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Proposed Equation of Elastic Modulus of Hybrid Fibers Reinforced Concrete Cylinders

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Abstract- To control the cracks and to increase the serviceability of concrete members, different types of fibers are used. The present research is conducted to study the behavior of hybrid-fiber reinforced concrete (HFRC) to enhance the load carrying capacity of concrete in compression and tension. Two different types of fibers are studied in this research; one is steel fibers (SF), and the other is polypropylene fibers (PPF). By using a different volumetric combination of SF and PPF, 42 concrete cylinders are cast in order to study the compressive and tensile behavior of concrete. The results exhibited the physical changes in the concrete due to the addition of different low-volume fractions of SF and PPF. The maximum compressive strength was achieved using 0.7% SF along with 0.3% PPF and the maximum tensile strength was achieved at 0.8% SF and 0.9% PPF by the total volume of the sample. A comparative study was also made for the previously proposed equations of the elastic modulus of concrete in order to obtain an equation which predicts the elastic modulus of HFRC accurately.

Keywords- HFRC, workability, elastic modulus of concrete, stress-strain curves, compressive strength, tensile strength

I. Introduction

Because of the adaptability to any shape and ease of availability of materials worldwide, concrete is being most widely used in the construction industry. The main reason is economically available matrix ingredients with high compressive strength and workability; however, concrete brings with itself a few drawbacks as a construction material including low tensile strength, impact strength, fatigue resistance, post crack strength, ductility, deformation accommodability, and strain capacity at fracture all along with high brittleness and no warning before failure. Fracture follows localised cracking which in turn follows micro-cracking after the elastic range of concrete. These weaknesses of concrete as a construction material are owed to the micro-cracks in concrete. These drawbacks are now considered a weakness of concrete and hence many attempts have been made to improve these characteristics of concrete [1-2]. Strains within concrete are resisted by mono-filament type fibers; however, that resistance to cracks is limited [3]. Hybrid concrete is composed of two or more different types of fibers while being used in concrete in order to impart specific characteristic properties to concrete. It is a homogeneous and relatively ductile material as compared to conventional concrete or the single fiber reinforced concrete [4]. Fibers being more closely spaced as compared to steel reinforcements control cracks more efficiently [5]. Using a short length of fibers can improve the workability of concrete as compared to longer fibers or the fibers with higher aspect ratio [6]. Hybrid fiber reinforced concrete having polypropylene fibers (PPF) and steel fibers (SF) enhance the self-compacting properties of concrete [7]. In high seismic zones, the use of different fibers in concrete columns may decrease the requirement of the transverse reinforcement leading to an improved and economical condition of the construction industry [8].

Steel fibers (SF) are usually used to achieve ductile structures with crack control of concrete. In tunnel linings, slabs and concrete pavements, it was seen to be efficient to use 0.5% SF by volume of the sample [9-12]. For shrinkage crack control, a low-volume fraction of 0.1% PPF and glass fibers (GF) by volume is enough [13-14]. The use of fibers in concrete with low-volume fractions acts like a secondary reinforcement in concrete against cracking but does not affects the load carrying capacity of members. It was observed from the literature that the use of fibers in concrete does not effectively improve the compressive strength of concrete but sufficiently improves the flexural and tensile strength of concrete [15-20]. However, some previous researches [21-23] also showed that the compressive strength was increased due to the addition of fibers in concrete. Li et al. [24] studied the effect of basalt and steel fibers on the mechanical properties of concrete and concluded that shear toughness, shear load and direct shear strength significantly increased due to addition of hybrid fibers. Furthermore, they concluded that the 4.5kg/m^3 basalt fibers and 180kg/m^3

steel fibers showed the best results of shear strength and shear toughness. B. Li et al. [25] experimentally studied the effects of steel and polypropylene fibers on the flexural performance of concrete. 51 samples were tested under four point bending test which concluded that the tensile, compressive and flexural strengths of concrete increase with the increase of steel and polypropylene fibers. Moreover, different shapes of steel fibers; hooked, corrugated and straight were examined giving the better failure for hooked and corrugated shaped fibers. Pakravan et al. [26] made a review on the hybrid fiber reinforcement in concrete concluding that the steel fibers are more efficient for tensile and flexural strength as compared with other types of fibers and fiber geometry affects the fresh and hardened properties of concrete. Furthermore, the stiffer and harder fibers in hybrid fiber reinforcement improve the strength and fiber with low elastic modulus improve the toughness and ductility of concrete. Sadrinejad et al. [27] investigated the effects of polyolefin (PO) and polypropylene (PP) fibers on the fresh and hardened properties of concrete. The maximum used percentage of PO fibers was 1.5% and that of PP fibers was 0.2%. The percentage increases in compressive and tensile strengths were 7.5% and 23%, respectively with no significant effect on the post-peak behavior of concrete. Finally, the authors recommended the percentages of 0.9% and 0.1% of PO and PP fibers, respectively, for the practical use.

From the literature, it has been observed that the experimental behavior of HFRC is less defined and no work about the elastic modulus of GFRC has been done. Therefore, there is a need to experimental investigate the mechanical behavior such as compressive and tensile strength and the elastic modulus of HFRC. This paper collaborates the comparative study of experimental investigation for compressive and tensile behavior of HFRC along with the stress-strain curves of cylinders. Furthermore, the present study also proposes the optimum quantity of SF and PPF for the maximum compressive strength and tensile strength of concrete. Usually, low-volume fractions of steel fibers give efficient effect in tensile and flexural properties of concrete [28-30].

