Eng. &Tech.Journal, Vol. 33,Part (A), No.4, 2015

Studying the Combined Effect of Steel Fiber and Silica Fume on Elastic Modulus of High Performance Concrete

Muntadher J. Taher
Building and Construction Engineering Dept,University of Technology /Baghdad.
Email:montazer.88.kat@gmail
Dr. Maan S. Hassan
Building and Construction Engineering Dept,University of Technology /Baghdad.
Dr. Zeyad M. Al-azawi
Building and Construction Engineering Dept,University of Technology /Baghdad.

Received on:27/5/2013 & Accepted on:7/8/2014

Abstract

Concrete elastic modulus is a basic property required for the appropriate predicting of its basic behavior and for its correct implementation in a variety of constructional and engineering applications. This study presents an experimental and analytical evaluation of elastic modulus of high performance concretes (HPC) produced by steel fiber and silica fume. The aim of this study is to develop the elastic modulus property of HPC and to show the applicability of ACI models to predict the elastic modulus of HPC from compressive strength. Four volume fractions of steel fiber with aspect ratio (fiber length/ fiber diameter) of 60 were used (0, 0.5, 1.0, and 2.0 %). Incorporations of silica fume into the concrete were 0% and 15% by weight as a cement replacement. Water/cement ratio was ranged (0.28-0.4) with different amount of superplasticizer, and the reference slump was 170 mm. Both compressive and elastic modulus tests were made on hardened concretes reinforced with steel fibers and then compared with control specimens at 14 and 28 days. The results showed that the presence of silica fume enhanced the compressive strength and modulus of elasticity of evaluated concretes. In addition, adding steel fiber slightly increased both strength and modulus of elasticity values. Also, results showed that the elastic modulus of HPC is relative to the compressive strength, the ACI 318 expression is predicting elastic modulus of HPC and HPC-SF superior than ACI 363, but ACI 363 equation seems to be better in prediction modulus of elasticity of HPC-SF0.5S, HPC-F1.0S, and HPC-SF2.0S in comparison with ACI 318.

Key words: Modulus of elasticity of HPC, silica fume, steel fiber.

دراسة التأثير المشترك لالياف الحديد وغبار السيليكا على معامل المرونة للخرسانة عالية الاداء

https://doi.org/10.30684/etj.33.4A.10
2412-0758/University of Technology-Iraq, Baghdad, Iraq

الخلاصة

ان معامل مرونة المادة هو من الخواص الأساسية اللازمة للتصميم السليم لسلوكها التكويني والاستخدام المناسب لها في مختلف التطبيقات الانشائية. تقدم هذه الدراسة تقييماً تجريبي وتحليلي لحساب معامل مرونة نماذج الخرسانة عالية الأداء (HPC) المنتجة بإستخدام غبار السيليكا والياف الحديد. *ان* الهدف الرئيسي من هذا العمل هو تطوير معامل المرونة لل(HPC) وإظهار مدى توافق معادلات (ACI) للتنبؤ بمعامل مرونة (HPC) بالاعتماد على مقاومة الانضغاط. أُستخدِمت أربعة أجزاء حجمية من الالياف الحديدية (الطول/القطر) 60 (aspect ratio)(0, 0.5, 1.0, & 2.0%). كانت نسبة مزج غبار السيليكا في الخرسانة (0 & 15%)كنسبة إستبدال وزنية من محتوى السمنت. وقد تراوحت نسبة الماء الى السمنت (0.28-0.4) مع كميات مختلفة من الملدن المتفوق، وكان الهطول المرجعي 170 ملم. اجريت فحوصات مقاومة الانضغاط ومعامل المرونة على نماذج الخرسانة المتصلبة. تم مقارنة النتائج لتلك العينات مع نتائج النماذج المرجعية بعمر 14 و 28 يوم. أظهرت النتائج أن وجود غبار السيليكا أدت إلى زيادة في القوة ومعامل المرونة. وبالإضافة إلى ذلك، ان إضافة الياف الحديد يؤدي الى زيادة طفيفة في قيم مقاومة الانضغاط و معامل المرونة. أيضا، أظهرت النتائج ان معامل مرونة ال (HPC) يتناسب مع مقاومة الإنضغاط، ولكن معادلة تنبؤ ACI-318 تعطي قيم اقرب لمعامل المرونة للخلطات HPC وHPC-SF مقارنة بمعادلة ACI-363 التي تعطي قيماً اقرب لمعامل المرونة للخلطات HPC-SF0.5Sو ,HPC-F1.0S وHPC-SF2.0S مقارنة بمعادلة ACI-318.

