International Journal Of Engineering Research And Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 20, Issue 5 (May. 2024), PP. 56-69

Mechanical Properties of Steel Fiber Reinforced Concrete: A Comprehensive Review

Kazi Shahariar Hasan*[1,a], Kazi Md. Mostafizur Rahman [1,b], Ayon Biswas[1,c], Dr. Sharmin Reza Chowdhury[*1,d].
[1]*Department of Civil Engineering, Ahsanullah University of Science & Technology, Dhaka-1208, Bangladesh.*
[*]*Corresponding author*

Abstract
Every aspect of civil engineering work revolves around concrete in one way or another. It is one of the most versatile building materials for construction procedures. Concrete has low ductility and is brittle. It takes high compressive stress but is less capable when taking tensile stress. It shows abrupt failure when subjected to tension beyond its strength. With human advancement, construction methods have become more demanding, which requires every building component, such as concrete, to be more resilient than ever before. Various reinforcement techniques are practiced to improve the mechanical properties of concrete. Fiber-Reinforced concrete *is a composite material combining concrete and randomly dispersed fiber. Adding fibers is one of the most practiced techniques for improving concrete properties and controlling the "Hairline-cracks" formed at the outer surface. A fiber is a thin material having extremely low thickness compared to its length. These fibrous materials help mitigate cracks in concrete to some extent and provide impact resistance, compressive strength, flexural toughness, splitting tensile strength, blast resistance, and other desirable mechanical properties. Steel Fiber-Reinforced Concrete (SFRC) is one of the most popular methods among other fiber reinforcement techniques. Steel fibers are discrete, short (15 mm-70 mm), and have a high ratio of length to diameter (AR20-AR100) with various cross-sections (ACI 544.IR, 1996). Fibrous materials in FRC are used at a fraction of the total volume. Typically for steel fiber, the range of optimal usage is around 1% to 1.5% SF with the aspect ratio of the steel fiber being AR75. These are extremely small compared to the main reinforcement, and they should not be considered a total replacement of the main reinforcement by any means. This paper presents a synopsis of the performance improvement found by the adaption of Steel Fiber Reinforced Concrete, comparing its benefits and use cases.*
Keywords: *Concrete, Hairline-cracks, Steel Fiber-Reinforced Concrete (SFRC), Aspect Ratio.*

Date of Submission: 05-05-2024 Date of Acceptance: 17-05-2024

I. INTRODUCTION

Advanced civilization requires more resilient building components, thus requiring the practice of advanced construction techniques like Steel Fiber Reinforced (SFRC) to be a regular part of construction technology. Steel Fiber Reinforced Concrete usually consists of conventional hydraulic cement, Fine aggregate, Coarse aggregate, Steel Fiber(SF), water, and other additives if required. Typically Superplasticizers are always required as the SFRC has less workability than typical concrete.Myriad of fibrous materials are used for Fiber-Reinforced Concrete (i.e., Steel, Stainless Steel, Carbon Type-I&II, Crocidolite Asbestos, Chrysotile Asbestos, Cellulose, Glass, Fibrillated Polypropylene, Kevlar, Nylon type-242,).

Figure 1: Different types of fiber.*(Al-Najjar et al. 2020).*

Figure 1 illustrates some of the fibers. The steel fibers remain randomly dispersed and added at the time of mixing. The random dispersal of fiber enables uniform distribution in all regions at random orientations. The fiber parallel to the direction of the applied stress then acts as an additional reinforcing element. The region near the outer surface of the concrete face of different building components, such as beams and slabs, helps reduce surface cracks. Steel fiber is added at a percentage of the total concrete mix volume (i.e., 0%, 1%, 1.5%, 2%). To deal with the reduced workability, SPs such as sulfonated melamine formaldehyde condensate, acetone formaldehyde condensate, sulfonated naphthalene formaldehyde condensate, etc. are used. Besides commercially available Steel Fibers, recycled Steel shredded to form steel fibers can also be used. These can be slightly low-performing, but they are considered a good alternative in the context of economic structure. Previous studies on the performance evaluation of SFRChave shown increase in the performance of various mechanical properties of concrete. This literature review also supports the idea.

II. STEEL FIBER REINFORCED CONCRETE (SFRC)

Steel fibers were first thought of at the beginning of the 20th century. The concept was taken from the mudbricks created using horsehair mixed with straw and mortar. It was first proposed to be used by Porter in 1910 (Naaman,1985). However, it did not catch on until the research conducted by the United States in 1963 *(Romualdi& Baston,1963)*proved its usefulness.

SFRC can be classified by the percentage added to the total volume of the mix.

1. Very low SF (<1%); controls plastic shrinkage.
2. Moderate SF (1%-2%); improves (MOR), flexural strength, and impact resistance.
3. High SF (>2%); used only for special applications. (i.e., blast-resistant structure,SIFCON, SIMCON)

The performance of SFRC can vary due to its shape, cross-section, type of steel, length of the fiber, cement used for the concrete, mixing of the concrete, matrix of the concrete, and other parameters. According to ASTM 820, steel fibers used can be deformed or straight. The type specified by ASTM are,

1. Type-I (Cold-Drawn Wire)
2. Type-II (Cut sheet and Deformed cut sheet)
3. Type-III (Melt-Extracted)
4. Type-IV (Other Fibers)

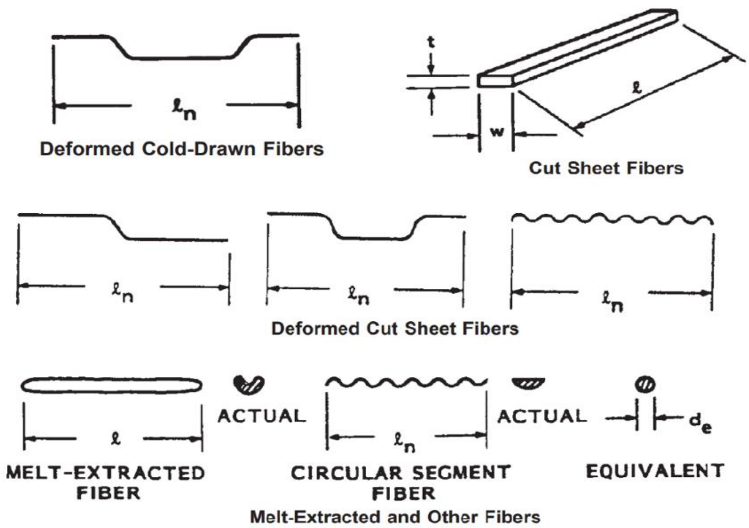


Figure 2:Different Types of Steel Fiber (ASTM 820-01)

Figure 2 shows steel fibers of different shapes by the standard of ASRM 820-01. One of the benefits of SFRC is its load-bearing capacity and ductile behavior. SFRC takes greater load, showing greater deflection before failure compared to regular plain concrete. A typical concrete mix does not show ductility, but an SFRC would significantly deform before failure at a greater load than PC can ever withstand. This is a desirable feature that helps predict and avoid catastrophic failure of structures and maintains the safety of human life.