The importance of the presented paper is based on the utilization of the specific low-volume hybrid fibers, i.e. of SF and PPF in concrete which should be used in different applications such as slabs, concrete linings and pavements. The first main objective of the present study is to experimentally investigate the compressive and tensile behavior of HFRC by performing experiments and the second objective is to study the different proposed equations of the modulus of elasticity of concrete using the experimental data in order to propose an equation which predicts the elastic modulus of HFRC with accuracy. The significance of this research is that the outcomes of the experimental results will be useful for the implementation of the HFRC to meet the current demand of the construction industry. Nevertheless, it would be unpractical for the structural designers to measures to the experimental elastic modulus of HFRC when designing the new HFRC structures.

II. Experimental Program

In the current study, a total of 42 hybrid-fiber reinforced concrete (HFRC) cylinders were cast using different low-volumetric ratios of SF and PPF to find the optimum quantity of fibers for improved mechanical properties of concrete. The ratios of SF and PPF were selected according to the manufacturer's recommendations to be used in concrete construction to prevent shrinkage and to crack due to initial loadings. The water to cement ratio of 0.5 was used for all the specimens to achieve reasonable strength and workability.

1.1. Material Properties

Cement is the binding material which performs an essential role in the manufacturing of concrete. The cement with specifications shown in Table 1 and conforming to ASTM C150/150M-18 [31] was used for the casting of the specimens.

TABLE 1: PROPERTIES OF CEMENT

S. No.	Description	Results
1.	Specific gravity	3.030
2.	Final Setting Time	225 minutes
3.	Consistency	28.75%
4.	Soundness	No Expansion
5.	Initial Setting Time	91 minutes
6.	Compressive Strength at 28 days	41.13 MPa
7.	Fineness	319 m^2/kg

The fine and coarse aggregates conforming to ASTM C33 / C33M-18 [32] and with specifications shown in Table 2 were used for casting of the specimen, maximum passing size of aggregate was taken as 19 mm keeping in view the maximum designed a cover for columns (in the industry) that was 20 mm.

TABLE 2: PROPERTIES OF COARSE & FINE AGGREGATES

S. No.	Description	Fine-Aggregates	Coarse-Aggregates
1	Specific Gravity (SG)	2.670	2.712
2	Fineness Modulus	2.41	-
3	Water Absorption	1.211 %	0.821 %

The SF used in this research were cold drawn wires with hooked ends as shown in Fig. 1(a). The properties of used SF were presented in Table 3.

TABLE 3: PROPERTIES OF STEEL FIBERS

Property	Description/Value
Length	25 ± 1mm
Aspect Ratio (L/D)	>45 (52)
Diameter	0.55 ± 0.05 mm
Ultimate Strength	>600 MPa (1100)
Standard	ASTM A820
Specific Gravity	7.82
Melting point	253 C^{o}
Young's modulus (GPa)	20
Elongation at Failure	-3.5%
Thermal conductivity	Low

Monofilament PPF as shown in Fig. 1(b) with specifications shown in Table 4 were used for casting of the specimen.

Super Plasticizer increases the fluidity in order to allow the flow of fluid under gravity for the achievement of a required degree of consolidation in concrete. Chemrite NN, as a super-plasticizer was used with specifications shown in Table 5 conforming to ASTM C494 [33].

(a) (b)

Fig 1. Types of fibers used in experimental studies (a) Steel fibers (b) Polypropylene fibers

The SF of 0.7%, 0.8%, 0.9% and 1.0% of the total volume of the specimen were used and the quantities of PPF were 0.1%, 0.3%, 0.5%, 0.7% and 0.9% of the total volume of cylinder specimen, respectively. The mix designs of concrete for all HFRC cylinders were same with ratios of 1:1.4:2.8 except the fibers (detail mentioned in Table 6), and each mix design consists of two specimens with the same label; one for compressive strength test and the second for the tensile strength test.

TABLE 4: PROPERTIES OF POLYPROPYLENE FIBERS

Description	Monofilament PPF
Length (mm)	14
Diameter	22 µm
Aspect Ratio	-
Specific Gravity	0.91
Tensile strength (MPa)	400
Melting point	170 C^{o}
Young's modulus (KN/mm2)	0.45
Elongation at Failure	15%
Thermal conductivity	-

TABLE 5: PROPERTIES OF CHEMRITE NN, SUPERPLASTICIZER USED

S. No.	Description	Details
A) Technical details		
1.	The density of at 25°C	Approximately 1.18 Kg/l
2.	pH value	Approximately 8
3.	Chloride content of NN	Nil (EN 934-2)
5.	Transportation	Non-hazardous
B) Application details		
1.	Dosage of	0.6–2 % by wt. of cement.
2.	Dispensing	Can be added to the water prior to its addition to the concrete mixer.
3.	Mixing	It may be mixed to the fresh concrete immediately before discharge.

All the HFRC cylinders cast with mix designs (as discussed in Table 6) with the water-cement ratio of 0.50 with a varying quantity of SF and PPF in each cylinder and an admixture for the workability of concrete which also fixed to the weight of cement. The casting procedure was a bit modified to the one previously used in research for polypropylene fiber reinforced concrete (PFRC) in past researches with the addition of SF. The cylinders of the size with a diameter of 150 mm and length/ height of 300 mm as per ASTM C 192/C 192M–02 standards (2002) cast for the analysis of 28 days compressive strength and tensile strength of concrete as per ASTM C39 [34].

The slump test of the concrete conducted according to ASTM C143 having the slump value of 17$\pm$4 cm. The use of fibers decreased the workability of concrete [35]. The slump values for different mix designs of hybrid-fibers in concrete presented in Fig. 2. The slump value of concrete decreases with the increase of fibers being used in concrete. A percentage decrease of 188% occurred in the slump value when the steel fibers increased from 0% to 1.0% and polypropylene 0% to 0.9%.

