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PERFORMANCE EVALUATION OF FIBER-REINFORCED CONCRETE INCORPORATING STEEL AND GLASS FIBERS

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Article Info

Abstract

In Practice 3000 psi control concrete, with steel fibers added by volume of concrete and glass fibers by weight of cement. Fibers were incorporated at 0.5%, 1%, and 1.5% dosage levels. In addition to individual fiber mixes, hybrid fiber-reinforced concrete (HFRC) specimens were cast using combined proportions of both fiber types. The mechanical properties evaluated include compressive strength, split tensile strength, flexural strength, and modulus of elasticity. Results showed a consistent improvement in performance with fiber addition. At 0.5% fiber content, compressive strength increased by 4% with GF, 10% with SF, and 13% with HFRC. At 1%, the increases were 7.79% (GF), 12% (SF), and 15% (HFRC). At 1.5%, the highest gain was observed, with 8.5% (GF), 15% (SF), and 18% (HFRC) improvement. In terms of E-value, 0.5% fiber content led to increases of 4% (GF), 8% (SF), and 12% (HFRC). With 1% fiber, gains were 5% (GF), 10% (SF), and 14% (HFRC). At 1.5%, the E-value improved by 5.9% (GF), 12% (SF), and 16% (HFRC), showing the highest enhancement among all samples. Split tensile strength showed 17.79% (GFRC), 55.08% (SFRC), and up to 85.59% (HFRC). For flexural strength increased with fiber dosage at 0.5%, gains were 10% (GF), 19.9% (SF), and 34.92% (HFRC). At 1%, increases were 14% (GF), 36.58% (SF), and 44.88% (HFRC). At 1.5%, the gains reached 19% (GF), 39.9% (SF), and 54.85% (HFRC). Overall, results showed that the combination of steel and glass fibers significantly enhancing the mechanical properties of concrete instead of individual fiber types.

Keywords: *Fibrous concrete steel fiber durability of concrete sustainable concrete*

1. Introduction

Ordinary cement concrete has a low damage rate and loses practically in all load-bearing capability once damaged. These features which limit the use of materials, can be addressed by the inclusion of tiny particles (steel, glass, synthetic and natural) that give low resistance to growth, shrinkage, and maintainability and so on. It may be utilized to address additional concrete flaws such as low growth resistance, severe shrinkage cracking, and low durability. Modifying elements such as cement, water and aggregates as well as adding specific materials may enhance concrete's strength and durability. As a result, concrete is ideal for a wide range of uses. However, concrete has flaws such as low compressive strength, dry shrinkage, limited tensile strength, and poor impact resistance. The existence of micro-cracks in mini-composites (mortar aggregate) causes ordinary concrete to be brittle. Fiber can be used to remove weaknesses in the combination. Engineers mix various types of fibers, such as those used in conventional composite materials, into the concrete to boost its strength or resistance to crack formation. The fiber facilitates the transmission of charge to the micro within. The concrete is known as fiber reinforced concrete (FRC).

Fibers can be thought of as aggregates having significant shape variations from a continuous line. Fiber binds and holds all components together, drastically limiting efficiency, while mixing becomes denser and less prone to separate. The fibers are disseminated throughout the concrete during the mixing process, increasing its characteristics in all directions. Before shrinking, fiber offers the same strength, compressive strength, tensile strength, and heat dissipation, as well as helping to improve the performance of body components. In particular, the fiber functions as a distractor, preventing harm from growing and changing the initial matrix, which was cement with poor tensile strength and impact resistance, into a robust form with high resistance, so enhancing posture and other behavior after the lesion has healed. This study illustrates the utilization of steel and glass fibers, as well as the purpose of parametric workouts for self-injurious strength and equal strength training. Because of its superior mechanical qualities, fiber reinforced concrete is widely employed in large-scale projects such as roads, dams, and industrial floors.

2. Material and Methodology

The material used for the research is Ordinary Portland cement type-1 cement, Lawrencepur sand, ¾ inch down Sargodha crush, Steel Fiber and Glass Fiber. The size of both fibers is one inches. Admixture also.

