International Journal of Civil
Engineering (IJCE)
ISSN 2278-9987
Vol.2, Issue 1 Feb 2013 1-12

International Academy of Science, Engineering and Technology
Connecting Researchers; Nurturing Innovations

MECHANICAL PROPERTIES OF HIGH STRENGTH CONCRETE (HSC) WITH AND WITHOUT CHOPPED CARBON FIBER (CCF)

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ABSTRACT

In this investigation the mechanical properties of high strength carbon fiber concrete are studied. For this purpose number of high strength concrete samples with compressive strengths ranged from 60 MPa to 100 MPa with different volume fractions (0%, 0.25% and 0.50%) of chopped carbon fibers were tested, for studying the effect of the chopped carbon fibers on the mechanical properties (compressive strength, splitting tensile strength, flexural strengths and modulus of elasticity) of the high strength concretes. The analysis of test results showed that the compressive strength slightly increases with increasing of volume fraction of CCF while the splitting tensile strength, flexural strengths and modulus of elasticity were significantly increased with increasing in the volume of fraction of the chopped carbon fiber.

KEYWORDS: High Strength Concrete (HSC), Chopped Carbon Fiber (CCF), Volume of fraction (Vf), Super Plasticizer, Silica Fume

INTRODUCTION

HSC is considered as a relatively brittle material and the post-peak portion of its stress-strain diagram almost vanishes and descends steeply with the increase in compressive strength. This inverse relation between strength and ductility is a serious drawback in the use of high strength concrete, a compromise between strength and ductility can be obtained by using discontinuous fibers. Addition of fibers to concrete makes it a homogeneous and isotropic materials and converts brittleness into a ductile behavior. When concrete cracks, the randomly oriented fibers start functioning, arresting both the randomly oriented micro-cracking and its propagation and thus improving strength and ductility [1].

ACI committee 363[2] defined high strength concrete (HSC) as a concrete having cylinder compressive strength exceeding 41 MPa and it excludes concrete made using exotic materials or exotic techniques. High performance concrete (HPC) is defined as any concrete which satisfies certain criteria proposed to overcome limitations of conventional concrete, so high strength concrete (HSC) is one type of (HPC) [3].

For many years, concrete with compressive strength in excess of 6000 psi (41 MPa) was available at only a few locations. However, in recent years, the applications of high-strength concrete have increased, and high-strength concrete has now been used in many parts of the world. The growth has been possible as a result of recent developments in material technology and a demand for higher-strength concrete [2].

The compressive strength curves illustrate important differences compared with normal strength concrete, including higher elastic modulus and an extended range of linear elastic response: disadvantages include brittle behavior and somewhat reduced ultimate strain capacity [4].

Previous research findings clearly establish that ductility of concrete structural members can be greatly enhanced with the use of fibers. In addition, fibers generally give favor improvements in first crack, ultimate member strength, impact resistance and shear resistance. If property designed, fibers can be added to structural member especially when used together with conventional steel main reinforcements (rebar) [5].

Carbon fiber has gained more popularity in structural materials due to their high strength, additional properties imbued by carbon fiber, particularly electrical properties, have gained attention for their possible applications to structural sensing and electrical actuation [6].

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 [7]. 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 [4].

Carbon fiber cement-matrix composites are structural materials that are gaining in importance quite rapidly due to the decrease in carbon fiber cost and the increasing demand of superior structural and functional properties. The improved structural properties rendered by carbon fiber addition pertain to the increased tensile and flexural strengths, the increased tensile ductility and flexural toughness, the enhanced impact resistance, the reduced drying shrinkage and the improved freeze-thaw durability [8].

EXPERIMENTAL WORK

Materials

The following materials were used for producing concrete mixes:

1. Ordinary Portland Cement (OPC -I 42.5 R), according to ASTM C150 [9].
2. Silica Fume (CSF-90), according to ASTM C1240 [10].
3. Normal Fluvial Sand, according to ASTM C33 [11].
4. Coarse aggregate (Gravel), crushed gravel with maximum size of 9.5mm, according to ASTM C33
5. Super plasticizer- Glenium ACE 30
6. water, normal drinking water
7. Chopped carbon fiber, with: *l*=20 mm, Ø =7-8 µm, fu = 2.84 GPa & E=235 GPa.