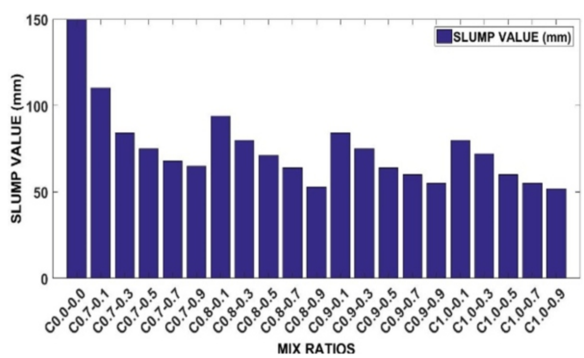

Fig 2: Effect of hybrid-fibers on the slump value of concrete

TABLE 6: EXPERIMENTAL PROGRAM AND TEST MATRIX

Sr. No.	Sample Label	SF (%)	PPF (%)
1	C0.0-0.0	0.0	0.0
2	C0.7-0.1	0.7	0.1
3	C0.7-0.3	0.7	0.3
4	C0.7-0.5	0.7	0.5
5	C0.7-0.7	0.7	0.7
6	C0.7-0.9	0.7	0.9
7	C0.8-0.1	0.8	0.1
8	C0.8-0.3	0.8	0.3
9	C0.8-0.5	0.8	0.5
10	C0.8-0.7	0.8	0.7
11	C0.8-0.9	0.8	0.9
12	C0.9-0.1	0.9	0.1
13	C0.9-0.3	0.9	0.3
14	C0.9-0.5	0.9	0.5
15	C0.9-0.7	0.9	0.7
16	C0.9-0.9	0.9	0.9
17	C1.0-0.1	1.0	0.1
18	C1.0-0.3	1.0	0.3
19	C1.0-0.5	1.0	0.5
20	C1.0-0.7	1.0	0.7
21	C1.0-0.9	1.0	0.9

III. Discussion of Experimental Results

As concerned with experimental results, the compressive strengths of all the cylinders were investigated at 28 days using Compression Testing Machine (CTM) in the Concrete Laboratory of Civil Engineering Department, University of Engineering and Technology Taxila, Pakistan as shown in Fig. 3. The experimental programme was so devised that the machine would stay for five seconds at every stress interval which was maintained at 0.2-0.26 MPa corresponding to a load of 5-6 KN depending upon the stress release in the material. The relevant axial strains were continuously measured with load application at specific intervals with an increment of 10 MPa Stress, which equalled approximately 200 KPa load. Meanwhile, the vertical and central horizontal deflections with strain gauges were also measured at intervals of every 50 KN load and were noted manually to find out the coherence between the material strain and load deflection strain.

(a) (b) (c)

Fig. 3: (a and b) Compression testing and (c) tensile testing of HFRC cylinders

3.1. Stress-Strain Behavior for HFRC Cylinders

The stress-strain curves obtained from experimental results of all specimens were shown in Fig. 4 with four subplots related to the four different volumetric ratios of SF. The assessment of the analysis results obtained from the experimental measurements shows that the maximum stress was given by the specimen C0.7-0.3 and the minimum stress was provided by the specimen C0.9-0.7. In each sub Fig, a fixed value of SF was used against different values of PPF. It is clear from the Fig. 4 that the compressive strength of concrete does not increases by continuously increasing the fibers content, but there is an optimum content of fibers which is 0.7% SF and 0.3% PPF.

3.2. Crack Patterns

The crack patterns of the HFRC cylinders were also studied. Fig. 5 shows the cracking of two concrete cylinders C0.7-0.3 & C0.8-0.7 after compression testing and one cylinder after tension testing. It was observed that the cracks in HFRC specimens were occurred slowly and pieces of concrete were remained together after cracking. While, the plain concrete specimen was separated in to two pieces after testing.