2.1 Material Testing

2.1.1 Cement Testing

Following tests were conducted on cement:

2.1.2 Setting Time

This test is performed to determining the plasticity of cement paste for accurate placing of concrete. According to ASTM C191-13 standards initial and final setting time 45 minutes to 600 minutes respectively and Vicat apparatus is used for this purpose. Initial setting time and final setting time was (228-547) minutes which lie in boundary of specified limits.

2.1.3 Fineness of Cement

Rate of hydration depends on cement fineness. Fineness is more hydration is more and strength is developed. Cement sieved using 200 No. sieves and found weight retained 0.4% of its sample weight. According to standard ASTM C184-94 which limit is below 10% and experiment value is 0.4%.

2.1.3 Specific Gravity

Kerosene oil is used which is free from moisture and Le-chatlier flask and following the procedure specification ASTM the specific gravity was 3.10 that is lie in limits. ASTM C188 specific gravity for type I cement range is 3.1 to 3.15.

2.1.4 Soundness

According to BS 4550: part 3: section 3.7 the soundness of cement paste in hardened state is to sustain volume after setting limit is 10 mm. Le-chatlier apparatus is used for determining the cement expansion was 5 mm which is in limit according to standard.

Table 2:1 Ordinary Portland cement test Results

Sr. No.	Types of test	Results	Standards

1.	Specific Gravity	3.10	3.1 to 3.15
2.	Standard Consistency	32.4	Should not less than 25
3.	Initial Setting time	228 min	Should not less than 45 min.
4.	Final Setting time	547 min	Should not more than 600 min.
5.	Soundness	5 mm	Less than 10

2.2 Fine Aggregate Testing

Test performed on the fine Aggregate are:

2.2.1 Sieve Analysis

Sieve analysis is usually carried to find the grain size distribution and the fineness modulus. According to BS 882:1973 the fineness modulus range is 2.3 to 3.1 and this research fineness modulus was 2.97 and results is shown grading curve fig. 2.1.

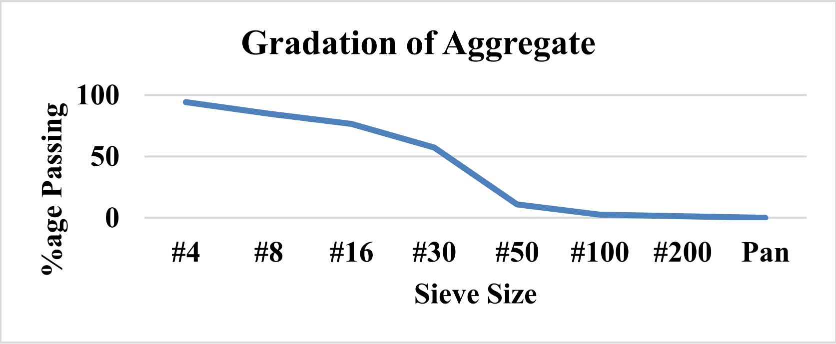


Figure 2:1 Grading Curve of Fine Aggregate

2.2.2 Specific Gravity and Water Absorption

Bulk Specific gravity of oven dried sand was finding out according to standard ASTM C 128-15. The result of Bulk Specific Gravity of sand was 2.70 and after 24 hours immersing of sand in water, the percentage of absorption was 1.22.

Table 2:2 Fine Aggregate Test Result Summary

Sr. No.	Test	Results	Standard
1	Specific Gravity	2.70	2.25 to 2.9
2	Water Absorption	1.22%	Less than 2
3	Fineness Value	2.98	2.3 to 3.1
4	Grading	Coarse Sand	

2.3 Coarse Aggregate Testing

Following tests of coarse aggregate

2.3.1 Grading

According to standard BS, Sieve analysis test is used for grading of coarse aggregate. Results are in grading curve of coarse aggregate is in fig 2.2.

