry of construction & Housing, Baghdad, Iraq.

Table (2) Physical properties of cement

Properties	Cement	IOS 5:1984 requirements
Fineness Blaine method (m^2 /kg)	481	≥230
Vicat set times(hr:min) Initial Final	 3: 20 4; 40	 ≥45 min ≤10 hours
Compressive Strength (MPa) at 3 days 7 days	 33.4 42.2	 >15 >23
Soundness: autoclave %	0.19	< 0.8

The chemical and physical tests were made by NCCLR, Ministry of construction & Housing, Baghdad, Iraq.

Table (3) Typical properties of carbon fiber

Fiber Density	1.79 gm/cm3
Tensile strength	3900 MPa (nominal)
Tensile E-modulus	230000 MPa
Elongation at breaking	1.5% (nominal)
Length of fiber	10 mm
Water absorption*	32 (%)

Notes:
1. The CF properties are provided by the manufacturer
2. Water absorption test was made at the Laboratories of The University of Technology, Baghdad, Iraq.

Table (4) Grading of fine aggregate

Sieve size (mm)	%Passing by Weight	Limitations of the Iraqi SpecificationNo.45/1984(zone 3)
4.75	100	100
2.36	93	90-100
1.18	88	85-100
0.60	76	75-100
0.30	18	12-40
0.15	2	0-10

The tests were made by the Laboratories of The University of Technology, Baghdad, Iraq.

Table (5) Physical properties of fine aggregate

Physical Properties	Test Results	Limitations of the Iraqi SpecificationNo.45/1984
Specific gravity	2.64	-
Sulfate content %	0.39 %	≤ 0.50 %
Absorption%	0.9	-
Materials finer than 75 µm sieve	0.8%	< 5%
Fineness Modulus	2.51	-

Physical tests were made at the Laboratories of The University of Technology, Baghdad, Iraq.

Table (6) Grading of natural coarse aggregate uncrushed

sieve size (mm)	%Passing by Weight	Limitations of the Iraqi SpecificationNo.45/1984
20.0	96	95-100
14.0	78	-
10.0	52	30-60
5.00	7	0-10

The tests were made at the Laboratories of The University of Technology, Baghdad, Iraq.

Table (7) Physical properties of coarse aggregate

Physical Properties	Test Results	Limitations of the Iraqi SpecificationNo.45/1984
Specific gravity	2.62	-
Sulfate content %	0.06 %	≤ 0.1 %
Absorption%	0.6	-

Physical tests were made at the Laboratories of The University of Technology,Baghdad, Iraq.

Table (8) Physical properties silica fume

Oxides	%
Appearance	Grey powder
Dry bulk density	0.65 ± 0.1kg
SiO2	1.38
Fe2O3	0.12
Al2O3	0.72
CaO	56.1
MgO	0.13
SO3	0.21

Given by the manufacturer

Table (9) Chemical composition properties limestone

Oxides	%
SiO2	1.40
Fe2O3	0.32
Al2O3	1.02
CaO	53.3
MgO	0.27
SO3	0.45

The chemical and physical tests were made by NCCLR, Ministry of construction & Housing, Baghdad, Iraq.

Table (10) Typical properties of (Glenium 51)

Main action	Concrete superplasticizer
Color	Light brown
pH. Value	6.6
Form	Viscous liquid
Subsidiary effect	Hardening
Relative density	1.1 at 20°C
Viscosity	128 ± 30 cps at 20°C
Transport	Not classified as dangerous
Labeling	No hazard Table required

Given by the manufacturer

Table (11) Yielding and ultimate strength of steel reinforcement

Diameter (steel bar) mm	f_y MPa	f_u MPa
9.54	585.7	738.85
15.82	557.1	706.12

Physical tests were made at the Laboratories of The University of Technology, Baghdad, Iraq.

Table (12) Details of mixes

Mix	Cement kg/m3	Silica fume kg/m3	Lime-stone kg/m^3	Fine Aggregate kg/m^3	Coarse Aggregate kg/m^3	V_f %	Superplasticizer Dosage (SPD) lit/m^3
M0.00*	425	75	200	600	900	0	5
M0.50**	425	75	200	600	900	0.5	11.5
M0.75***	425	75	200	600	900	0.75	12.5
M1.00****	425	75	200	600	900	1	14

M0.00 :mix without Carbon Fiber ($V_f = 0.00$ %)
M0.50 :mix with Carbon Fiber ($V_f = 0.50$ %)
M0.75 :mix with Carbon Fiber ($V_f = 0.75$ %)
M1.00 :mix with Carbon Fiber ($V_f = 1.00$ %)

Table (13) Details of push-off specimens

Symbol	V_f(%)	$\rho_{vf} f_y$ * (MPa)	Spacing (mm)
AM0.00	0.0	0.0	------
BM0.00		2.66	92
CM0.00		5.33	61
DM0.00		7.99	46
AM0.50	0.5	0.0	------
BM0.50		2.66	92
CM0.50		5.33	61
DM0.50		7.99	46
AM0.75	0.75	0.0	------
BM0.75		2.66	92
CM0.75		5.33	61
DM0.75		7.99	46
AM1.00	1.0	0.0	------
BM1.00		2.66	92
CM1.00		5.33	61
DM1.00		7.99	46

