Mechanical Properties of High Performance Carbon Fiber Concrete

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Abstract

In this research mechanical properties of high performance carbon fiber concrete are studied. The experimental work includes, producing high performance concrete using superplasticizer and condensed silica fume reinforced with different volume fractions (0%, 0.2%, 0.3%, 0.4% and 0.5%) of carbon fibers. The effect of chopped carbon fibers on the mechanical properties (compressive strength, splitting tensile and flexural strengths, and modulus of elasticity) of high performance concrete was also studied. Generally, the results show that the addition of carbon fibers improves the mechanical properties of high performance concrete. Also the results show that Using condensed silica fume as addition by weight of cement increases the compressive strength more than that as replacement by weight of cement. The percentages increase in compressive strength of concrete containing 15% silica fume as replacement and as addition by weight of cement are about 14% and 26% respectively. The addition of carbon fibers causes a slight increase in compressive strength and modulus of elasticity of high performance concrete when the fiber volume fraction increases, while the splitting tensile and flexural strengths shows a significant increase relative to the reference high performance concrete (without fiber). The percentage increase in splitting tensile and flexural strengths for high performance concrete with fiber volume fraction 0.5% at 28 days is about 45% and 46% respectively.

Keywords: High performance concrete, Carbon fibers, Silica fume, Superplasticizer

الخواص الميكانيكية لخرسانة ألياف الكاربون العالية الاداء

الخلاصة

يشمل البحث دراسة الخواص الميكانيكية لخرسانة ألياف الكاربون عالية الاداء. تضمن البرنامج العملي إنتاج خرسانة عالية الأداء بإستخدام الملدن المتفوق وأبخرة السليكا المكثفة وبنسب حجمية مختلفة (0%, 0.2%, 0.3% ,0.4% 0.5%) من ألياف الكاربون. تم دراسة تأثيرإضافة ألياف الكاربون على الخواص الميكانيكية (مقاومة الانضغاط, مقاومة الشد الانشطاري, مقاومة الانثناء, معامل المرونة) للخرسانة عالية الاداء.

بشكل عام فقد أظهرت النتائج بأن إضافة ألياف الكاربون تحسن الخواص الميكانيكية للخرسانة عالية الأداء. كذلك فإن النتائج بينت بأن إستخدام أبخرة السليكا المكثفة كإضافة من وزن الاسمنت تؤدي الى زيادة مقاومة الانضغاط بمقدار أكبر من إضافة أبخرة السليكا كبديل من وزن الاسمنت. كانت نسبة الزيادة في مقاومة الانضغاط للخرسانة الحاوية على 15% أبخرة السليكا كبديل وكأضافة من وزن الاسمنت بحدود 14% و 26% على التوالي. بينت النتائج إن إضافة ألياف الكاربون تؤدي الى زيادة طفيفة في مقاومة الانضغاط ومعامل المرونة للخرسانة عالية الاداء عند زيادة النسبة الحجمية للالياف في حين تحدث زيادة مؤثرة في مقاومة الشد الانشطاري ومقاومة الانثناء

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بالمقارنة مع الخرسانة عالية الاداء المرجعية (غير الحاوية على الالياف). كانت نسبة الزيادة في مقاومة الشد الانشطاري ومقاومة الانثناء للخرسانة عالية الاداء الحاوية على ألياف الكاربون بنسبة حجمية 0.5% بعمر 28 يوم حوالي 45% و 46% على التوالي.

1-Introduction

High performance concrete (HPC) is considered as a high strength and relatively brittle material, this inverse relation between strength and ductility is a serious drawback in the use of HPC. .A compromise between strength and ductility can be obtained by using discontinuous fibers[1]. Addition of fibers to concrete makes it an isotropic material and converts its brittle behavior to ductile behavior. Steel fibers tend to rust and glass fibers deteriorate in the high alkaline environment of cement. Carbon fibers are inert, medically safe and stronger than steel fibers and more chemically stable than glass fibers in an alkaline environment. Moreover, Carbon fibers are low in density, especially compared to steel fibers; their strength-to-density ratio is one of the highest among all fiber types[2]. Carbon fibers have much higher specific strength and stiffness than metallic fibers and for this reason their use for strengthening and stiffening building materials such as plastics and concrete, are attractive[3]. Little work [4, 5, 6] has been done to investigate the mechanical properties of normal strength carbon fiber concrete and no detailed studies are found on the Properties of high strength carbon fiber concrete.

Chen and Chung [7] reported that the use of chopped carbon fiber with nominal length from 3.0 to 12.7mm With volume fraction 0.189% together with a dispersant, chemical agents and silica fume in normal strength concrete resulted in:

- Flexural strength increase of 85%,
- Flexural toughness increase of 205%,
- Compressive strength increase of 22 %,
- Drying shrinkage decrease by up to 90%,
- Slump decrease from 152mm to 102mm.

They concluded that:

- The minimum carbon fiber fraction for the fibers to be effective for increasing the flexural strength is 0.1 by volume of concrete. Below this fiber volume fraction, the fibers are still effective for increasing the flexural toughness,
- The optimum fiber length is 5.1mm.

Chen and Chung [8] considered the effect of chopped carbon fibers and silica fume on low-drying shrinkage normal strength concrete (with fine and coarse aggregates). Different volume fractions of the carbon fibers and different dosages of the silica fume were used. They concluded that the use of 0.19 vol. % chopped carbon fiber (nominally 5mm length, 10µm diameter) and silica fume (15% by weight of cement) in concrete results in an 84% decrease of drying shrinkage strain and increases the flexural strength, flexural toughness and freeze-thaw durability. They also found that the combined use of fibers and silica fume maintains good compressive strength and good chemical resistance.

Al-Attar [9] studied the microstructure and mechanical properties of lightweight aggregate concrete containing polypropylene and carbon fibers with volume fractions 0.5-3% and 3-4.5% respectively using 8% silica fume and 8% metakaoline as a partial replacement by weight of cement. The results show that the inclusions of silica fume, metakaoline, fibers, enhance the mechanical properties of lightweight concrete at all ages of curing compared with reference lightweight concrete (without fibers, silica fume, metakaoline).

