Mechanical Properties of Different Concrete Ductile Materials

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Abstract

This paper aimed to study the mechanical properties of brittle materials such as concrete as well as three different ductile materials. The ductile materials used were steel fibers reinforced concrete (SFRC), slurry infiltrated fiber concrete (SIFCON), and ultra-high performance fiber reinforced concrete (UHPFRC). Hooked-end steel fiber with a length of 30 mm and diameter of 0.5 mm (aspect ratio of 60) was used to reinforce ductile materials with volume fractions (V_f) of 1%, 1.5%, and 2% for SFRC and $V_f$of 1.5% and 7.5% for UHPFRC and SIFCON respectively. For this purpose, three cubes, four cylinders, and a prism for each material were cast and tested to investigate compressive strength, splitting tensile strength, modulus of rupture, modulus of elasticity, and stress-strain relationship under compressive stress. The experimental results showed that the failure mechanism for cubes, cylinders, and prism specimens of concrete changed from brittle to ductile failure by the presence of hooked-end steel fibers. Furthermore, increasing the V_f of steel fibers from (1 to 2) % improved the compressive strength, splitting tensile strength, modulus of rupture, and modulus of elasticity of concrete by (19.90-29.50) %, (90.59-141.40) %, (32.23-53.75) %, and (12.70-48.54) %, respectively, and increased the strain capacity of concrete at failure at least two times more than normal concrete without steel fibers. In addition, the compressive strength, splitting tensile strength, and flexural strength of UHPFRC increased by 132.67%, 293.95 %, and 237.43 %, respectively, and for SIFCON increased by 146.06%, 503.15 %, and 615.77 %, respectively, as compared to normal concrete.

Keywords: Ductile materials; SFRC; SIFCON; UHPFRC; Mechanical properties; Concrete.

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1. Introduction

As it is known, brittle material such as normal concrete (NC) has undesirable characteristics like low tensile strength and limited strain capacity. On the other hand, ductile materials such as fiber reinforced concrete (FRC) have high tensile strength and deformation ability in comparison with NC [1].

FRC is concrete made of cement, aggregates, and discrete reinforcement fibers. The concrete may be mortars, normally proportioned concrete mixes, or mixes specially designed for a specific application. Many types of fibers are used for reinforcing concrete as steel, glass, synthetic, and natural fibers. Steel fibers are the most common type of fibers used [2]. The most common shapes of steel fibers are hooked-end and crimped [3]. Hooked-end is considered to perform better than other shapes of steel fibers, such as crimped and deformed, from a ductility point of view [4] and prevent slippage between the concrete and the steel fibers [5].

One of the most significant advantages of using fiber reinforcement is the better long-term serviceability of the structure [6]. The main advantages of FRC are the prevention of micro-cracks development to the macroscopic level and improvement of ductility and residual strength after the formation of the first crack, as well as the strength, toughness, and durability improved by using fibers[7].

The classification of FRC that exhibits strain-hardening under uniaxial tension stress and high toughness under compressive stress is shown in Figure 1[8]

