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EFFECT OF STEEL FIBERS ON THE COMPRESSIVE AND SPLITTING TENSILE STRENGTH OF NORMAL, MEDIUM AND HIGH STRENGTH CONCRETE

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ABSTRACT

The effect of steel fiber type and content on static compressive and splitting tensile strength of concrete was assessed for normal, medium and high strength concrete. Two different steel fibers, namely, hooked end and corrugated fibers, and five fiber contents by volume (i.e. 0.5, 1.0, 1.5, 2.0, and 2.5%) were the main variables. It was observed that the compressive and splitting tensile strengths increased with the addition of fibers. However, the rate of increase was dependant on the type of concrete (normal, medium or high), fiber type and fiber content. The highest increase in compressive and tensile strength was observed for medium strength concrete when reinforced with 2.5 % hooked end fibers, namely 54 and 140%, respectively. The increase in splitting tensile strength was, in some cases, triple that observed for the compressive strength. The considerable increase in strength observed in this study is due to the use of a superplasticizer and/or silica fume in the mixes with fibers. This helped in the efficient preparation of the samples and improved the bond between the fibers and matrix, which in turn improved the measured strength.

Keywords: compressive strength, high strength concrete, normal strength concrete, splitting tensile strength, steel fibers.

1 INTRODUCTION

Reinforcing brittle matrices to improve their mechanical properties is an age-old concept. The ancient Egyptians used straw to reinforce mud bricks [1]. However, the modern development of fiber reinforced concrete dates back only to the 1960's [2]. A brittle matrix subjected to tension initially deforms elastically. The elastic response is then followed by microcracking, localized macrocracking and finally fracture. Introduction of fibers results in post elastic property changes that range from subtle to substantial, depending upon a number of factors, including matrix strength, fiber type, fiber modulus, fiber aspect ratio, fiber strength, fiber surface bonding characteristics, fiber content, fiber orientation and aggregate size effects [3]. Fiber reinforced concrete is generally viewed as a concrete with increased strain capacity, impact resistance and energy absorption [4]. Initially it was assumed that the tensile strength of concrete can be substantially increased by fiber inclusion since the closely spaced fibers obstruct the propagation of microcracks and hence delaying the onset of

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tension cracks and increasing the tensile strength of the material [1]. However, most of the previous studies stated the minor effect of fibers on the compressive strength and the results of the splitting tensile strengths were inconclusive and difficult to interpret [5].

It is now generally accepted that at the steel fiber contents used in practice, which do not exceed 0.75 – 0.9 %, no significant increase in compressive or tensile strength is observed [2 and 6]. Mixing difficulties is the main reason why such low percentages of fibers are usually specified in concrete. However, some studies have been successful in incorporating up to 8% of fibers in typical test specimens [7], and in full-scale members prepared in the laboratory [8 and 9] fiber contents up to 2.5 % were included. It is necessary to study the effect of these higher fiber percentages on the compressive and splitting tensile strengths of the concrete.

The main objective of this study was to evaluate the effect of different types and percentages of short steel fibers on compressive and splitting tensile strength of normal (NSC), medium (MSC) and high (HSC) strength concrete. Statistical analysis was carried out in order to obtain a relationship between the cube compressive strength and the splitting tensile strength for different concrete types (NSC, MSC and HSC) with steel fibers as the literature survey did not cite such a relationship.

2 EXPERIMENTAL PROGRAM

2.1 Materials

The tested specimens were produced from ordinary Portland cement, natural sand and crushed basalt with a maximum size of 15 mm. The specific gravities of the sand and crushed basalt were 2.55 and 2.65, respectively. Steel fibers of varying amounts and types were added in the mixes. Two types of fibers were used, namely, hooked-end and corrugated steel fibers having a yield strength of 400 MPa. The aspect ratio of the two types of fibers was constant (L_f / D_f = 60 mm /1 mm = 60). Tap water was used in mixing and curing the test specimens. In all mixes with fibers and in the control MSC and HSC mixes without fibers, a superplasticizer, based on polynaphthalene sulfate, was added to maintain the slump for the mixes between 120 and 150 mm. In addition, 6.3 and 9.1 % silica fume by weight of cementitious material was used in the medium and high strength concrete mixes, respectively, in order to obtain the desired strength.

2.2 Details of Mixes and Test Specimens

A total of 29 mixes were made in this study, 7 mixes for normal strength concrete (NSC), 11 mixes for medium strength concrete (MSC) and 11 mixes for high strength concrete (HSC). The liquid (water + superplasticizer) / cementitious (cement + silica fume) ratios of the NSC, MSC and HSC mixes were 0.50, 0.37 and 0.28, respectively. Volume fractions of steel fibers were varied from 0 to 2.5% in increments of five-tenths of a percent. The details of the mixes used in this investigation are shown in Table 1. The test specimens were cubes of dimensions 150 x 150 x 150 mm for compression strength testing and 150 x 300 mm cylinders for splitting tensile strength test.