INTRODUCTION

High performance concrete (HPC) is widely used throughout the world, HPC offers significant economic and architectural advantages over normal concrete. It is also suited for special constructions that require long service life and high durability.HPC is achieved by using superplasticizer to reduce water-binder ratio and by using supplementary cementing materials, such as silica fume, which usually combines high–strength with high durability.

High performance concrete is received increasing attention due to it wide applicability and significance as a new materials available to be utilized in new building and of structures emendation, bridges, highways and other structural applications. Associated with such growing raise in the employing of this promised concrete type, accurately predict to its mechanical and physical characteristics including modulus of elasticity, permeability, creep, shrinkage, and durability that became more requested and needed for structural designers. The modulus of elasticity is one of the most important properties needed among them, due to its ability to evaluate concrete sections stiffness and deflections. Therefore, make effective use of high performance concrete require to predict its elastic modulus accurately and to investigate the influence of the presence of pozzolanic materials and addition of steel fiber on this important hardened concrete property.

Models derived based on the regression analysis of 60 test data for various mechanical properties of steel fiber-reinforced concrete were presented by **(Thomas &Rawaswamy, 2007) [1**]. They were using an experimental and an analytical assessment program to showthe influence of addition of fibers on modulus of elasticity of concrete. The variables considered were grades of concrete, namely normal strength 35 MPa, moderately high strength 65 MPa, and high strength concrete 85 MPa, and the volume fraction of the fiber (0.0, 0.5, 1.0, and 1.5%). The results showed that the maximum increase in modulus of elasticity was found to be quite small less than 10% in all various grades of concrete.

Silica fume effects on the mechanical properties of high performance concrete (HPC) was studied by **(Koksal, et, al. 2008) [2]**. The results showed that the use of silica fume increased themodulus of elasticity of concrete.

Modulus of elasticity was also investigated by **(Ozbay, et, al. 2011) [3]**. The results indicated that the increasing of fine to total aggregate ratio and superplasticizer contents did not influence significantly on the modulus of elasticity of HPC, while the water/binder ratio increase remarkably decreased the modulus of elasticity, and increasing the total binder content (cement + silica fume) increased the elastic modulus of high performance concrete (HPC).

(Prashant, et, al. 2011) [4], discussed the influence of silica fume and steel fiber in enhancing properties of concrete. The tests were carried out at 28 and 90 day of curing ages.The results show that the addition of silica fume enhanced modulus of elasticity. Also, for thefurther improving of modulus of elasticity, steel fibers were used in addition to silica fume. However, the enhancement depends upon the percentage of fibers and on the diameter of fibers, for 0.5 mm diameter fibers the enhancement is less as compared to 1.0 mm diameter fiber.

This paper is aimed to investigate the influence of combined effects of steel fibers and silica fume on a key hardened property like elastic modulus of HPC. Previous published expressions concerning the elastic modulus, E, and concrete compressive strength, f_c', are evaluated for its applicability based on the experimental evaluation results. In addition, the experimental concrete test results are compared with ACI-318and ACI-363 equations to validate its suitability.

Research significance

Implementation of high-performance concrete (HPC) in the construction of structures could improve their service life and minimize maintenance requirements. This new emerging material can be safely and effectively used if further understanding of its stress–strain behavior is achieved, taking into account that elastic modulus and compressive strength became two of the most vital properties of this response. Moreover, improving deep knowledge of the modulus of elasticity is vital to predict long-term effects and durability characteristics of concrete building and structures. Accordingly, providing more insight regarding the elastic modulus and study the factors could control its behavior could be useful for structural designers and site engineers as well.

Experimental work

Material and concrete composition

In order to achieve the scopes of this study, the work was includingfive mixtures with 14 mm maximum aggregate size. Trial mix design method which is compliance with (ACI 211.4R-08, 2008)**[5]**, was used in this work to obtain the compressive strength above 50 MPa and workability around 170 mm slump for all mixtures.The chemicaland physical properties of both cement and silica fume aregiven inTable (1). Hooked ends steel fibers which are commercially known as Sika Fiber (Sika, 2012)**[6]**, were also used throughout the experimental program. These fibers were 30 mm long and 0.5 mm diameter (aspect ratio, L/D = 60), as shown in Figure (1), with ultimate tensile strength for individual fibers of 1180 MPa. The density of the steel fibers is 7800 kg/m^3. The properties of the used steel fibers are presented in Table (2).

Table(1): Chemical composition and main compounds of cement and silica fume.