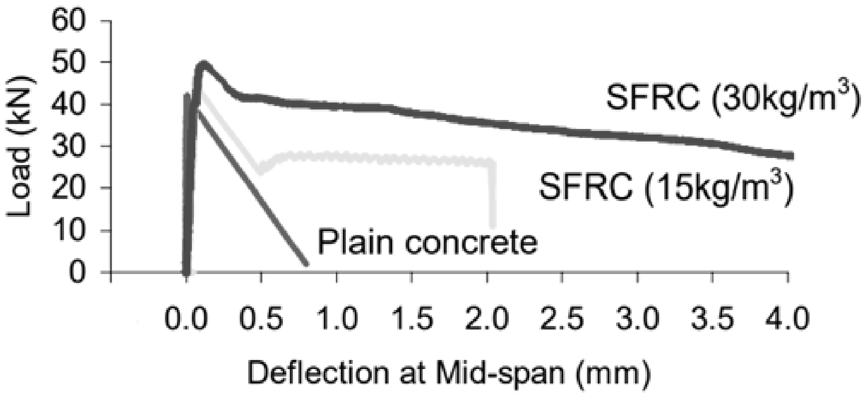


Figure 3: Load-Deflection response for simply supported beams *(Elsaigh and Kearsley, 2002)*

Figure 3 is a graph showing the load capacity enhancement by using SFRC at different volume fraction. The line of plain concrete abruptly drops showing brittle failure whereas adding 15kg/m^3 of SF provided ductility making the concrete fail at grater load and showing greater deflection as a result. 30kg/m^{3}showed the same characteristics signifying even greater deflection and load capacity.SFRC also delays the flexural cracking, acting as a crack-control mechanism. This reduced crack widths, improving the durability of the structure. SFs can never replace main reinforcement but can reduce the use of main steel used. They also increase freeze-thaw resistance.

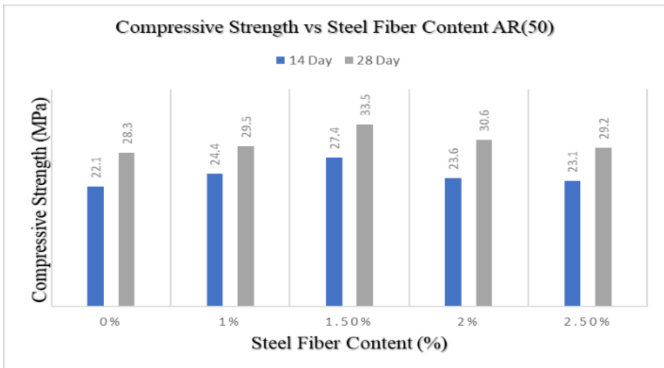
Recently many researchers have been looking into the realm of SFRC and how to improve upon the previous findings. Many have suggested the use of recycled steel as SF. High-Performance Steel Fiber Reinforced Concrete (HPFRC) is on the brink of commonly used technology for construction practices. The latest researches show, High Performance Fiber Reinforced Concrete can inhibit hairline cracks in a unique manner by controlling the crack, beyond elastic region. Studies show the crack width remains within 100µm by using HPFRC when subjected to several percent tensile strain.

III. State of the art review of SFRC

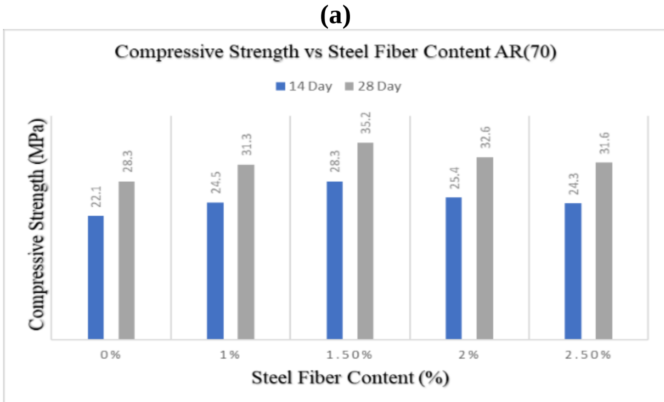
Research on SFRC in the previous decade is on the rise. Composite construction material is becoming very popular and demanding for new research. Previously conducted researches have shown significant benefits of using SFRC over PC. SFRC is both economical and high performing in all regards. Adding SF to PC enables achieving better mechanical properties that require using expensive construction materials otherwise. Studies show SFRC provides advantages such as compressive strength increase, flexural strength increase, ductility, impact resistance, blast resistance, etc. Some of the enhancement in strength are elaborated below.

3.1 Compressive Strength

An experimental research by ***Nafisa et al. (2018)*** compared the compressive and flexural strength behavior of SFRC and plain concrete beam. The research found that the addition of steel fibers enhanced the mechanical properties of concrete. They conducted the tests using different volume fractions (1.0%, 1.5%, 2.0% and 2.5%) of SF and 54 nos. 100mm concrete cube specimen cast from M25 concrete (ACI 211.1-91). The experiment used two aspect ratios of steel fiber (50 and 70). The maximum enhancement found in their paper was at 1.5% inclusion of steel fiber for compressive strength. The prepared specimens were tested as per the specification of IS 516-1959.



(a)



(b)

Figure 4:Graphical illustration showing variation in compressive strength of concrete specimen due to the addition of different steel fiber fraction at 14day and 28day curing age. AR50(a)and AR70(b)

Figure 4 shows that the maximum compressive strengthwas found for the inclusion of 1.5% steel fibers to the mix for both 14 days and 28 days specimen with SF having AR50 and AR70. The compressive strength increased with the increase of steel fiber till this point and then again started to decline with the addition of steel fiber beyond 1.5%.