All reinforcing bars were deformed with db=9.54mm

Table (14) Test results of uncracked specimens

Symbo specim en	V_f %	$\rho_{vf} f_y$ MPa	f'_c MPa	f_{ct} MPa	P_{cr} kN	v_{cr} MPa	$P_{r\,Exp.}$ kN	$v_{r\,Exp.}$ MPa	* $\frac{v_{r\,Exp.}}{(v_{r\,Exp.})\rho_{vf}f_y=}$	** $\frac{v_{r\,Exp.}}{(v_{r\,Exp.})AM_{0.0}}$
AM0.00	0.00	0.00	64.92	5.39	150	4.77	150	4.77	–	–
BM0.00	0.00	2.66	64.92	5.39	212	6.74	300	9.54	100	100
CM0.00	0.00	5.33	64.92	5.39	282	8.97	400	12.72	167	167
DM0.00	0.00	7.99	64.92	5.39	324	10.30	460	14.63	207	207
AM0.50	0.50	0.00	63.40	5.75	180	5.72	180	5.72	–	20
BM0.50	0.50	2.66	63.40	5.75	304	9.67	340	10.81	89	127
CM0.50	0.50	5.33	63.40	5.75	383	12.18	428	13.61	138	185
DM0.50	0.50	7.99	63.40	5.75	439	13.96	490	15.58	173	227
AM0.75	0.75	0.00	59.90	7.07	220	6.99	220	6.99	–	47
BM0.75	0.75	2.66	59.90	7.07	290	9.22	380	12.08	73	153
CM0.75	0.75	5.33	59.90	7.07	339	10.78	445	14.15	103	197
DM0.75	0.75	7.99	59.90	7.07	396	12.60	520	16.53	137	247
AM1.00	1.00	0.00	57.15	6.37	200	6.36	200	6.36	–	33
BM1.00	1.00	2.66	57.15	6.37	252	8.01	320	10.18	60	113
CM1.00	1.00	5.33	57.15	6.37	329	10.46	418	13.29	109	177
DM1.00	1.00	7.99	57.15	6.37	378	12.02	480	15.26	140	220

Percentage increase in $v_{r\,Exp.}$, compared to $v_{r\,Exp.}\left(\rho_{vf} f_y = 0.00\text{ MPa}\right)$

Percentage increase in $v_{r\,Exp.}$, compared to $v_{r\,Exp.}$ (AM0.00)

Table (15) Results of control specimens of SCC at 60 days with $\rho_{vf} f_y = 0.00$ MPa

Symbol Mix1	f'_c (Comp. Strength) MPa	* f'_c Drop %	f_{ct} (Spitting Strength) MPa	* f_{ct} % Rise	$v_{r\,Test}$ (Direct Shear) MPa	* $v_{r\,Test}$ % Rise
M0.00	64.92	–	5.39	–	4.77	–
M0.50	63.40	2.39	5.75	6.78	5.72	20.0
M0.75	59.90	8.38	7.07	31.17	6.99	46.67
M1.00	57.15	13.58	6.37	18.18	6.36	33.33

compared to M0.00

Table (16) Existing models for predicting direct shear capacity

	Shear Strength Formula	Reference
$v_{r\,ACI}$	$0.75\,\rho_{vf} f_y * 1.4$	ACI Code 318M-11 [1]
$v_{r\,PCI}$	$0.75\,\rho_{vf} f_y\ 1.4 * \left[\left(\frac{2.1 * 1.4}{5.79}\right) + 0.5\right]$	PCI Design Handbook [14]
$v_{r\,CAN}$	$0.6\,\rho_{vf} f_y * 1.25$	CAN Standard Association [15]
$v_{r\,BS}$	$0.6\left(0.95\,\rho_{vf} f_y\right) * 1.7$	BS British Standard 8110 [17]
$v_{r\,MH}$	$2.8 + 0.8\left(\rho_{vf} f_y + \sigma_{nx}\right)$	Mattock and Hawkins [17]
$v_{r\,H}$	$0.822(f'_{cc})^{0.406}(\rho_{vf} f_y)^{c}$	Hsu et al. [18]
$v_{r\,LP}$	$0.573\ (f'_c)^{0.45}(\rho_{vf} f_y)^{0.55}$	Loov and Patnaik [19]
$v_{r\,MJ}$	$2.78\sqrt{\rho_{vf} f_y}$	Mattock et al. [20]
$v_{r\,M3}$	$K_1 + 0.8\left(\rho_{vf} f_y + \sigma_{nx}\right)$ $2.25\left(\rho_{vf} f_y + \sigma_{nx}\right)$	Mattock [21]

Note: $\sigma_{nx} = 0$ (According to Mattock and Hawkins [17]

Table (17) Comparison for predicting $(v_{rExp.}/v_{rCal.})$ based on eleven different methods applied to all 273 push-off results

No.	Model	Mean	SD	COV (%)
1	Model 1	1.32	0.2	15.15
2	Model 2	1.38	0.23	16.67
3	ACI Code 318M-11 [1]	1.79	0.76	42.45
4	PCI Handbook [14]	1.77	0.76	42.94
5	CAN Standard Association [15]	2.57	1.0654	41.46
6	BS British Standard 8110 [16]	1.94	0.83	42.78
7	Mattock and Hawkins [17]	1.64	0.70	42.68
8	Hsu et al. [18]	0.92	0.22	23.91
9	Loov and Patnaik [19]	1.17	0.28	23.93
10	Mattock et al. [20]	1.53	0.46	30.07
11	Mattock [21]	1.05	0.34	32.38