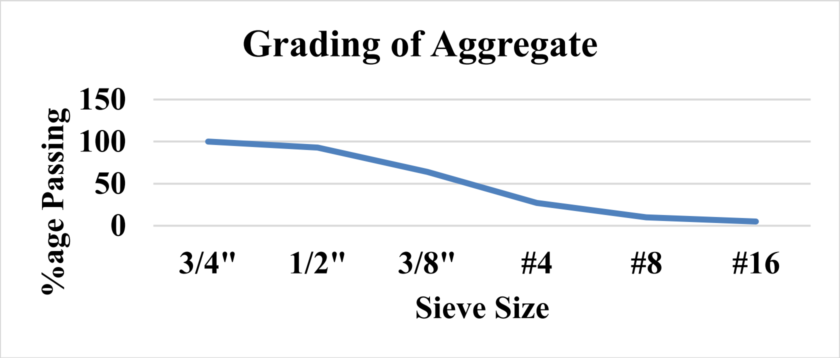


Figure 2:2 Grading Curve if Coarse Aggregate

2.3.2 Specific Gravity and Water Absorption

According to standard ASTM C 127-15, range of specific gravity is between 2.4 to 2.9. Specific gravity and water absorption have less when stone is weak. These two aspects indicate the quality of aggregate. Absorption is an indicator of the porosity of coarse aggregates, which plays a significant role in influencing concrete properties such as abrasion resistance and permeability. Highly porous aggregates tend to absorb more water over a 24-hour period. Typically, absorption values range from 0% to 8%, but for quality aggregates, the absorption is usually less than 1%. In this case, the aggregate tested showed an absorption value of 0.96%, indicating good quality. Results are shown in table 3.5.

2.3.3 Crushing value

Crushing value of coarse aggregate was found according to standard procedure of BS-812- 1967 which found was 21.2. Coarse aggregate test summary is in table 2.5.

Table 2:3 Coarse Aggregate Test Result

Sr. No.	Test	Result	Standard
1	Water absorption	0.97%	Less than 1
2	Specific Gravity	2.8	2.5 to 3

3	Crushing Value	21.2	Not more than 30
4	Aggregate Impact value	16.27%	-

2.4 Fibers

In this research two types of fibers, Steel and Glass Fiber were used that is locally available in market.

2.4.1 Steel Fiber

Steel fixing or binding wire that is locally available in market in the form of rolls was chosen for detailed work.

1. Converting the steel wire Rolls into Fiber

Converting the steel wire roll into fibers by using mechanical cutter wire was cut into pieces as shown in (Figure 2.3).

2. Steel fiber properties

Length	30.1 mm
Diameter	0.4 mm
Aspect Ratio	75

Figure 2:3 Steel Fibers

Aspect Ratio (L/d)

It obtained by division of fiber length to its diameter. It defines the ability of its surface area for matrix bonding.

2.4.2 Glass Fiber

Alkali Resistant glass fiber were used in the research are shown in fig. 2.4 a properties in table 2.6

Figure 2.4: Glass Fiber

Glass fiber properties provided by vendor are given in table 2.6.

Table 2:4 Properties of Glass Fiber

Material	**ZrO_2 %**	**Elastic Modulus(N/mm^2)**	**Diameter (um)**
AR- Glass Fiber	14.6	80.2	15±2

2.6 Mix Proportioning

According to ACI Code 211.1 were used concrete mix proportioning. Mix proportioning detail are shown in table 2.7

ACI code, 2.7 Table of mix proportion

Sr. No	Mix Code	Cement (kg/m^3)	Sand (kg/m^3)	Aggregate (kg/m^3)	Water (kg/m^3)	Glass Fiber (%)	Steel Fiber (%)	Plasticizer (mL/kg) of Cement
01	CC	370	740	1110	222	-	-	10
02	SFRC	370	740	1110	222	-	0.5/1/1.5	10
03	GFRC	370	740	1110	222	0.5/1/1.5		10
04	H50G50S	370	740	1110	222	0.5	0.5	10
05	H100G100S	370	740	1110	222	01	01	10
06	H150G150S	370	740	1110	222	1.5	1.5	10

2.7 Batching Quantities

In the university's civil engineering lab, a concrete mixer with a capacity of 1.25 cubic feet was used for each mix. Four cylinder specimens were cast in each batch. To weigh the fibers accurately, a digital weighing balance with a precision of up to one gram was used.