In a study by ***Prachi et al. (2017)*** on the topic"Study of Compressive Strength of SFRC with Different grades of concrete", they also found supporting the idea that the addition of SF at a certain proportion improved various mechanical properties such as inhibiting propagation of cracks, increased compressive strength, etc. In their experiment, they varied the concrete grade (M30, M50, M60) with the variation in SF fraction (0%, 0.5%, 0.75%, 1%). They, however, kept the aspect ratio fixed as they found in their literature review that most research proved SF having AR75 is optimum for SFRC. The compressive test was conducted using cubical specimen of 150mm in all dimensions. Three mix ratios were used to create M30(M1), M50(M2), and M60(M3) concrete with average initial setting and final setting times of 35min and 600min, respectively. The tests found the following compressive strength increase the percentage for various SF fractions shown in the graph,

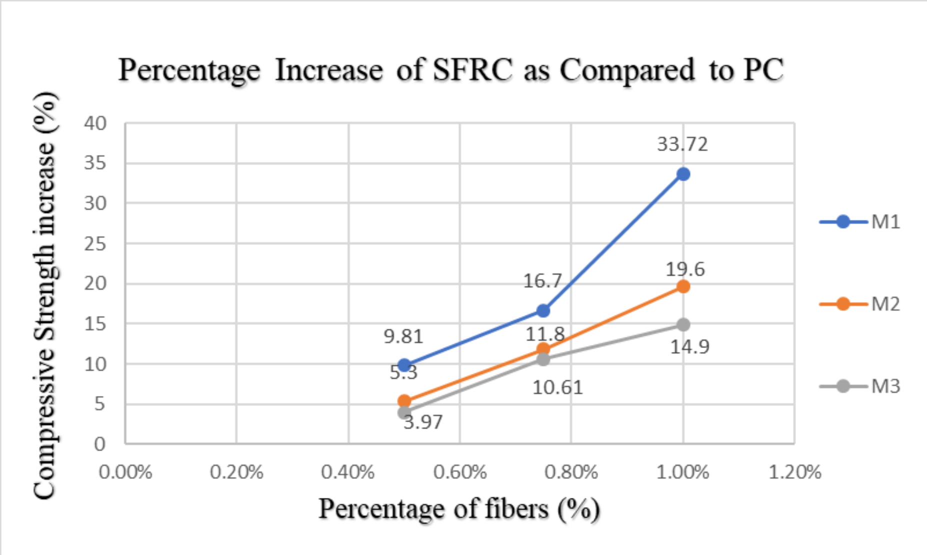


Figure 5:Percent increase of SFRC strength as compared to plain concrete.

In figure 5 the enhancement in compressive strength for M1 was observed 9.81%;(0.5%-SF), 16.7%;(0.75%-SF), and 33.72%;(1%-SF). For M2 it was 5.3%;(0.5%-SF), 11.8%;(0.75%-SF), and 19.6%; (1%-SF) and finally for M3 3.97%;(0.5%-SF), 10.61%;(0.75%-SF), and 14.9%; (1%-SF).***Prachi et al.(2017)***alsosaw immediate cracks at crushing load for normal-strength plain concrete and more explosive-type failure as the plain concrete strength increased. In the case of SFRC, ductile behavior where observed with a "popping" sound made due to SF failure. An enhancement in strength was foundfor the increased SF fraction. They also concluded that M1 (M30 Grade) with 1% SF added showed the maximum enhancement of a 33.72% increase in compressive strength. This characteristic had a diminishing effect as the grade of the concrete used improved. For M2 and M3 maximum increase in compressive strength was 19.6% and 14.9% compared to plain concrete. This means ordinary (M30) grade concrete is ideal for the use of SFRC enhancement, but all grades of concrete benefit from SFRC technology to some extent.

Another experimental investigation by ***Syed et al. (2015)*** was done regarding the behavior of SFRC concrete beams and plain concrete beams for compressive strength and flexural strength. The research used M35 (w/c = 0.45) grade concrete with various fraction of SF. The steel fiber variations were 0.25%, 0.50%, 0.75%, and 1% of the total volume (Having an aspect ratio of 60). To evaluate the compressive strength, cubes were used with the dimension of 150mmX150mmX150mm. Tests were conducted at 7 days, 14 days, and 28 days. In this experiment, cement (OPC 43 grade), steel fibers (ISO 9001:2008 Company crumbled SF with a length of 30 mm and diameter of 0.5 mm), fine aggregate (river sand of IS 383-1970), coarse aggregate (ballast stone of IS 383-1970) and water was used. After conducting the compressive strength test for the cubes, it was founded that maximum compressive strength was obtained by using 0.75% steel fiber.

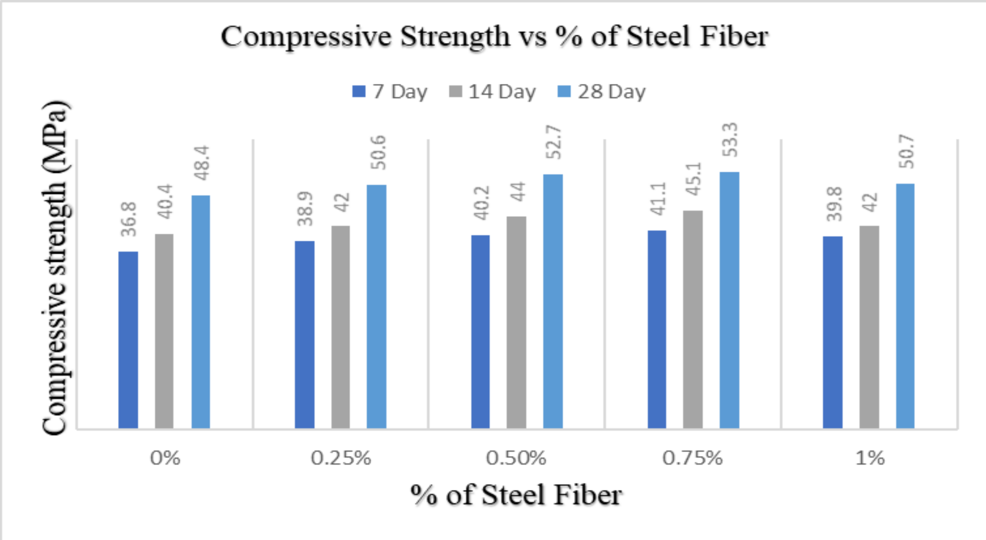


Figure 6:Graphical illustrationshowing variancein compressive strength of concrete specimen for different steel fiber fraction at 7day, 14day and 28day curing age (AR60).