Oxide composition	Abbreviation	Silica fume	Cement	Limits of IQS No.5/1984for cement
Lime	CaO	1.22	61.89	-
Silica	SiO_2	90.65	21.77	-
Alumina	Al_2O_3	0.02	4.61	-
Iron oxide	Fe_2O_3	0.01	3.35	-
Sulphate	SO_3	0.24	2.4	$\leq$ 2.8%
Magnesia	MgO	0.01	3.05	$\leq$ 5%
Loss on Ignition	L.O.I.	2.86	2.16	$\leq$ 4%
Lime saturation factor	L.S.F.	…	0.87	0.66-1.02
Insoluble residue	I.R.	…	0.6	$\leq$ 1.5
Specific surface (m^2/kg)	S.S	20000	391	< 230

* Tests were carried out in the Central Organization for Standardization and Quality Control.

Table (2): Properties of the used steel fibers*.

Description	Hooked end
Length	30 mm
Diameter	0.5 mm
Aspect ratio (***lf/df***)	60
Relative Density	7800 kg/m^3
Ultimate Tensile Strength	1180 MPa

*According to manufacturer

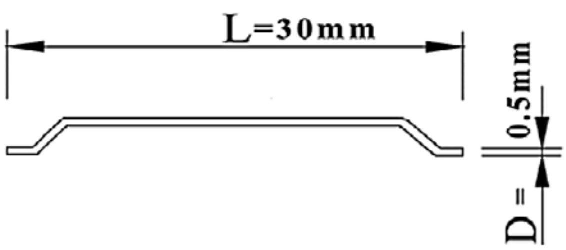

Figure (1): Sika Fiber end hooked steel fibers.

A constant cementitious material (cement, and silica fume) contents of 450 kg/m^3 was used; both sand and gravel content are constant, different water to binder ratio, steel fiber, and superplasticizer were used, as shown in Table (3).

Mixing of concrete constitutions start firstly by blending of cement, silica fume and all aggregates, then a mixture of water and high-range water reducing admixture was added to the mixture. Steel fibers were finally scattered carefully to the mixture to provide a uniform distribution of fibers throughout the mixture constituents, and mixed foe 3 additional minutes to achieve homogenous distribution of the fibers.

Making and curing of concrete specimens were carried out following ASTM C 192M-02. The specimens were cast in clean and oiled steel moulds and compacted on a vibration table. The specimens were then demoulded after about (24 h) and subjected to standard curing until the age of 28 days.

Fresh concrete test

Following in (ASTM C 143-03, 2007)**[7]**, all concrete mixes workability were measured immediately after mixing using slump test. The w/c or w/b for high performance concrete without fibers was adjusted to have the same workability of slump 170 ± 8 mm.

The addition of fibers to concrete mix caused a reduction in workability as the fiber content increased. This was also noted by other researcher (Chanh) [8], the experimental work showed that the concrete mix was still workable after the inclusion of fibersas shown in Table (3).

Table (3): Concrete mix proportions used through this work

Material	Control mix	Mix1	Mix2	Mix3	Mix4
Symbol	HPC	HPC-SF	HPC-SF0.5S	HPC-SF1.0S	HPC-SF2.0S
OPC (kg/m^3)	450	382.5	382.5	382.5	382.5
Sand (kg/m^3)	700	700	700	700	700
Gravel (kg/m^3)	1100	1100	1100	1100	1100
Water content (l/m^3)	180	126	135	144	153
Super plasticizer (l/100kg)	0.5	3	3	3	4
Silica fume replacement (kg/m^3)	……	67.5	67.5	67.5	67.5
Steel fiber (kg/m^3)	……	……	39	78	156
Fiber V_f (%)	……	……	0.5	1.0	2.0
w/b	0.4	0.28	0.3	0.32	0.34
Slump 170 ± 10 (mm)	178	175	172	168	163

Compressive strength and modulus of elasticity testing procedures

Compressive strength tests are performed following (ASTM C-39, 2006) **[9]**. Three cylinders of (100 * 200) mm size were tested for each test at two ages: 14 and 28 days. All compressive strength and modulus of elasticity tests were performed by using 2000 kN standard testing machine, and were carried out on the same day. All specimens tested for modulus were first subjected to equal initial loadings pressure in spite of of the compressive strength. Cycles of loading and unloading were repeated two times before start loading the specimen to the preferred load level. As mentioned in the ASTM C-469, 2006 [10], modulus of elasticity tests were loaded to a maximum stress equal to 40% of the maximum compressive strength with a constant loading rate at 0.2–0.24 MPa/s. A computer control program was used to record load and the deflection response for each concrete specimen and then the value of the modulus of elasticity was measured according to ASTM [10].