2.3 Preparation of Test Specimens

The mixing process was carried out by mixing all aggregates and half the mixing water in a 0.5 m^3 mixer for 2 minutes. After a standing period of 1 min, the cement, silica fume and/or superplasticizer, when used, were added and mixing was resumed for a further 2 min. During that time the fibers were slowly sprinkled by hand on the concrete in the revolving mixer. The moulds were filled and simultaneously vibrated on a vibrating table in order to obtain a homogeneous matrix. The concrete was finished with a trowel in the normal manner. The specimens were kept under wet hessian for one day before de-moulding. All samples were cured in water until testing at 28 days. The mean compressive strength of the concrete is shown in Table 1.

Table 1: Concrete Mix Proportions

Mix No.	Mix	Average Strength, f_c, Mpa	OPC, kg/m^3	Sand, kg/m^3	Crushed Basalt, kg/m^3	Water, Liter	Silica fume, kg/m^3	Superplasti-cizer Liter/ m^3	Fiber Shape *	v_f, %
1	NSC_1	32.4	350	700	1100	175	--	----	---	--
2	NSC_2	36	350	700	1100	171	--	4	HE	0.5
3	NSC_3	42	350	700	1100	169	--	6	HE	1.0
4	NSC_4	45	350	700	1100	167	--	8	HE	2.0
5	NSC_5	34.6	350	700	1100	171	--	4	CR	0.5
6	NSC_6	39	350	700	1100	169	--	6	CR	1.0
7	NSC_7	42	350	700	1100	167	--	8	CR	2.0
8	MSC_1	41	450	660	1180	168	30	10	--	--
9	MSC_2	52	450	660	1180	166	30	12	HE	0.5
10	MSC_3	55	450	660	1180	164	30	14	HE	1.0
11	MSC_4	56	450	660	1180	163	30	15	HE	1.5
12	MSC_5	59.5	450	660	1180	163	30	15	HE	2.0
13	MSC_6	65	450	660	1180	162	30	16	HE	2.5
14	MSC_7	48	450	660	1180	166	30	12	CR	0.5
15	MSC_8	51	450	660	1180	164	30	14	CR	1.0
16	MSC_9	53	450	660	1180	163	30	15	CR	1.5
17	MSC_{10}	55	450	660	1180	163	30	15	CR	2.0
18	MSC_{11}	57	450	660	1180	162	30	16	CR	2.5
19	HSC_1	73	550	600	1250	150	55	20	--	--
20	HSC_2	87	550	600	1250	148	55	22	HE	0.5
21	HSC_3	93	550	600	1250	147	55	23	HE	1.0
22	HSC_4	96	550	600	1250	146	55	24	HE	1.5
23	HSC_5	98	550	600	1250	145	55	25	HE	2.0
24	HSC_6	99	550	600	1250	143	55	27	HE	2.5
25	HSC_7	81	550	600	1250	148	55	22	CR	0.5
26	HSC_8	85	550	600	1250	147	55	23	CR	1.0
27	HSC_9	88	550	600	1250	146	55	24	CR	1.5
28	HSC_{10}	90	550	600	1250	145	55	25	CR	2.0
29	HSC_{11}	91	550	600	1250	143	55	27	CR	2.5

* HE , Hooked End fiber – CR, Corrugated Steel Fiber

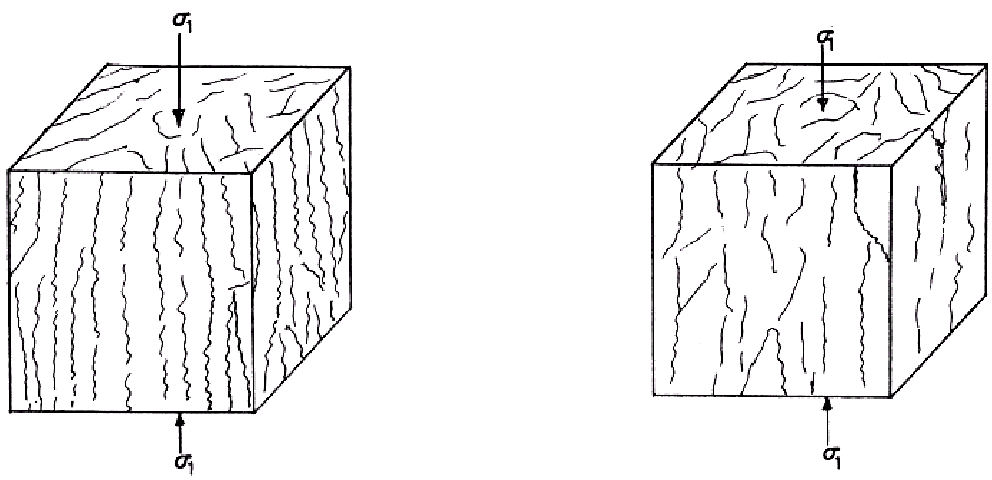
2.4 Test Techniques

Compressive strength tests were conducted on 150 mm x 150 mm x 150 mm cubes according to ECCS 203-2003, Part 3, Section 7-2 [10]. Three cubes were tested for each test variable to comprise a total of 87 cubes. Splitting tensile strength tests were conducted by loading the 150 x 300-mm cylinders across the diagonal according to ECCS 203-2003, Part 3, Section 7-3 [11]. Two samples were tested for each test variable to comprise a total of 58 cylinders. Only failure load was recorded.

