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Mechanical Properties of High-Strength Fiber Reinforced Concrete

Dr.Kaiss Sarsam*& Zaid Muhammad Kani Al-Azzawi**

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Abstract

Experimental results of this work in addition to a wide range of data from previous work were analyzed to study the mechanical properties and strength of high-strength concrete with and without fibers. Different types of steel fibers (straight, hooked, duoform, crimped) with a volume fraction ranging from 0 to 2 percent were studied. The concrete compressive strength ranged from 41 to 115 MPa. The influence of fiber on the compressive strength, axial strain, modulus of elasticity, Poisson's ratio, modulus of rupture, and splitting tensile strength, were studied. In addition to that, size effect of control specimens on high-strength fiber reinforced concrete materials, was observed. The main conclusion indicates that high-strength concrete (HSC) properties, especially with fibers are significantly different from normal-strength concrete (NSC).

Keywords: axial strain, compressive strength, fiber reinforced concrete, high-strength concrete, modulus of elasticity, modulus of rupture, Poisson's ratio, splitting tensile strength, steel fibers, size effect.

الخواص الميكانيكية للخرسانة عالية المقاومة والمسلحة بالألياف

الخلاصة

تم تحليل النتائج العملية لهذا البحث بالإضافة إلى مدى واسع من النتائج العملية لبحوث سابقة لدراسة الخواص الميكانيكية للخرسانة عالية المقاومة مع أو بدون الألياف. تمت دراسة أنواع مختلفة من الألياف الحديدية وبنسب حجمية مختلفة تتراوح بين صفر إلى 2%. لقد تراوحت مقاومة الخرسانة من 41 إلى 115 MPa.

تمت دراسة تأثير الألياف الحديدية على مقاومة الإنضغاط ومعامل التصدع ومقاومة الإنشطار ومعامل المرونة والإنفعال المحوري ونسبة بواسون. بالإضافة إلى ذلك تمت دراسة تأثير حجم النموذج على نتائج الفحوصات. وتشير نتائج البحث إلى أن الخواص الميكانيكية للخرسانة عالية المقاومة, خصوصاً بوجود الألياف تختلف بشكل واضح عن الخرسانة ذات المقاومة الإعتيادية.

Introduction

The term high-strength concrete (HSC) is generally used for concrete with compressive strength higher than 41 MPa(1). The use of HSC has steadily increased over the past years, which leads to the design of smaller sections. This in turn reduces the dead weight, allowing longer spans and more usable area of buildings. Reduction in mass is also important for economical design of earthquake resistant structures(1-4). Such advantages outweigh the higher production cost of HSC.

HSC is a brittle material, and as the concrete strength increases the post-peak portion of the stress-strain diagram almost vanishes or descends steeply(1,3-8). The increase in concrete strength reduces its ductility, and this is a serious drawback for the use of HSC. A compromise between these two characteristics of concrete (strength and ductility) can be obtained by adding steel fibers. Addition of fibers to concrete makes it more homogeneous and isotropic and transforms it from a brittle to a more ductile material(4). When

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*** Building & Construction Engineering Department, University of Technology/Baghdad**
**** Engineering College, University of Anbar/ Anbar**

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

concrete cracks, the randomly oriented fibers arrest a microcracking mechanism and limit crack propagation, thus improving strength and ductility. Previous researches indicate that while keeping other parameters constant, the ductility of high-strength fiber reinforced concrete (HSFRC) may be several times greater than that of plain HSC(4,9,10).

As is common with many new materials, i.e. the use of HSC requires full information on its engineering properties(11).

The main objective of this paper is to study the mechanical properties of (HSFRC) materials.

In this work a total of 312 HSFRC specimens were prepared and tested to determine the compressive strength, modulus of elasticity, axial strain, Poisson's ratio, modulus of rupture, and splitting tensile strength. In addition, data from previous researches(4,5,7,12-22) were gathered with the results obtained from this work and analyzed, to study the mechanical properties of HSC and the effect of including steel fibers on these properties.

