Effect of Steel Fibers on Behavior of Ultra High Performance Concrete

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Abstract: Ultra-high performance fiber-reinforced concrete (UHPC) is a new class of concrete that has been developed in recent years. UHPC results from the addition of either short discrete fibers or continuous long fibers to the cement based matrix. When UHPC compared with high performance concrete (HPC), UHPC exhibits superior properties in terms of compressive behavior, tensile behavior, workability, toughness, ductility and durability. UHPC has exceptional mechanical and transport properties including a very high tensile strength, strain hardening, and a density leading to a very low permeability. In this research, tests were carried out on a total 42 cubes, 84 cylinders and 21 prisms of UHPC samples to study the effect of adding steel fibers on the mechanical properties of UHPC such as, compressive strength, modulus of elasticity, poisson's ratio, flexural strength and tensile strength. The major parameters included in this research were the volume fraction of steel fibers and aspect ratio. The test results showed that the increase of volume fraction of steel fiber from 0% to 3% for UHPC causes maximum increase in compressive strength by 18.2%, flexural strength by 40% and tensile strength by 66.1% for higher side of aspect fiber ratio. Furthermore, adding steel fiber to UHPC can change the crack patterns, delay the crack appearance and restrain the crack expansion in concrete specimen.

Keywords:UHPC, Steel Fibers, strain hardening.

1. Introduction

The use of (UHPC) in structural applications has significantly increased owing to its numerous advantages compared with conventional normal concrete (NC) and high-performance concrete (HPC). UHPC exhibits superior properties in terms of compressive behaviors, tensile behaviors, and durability. Moreover, UHPC is more efficient in producing smaller and thinner sections, **Aldahdooh et al.,** (2013). **Perry et al.,**(2003) demonstrated that UHPC is capable of reaching compressive strengths of 25- 33 ksi. This was supported by **Kollmorgen,** (2004) with research showing a compressive strength of over 28 ksi. The increase in compressive strength, over NSC or HPC, can be attributed to the particle packing and selection of specific constituents, and thermal curing of UHPC. In recent years the collaboration between structural and material engineering led to an integrated design, based on the tailoring of the material's composition to meet specific requirements for structural applications (**Li et al**. (2002)). UHPC can be considered as the advanced result of this collaboration. The material was optimised with respect to mechanical strengths, fractural toughness, durability, placing method and time, keeping mixing and casting procedures as close as possible to existing practice (**Acker P. and Behloul M**.(2004)). **Graybeal,** (2005) attributed the increase in the flexural behavior of UHPC to the particle packing and the addition of fibers which hold the cement matrix together after cracking has occurred. UHPC exhibits ductility because as the specimen begins to micro crack the small scale fibers reinforce the matrix causing smaller, less damaging cracks to form. **Garas et al**.,

(2009) concluded that usage of fibres and the application of thermal treatment decreased 14-day drying shrinkage by more than 57% and by 82%. Increasing the stress-to-strength ratio from 40% to 60% increased the tensile creep coefficient by 44% and the specific creep by 11%, at 14 days of loading.

2. Experimental Program

2.1. Descriptions of Tested Specimens

A total of 42 cubes (100 × 100 × 100 mm), 84 cylinders (100 mm diameters and 200 mm height)and 21 prisms (100 × 100 mm cross section and 500 mm total length)of UHPC specimens were cast and tested in this research. These UHPC specimens were arranged into seven groups.Group (1) consist of six UHPC cubes, twelve UHPC cylinders and three UHPC prisms. All these specimens were mixed and casted without steel fibers (fiber volume fraction (V_f) = 0% , control mixing). Groups from (2) to (7) consisting from the same number of specimens as described in group (1) but were mixed and casted with volume fractions of steel fiber (V_f = 1, 2 and 3%) and with two aspect ratio (l/d = 30) for groups (2), (4) and (6),respectively and with (l/d = 50) for groups (3), (5) and (7),respectively.