2- Experimental Work

2-1 Materials

2-1-1 Cement

Ordinary Portland local cement from Tasluja factory was used in all mixes throughout this research. The physical and chemical properties of this cement are presented in Tables (1) and (2) respectively. The test results indicate that the cement conforms to the provisions of Iraqi specification No. 5/1984.

2-1-2 Fine Aggregate

Natural sand passed 4.75mm sieve was used in this research. It was brought from Darbandikan region. Its gradation lies in zone (2) which conforms to the requirements of Iraqi specification No. 45/1984 as shown in Table (3) and. The physical and chemical tests of the sand are shown in Table (4). The results of the chemical tests are within the requirements of the Iraqi specification No. 45/1984.

2-1-3 Coarse Aggregate

Normal weight, crushed aggregate of maximum size 12.5mm brought from Tanjaraw region was used. Its grading conformed to the requirements of Iraqi specification No. 45/1984 as shown in Table (5).The physical and chemical tests on crushed aggregate are shown in Table (6). The results indicate that the chemical tests are within the requirements of the Iraqi specification No. 45/1984.

2-1-4 Admixtures

Two types of concrete admixtures were used in this work:

2-1-4-1 Superplasticizer

A high range water reducing admixture (HRWRA) was used to produce the HPC mix. Chemically it is Naphthalene Formaldehyde Sulphonate, and it is known commercially as Sikament-FFN. It was used in its liquid state as a percentage of cement content (by weight). The ACI committe212 instructions [10] were followed to determine the optimum dosage of the admixture. The technical description of this superplasticizer is shown in Table (7) [11].

2-1-4-2 Silica Fume

Condensed silica fume produced by Holcim / U.A.E was used as pozzolanic admixture. The ACI committee 234 instructions [12] were followed to determine the optimum dosage of silica fume. The physical requirement and pozzolanic activity index are given in Table (8), while the chemical oxide compositions of silica fume is given in Table (9). The results show that silica fume used in this investigation conforms to the requirements of ASTM C1240-05 [13] specifications.

2-1-5 Chopped Carbon Fibers

High performance high strength chopped carbon fiber brought form Dacheng Xinhua factory in China as filaments was used in this investigation. Table (10) indicates the mechanical properties of chopped carbon fiber used in this investigation[14].

2-1-6 Mixing Water

Ordinary potable water was used for mixing and curing all concrete mixes in this investigation.

2-2 Concrete Mixes

Reference concrete mix was designed in accordance with ACI 211.1-91 [15] to obtain a minimum cylinder compressive strength of 45 MPa at 28 days without any admixtures, the mix proportions are (1:1.19:1.80) by weight with w/c ratio of 0.40 which produce a slump of 80±5 mm. Several trial mixes were carried out to determine silica fume content and dosage of superplasticizer in order to obtain a mix with cube compressive strength higher than 70 MPa. Finally chopped carbon fiber with different volume fractions (0.2%, 0.3%, 0.4%, and 0.5%) were added to the selected high performance concrete mix. The workability test was carried out for each batch of concrete immediately after mixing; it was measured by slump test and Vebe test method. Slump test is used for non-fibrous concrete mixes, while Vebe test used for carbon fiber reinforced concrete mixes because this test is most suitable for the measurement of fresh concrete with very low workability. The w/c ratio for all concrete mixes was adjusted to maintain almost similar workability of slump 80±5 mm.

2-3 Mixing of Concrete Batches

Mixing was performed by using revolving drum, tilting mixer with capacity of 0.1 m^3. The mechanical mixing procedure for fibrous and non-fibrous concrete was different in sequence of mixing process and mixing time. The procedure of mixing non-fibrous concrete conforms to $ASTM_{C\ 192/C\ 192M-07}$ specifications. Coarse aggregate, some of the mixing water, and the solution of admixture (when required) were placed in the mixer and mixed for about 1 min, after that, fine aggregate, cement, silica fume and the remaining water were loaded to the mixer and mixed for about 3 min followed by 3 min rest to check any unmixed materials, followed by 2 min final mixing. Mixing of carbon fiber concrete raised a number of problems because of the small diameter and short length of the fiber filaments. After the water, aggregate and cement have been fully mixed, fibers were slowly added to the concrete by hand spraying, while the mix was rotating. Mixing was continued for 3 min to encourage a uniform distribution of fibers throughout the concrete.

2-4 Preparation of Specimens

A number of specimens were prepared, cured for different periods (7, 28, 60, and 90 days) then tested to study the effect of using silica fume and different volume fractions of chopped carbon fiber on the mechanical properties (compressive strength, splitting tensile strength, modulus of rupture,and modulus of elasticity) of HPC. Accordingly the details of specimens were as shown below:

1. Compressive strength of concrete (cubes of 100 mm).
2. Splitting tensile strength of concrete (cylinders of 150 x 300 mm).
3. Static modulus of elasticity of concrete (cylinders of 150 x 300mm).
4. Modulus of rupture (prisms of 100 x 100 x 500 mm).

2-5 Curing

After demoulding the specimens curing process was done by completely immersion the specimens in water storage tank until the time of testing. The water temperature was kept (20±2˚C) by providing automatic control thermometer which conforms to ASTM $_{C\ 511\text{-}06}$ specifications.

3- Results and Discussions

3-1 Selection of Mix Proportions for HPC:

The results of designed reference concrete mix with mix proportions 1:1.19:1.80 by weight with w/c=0.4 containing different dosages of superplasticizer are shown in Table (11) and Figures (1) and (2). The water/cement ratio was adjusted to obtain the same workability of reference mix (80±5 mm). Results indicate that the superplasticizer leads to a considerable improvement in early and later compressive strength and allows a reduction in water/cement ratio relative to the reference mix. This may be attributed to the mode of action of the superplasticizer whose long molecules warp themselves around the cement particles giving them a negative charge, so they repel each other resulting in deflocculating and dispersion of cement particles. Thereby greatly enhancing the fluidity of the system and consequently lowering the amount of water required to obtain a certain consistency and thus increasing the compressive strength [16, 17]. Figure (1) shows that the maximum water reduction is 25% attained at dosage of 3% and 4% by weight of cement, while Figure (2) indicates that the compressive strength at 28 days reaches its maximum value when the dosage of HRWRA is 4%. There is a slight difference between the compressive strength of concrete mixes containing 3% and 4% by weight of cement HRWRA (about 1 MPa), so for economical purpose the selected optimum dosage of HRWRA is 3% by weight of cement.