PROPERTIES OF HSC

Compressive Strength (*f´c*)

Twenty six trial mixes were done to get different classes of strengths with and without chopped carbon fiber. For each concrete mix, six 150 mm³ cubes were cast; two of them were tested at age of 7, 28 and 56 days. The cubes were subjected to standard curing regime at 20° C, and then normally cured in the laboratory temperature and humidity until 28 days. The marked mix proportions from Table 1 and were selected to obtain required different concrete compressive strength and compositions for series of remained tests in the planed schedule; the amounts of materials required for (1 m^3) of concrete in each mix, are listed in Table 2.

For determining the HSC compressive strength 150 mm³ cubes were used according to BS 1881[12], for the relation between cubes and cylinder's compressive strength equation 1 was used.

$$\frac{\text{Cylinder Strength}}{\text{Cube Strength}} = 0.76 + 0.2 \log_{10} \frac{f_{cu}}{2840} \qquad \text{------ } 1[13]$$

Table 3 is showing the results of trial mixes compressive strength of high strength concretes with and without chopped carbon fiber. The compressive strength test results for the selected high strength concrete mixes with and without different carbon fiber volume fractions are presented in Table 4, and Figure (1). Generally the results illustrate that there is a slight increase in the compressive strength with the increase in fiber volume fraction.

Increasing the CCF fiber volume fractions from 0% to 0.25% tends to increase the concrete compressive strength at age 56 days by 1.60%, 1.98%, and 2.65% for concrete compressive strengths 60 MPa, 80 MPa and 100 MPa respectively, while increasing the CCF fiber volume fractions from 0% to 0.50% tends to increase the concrete compressive strength at age 56 days by 2.11%, 2.55%, and 2.93% for concrete compressive strengths 60 MPa, 80 MPa and 100 MPa respectively

Fig.2 show that the compressive strength increases with age, the rate of increase is rapid at early ages (7 days), while there is a slight increase at 28 and 56days for all fiber volume fractions.