2.2. Materialsand Mix Proportions

Natural crushed basalt graded from 1.18 mm to 10 mm (nominal max. size) with fineness modulus equal 5.3 was used. Harsh desert fine sand with fineness modulus equal 2.28 was used, it was almost free from impurities, silt, loam and clay. Ordinary Portland cement with high grade 52.5N was used.The silica fume used in preparing ultra-high strength concrete mixes, is locally produced by Sika Egypt (Sika Fume-HR). Sikament-NN, is used as a high-range water-reducing admixture. For all test specimens, a W/C of 0.18 was applied.Steel fibers with hooked ends were considered in three different volume fractions (1, 2 and 3%),with aspect ratios (50 and 30) and diameter = 1.0 mm leading to four series of concrete mixes, the tensile strength of steel fiber = 800 – 1500 MPa.The concrete mix proportions required for one cubic meter concrete are given in Table (1)

2.3. Test Setup and procedure

2.3.1. Compression Test

The compression test was carried – out on 42 cubes and on 42 cylinders at ages of 7 and 28 days of curing. Compression tests were completed primarily according to the ASTM C39 standard test method for cylinders and the ASTM C109 standard test method for cubes. The current standard sets the load rate at 35 ± 7 psi per second which would dictate that a specimen of UHPC could take up to 15 minutes to break.

Table 1.Concrete Mix Proportions.

Ingredient	Amount (kg/m^3)			
	Batch 1	Batch 2	Batch 3	Batch 4
Cement, c	720	720	720	720
Silica fume, s	215	215	215	215
Basalt 1.18 – 2.36 mm	190	187	183	179
Basalt 2.36 – 5.0 mm	477	467	457	448
Basalt 5.0 – 10 mm	286	281	274	269
Sand	408	400	392	384
Steel fibers	0	78	156	234
Water, w	129.6	129.6	129.6	129.6
Superplasticizer	35.4	35.4	35.4	35.4
w/c	0.18	0.18	0.18	0.18

2.3.2. Modulus of Elasticity and Poisson's Ratio

The modulus of elasticity and Poisson's ratio were conducted on 21 cylinders at age of 28 days. The testing process followed ASTM C 469, except the load rate was increased to 150 psi per second. In this test, electrical strain gauge was located on the face of cylinder specimens in order to measure transverse and vertical strains. Modulus of elasticity can be calculated as following:

$E = (S_2 - S_1)/ (\varepsilon_2 - 0.000050)$ (1), where :

E = chord modulus of elasticity; S_2 =stress corresponding to 40% of the ultimate load of the concrete; S_1=stress corresponding to a longitudinal strain of $\varepsilon_1$at 50 millionths; ε_2=longitudinal strain produced by S_2
Poisson's ratio, to the nearest 0.01, as following:
$\mu = (\varepsilon_{t2} - \varepsilon_{t1})/ (\varepsilon_2 - 0.000050)$ (2), where:
μ = Poisson's ratio; ε_{t2} = transverse strain at mid height of the specimen produced by stress S_2, andε_{t1} = transverse strain at mid height of the specimen produced by stress S_1.

2.3.3. Flexure strength

Testing was conducted on 21 prisms after 28 days of curing. ASTM C 1018 (Using a Beam with Third Point Loading) was used to determine the flexural strength. The deflection measurement device was secured to the prism at the neutral axis of the prism using Linear Variable Distance Transducers ,LVDT, having a maximum range of 100 mm and reading to 0.01 mm , directly above the support points. The flexural strength was calculated as following:

$f_{tb} = \frac{P.L}{b.d^2}$ (M pa) (3), where:
P = Failure load;L = Center to center distance between the support = 400 mm;b = specimen width = 100 mm;d = specimen depth = 100 mm.