Table (12) and Figure (3) show the details of concrete mixes (1:1.19:1.80 with HRWRA 3% by weight of cement) that contain different dosages of silica fume as partial replacement by weight of cement. It can be noted that the compressive strength is continuously increases as the dosage of silica fume increases; the optimum dosage of silica fume that can be replaced partially by weight of cement is 15%, which produces a compressive strength of about 84 MPa at 28 days. This dosage causes an increase in compressive strength of about 14% in comparison to concrete mix not containing silica fume. This increase in compressive strength is due to the formation of additional calcium silicate hydrate (CSH) binder, through the reaction of the silica fume (SiO_2) with the free lime $Ca(OH)_2$ preset in the cement[16,18,19]. The results of concrete mixes (1:1.19:1.80 by weight with HRWRA 3% by weight of cement) containing different dosages of silica fume as addition by weight of cement are shown in Table (13) and Figure (4). It is clear that the compressive strength is continuously increases as the dosage of silica fume increases. The results also show that the optimum dosage of silica fume that can be added by weight of cement is 15% to obtain maximum compressive strength of about 93 MPa at 28 days. The percentage increase in compressive strength is about 26% relative to the reference mix (not containing silica fume). It can be concluded that the optimum dosage of silica fume is 15% as addition by weight of cement. The addition of carbon fiber causes a great reduction in the workability of concrete mix, the reduction in workability increases with the increase of fiber volume fraction. This may be due to the very small diameter of carbon fibers. So the selected mix (1:1.19:1.80 by weight, w/c=0.29, HRWRA 3% by weight of cement and SF 15% as addition by weight of cement) was modified by increasing the water/cement ratio from 0.29 to 0.33 to have a suitable workability after the addition of fibers. The compressive strength for this mix is 78.8 MPa.

3-2 Mechanical Properties of High Performance Carbon Fiber Concrete

3-2-1 Compressive Strength

The compressive strength test results for the selected HPC mix (1:1.19:1.80 by weight, w/c=0.33, HRWRA 3% by weight of cement and SF 15% as addition by weight of cement) with different carbon fiber volume fractions at various ages are presented in Table (14) and Figure (5). Generally the results illustrate that there is a slight increase in the compressive strength with the increase in fiber volume fraction for all ages. The percentage increase in compressive strength for concrete with fiber volume fractions 0.2, 0.3, 0.4 and 0.5 at age 28 days are 2.4, 2.2, 4.3 and 5.9 respectively.

Table (14) and Figure (6) show that the compressive strength increases with age.

3-2-2 Splitting Tensile Strength

Table (15) and Figure (7) show the splitting tensile strength results of high performance carbon fiber concrete containing different fiber volume fractions at various ages. Generally it can be observed that the addition of carbon fibers cause a significant increase in the splitting tensile strength relative to the reference specimen (without fiber). The percentage increase is about 45% for concrete with fiber volume fraction 0.5% at age of 28 days. It can also be seen that the splitting tensile strength increases as the fiber volume fraction increases for all ages. From Table (15) and Figure (8) it can be noted that the splitting tensile strength increases with age, especially for concrete with fiber volume fraction 0.5%.

3-2-3 Flexural Strength (Modulus of Rapture)

Flexural strength test results of high performance carbon fiber concrete with different fiber volume fractions and various ages are presented in Table (16) and Figures (9) and (10). The results demonstrate that using carbon fiber causes a considerable increase in flexural strength in comparison with the plain concrete and the flexural strength increases with the increase in fiber volume fraction. The increase in flexural strength for concrete specimen with fiber volume fraction 0.5% is about 72% at the age of 90 days relative to the plain concrete.

Generally it can be seen that the flexural strength of carbon fiber concrete increases with age for all mixes with various fiber volume fraction. It can be noticed from the experimental test that plain concrete specimen (without fiber) suddenly failed in a brittle manner and separated into two parts, while fiber concrete specimen have many cracks before the failure. This is attributed to the role of the action of fibers in matrix in which arresting both the initiation of randomly oriented micro-cracks and its propagation, lead to improving the strength and ductility [20, 21].

3-2-4 Static Modulus of Elasticity

Table (17) shows the results of the static modulus of elasticity for the selected HPC without fibers and concrete containing different amount of fibers. The results show that the modulus of elasticity increases with the increase of fiber volume fraction. This may be due to a considerable improvement in the fiber-matrix bond [20]. The increase in modulus of elasticity due to the addition of carbon fibers with volume fractions 0.2, 0.3, 0.4 and 0.5 is 3.6, 4.95, 5.2 and 6.04 respectively.

Table (17) also shows the estimated modulus of elasticity for plain high performance concrete according to **ACI 318M-08** [22] {equation (1)} and for fiber reinforced high performance concrete (f'c ≤ 85MPa) according to **Thomas and Ramaswamy**[21] {equation (2)}.

$$E_c = 4.7\,(f'_c)^{0.5} \qquad ....(1)$$

Where:

E_c = Modulus of elasticity, (GPa).

f'_c = Compressive strength, (MPa).

$$E_{cf} = 4.58(f'_c)^{0.5} + 0.00042(f'_c)RI + 0.39RI \qquad ………..\ (2)$$

Where:

E_{cf} = Modulus of elasticity of fiber reinforced concrete, (GPa).

$f'c$ = Compressive strength of concrete, (MPa).

