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Experimental Investigation of the Compressive, Tensile and the Flexural Capacity of Beams made of Steel Fiber Reinforced Concrete (SFRC)

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Abstract : *Experimental investigations are conducted to study the increase in compressive, tensile and flexural capacity of fixed, cantilever and simply supported test beams made of Steel Fiber Reinforced Concrete (SFRC). In this research customized enlarged end fibers are used with a volume fraction of 1.5%. Fibers consists of low aspect ratio are used and sufficient capacity enhancement is observed by experimental testing in this study. Two different aggregate types are used to make the concrete i.e. stone and brick and the effects of steel fibers on these two types of concrete specimens are also evaluated. Stone and brick concrete specimens show significant increase in the compressive, tensile and flexural capacity and in some cases ductility due to the presence of steel fibers. Flexural test shows the increase in flexural capacity of about 8% to 60%, compressive strength is increased by about 8% to 19% and tensile strength by about 39% to 149%. This investigation proposes steel fibers as an additive for concrete to make flexural members of structures to increase the capacity as well as ductility which will reduce the risk of brittle failure during earthquake or any other load.*

Keywords: *Steel Fiber Reinforced Concrete (SFRC), flexural capacity, steel fiber volume, aspect ratio of fiber, compressive strength, tensile strength, ductility.*

Introduction

Fibers have been used to strengthen a weaken matrix for many centuries, such as straw in mud bricks, a horse hair in gypsum plastering etc. For the last few decades, asbestos fiber is being used to reinforce cement mortar in the asbestos cement industry. Recently other types of fibers have been introduced in both research and industry fields. Steel, carbon, glass, polypropylene and polyethylene short fibers are used to strengthen the concrete and cement mortar. For many years, ACI 544.4R-88 has been working towards the development of standardized testing techniques as applied to fiber reinforced concrete. The ACI committee suggested that the work is not finished and a continuous research effort is needed to improve testing and reporting methods for SFRC.

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Ramakrishnan et al. (1980) stated that Steel fiber reinforced concrete can be considered as a new and totally different concrete construction material. Fiber reinforcement has considerably improved the flexural strength, direct tensile strength, fatigue strength, shear and torsional strength, shock resistance, ductility and failure toughness (Uddin et al., 2013). According to Ghalib (1980), fiber reinforcement presents several advantages such as superior crack control, ductility, energy absorption capacity and improving the internal tensile strength of the concrete due to bonding force between the fiber and the matrix. Steel fibers arrest the advancing cracks and increase post cracking stiffness at all stages of loading, which results in narrow crack width and substantially less deformation (Swamy and Al-Ta'an, 1981). Concrete inherently exhibits low tensile strength and insufficient ductile behavior. These deficiencies are commonly circumvented by providing conventional steel reinforcement or applying prestress in concrete members. Alternatively, inclusion of steel fibers into concrete has been found to enhance tensile strength and ductility of the material itself. Considering the importance of concrete in the construction industry and its weakness in tension and against impact, steel fibers are best suited to obtain desirable modifications in concrete properties (Dwarakanath and Nagaraj, 1991).

Based on past study, experimental investigations are conducted to study the increase in flexural capacities of simply supported, cantilever and fixed beam using steel fiber reinforced concrete (SFRC). Experimental evidences are gathered in this work and supported also by a few past studies suggest that steel fiber mixed with concrete offer higher flexural, compressive and tensile strengths. However beams made of such concrete must have larger ductile property under load. This fundamental perception motivated the current research to evaluate the attainable flexural capacity enhancement in concrete beams made concrete containing locally available fibers in Bangladesh. In this context, Steel Fiber Reinforced Concrete (SFRC) beams made with two different aggregates (i.e. stone and brick) are tested. According to ASTM C 1609/C 1609M–06 and ASTM C 78–02 specimen dimension is selected but two new different type of support condition is introduced i.e. fixed and cantilever support in this research to be tested experimentally.

The main objective of this research is to investigate the property enhancements using the steel fiber reinforced concrete. Effect due to the fiber volume ratio on capacity enhancement is analyzed. Besides these, this investigation also tends to examine failure patterns of the beams made of SFRC and to investigate the member ductility by using SFRC. In the absence of a reliable experimental results of the compressive strength, tensile strength and flexural strength (with different support condition) of

SFRC with the easily available fibers in context of Bangladesh, the current research aims to investigate the capacity enhancement of SFRC from experimental investigations.

Mechanism behind Crack Areesting

Recent earthquake in different parts of the world have revealed again the importance of design of reinforced concrete with high ductility. Strength and ductility of structures depend mainly on proper detailing of the reinforcement in flexural members. Brittle failure of these members may lead to catastrophic damages to the structure and the people living on these structures. To increase the ductility of the flexural members, using Steel Fiber Reinforced Concrete (SFRC) can be an efficient technique. Load carrying capacity of steel fiber at post-cracking stage made it point of interest in modern research. Cracks are initiated due to the tension and propagate to the neutral axis of the flexural member. Steel fibers arrest the micro-cracks and cracks are resisted by the tensile property of the fiber. In the hardened state, when fibers are properly bonded, they interact with the matrix at the level of micro-cracks and effectively bridge these cracks thereby providing stress transfer media that delays their coalescence and unstable growth (Figure 1). Steel Fibers are used as a volume percentage in the concrete mortar which will create a matrix and bond strength will be increased. If the fiber volume fraction is sufficiently high, this may result in an increase in the tensile strength of the matrix . Indeed, for some high volume fraction fiber composite, a notable increase in the tensile as well as flexural strength over and above the plain matrix has been reported. Once the tensile capacity of the composite is reached and coalescence and conversion of micro-cracks to macro-cracks has occurred, fibers, depending on their length and bonding characteristics continue to restrain crack opening and crack growth by effectively bridging across macro-cracks. This post peak macro-crack bridging is the primary reinforcement mechanisms of steel fiber reinforced concretes (SFRC).