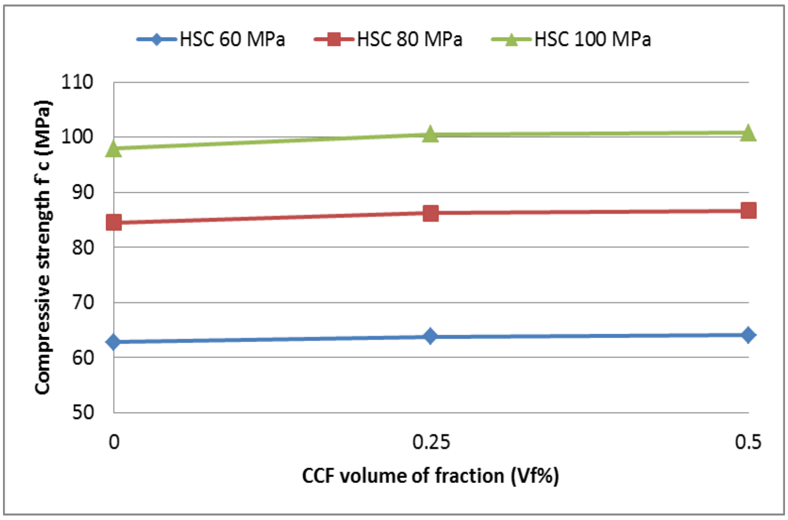
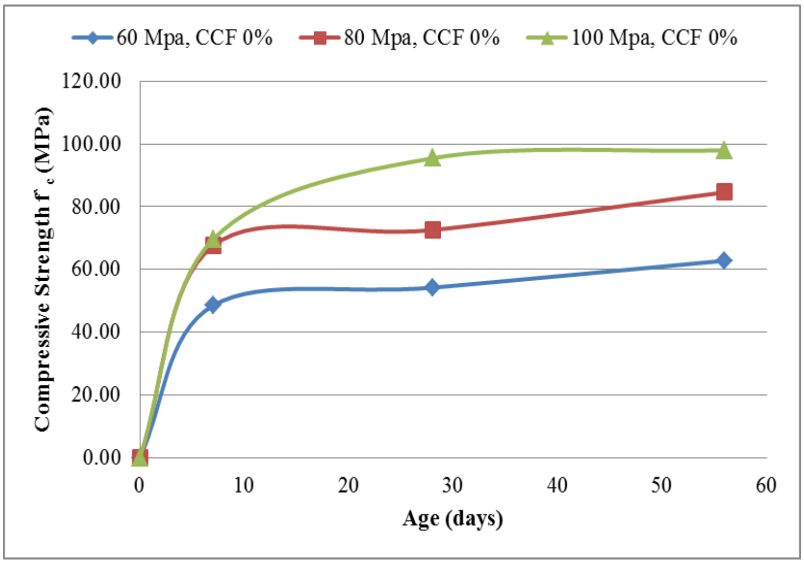
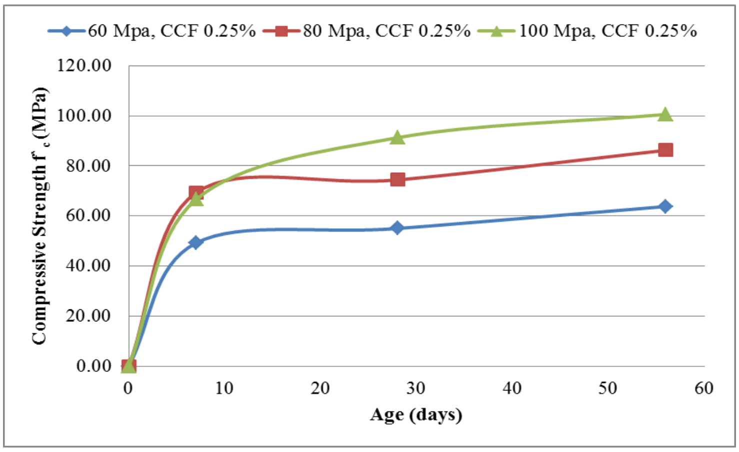


Fig.1: Relationship between the Fiber Volume Fraction and the Compressive Strength of High Strength Carbon Fiber Concrete





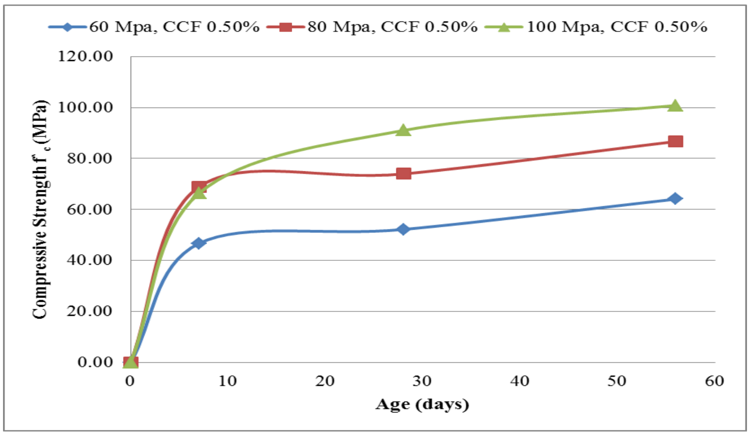


Fig.2: Relationship between the Compressive Strength of High Strength Carbon Fiber Concrete and the Age

Table 1: Trial Mixes (by Weight)