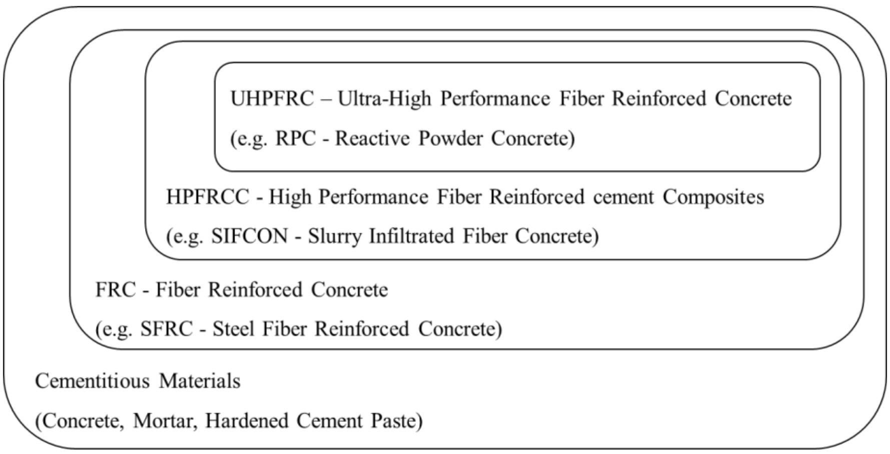


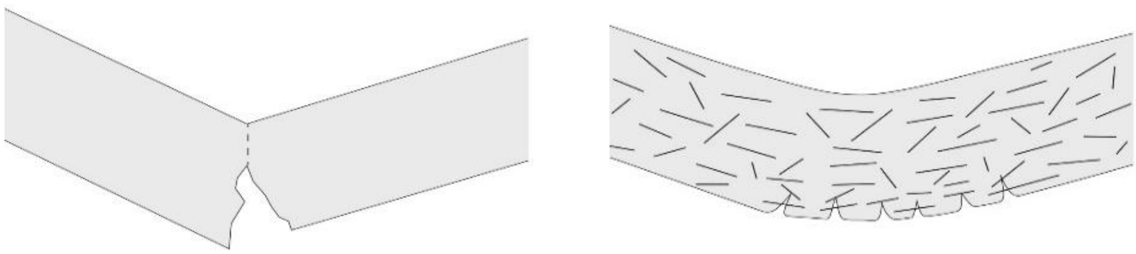
Figure 1 Classification of FRC[8]

A few studies have been carried out to study the mechanical properties of ductile materials under the same loading conditions, where most of the studies used each material individually. Thus, this paper aimed to study the mechanical properties of ductile materials, such as compressive strength, splitting tensile strength, modulus of rupture, modulus of elasticity, and stress-strain relationship under compressive stress. The ductile materials used in this study were steel fibers reinforced concrete (SFRC), slurry infiltrated fiber concrete (SIFCON), and ultra-high performance fiber reinforced concrete (UHPFRC). To achieve the goal of the study, three cubes, four cylinders, and a prism for each material were cast and tested to investigate mechanical properties.

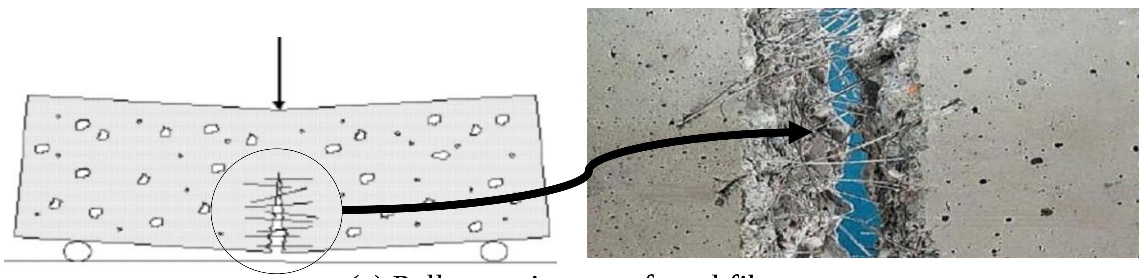
2. Background

2.1 Steel fiber reinforced concrete (SFRC)

Porter proposed using steel fibers in concrete for the first time in 1910. However, in 1963, Romualdi and Baston published the first scientific research on FRC [1]. SFRC is a type of FRC made of cement, fine and coarse aggregates, water, and steel fibers that are actually randomly distributed in the concrete. The purpose of randomly distributed discontinuous steel fibers is to bridge across the cracks that formed inside concrete to provide ductility after cracking through the pullout resistance of steel fibers [9]. Moreover, the presence of steel fibers in concrete leads the fracture mode change from single crack propagation to irregular multi cracks mode under flexural load [10], as shown in Figure 2.



(a) Single crack(without steel fibers)   (b) Multi cracks (with steel fibers)



(c) Pullout resistance of steel fibers

Figure 2 Failure mechanism of concrete with and without steel fibers[11]

The addition of steel fibers to concrete improved its properties, such as flexural strength, shear strength, split tensile strength, and compressive strength, in addition to increasing the compressive strain at the ultimate stage [12]. SFRC can sustain a compressive strain value of 0.005– 0.009 on failure [13].

The flexural strength of SFRC increases significantly with increased aspect ratio and volume fractions (V_f) of steel fibers [12]. The typical range of V_f of steel fibers used for SFRC is (0.25 to 1.5) % [6].

The ductility of SFRC mainly depends on the volume fractions. Other factors, such as fiber shapes, aspect ratio, orientation of fiber, and tensile strength, are also affecting the performance of concrete [14].

2.2 Slurry infiltrated fiber concrete (SIFCON)

In 1979, SIFCON was created by Lankard[3]. SIFCON is a unique type of high-performance fiber-reinforced cement composite with more advantageous properties than traditional FRC, such as tensile, compressive, flexural, and shear strengthsand toughness. SIFCON is different from traditional FRC in respect of composition and fabrication. The fiber content in FRC usually ranges from (1 to 3) % by volume, whereas fiber content in SIFCON typically ranges from (5 to 20) % by volume [15].