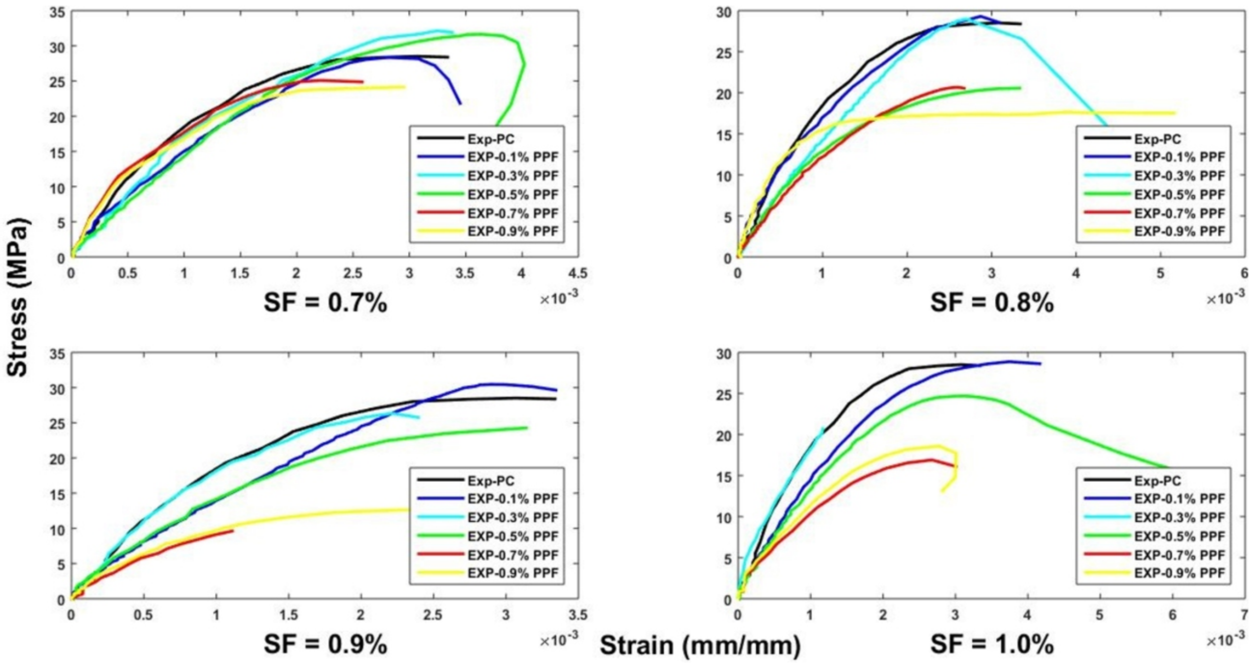

Fig. 4: Stress-strain curves of HFRC cylinders from experimental results

3.3. Effect of Hybrid-Fibers on Compressive Strength and Strain

The experimental results depict that the specimen with 0.7% steel fibers & 0.3% polypropylene fibers percentage have the highest compressive strength showing the optimum percentage content of polypropylene fibers as 0.3% and that of steel fibers as 0.7% by total volume of the sample. There was an increase of 11.92% in the compressive strength and no change in the axial strain of cylinder specimen C0.7-0.3 as compared with the plain concrete specimen. The maximum strain was observed for the specimen C1.0-0.7 which was 34% in comparison with the plain concrete specimen. Overall, there was no significant effect of the addition of fibers on the compressive strength of concrete.

Fig. 5: Experimental crack patterns of (a) C0.7-0.3 (b) C0.8-0.7 in Compression Testing and (c) Tensile Testing

Fig. 6 & Fig. 7 show the experimental effects of SF and PPF on the compressive strength and strain of cylinders, respectively. In each sub Figure, a fixed value of SF was used against different values of PPF. Fig. 8 shows the combined effect of SF and PPF on the compressive stress and strains of HFRC cylinders.

3.4. Effect of Fibers on Tensile Strength

There was a more favourable effect of fibers on the tensile behavior of concrete. The effect of different percentage quantities of the SF and PPF on the tensile behavior of concrete was shown in Fig. 9. It can be observed from Fig. 9

That the tensile strength of HFRC is larger than the that of plain concrete cylinders and the optimum percentage content of fibers is 0.8% SF and 0.9% PPF giving the tensile strength of 4.91 MPa. The maximum percentage increase in the tensile strength was 55.98% as compared with the plain concrete cylinder. In each subFig, a fixed value of SF was used against different values of PPF.

The combined effect of the SF and PPF on the tensile strength of HFRC cylinder specimens was presented in the 3D graph presented in Fig. 10 showing that the maximum tensile strength was achieved at 0.8% steel fibers (SF) and 0.9% polypropylene fibers (PPF). The maximum tensile strength of concrete was 155.98% of that of plain concrete.