Trail No.	Binders		Aggregate		CCF	SP	W/b
	C	SF	S	G			
1*	0.90	0.10	2.47	2.81	0.00	0.01	0.47
2	0.90	0.10	1.89	2.32	0.00	0.01	0.39
3*	0.90	0.10	1.41	1.92	0.00	0.02	0.31
4	0.90	0.10	1.09	1.65	0.00	0.03	0.25
5*	0.90	0.10	0.79	1.40	0.00	0.04	0.20
6	0.90	0.10	0.49	1.15	0.00	0.05	0.14
7	0.90	0.10	0.49	1.15	0.00	0.06	0.14
8	1.00	0.00	1.92	2.32	0.00	0.02	0.38
9	1.00	0.00	2.50	2.81	0.00	0.01	0.48
10	1.00	0.00	1.92	2.32	0.00	0.01	0.39
11	1.00	0.00	1.69	2.29	0.00	0.03	0.29
12	1.00	0.00	1.52	2.15	0.00	0.03	0.26
13	0.90	0.10	1.46	2.07	0.00	0.03	0.24
14	0.90	0.10	1.46	2.07	0.00	0.04	0.23
15	1.00	0.00	2.35	1.15	0.00	0.00	0.55
16	1.00	0.00	1.87	0.85	0.00	0.01	0.45
17	1.00	0.00	1.59	0.65	0.00	0.01	0.40

Table 1: Trial Mixes (by Weight) – Contd.,

Trail No.	Binders		Aggregate		CCF	SP	W/b
	C	SF	S	G			
18	1.00	0.00	0.51	1.46	0.00	0.02	0.25
19	1.00	0.00	1.89	2.17	0.00	0.00	0.60
20	1.00	0.00	2.26	2.45	0.00	0.00	0.67
21*	0.90	0.10	2.47	2.81	0.25	0.01	0.47
22*	0.90	0.10	1.41	1.92	0.25	0.02	0.31
23*	0.90	0.10	0.79	1.40	0.25	0.04	0.20
24*	0.90	0.10	2.47	2.81	0.50	0.01	0.47
25*	0.90	0.10	1.41	1.92	0.50	0.02	0.31
26*	0.90	0.10	0.79	1.40	0.50	0.04	0.20

* Mix proportions selected for series of planned tests

C: Cement, SF: Silica Fume, G: Gravel, S: Sand, G: Gravel, CCF: Chopped Carbon Fiber, SP: Super-Plasticizer, W: Water, B: Binders (cementations materials), A: Aggregates

Table 2: Selected Concrete Mixes

Trail No.	Mix Symbol	C	SF	S	G	CCF	SP	Water
		Kg				Kg/m^3 (Vol. %)	$Liter/m^3$	
1	HSC^0 60	319	35	873	993	0	166	4
3	HSC^0 80	466	52	728	993	0	160	10
5	HSC^0 100	637	71	561	993	0	142	28
21	$HSC^{0.25}$ 60	319	35	873	993	4.45 (0.25%)	166	4
22	$HSC^{0.25}$ 80	466	52	728	993	4.45 (0.25%)	160	10
23	$HSC^{0.25}$ 100	637	71	561	993	4.45 (0.25%)	142	28
24	$HSC^{0.50}$ 60	319	35	873	993	8.9(0.25%)	166	4
25	$HSC^{0.50}$ 80	466	52	728	993	8.9(0.25%)	160	10
26	$HSC^{0.5}$ 100	637	71	561	993	8.9(0.25%)	142	28

Table 3: Compressive Strength of Trial Mixes (MPa)

Trail No.	f_{cu} (Mpa)			$f`_c$ (Mpa)
	7 day	28 day	56 day	56 day
1	56.90	62.97	72.00	62.77
2	69.05	70.14	75.40	66.03
3	76.90	82.11	94.43	84.55
4	81.90	100.28	104.30	94.28
5	79.05	105.45	108.00	97.96
6	93.76	105.70	112.30	102.24
7	90.00	96.16	109.95	99.90
8	60.85	65.60	83.62	73.99
9	53.95	62.41	72.45	63.20
10	59.55	72.75	78.09	68.63
11	86.65	87.07	93.60	83.73
12	89.60	94.80	106.82	96.78

Table 3: Compressive Strength of Trial Mixes (MPa) – Contd.,

Trail No.	f_{cu} (Mpa)			$f`_c$ (Mpa)
	7 day	28 day	56 day	56 day
13	97.70	108.00	114.14	104.07
14	82.95	106.60	112.48	102.42
15	39.25	47.02	55.81	47.42
16	39.04	51.73	57.52	49.02
17	44.16	54.26	66.34	57.36
18	81.80	83.52	89.78	79.99
19	28.95	30.82	38.05	31.06
20	16.10	19.05	23.73	18.40
21	57.65	63.81	73.05	63.78
22	78.68	84.02	96.13	86.22
23	75.89	101.23	110.61	100.55
24	55.03	60.90	73.38	64.09
25	78.28	83.59	96.62	86.70
26	75.70	100.99	110.88	100.82