The SIFCON matrix has a high cement content. It may contain fine aggregate, as well as mineral and chemical admixture, but no coarse aggregates. Therefore, the SIFCON matrix is either cement paste or flowing cement mortar as opposed to the traditional FRC [16]. Also, SIFCON production differs from FRC. In the production of SIFCON, the fibers are placed in a casting mold then a slurry of cement is infiltrated over the rich fiber layers, as shown in Figure 3. Fibers are placed in the mold by hand or with the use of fiber–dispersing units [17]. Vibration is often required to achieve proper slurry infiltration to the fiber bed [3]. While in the production of FRC, fibers are added to the dry or wet concrete mix.

Figure 3 Adding slurry of SIFCON over steel fibers layer

2.3 Ultra-high performance fiber reinforced concrete (UHPFRC)

Ultra-high performance concrete (UHPC) is a type of cementitious composite with a high cement content, small aggregate size, and binder (pozzolana, fly ash, silica fume, reactive powder) as well as a low water/cement ratio. UHPC has a microstructure that is dense and interconnected, with high homogeneity, low capillary porosity, and high compressive strength. As a result, these characteristics create concrete with better performance, excellent durability, high strength, and high toughness compared to normal and high-strength concrete [18].

Because of the low water/cement ratio, UHPC mixes are characterized by low workability. One method to improve the workability of UHPC is using a superplasticizer. Furthermore, using silica fume can improve the properties of UHPC by filling spaces between coarser particles due to its smaller size and spherical form, so enhancing the strength properties via pozzolanic reactions. Despite enhancing the stiffness and strength, the failure mode of plain UHPC is very brittle. Therefore, post-cracking behavior is limited [19]. Fibers can change the failure mode of plain UHPC from brittle to ductile mode and increase the tensile strength, toughness, and deformation ability of the resultant composite, the name of this type of concrete is ultra-high performance fiber reinforced concrete (UHPFRC) [20].

In the mid-1990s, Richard and Cheyrezy developed ultra-high performance fiber reinforced concrete, also known as ultra-high performance ductile concrete (UHPDC) or reactive powder concrete (RPC), which was one of the most significant developments in the field of concrete technology [21]. UHPFRC belongs to the group of HPFRCC, which is defined as a type of FRC that exhibits strain hardening when subjected to uniaxial tension. However, UHPFRC has a dense matrix and thus a very low permeability as compared to HPFRCC and NC [8], [20].

UHPFRC is typically cured by pressure or a high temperature. This improves its properties by accelerating the binder's hydration reaction. However, this is not only expensive in terms of energy, but also limits the use of UHPFRC for the production of precast elements [22]. Therefore, the UHPFRC investigated in this study has a rapid strength growth and does not require heat or special mixing techniques for curing.

3. Experimental program

The experimental program involves the preparation of materials, tests of materials, mix proportions, casting, curing, and testing setup.

3.1 Materials preparation

All materials used throughout the work are shown in Figure 4. The NC mix consists of cement, sand, gravel, and water in addition to a super-plasticizer. The SFRC mix differs from the NC mix by containing steel fibers. UHPFRC and SIFCON mix consist of cement, quartz sand, water, super-plasticizer, and steel fibers. Furthermore, mineral admixtures such as silica fume are used as a partial replacement (10%) of cement weight in the UHPFRC mix.

Figure 4 The materials used in this work

The materials used throughout the work are portland cement 42.5 grade, natural sand as fine aggregate with a maximum size of 4.75 mm, crushed coarse aggregate (Gravel) locally available with a maximum nominal size of 14 mm, pure water, high-performance super-plasticizer concrete admixture, densified silica fume with grading below 1μm, and quartz sand with small grading 0.3 – 0.7 mm to ensure complete infiltration of the slurry over the dense steel fiber[23]. Finally, hooked-end steel fiber was used in this work which has a length of 30 mm and diameter of 0.5 mm with an aspect ratio (l/d) of 60 and ultimate tensile strength of 1200 MPa based on the manufacturer company requmdations. All materials used were conformed to the requirement of ASTM.

3.2 Mix proportions

The final mix proportions of NC, SFRC, UHPFRC, and SIFCON are presented in Table 1. The NC mix was designed to obtain a cylinder compressive strength of 35 MPa at the age of 28 days.