2.4.4. Indirect tensile test (Splitting test)

Splitting or indirect tensile test was carried out on 21 cylinders according to ASTM C 496 after 28 days of curing. ASTM C496 indicates that the maximum tensile stress can be calculated based on Equation 4. In this equation, P is the failure load, L and D are the length and diameter of the cylinder, and f_θ is the tensile stress.

$$f_\theta = 2P/\pi LD \quad (4)$$

3. ExperimentalResults

3.1. Compressive Strength

Table 2 summarizes the compressive strength test results for various steel fiber and age. Results showed that compressive strength increase from 7.7 % for (UHPC) with steel fiber volume fraction equals 1% and l/d=50 comparing with (UHPC) without steel fibers to 18.2 % for (UHPC) with steel fiber volume fraction equals 3%and l/d=50 comparing with (UHPC) without steel fibers for cubes at 28 days. Figure 1 represents the effect of steel fiber on compressive strength at age 28 days. From results it was found that the increase in aspect ratio of steel fiber (from l/d =30 to l/d =50) appears a slight improvement in compressive strength with range of 2%. Normally, a compression test on high strength concrete would result in a very brittle failure. The UHPC that is reinforced with steel fibers does not exhibit explosive failures during compression tests.

For Ultra-high performance fiber-reinforced concrete (UHPC):

$$f_{cylinder(100mm\ diameter)} = 0.9 f_{cube\ (100mm)} \quad (5)$$

Table 2. Compressive Strength Results

Group	description	Mean compressive strength (Mpa)			
		7 days		28 days	
		cube	cylinder	cube	cylinder
1	V_f = 0 %	121	105	143	124
2	V_f= 1 % , l/d = 30	128	116	151	137
3	V_f= 1 % , l/d = 50	131	120	154	141
4	V_f= 2 % , l/d = 30	136	122	160	144
5	V_f= 2 % , l/d = 50	139	126	163	148
6	V_f= 3 % , l/d = 30	141	128	166	151
7	V_f = 3 % , l/d = 50	144	131	169	154

Also results showed that as percentage of steel fiber volume fraction increased as percentage of difference between cylindrical and cube specimens decreased, in addition the increase in aspect ratio of steel fiber (from l/d =30 to l/d =50) decreases percentage difference between cylindrical and cube specimens because of the improvement of lateral stress due to the presence of steel fibers. Figure 2 represents compressive strength results for age 7 and 28 days at different steel volume fraction , the results showed that compressive strength at test age 7 days roughly equal 85 % from the compressive strength at test age 28 days. For Ultra-high performance fiber-reinforced concrete (UHPC):

$$f_c\ (7\ days) = 0.85 f_c\ (28\ days) \quad (6)$$

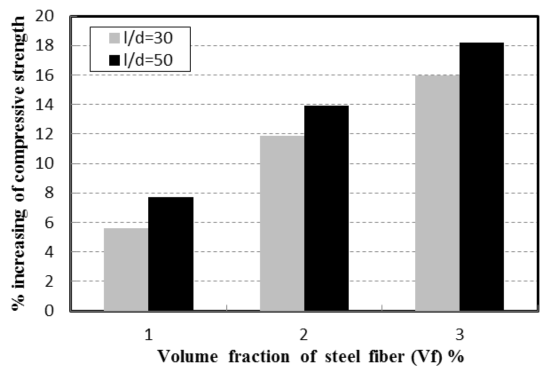

Figure 1.% Increasing of Compressive Strength for Cube Specimens at Different Steel Fiber Content at Age 28 Days.

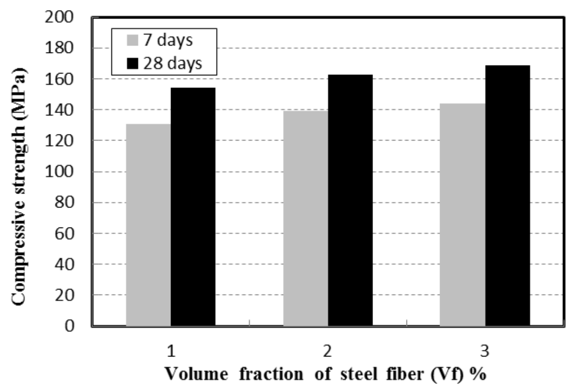

Figure 2. Compressive Strength for Cube Specimens at Age 7 and 28 Days with Different Steel Fibers Volume Fractions and Aspect Ratio Equals 50