Table 4: Compressive Strength of Control Mixes (MPa)

Mix Symbol	$f`_c$ (Mpa)	Vf %	$f`_c$ (Mpa)	Percentage Increase in Strength Relative to Vf=0%
			56 days	
HSC^{0} 60	62.77	0.00	62.77	
$HSC^{0.25}$ 60	63.78	0.25	63.78	1.60
$HSC^{0.50}$ 60	64.09	0.50	64.09	2.11
HSC^{0} 80	84.55	0.00	84.55	
$HSC^{0.25}$ 80	86.22	0.25	86.22	1.98
$HSC^{0.5}$ 80	86.70	0.50	86.70	2.55
HSC^{0} 100	97.96	0.00	97.96	
$HSC^{0.25}$ 100	100.55	0.25	100.55	2.65
$HSC^{0.50}$ 80	100.82	0.50	100.82	2.93

Splitting Tensile Strength (f_t)

Tests were carried out on Ø150/300 mm cylindrical specimens according to ASTM C496 [14] standards. The average splitting tensile strength of three cylinder specimens in each size was recorded.

Table 5 and Fig.3 shows the splitting tensile strength results of high strength carbon fiber concrete containing different fiber volume fractions. Generally it can be observed that the addition of carbon fibers cause a significant increase in the splitting tensile strength relative to the specimens (without fiber). Increasing the CCF fiber volume fractions from 0% to 0.25% tends to increase the splitting tensile strength at age 56 days by 4.070%, 5.38%, and 5.71% for concrete compressive strengths 60 MPa, 80 MPa and 100 MPa respectively, while increasing the CCF fiber volume fractions from 0% to 0.50% tends to increase the splitting tensile strength at age 56 days by 23.56%, 26.08%, and 28.57%for concrete compressive strengths 60 MPa, 80 MPa and 100 MPa respectively.

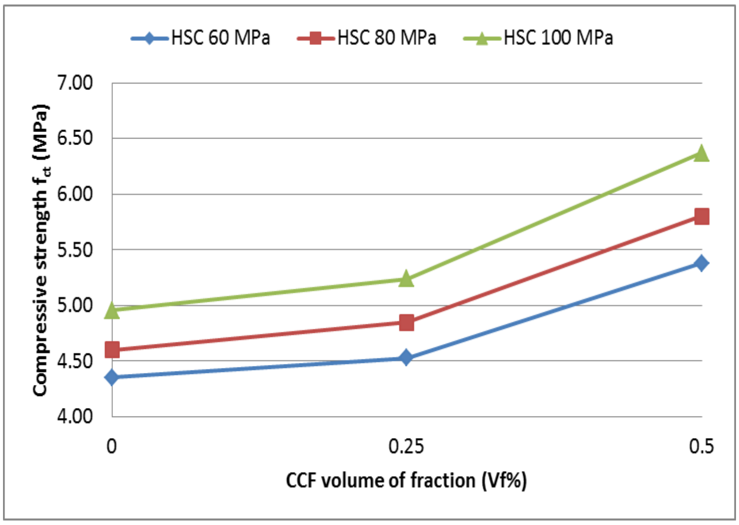


Fig.3: Relationship between the Fiber Volume Fraction and the Splitting Tensile Strength of High Strength Carbon Fiber Concrete