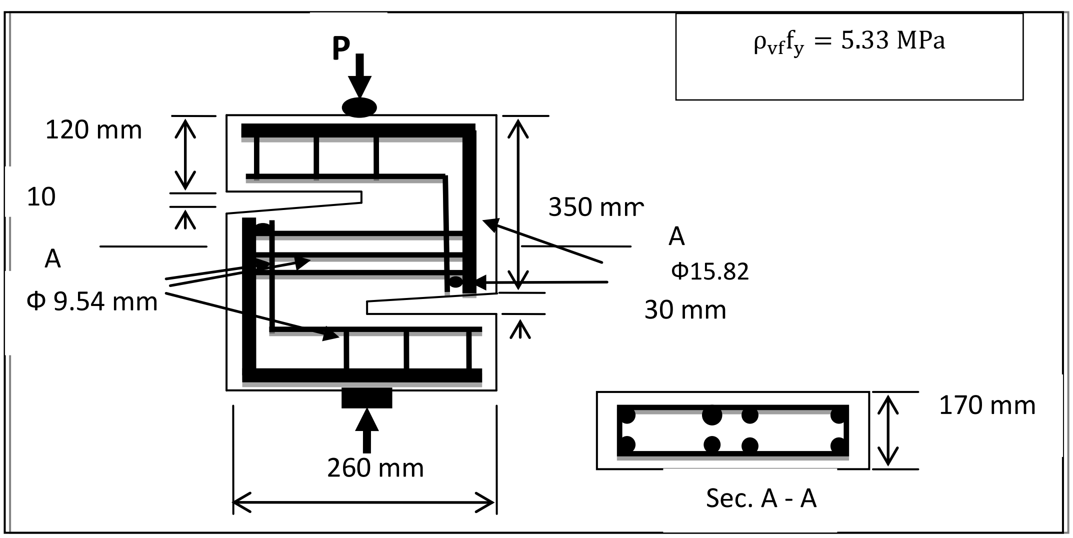


Figure. (1) Details of push-off specimens

Figure. (2) The test set up the push-off specimens

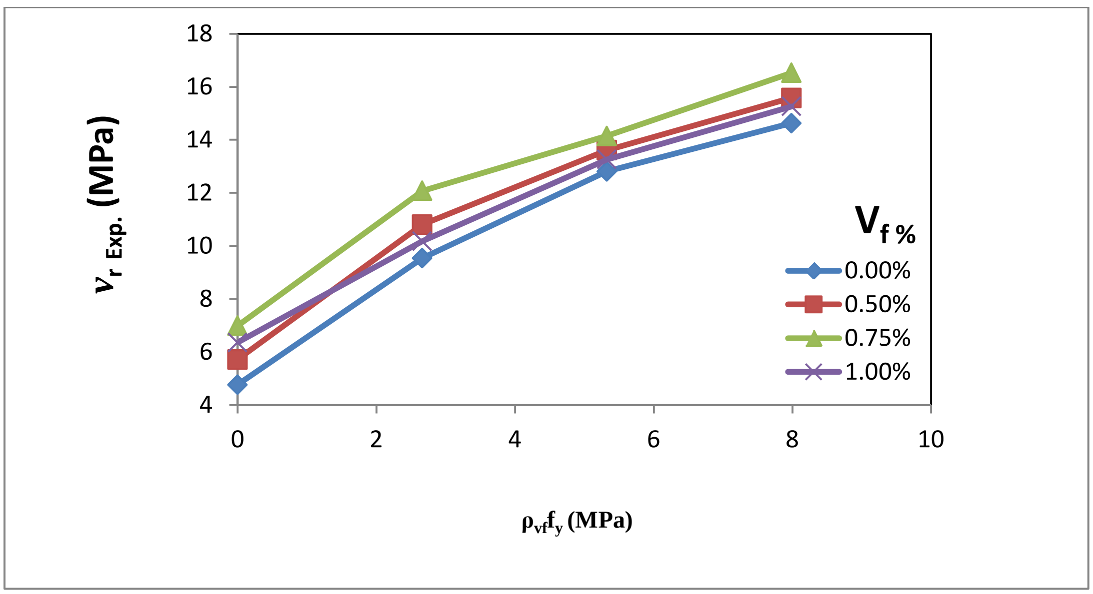
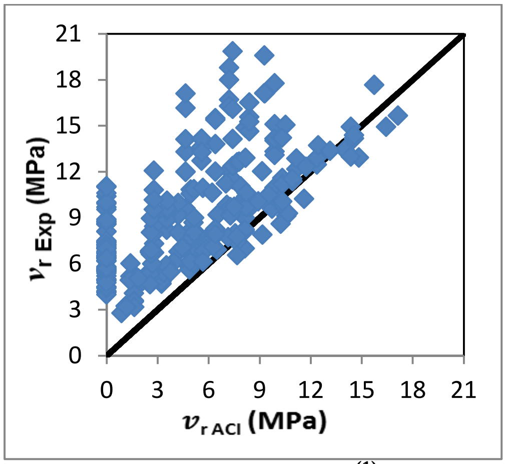
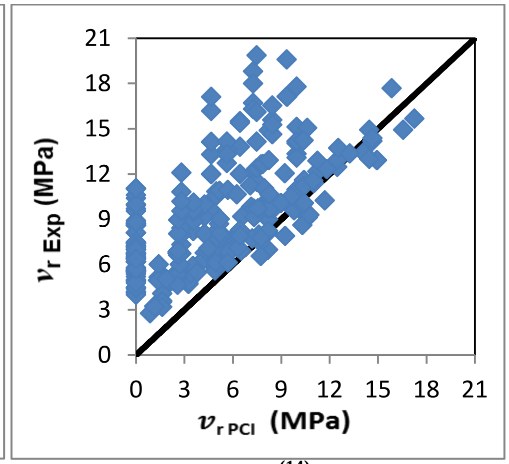


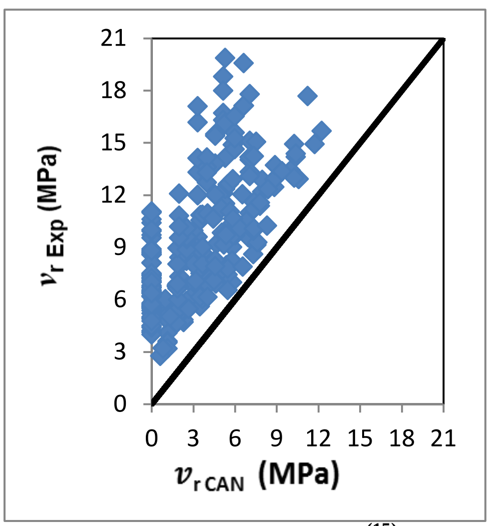
Figure. (3) Effect of $\rho_{vf} f_y$ content on shear strength of initially uncracked specimens, for various V_f value



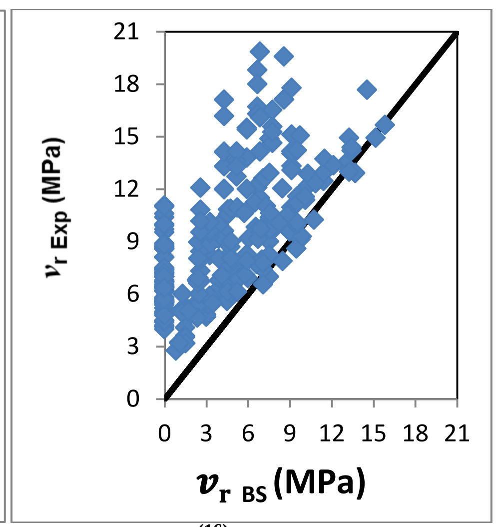
a-ACI Code [(1)]



b- PCI Handbook [(14)]