From the experimental data in figure 6 for compressive strength test, it is found that the strength increases with the increase of the steel fiber content up to 0.75%. After that any further addition of steel fiber reduces the compressive strength of the concrete.

Compared to PC the compressive strength was enhanced around 5.4%, 8.46%,10.46% and 7.53% for 0.25%,0.50%,0.75% and 1% of SF respectively for the 7 days curing period. For 28 days curing the strength increased around 4.34%,8.16%,9.2% and 4.54% for 0,25%,0.5%,0.75% and 1% of SF respectively. The findings show, maximum compressive strength was gained at addition of 0.75% steel fibers being the optimal solution for all curing ages (7 days, 14 days, 28 days).

According to ***Shende et al. (2012)*** SFRC of M-40 grade with mix design of 1:1.43:3.04 attains highest compressive strength of 56.30 MPa at 3% SF (AR50). Their investigation comprised of testing with various SF fractions (0%, 1%, 2% and 3%). The water cement ratio was 0.35.
For this experiment steel fibers had three different aspect ratios which are tabulated and given below,

Table 1: Dimensions of different aspect ratio of SF used for the test.

Aspect Ratio	Length (mm)	Diameter (mm)
50	35	0.70
60	30	0.50
67	30	0.40

The compressive strength test was conducted using cubes with the dimension of (150mm x 150mm x 150mm). Superplasticizer was used for the casting of M-40 grade concrete (0.6%, 0.8% by weight of cement). The test was conducted after 28 days of curing, using the digital compression testing machine according to I.S. 516-1959.
The compressive strength test data is graphically presented and given below,

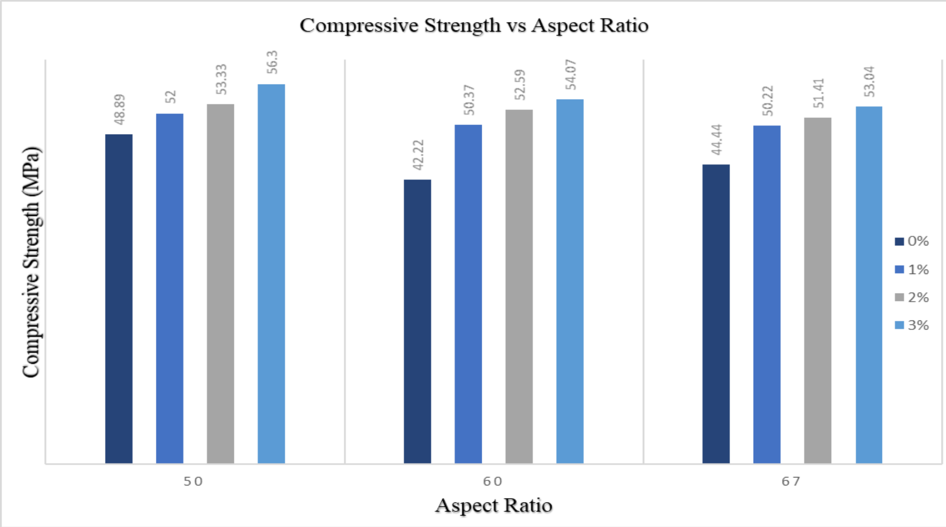


Figure 7:Graphshowing variancein compressive strength of concrete specimen by addingdifferent steel fiber fractionafter 28 days of curing.

From figure 7, it observed that the maximum compressive strength (56.30 MPa) for the M-40 grade concrete was obtained at the AR50 with an SF fraction of 3% of the total volume. The graphical representation also depicted that the compressive strength has an adverse effect with the increase of aspect ratio. The compressive strength for 3% SF at AR67 was 53.04 MPa which was less than the compressive strength at AR50. In the SFRC, the compressive strength enhanced11% to 24% compared to conventional concrete.In order to study the compressive strength of SFRC, another research was conducted by Ankur et al. (2018) using M25 grade concrete with mix proportions of 1:1:2 and W/C of 0.44. Steel fibers (Hook end) with volume fractions of 0%,0.45%,0.95%,1.45%, and 1.95% by cubes of 150mm X 150mm X 150mm were used for the compressive strength test with aspect ratio of the fiber being AR80 as per the specification of IS: 10262:2009.Their findings for compressive strength were graphically plotted and given below,

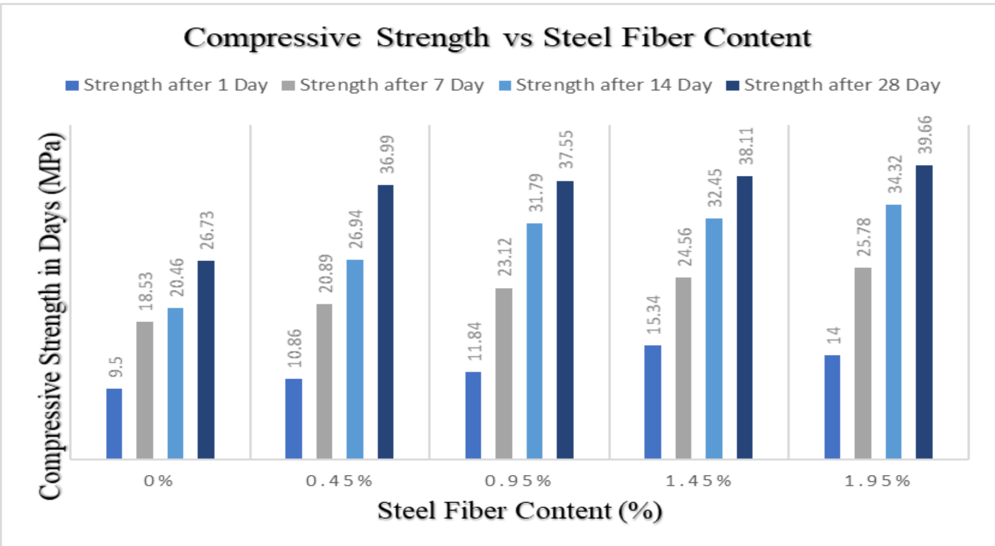
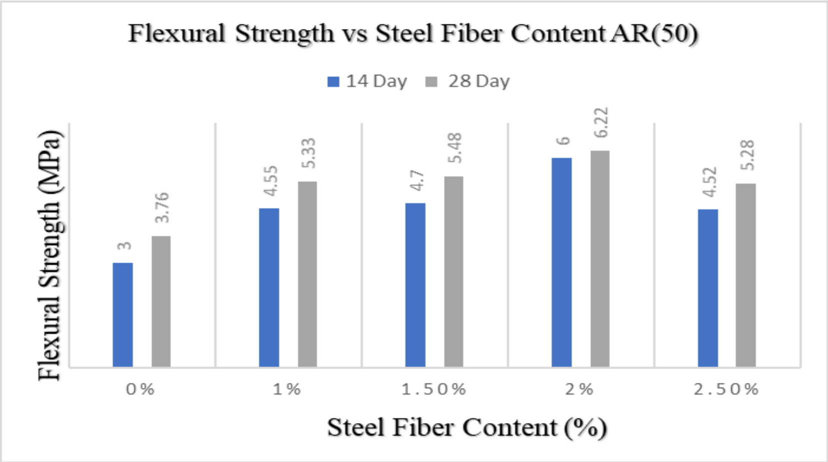