Results and discussion

The modulus of elasticity is strongly influenced by the concrete materials and their proportions used, it is a function of modulus of elasticity of each component and its content ratio in the composite. An increase in the modulus of elasticity is expected with an increase in compressive strength since the slope of the ascending branch of the stress-strain diagram becomes steeper **(Mahdi, 2009) [11].**

Table (4); and Figures (2) & (3) show the results of compressive strength and static modulus of elasticity for all concrete mixes. It can be observed that the compressive strength and modulus of elasticity increased with time. The percentages of increasing of HPC, HPC-SF, HPC-SF0.5S, HPC-SF1.0S, and HPC-SF2.0S with time are 5.6%, 14.5%, 14.4%, 15.9%, and 13.6% for compressive strength and 3.6%, 5.4%, 5.7%, 7.8%, and 5.5% for modulus of elasticity, respectively. This is referred to the continuous hydration process which increased the dense hydrated calcium silicate in concrete structure.

Compressive strength and modulus of elasticity are increased by using superplasticizer and silica fume as described in Table (4). This is because the elastic behavior of concrete depends on the bond strength, density of the interfacial zone, and densities and void contents of the concrete. Mineral admixtures improved microstructure, reduced thickness of the transition zone, and densified both the paste and interfacial zone due to the fine filler effect (Johnston, 2006)**[12]**.

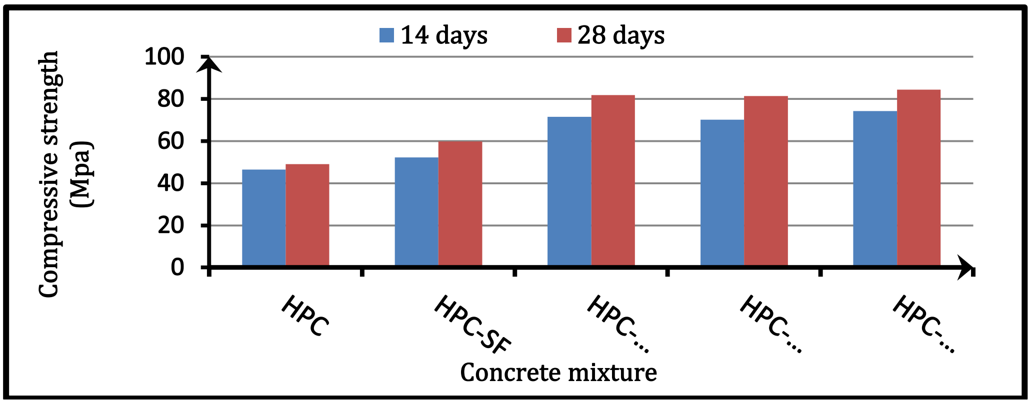

Figure (2): Compressive strength of different types of concrete.

The percentages of increasing of compressive strength at 14 and 28 days are 12.5 %, and 22% and elastic modulus are 11.1%, 13.1%, respectively.

Results in Table (4) show the influence of steel fiber content on the compressive strength and modulus of elasticity. Both compressive strength and modulus of elasticity increased with steel fiber content increased. The percentages of increase of (0.5, 1.0, and 2.0) % fiber content relative to HPC-SF of compressive strength are 37.1%, 34.3%, and 42.1% at 14 days and 36.6%, 35.9%, and 40.9% at 28 days. This ascribed to the enhancement of the cementitious matrix around the steel fiber with time.

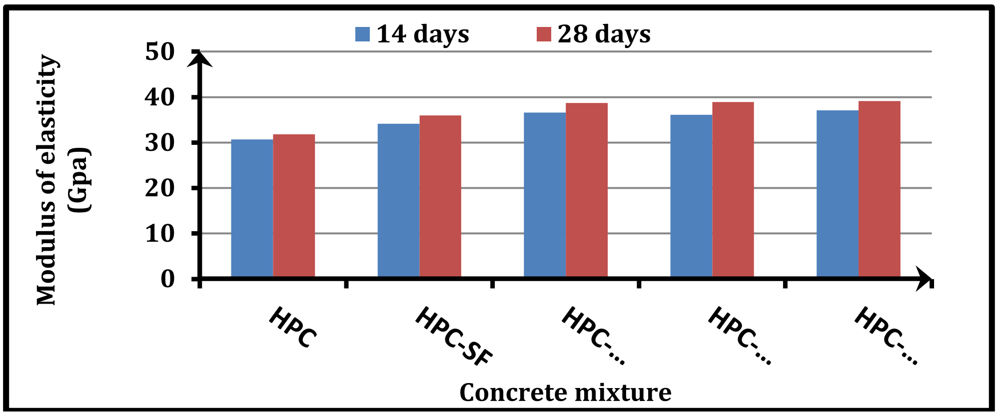

Figure (3): Modulus of elasticity of of different types of concrete.