2.8 Mixing of Fibers in Concrete

The ingredients were mixed using a mechanical mixer. Coarse aggregate was added first, followed by cement and sand. These materials were dry mixed thoroughly for about one minute. After that, the calculated amount of water was added, and then the plasticizer was introduced into the control concrete mix. The mixture was stirred for another minute to ensure a uniform, homogeneous blend. To achieve uniform distribution and reduce the likelihood of fiber clumping, steel fibers were introduced gradually during the mixing process. The same approach was followed when preparing the Glass Fiber Reinforced Concrete (GFRC). For the hybrid fiber-reinforced mix, both glass and steel fibers were incorporated toward the end of mixing. A slight tendency for fiber clumping was noted with the inclusion of steel fibers.

2.9 Casting and Curing

In accordance with ASTM C192 guidelines, concrete samples including both cylinders and prisms were prepared using casting molds. To facilitate easy removal, a layer of oil was applied to the internal surfaces of the molds. The concrete mix was placed in three approximately equal portions, with each layer compacted using a tamping rod. After the molds were filled, the surface was finished and leveled with a trowel. Subsequently, the filled molds were subjected to vibration on a table for approximately one minute to achieve thorough compaction. The cast specimens were then kept at room temperature in the laboratory for 24 hours. After this period, they were removed from the molds, labeled, and transferred to a curing tank for a duration of 28 days.

Figure 2:5 Concrete Batching and Poured Samples

3. Test Methodology

3.1 Workability

Workability refers to how easy it is to place, compact, and finish concrete. When steel fibers are added, they tend to make the mix harsher, which reduces its workability. To measure workability, the slump test is commonly used, following the ASTM C143 standard. The results for different types of fibers, including hybrid combinations, are presented in Table 4.1 of Chapter 4.

3.2 Compression Strength Testing

After 28 days of curing, all specimens were removed from the curing tank and placed in the laboratory at room temperature to allow their surfaces to dry. Once the surfaces were dry, the specimens were tested for the required parameters. Compressive strength was tested using standard cylinders measuring 6 inches in diameter and 12 inches in height. A 50-ton capacity load cell was used to apply the load at a stroke rate of 2 mm per minute. The compressive strength was calculated as the average of two test specimens. The results are presented in Chapter 4, Table 4.2.

3.3 Stress- Strain Test

The cylinder was first installed in the testing equipment, which included gauges and LVDTs (Linear Variable Differential Transformers). Strain tests were performed by carefully placing the cylinder into the designated testing setup, making sure the delicate LVDTs were properly positioned. The gauges were attached to the cylinder, and the LVDTs were aligned with the gauges containing the specimen. The specimen was then placed into the sensitive Universal Testing Machine (UTM), with the load cell positioned on top of the specimen. The load application began at a stroke rate of 2 mm/min. As the load increased, so did the stress on the specimen, gradually intensifying until failure occurred. Even after the specimen failed, the load continued to be applied, and the corresponding strain was continuously recorded.

Figure 2.8: E-value Testing Arrangement for Cylinders

3.4 Modulus of Elasticity

As per ASTM C469, the standard procedure for determining concrete’s elastic modulus involves calculating the chord modulus, which represents the slope between two specific points on the stress-strain diagram. This approach yields both the stress-to-strain ratio and the ratio of lateral to longitudinal strain in hardened concrete. In practical testing, the modulus of elasticity is typically close to 50,000 psi. Ec = (S2 – S1)/EL- 0.00050. Results are presented in chapter 04, table 4.3.

3.5 Splitting Tensile Strength

Concrete undergoes two main types of tensile tests: direct tension and indirect tension (splitting tension). In the direct tension test, a specimen shaped like a dog-bone is subjected to axial tension. On the other hand, the splitting tension test is quite popular and involves applying tension along the axis of a cylindrical specimen, causing it to split. This test can also be performed on cubes. According to ASTM C496, tensile strength is measured by applying a diametric force to a cylindrical specimen placed horizontally between the machine's platens. Splitting tensile strength is determined as follows. Chapter 04 table 4.4.