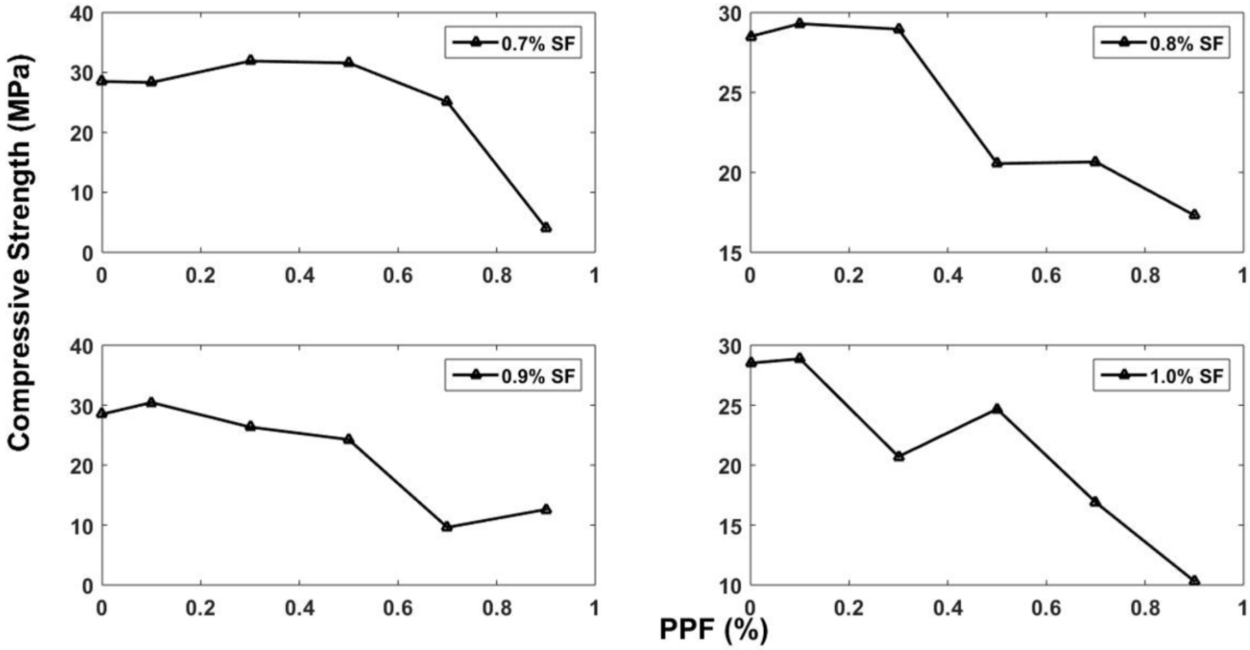

Fig. 6: Effect of fibers on the compressive strength of HFRC cylinders

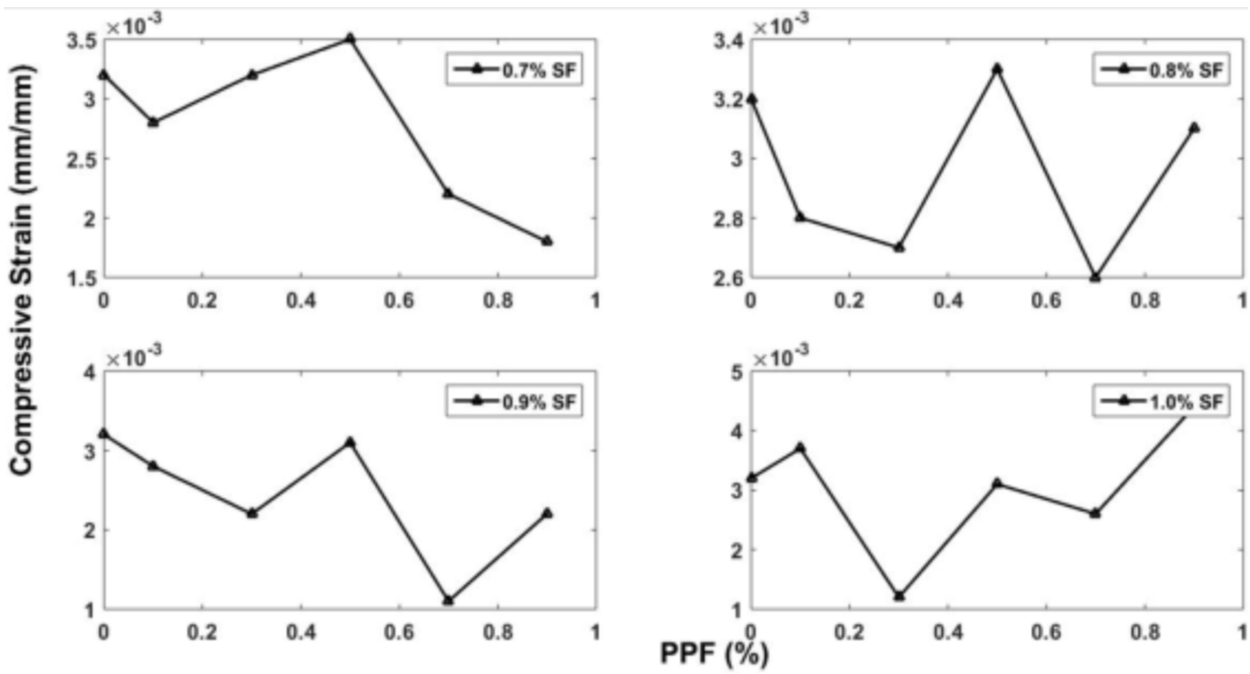

Fig. 7: Effect of fibers on the axial strain of HFRC cylinders

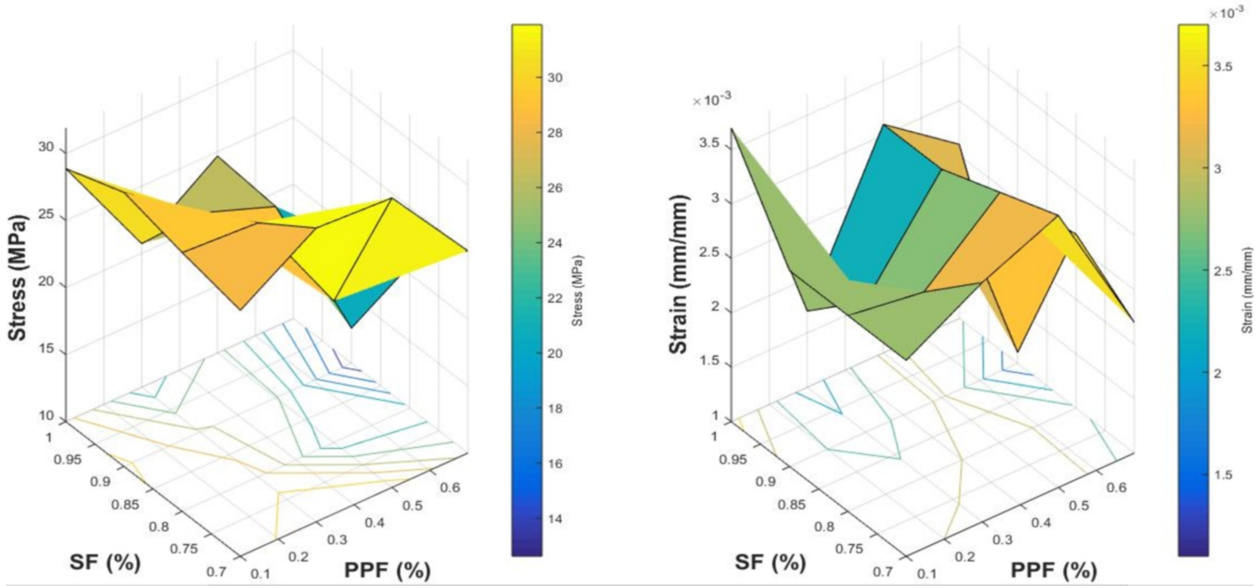

Fig. 8: Experimental results of compressive strength and strain, respectively against the quantity of hybrid-fibers

