Determination of Mechanical Properties of Hybrid Steel-Nylon Fiber Reinforced Concrete

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Abstract

This study aims to characterize and quantify the mechanical properties of hybrid steel-nylon fiber reinforced concrete. In order to achieve and verify that, 0.5%, 1% and 1.5% fiber percentage by volume of concrete are used in this study with five different mixes of 100-0%, 70-30%, 50-50%, 30-70% and 0-100% for each fibers percentage (nylon to steel).

28-day compressive strength, split tensile strength and modulus of rupture (MOR) tests have been performed in the hardened state. The total tested specimen are 144 specimens. Superplsticizer and silica fume are used in all the mixes to enhance the FRC mechanical properties.

When compared to the control sample that contains no fibers, with the increase of fiber ratio, compression strength, split-tensile strength and flexural strength of concrete increase up to 242%, 182% and 181% respectively. The result showed that the steel fibers improve the concrete properties better than the nylon fiber due to their higher tensile strength.

Keywords: Steel fiber, Polypropylene fiber, Concrete admixtures, Concrete tests

1. Introduction

Concrete is a tension-weak building material, which is often crack ridden connected to plastic and hardened states, drying shrinkage, and the like.

The cracks generally develop with time and stress to penetrate the concrete, thereby impairing the waterproofing properties and exposing the interior of the concrete to the destructive substances containing moisture, bromine, acid sulfate, etc. The exposure acts to deteriorate the concrete, with the reinforcing steel corrosion. To counteract the cracks, a fighting strategy has come into use, which mixes the concrete with the addition of discrete fibers (Xiang Gao B. Eng.2007, R. Siddique, 2003 and A. E. Naaman, 1998).

Experimental studies have shown that fibers improve the mechanical properties of concrete such as flexural strength, compressive strength, tensile strength, creep behaviour, impact resistance and toughness. Moreover, the addition of fibers makes the concrete more homogeneous and isotropic and therefore it is transformed from a brittle to a more ductile material (Xiang Gao B. Eng.2007, A. E. Naaman, 1998 and. Kaiping, C. Hewei, Z. Jing'en, 2004).

The concrete-reinforcing fibers include metal, polymer, and various others. Among them, polymer fibers and the steel fibers enjoy popularity in the domain of concrete (O. A. Du¨zgu¨n, R. Gu¨l, A. C. Aydin, 2005, E. M. Almansa, M. F. Cánovas, 1999 and J. F. Trottier and N. Banthia, 1994) and the nylon fibers show a rising acceptance (P.S. Song and S. Hwang, B.C. Sheu, 2005).

The addition of steel fibers significantly improves many of the engineering properties of mortar and concrete, notably impact strength and toughness. Tensile strength, flexural strength, fatigue strength and ability to spalling are also enhanced (E. M. Almansa, M. F. Cánovas, 1999 and P.S. Song, J.C. Wu, S. Hwang, B.C. Sheu, 2005).

On the other hand, the nylon fibers have stepped up the performance after the presence of cracks and have sustained high stresses (P.S. Song , J.C. Wu, S. Hwang , B.C. Sheu, 2005). However, the establishment has been awaiting as to how the steel fibers compete with the nylon rivals in advancing the performance of concrete under compression, tension, flexure, etc.

2. Research Significant

To open new application areas, FRC should be designed so as to perform with adequate strength, sufficient ductility, high durability, and adequate workability. Utilizing the concept of hybridization, a concrete with superior properties can be developed.

The present investigation is, therefore, planned to investigate the mechanical properties of hybrid steel-nylon fibrous concrete for different fibers percentage as well as different hybridization ratio.

Results obtained from this study are expected to contribute to the efforts made to characterize the mechanical properties of HFRC. With the appropriate interpretation of the obtained results, it can be possible to make various optimization analyses like optimization for a desired mechanical property or optimization for a certain fiber type and content.

3. Experimental

3.1 Materials

The properties of materials used in concrete mixtures are given below.

3.1.1 Cement

Ordinary Portland cement type (UCC, TASLUJA) is used. It is tested per Iraqi standard Specifications I.O.S No. 5/1984, and has met all the requirements. The chemical and physical properties of this cement are presented in (Table 1).

3.1.2 Fine aggregate

Natural sand with a 4.75-mm maximum size is used as fine aggregates. The grading of the sand conformed to the requirement of ASTM C33-01. Its sieve analysis results are given in (Table 2).

3.1.3 Coarse aggregate

Coarse aggregate used in this study is 12.5-mm nominal size. It is tested per ASTM C33-01; Its sieve analysis results are given in (Tables 3).

3.1.4 Fibers

Two different types of fiber are used. The first is the steel fiber manufactured by Bekaert - Dramix® ZP305 (Fig.1-a) and having a 'trough' shape with hooks at both ends, and glued in bundles. Steel fibers are 35 mm long and 0.55 mm in diameter (aspect ratio of 64), while the second is nylon fiber (Fig.1-b) of crimped shape and rectangular cross section (of dimension 0.8*0.5 mm) with length of 45 mm. In this investigation, three percentages by volume of concrete (0.5%, 1% and 1.5%) are used with mix proportion of 100-0%, 70-305%, 50-50%, 30-70% and 0-100% for each fibers percentage (nylon to steel).