Table 1 Mix proportions for 1 m^3 of concrete

Materials	Concrete type			
	NC	*SFRC*	*UHPFRC*	*SIFCON*
Cement (Kg)	410	410	900	850
Silica fume (Kg)	-	-	90	-
Sand (Kg)	750	750	-	-
Quartz sand (Kg)	-	-	990	850
Gravel (Kg)	1100	1100	-	-
W/C or W/B ratio	0.45	0.45	0.19	0.31
Steel fiber (%)	-	1,1.5,2	1.5	7.5
Superplasticizer (%)	0.4	0.4	1.8	1.6

3.3 Mixingprocedure

Mixing was done in laboratory mixers, and the mixers were cleaned and moistened before using it. The procedure of mixing of SFRC is similar to that of NC. Initially, coarse aggregate and sand were mixed. Further, steel fibers were added by hand to the dry mixture for another minute. After that, cement was added to the mixture, and (2/3) of mixing water was added to the rotary mixer, then super-plasticizer with (1/3) of mixing water was added to the mixture, and the mixing was continued for another 4 minutes to ensure even distribution of steel fibers in the fresh concrete. Figure 5 (a) shows the homogenous mix of NC and SFRC with volume fractions of 1%, 1.5%, and 2% after completing the mixing process.

Regarding the mixing of UHPFRC and SIFCON slurry, UHPFRC was mixed by the following procedure:Binder materials (cement and silica fume) were mixed with quartz sand for about 2 min. (2/3) of mixing water was added into the mixture for about 1 min, followed by (1/3) of mixing water with super-plasticizer were added into the mixture for another 2 min. Finally, the steel fibers were added to the wet mixture and mixed for approximately (5-7) min until the homogeneous mixture of UHPFRC was obtained, as shown in Figure 5 (b), while SIFCON slurry was mixed by the following procedure:firstly, added quartz sand to the mixer, then cement was added to quartz sand and mixed for about (1-2) min. (2/3) of mixing water was added into the mixture for about 1 min, followed by (1/3) of mixing water with super-plasticizer were added into the mixture for another 3 min. After emptying the slurry from the mixer to the pan, manual mixing is continued from time to time to achieve more homogeneity, as shown in Figure 5 (c).

NC (V_f 0%) SFRC (V_f 1%) SFRC (V_f 1.5%) SFRC (V_f 2%)

(a) Effect of Vf of steel fibers on the homogenous mix of NC and SFRC

(b) Homogenous mix of UHPFRC (c)Homogenous mix and manual mixing for SIFCON

3.4Casting and curing

The castingand curing processes of the specimens are shown in Figure 6. Firstly, three cube specimensmolds (100×100×100) mm, four-cylinder specimensmolds (100×200) mm, and a prism (100×100×500) mm for each material were prepared, then the oil was applied to the internal side of the mold with a thin layer for lubrication. After casting all specimens, it was covered with plastic sheets and demolded at the age of two days and all specimens were immersed in water until testing.

Figure 6 The casting and curing processes of specimens

3.5 Testing the specimens

3.5.1 Compressive strength test

The compressive strength was determined using the average value of three cubes (100x100x100) mm. The test was done according to BS EN 12390-3 [24] with a constant loading rate of 0.6 MPa per second by using a standard testing machine with a capacity of 2000 kN, as shown in Figure 7 (a,g).

3.5.2Splitting tensile strength test

The splitting tensile strength was determined using the average value of two cylinders (100×200) mm. The test was done according to ASTM C496/C496M [25]. Cylinders were loaded with a constant loading rate of 0.023 MPa per second up to failure by using a standard testing machine with a capacity of 2000 kN, as shown in Figure 7 (a,f).

3.5.3 Modulus of rupture (Flexural strength) test

The flexural strength was determined using a concrete prism with dimensions of (100×100×500) mm. The test was done under three-point loading to estimate the modulus of rupture according to ASTM C293/C293M [26]by using the flexural testing machine with a capacity of 200 kN, as shown in Figure 7 (b,d).

3.5.4Compressive stress-strain test

The stress-strain relationships were estimated using the average value of two cylinders (100×200) mm. This test was done according to ASTM C39/C39M [27] and ASTM C469/C469M [28] using two rigid circular rings that were secured together at approximately two-thirds the height of the cylinder using clamping bolts. A dial gauge with a capacity of 25 mm and an accuracy of 0.01mm was inserted between the rings to measure the deformation of the middle part of the cylinder. The test was conducted using a constant loading rate of 0.3 MPa per second under compression stress by using a standard testing machine with a capacity of 2000 kN, as shown in Figure 7 (a,c,e).