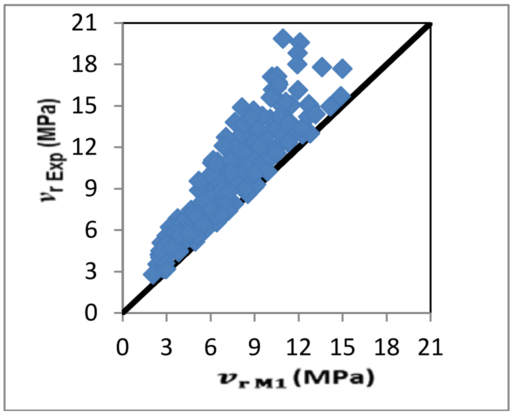


c- CAN Code [(15)]

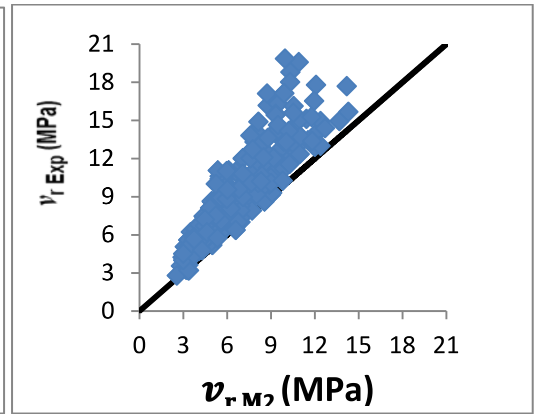


d- BS Code [(16)]

Figure. (4) Compression between $v_{r\ Exp.}$results and $v_{r\ Cal.}$ resultsfor all 200 push-off tests

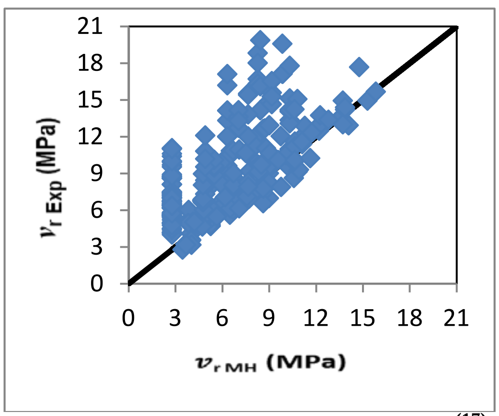


a-M 1

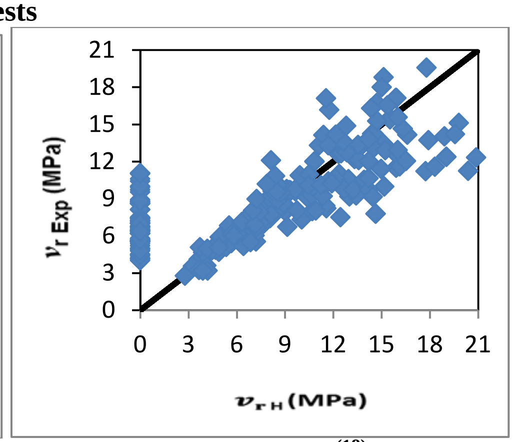


b- M 2

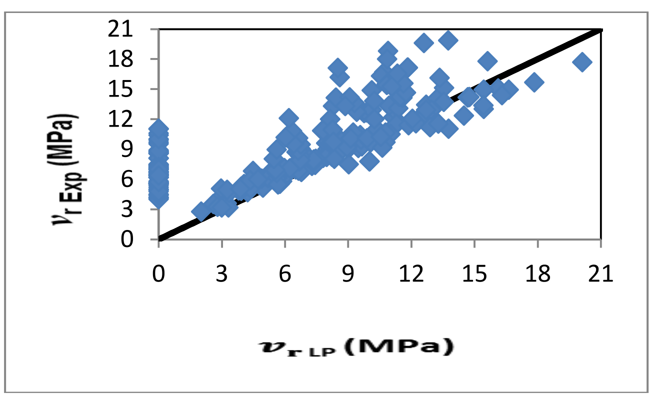
Figure. (5) Compression between $v_{r\ Exp.}$ results and $v_{r\ Cal.}$ resultsfor all 273 push-off tests



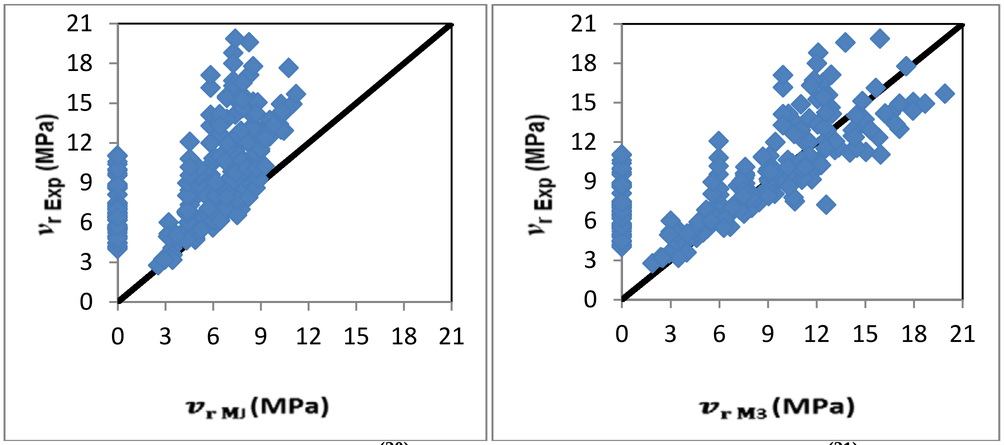
a-Mattock and Hawkins [17]



b- Hsu et al.[18]