3.1.5 Superplasticizer

A commercially available super-plasticizer Sikament® FFN (Fig.2-a) is used throughout this work as a (HRWRA) in all mixtures. Sikament® FFN does not contain chlorides or other ingredients promoting corrosion of steel reinforcement. It is, therefore, suitable for reinforced and prestressed steel. The weight percentage (according to cement weight) is the same for all mixes and is 3%.

3.1.6 Silica Fume

Dry undensified SikaFume® HR/TU (Fig.2-b) is used as Silica fume. It meets the requirements of BS EN 13263-1:2005.The used weight percentage (by cement weight) for all mixes is 10%. The purpose behind using of Silica fume is the improve outcome result get in the strength of concrete which may be ascribed to the pozzolanic reaction with $Ca(OH)2$ crystals located in the transition zone and as a result improving the bond between the cement particles and aggregate surface (Al-Attar A. A., 2006).

3.2 Mixture proportions

Sixteen series of concrete specimens are prepared and cast. First, a control mixture (without fibers) is designed in accordance with the provisions of Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete, ACI 211.1-91, to have a 28-day cube compressive strength of 35 MPa (Table 4). After this, three percentages by volume of concrete (0.5%, 1% and 1.5%) are used with five mix proportion of 100-0% , 70-30%, 50-50%, 30-70% and 0-100% for each fibers percentage (nylon to steel). Thus, the total concrete mixes which contain fibers are fifteen.

The W/Cm ratio is maintained at 0.33 ± 0.02. Superplasticizer/cementitious materials ratio is kept around 3%. Also, the silica fume/cement are kept at 10%. Concrete mixtures were made in power-driven revolving-type drum mixers of 0.05 m^3 capacity.

3.3 Mixing, Casting, Curing

The procedures for mixing the fiber-reinforced concrete involved the following: firstly, the gravel and sand were placed in a concrete mixer and dry mixed for 1 min. Secondly, the cement in addition to silica fume are spread and dry mixed for 1 min. Thirdly, about the half of the mixing water in addition to the total amount of the superplasticizer is slowly added and mixed for 2 min. After that, the specified amount of fibers is distributed and mixed for 3 minutes. Fourthly, the remaining water is added and the mixing is done until good homogeneous mixture, as visually observed, is obtained. If any lumping or balling was found at any stage, it is taken out, loosened and again added manually. Lastly, the freshly mixed fiber-reinforced concrete is fed into the molds (Fig.3-b). The molds are cubic molds for the compressive strength measuring 15 cm, prism molds for the flexural specimens measuring 10*10*40 cm and cylinder molds for the tensile strength specimens 10*20 cm. three specimens are cast for each mentioned test. Thus, the number of specimens of one series is twelve, hence, the total numbers for the total series is 192 specimen. After the feeding operation, each of the specimens is allowed to stand for 24 hrs before demolding, stored in water at 24±3 ^{o}C for 27 days (Fig.3-c), and then removed and kept at room temperature until the time of testing.

4. Testing

4.1 Compressive Strength

Compressive strength of concrete is measured on 150 mm cubes in conformity with B.S 1881: part 116: 1989. An electrical testing machine with capacity of 2000 kN at loading rate 4 kN per seconed is used. The average of the compressive strength of three cubes is adopted for each test, and the test was conducted at age of 28 days.

4.2 Split Tensile Strength

The split tensile strength is determined as per the procedure outlined in ASTM C 496 to asses the split tensile strength of concrete cylinder specimens of (100*200)mm (Fig.4). For each mix, the average results of three specimens are adopted.

4.3 Flexural Strength

The 100mm*100mm*400mm prisms are tested according to ASTM C78-00. Two points load are applied at the specimen (Fig.5). The specimen is tested at the age of 28 days and the average of three specimens to a mix are accepted as the flexure tensile strength of that mix.

5. Results and Discussion

5.1 Compressive Strength

The results of compression tests are given in Fig.(6) to Fig.(9). Compressive strength is determined at the age of 28 days, as a means of quality control.

Figure (6) shows the effect of fiber percentage on compressive strength. It can be seen that the highest compressive strength can be got for composite have equal percentage for S.F and N.F.

On the other hand, figures (7) to (9) demonstrate the effect of altering the hybridization ratio on the value of compressive strength for different fiber volume fraction.

From these figures, it can be observed that the compressive strength value is increased due to the incorporation of the fiber to the mix for the used fiber fraction compared to the reference mix. The explanation for this is that, under axial loads, cracks occur in microstructure of concrete and fibers reduce the crack formation and development. Thus, compressive strength of concrete increased. For the all fiber fraction mixes, the maximum increase is obtained (as mentioned before) for the hybridization ratio (50% N.F- 50% S.F) and was equal to 242%, 227%, and 210% for 0.5%, 1% and 1.5% fiber percentage respectively, and the peak increase is for 0.5% fiber fraction (242%).