Research Significance

HSC joint tests with and without fibers, possess properties that are significantly different from normal-strength concrete (NSC) materials(4,11). This paper presents an experimental investigation of the mechanical properties of HSC, and studies the effect of addition of steel fibers on improving these properties.

Data form previous work(4,5,7,12-22) in addition to the data obtained from this work were gathered and analyzed to propose equations representing the engineering properties of HSC and the effect of steel fibers on it.

Experimental Program

This study is a part of a broad research program on material and structural properties of HSFRC(10,12,13). In this paper, various properties of HSFRC are reviewed and the applicability of the current and proposed expressions for predicting the properties of HSFRC are examined.

Materials

HSFRC has been produced using certain proportions of steel fibers, fine aggregate, coarse aggregate, and paste. The paste consists of cement, water, and superplasticizer. In the testing program, the concrete matrix compressive strength was kept constant, and the variables were the fiber type and fiber volume fraction. The mix proportion by weight was 1:1.24:1.86:0.285:0.05 for the cement, sand, gravel, water, and superplasticizer, respectively. Ordinary Portland cement (type I) with a content of 550 kg/m^3 was used. Al-Ukhaidher natural sand with a fineness modulus of 2.5 and a bulk specific gravity of 2.6 was used. Natural river gravel with a maximum size of 10mm and a bulk specific gravity of 2.7 was used. Steel fibers of 1100 MPa tensile strength were used. The straight fibers had a length of 25.4mm, a diameter of 0.4mm and an aspect ratio (***L/D***) of 63.5; while the hooked fibers had a length of 50mm, a diameter of 0.5mm and an aspect ratio of 100.

Due to the relatively low water and high cement contents, and the absence of larger coarse aggregate, the efficient mixing of HSC is more difficult than conventional concrete.

For this reason, a superplasticizer (Melment L-10) was used and the mixing time was increased to produce uniform concrete without any segregation. There was no evidence of balling through mixing procedure. And in order to gain stronger concrete, all specimens were covered with wet burlap for 56 days, and dried for 14 days before testing.

Test Results

All test results are summarized in Table-1, while graphical representations of these results are displayed in Fig's. (1-17). A total of 312 specimens were tested in this investigation.

One of the major problems in fiber reinforced concrete (FRC) is how to represent the effect of including fibers, in the concrete matrix, in estimating the mechanical properties of HSFRC.

The fiber factor (***F***) is the most reliable solution for this problem; ***F*** can be expressed as follows:

$$F = V_f . b_f . L / D \qquad \text{........} \quad (1)$$

where:

V_f is the fiber volume fraction, b_f is the fiber bond factor, and ***L***&***D*** are the fiber length and diameter, respectively.

This nondimensional factor represents the effect of fiber powerfully, as it represents the fiber in its volume fraction, bond factor, and aspect ratio. Thus ***F*** can be used to represent any type and volume fraction of fibers.

This study is a part of a broad research program on material and structural properties of (HSFRC) conducted at the University of Technology(10,12,13). Data from these three researches were obtained using the same materials and mix proportions. Because of this only these three researches were used in obtaining the effect of including fibers on the mechanical properties of HSFRC represented by the fiber factor (***F***). All other researches (References 4,5,7,12-22), in addition to this work were used to obtain the mechanical properties of HSC.

Compressive strength

12 control specimens of two types and two sizes were cast and tested, (150×300) mm and (100×200) mm cylindrical specimens were tested according to ASTM C39. In addition to 150mm and 100mm cube specimens were tested according to BS 1881.

Based on these results, the compressive strength of HSFRC f'_{cf150} and f_{cuf150} (Fig's 1,2) may be estimated in terms of the compressive strength of plain concrete f'_{c150} and f_{cu150} and the fiber factor (***F***) as follows:

$$f'_{cf150} = f'_{c150} + 6.0F \qquad \text{...........} \quad (2)$$

$$f_{cuf150} = f_{cu150} + 2.8F \qquad \text{.........} \quad (3)$$

From Fig's (1,2) and Eq's 2&3 it can be seen that the effect of including fibers on compressive strength of cylindrical type specimens is approximately twice that of cubic specimens.