3 TEST RESULTS AND DISCUSSION

3.1 Crack Pattern and Failure Mode

Figure 1 shows the crack pattern and failure modes for two cubes, plain concrete and 1% fiber concrete tested by Traina and Mansour [12]. Figure 2 shows the crack pattern and failure modes of three cubes in the current study, plain concrete, 0.5% and 1% fiber concrete, respectively. Figures 1(a) and 2(a) show the pattern of the cracks in the plain concrete specimen after failure under uniaxial compression, and it can be seen that the cracks are formed in two planes parallel to the applied load producing the common column-type fragments. The parallel cracks are caused by a splitting tensile stress in a direction normal to the compressive load. It can be seen from Figures 1(b), 2(b) and 2(c) that steel fiber concrete specimens showed similar crack patterns to plain concrete. The cracks formed on the unloaded surfaces are essentially parallel to the applied load. In addition, the cracks on the loaded surfaces are random. The use of fibers in Figures 2(b) and 2(c) resulted in a reduction in the number of visible cracks and less peeling in the outer surfaces of the specimens. Shah [13] argued that the presence of fibers introduces additional closing pressure during crack growth. This results in an increased resistance to crack growth in the matrix containing fibers. In other words the fibers suppress the transformation of microcracks into macrocracks and consequently the apparent tensile strength increases. This may also be attributed to the confinement effect of the steel fibers [12].



(a) Plain Concrete (b) 1% Hooked-End Fibers

Fig. 1: Failure modes under uniaxial compression [12].

(a) Plain Concrete (b) 0.5% Hooked-End Fibers (c) 1% Hooked-End Fibers

Fig. 2: Crack pattern and failure modes in the current study

3.2 Compressive Strength

3.2.1 Effect of fiber content

Figure 3 shows the gradual increase in the compressive strength with the increase in fiber content for the different types of concrete. Figure 4, shows the percentage increase in compressive strength due to fiber addition for the different types of concrete. For NSC, the increase of the steel fiber content from 0.0 to 0.5% resulted in an increase in the compressive strength by 11.1 and 6.8 % for concrete containing hooked-end fibers and corrugated steel fibers, respectively. Increasing the fiber content to 1% for the same concrete type resulted in a dramatic increase in the compressive strength by 30 and 20.4%, respectively. A further increase in fiber content to 2% led to a further increase of the compressive strength by 39 and 29.6%, respectively. It appears from Figure 3 that the increase in compressive strength at fiber percentages higher than 2% is insignificant.

For MSC, adding 0.5% fibers to the plain concrete resulted in increasing the compressive strength by 24.4 and 22% for concrete containing hooked-end and corrugated steel fibers, respectively. It was noticed that increasing the fiber content to 2.5% resulted in an increase in compressive strength of MSC by 54 and 46.6%, respectively. The increase in compressive strength for this type of concrete is higher than that observed for NSC and HSC.

It can be seen from the figures that adding 0.5% fibers led to an increase in compressive strength of HSC by 19.7 and 10.7 % for concrete containing hooked-end and corrugated steel fibers, respectively. Increasing the fiber content to 1% resulted in an increase in the compressive strength by 27.9 and 16.2 %, respectively. The maximum fiber content added to the HSC mix was 2.5% and led to an increase in the compressive strength for hooked-end fibers and corrugated steel fibers by 35.6 and 24.6 %, respectively.

Most researchers reported only a small effect of adding steel fibers on the concrete compressive strength, i.e. 0 – 15% increase in compressive strength at 1.5% fibers, [14]. Wafa and Ashour [15] reported a maximum increase in strength of only 4.6% with the use of 1.5% fibers. However, the fibers they used came in bundles collated together by water-soluble glue. In addition, the yield stress of the fibers was only 260 MPa. Such relatively weak and probably poorly dispersed fibers may be the reason for the reported small increase in compressive strength. On the other hand, Traina and Mansour [12] found a 22% increase in strength for concrete with 1.5% hooked end fibers. Their specimens had a strength of 40 – 50 MPa, which is the range for medium strength concrete in this investigation, but no superplasticizer or silica fume was used in the preparation of their samples. It may be argued that adding superplasticizer to the mixes with steel fibers while keeping the liquid (water + superplasticizer) / cementitious ratio constant in order to maintain the workability, as mentioned previously, contributed in increasing the compressive strength beside the contribution of steel fibers mentioned above. In support of this argument, Balaguru and