When withstanding an increasing compression load, the fibrous concrete specimens may develop lateral tension, and then it initiates those cracks and advance them. As the advancing crack approaches a fiber, the debonding at the fiber–matrix interface begins due to the tensile stresses perpendicular to the expected path of the advancing crack. As the advancing crack finally reaches the interface, the tip of the crack encounters a process of blunting because of the already present debonding crack. The blunting process reduces the crack-tip stress concentration, thus blocking the forward propagation of the crack and even diverting the path of the crack. The blunting, blocking, and even diverting of the crack allow the fibrous concrete specimen to withstand additional compressive load, thus upgrading its compressive strength over the non-fibrous control concrete.

5.2 Splitting Tensile Strength

The relation between the split tensile strength and the fiber volume fraction for different hybridization ratio of S.F with N.F can be shown in Figure (10). It can be seen that are the maximum increase in split tensile strength is for fiber percentage equal to 1% for the all mixes of different hybridization ratio. And the highest value for the all fiber fraction is for hybridization ratio (0% N.F with 100% S.F).

The increase in split tensile strength with respect to the control (no fiber) mix for the all fiber volume fraction is shown in Figures (11) to (13). These figures show that the results are almost normally distributed. The maximum increase is for fiber fraction equal to 1% that is 182%.

The substantial increase in splitting-tensile strength can contribute to the bridging action of the fibers. Once the splitting occurs and continues, the fibers bridging across the split portions of the matrix act through the stress transfer from the matrix to the fibers and, thus, gradually supported the entire load. The stress transfer improves the tensile strain capacity of the two fiber-reinforced concretes and, therefore, increases the splitting tensile strength of the reinforced concretes over the unreinforced control counterpart.

As just stated, the increasing in tensile strength due to incorporation of steel fiber is greater than that of using nylon fiber only. This may contribute to the highest tensile strength of steel fibers comparing to the nylon fibers as well as the geometry type of steel fibers.

Fibers, especially S.F fibers, make the concrete less brittle and more ductile. Tensile strength of ductile materials is higher than brittle materials.

In general, the results manifest that the incorporation of the two types of fibers invited improvement in the absence of unfavorable effect on the variability of splitting tensile strength.

5.3 Modulus of Rupture (M.O.R)

The average results of the flexure tests are given in Figures (14) to (17). The flexural strength trend for polypropylene and steel fiber varies when fiber increased. For different hybridization ratio, Figure(14) generally illustrate that the maximum increase in modulus of rupture can be achieved for fiber percentage equal to 1% as similar to the case of split tensile strength.

Figure (15) to (17) show graphical representation for the variation of the average flexural strength for reference concrete mixes and concrete mixes containing different fraction and hybridization ratio of fibers. In general, for the all fiber percentage, the flexure strength of the FRC specimens increased as the steel fiber percentage increases and it can be seen that the addition of polypropylene fibers slightly increases the flexural strength.

When compared to the control samples that contain no fiber, increasing the total hybrid fiber percentage in the ratios of 0.5%, 1.0%, and 1.5% by volume, provides an increase in the flexural strength by about 154%, 157% and 181%

This increase results primarily from the fibers intersecting the cracks in the tension half of the specimens. These fibers accommodate the crack face separation by stretching themselves, thus providing an additional energy-absorbing mechanism and also stress relaxing the microcracked region neighboring the crack-tip. As stated for compressive and splitting tensile strengths, the steel and polypropylene fiber additions make bearable differences in the variability carried by the MOR for the two fibrous concretes, compared to the plain concrete counterpart.

6. Conclusions

The following conclusions are driven from the present study:

1) Inclusion of steel and nylon fibers to the concrete mix strongly increased the compressive strength. The increasing up to 242% for fiber volume fraction equal to 0.5%. However, this increasing could have been obtained with more economical method like reducing w/c ratio.

2) The use of hybrid steel-nylon fibers will increase the split tensile strength of concrete. The maximum raise is for fiber ratio 1% and reaches to 182%. However, the nylon fiber seems to have a slight effect on the split tensile strength and the effect of steel fiber alone is larger than that of nylon fiber by about 145% (for 1% volume fraction)

3) When compared to the control mix which contain no fiber, increasing of fiber volume fraction providing an enhancement in the flexure strength for the all hybridization ratio, and the maximum increase reach to 181% for fiber volume fraction 1.5%. Alike for the split–tensile strength, the inclusion of nylon fiber seems

to have a slight effect on the flexure strength. This may contribute to the highest tensile strength of steel fibers comparing to the nylon fibers as well as the geometry type of steel fibers.