Figure 2:9 Splitting Tensile Strength

3.6 Modulus of Rupture

The modulus of rupture, also called flexural tension, represents the highest tensile stress experienced at the bottom surface of a specimen during testing. The preparation methods for beam and cylinder samples used in modulus of rupture testing are specified in ASTM standards C192 and C31, applicable for both laboratory and field environments. As per ASTM C31, the beam's length should be at least two inches longer than three times its depth, and its width must not be greater than one and a half times the depth. Furthermore, the minimum depth or width should be no less than three times the largest coarse aggregate size utilized. Typically, prism specimens measuring 6" x 6" x 22" are tested under four-point loading conditions according to ASTM C78. When a fracture occurs within the middle third of the beam, the modulus of rupture is determined based on elastic theory. The results for the modulus of rupture and the load-deflection curves is in Chapter 4, in Table 4.5 and Figures 4.5, 4.6, 4.7, and 4.8.

Figure 2.10: Flexure Testing

4. RESULTS AND DISCUSSION

This research was organized into two primary sections for both the study and laboratory experiments. The initial section concentrated on the application of individual fibers in concrete, particularly in the form of fiber-reinforced concrete, including Glass Fiber Reinforced Concrete (GFRC) and Steel Fiber Reinforced Concrete (SFRC). The second part explored the combination of two different types of fibers in varying percentages to create Hybrid Fiber Reinforced Concrete (HFRC).

4.1 Workability

The slump test is used to assess the workability of concrete, and the results of this test can be found in Table 4.1. The observations from the test are as follows: The study reveals that the workability of concrete is reduced when steel fibers are included. When steel fibers were used, both single and hybrid forms showed a small amount of balling. The workability of the concrete was minimally influenced by the inclusion of glass fibers. (Slump increase/ decrease, %age of increase/ decrease, Reason why it happens)

Table 4:1 Impact of fiber on workability of concrete

Sr.NO	Type of Concrete	Slump (in)
1	Control Concrete	3.5
2	GFRC (0.5%, 01%, 1.5%)	2.9 to 3.3

3	SFRC (0.5%, 01%, 1.5%)	2.3 to 3.1
4	HG50S50	2.9
5	HG100S100	2.5
6	HG150S150	2.16

4.2 Compression Test

The results of the compression testing are presented in Table 4.2 and graphically shown in Figure 4.1. Based on the analysis of the test results, the following observations can be made:

Incorporating steel fibers into the concrete notably improved its compressive strength, outperforming glass fibers in this aspect. Moreover, the compressive strength increased proportionally with the rise in steel fiber content. At 0.5% fiber content, glass fiber improved compressive strength by 4%, while steel fiber gave a 10% increase. When both fibers were used together (hybrid fiber reinforced concrete), the strength increased by 13%. With 1% fiber content, glass fiber led to a 7.79% increase, steel fiber improved it by 12%, and the hybrid mix showed a 15% improvement. At 1.5%, glass fiber increased strength by 8.5%, steel fiber by 15%, and the hybrid mix resulted in an 18% increase in compressive strength the highest observed improvement compared to the control concrete. These results suggest that combining both steel and a glass fiber creates a synergistic effect, where the combined performance is better than using either fiber alone.

During testing, different failure behaviors were observed. Control and glass fiber concrete samples showed sudden failure after the first crack, indicating brittle behavior. In contrast, steel fiber and hybrid fiber concrete failed more gradually. Multiple cracks formed before complete failure, indicating ductile behavior. This conclusion was supported by measurements from the LVDT attached to the UTM testing machine. Overall, incorporating steel fibers contributes to improved compressive ductility of concrete, while both control and glass fiber mixes tend to fail in a more brittle manner.