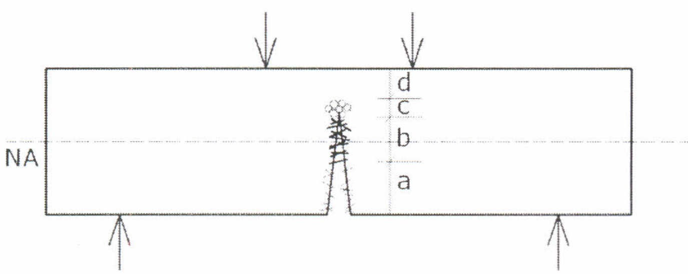


Figure 1: Mechanism of fibers in flexure (a) free area of stress, (b) fiber bridging area, (c) micro-crack area and (d) undamaged area

Types of Steel Fibers

There are different types, sizes and shapes of fiber that can be used as a construction material (Figure 2). Steel fibers intended for reinforcing concrete are defined as short, discrete lengths of steel having an aspect ratio in the range of 20-100, with any cross section and that are sufficiently small to be randomly dispersed in an unhardened concrete mixture using usual mixing procedures. According to ASTM A 820/A 820M – 06, five general types of steel fibers are identified based upon the product or process used as a source of the steel fiber material, they are, Type I: cold-drawn wire, Type II: cut sheet, Type III: melt-extracted, Type IV: mill cut, Type V: modified cold-drawn wire and the fibers shall be straight or deformed.

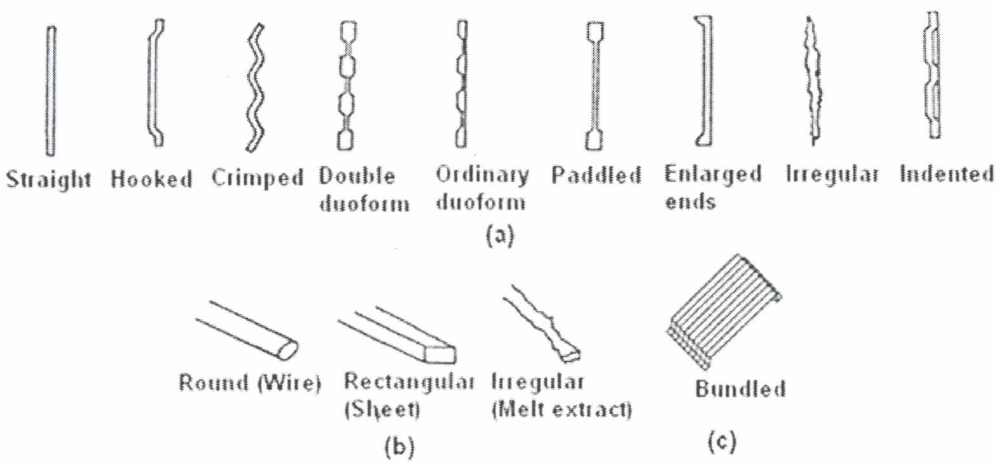


Figure 2: Different shape of steel fibers (a) steel fiber shapes, (b) steel fiber cross sections and (c) fiber glued together into a bundle

Experimental Program and Data Aquisition

Properties of concrete

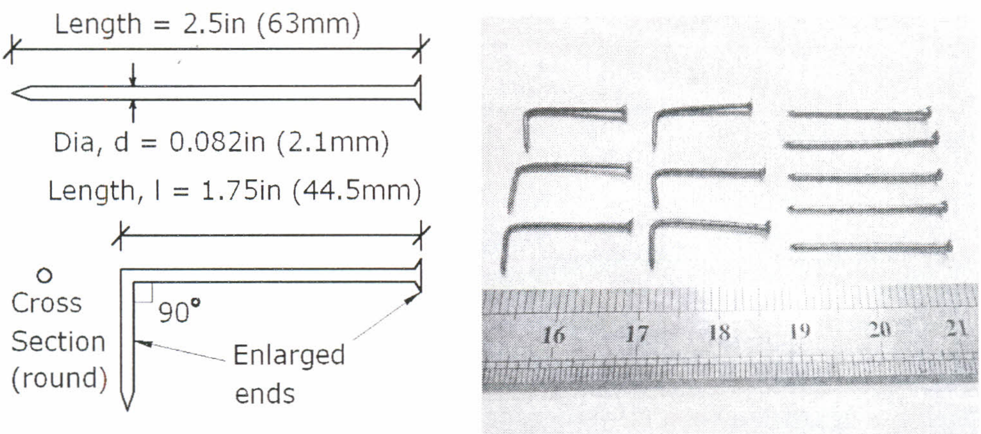
Steel Fiber Reinforced Concrete (SFRC) made with hydraulic cements and containing fine and coarse aggregates along with discontinuous discrete steel fibers are considered in this research. But ACI Committee (ACI 544.4R-88) believes that many other applications will be developed once engineers become aware of the beneficial properties of the material and have access to appropriate design procedures. Two types of aggregates i.e. brick and stone are chosen to make the plain concrete and SFRC. The sizes of the aggregates are maintained 1in passing & 3/4in retained and 3/4in passing & 1/2in retained with a weight ratio 1:1. The concrete mix ratio is maintained 1:1.5:3 and water cement ratio is 0.45. The compressive and tensile (splitting) strengths are measured according to ASTM C 39/C 39M–05 and ASTM C 496/C 496M–04 respectively with the concrete cylinder specimens of 4in (100mm) diameter and 8in (200mm) height. The average compressive strength of brick and stone plain concretes are 3500 psi (24.5 MPa) and 4100 psi (28.7 MPa) respectively and tensile strengths are 648 psi (4.5 MPa) and 448 psi (3 MPa) respectively. Again the average compressive strength of brick and stone SFRC (1.5% steel fiber volume) are 4100 psi (28.7 MPa) and 4800 psi (33.6 MPa) respectively and tensile strengths are 944 psi (6.5 MPa) and 1104 psi (7.6 MPa) respectively. These results are provided in Table 1. A steel fiber volume ratio of 1.5% is selected for making SFRC after parametric experimental investigation.