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Table 1. Chemical Composition and Physical Properties of Cement

Composition	Content %	Limit of Iraqi specification No. 5/1984
Silica, SiO2	13.4 %	21 % Max.
Alumina, Al2O3	4.6 %	8 % Max.
Iron oxide, Fe2O3		6 % Max.
Magnesia, MgO		5 % Max.
Sulfate, SO3	1.1 %	2.8 % Max.
Loss on Ignition, (L.O.I)	0.95 %	4 % Max.
Insoluble material	1.05 %	1.5 % Max.
Lim Saturation Factor, (L.S.F)	0.9	(0.66-1.02)
Physical Properties	**Test Results**	**Limit of Iraqi specification No. 5/1984**
Specific surface area (Blaine method), (m2/kg)	301.5	250 m2/kg (lower limit)
Setting time (vacate apparatus)		
Initial setting, hrs : min	0:55	Not less than 45 min
Final setting, hrs : min	7:00	Not more than 10 hrs
Compressive strength MPa For 3-day	28.7	15 MPa (lower limit)

Table 2. Grading of fine aggregate

Sieve size	Cumulative Passing %	Limit of ASTM c33-01)
9.5-mm (3⁄8-in.)	100	100
4.75 mm (No. 4)	93.12	95 to 100
2.36 mm (No. 8)	81.6	80 to 60
1.18-mm (No. 16)	62.79	50 to 80
600-µm (No. 30)	23.4	25 to 60
300-µm (No. 50)	4.45	5 to 30
150-µm (No. 100)	0	0 to 10

Table 3. Grading of Coarse aggregate

Sieve size	Cumulative Passing %	Limit of ASTM c33-01
37.5mm(11⁄2 in.)	100	100
25.0 mm (1 in.)	93.57	95 to 100
12.5mm (1⁄2 in.)	37.22	25 to 60
4.75 mm (No. 4)	5.09	0 o 10
2.36 mm (No. 8)	2.11	0 to 5

Table 4. Concrete Mix Proportions

Constitute	Content kg (per m^3 of concrete)
Cement	337
Coarse aggregate	1131
Fine aggregate	646
Water	119
Superplasticiser	11.35
Silica fume	29.32

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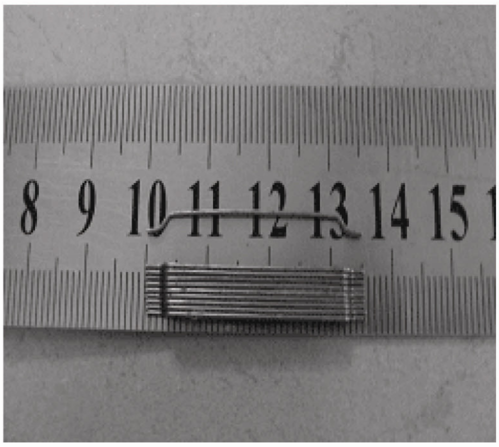
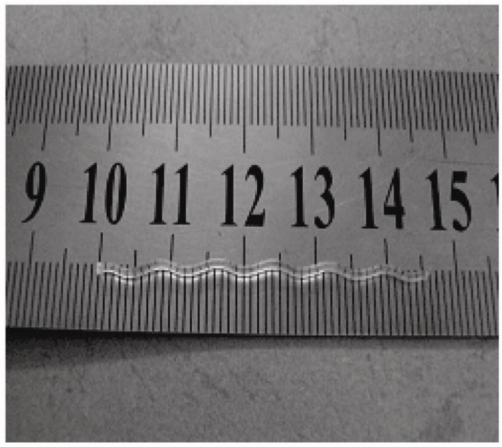


a



b

c

Figure (1): a. Steel Fibers b. Nylon Fibers c. The Used Steel and Nylon Fibers

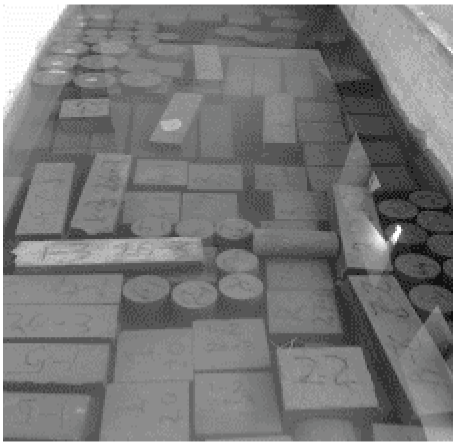
a

b

Figure (2): a. High Range Water Reducing Admixture Sikament® FF b. SikaFume® HR/-TU

a

b



c

Fig.(3): a. Fresh Concrete Introducing b. Casting of The Specimens c. Curing of The Specimens