RI =Reinforced index of fiber ($V_f L_f/\varphi_f$).
V_f = Volume fraction of the fiber.
L_f = length of the fiber.
φ_f = diameter of the fiber.

From the comparison between the tested results and the predicted modulus of elasticity, it can be concluded that the **ACI 318M-08**[22] when extrapolated for plain high performance concrete (without fiber), gives overestimation for the modulus of elasticity. The modulus of elasticity reported by **Thomas and Ramaswamy**[21]for fiber reinforced high strength concrete has slightly higher values in comparison with the test results of high strength carbon fiber concrete.

4- Conclusions

From the experimental results, the following conclusions can be drawn:

1. Using silica fume as addition by weight of cement increases the compressive strength more than that as replacement by weight of cement. The percentages increase in compressive strength of concrete containing 15% silica fume as replacement and as addition by weight of cement are about 14% and 26% respectively.
2. The addition of carbon fiber causes a great reduction in the workability of concrete mix, the reduction in workability increases with the increase of fiber volume fraction. The percentage of reduction in workability is about 68% when volume fraction is 0.5%.
3. The addition of carbon fibers causes a slight increase in compressive strength of high performance concrete when the fiber volume fraction increases, while the splitting tensile and flexural strengths shows a significant increase relative to the reference high performance concrete (without fiber). The percentage increase in compressive, splitting tensile and flexural strengths for high performance concrete with fiber volume fraction 0.5% at 28 days is about 5%, 45% and 46% respectively.
4. The modulus of elasticity increases with the increase of fiber volume fraction. The percentage increase in modulus of elasticity due to the addition of carbon fibers with volume fractions 0.2%, 0.3%, 0.4% and 0.5% is 3.6%, 4.95%, 5.2% and 6.04% respectively.

5- References

[1]Akar, A. M, “**Bending Properties of High Strength Carbon Fiber Reinforced Concrete Beams”,** M.Sc. Thesis, University of Sulaimani, Sulaimani, Iraq, Feb.2009.

[2] Zheng, Q. and Chung, D. D. L., **“Carbon Fiber Reinforced Cement Composites Improved by Using Chemical Agents”**, Cement and Concrete Research, Vol. 19, 1989, PP. 25-41.

[3] Raouf, Z. A., **“Dynamic Mechanical Properties of Fiber-Reinforced Cement Composites”**, Ph. D. Thesis, University of Manchester, May, 1975.

[4] Chung, D. D. L., **“Carbon Fiber Cement-Matrix Composites”**,

Composite, No. 190, 1999, PP. 300-311.

[5] Chung, D. D. L., **"Cement Reinforced with Short Carbon Fibers: Multifunctional Materials"**, Composites Part B: Engineering, Vol. 31, 2000, PP. 511-526.

[6] Cao, J. and Chung, D. D. L., **"Carbon Fiber Reinforced Cement Mortar Improved by Using Acrylic Dispersion as an Admixture"**, Cement and Concrete Research, Vol. 31, 2001, PP. 1633-1637.

[7] Chen, P. W and Chung, D. D. L., **"Cement Reinforced with Up to 0.2 vol. % of Short Carbon Fibers"**, Composites, Vol. 24, No. 1, 1995, PP. 33-52.

[8] Chen, P. W. and Chung, D. D. L.,**"Low-Drying-Shrinkage Concrete Containing Carbon Fiber"**, Composites, Part B 27B, 1996, PP. 269-274.

[9] Al-Attar, A. A., "**Microstructure and Mechanical Properties of Lightweight Aggregate Concrete Containing Fibers**", Ph.D. Thesis, University of Technology, Baghdad, Iraq, August, 2006.

[10] ACI Committee 212 (ACI-2R-81), **"Guide for Use of Admixture in Concrete"**, ACI Manual of Concrete Practice, Part 1, 1990.

[11] Sika, S.A.L., **"Sika Data Book"**, Edition 2003-2004.

[12] ACI Committee 234 (ACI-234R-96), **"Guide for Use of Silica Fume in Concrete"**, ACI Manual of Concrete Practice, Part 1, 1996.

[13] ASTM $_{C\ 1240\text{-}05}$, **"Standard Specification Silica Fume Used in Cementitious Mixtures"**, Manual of A04-02, October, 2007.

[14] Dacheng Xinhua Factory, **"Technical data Sheet catalogue"**, January, 2008, PP. 1084.

[15] ACI 211-1-91, **"Standard Practice for Selecting Proportions for Normal, Heavy Weight, and Mass Concrete"**, ACI Manual of Concrete Practice, Part 1, Materials and General Properties of Concrete, PP. 38.

[16] Caldarone M. A., **"High-Strength Concrete: Practical Guide"**, First Published 2009 in the USA & Canda, 2009, PP. 63-67.

[17] Khalil, W. I, **"Properties of High Performance Lightweight Concrete Sandwich Panels Using Local additives"**, PH.D. Thesis, Building and Construction Engineering Department, University of Technology, Baghdad, Iraq, August, 2006.

[18] Mazloom, M., Ramezanianpour, J. J. and Brooks, J. J. **"Effect of Silica Fume on Mechanical Properties of High-Strength Concrete"**, Cement and Concrete Composites, Vol.26, 2004, PP.347-357.

[19] Bhanja, S. and Sengupta, B. **"Influence of Silica Fume on the Tensile Strength of Concrete"**, Cement and Concrete

Research, Vol.35, 2005, PP.743-747.

[20] Johnston, C. D., **“Fiber-Reinforced Cement and Concrete”**, Advance in Concrete technology, Vol. 3, 2006, PP. 185-187.

[21] Thomas J. and Ramaswamy A. **“Mechanical properties of Steel fiber-Reinforced Concrete”**, Journal of Materials in Civil Engineering (ASCE), Vol. 19, No. 5, May 1, 2007, PP. 385-392.

[22] ACI 318M-08 **“Building Code Requirements for Structural Concrete (ACI 318M-08) and Commentary”**, An ACI Standard, Reported By ACI Committee 318, 2008.