Table 1: Engineering properties of concretes

Type of concrete	Steel fiber volume (%)	Compressive strength psi (MPa)	Tensile strength psi (MPa)
Brick concrete	0	3500 (24.5)	648 (4.5)
Stone concrete	0	4100 (28.7)	448 (3)
Brick SFRC	1.5	4100 (28.7)	944 (6.5)
Stone SFRC	1.5	4800 (33.6)	1104 (7.6)

Properties of Steel Fibers (SF)

An advantage of the pullout type of failure is that it is gradual and ductile compared with the more rapid and possibly catastrophic failure that may occur if the fibers break in tension. Generally, the more ductile the steel fibers are, the more ductile and gradual the failure of the concrete. In this research customized enlarged end fibers are used to make SFRC specimens. The average tensile strength of each fiber shall not be less than 345 MPa (50,000 psi) according to ASTM A 820/A 820M–06. In this research tensile strength of each fiber is about 71,578 psi (494 MPa) at an average and attained maximum value of up to 80,619 psi (556 MPa) which satisfies the ASTM code requirement. Since pullout resistance is proportional to interfacial surface area, smaller diameter round fibers offer more pullout resistance per unit volume than larger diameter round fibers because they have more surface area per unit volume. Thus, the greater the interfacial surface area (or the smaller the diameter), the more effectively the fibers bond. The diameter and cross-sectional area of the fibers are 0.083in (2.1mm) and 0.0054 in^2 (3.46 mm^2) respectively. The second factor which has a major effect on workability is the aspect ratio (*l/d*) of the fibers. The length of the fiber is 2.5in (63 mm) and the diameter is 0.083in (2.1 mm) which is given in Figure 3. The aspect ratio of this fiber is 21.16 considering the effective length 1.75in (44.5mm).



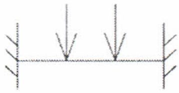
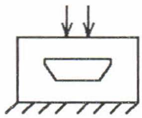
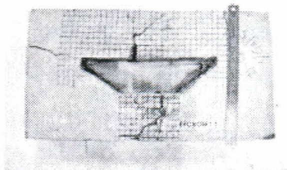
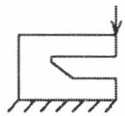
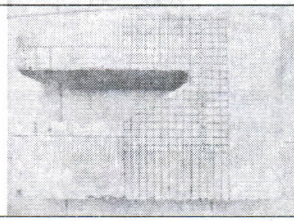
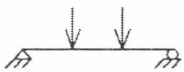
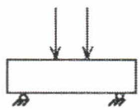
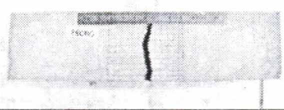
(a) (b)

Figure: 3: (a) and (b) Size and geometry of the customized enlarged ends steel fibers employed in this research.

Strategy behind the sizes and shapes of the flexural specimens

Usually flexural tests of concrete are done on simply supported beam. This research intends to study the flexural behaviours of cantilever and fixed supported beams in addition to simply supported beam. To this end, the sizes and shapes of the flexural specimens are selected to be tested in different support conditions. In this regard, the ends of fixed and cantilever beam are made higher rigidity and stiffness by gradual increase of cross sectional area in the vertical part. Table 2 provides in detail the considerations selected for sizes and shapes of flexural specimens. The sizes of the simply supported test beams are 6x6x24in (150x150x600mm) with an effective span of 18in (450mm), cantilever test beams are 4x4x12in (100x100x300mm) and the fixed supported test beams are also 4x4x12in (100x100x300mm). The simply supported and fixed beams are tested applying 2 point loading and the cantilever beams are tested applying 1 point loading at the free end.