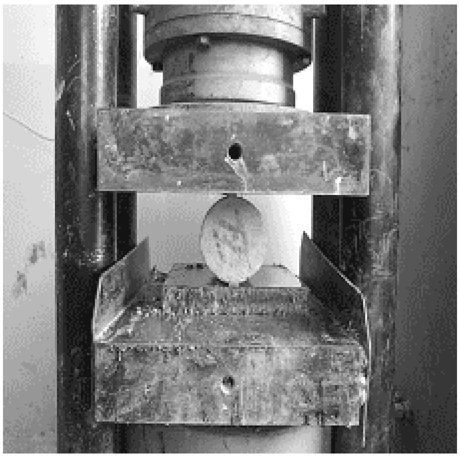


Fig.(4): Splitting Tensile Strength test

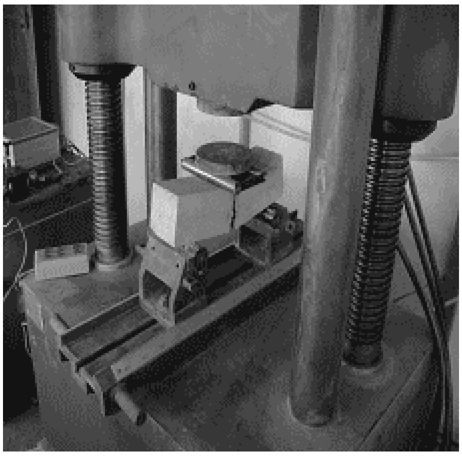


Fig.(5): Flexure Strength Test

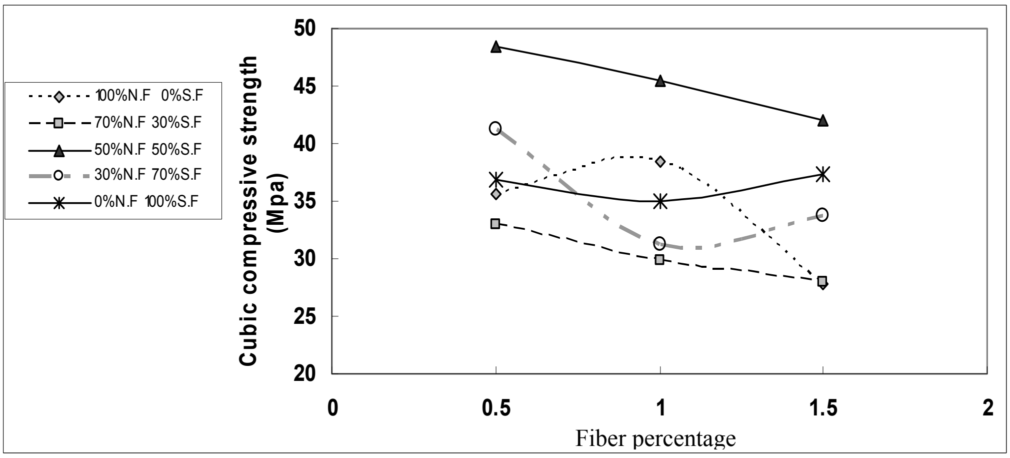


Figure 6. Effect of fiber percentage on concrete compressive strength

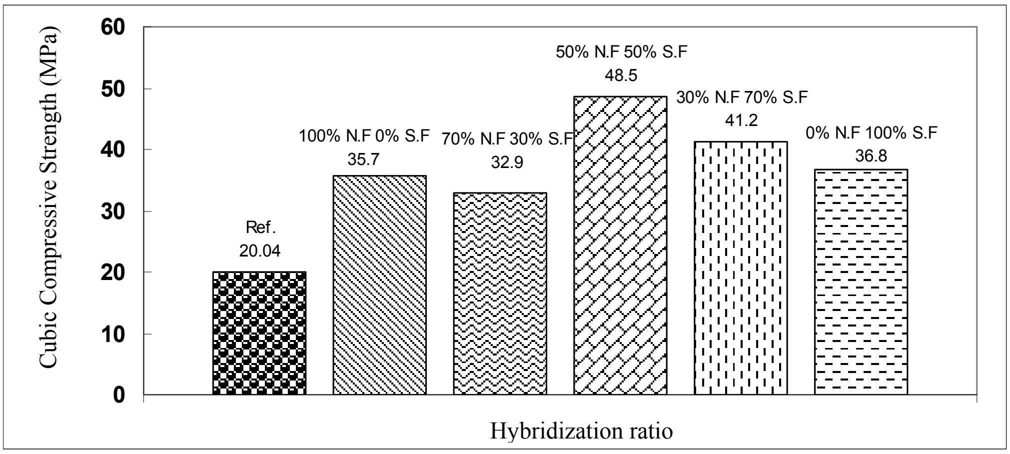


Figure 7. Effect of hybridization ratio on concrete compressive strength for 0.5%fiber