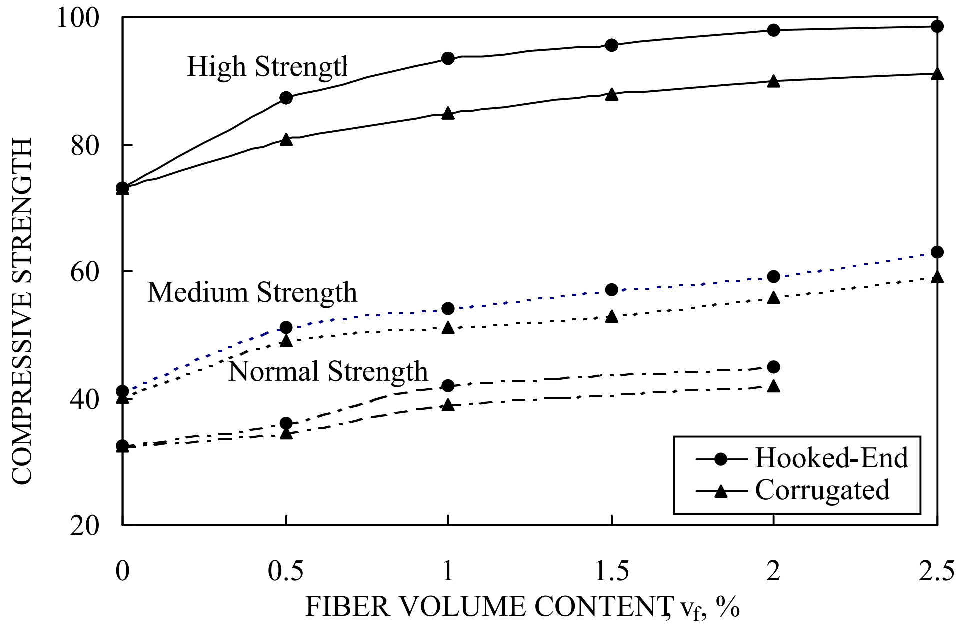


Fig. 3: Effect of fiber type and fiber content on the compressive strength of NSC, MSC and HSC cubes.

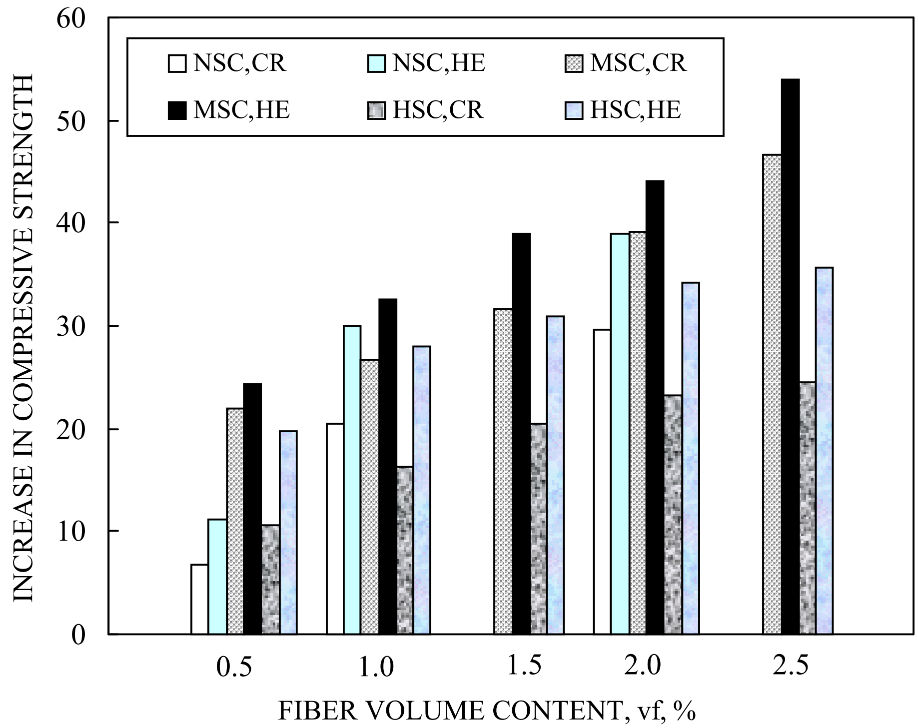


Fig. 4: Percentage increase in compressive strength with the addition of fibers for NSC, MSC, and HSC cubes.

Foden [16] found that the strength of light weight aggregate concrete increased from 22 MPa for the control concrete with no silica fume or fibers to around 45 MPa for concrete with 10% silica fume and 90 kg/m^3 hooked end fibers. Hence, by comparing the results of the current investigation with other reports, it would appear that the fiber properties (not only aspect ratio but also yield strength), and mix composition (the presence of superplasticizers and silica fume) play a major role in the effectiveness of the fiber in increasing the compressive strength.