Figure 8: Graphical illustrationshowing variance of compressive strength of concrete specimen for the addition of different steel fiber fractionafter different curing age.

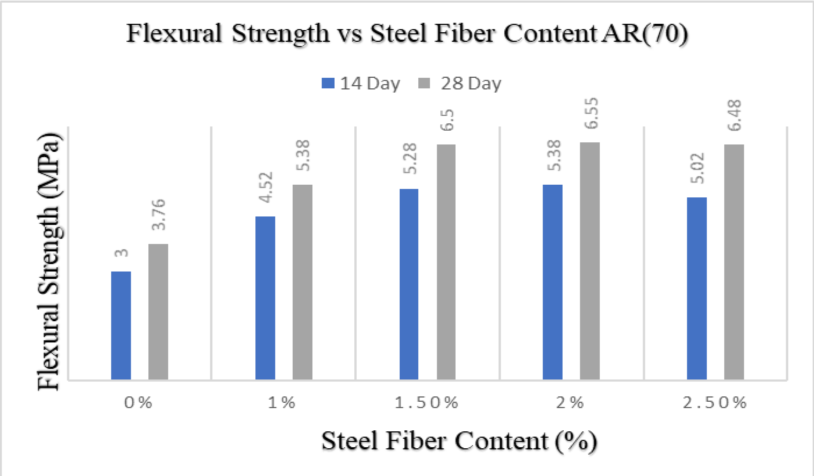
Figure 8 depicts the percentage rise in compressive strength for concrete. The test was conducted after 1 day, 7 day, 14 day, and 28 day of curing. Here it can be seen that the SFRC has gained more strength in comparison to conventional concrete. The highest compressive strength (39.66 MPa) was gained at the addition of 1.95% SF of total volume.They also found the workability to be significantly reduced due to the addition of steel fiber. Thus addition of superplasticizer is advised.

3.2 Flexural Strength:

In a paper by ***Nafisa et al. (2018),*** they cast 44 nos. 100 mm x 100 mm x 500 mm concrete beam specimen with M25 grade concrete. From the flexural test, the failure pattern of SFRC was found to be improved when compared to plain concrete, minimizing cracks at the tension face of the structure and signifying ductility. Specimens were evaluated as per the specification of IS 516-1959.



(a)



(b)

Figure 9: Graphical illustration showing variancein flexural strength of concrete specimen due to addition of different steel fiber fractionafter 14 and 28day of curing AR50(a)and AR70(b)

In figure 9 it isillustrated that the maximum flexural strength found was at 2% addition of SF, after which the addition of steel fibers inversely impacted the performance for both 14 and 28 days of cured concrete. These results were constant for all two tested aspect ratios (50 and 70).

Ina study by ***Syed et al. (2015),*** flexural strength was evaluated using beams whose dimension was 75mmX100mmX500mm. The maximum flexural strength of beam specimens was obtained using 1% steel fiber in the concrete mix.

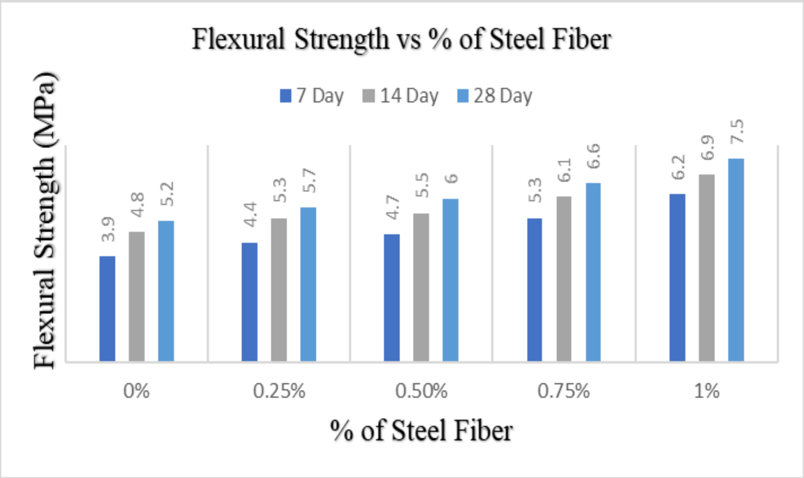


Figure 10: Graphical illustration for the variation in flexural strength of concrete due to the addition ofdifferent steel fiber fractionsafter 7day, 14day and 28day of curing (AR60)

Figure 10illustrates that theflexural strength enhances as the percentage of SF fraction increases. The enhancement is seen till the addition of 1% of SF in their test, as that was the highest fraction of SF added. With the addition of 0.25%, 0.50%, 0.75%, and 1% of SF at the 7-day curing period, the flexural strength was enhanced by 11.36%, 17.02%, 26.41%, and 37.1%, respectively, while compared to conventional concrete. The flexural strength improved by 8.77%,13.33%,21.21%, and 30.67% for 0.25%,0.5% and 0.75%, and 1% of SF, respectively, at the 28 days curing age. According to the experimental results, the maximum flexural strength was attained by adding 1% SF.