Table 1: Experimental strategy on flexural beams

Type of beam	Theoretical	Strategical	Experimental
Fixed supported beam			
Cantilever beam			
Simply supported beam			

Gathering the vertical and horizontal load and displacement data

A total of 24 short concrete cylinders and 12 flexural members are tested under axial compression at constant displacement rate of 0.5mm/min, until the failure in a 1000 kN capacity digital Universal Testing Machine (UTM). Vertical displacement and axial loads are recorded from the load cell of UTM. The lateral strain in tension test is measured by analyzing the image histories obtained from High Definition (HD) video camera (60 frames per second) and employing an image analysis technique which is called Digital Image Correlation Technique (DICT) which is also done in the work of Islam (2011) and Islam et al. (2011). The measurements are taken by using a customized DICT simultaneous vertical load and horizontal strain data acquisition system (Figure 4). There exists an extra advantage of DICT over conventional electric strain gauge measurement i.e. the failure location may not be predicted (especially in new specimens) so that actual strain data acquisition at failure location may be failed which is not desired. The strain is measured by selecting different frames from a test video and measuring the pixels of two definite points which change position due dilation under loading. The load and displacement histories obtained from the load cell of the digital UTM are synthesized with the strain measurement results gathered from image analysis outputs.

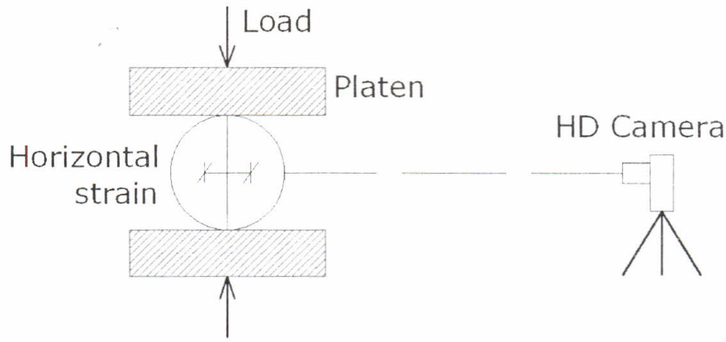


Figure 4: Digital Image Correlation Technique (DICT) for horizontal strain data acquisition.

Effects Dut to Steel Fiber Reinforcements

Effect of steel fiber volume ratio

Concrete reinforced with low-volume fractions (up to 2 percent) of short fibers usually has a compressive strength very similar to that of the plain unreinforced concrete, but exhibits much greater resistance to crack formation and propagation. In the 1st phase of the investigation, the compressive and tensile strength are evaluated with 1.0%, 1.5% and 2.0% steel fiber volume with concrete by making cylinders. Figure 5 shows the legend style of different specimens. In compression test, the compressive strength of brick SFRC is increased about 7%, 36% and 44% for 1, 1.5 and 2 percent fiber volume respectively (Figure 6a), but for stone SFRC these percentages are 5%, 20% and 26% respectively (Figure 6b) with respect to plain concretes. In tension test, the tensile capacities of brick concretes are increased about 39%, 89% and 217% for 1, 1.5 and 2 percent fiber volume respectively (Figure 7a), but for stone aggregate these percentages are 28%, 49% and 78% respectively (Figure 7b). The experimental results showed that, tensile and compressive strengths increased with the increase in percentage of fiber volume. From the view point of the above discussion a clear understanding is created i.e. fiber volume up to 2 percent can give maximum strength. Emphasize is given in major two concerns, i.e. (i) Economy and (ii) Strength. This investigation shows that, significant enhancement is achieved using 1.5% steel fiber volume while 2% fiber volume become uneconomic. So, in the 2[nd] phase, fiber volume of 1.5% is selected for preparing the flexural specimens as well as cylinder to get representative compressive and tensile strengths.

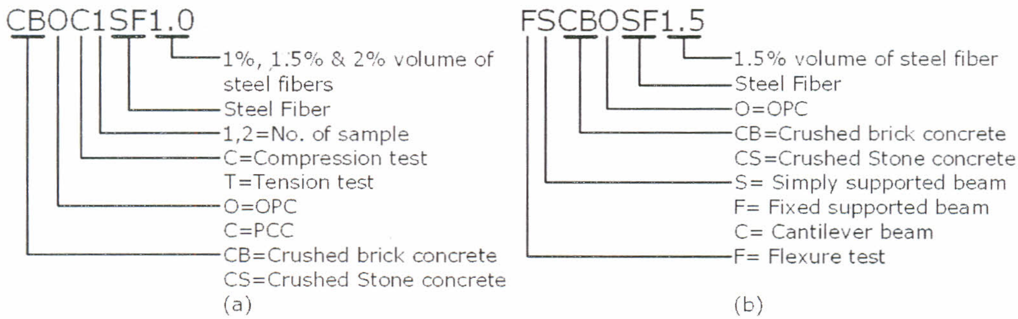
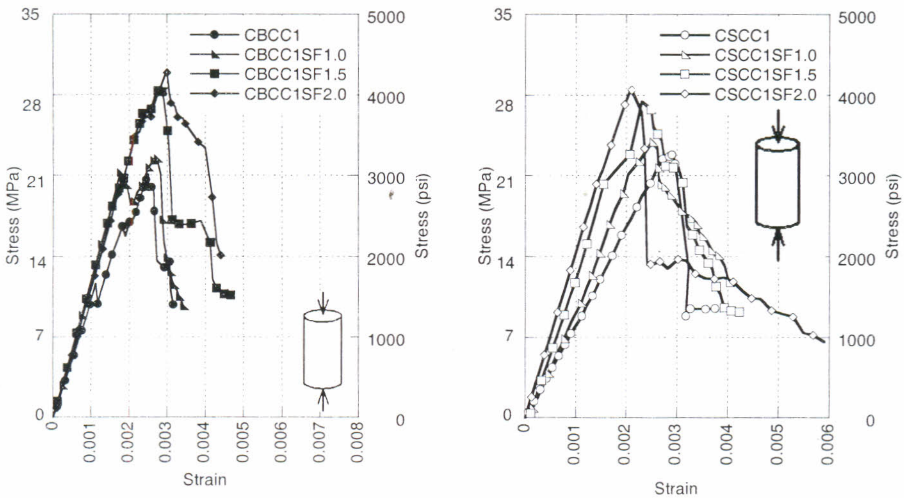
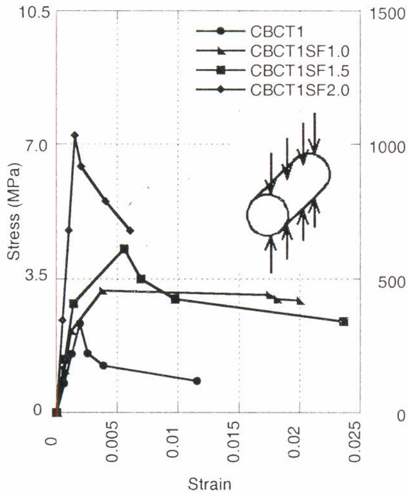