Table (1) Physical properties of cement

Physical properties		Test results	Limit of Iraqi Specification No. 5/1984	
			Minimum	Maximum
Compressive Strength	3 days (MPa)	31.1	15 MPa	
	7 days (MPa)	38.0	23 MPa	
Setting Time, Vicat's method	Initial Time, hr:min	2:25	00:45	
	Final Time, hr:min	3:15		10:00
Soundness, Le-chatielier method, mm		2.0		10
Specific surface area, blaine method, m^2/kg		290.5	230	

Table (2) Chemical composition and main compounds of cement used in this investigation*

Oxides Composition	Chemical Symbol	Content	Limit of Iraqi Specification No. 5/1984	
			Minimum	Maximum
Calcium Oxide	CaO	62.96%		
Silicon Dioxide	SiO_2	21.10%		
Aluminum Trioxide	Al_2O_3	5.12%		
Ferric Oxide	Fe_2O_3	3.15%		
Potassium Oxide	K_2O	0.68%		
Sodium Oxide	Na_2O	0.14%		
Magnesium Oxide	MgO	2.24%		5.0 %
Sulphate	SO_3	2.30%		2.8 %
Loss of Ignition	L.O. I	2.42%		4.0 %
Insoluble Residue	I. R	1.03%		1.5 %
Lime Saturation Factor	LSF	91.34	66	102
Free Lime	FL	1.13		
Silica Ratio	SM	2.55		
Alumina Ratio	AM	1.63		
Main Compounds (Bogues Equation)				
Tricalcium Silicate	C_3S	50.43 %		
Dicalcium Silicate	C_2S	22.45 %		
Tricalcium Aluminates	C_3A	8.24 %	> 5%	
Tetra calcium Aluminoferrate	C_4AF	9.58 %		

* Chemical test was carried out by the Quality Control Department for the United Cement Co., Sulaimaniayh-Iraq.

Table (3) Grading of fine aggregate

Sieve size (mm)	Passing %	Limit of Iraqi specification No. 45/1984. Zone (2)
4.75	100.0	90-100
2.36	91.0	75-100
1.18	79.3	55-90
0.60	52.6	35-59
0.30	19.3	8-30
0.15	3.0	0-10

Fineness Modulus: 2.55

Table (4) Physical and chemical properties of fine aggregate

Properties	Test done according to specification of:	Test results	Limit
Apparent specific gravity	ASTM $_{C\ 128\text{-}07a}$	2.63	
Saturated and surface dry specific gravity	ASTM $_{C\ 128\text{-}07a}$	2.56	
Absorption, %	ASTM $_{C\ 128\text{-}07a}$	1.70	
Dry rodded bulk density, kg/M^3	ASTM $_{C\ 29\ C\ 29M\text{-}03}$	1,690	
Void ratio, %	ASTM $_{C\ 29/C\ 29M\text{-}03}$	34	
Materials finer than 75 µm, %	ASTM $_{C\ 117\text{-}04}$	1.70	≤ 5.0
Sulfate content (SO_3), %	(I.O.S.) N0. 45-84	0.028	≤ 0.5

Table (5) Grading of coarse aggregate

Sieve size (mm)	% Passing	Limit of Iraqi specification No. 45/1984
12.50	100.0	95-100
9.50	94.0	85-100
4.75	23.0	0-25
2.63	2.6	0-5

Table (6) Physical and chemical properties of coarse aggregate*

Properties	Test done according to specification of:	Test results	Limit
Apparent specific gravity	ASTM $_{C\ 127\text{-}07}$	2.64	
Saturated and surface dry specificgravity	ASTM $_{C\ 127\text{-}07}$	2.61	
Absorption, %	ASTM $_{C\ 127\text{-}07}$	0.75	
Dry rodded bulk density, kg/m^3	ASTM $_{C\ 29/C\ 29M\text{-}03}$	1,600	
Void ratio, %	ASTM $_{C\ 29/C\ 29M\text{-}03}$	38.7	
Sulfate content (SO_3), %	(I.O.S.) N0. 45-84	0.01	≤ 0.1

*Chemical test was carried out by the Chemical Testing Department for Sulaimaniayh Building Laboratory, Sulaimaniayh-Iraq.

Table (7) Technicsal data of superplasticizer used in this investigation

Data	Description
Form state	Viscous liquid
Color	Brown
Density	1.21 gm/cm^3
Recommended Dosage	0.6%-3.0% by weight of cement

Table (8) Physical requirements and pozzolanic activity index for condensed silica fume*

Parameter	Results	ASTM $_{C\ 1240\text{-}05}$ Specification Minimum	Maximum
Accelerated Pozzolanic Activity (7 day).	115	105.0	
Oversize on 45 μmm. %	0.77		10.0
Specific Density, kg/m^3	1780		
Loose Bulk Density, kg/m^3	638.20		
Specific Surface Area, m^2/gm	23.80		

* Physical test and activity index were carried out by the Arab Center for Engineering Studies (ACES). Dubai-U.A.E.

Table (9) Chemical compositions for condensed silica fume*

Parameter	Result	ASTM $_{C\ 1240\text{-}05}$ Specification Minimum	Maximum
SiO_2, %	91.00	85.0	
Moisture Content, %	1.00		3.0
LOI (includes Carbon), %	2.90		6.0
Alkalis like Na_2O, %	0.70		
AL_2O_3, %	1.60		
Fe_2O_3, %	1.30		
CaO, %	0.10		
MgO, %	1.00		
SO_3, %	0.50		

* Chemical test was carried out by the Arab Center for Engineering Studies (ACES). Dubai-U.A.E.