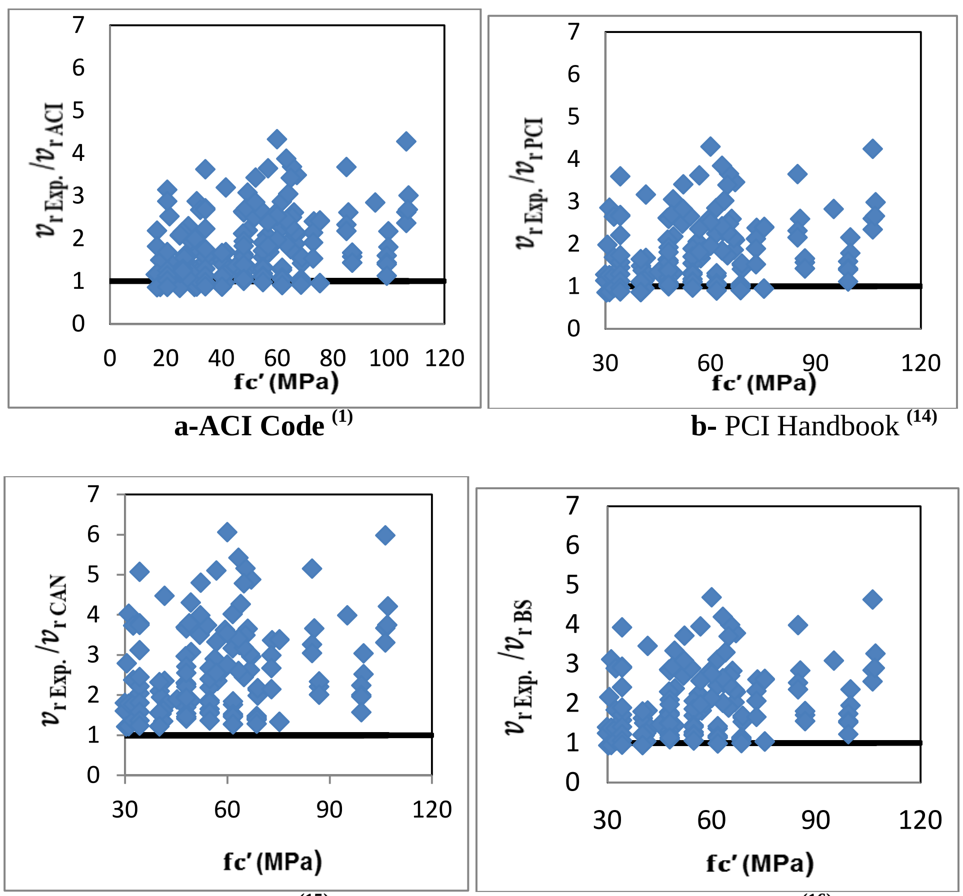


c-Loov and Patnaik [19]



e- Mattock et al. [20] **f- Mattock[21]**

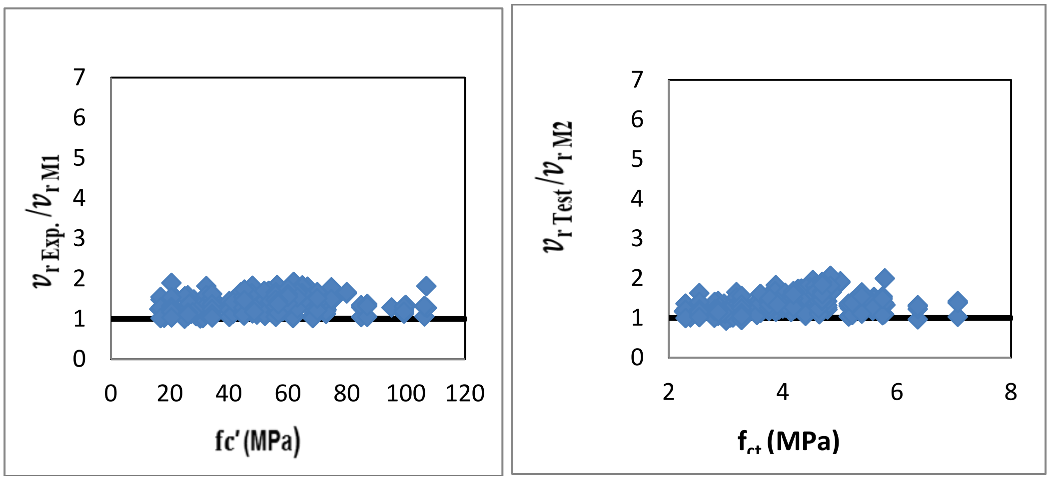
Figure. (6) Compression between $v_{r\,Exp.}$ results and $v_{r\,Cal.}$ resultsfor all 273 push-off tests



a-ACI Code [1] **b-** PCI Handbook **[14]**

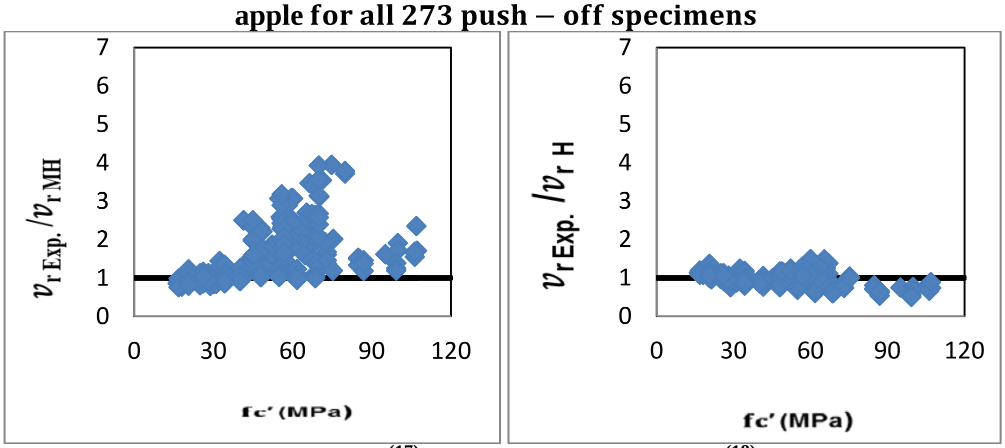
c- CAN Code[15] **d- BS Code [16]**

Figure. (7) Compression between $v_{r\,Exp.}/v_{r\,Cal.}$ and f_c' for all 273 push-off specimens