The size effect and conversion factors are shown by Fig's (3-6). From these figures the following equations are observed:

$$f'_{cf150} = 0.94\, f'_{cf100} \qquad \text{........} \quad (4)$$

$$f_{cuf150} = 0.90\, f_{cuf100} \quad \ldots\ldots\ldots \quad (5)$$

$$f'_{cf150} = 0.90\, f_{cuf150} \quad \ldots\ldots\ldots \quad (6)$$

$$f'_{cf100} = 0.83\, f_{cuf100} \quad \ldots\ldots\ldots \quad (7)$$

Eq. 4 is close to the work by Carrasquillo etal(5) who stated an average factor close to 0.9.

Axial and lateral strain, modulus of elasticity, and Poisson's ratio

Axial and lateral strain were determined using 150×300mm cylinder according to ASTM C469. Modulus of elasticity and Poisson's ratio were also determined from this test.

Fig. 7 represents the relationship between modulus of elasticity (***E$_c$***) and compressive strength f'_c of plain HSC. From this figure and Fig. 8, which represent the effect of fibers on ***E$_c$*** , the following formula is derived by regression analysis:

$$E_{cf} = 4.2\sqrt{f'_{c150}} - 2.3F \ \ldots \quad (8)$$

From Eq. 8 and Fig. 8 it is clearly shown that introducing fibers into concrete matrix reduced the modulus of elasticity of HSFRC.

Fig's (9,10) represent the relationship between axial strain and f'_c for plain HSC and the effect of fiber on axial strain, respectively. From these two figures, the axial strain in terms of compressive strength and fiber factor can be estimated as follows:

$$e_{cf} = 0.0003\sqrt{f'_{c150}} + 0.0004F \quad \ldots\ldots\ldots \quad (9)$$

Eq. 9 shows that addition of fibers slightly increases the peak axial strain which is in agreement with previous work(4).

Poisson's ratio and its relationship with f'_c and fiber factor can be shown by Fig's (11,12), respectively, hence:

$$n_f = 0.02\sqrt{f'_{c150}} + 0.12F \ \ldots \quad (10)$$

Eq. 10 shows that including fiber in the concrete matrix affects Poisson's ratio and increases it significantly.

Splitting tensile strength

Six control specimens of two sizes were cast, (150×300) mm and (100×200)mm cylindrical specimens. These specimens were tested according to ASTM C496 to determine the indirect tensile strength (splitting tensile strength).

Fig. 13 shows the variation of ***f$_{sp}$*** as a function of the concrete compressive strength f'_c of plain HSC. A regression analysis provided the following relation:

$$f_{sp150} = 0.47\sqrt{f'_{c150}} \quad \ldots\ldots \quad (11)$$

The factor 0.47 obtained from this equation is less than the value given by Nilson(2) of 0.68, and that given by Wafa etal(4) of 0.58, for HSC.

Table 1 and Fig. 14 show that the value of ***f$_{sp}$*** of HSFRC depends also on the fiber factor and can be expressed as follows:

$$f_{spf150} = 0.47\sqrt{f'_{c150}} + 4.2F \quad \ldots\ldots \quad (12)$$

Fig. 15 shows the size effect on splitting tensile strength control specimens of 150×300mm and 100×200mm cylinders. The relationship can be estimated as follows:

$$f_{spf150} = 0.89 f_{spf100} \qquad \ldots\ldots \quad (13)$$

Modulus of rupture

Three 100×100×400mm beam specimens (prism) were cast and tested using third point loading test according to ASTM C78. Table 1 and Fig. 16 present the variation of the modulus of rupture f_r as a function of the compressive strength f'_c of plain HSC. A regression analysis of the test results provided the following equation:

$$f_r = 0.93\sqrt{f'_{c150}} \qquad \ldots\ldots \quad (14)$$

The factor 0.93 obtained from this equation is higher than that obtained by ACI 318(23) of 0.63 for NSC and nearly similar to that by Nilson(2) of 0.9 for HSC.