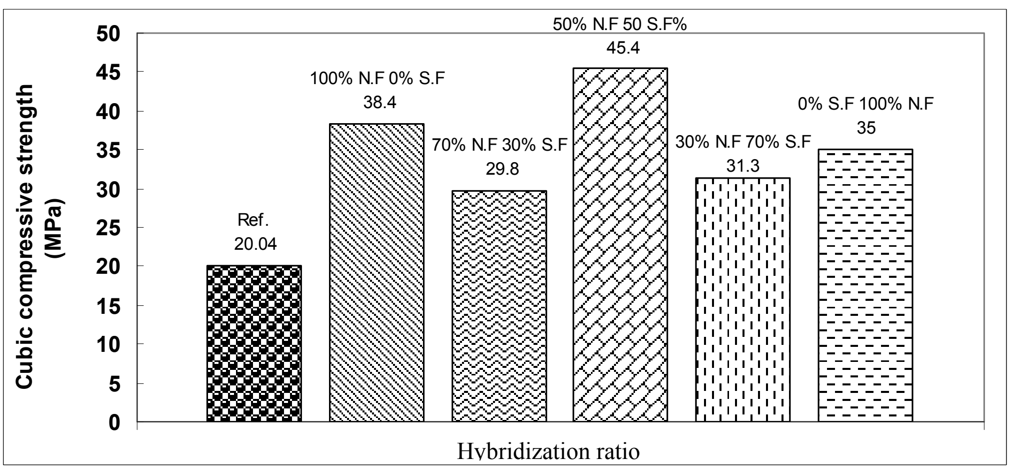


Figure 8. Effect of hybridization ratio on concrete compressive for 1%fiber

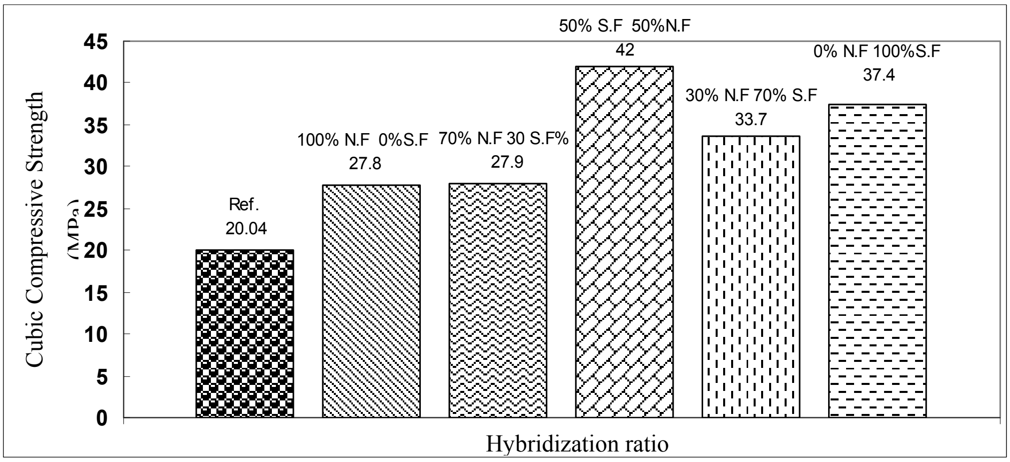


Figure 9. Effect of hybridization ratio on concrete compressive strength for 1.5%fiber

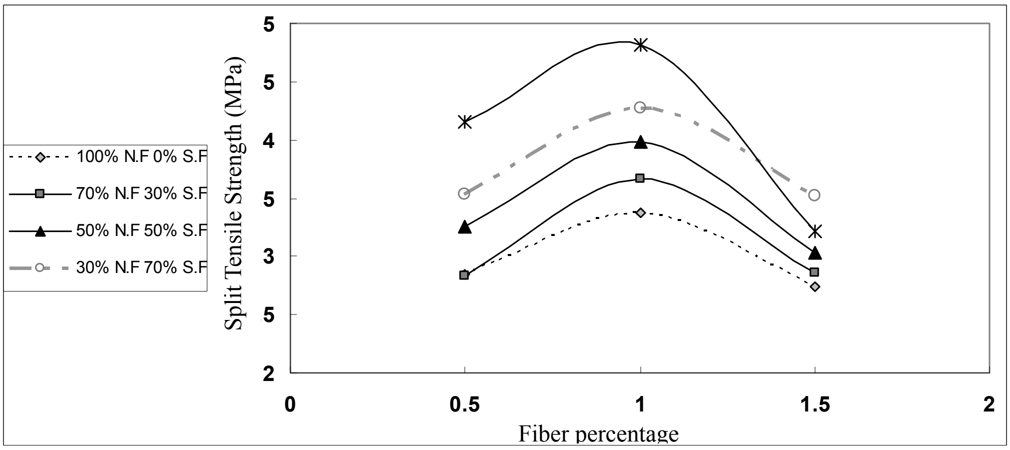


Figure 10. Effect of fiber percentage on concrete split tensile strength

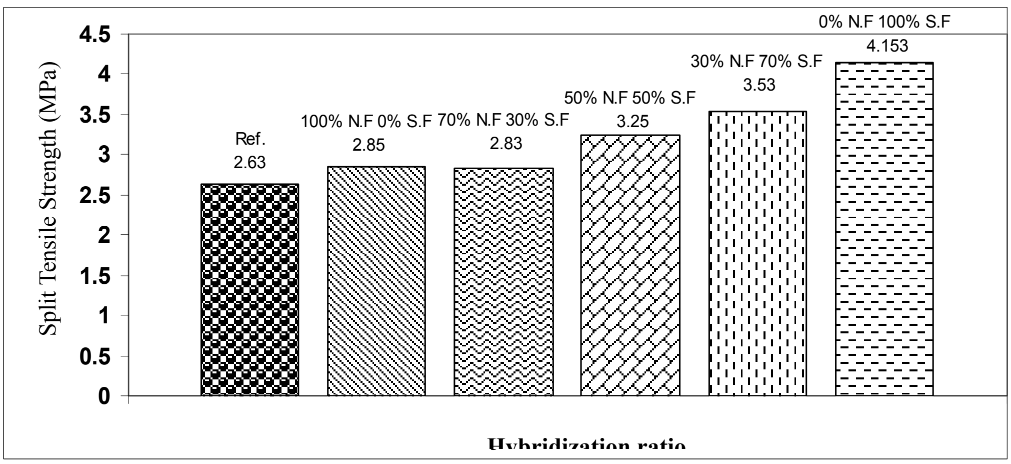


Figure 11. Effect of hybridization ratio on concrete split tensile strength for 0.5%fiber