Shende el at. (2012)tested flexural strength using (100 x 100 x 500) mm beam. Their findings show that at the addition of 3% SF the maximum flexural strength is attained (10.4 MPa). The research was done by using various SF fractions (0%, 1%, 2% and 3%). According to I.S. 516-1959, the beam specimens were tested for flexural strength under two-point loading after 28 day curing period. Flexural strength test data for M-40 grade SFRC and plain concrete is graphically plotted and given below.

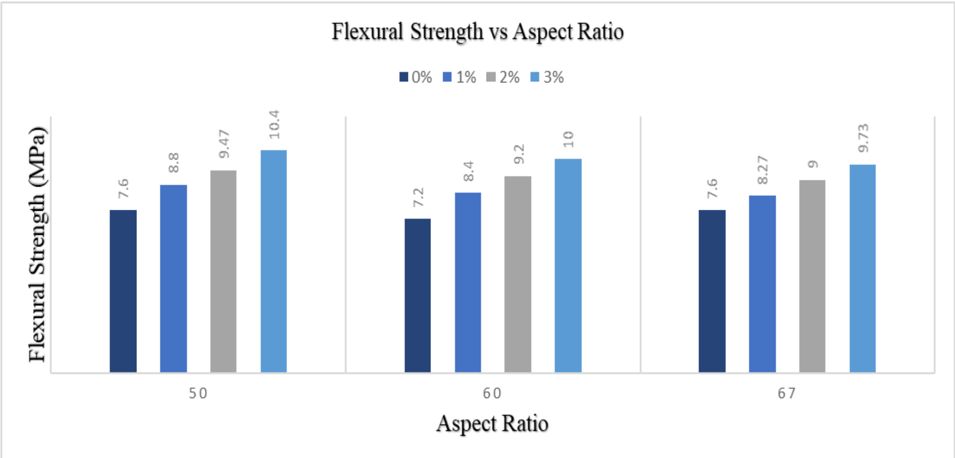


Figure 11: Graphical illustration of variation in flexural strength of concrete specimendue to the additionof various steel fiber fractionsforAR50, AR60 and AR67.

Figure 11 demonstrates that the flexural strength of Steel Fiber Reinforced Concrete (SFRC) increases as the percentage of steel fibers (SF) increases. The maximum flexural strength was obtained at 3% SF content. In AR60 and AR67, the flexural strength improves compared to conventional concrete, but the maximum flexural strength was gained at AR50 (10.40 MPa > 10.00MPa >9 .73MPa).
For M-40 grade SFRC, the enhancement in flexural strength was12% to 49% compared to the regular concrete.

3.3 Split Tensile Strength

According to a study conducted by ***Shende el at. (2012),*** the split tensile strength of the concrete also increases with the addition of steel fibers. The split tensile strength test was conducted using cylinder specimens of M-40 grade. The cylinders had a length of 300 mm and a diameter of 150mm. The specimens were tested after 28 day curing period.
The split tensile strength test data is graphically depicted and given below,

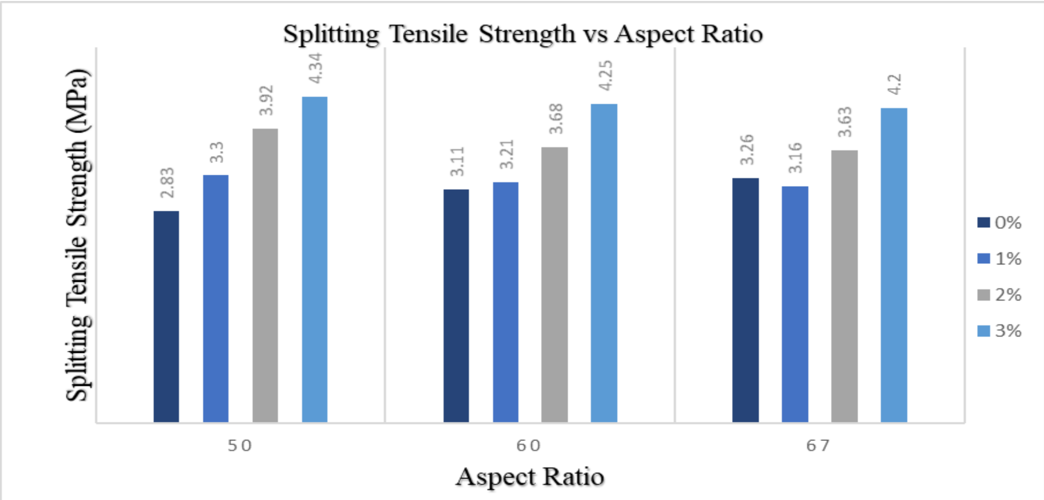


Figure 12: Graphical illustrationshowing variance inSplitting Tensile Strength of concrete specimen due to the addition of different steel fiber fractionhaving different aspect ratios.

After analyzing figure 12, it was found that the tensile strength had enhanced significantly after the addition of the steel fibers. The test data shows that the conventional concrete had a tensile strength of 3.07 MPa, which improved with the additionof SF.

The SFRC had the maximum tensile strength of 4.34 MPa by using 3% steel fiber of total volume having an aspect ratio of 50. The split tensile strength test was also conducted using two other aspect ratios (AR60 and AR67). The tensile strength of AR60 and AR67 was 4.25 MPa and 4.20 MPa, respectively, which were less than the tensile strength of AR50. This means that with the increase of AR, the split tensile strength decreases. Their findings show split tensile strength of SFRC increased by 3% to 41% compared to plain concrete.

An experimental study by ***Reddy et al. (2022)*** was conducted regarding splitting tensile strength of concrete cylinders with varied fractions of mixing steel fibers (Hooked Ends). 16 cylinders were molded for the test having the dimension of 150 mm x 300 mm. The test was conducted using 0%, 0.50%, 1%, and 1.50% SF fractions (AR80) of the total mix volume. As per IS 5816 (1999) the splitting tensile strength test was conducted at 3day, 7day, 14day and 28day curing age. The test result is graphically plotted in Figure 15.