3.2. Modulus of Elasticity and Poisson's Ratio

Table 3 summarizes the modulus of elasticity and poisson's ratio based on steel fiber volume fraction and aspect ratio. It can be seen that modulus of elasticity increase from 6.0% for (UHPC) with steel fiber volume fraction equals 1% to 12.8 % for (UHPC) with steel fiber volume fraction equals 3% comparing with (UHPC) without steel fibers. From the results it can be seen that steel fiber had a slight effect on Poisson's ratio. The following equation gives the best-fit line for the relationship between the measured static modulus of elasticity and the square root of the compressive strength of ultra-high performance fiber-reinforced concrete (UHPC) used in this study: $E_c = 4100\sqrt{f_c}$ Mpa (7)

Table 3. Modulus of Elasticity and Poisson's Ratio at Age 28 Days

Group	Compressive strength (Mpa)	modulus of elasticity (Gpa)	Poisson's Ratio
1	124	45.2	0.198
2	137	47.9	0.199
3	141	48.8	0.197
4	148	49.0	0.20
5	144	49.7	0.195
6	154	50.1	0.20
7	151	51.0	0.21

3.3. Flexural Strength

Table 4 lists the results of the flexural testing for different steel fibers (volume fraction and aspect ratio). The first-crack flexural stress is used as an indicator of the maximum tensile stress for UHPC. Table 4 indicated that, the specimen without steel fibers seem to have a larger first-crack stress than the specimen cast with steel fibers. Hence the lower first-cracking stress in UHPC with fibers. However, the difference in first-cracking stress is very small and the purpose of the fibers is to bridge the crack and provide post-crack ductility.Figure 3 shows the effect of steel fiber on flexure strength, It can be seen that flexure strength increased from 15% for (UHPC) with steel fiber volume fraction equals 1% to 40.0 % for (UHPC) with steel fiber volume fraction equals 3% comparing with (UHPC) without steel fibers , although it was found that the increase in aspect ratio of steel fiber (from l/d =30 to l/d =50) appears a slight improvement in flexure strength with range of 5%. Figure 4 shows the effect of steel fiber on maximum deflection of tested prism. Comparison of the peak deflection at maximum load reveals that there was great improvement in the ductility, due to the inclusion of steel fiber. Test results showed that the vertical deflection is directly proportional to amount of steel fibers and the UHPC that is reinforced with steel fibers does not exhibit explosive failure during flexure test. From results of compressive strength as shown in table 2 and results of flexure strength (first crack) as shown in table 4, we can get approximate relation between flexure strength (first crack) and compressive strength at age of 28 days using the same shape of relation used in ACI code for normal concrete. The equation of the fit line for the results of this study is:

$$f_r = 1.10\sqrt{f_c} \quad \text{Mpa} \qquad (8)$$

Shan SP. suggested the rule of mixture to consider the fiber content in calculating the flexural strength for FRC, given below as

$$\sigma_{bf} = A\,\sigma_{bf0}\,(1-V_f) + B\,V_f\,(l_f/d_f) \quad \text{Mpa} \qquad (9)$$

In which: σ_{bf} andσ_{bf0} is the flexural strength with fiber and without fiber, respectively;
V_f is the fiber volume fraction; l_f and d_f are the length and the diameter of fiber, respectively; andA and B are the experimental coefficients.

The flexural strength of UHPC is approximately linearly dependent on the fiber content, and from results we can get value of constant A equals 1.0 and value of constant B equals 4.75. Therefore relation between flexure strength of UHPC and fiber content can be summarized as follows:

$$f_{bf} = f_{bf0}\,(1-V_f) + 4.75\,V_f(l_f/d_f) \quad \text{Mpa} \qquad (10)$$

Table 4.(Cracking and Maximum) Load, Deflection and Flexural Strength

Group	cracking conditions			Max. conditions		
	load KN	flexural strength Mpa	def. mm	load KN	flexural strength Mpa	def. mm
1	35	14	2.0	40	16	3.0
2	32	12.8	3.0	42	16.8	4.8
3	30	12	3.1	46	18.4	6.0
4	32	12.8	3.2	48	19.2	7.7
5	33	13.2	3.35	50	20	10
6	33.5	13.4	3,25	54	21.6	12.5
7	34	13.6	3.4	56	22.4	14.2