Table 1 and Fig. 17 show the effect of including fibers on f_r. Using the experimental results, the value of f_{rf} of HSFRC may be as follows:

$$f_{rf} = 0.93\sqrt{f'_{c150}} + 4.5F \quad \ldots \quad (15)$$

From Eq. 15 it can be seen that the addition of fibers to the concrete matrix increased f_r , significantly, in a similar manner to that of f_{sp} .

Conclusions

Based on this work the following conclusions are drawn:

1. Engineering properties of HSC are different from those of NSC. Therefore, equations used for NSC cannot be used any more to predict mechanical properties of HSC.
2. Addition of 1.5 percent by volume of straight steel fibers resulted in a small increase of 6% in compressive strength, and resulted in an increase of 24.5% in modulus of rupture and 32% in splitting tensile strength; compared to an increase of 17.5% in compressive strength, 77% in modulus of rupture, and 99% in splitting tensile strength; when using 1.5% volume fraction of hooked steel fiber.
3. Compressive strength of HSFRC may closely be estimated from plain HSC using the following equations:

$$f'_{cf150} = f'_{c150} + 6.0F$$
$$f_{cuf150} = f_{cu150} + 2.8F$$

4. Modulus of elasticity of HSFRC may be closely estimated from plain HSC using the equation:

$$E_{cf} = 4.2\sqrt{f'_{c150}} - 2.3F$$

5. Axial strain of HSFRC may be closely estimated using the equation:

$$e_{cf} = 0.0003\sqrt{f'_{c150}} + 0.0004F$$

6. Poisson's ratio of HSFRC may be closely estimated using the following equation:

$$n_f = 0.02\sqrt{f'_{c150}} + 0.12F$$

7. Modulus of rupture of HSFRC may be closely estimated using the following equation:

$$f_{rf} = 0.93\sqrt{f'_{c150}} + 4.5F$$

8. Splitting tensile strength of HSFRC may be closely estimated from the following equation:

$$f_{spf150} = 0.47\sqrt{f'_{c150}} + 4.2\,F$$

9. Smaller size control specimens may be cast and tested. The value of the larger size control specimens may be predicted from the conversion factors estimated in this work as follows:

$$f'_{cf150} = 0.94\, f'_{cf100}$$

$$f_{cuf150} = 0.90\, f_{cuf100}$$

$$f_{spf150} = 0.89\, f_{spf100}$$

10. The relationship between cylindrical and cubic specimens is as follows:

$$f'_{cf150} = 0.90\, f_{cuf150}$$

$$f'_{cf100} = 0.83\, f_{cuf100}$$

Acknowledgment

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Notation

b_f	Fiber bon factor, = 0.5 for straight fibers, = 0.75 for hooked fibers, =1.0 for duoform and crimped fibers.
E_c	Characteristic modulus of elasticity of concrete.
E_{cf}	Secant modulus of elasticity of HSFRC.
F	Fiber factor
f'_c	Characteristic compressive strength of concrete.
f'_{c150}	Concrete compressive strength based on 150×300mm cylinders.
f'_{c100}	Concrete compressive strength based on 100×200mm cylinders.
f'_{cf150}	Fiber reinforced concrete compressive strength based on 150×300mm cylinders.
f'_{cf100}	Fiber reinforced concrete compressive strength based on 100×200mm cylinders.
f_{cu150}	Concrete compressive strength based on 150mm cubes.
f_{cu100}	Concrete compressive strength based on 100mm cubes.
f_{cuf150}	Fiber reinforced concrete compressive strength based on 150mm cubes.
f_{cuf100}	Fiber reinforced concrete compressive strength based on 100mm cubes.
f_r	Concrete modulus of rupture
f_{rf}	Modulus of rupture of HSFRC.
f_{sp150}	Concrete splitting tensile strength based on 150×300mm cylinders.
f_{sp100}	Concrete splitting tensile strength based on 100×200mm cylinders.
f_{spf150}	Fiber reinforced concrete splitting tensile strength based on 150×300mm cylinders.
f_{spf100}	Fiber reinforced concrete splitting tensile strength based on 100×200mm cylinders.
L	Fiber length.
r^2	Coefficient of determination R-squared.
V_f	Fiber volume fraction in concrete matrix.
ε_o	Concrete strain at extreme compression fiber.
ε_{of}	Fiber reinforced concrete strain at extreme compression fiber.
v	Concrete Poisson's ratio.
v_f	Fiber reinforced concrete Poisson's ratio.