Table 5: Splitting Tensile Strength of Selected Mixes

Mix Symbol	f`c (Mpa)	Vf %	f_{ct}(Mpa) 56 days	f_{ct} / f`c %	f_{ct} / √f`c	Percentage Increase in Strength Relative to Vf=0%
HSC^0 60	62.77	0.00	4.35	6.93	0.55	
HSC$^{0.25}$ 60	63.78	0.25	4.53	7.10	0.57	4.07
HSC$^{0.50}$ 60	64.10	0.50	5.38	8.39	0.67	23.58
HSC^0 80	84.55	0.00	4.60	5.44	0.50	
HSC$^{0.25}$ 80	86.22	0.25	4.85	5.62	0.52	5.38
HSC$^{0.50}$ 80	86.70	0.50	5.80	6.69	0.62	26.08
HSC^0 100	97.96	0.00	4.95	5.06	0.50	
HSC$^{0.25}$ 100	100.55	0.25	5.24	5.21	0.52	5.71
HSC$^{0.50}$ 80	100.83	0.50	6.37	6.32	0.63	28.57

Flexural Strength (f_r)

Tests were performed for the selected concrete mixes (HSC with and without (CCF) with prisms 75x75x300 mm, and loaded in third point according to ASTM C1018 [15], the point load was located in 75 mm from supports with shear span to depth ratio of one. The results demonstrate that using carbon fiber causes a considerable increase in flexural strength with increasing in fiber volume fraction. Table 6 and Fig.4 shows the splitting tensile strength results of high strength carbon fiber concrete containing different fiber volume fractions.

Increasing the CCF fiber volume fractions from 0% to 0.25% tends to increase the flexure strength at age 56 days by 23.76%, 23.77%, and 20.90% for concrete compressive strengths 60 MPa, 80 MPa and 100 MPa respectively, while increasing the CCF fiber volume fractions from 0% to 0.50% tends to increase the flexure strength at age 56 days by 40.59%, 40.98%, and 41.04% for concrete compressive strengths 60 MPa, 80 MPa and 100 MPa respectively.

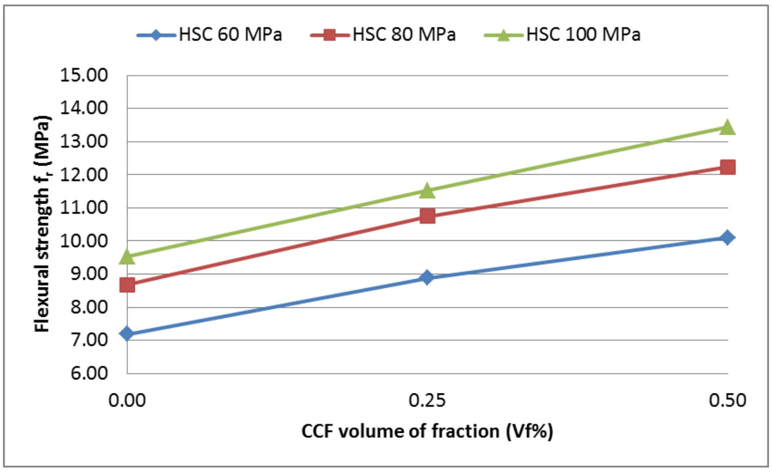


Fig.4: Relationship between the Fiber Volume Fraction and the Flexural Strength of High Strength Carbon Fiber Concrete

Table 6: Flexural Strength of Selected Mixes

Mix Symbol	$f`_c$ (Mpa)	Vf %	f_r(Mpa) 56 days	$f_r/f`_c$ %	$f_r / \sqrt{f`_c}$	Percentage Increase in Strength Relative to Vf=0%
HSC^{0} 60	62.77	0.00	7.18	11.44	0.91	
$HSC^{0.25}$ 60	63.78	0.25	8.89	13.94	1.11	23.76
$HSC^{0.50}$ 60	64.10	0.50	10.10	15.75	1.26	40.59
HSC^{0} 80	84.55	0.00	8.68	10.26	0.94	
$HSC^{0.25}$ 80	86.22	0.25	10.74	12.45	1.16	23.77
$HSC^{0.50}$ 80	86.70	0.50	12.23	14.11	1.31	40.98
HSC^{0} 100	97.96	0.00	9.53	9.73	0.96	
$HSC^{0.25}$ 100	100.55	0.25	11.52	11.46	1.15	20.90
$HSC^{0.50}$ 80	100.83	0.50	13.44	13.33	1.34	41.04

Modulus of Elasticity (E_c)

Modulus of Elasticity was determined using Ø150/300 mm cylinders. Concrete strain gauges 60mm in length were used for determining axial compression, Young's Modulus (E). The results of modulus of elasticity were obtained by concrete strain gauges (CSG) principles, were depend on (0.000050) axial strain and 40% of ultimate load, as described in ASTM C469 [16];

Table 7 and Fig.4, shows the results of the static modulus of elasticity for concrete without fibers and concrete containing different amount of fibers. The results show that the modulus of elasticity increases with increase of the fiber volume fraction. This may be due to a considerable improvement in the fiber-matrix bond.