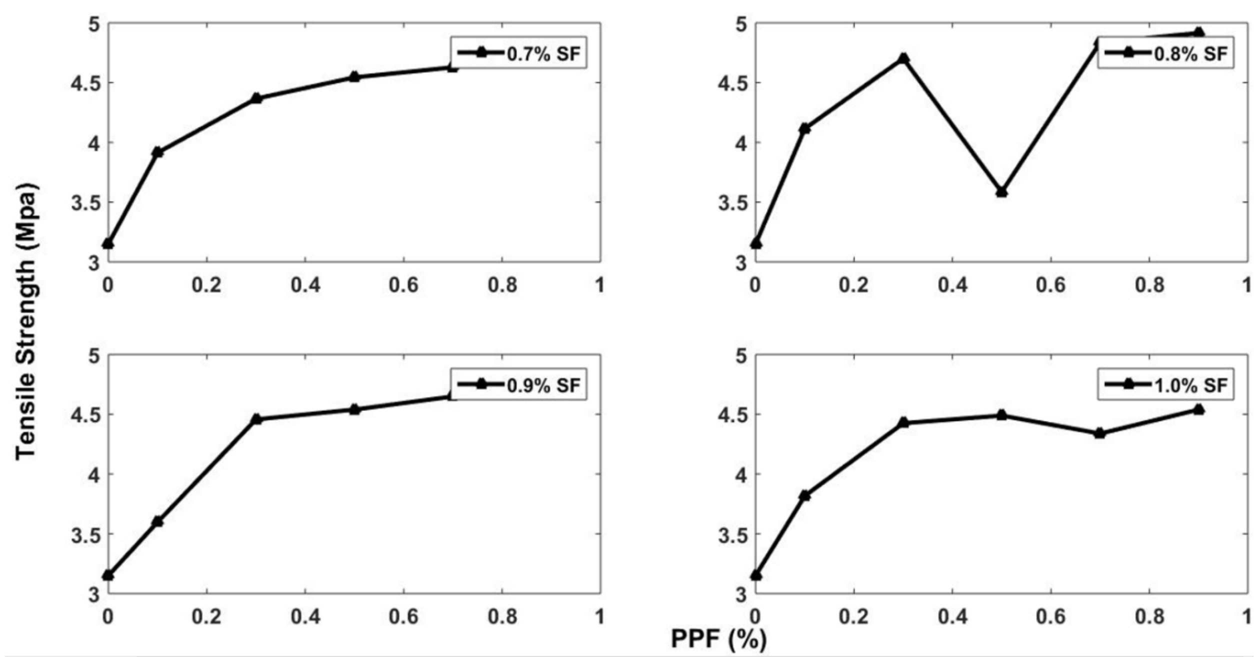

Fig. 9: Experimental results of tensile strength of HFRC cylinders

3.5. Elastic Modulus of HFRC

The elastic modulus is the parameter which defines the elastic behavior of a material. The experimental values of elastic modulus (E_e) of SF and PPF concrete were determined using ASTM C469-14 [36]. All the measured elastic moduli of HFRC specimens is shown in Fig. 11. The maximum E_e was given by the sample C0.7-0.3 with the value of 15.21 GPa. This present work summarizes the elastic moduli of 21 HFRC specimens obtained from experimental stress-strain curves and empirical equations available in the literature and determining an equation which predicts the elastic moduli of HFRC accurately. The different equations used for the calculation of elastic modulus of concrete are presented in Table 7.

All these equations directly relate the compressive strength of concrete to the elastic modulus of concrete. It can be noted here that the limitations of these equations were ignored to determine the best general elastic modulus equations for HFRC based on the experimental data.

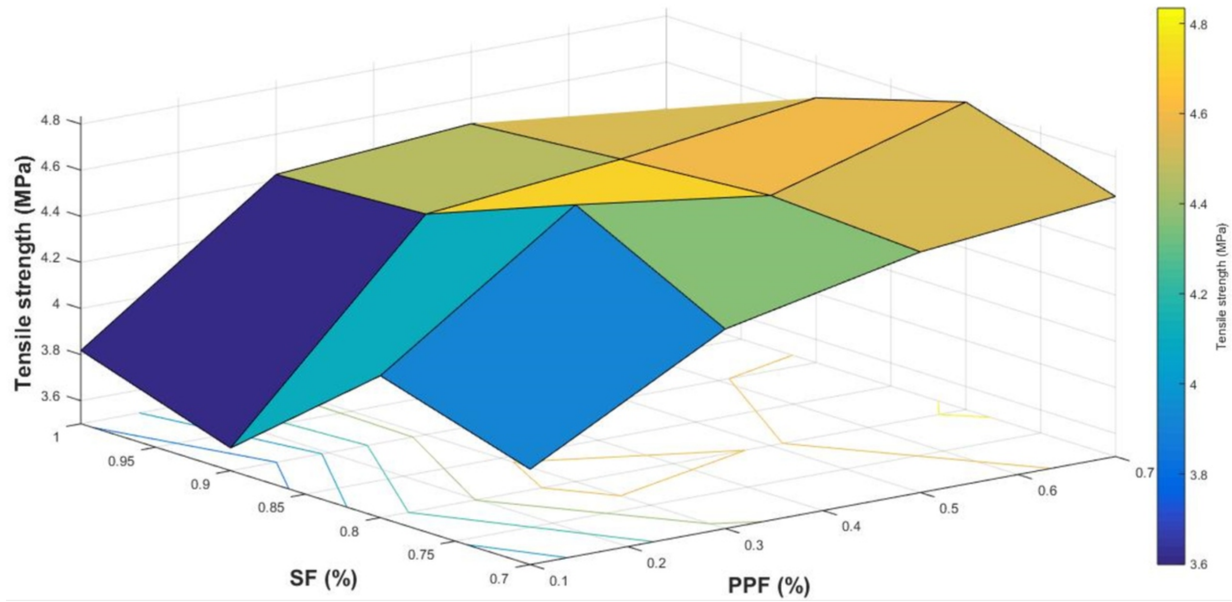

Fig 10: Combined effect of SF and PPF on the tensile behavior of cylinders

The preliminary evaluations were done for the previously proposed equations of elastic moduli for minimizing the errors using two indices; one is coefficient of variance (COV) and second is the coefficient of determination (r^2) given by the Eq. 6 and Eq. 8, respectively.

$$\mathrm{COV} = \frac{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(E_{cp}-E_{e})}}{\mu} \quad (6)$$