Figure 5: Legend styles used in the figures (a) concrete compressive and tensile test specimens (b) different flexural specimens.

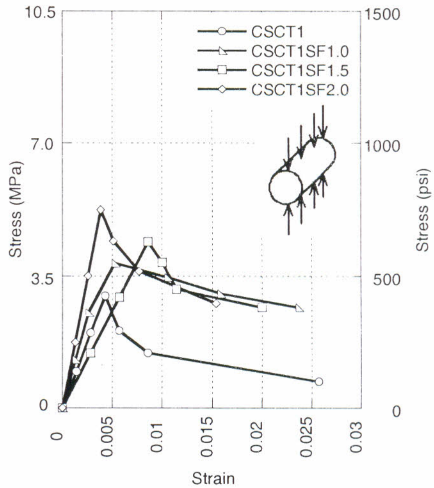


(a) (b)

Figure 6: Compressive stress-strain behaviour of concrete specimens made of 0%, 1%, 1.5% and 2% steel fiber volume ratio (a) brick concrete (b) stone concrete.



(a)



(b)

Figure 7: Tensile stress-strain behaviour of concrete specimens made of 0%, 1%, 1.5% and 2% steel fiber volume ratio (a) brick concrete (b) stone concrete.

Effect on compressive strength

The compressive strength of SFRC is evaluated according to ASTM C 39/C 39M–05. The steel fiber has a significant effect on the enhancement of tensile strength but in case of compressive strength the effects are found less significant. The concrete member under compression begins to dilate laterally and it fails due to spalling of concrete as a result of Poisson's effect. Crack bridging by steel fibers resist the spalling which increases the compressive strength up to certain limit (Figure 8). The concrete at the hoop direction suffers from extensive hoop tension which leads to failure of concrete under uniaxial loading. In SFRC the steel fibers with the volume of 1.5% are found not so efficient in enhancing the compressive strength of concrete by arresting the hoop tension. The other reason may be the present concrete strength with this fiber volume ratio is not enough to arrest the hoop tension. The compressive strength is increased by about 8% for SFRC made of brick concrete compared to plain concrete (Figure 9a), while the increment is about 19% for SFRC made of stone concrete (Figure 9b).

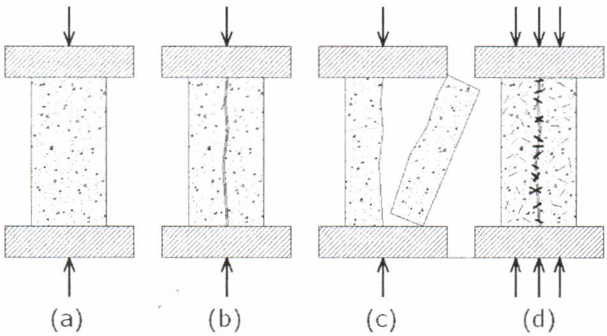


Figure 8: Mechanism under compressive load (a) uniaxial loading, (b) crack initiation, (c) spalling of plain concrete and (d) crack bridging by steel fibers in SFRC.