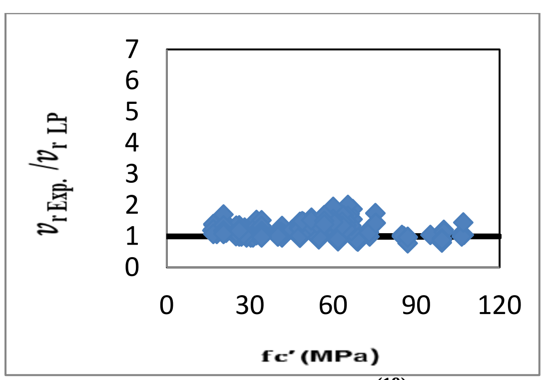


a-M 1 **b- M 2**

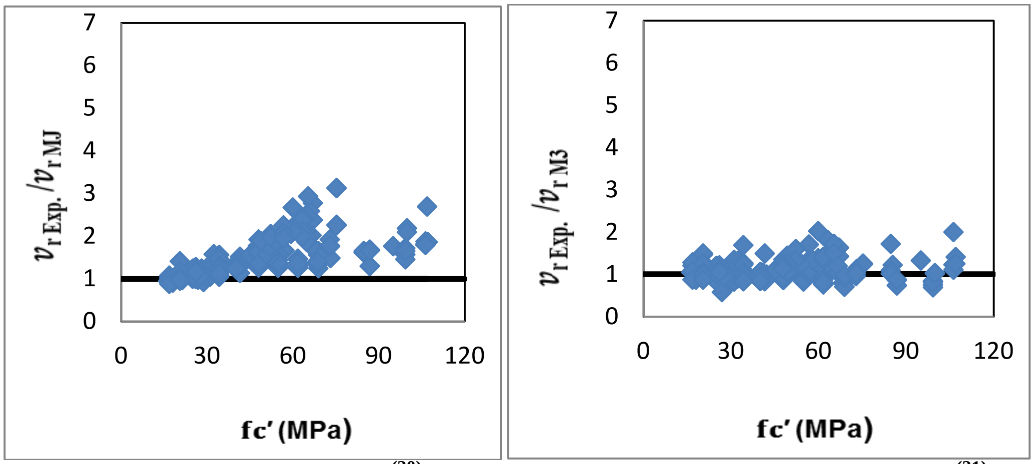
Figure. (8) Compression between $v_{r\,Exp.}/v_{r\,Cal.}$ and f'_c, f_{ct} by apple for all 273 push − off specimens



a- Mattock and Hawkins [17] **b- Hsu et al.** [18]

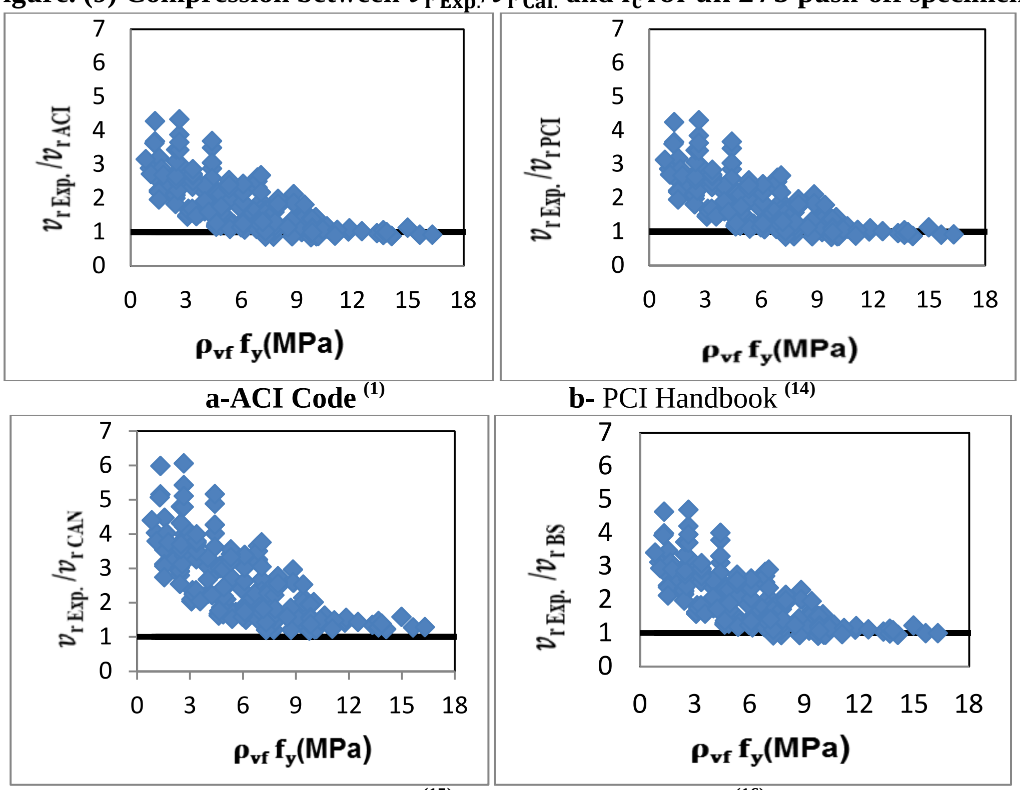


c-Loov and Patnaik [19]



e- Mattock et al. [20] **f- Mattock**[21]

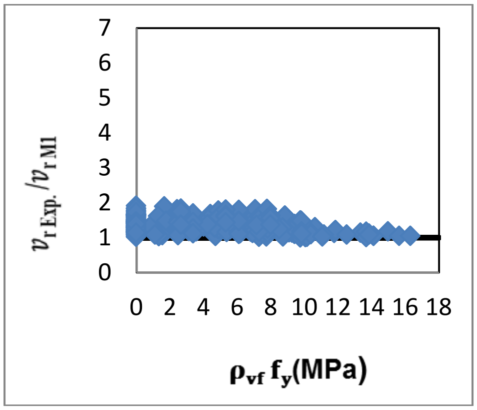
Figure. (9) Compression between $v_{r\,Exp.}/v_{r\,Cal.}$ and f'_c for all 273 push-off specimens