Where, E_e and E_{cp} are the measured and predicted values of elastic modulus of HFRC, respectively and μ is the mean calculated by the following equation:

$$\mu = \frac{\sum_{i=1}^{n} E_e}{n} \quad (7)$$

$$r^2 = \left(\frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}}\right)^2 \quad (8)$$

Where, x and $\bar{y}$ are the means of measured and predicted values of elastic moduli. The proposed equation for elastic modulus of HFRC with the maximum fiber volumetric-fraction of 1.9% based on the regression analysis ($r^2 \approx 65\%$) of 21 tested specimens was presented by Eq. (9).

$$E_{cp} = 1508\sqrt{f_c'} + 6695(\mathrm{MPa}) \quad (9)$$

The results of the performance of measured and predicted elastic moduli were plotted in Fig. 12. The straight line plotted at 45-degrees represents the perfect co-relation among calculated and predicted values of elastic modulus. The data points lying above and below the perfect line show the unconservative and conservative deviations of the elastic modulus equations, respectively.

It was observed that the COV for different previously proposed equations were high, ranging from 22% to 100%. The equation proposed by Jo, B.W et al. [43] also performed well for the prediction of the elastic modulus of HFRC with COV of 22.2% as compared with the experimental results. The proposed equation provided the conservative approximation of the elastic modulus of HFRC with the COV of 8.18% as represented by Fig. 12 (h). While using the ACI 318 equation, a COV of 65.37% was observed which shows that the elastic modulus of hybrid-fibers reinforced concrete cannot be predicted by the ACI 318 equation.

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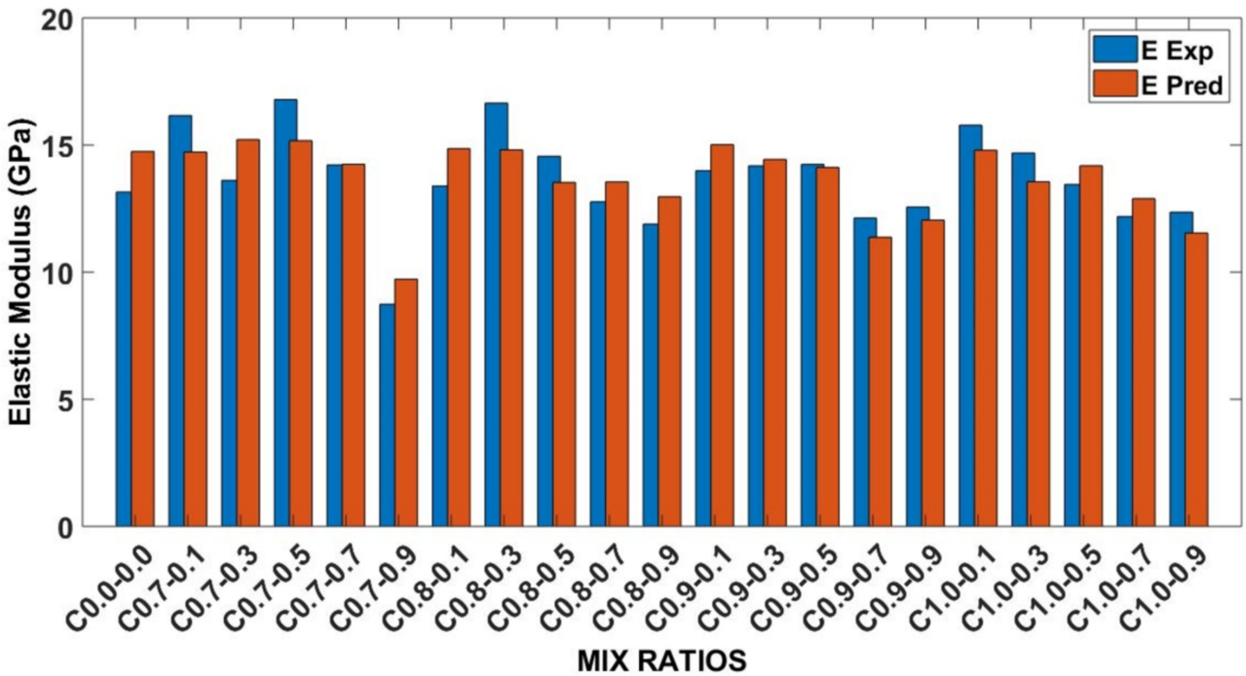

Fig 11: Elastic moduli of HFRC specimens by ASTM C469 and Proposed Equation

TABLE 7. EQUATIONS AVAILABLE FOR ELASTIC MODULUS OF CONCRETE

Sr. No.	Reference	Equation	Limitation
1	ACI 318 [37]	$E_c = 4700\sqrt{f_c'}$	NSC
2	Graybeal [38]	$E_c = 3840\sqrt{f_c'}$	High strength
3	NS 3473 1992 [39]	$E_c = 9.5(f_c')^{0.3}$	-
4	Hsu and Hsu [40]	$E_c = af_c' + c$	$V_{f(\%)}$ / a / c 0.5 / 43.66 / 3629.24 0.75 / 35.51 / 3792.86 1 / 33.77 / 3792.59
5	Mansur et al. [41]	$E_c = (10{,}300 - 400\,X\,V_f)f_c'^{\frac{1}{3}}$	$Vf \leq 1.5$
6	ACI 363R [42]	$E_c = 3320\sqrt{f_c'} + 6900$	High strength
7	Jo, B.W et al. [43]	$E_c = \left(\frac{\gamma}{2.4}\right)^{1.5}(10{,}000\sqrt{f_c'} + 73{,}000)$ (Kgf/cm^2)	$f_c' \leq 36$ MPa