3.2.2 Effect of fiber shape

The effect of fiber shape on the compressive strength of NSC, MSC, and HSC is shown in Figures 3 and 4. It can be seen from these figures that, generally, the addition of steel fibers to plain concrete increased the compressive strength for NSC, MSC and HSC containing hooked-end or corrugated steel fibers to different degrees. The difference in results of the effect of steel fibers on compressive strength for any given mix can be attributed to fiber shape since all other variables (e.g., water-cement ratio, specimen size, curing condition, and testing equipment) were identical for both types of fibers. The configuration of hooked-end fibers provides better anchorage than corrugated steel fibers, which in turn, enhances the confinement of fibers on the specimens. This led to an improvement of compressive strength of concrete containing hooked-end fibers over that containing corrugated steel fibers [2].

It can be seen from Figure 3 that the effect of fiber shape is more significant in HSC compared with that in MSC and NSC. For example, at 0.5 % fiber content, the percentage increase in compressive strength for HSC containing hooked-end fibers was almost double that for HSC with corrugated steel fibers (19.7% and 10.7%, respectively). For the same fiber content, only a slight increase in compressive strength, for MSC containing hooked-end fibers over that with corrugated steel fibers, was observed (24.4 and 22%, respectively). The difference in fiber performance is also apparent at higher fiber contents. This may be due to the better bond and better crack resistance offered by the HSC matrix and hence the anchorage action of the hooked end fibers was enhanced in this type of concrete.

3.2.3 Effect of original concrete strength on the fiber effectiveness

It can be seen from Figure 4 that the highest increase in compressive strength, at different fiber contents, was for the MSC mix containing hooked end fibers. The superior action of the hooked end fibers in concrete was explained in the previous section. It can be argued that a matrix containing silica fume tends to provide a better bond with the fibers making them more effective [2]. NSC offers a poorer bond to the fibers than the MSC and HSC mixes as it does not contain silica fume, therefore the action of the fibers in this concrete was impaired. On the other hand, as the concrete strength is increased, it becomes more brittle and as a result, a higher fiber content is needed to improve its performance [2]. Therefore, at the fiber contents used in this investigation, which were the same for all mixes, MSC exhibited the highest strength increase.

3.3 Splitting Tensile Strength

3.3.1 Effect of fiber content

Figures 5 and 6 show the effect of fiber type and fiber content on the splitting tensile strength of NSC, MSC and HSC containing either hooked-end or corrugated steel fibers. It can be seen that the increase in fiber content led to a steady increase in the splitting tensile strength. The trend lines seem to continue to go upwards beyond the fiber contents used in this investigation. The NSC was tested with 0.5, 1.0 and 2.0% fibers. It is clear from Figure 6 that NSC benefited the most from fiber inclusion, i.e. 20, 40 and 83.3% increase in splitting tensile strength with the percentages noted above of corrugated fibers compared to only 12.4,

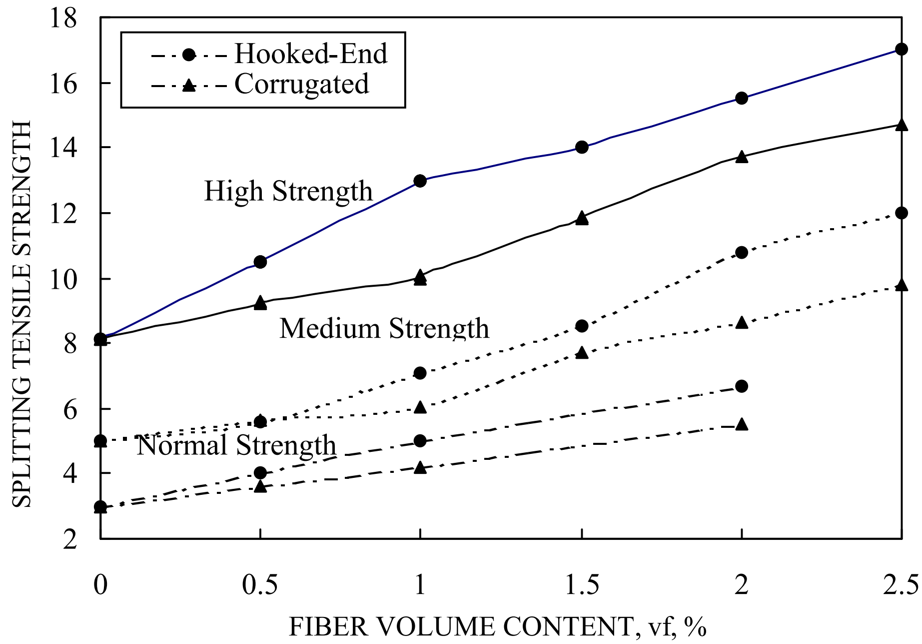


Fig. 5: Effect of fiber type and fiber content on the splitting tensile strength of NSC, MSC, and HSC cylinders.