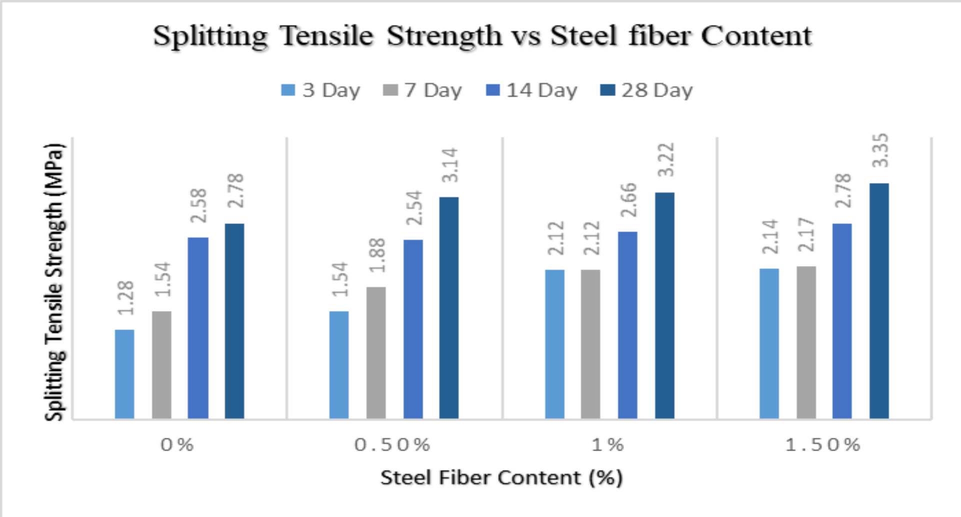


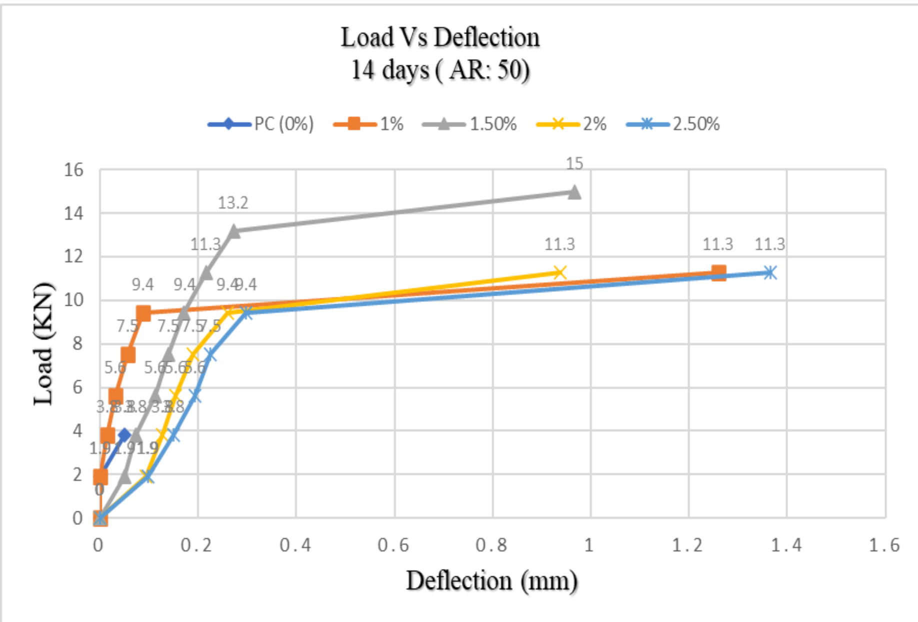
Figure 13: Graphical illustration showing splitting tensile strength variation of concrete specimen for the addition of various steel fiber fractions.

From Figure 15 it was seen that the SFRC has gained more splitting tensile strength compared to PC. The improvement of splitting tensile strength in SFRC was around 11.46% and 13.66% for 0.5% and 1% SF fractions respectively. The maximum splitting tensile strength was attained at 1.5% SF fraction which was about 24.15% greater than the conventional concrete.

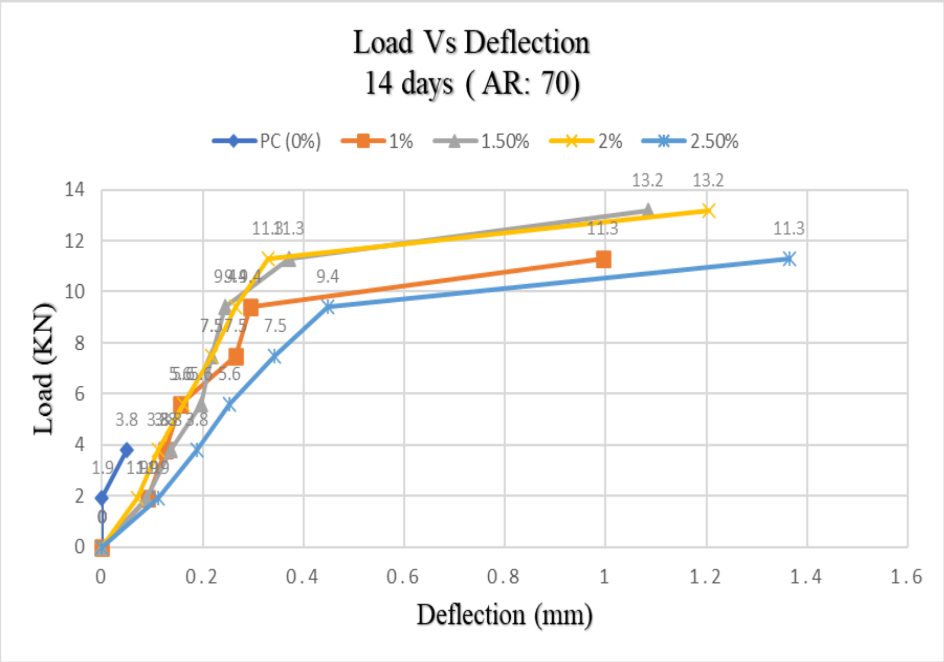
3.4 Ductility:

Nafisa et al. (2018) found that the SF acts as a “crack arrestor,” These randomly dispersed fibers provided tensile support when stresses at their parallel direction were applied. This behavior showed ductile behavior in the beam deflection test.