IV. SUMMARY AND CONCLUSIONS

A total of 42 hybrid-fiber reinforced concrete (HFRC) cylinders of 150 mm diameter and 300 mm height were cast using the w/c ratio of 0.5. Both steel and polypropylene fibers were used in cylinders with different low percentage volume fractions of the total sample. The percentages of 0%, 0.7%, 0.8%, 0.9% and 1.0% of the volume of sample were used for steel fibers and percentages of 0%, 0.1%, 0.3%, 0.5%, 0.7% and 0.9% of the total volume of sample were used for the polypropylene fibers. The slump value, compressive strength and tensile strength of hybrid-fiber reinforced concrete were determined. Finally, an equation was proposed for the prediction of the elastic modulus of HFRC. Finally, an equation was proposed for the prediction of the elastic modulus of HFRC after performing the preliminary evaluations on the previously proposed models using the experimental data. The following main conclusions were drawn from the present research:

1. The workability of HFRC was decreased by the addition of fibers. About 188% decrease in the slump value occurred by using the 1.0% steel fibers and 0.9% polypropylene fibers of the total

volume of sample as compared with plain concrete.

2. There was a slightly significant effect of the addition of fibers on the compressive strength of concrete. The maximum strength of concrete given by the cylinder (C0.7-0.3) was 11.07% of that of the plain concrete cylinder (C0.0-0.0). However, a significant effect of the fibers was examined for the tensile strength of concrete shown by the cylinder C0.8-0.9 giving the 55.98% increase as compared with plain concrete.

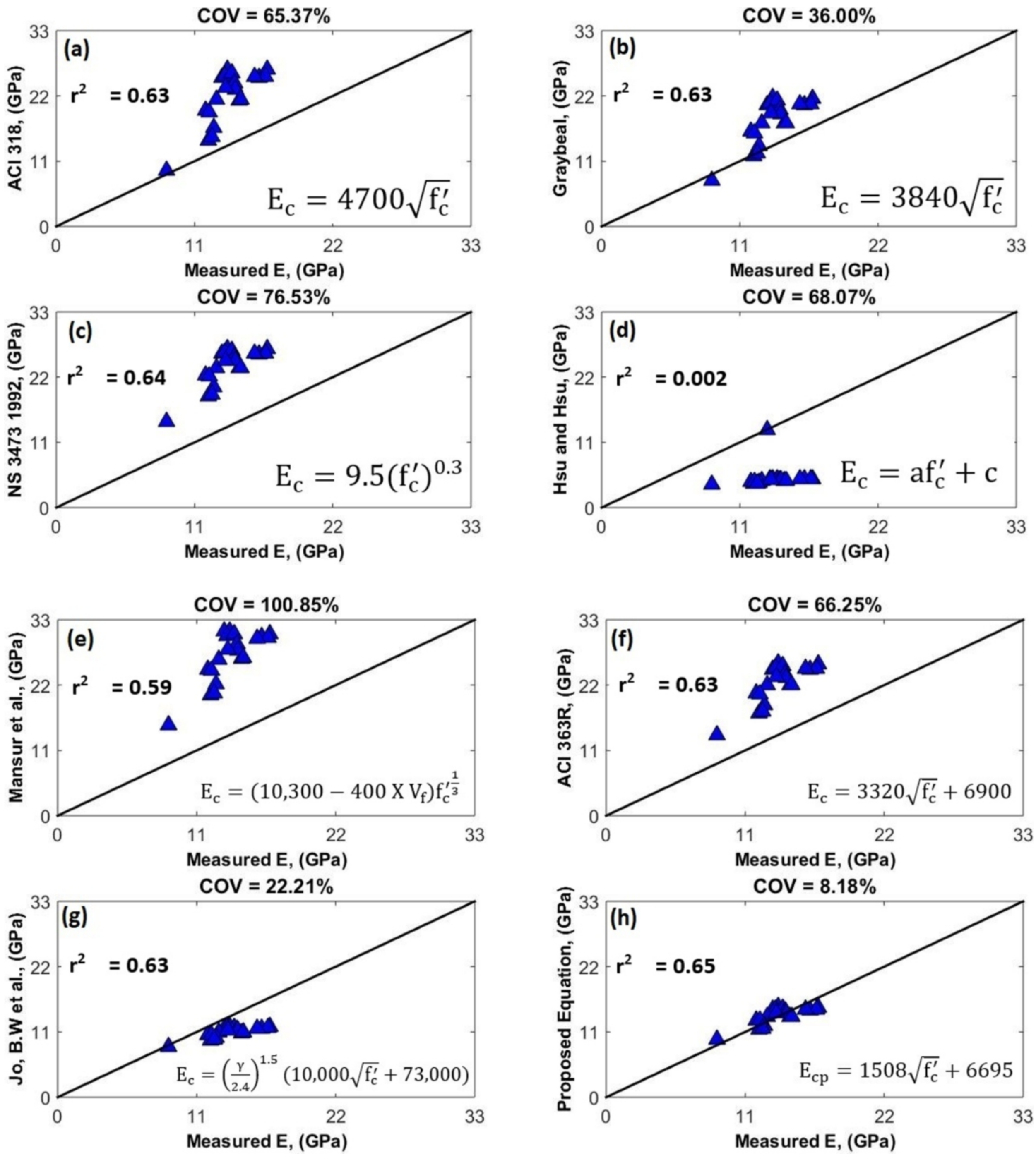

Fig 12: Comparison between experimental and predicted values of elastic moduli of HFRC

3. The vertical cracks were occurred in the specimens tested in compression with increased ductility of HFRC specimens. Fibers acted as an internal reinforcement for the concrete to keep the cracked parts together after testing.
4. The proposed empirical equation predicted the elastic modulus of HFRC with a coefficient of variance of 8.18% and coefficient of determination of 0.65 while the other codes could not be able to predict the elastic modulus of hybrid-fibers reinforced concrete (HFRC) accurately.

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