3.5.5 Modulus of elasticity (*Ec*)

It is important to know the static modulus of elasticity, which is one of the most important properties of solid materials because it describes the stiffness of the material. The elastic modulus of concrete is significantly influenced by materials used in concrete production, as well as their proportions [3]. The modulus of elasticity was determined by the slope of the stress-strain curve

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between stress at 40% of compressive strength and the stress corresponding to the strain of 0.00005, according to ASTM C469/C469M [28] using Equation (1).

$Ec = (S_2 - S_1) / (\varepsilon_2 - 0.00005)$ …………... Equation (1)

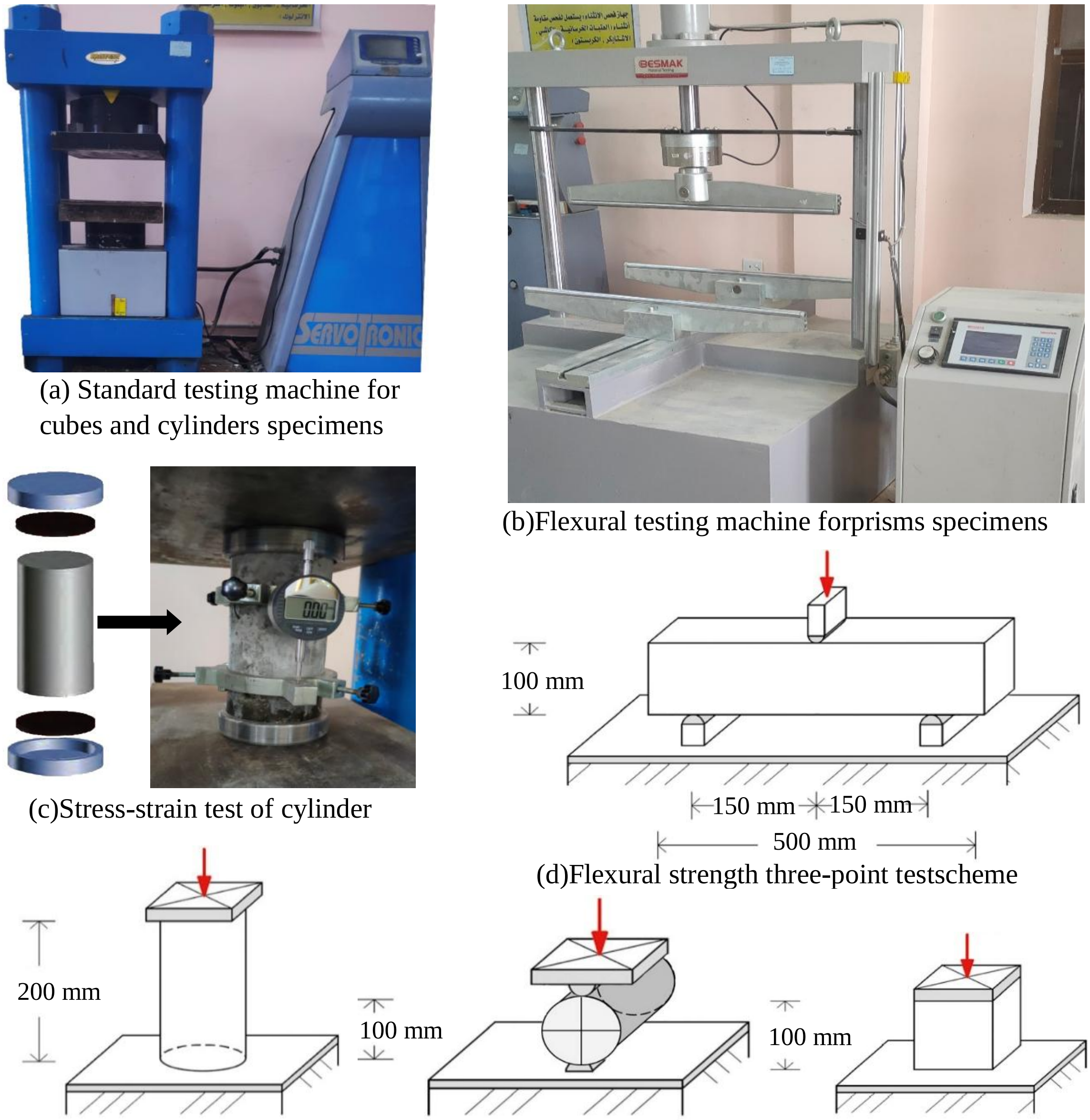
where:

Ec = static modulus of elasticity, MPa

S_2 = stress at 40% compressive strength, MPa

S_1 = stress corresponding to a longitudinal strain of 0.00005, MPa

ε_2= longitudinal strain produced by stress S_2.