Table (4): Compressive strength and modulus of elasticity results

Symbol	Compressive strength (MPa)		Modulus of Elasticity (GPa)	
	14 (days)	28 (days)	14 (days)	28 (days)
HPC	46.5	49.1	30.73	31.82
HPC-SF	52.3	59.9	34.13	35.98
HPC-SF0.5S	71.6	81.9	36.63	38.72
HPC-SF1.0S	70.2	81.4	36.09	38.90
HPC-SF2.0S	74.3	84.4	37.08	39.13

Generally, it was found that the increase in compressive strength of high performance steel fiber concrete is ascribed to the capability of steel fibers to delay the unstable development of micro cracks and limit the propagation of these micro cracks. It is interesting to notice that the observed rate of increments in compressive strength were more than the expected values, therefore its be need more investigation for study this behaviour.

At 14 days of curing, the percentages of increasing of (0.5, 1.0, and 2.0) % fiber content relative to HPC-SF of modulus of elasticity are 14%, 12.3%, and15.4%, respectively. At 28 days, the percentages of increasing are 13.9%, 14.5%, and 15.2%, respectively. This is may be depicted to the modulus of elasticity was calculated to the stress corresponding to 40% of the ultimate load, so it is determined prior to concrete cracking; therefore, the fibers were not activated **(Chen, et, al. 2012) [13]**or may be attributed to high stiffness of steel fiber which leads to a higher modulus of elasticity for HSFC**(Dawood, et, al. 2012) [14].**

Relationship between compressive strength and modulus of elasticity

Modulus of elasticity of HPC was calculated using proposed equations by many researchers. Integral Absolute Error(IAE) index has been used by **(Arıoglu, et al., 2006) [15]** to evaluate the goodness of fit of proposed relationships, and it is computed from Equation (1).

$$IAE=\sum\frac{\sqrt{(Oi-Pi)^2}}{\sum Oi}*100 \qquad \ldots(1)$$

Where:

Oi: is the observed value, and
Pi: is the predicted valuefrom the regression equation.

The IAE measures the relativedeviations of data from the regression equation. When theIAE is zero, the predicted values from the regression equationare equal to the observed values; this situation rarely occurs.When comparing different equations, the regression equationhaving the smallest value of the IAE can be judged as themost reliable.

The most widely used and simple empirical relationships between the compressive strength and static modulus of elasticity which were adopted by (ACI 318, 2011)**[16]** and (ACI Committee 363-92, 2007)**[17]** are used to predict the elastic modulus. Table (5) shows the IAE% values which is an indicator of applicability of these equations with the experimental data, it can be noticed that the predicted modulus of elasticity by these two equations have a good agreement with elastic modulus measured values.

Table 5: Calculated integral absolute errors for several relationships (Modulus of elasticity and compressive strength)

Source	Relationship	IAE %				
		HPC	HPC-SF	HPC-SF0.5S	HPC-SF1.0S	HPC-SF2.0S
ACI 318-11 [16]	$E_c=4.7*\sqrt{F_c}$	3.9	1.0	11.1	10.9	11.9
ACI 363R-92 [17]	$E_c=3.32*\sqrt{F_c}+6.9$	4.6	10.6	5.5	5.5	5.3

Conclusion

This study demonstrates the beneficial combined effect of silica fume, and steel fiber on the strength and modulus of elasticity of high performance concrete. Depending up on the experimental results presented in this study, the following conclusions can be drawn:

- Compressive strength and modulus of elasticity are increased by using superplasticizer and silica fume significantly. However, the increasing rate of elastic modulus is less than that of compressive strength.
- Based on the error analysis IAE values, the evaluated elastic modulus of concrete are convergent for all experimental models. The evaluated models which depending on the compressive strength are overestimated the modulus of elasticity of all concretes. The ACI 318 equation seems to provide a better prediction of the elastic modulus of high performance concrete with or without steel fiber, compared with ACI 363, ACI 363 equation, however, seems to predict the elastic modulus of HPC-SF0.5S, HPC-F1.0S, and HPC-SF2.0S in better way compared with ACI 318.

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