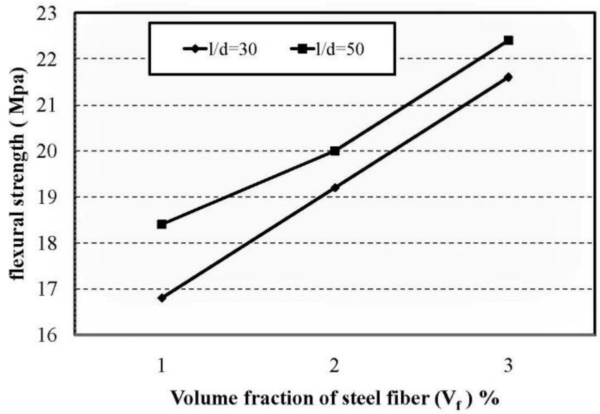

Figure 3. Flexure Strength at Different Steel Fiber Content at Age 28 Days.

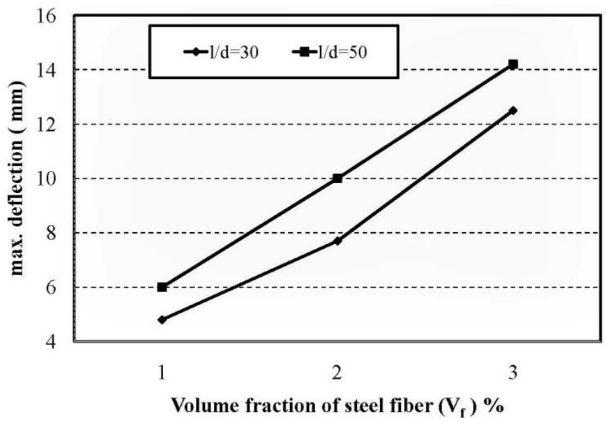

Figure 4.Effect of Steel Fiber on Maximum Deflection.

3.4. Tensile Splitting Strength

Table 5 represented the effect of steel fibers on the tensile strength, from results of splitting test, it can be seen that steel fiber had large effect on tensile strength, tensile strength increased from 34% for (UHPC) with steel fiber volume fraction equals 1% to 66.1 % for (UHPC) with steel fiber volume fraction equals 3% comparing with (UHPC) without steel fibers, although it was found that the increase in aspect ratio of steel fiber (from l/d =30 to l/d =50) at the same value of volume fraction appears an improvement in tensile strength with range of 12%.Figure 5 shows the effect of steel fiber on splitting tensile strength. Failure mode of UHPC without steel fiber is a brittle failure ,while failure mode of UHPC with steel fiber combined with large ductile failure.From results of compressive strength as shown in table 2 and results of splitting tensile strength as shown in table 5, we can get approximate relation between the tensile splitting strength and compressive strength at age of 28 days. The equation of the fit line for the results of this study is:

$f_{sp} = 0.93\sqrt{f_c}$ Mpa (11)

Test results carried by **Hashem**,(1999), is used to evaluate the splitting tensile strength for normal and high strength concrete.

$f_{sp} = 0.076\ [f_c + 10\sqrt{F}\ (3.0 - \frac{20}{f_c})]$ Mpa (12)