Increasing the CCF fiber volume fractions from 0% to 0.25% tends to increase the modulus of elasticity at age 56 days by 13.00%, 16.82%, and 21.46% for concrete compressive strengths 60 MPa, 80 MPa and 100 MPa respectively, while increasing the CCF fiber volume fractions from 0% to 0.50% tends to increase the modulus of elasticity at age 56 days by 20.47%, 22.94%, and 33.99% for concrete compressive strengths 60 MPa, 80 MPa and 100 MPa respectively.

The experimental results were compared with the theoretical results that obtained by the equations of codes of practice, like for fiber reinforced high strength concrete ($f'c \le 85$MPa) according to Thomas and Ramaswamy [17], ACI 318-08 [18], CEB-90 [19] and ACI-363 [2], respectively in equations (2, 3, 4 and 5)

$$E_c = 4.58\sqrt{f_c^{`}} + 0.00042 * f_c^{`} * RI + 0.39 * RI \quad \text{........ (2) [17]}$$

$$E_c = 4700\sqrt{f_c^{`}} \quad \text{........ (3) [18]}$$

$$E_c = 9500\sqrt[3]{f_c^{`}} \quad \text{........ (4) [19]}$$

$$E_c = 3320\sqrt{f_c^{`}} + 6900 \quad \text{........ (5) [2]}$$

Where:

E_c = Modulus of elasticity of plain concrete.

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

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

RI = Reinforced index of fiber ($V_f L_f/_f$).

By comparing the data with the results of above equations, it is clear that the results of HSC without fiber are closest to CEB-90 equation. While the comparison between the tested results and the predicted modulus of elasticity, by Thomas and Ramaswamy for fiber reinforced high strength concrete has lower values in comparison with the test results of high strength carbon fiber concrete.

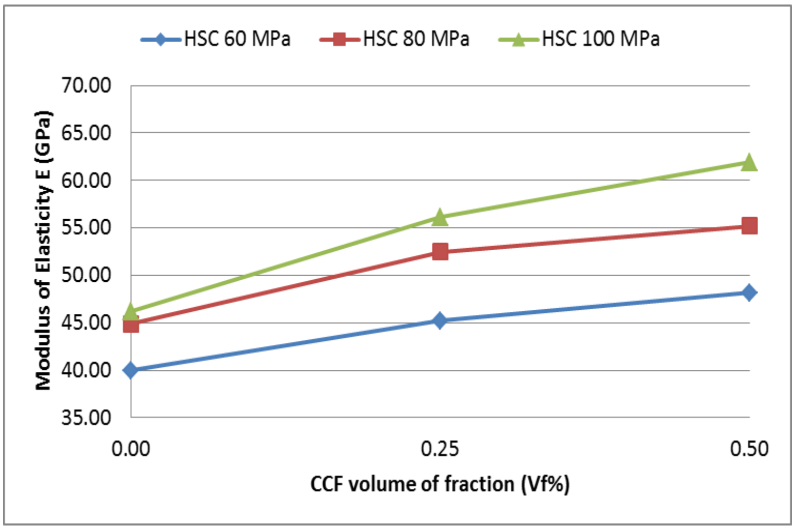


Fig.5: Relationship between the Fiber Volume Fraction and the Modulus of Elasticity of High Strength Carbon Fiber Concrete