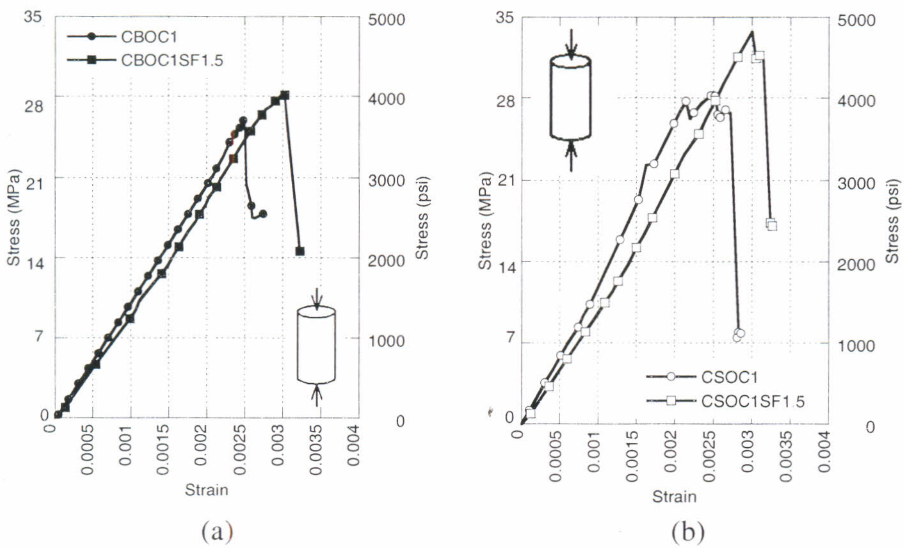


Figure 9: Compressive stress-strain behaviour of plain concrete and SFRC made of (a) brick concrete (b) stone concrete.

Effect on tensile strength

The tensile strength of the SFRC is evaluated according to ASTM C 496/C 496M–04 which determines the tensile strength of concrete. Plain concrete is a brittle material which splits under load as shown in Figure 10(a). Crack bridging of steel fibers arrests the initial cracks and prevents the concrete from splitting (Figure 10b) and the concrete continue to carry load without failure. Figure 11(a) shows that the tensile capacity of brick concrete with 1.5% steel fiber is increased 39% compared to the plain brick concrete. The increase for stone aggregate concrete is significantly large and about 149% for 1.5% steel fiber compared to plain stone concrete.

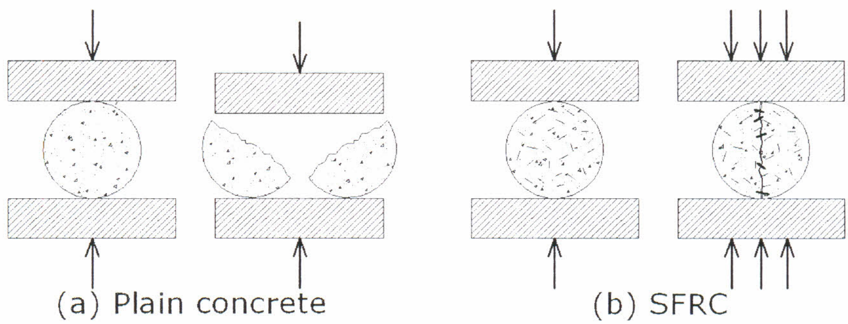


Figure 10: Mechanism under tension (a) brittle failure of plain concrete (b) crack bridging of SFRC

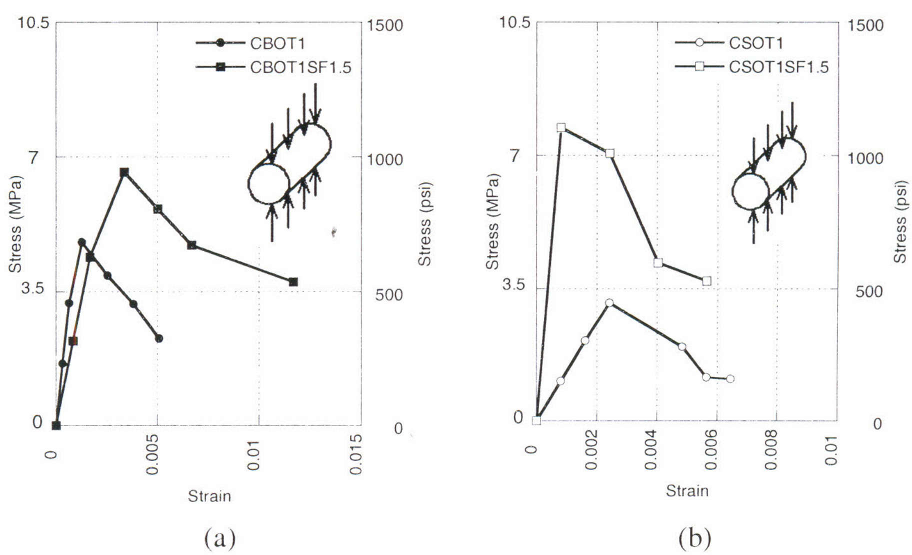


Figure 11: Tensile stress-strain behaviour of plain concrete and SFRC made of (a) brick concrete (b) stone concrete.

Effect of flexural capacity

Flexural capacity of the member is very important in case of concrete structures. As an engineering material and in context of seismic consideration the concrete should be ductile with a significant stiffness in flexure. To this end, three kinds of flexural members are considered in this experiment, they are simply supported beam, cantilever beam and fixed supported beam. Generally to evaluate the flexural capacity of concrete, simply supported beams are considered so far in the previous researches. In this study, the effects of cantilever action and fixed supported action are also extensively analyzed with both plain concrete and SFRC. For simply supported beams, the flexural capacity is increased due to SFRC in brick concrete is about 55% Figure 12(a) while 60% increased in stone concrete (Figure 12b). The increase in ductility is almost 3 times for SFRC beams made of brick and stone concretes compared to plain concretes.