Abbreviations

FRC	Fiber reinforced concrete.
NSC	Normal-strength concrete.
HSC	High-strength concrete.

HSFRC High- strength fiber reinforced concrete.

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Table 1- Mechanical properties of HSFRC tested by Reference 10.*

Fiber type	L/D	V_f %	h_f	F	f'_{c28} MPa	f'_{c90} MPa	f_{cu28} MPa	f_{cu90} MPa	f_{sp28} MPa	f_{sp90} MPa	f_{rf} MPa	E_{cf} kN/mm^2	ε_{cf} x 10^{-3}	υ_{cf}
-	-	0.0	-	0.000	60.40	66.45	67.15	75.90	4.60	5.34	7.50	34.09	2.00	0.138
hooked	100	0.5	0.75	0.375	64.00	69.13	70.35	78.80	6.14	7.00	9.42	33.71	2.25	0.185
hooked	100	1.0	0.75	0.750	67.50	71.60	73.40	81.40	7.65	8.57	11.32	33.33	2.65	0.240
hooked	100	1.5	0.75	1.125	71.00	73.80	76.35	84.00	9.15	10.1	13.25	33.85	2.85	0.282
straight	63.5	0.5	0.5	0.159	61.55	67.10	68.00	76.55	5.09	5.90	8.12	34.8	2.15	0.185
straight	63.5	1.0	0.5	0.318	62.66	67.85	68.90	77.40	5.57	6.40	8.73	34.95	2.30	0.212
straight	63.5	1.5	0.5	0.476	63.90	68.50	69.90	78.10	6.05	6.88	9.34	35.16	2.55	0.265
-	-	0.0	-	0.000	59.40	65.40	66.20	75.20	4.50	5.20	7.20	33.48	2.10	0.145
hooked	100	1.0	0.75	0.750	66.70	70.70	72.00	80.50	7.50	8.50	11.00	32.90	2.69	0.237
hooked	100	1.0	0.75	0.750	66.30	69.90	72.60	79.80	6.95	7.78	10.86	32.69	2.70	0.243
hooked	100	1.0	0.75	0.75	67.95	68.95	71.20	82.50	8.84	9.66	12.50	34.65	2.85	0.235
-	-	0.0	-	0.000	61.10	65.14	69.15	76.80	4.95	6.10	8.95	33.21	2.25	0.155
hooked	100	1.0	0.75	0.750	68.54	72.52	73.90	79.64	6.95	7.54	10.66	35.26	2.71	0.248