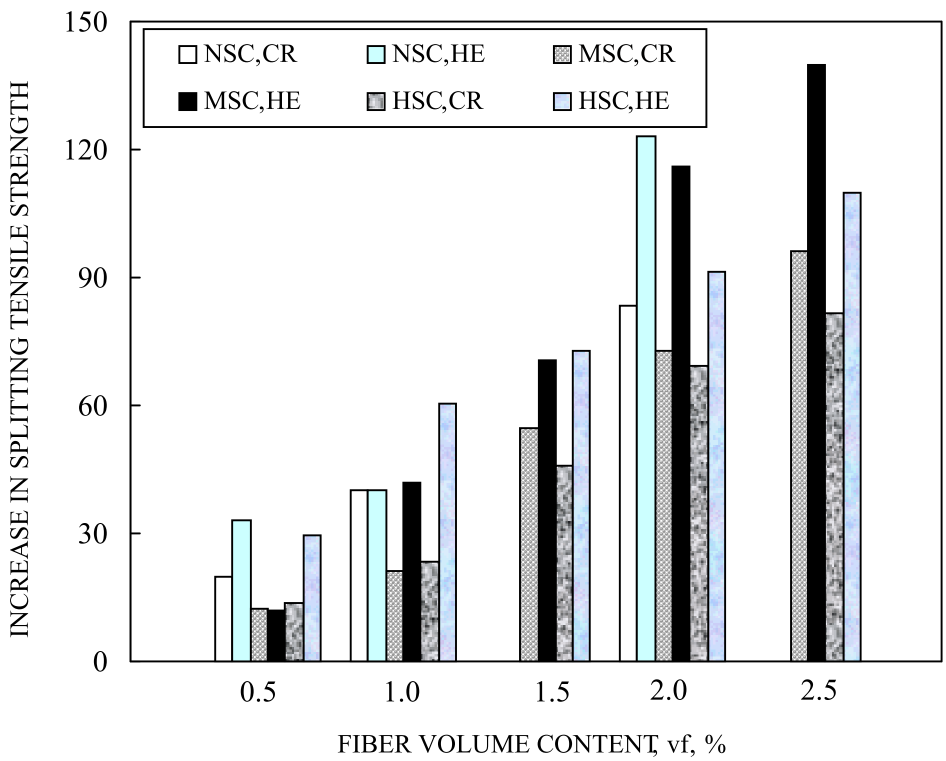


Fig. 6: Percentage increase in splitting tensile strength with the addition of fibers for NSC, MSC, and HSC cylinders.

21.4 and 73% for MSC, and 13.6, 23.4 and 69.1 for HSC, respectively. This increase in the splitting tensile strength for NSC seems in line with the findings of Balaguru and Foden [16] for light weight aggregate concrete for which the splitting tensile strength was more than doubled by the addition of fibers in mixes without silica fume. At the highest fiber percentage (2.5%), MSC recorded 140% increase in splitting tensile strength with hooked end fibers compared to 110% for HSC.

Shaaban and Gesund [7] carried out tests on concrete cylinders in order to establish the effect of compaction method (i.e., rodding or vibration) on the split cylinder tensile strength. They used 0, 2, 4, 6 or 8% of corrugated steel fibers and a w/c ratio of 0.5 to prepare their samples. Their data showed some reduction in the compressive strength and splitting tensile strength with the inclusion of the fibers for samples compacted by rodding especially when the percentage of fibers was 2 or 4%. Samples compacted by vibration showed a systematic increase in strength with the inclusion of fibers. The increase in splitting tensile strength was 18, 36 and 43% when the percentage of fibers was 4, 6 and 8%, respectively for the samples containing 38 mm maximum size of aggregates. Alternatively, the increase in splitting tensile strength was only 0, 7 or 22% when the fiber percentage was 2, 4 or 6%, respectively, for samples with maximum size of aggregates of 25 mm.

The results of Shaaban and Gesund [7] are not in agreement with the current investigation. By examining their mix proportions it is revealed that no superplasticizer was used in their sample preparation. It may be argued that the use of superplasticizer in the mixes of the current investigation , not only improved the strength through more efficient hydration of the cement, but it also helped in the efficient mixing and compaction of fiber concrete. Therefore, the recorded compressive and splitting tensile strengths were higher than those reported in Shaaban and Gesund's investigation [7].

3.3.2 Effect of strength level on the increase in tensile strength of fiber concrete

It can be seen from Figures 5 and 6 that the splitting tensile strength consistently increased with the increase of fiber content and the rate of increase was dependent on concrete type (NSC, MSC and HSC). For example, adding 0.5% hooked end fibers for NSC resulted in increasing the splitting tensile strength by 33.3% while adding the same content and same type of fibers to MSC and HSC resulted in increasing their splitting strength by 12 and 29.6 %, respectively. Adding 1% hooked-end fibers for NSC resulted in increasing the splitting strength by 40% (6.7% only higher than that with 0.5% fibers). Adding the same fiber content to MSC and HSC led to a large increase in their splitting strength, 42% and 60.4%, compared to plain concrete, which are higher than those with 0.5% fibers by 30% and 30.8%, respectively. This is in agreement with the argument of Balaguru and Shah [2] who reported that the higher the strength of the concrete, the higher the fiber percentage needed for strength improvement.