Table 7: Modulus of Elasticity of Selected Mixes

Mix Symbol	f`c (Mpa)	Vf %	Experimental E (Gpa) 56 days	Percentage Increase in Strength Relative to Vf=0%	Estimated Fibrous Concrete Thomas and Ramaswamy [17]	CEB 90 [18]	ACI 363 [2]
HSC^{0} 60	62.77	0.00	40.00			39.30	33.05
$HSC^{0.25}$ 60	63.78	0.25	45.20	13.00	39.55		
$HSC^{0.50}$ 60	64.10	0.50	48.19	20.47	42.62		
HSC^{0} 80	84.55	0.00	44.90			42.97	37.24
$HSC^{0.25}$ 80	86.22	0.25	52.45	16.82	45.57		
$HSC^{0.50}$ 80	86.70	0.50	55.20	22.94	48.74		
HSC^{0} 100	97.96	0.00	46.22			44.95	39.56
$HSC^{0.25}$ 100	100.55	0.25	56.14	21.46	49.01		
$HSC^{0.50}$ 80	100.83	0.50	61.93	33.99	52.17		

CONCLUSIONS

From the tests performed on the properties of HSC, the following conclusions can be drawn:

1. The addition of carbon fibers causes a slight increase in compressive strength of high strength concrete when the fiber volume fraction increases.

a. Adding the CCF with fiber volume 0.25% tends to increase the concrete compressive strength compared with samples without fibers by

- 1.60% for concrete samples with compressive strength of 60 MPa,
- 1.98% for concrete samples with compressive strength of 80 MPa
- 2.65% for concrete samples with compressive strengths of 100 MPa.

b. Adding the CCF with fiber volume 0.50% tends to increase the concrete compressive strength compared with samples without fibers by

- 2.11% for concrete samples with compressive strength of 60 MPa.
- 2.55% for concrete samples with compressive strength of 80 MPa.
- 2.93% for concrete samples with compressive strengths of 100 MPa.

2. The significant increase in the splitting tensile strength of fibers concrete obtained when compared with the reference high strength concrete (without fibers)

a) The rate of increase in splitting tensile strength of high strength concrete with fiber volume fraction 0.25% compared with samples without fibers

- 4.070% for concrete samples with compressive strength of 60 MPa.
- 5.38% for concrete samples with compressive strength of 80 MPa.
- 5.71% for concrete samples with compressive strengths of 100 MPa.

b) The rate of increase in splitting tensile strength of high strength concrete with fiber volume fraction 0.50% compared with samples without fibers

- 23.56% for concrete samples with compressive strengths of 60 MPa.
- 26.08% for concrete samples with compressive strengths of 80 MPa.
- 28.57%for concrete samples with compressive strengths of 100 MPa .

3. The flexural strengths increases with increasing the volume of fibers related to the reference high strength concrete samples without fibers

a. The percentage of increase in the flexure strength of high strength concrete with fiber volume fraction 0.25% relatively to 0% of fiber volume fraction

- 23.76% for concrete samples with compressive strength of 60 MPa.
- 23.77% for concrete samples with compressive strength of 80 MPa.
- 20.90% for concrete samples with compressive strength of 100 MPa ,
- The percentage of increase in the flexure strength of high strength concrete with fiber volume fraction 0.50% relatively to 0% of fiber volume fraction
- 40.59% for concrete samples with compressive of 60 MPa.
- 40.98% for concrete samples with compressive of 80 MPa.
- 41.04% for concrete samples with compressive of 100 MPa.

4. The modulus of elasticity increases with increasing the fiber content.

a. The percentage increase in modulus of elasticity due to the addition of carbon fibers with volume fractions 0.25% tend to increase of modulus of elasticity related to samples with 0% by

- 13.00% for concrete samples with compressive strength of 60 MPa.
- 16.82% for concrete samples with compressive strength of 80 MPa.
- 21.46% concrete samples with compressive strength of 100 MPa.

b. The percentage increase in modulus of elasticity due to the addition of carbon fibers with volume fractions 0.50% tend to increase of modulus of elasticity related to samples with 0% by

- 20.47% for concrete samples with compressive strength of 60 MPa.
- 22.94% for concrete samples with compressive strength of 80 MPa.
- 33.99% for concrete samples with compressive strength of 100 MPa.

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