Table (10) Mechanical properties for chopped carbon fibers

Properties	Results
Fiber Type	Carbon
Filament diameter, μmm	7
Filament length, mm	5-6
Specific gravity,	1.8
Elongation, %	1.5
Tensile strength, MPa	3450
Tensile modulus of elasticity, GPa	230
Electrical resistivity, Ω.cm	3×10^{-3}
Carbon content, %	98

Table (11) Details of trail mixes for various dosages of HRWRA

Mix proportions by weight	Mix Symbol	W/C ratio	HRWRA % by weight of cement	Slump (mm)	Water reduction (%)	Compressive Strength (MPa)		Increase in strength with respect to reference mix (M_{H0}) (%)	
						7 days	28 days	7 days	28 days
1:1.19:1.80	M_{H0}	0.40	0	85	0	42.2	48.2		
	M_{H1}	0.35	1	80	12.5	49.5	58.1	17.3	20.5
	M_{H2}	0.32	2	75	20.0	59.6	69.8	41.2	44.8
	M_{H3}	0.30	3	75	25.0	64.2	73.9	52.1	53.3
	M_{H4}	0.30	4	75	25.0	65.9	75.3	56.2	56.2

Table (12) Details of trail mixes for various dosages of silica fume (SF) as partial replacement by weight of cement

Mix proportions by weight	Mix Symbol	W/C ratio	HRWRA (% by weight of cement)	SF (% as a replacement by weight of cement)	Slump (mm)	Compressive Strength (MPa)		Increase in strength with respect to Mix ($M_{H3-RSF0}$) (%)	
						7 days	28 days	7 days	28 days
1:1.19:1.80	$M_{H3-RSF0}$	0.30	3	0	75	64.2	73.9		
	$M_{H3-RSF7}$	0.30	3	7	85	71.3	78.4	11.1	6.1
	$M_{H3-RSF10}$	0.29	3	10	80	77.6	83.8	20.9	13.4
	$M_{H3-RSF12}$	0.29	3	12	85	74.3	81.7	15.7	10.6
	$M_{H3-RSF15}$	0.29	3	15	75	74.0	84.4	15.3	14.2

Table (13) Details of trail mixes for various dosages of silica fume as addition by weight of cement

Mix proportions by weight	Mix Symbol	W/C ratio	HRWRA (% by weight of cement)	SF (%as addition of by weight cement)	Slump (mm)	Compressive Strength (MPa)		Increase in strength with respect to Mix ($M_{H3-ASF0}$) (%)	
						7 days	28 days	7 days	28 days
1:1.19:1.80	$M_{H3-ASF0}$	0.30	3	0	75	64.2	73.9		
	$M_{H3-ASF7}$	0.30	3	7	85	66.2	80.1	3.1	8.4
	$M_{H3-ASF10}$	0.29	3	10	85	71.1	85.3	10.7	15.4
	$M_{H3-ASF12}$	0.29	3	12	80	72.7	81.3	13.2	10.0
	$M_{H3-ASF15}$	0.29	3	15	80	75.4	93.3	17.4	26.3

Table (14) Compressive strength test results for high performance carbon fiber concrete used throughout the investigation

Mix symbol	Fiber volume fraction (%)	Compressive strength (MPa)				Percentage increase in strength relative to\ $M_{H3-ASF15-CF0.0}$ (%)				slump mm	V.B factor
		7 days	28 days	60 days	90 days	7 days	28 days	60 days	90 days		
$M_{H3-ASF15-F0.0}$	0.0	64.6	78.8	80.9	81.5					160	
$M_{H3-ASF15-F0.2}$	0.2	65.6	80.0	81.5	82.2	1.5	2.4	0.7	0.9	110	2.5
$M_{H3-ASF15-F0.3}$	0.3	66.5	80.5	81.7	82.9	2.3	2.2	1.0	1.7	95	2.5
$M_{H3-ASF15-F0.4}$	0.4	67.4	82.2	82.8	83.3	4.3	4.3	2.3	2.2	80	2.6
$M_{H3-ASF15-F0.5}$	0.5	71.1	83.5	83.9	85.6	7.0	5.9	3.7	3.8	65	2.7

Table (15) Splitting tensile strength test results for high performance carbon fiber concrete used throughout the investigation

Mix symbol	Fiber volume fraction (%)	Splitting tensile strength (Mpa)				Percentage increase in strength relative to $M_{H3-ASF15-CF0.0}$ (%)			
		7 days	28 days	60 days	90 days	7 days	28 days	60 days	90 days
$M_{H3-ASF15-CF0.0}$	0.0	3.9	4.1	4.2	4.5				
$M_{H3-ASF15-CF0.2}$	0.2	4.8	5.2	5.4	5.6	23.1	26.8	28.6	23.7
$M_{H3-ASF15-CF0.3}$	0.3	5.0	5.2	5.4	5.7	28.2	26.8	28.6	25.0
$M_{H3-ASF15-CF0.4}$	0.4	5.1	5.4	5.8	5.9	30.8	31.7	38.1	30.3
$M_{H3-ASF15-CF0.5}$	0.5	5.5	5.9	6.2	6.8	41.5	44.9	48.2	51.1

Table (16) Flexural strength test results for high performance carbon fiber concrete used throughout the investigation

Mix symbol	Fiber volume fraction (%)	Flexural strength (MPa)				Percentage increase in strength relative to $M_{H3-ASF15-CF0.0}$ (%)			
		7 days	28 days	60 days	90 days	7 days	28 days	60 days	90 days
$M_{H3-ASF15-CF0.0}$	0.0	6.1	7.4	7.6	7.9				
$M_{H3-ASF15-CF0.2}$	0.2	7.4	10.1	10.6	11.1	21.1	36.3	32.9	41.2
$M_{H3-ASF15-CF0.3}$	0.3	7.3	10.4	11.0	11.5	20.2	40.7	44.7	46.3
$M_{H3-ASF15-CF0.4}$	0.4	8.1	11.3	12.1	12.5	33.3	52.5	59.2	59.1
$M_{H3-ASF15-CF0.5}$	0.5	7.8	10.8	12.9	13.5	28.4	45.7	69.7	71.8

Table (17) Details of the measured and estimated static modulus of elasticity

Fiber volume fraction (%)	Experimental Modulus of elasticity (GPa)	Estimated Modulus of elasticity (GPa)	
		Plain concrete ACI 318M-08	Fibrous concrete Thomas and Ramaswamy [20].
0	36.2	39.7	
0.2	37.1		38.1
0.3	37.6		38.5
0.4	38.6		39.3
0.5	39.0		39.6