(a) Standard testing machine for cubes and cylinders specimens

(b)Flexural testing machine forprisms specimens

(c)Stress-strain test of cylinder

(d)Flexural strength three-point testscheme

(e)Compressive stress- strain test scheme

(f) Splitting tensile strength test scheme

(g)Compressive strength test scheme

Figure 7 Testing machines and schemes for cubes, cylinders, and prisms

4. Test results and discussion

4.1 Compressive strength

Table 2presents the average compressive strength of cubes for different concrete types. Figure 8 shows the modes of failure of concrete cubes for different concrete types.

Table 2 Average compressive strength for different concrete types

Concrete type	V_f of steel fibers (%)	Average compressive strength (MPa) *fcu*	The increase in compressive strength (%)
NC	0	46.40	-
SFRC	1	55.63	19.90
	1.5	58.07	25.15
	2	60.08	29.50
UHPFRC	1.5	107.96	132.67
SIFCON	7.5	114.17	146.06

NC SFRC (1% 1.5% 2%)

SIFCON UHPFRC

Figure 8 Modes of failure of concrete cubes

As shown in Table 2, adding hooked-end steel fibers with V_f of (1, 1.5, and 2) % to NC improved the compressive strength by (19.90, 25.15, and 29.50) %, respectively. This may be related to the ability of steel fibers to bridge across the cracks that develop as a result of the confining effect provided by steel fibers to the concrete, which has arrested the propagation of cracks depending on the bond strength between steel fibers and concrete.

Under the same loading conditions, the compressive strength of UHPFRC and SIFCON increased by 132.67% and 146.06%, respectively, as compared to NC.

It is clear from Figure 8 that the failure of SFRC, UHPFRC, and SIFCON cubes was affected by the presence of steel fibers. Noting the high fiber content in SIFCON in comparison with fiber content in SFRC and UHPFRC led to a higher bond between steel fibers and matrix interfaces. Furthermore, the cubic specimens of SFRC, UHPFRC, and SIFCON did not crush and maintained their integrity until the end of the test, unlike NC cubes.

4.2 Splitting tensile strength

Table 3 presents the average splitting tensile strength of two cylinders for different concrete types. Figure 9 shows the modes of failure of concrete cylinders for different concrete types.

Table 3 Average splitting tensile strength for different concrete types

Concrete type	V_f of steel fibers (%)	Average splitting tensile strength (MPa) *ft*	The increase in splitting tensile strength (%)
NC	0	4.13	-
SFRC	1	7.83	89.59
	1.5	8.35	102.18
	2	9.97	141.40
UHPFRC	1.5	16.27	293.95
SIFCON	7.5	24.91	503.15

NC SFRC (1% 1.5% 2%)

UHPFRC SIFCON

Figure 9 Modes of failure of concrete cylinders under splitting stress

As shown in Table 3, unlike the compressive strength of the SFRC, the addition of hooked-end steel fibers with V_f of (1, 1.5, and 2) % to concrete led to a more pronounced improvement in the tensile strength by (89.59, 102.18, and 141.40) %, respectively. This may be related to arresting the cracks through steel fibers bridging. The benefit of the steel fibers for the improvement in the tensile strength of concrete is based on cracks arresting and the steel fiber transferring energy [7], which were increased with the increase in steel fibers content. In addition, using hooked-end steel fibers improves the bond strength between fibers and concrete matrix, which improves the mechanical properties of FRC (ductile materials).

Under the same loading conditions, the splitting tensile strength of UHPFRC and SIFCON increased by 293.95 % and 503.15 %, respectively, when compared to NC

The failure mechanism of cylinders of ductile materials is affected by the presence of steel fibers, which started micro-cracking symmetrically on their sides, and the effect of steel fibers bridging avoided a sudden failure, while cylinders with NC usually fail suddenly and fracture in the middle section, as shown in Figure 9.

4.3 Modulus of rupture (Flexural strength)

Table 4presents the flexural strength of prisms for different concrete types. Figure 10 shows the modes of failure of concrete prisms.