3.4 Comparison Between the Effect of Fiber Addition on the Compressive and Tensile Strengths

It can be seen from Figures 3, 4 and 5, 6 that the effect of adding steel fibers is more significant on the splitting tensile strength compared to that on the compressive strength and this effect increases with the increase of fiber content. For example, the increase in splitting tensile strength for HSC was 1.5, and 3.1 that of compressive strength at 0.5% and 2.5% of hooked end fibers content, respectively. Wafa and Ashour [15], who also worked with HSC, found that the addition of 1.5% by volume of hooked-end fibers resulted in a small increase of approximately 4.6% in the compressive strength, and resulted in 159.8% increase in the splitting tensile strength.

By comparing Figure 3 and Figure 5 it can be seen that splitting strength values were more sensitive to the fiber shape than compressive strength results for the same concrete type. This is clear especially in MSC and HSC for fiber contents higher than 1%. For example, at 1% fiber content, the percentage increase in the compressive strength values for HSC containing hooked-end fibers was 1.72 that of the same concrete containing corrugated steel fibers, whilst the percentage increase in splitting strength values for HSC containing hooked-end fibers was 2.58 that of the same concrete containing corrugated steel fibers.

3.5 Prediction of Splitting Tensile Strength Using Compressive Strength Results

The relationship between tensile and compressive strength depends on the compressive strength level, type of aggregate used in concrete and the presence of mineral admixtures. In general as the compressive strength increases the tensile strength increases but at a decreasing rate [1].

Wang and Salmon [17] and ACI 318 [18] reported the relation between the split cylinder tensile and the cylinder compressive strengths for normal strength concrete. Chemrouk and Hamrat [19] predicted a similar relation for medium strength concrete whilst, Wafa and Ashour [15], Bakhsh et. al. [20] and Nilson [21] established formulae for high strength concrete. Regan et. al. [22] worked on functions between the split cylinder tensile strength and the cube compressive strength for normal and high strength concrete.

To the knowledge of the author no relationships were cited in the literature between the split cylinder tensile strength and the cube compressive strength when fibers are used. It would be useful to establish such relationships as both tests are standard tests and especially for different concrete strengths, fiber types and fiber contents.

Figure 7 shows the splitting tensile strength, f_{ct} as a function of the concrete cube compressive strength, f_{cu}, for different concrete types, NSC, MSC and HSC containing hooked-end and corrugated steel fibers. Regression analysis was carried out and Figure 7 also shows the best-fit curves for the three concrete types containing the two types of fibers. The relationships for different concrete types with fiber types used in this investigation are as follows:

For NSC

1- Concrete containing corrugated steel fibers

$$f_{ct} = (1 + 32\ v_f\ \%) \times 0.53 \times \sqrt{f_{cu}},\ \mathrm{N/mm^2} \tag{1-a}$$

2- Concrete containing hooked-end fibers

$$f_{ct} = (1 + 28\ v_f\ \%) \times 0.63 \times \sqrt{f_{cu}},\ \mathrm{N/mm^2} \tag{1-b}$$

For MSC

1- Concrete containing corrugated steel fibers

$$f_{ct} = (1 + 36\ v_f\ \%) \times 0.68 \times \sqrt{f_{cu}},\ \mathrm{N/mm^2} \tag{2-a}$$

2- Concrete containing hooked-end fibers

$$f_{ct} = (1 + 32\ v_f\ \%) \times 0.78 \times \sqrt{f_{cu}},\ \mathrm{N/mm^2} \tag{2-b}$$

For HSC

1- Concrete containing corrugated steel fibers

$$f_{ct} = (1 + 42\ v_f\ \%) \times 0.78 \times \sqrt{f_{cu}},\ \mathrm{N/mm^2} \tag{3-a}$$

2- Concrete containing hooked-end fibers

$$f_{ct} = (1 + 35\ v_f\ \%) \times 0.94 \times \sqrt{f_{cu}},\ N/mm^2 \qquad (3\text{-}b)$$

It can be noticed from the above equations (1-3) that the general form of these equation is:

$$f_{ct} = (1 + a\ v_f\ \%) \times b \times \sqrt{f_{cu}},\ N/mm^2 \qquad (4)$$

Where the first term in Equations (1-4) simulates the contribution of fiber content with a multiplication factor “a”, the second term “b” simulates the contribution of fiber type, and the last term is the square root of cube compressive strength. It can be observed from the above equations that both contributions of fiber content and type are dependant on concrete type and fiber type. The inclusion of superplasticizers in all mixes with fibers and the use of silica fume in MSC and HSC mixes have co-operated with the fibers in achieving the strength improvement. This may explain the observed considerable increase in both of the factors “a” and “b” with higher strength concrete as the equations also take the effect of superplasticizers and silica fume into account. The above equations also show that, for the same concrete strength, the multiplication factor, a, reduces while the term “b” increases with changing the fiber shape from corrugated to hooked end fibers. This means that the driving force behind the strength increase is either the use of a high percentage of corrugated fibers or the mere presence of hooked end fibers.