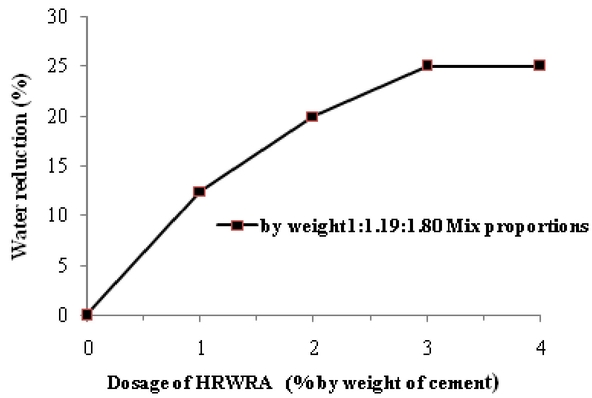

Figure (1) Relationship between the dosage of HRWRA and the water reduction of concrete mix

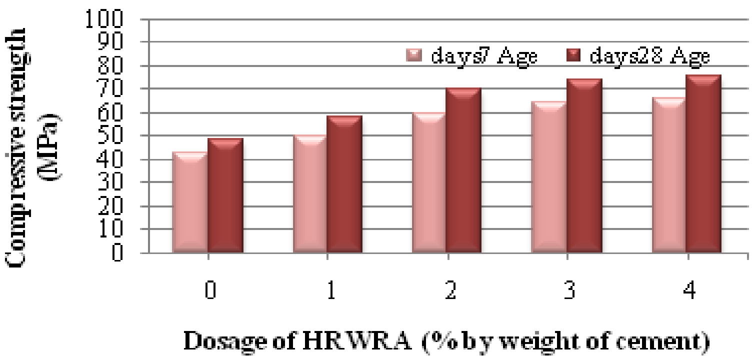

Figure (2) Effect of dosage of HRWRA on compressive strength of concrete mix

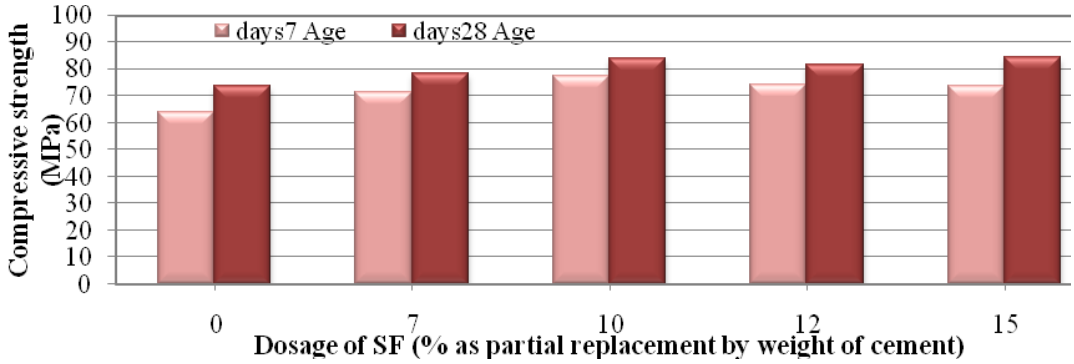

Figure (3) Effect of dosage of silica fume as partial replacement by weight of cement on compressive strength of concrete mix *

***(Mix proportion 1:1.19:1.80 by weight, HRWRA 3% by weight of cement).**

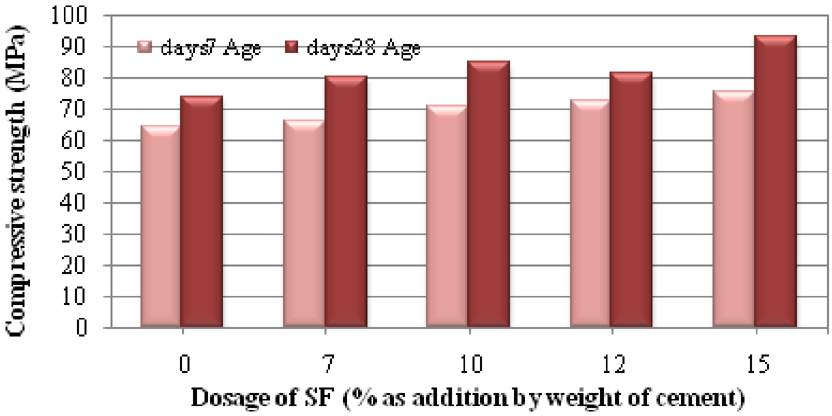

Figure (4) Effect of dosage of silica fume as addition by weight of cement on compressive strength of concrete mix *

***(Mix proportion 1:1.19:1.80 by weight, HRWRA 3% by weight of cement).**

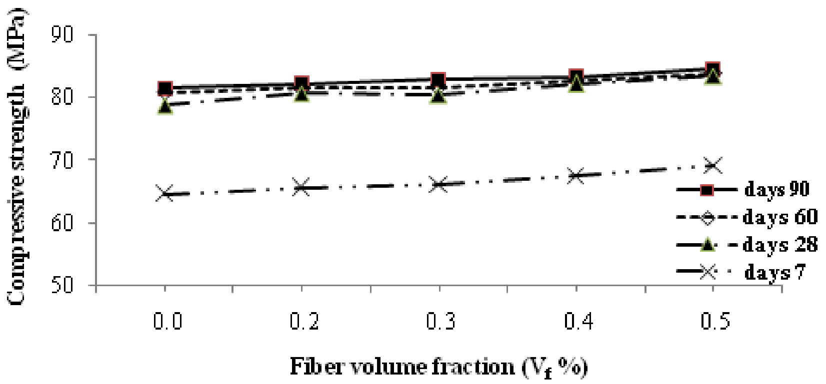

Figure (5) Relationship between the fiber volume fraction and the compressive strength of high performance carbon fiber concrete.