Table 4 Modulus of rupture for different concrete types

Concrete type	V_f of steel fibers (%)	Modulus of rupture (MPa) f_r	The increase in modulus of rupture (%)
NC	0	5.77	-
SFRC	1	7.63	32.23
	1.5	7.79	35.01
	2	8.87	53.75
UHPFRC	1.5	19.47	237.43
SIFCON	7.5	41.30	615.77

As shown in Table 4, adding hooked-end steel fibers with V_f of (1, 1.5, and 2) % to NC improved flexural strength by (32.23, 35.01, and 53.75) %, respectively. The flexural strength of UHPFRC and SIFCON increased by 237.43 % and 615.77 %, respectively, when compared to NC. The improvements in flexural strength of FRC can be related to the fact that; after cracking of the matrix, the hooked-end steel fibers continue to carry the load until the bond between the matrix and steel fibers is lost. Therefore, this lets to prevent sudden failure, as shown in Figure 10. In comparison to SFRC and UHPFRC failure, the high fiber content in SIFCON led to a stronger interface zone between matrix and steel fibers. Consequently, the bond strength improved, and thus the post-cracking strength increased, as shown in Figure 10.

NC (V_f 0%)   SFRC (V_f 1%)

SFRC (V_f 1.5%)   SFRC (V_f 2%)

UHPFRC (V_f 1.5%)   SIFCON (V_f 7.5%)

Figure 10 Modes of failure of concrete prisms under flexural stress

4.4 Stress-strain curves

Figure 11 shows compressive stress-strain relationships for NC, SFRC, UHPFRC, and SIFCON. It is clear from Figure 11 that the strain of all concrete cylinders increases linearly with increasing stress at the elastic stage. The strain at the elastic loading stage for cylinders of ductile materials seemed to be less than NC, and the strain after peak stress continued to increase with a slight increment in stress. This may be attributed to the use of hooked end steel fibers, which increased the rigidity of these cylinders during the elastic loading stage and increased their ductility at the ultimate stage.

In general, all ductile materials used showed high strength and strain capacity when compared to NC, which means that the ductility and toughness of ductile materials are higher than those of NC. The presence of hooked-end steel fibers with NC increased the strain capacity of concrete at failure from 0.0032 to 0.0067, 0.0080, and 0.0104 for V_f of (1, 1.5, and 2) %, respectively, which is at least two times more than that of NC.