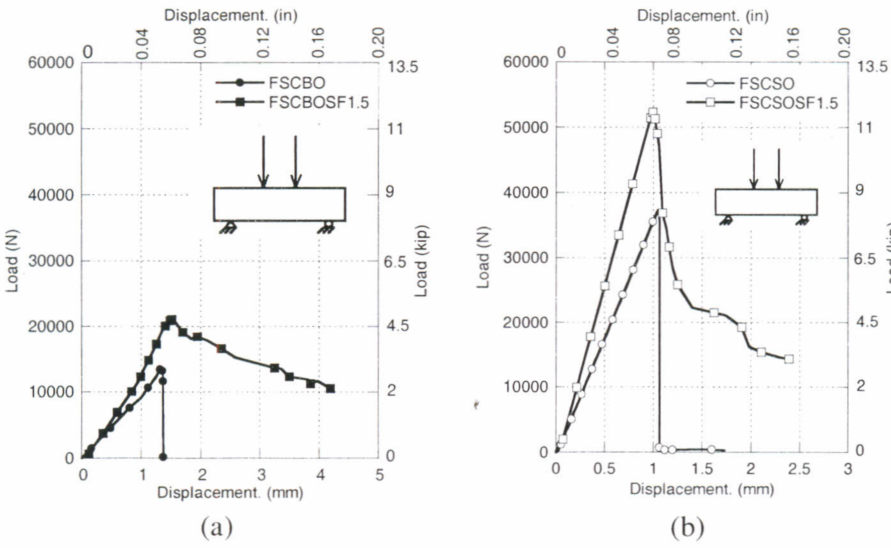


Figure 12: Evaluation of the load-displacement behavior of simply supported beams made of plain concrete and SFRC (a) brick concrete and (b) stone concrete.

From the experimental investigation, it is found that the flexural capacity of cantilever beams are increased about 8% and 10% in brick and stone concrete respectively (Figure 13 a & b), but in ductility improvement concern stone SFRC showed more ductility in presence of steel fibers. In stone SFRC the ductility is increased about 3 times while in brick SFRC is about 2 times than the control specimens (steel fiber 0%). Investigation indicates that higher ductility can be achieved by using steel fiber with stone concrete. The flexural capacity of SFRC increased in fixed support beam is about 40% in brick concrete and 51% in stone concrete (Figure 14 a & b). The ductility is increased 2 times and 5 times of brick and stone SFRC fixed supported beams compared to control specimens.

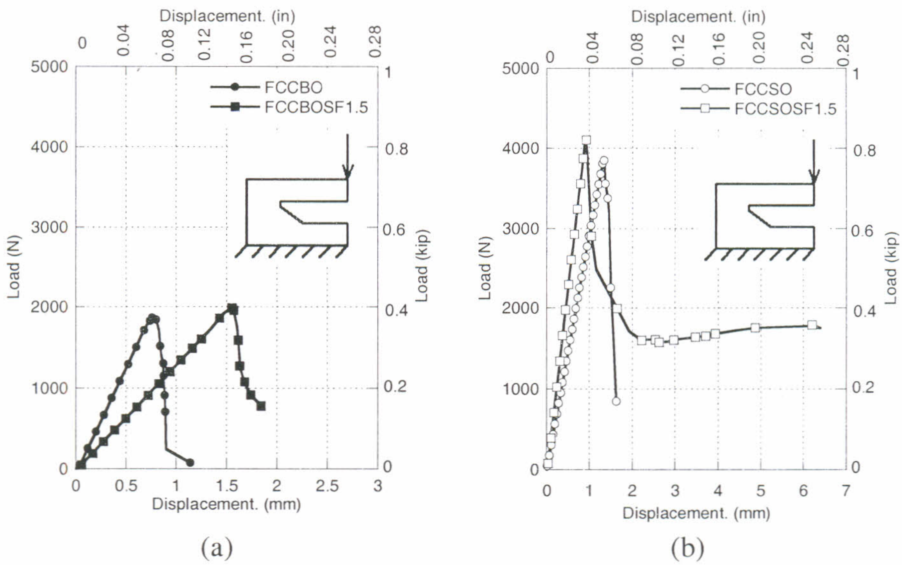
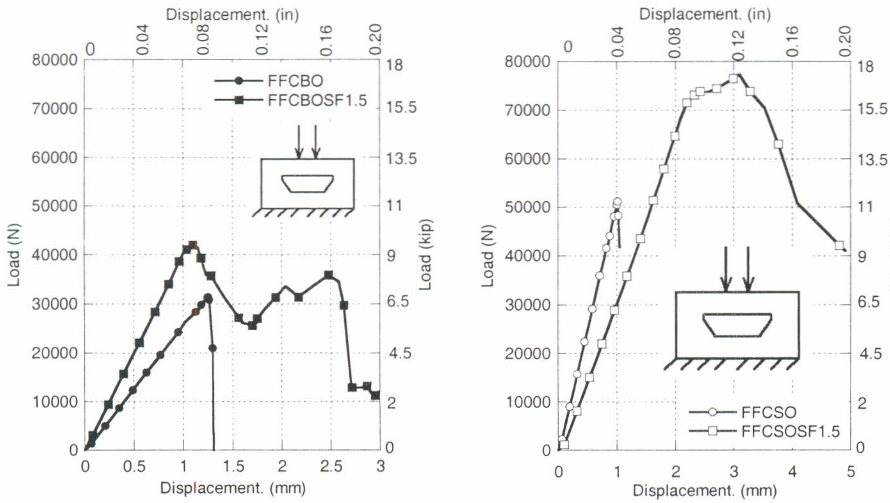