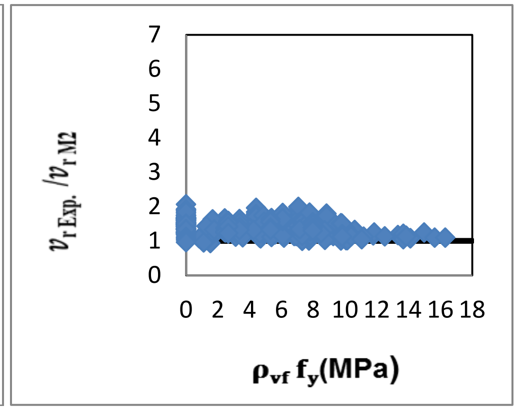
a-ACI Code [1] **b-** PCI Handbook [14]

c- CAN Code[15] **d- BS Code** [16]

Figure. (10) Compression between $v_{r\,Exp.}/v_{r\,Cal.}$ and $\rho_{vf}f_y$ for all 200 push-off tests

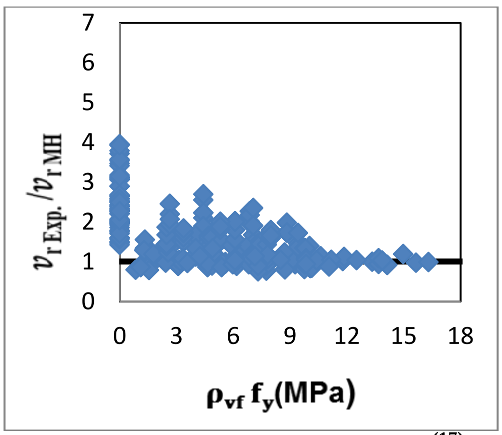


a-M 1

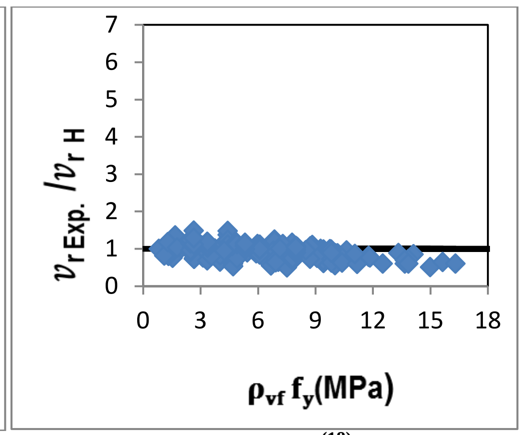


b- M 2

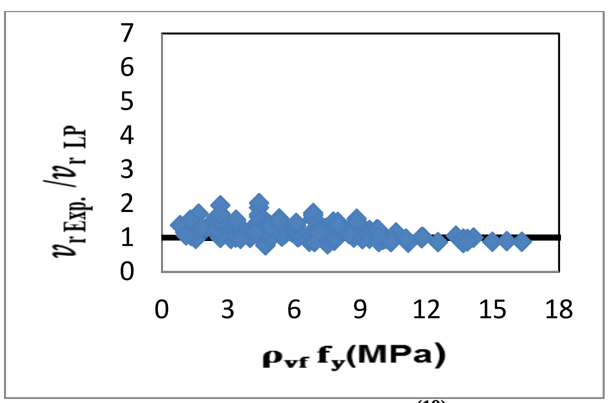
Figure. (11) Compression between $v_{r\ Exp.}/v_{r\ Cal.}$ and $\rho_{vf} f_y$ for all 273 push-off tests



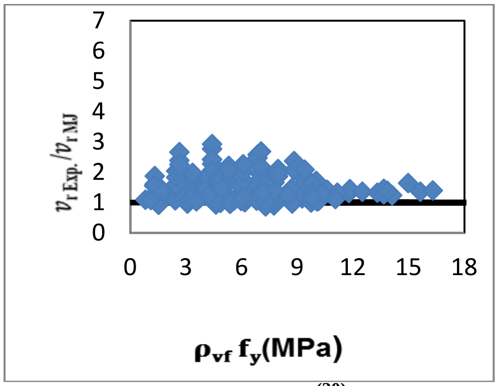
a-Mattock and Hawkins [17]



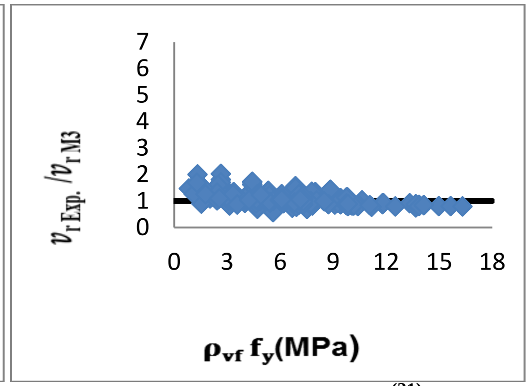
b- Hsu et al. [18]



c-Loov and Patnaik [19]

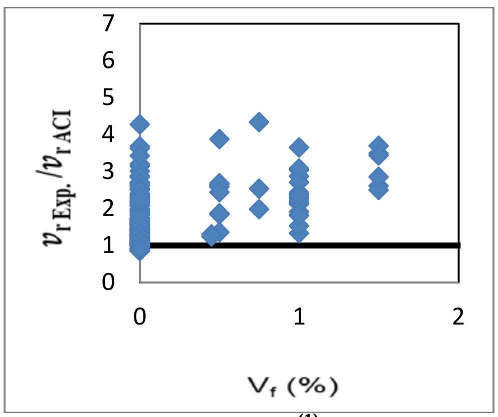


e- Mattock et al. [20]

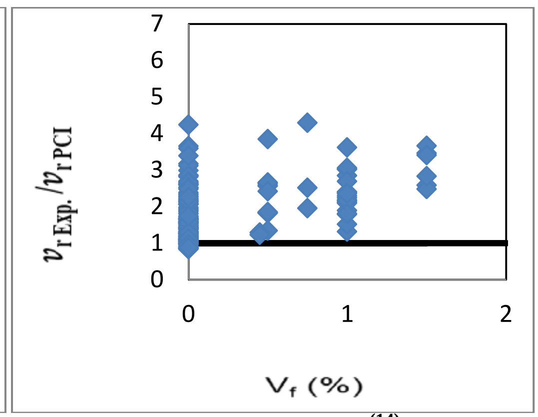


f- Mattock[21]