*** The variables were type and volume fraction of steel fibers.**

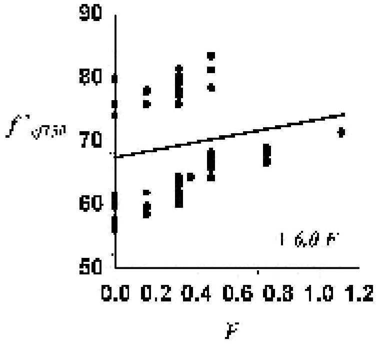

Fig.1- Effect of F on compressive strength

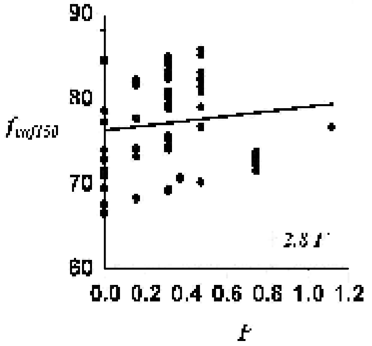

Fig.2- Effect of F on compressive strength

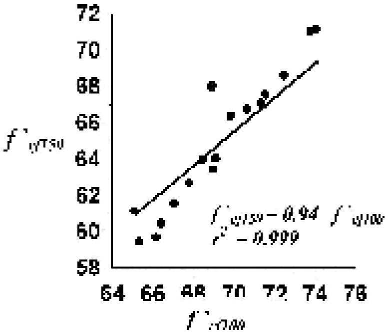

Fig.3- Different sizes cylinder relationship

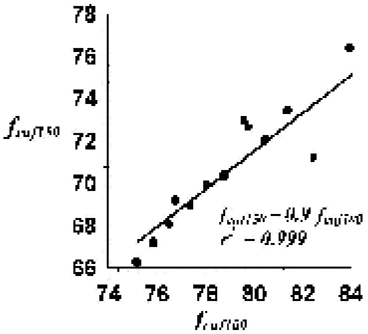

Fig.4- Different sizes cube relationship

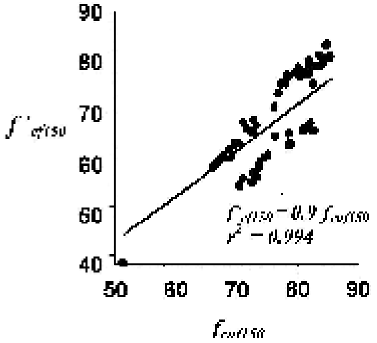

Fig.5- Relationship between cylinders & cubes

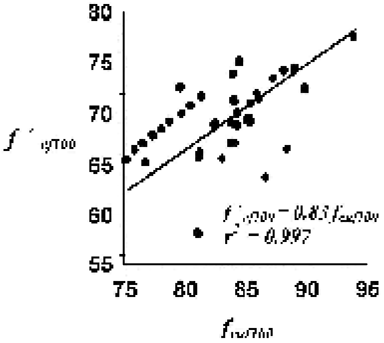

Fig.6- Relationship between cylinders & cubes

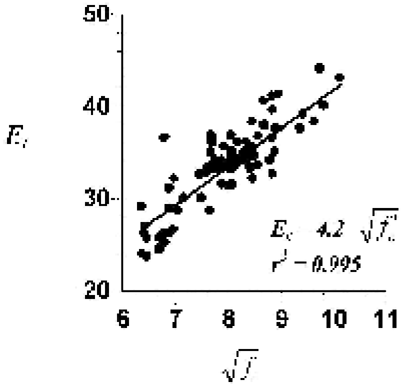

Fig.7- Variation of E_c with $\sqrt{f'_c}$

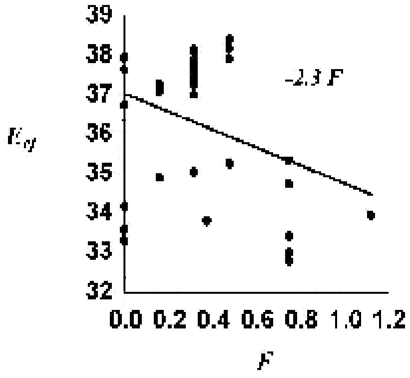

Fig.8- Effect of F on E_{cf}