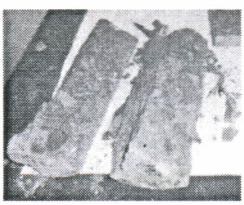
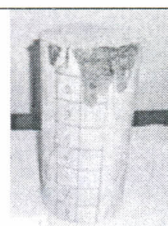
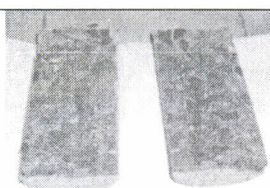
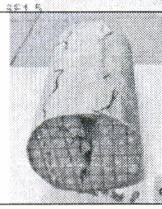
Figure 13: Evaluation of the load-displacement behavior of cantilever beams made of plain concrete and SFRC (a) brick concrete and (b) stone concrete.

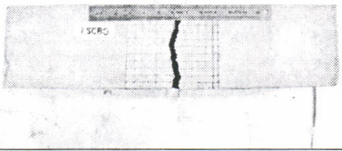
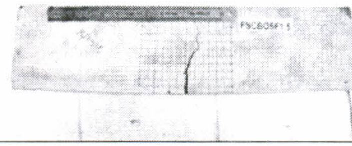
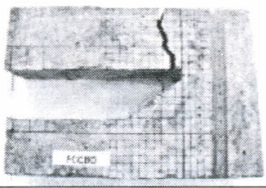
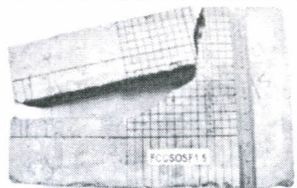
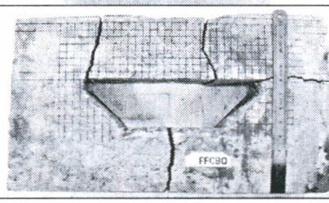
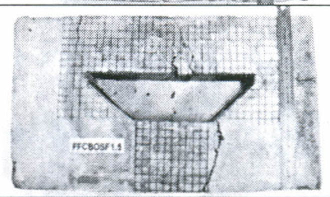


(a) (b)

Figure 14: Evaluation of the load-displacement behavior of fixed supported beams made of plain concrete and SFRC (a) brick concrete and (b) stone concrete.

Table 3: Failure patterns of plain concrete and SFRC specimens

Type of Specimen	Plain concrete	SFRC
Compression		
Tension		

Simply supported beam		
Cantilever beam		
Fixed supported beam		

Concrete can fail in two modes i.e. brittle and ductile. To this end, failure pattern of brick and stone concrete are observed during experiment. Another objective of this study is to prevent the brittle behavior of concretes by enhancing ductility without compromising the strength. Experimental investigation shows attractive results that supports the concept of experimental plan. Brittle failure of brick and stone aggregate is successfully resisted by using SFRC and ductility is increased in a significant amount. Table 3 provides some images of failure after experimental testing. Compression and tension testing of SFRC shows no indication of complete separation or splitting as found for plain concrete. This is also factual for the flexural specimens. Simply supported, fixed and cantilever beams made of plain concrete have failed by complete separation whereas SFRC specimens showed no disconnection of parts. Failure occurred at the root of cantilever in the cantilever specimens, at the mid span in the simply supported specimens and at mid span & root of fixed support in the fixed supported beams.

Conclusion

In the absence of a reliable experimental investigation for predicting the compressive, tensile and flexural strength (with different support condition) of SFRC made of easily available fibers in context of Bangladesh, the current research successfully investigated the capacity enhancement and stress field of the SFRC from experimental viewpoint to introduce this new engineering material in the Bangladesh construction industry. In this research innovative kind of specimens are introduced which unlock the new dimension in concrete flexure tests. The findings of this research are as follows:

1. Previous researches worked with steel fibers consisting of high aspect ratio (50 and above) but this research evaluates the performance of SFRC with available steel fibers of Bangladesh with a low aspect ratio (only *l/d* =21.6).
2. After extensive testing it is found that steel fiber volume fraction of 1.5% is the most acceptable and economic for capacity enhancement without compromising the strength.
3. The compressive strength is increased by about 8% for SFRC made of brick concrete compared to plain concrete, while the increment is about 19% for SFRC made of stone concrete.
4. Tensile capacity of brick concrete with 1.5% steel fiber is increased 39% compared to the plain brick concrete. The increase for stone aggregate concrete is significantly large and about 149% for 1.5% steel fiber compared to plain stone concrete.
5. For simply supported beams, the flexural capacity is increased about 55% in brick SFRC while 60% increased in stone SFRC. The increase of ductility is found almost 3 times for SFRC beams made of brick and stone concretes compared to plain concretes. The flexural capacity of cantilever beams are increased about 8% and 10% in brick and stone SFRC respectively, but in the ductility improvement concern stone SFRC showed more ductility in presence of steel fibers. In stone SFRC the ductility is increased about 3 times while in brick SFRC is about 2 times than the control specimens (steel fiber 0%). The flexural capacity of SFRC increased in fixed supported beam is about 40% in brick concrete and 51% in stone concrete as well as the ductility is increased 2 times and 5 times of brick and stone SFRC fixed supported beams compared to control specimens. Experimental investigations indicate that higher ductility as well as capacity can be achieved by employing steel fiber in stone concrete.

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