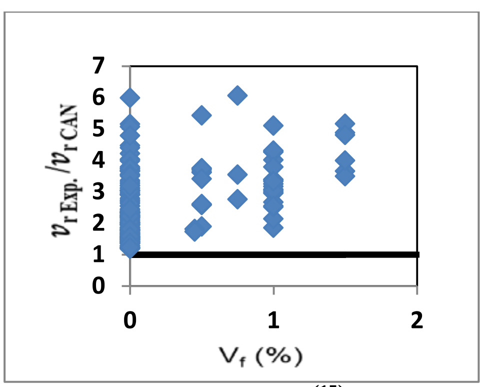
Figure. (12) Compression between $v_{r\ Exp.}/v_{r\ Cal.}$ and $\rho_{vf} f_y$ for all 273 Push-off tests



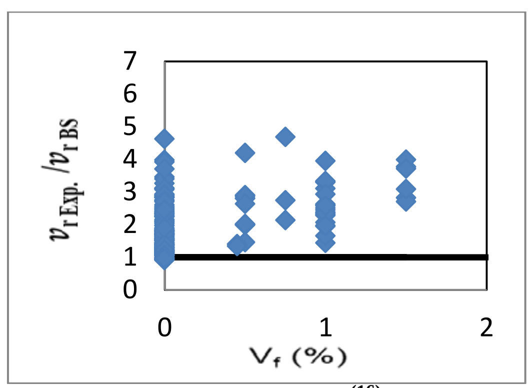
a-ACI Code [1]



b- PCI Handbook [14]

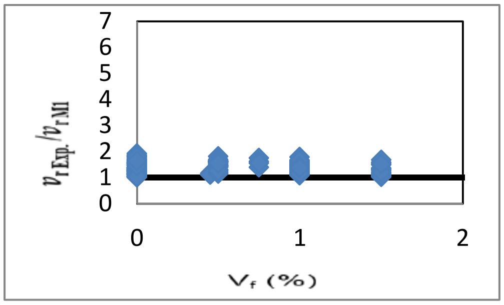


c- CAN Code[15]

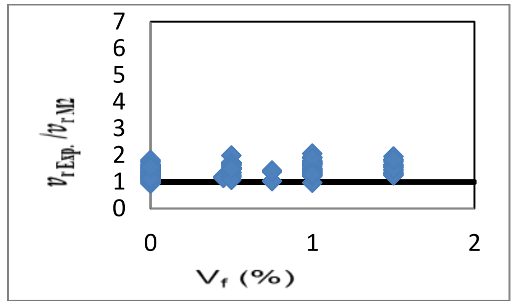


d- BS Code [16]

Figure. (13) Compression between $v_{r\ Exp.}/v_{r\ Cal.}$ andV_f for all 200 tests

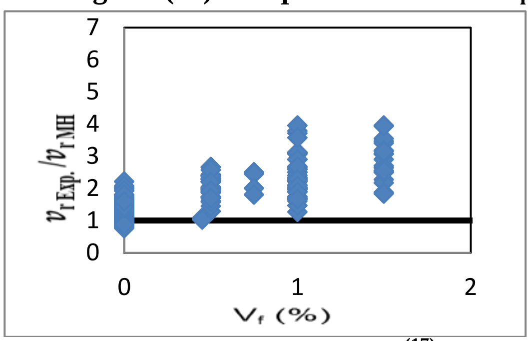


a-M 1

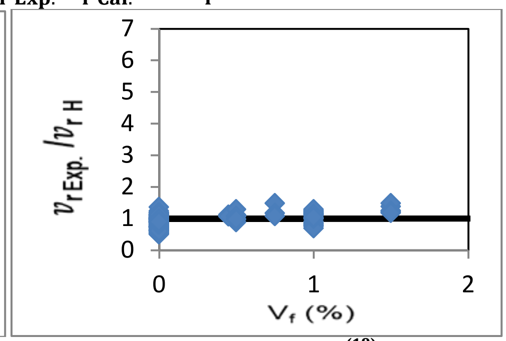


b- M

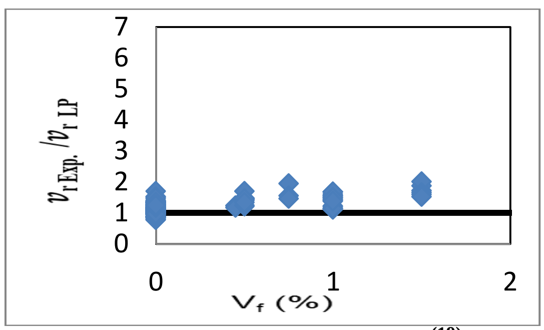
Figure. (14) Compression between $v_{r\,Exp.}/v_{r\,Cal.}$ andV_f for all 273 tests



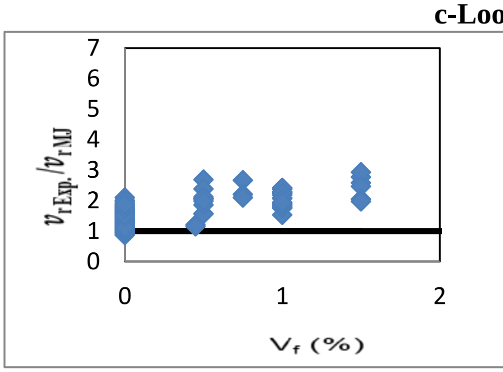
a-Mattock and Hawkins [17]

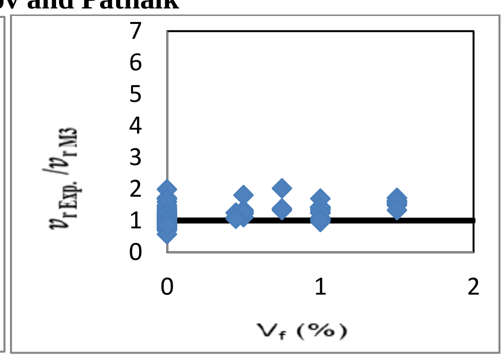


b- Hsu et al. [18]



c-Loov and Patnaik [19]





e-

Mattock et al. [20]　　**f- Mattock[21]**

Figure. (15) Compression between $v_{r\,Exp.}/v_{r\,Cal.}$ andV_f for all 273 push-off tests

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