In which: f_c : is the cylinder compressive strength of concrete, in Mpa;F : fiber factor = $(\frac{l_f}{d_f})$ $.V_f.b_f$, as reported by **Narayanan and Darwish**, where:$(\frac{l_f}{d_f})$: Fiber aspect ratio;V_f : Fiber volume fraction;b_f : Bond factor that accounts for differing bond characteristics of the fiber, the bond factor was assigned a relative value of 0.5 for fibers having circular cross section, 0.75 for crimped or hooked fibers, and 1.0 for indented fibers.When applying equation (12) on our study we can use:b_f = 0.75 (bond factor for hooked fiber),$\frac{l_f}{d_f}$ = (30 and 50), V_f = (1 , 2 and 3%) and from results of compressive strength as shown in table 2 and results of splitting tensile strength as shown in table 5, we can modify equation (12) to be qualified for determining splitting tensile strength for UHPC as following :

$$f_{sp} = 0.095\ [f_c + 10\sqrt{F}\ (3.0 - \frac{20}{f_c})]\ \text{Mpa} \qquad (13)$$

Table 5. Splitting Tensile Strength Results

Group	Failure load (KN)	Tensile strength (Mpa)
1	360	11.5
2	400	12.73
3	484	15.4
4	490	15.59
5	548	17.45
6	560	17.82
7	600	19.10

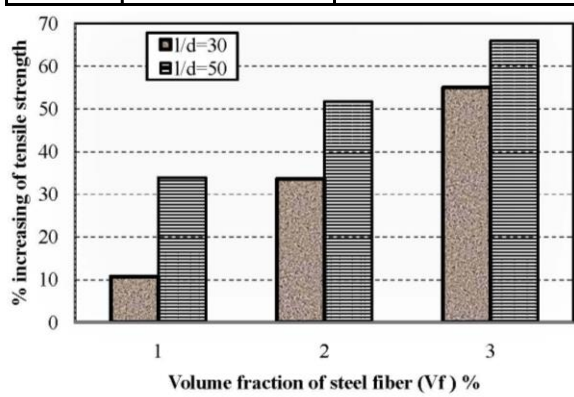

Figure 5.% Increasing of Tensile Strength Results at Different Steel Volume Fraction and Aspect Ratio.

4. Conclusions

Findings from the experimental study on the effect of adding steel fibers on behavior of UHPC are as follows:

1. It is observed that compressive strength, modulus of elasticity, splitting tensile strength and flexural strength are on higher side for 3% steel fibers volume fraction and aspect ratio of 50as compared to that produced from 1% and 2% fibers volume fraction.
2. It is observed that compressive strength increased from 7.7% for (UHPC) with steel fiber volume fraction equals 1% to 18.2 % for (UHPC) with steel fiber volume fraction equals 3% and l/d = 50 comparing with (UHPC) without steel fibers for cubes at 28 days.
3. It is observed that modulus of elasticity increased from 6.0% for (UHPC) with steel fiber volume fraction equals 1% to 12.8 % for (UHPC) with steel fiber volume fraction equals 3% comparing with (UHPC) without steel fibers.

4. It is observed that flexural strength increased from 15% for (UHPC) with steel fiber volume fraction equals 1% to 40.0 % for (UHPC) with steel fiber volume fraction equals 3% comparing with (UHPC) without steel fibers.
5. It is observed that splitting tensile strength increased from 34% for (UHPC) with steel fiber volume fraction equals 1% to 66.1 % for (UHPC) with steel fiber volume fraction equals 3% comparing with (UHPC) without steel fibers.
6. Addition of fiber to UHPC improves its ductility and its post-cracking load-carrying capacity.
7. The following equations are proposed for estimating the mechanical properties of ultra-high performance fiber-reinforced concrete (UHPC) with compressive strengths ranging from 125 to 155 Mpa :

$f_{cylinder(100mm\ diameter)} = 0.9 f_{cube\ (100mm)}$ (5)

$f_{c\ (7\ days)} = 0.85 f_{c\ (28\ days)}$ (6)

$E_c = 4100\sqrt{f_c}$ Mpa (7)

$f_r = 1.10\sqrt{f_c}$ Mpa(8)

$f_{bf} = f_{bf0}\ (1-V_f) + 4.75\ V_f\ (l_f/d_f)$ Mpa(10)

$f_{sp} = 0.095\ [f_c + 10\sqrt{F}\ (3.0 - \frac{20}{f_c})]$ Mpa(13)

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