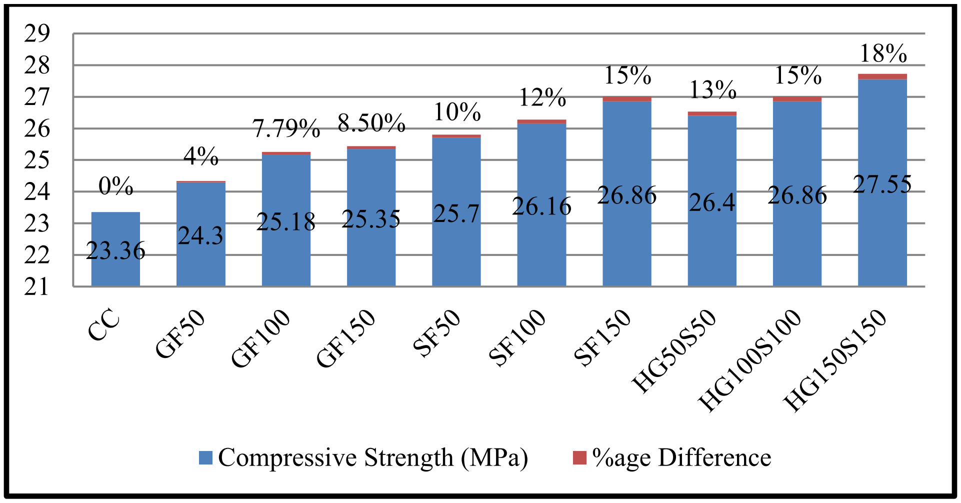


Figure 4.2: Average compressive strength of concrete with and without fibers

4.3 E-value Test

The results for the E value can be found in Table 4.3 and visually represented in Figure 4.2. After testing and analyzing the results, we can draw the following conclusions:

Samples containing steel fibers, whether used individually or in a hybrid form, were able to resist additional load even after the peak stress was reached. In contrast, both the control concrete and GFRC samples failed to resist any further load after peak loading. The strain showed a marked rise following the attainment of peak stress, which is attributed to the ductility introduced by the steel fibers. The E value of the concrete is primarily influenced by the type of fiber, the percentage of fiber volume, and the composition of the concrete itself. As the percentage of fiber volume increases, the strain value also rises. Glass fibers had a relatively small impact on the E value, while the addition of steel fibers caused a significant increase. At 0.5% fiber content, glass fiber improved E Value by 4%, while steel fiber gave an 8% increase. When both fibers were used together (hybrid fiber reinforced concrete), the E value is 12%. With 1% fiber content, glass fiber led to a 5% increase, steel fiber improved it by 10%, and the hybrid mix showed a 14% improvement. At 1.5%, glass fiber increased strength by 5.9%, steel fiber by 12%, and the hybrid mix resulted in a 16% increase in E value the highest observed improvement compared to the control concrete. Once the ultimate strength was reached, the strain continued to increase. This behavior is quite useful, as it serves as a warning before the structure reaches its final failure point, especially when steel fibers are used.