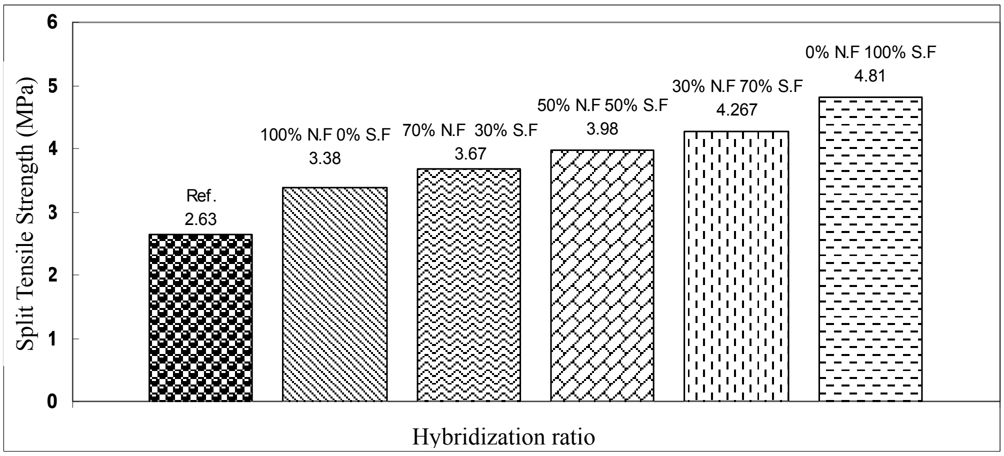


Figure 12. Effect of hybridization ratio on concrete split tensile strength for 1%fiber

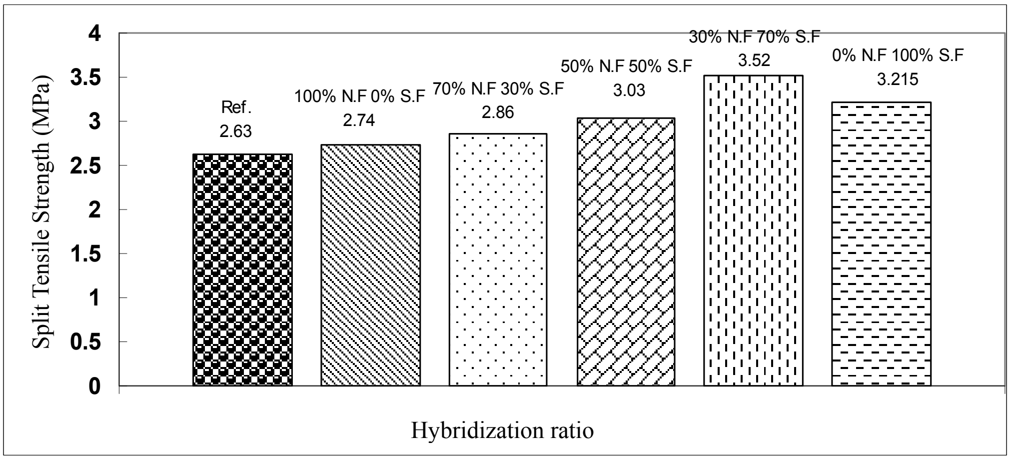


Figure 13. Effect of hybridization ratio on concrete split tensile strength for 1.5%fiber