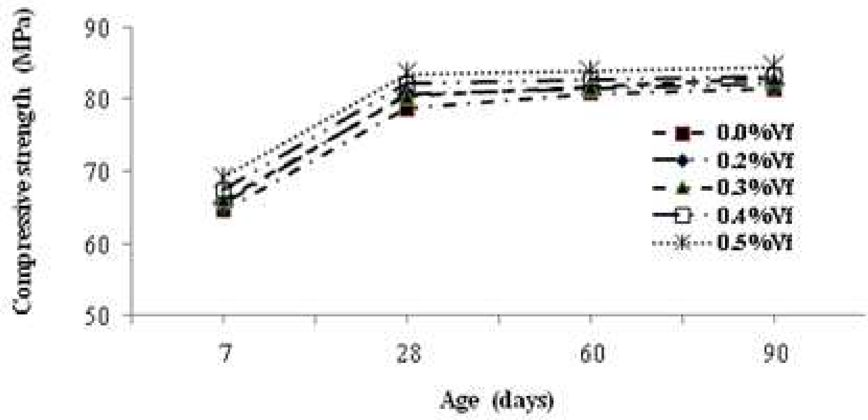

Figure (6) Relationship between the age and the compressive strength of high performance carbon fiber concrete.

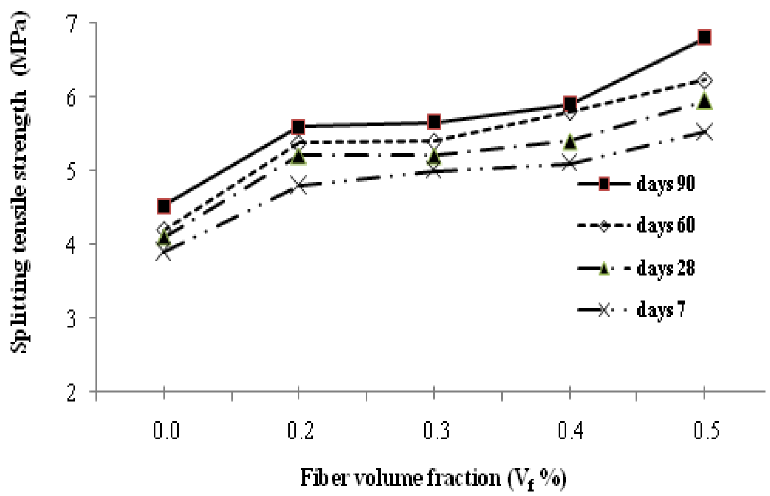

Figure (7) Relationship between the fiber volume fraction and the splitting tensile strength of high performance carbon fiber concrete.

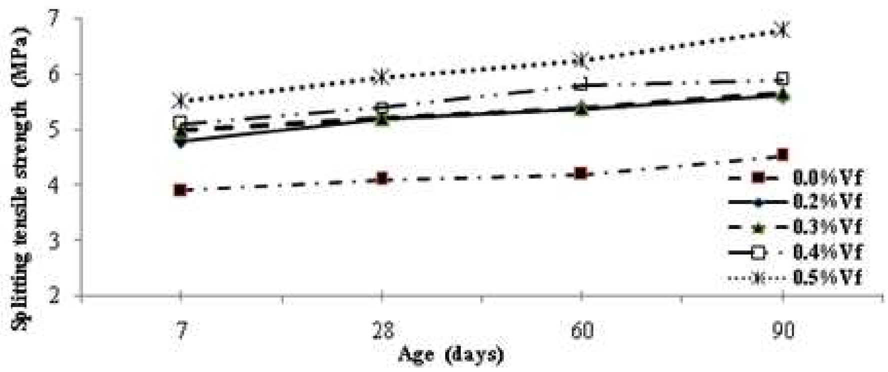

Figure (8) Relationship between the age and splitting tensile strength of high performance carbon fiber concrete.

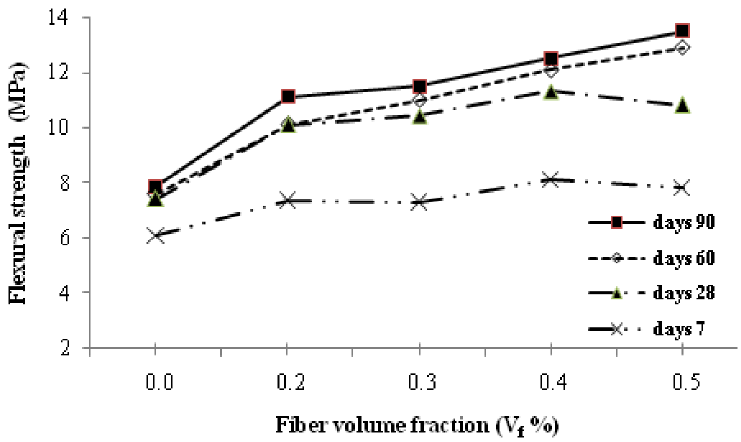

Figure (9) Relationship between the fiber volume fraction and the flexural strength of high performance carbon fiber concrete

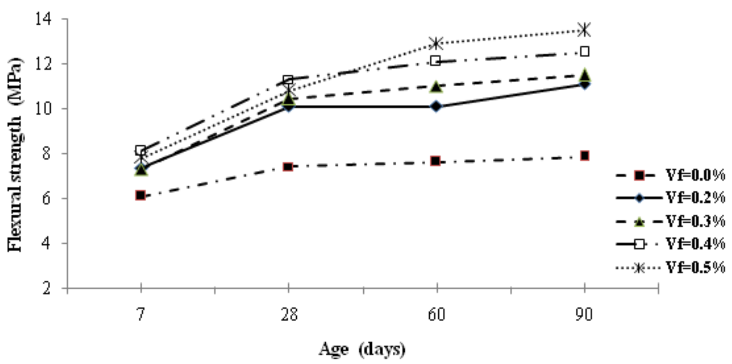

Figure (10) Relationship between the age and the flexural strength of high performance carbon fiber concrete.