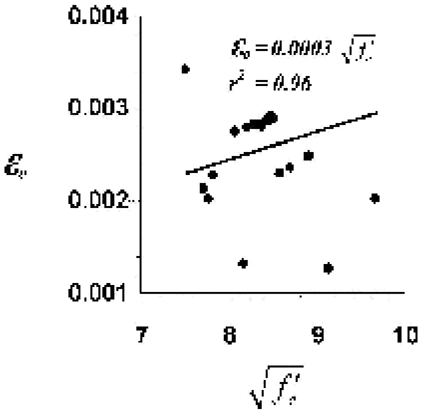

Fig.9- Variation of ε_o with $\sqrt{f'_c}$

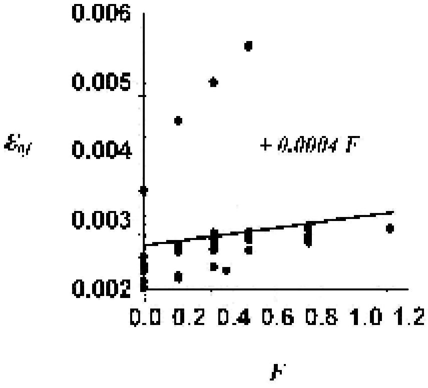

Fig.10- Effect of F on ε_{of}

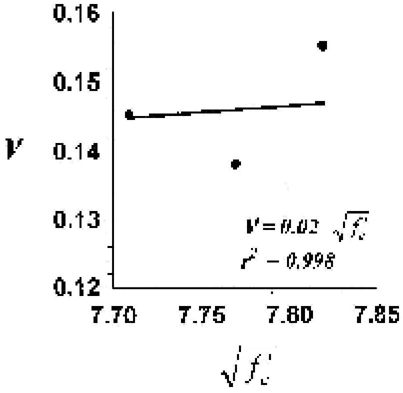

Fig.11- Variation of V with $\sqrt{f'_c}$

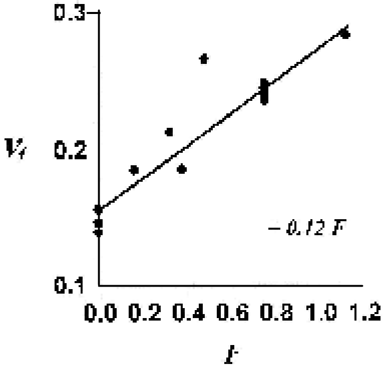

Fig.12- Effect of F on V_f

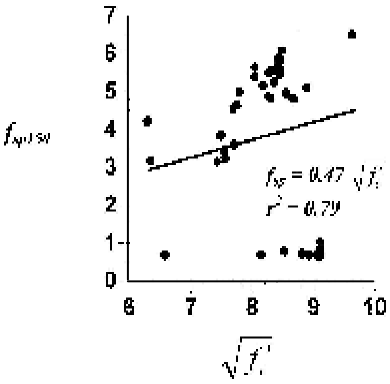

Fig.13- Variation of f_{sp150} with $\sqrt{f'_c}$

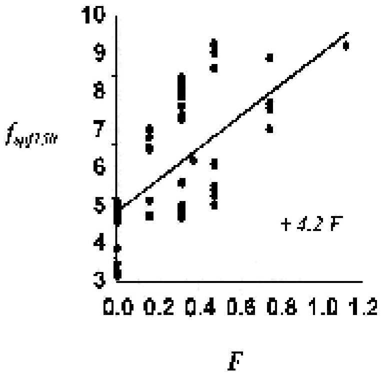

Fig.14- Effect of F on f_{spf150}

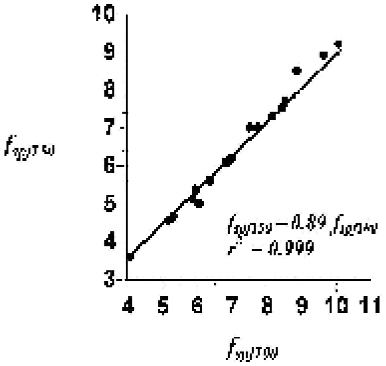

Fig.15- Different sizes cylinder relationship

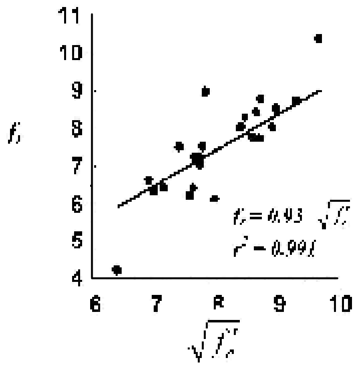

Fig.16- Variation of f_r with $\sqrt{f'_c}$

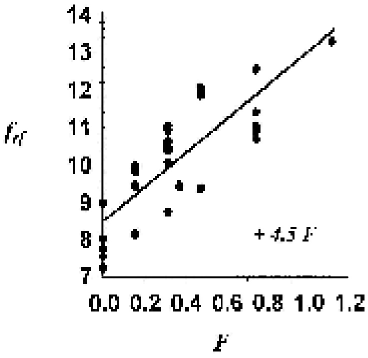

Fig.17- Effect of F on f_{rf}