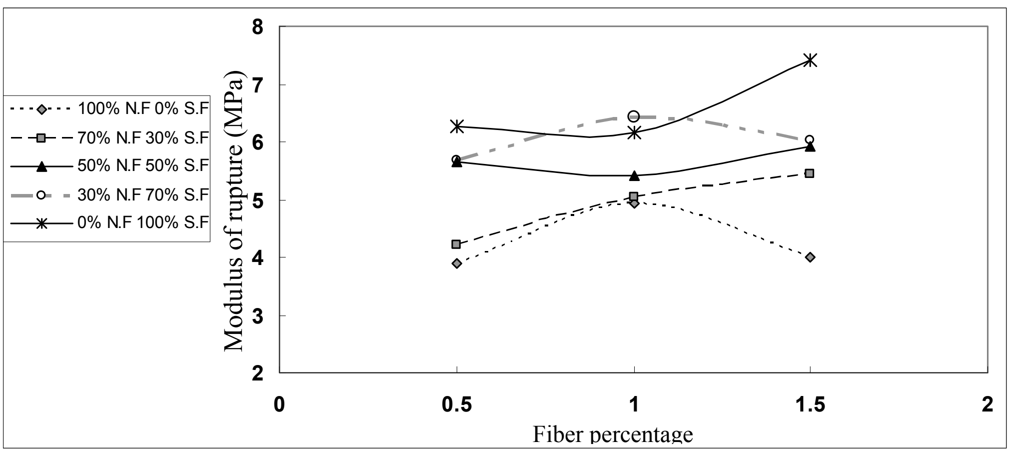


Figure 14. Effect of fiber percentage on concrete modulus of rupture

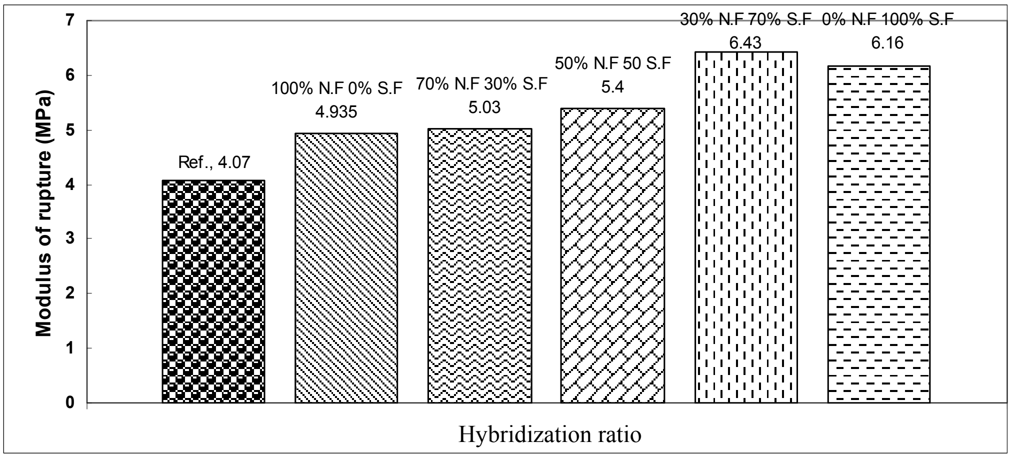


Figure 15. Effect of hybridization ratio on concrete modulus of rupture for 0.5%fiber

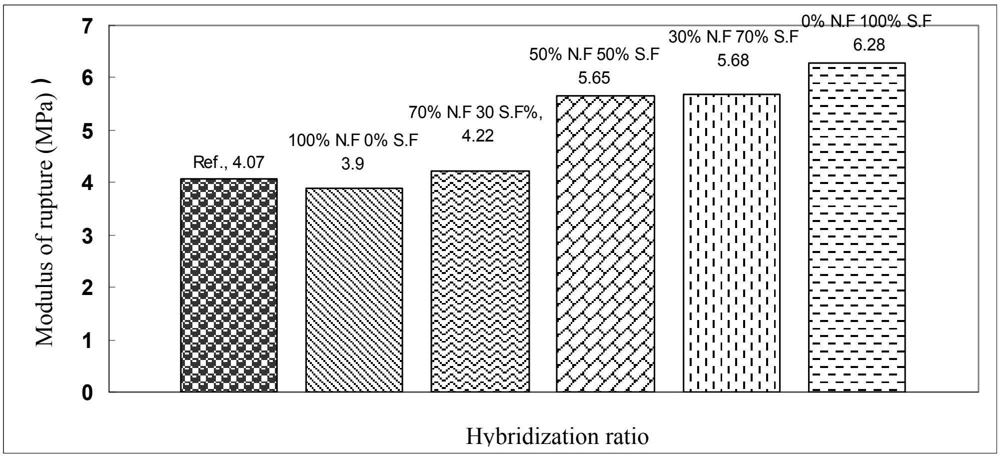


Figure 16. Effect of hybridization ratio on concrete modulus of rupture for 1%fiber

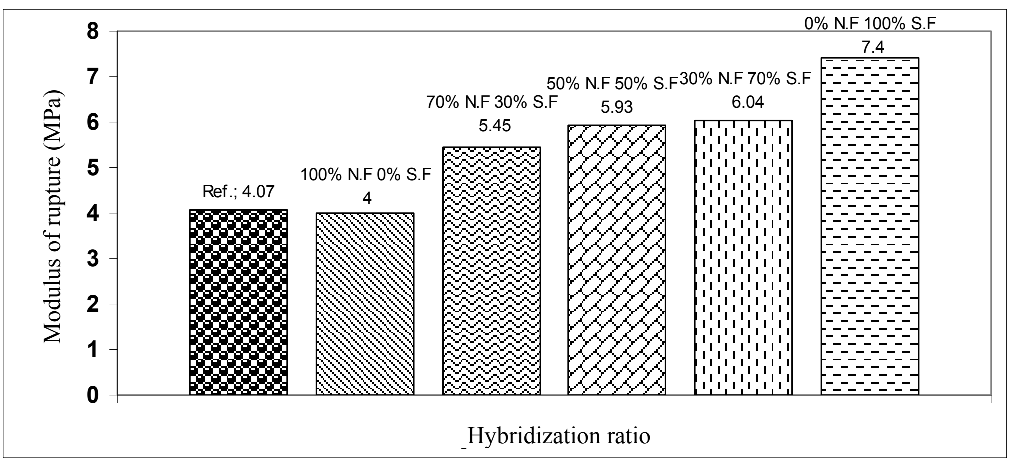


Figure 17. Effect of hybridization ratio on concrete modulus of rupture for 1.5%fiber