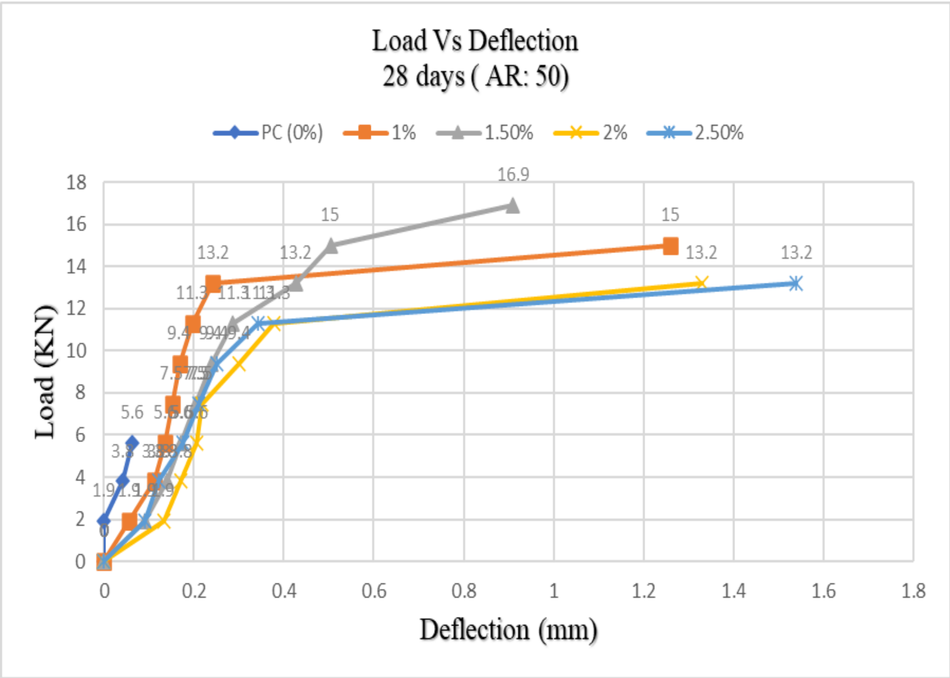
For the evaluation of the ductility of SFRC Load (KN) vs. Deflection (mm), graphs were plotted with varying aspect ratios and different fractions of SF at 14- and 28-day curing periods.



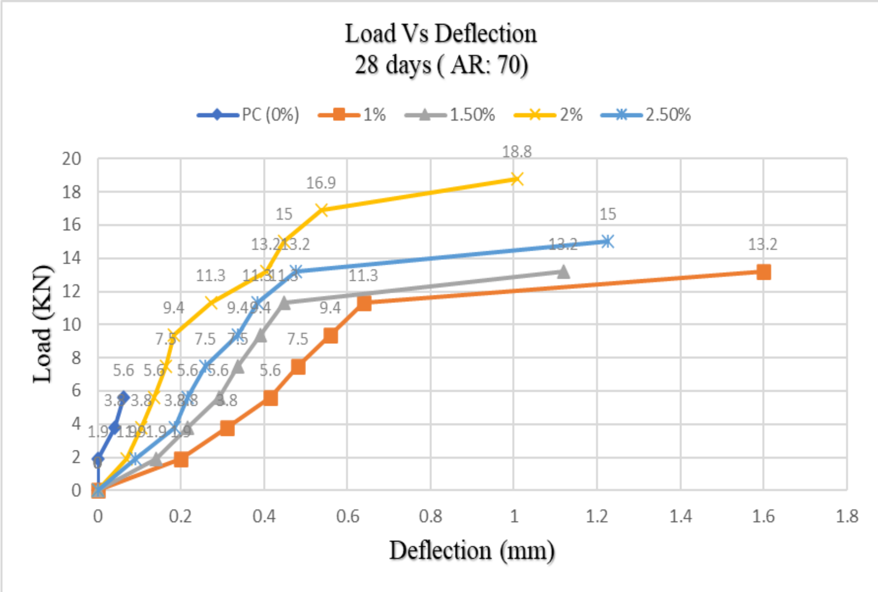
(a)


Load Vs Deflection
14 days (AR: 70)
PC (0%)
1%
1.50%
2%
2.50%
Load (KN)
Deflection (mm)

(b)


Load Vs Deflection
28 days (AR: 50)
PC (0%)
1%
1.50%
2%
2.50%
Load (KN)
Deflection (mm)

(c)



(d)

Figure 14: Deflection at different SF fraction seen at various curing ages. (a) 14 days curing using AR50, (b) 14 days curing using AR70, (c) 28 days curing using AR50,(d) 28 days curing using AR70

Figure 14shows the deflection values at different controlled applied loads at 14 day and 28 day of curing using AR50 and AR70 SF. They found that with the increment of the SF fraction, the deflection value at a certain load-imposed increase (i.e., at 3.8 KN load, the deflections are 0.049 mm for 0%, 0.014 mm for 1%, 0.0735 mm for 1.5% and increasing so on for 14 days cured beam). This behavior should have been undesirable if the deflection crosses the serviceability limit. However, in places where it satisfies the serviceability demand, it can be beneficial as the beam does not fail until it reaches greater deflection providing a visible warning to the user. Besides that, the ultimate load capacity also increases with the increment of SF to a certain point, as seen in the tables and graphs. In all possible cases, the plain concrete never exceeded 5.6KN capacity, whereas the paper found in the best-case scenario at 28 days of curing, the addition of 2% SF with AR70 yields 18.8KN load capacity showing 1.008mm deflection, which is far superior to simple PC.

IV. Conclusion& Recommendation :

❖ Steel fiber reinforced concrete provides a significant performance improvement over plain concrete. The optimal enhancements are obtained around 1% to 2% of SF fraction inclusion. The addition of more SF content may cause improper compaction which results in reduced compressive strength.

❖ Maximum strength is observed in high-grade concrete but ideally low-grade concrete benefits the most from the usage of SFRC. The highest percent increase in strength was observed for low-grade concrete(i.e.: M20, M25, M30). Thus SFRC is recommended to be used in low-grade concrete.

❖ The addition of SF significantly reduces workability. To use a high fraction of SF or to maintain regular workability, usage of admixtures such as superplasticizer (i.e. sulfonated melamine formaldehyde condensate, acetone formaldehyde condensate, sulfonated naphthalene formaldehyde condensate, etc.) is recommended.

❖ SFRC provides impact resistance, reduces plastic shrinkage, and controls crack propagation.

❖ Usage of SFRC can reduce cost by simply requiring fewer construction materials and reducing project time.

Further research on SFRC using different types of steel fibers such as fiber from scrap metal, and high-strength steel fiber will be beneficial for this technology.

Acknowledgements:

The review paper was made possible with the invaluable guidance of the faculty members of Civil Engineering Department of Ahsanullah University of Science & Technology, for which the authors are forever in debt.

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