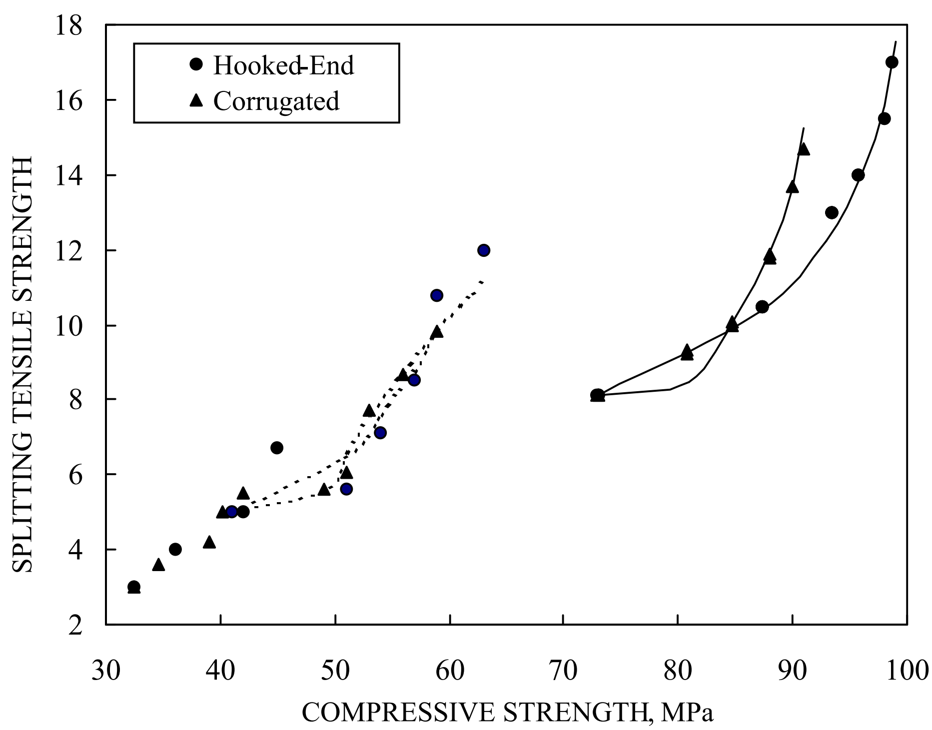


Fig. 7: Prediction of splitting tensile strength using experimental cube compressive strength results.

4 CONCLUSIONS

Based on the tests carried out in this investigation, the following conclusions can be drawn:

1. The failure mode of concrete with fibers shows less visible cracks and surface crushing compared to plain concrete without fibers due to the confining effect of fibers in concrete.
2. The increase of compressive strength, as a percentage of concrete strength without fibers, for NSC, MSC and HSC tested in this investigation reached a maximum of 39%, 54% and 35.6% when 2.0 and 2.5 and 2.5% volume of hooked end fibers, were introduced to the concrete, respectively. This is much higher than the increase reported in other studies. By careful examination of the materials properties and mix details of related work in the literature, it became clear that the use of fibers with a high yield strength, superplasticizer and silica fume in the current investigation has contributed to the strength gain exhibited here.
3. The fiber shape may have a profound effect on the magnitude of compressive strength increase due to the inclusion of fibers especially for HSC. Hooked end fibers almost doubled the strength gain of corrugated fibers at a volume of 0.5% fibers.
4. The original concrete strength plays an important role in the strength increase due to fiber addition. In this study, the compressive strength of MSC exhibited the highest increase with fiber addition. This was explained by the fact that MSC matrix has a better bond with the fibers than NSC, whilst the HSC concrete needs higher fiber percentages for strength improvement.
5. The increase in splitting tensile strength, as a percentage of plain concrete strength without fibers, reached a maximum of 123.3, 140, and 110% for NSC, MSC and HSC when 2.0 and 2.5 and 2.5% hooked end fibers, were introduced to the concrete, respectively. This increase was in agreement with most results reported in the literature.
6. The splitting tensile strength of NSC increased dramatically with fiber inclusion even at 0.5% fibers. However, MSC and HSC required higher percentages of fibers for substantial improvement in splitting tensile strength.
7. The increase in splitting tensile strength was much higher than that for the compressive strength due to fiber addition. This was especially clear at high fiber percentages. For example, the increase in splitting tensile strength with hooked end fibers for HSC was 1.5, and 3.1 that of compressive strength at 0.5% and 2.5% fiber content, respectively.
8. Relationships were developed between the splitting tensile and cube compressive strengths for fiber reinforced NSC, MSC and HSC. These relationships are highly dependant on both of the type and the content of fibers.

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