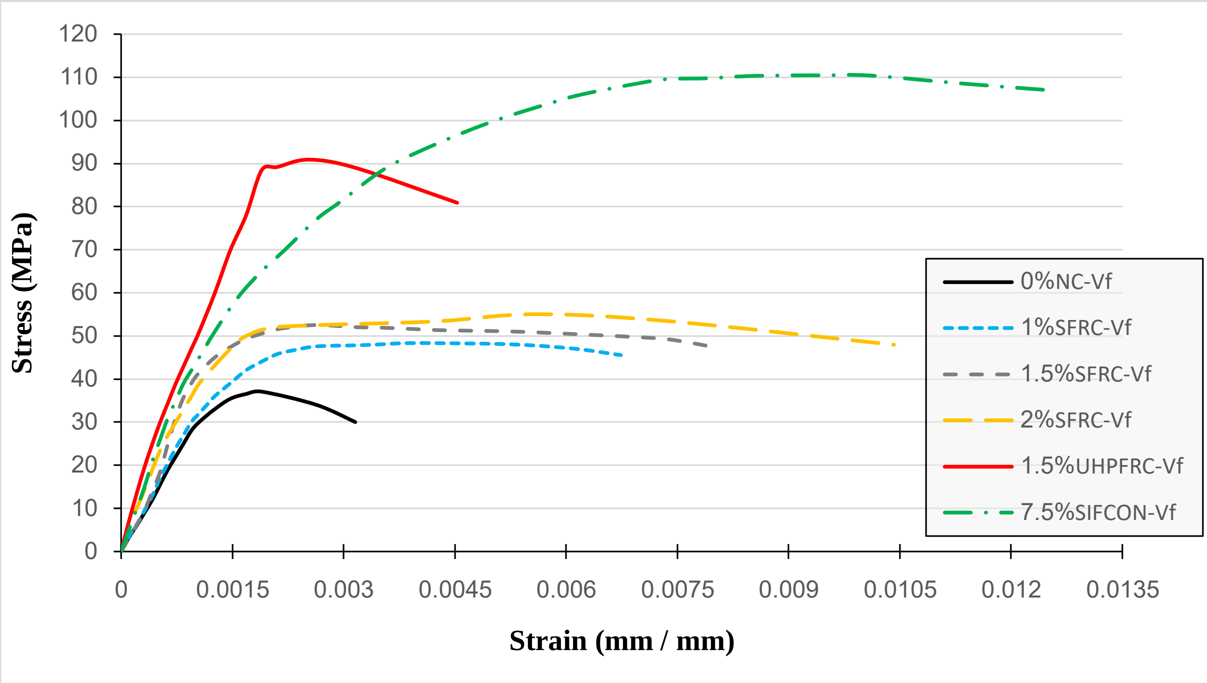


Figure 11 Compressive stress-strain relationships for different concrete types

As shown inFigure 11, UHPFRC and SIFCON showed high strength and strain capacity when compared to NC. Noting that despite using the same V_f of steel fibers (1.5 %) for UHPFRC and SFRC, UHPFRC exhibited strain capacity at failure less than SFRC, which was 0.0045. This may be related to the fact that the behavior of UHPC is more brittle, which led to reduced deformation ability in comparison to SFRC. In contrast, SIFCON exhibited strain capacity at failure greater than other types of FRC, which was 0.01263. This is attributed to the high content of steel fibers in SIFCON, which led to an increase the deformation ability.

Figure 12 shows two different failure modes in cylinders for NC and FRC. In the case of NC, the cracks were deep and randomly in different directions with a crushing in the middle part of the cylinder. On the other hand, multiple shallow cracks were observed in FRC cylinders near the failure zone. The cylinders were not severely damaged by these cracks and had lateral expansion in the middle part. This means ductile failure occurs due to using steel fibers. Furthermore, SIFCON exhibits more lateral expansion in the middle part compared to SFRC and UHPFRC. This is related to the high content of steel fibers in SIFCON.

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NC SFRC (1% 1.5% 2%)

UHPFRC SIFCON

Figure 12 Modes of failure for concrete cylinders under compressive stress

4.4.1 Modulus of elasticity

The modulus of elasticity and compressive strength of cylinders for different concrete types are presented in Table 5.

Table 5 Modulus of elasticity for different concrete types

Concrete type	V_f of steel fibers (%)	Average compressive strength (MPa) $f'c$	Modulus of elasticity (MPa) Ec	The increase in modulus of elasticity (%)
NC	0	37.05	28414	-
SFRC	1	48.28	32024	12.70
	1.5	52.47	37477	31.89
	2	55.08	42207	48.54
UHPFRC	1.5	90.90	53000	86.53
SIFCON	7.5	110.45	43020	51.40

As shown in Table 5, using hooked-end steel fibers with NC increased the modulus of elasticity of concrete by (12.70, 31.89, and 48.54) % for V_f of (1, 1.5, and 2) %, respectively. Also, the moduli of elasticity of UHPFRC and SIFCON increased by 86.53 % and 51.40 %, respectively, when compared to NC. This can be attributed to the increases in strength of ductile materials as compared to NC.

It should be noted that despite using the same V_f of steel fibers (1.5 %) for UHPFRC and SFRC, the modulus of elasticity of UHPFRC was greater than SFRC by 41.42%. This is attributed to the high strength of UHPFRC.

5. Conclusions

The main conclusions are as follows:

- Adding hooked-end steel fiberswith V_f of (1, 1.5, and 2) % to NC (SFRC) improved the compressive strengthby(19.90, 25.15, and 29.50) %, improved the splitting tensile strength by (89.59, 102.18, and 141.40) %, improved by (32.23, 35.01, and 53.75) % formodulus of rupture, and by (12.70, 31.89, and 48.54) % for modulus of elasticityrespectively.
- The compressive strength, splitting tensile strength, and flexural strength of UHPFRC and SIFCON increased by 132.67% and 146.06%, by 293.95 % and 503.15 %, and by 237.43 % and 615.77 %, respectively, as compared to NC. Also, the moduli of elasticity of UHPFRC and SIFCON increased by 86.53 % and 51.40 %, respectively, when compared to NC.
- The failure mechanism for cubes, cylinders, and prism specimens of NC changed from brittle to ductile failureby the presence ofhooked-end steel fibers (ductile materials). Furthermore, the strain capacity of the normal concrete at failure was 0.0032, while the strains of the ductile material (SFRC) were 0.0067, 0.0080, and 0.0104 for V_f of (1, 1.5, and 2) %, respectively. Also, the cylinder compressive strainreached 0.0045 and 0.01263 for UHPFRC and SIFCON, respectively.

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