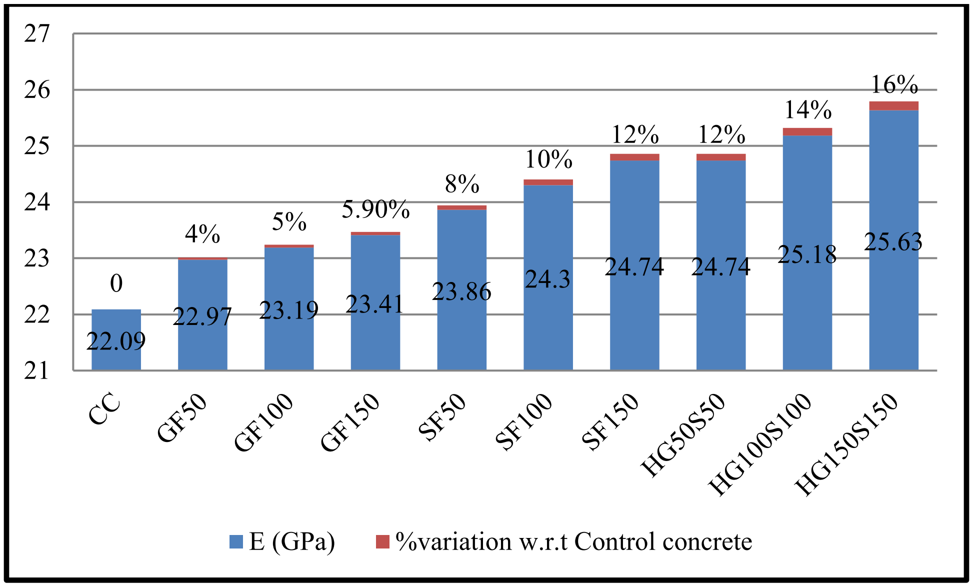


Figure 4.3: E-value Results with and without Fibers

4.4 Indirect/Split Tensile Test

The test results for the test cylinder units are provided in Table 4.4 and illustrated in Figure 4.3. Upon testing and analyzing the results, the following observations were made:

Both the control concrete and GFRC samples fractured into two pieces upon failure, exhibiting a completely brittle behavior. The SFRC samples showed higher tensile strength compared to both control concrete and GFRC. The tensile strength of GFRC was 17.79% higher than that of the control concrete. The tensile strength of Steel Fiber Reinforced Concrete (SFRC) improved by 55.08%. In the case of the hybrid mix HG100S100, the enhancement reached 60.16%, whereas for HG150S150, it increased significantly to 85.59%.

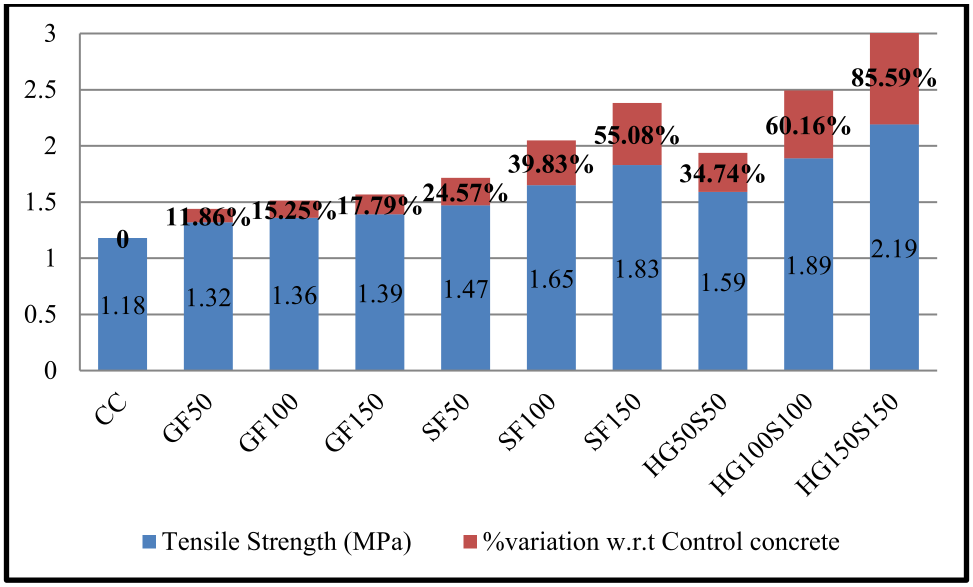


Figure 4.4: Tensile Strength Results with and without Fibers

4.5 Modulus of Rupture Testing

The results of the modulus of rupture tests are presented in Table 4.5 and Figure 4.4. Based on the observations during testing, along with the analysis of the results and sample disruptions, the following conclusions can be made:

The modulus of rupture significantly increased in Steel Fiber Reinforced Concrete (SFRC) compared to control concrete, whereas the strength gain in Glass Fiber Reinforced Concrete (GFRC) was relatively lower. In the hybrid form (combining both glass and steel fibers), there was a sharp increase in flexural strength. This is likely due to a synergistic effect, meaning that when glass and steel fibers are combined to create Hybrid Fiber Reinforced Concrete (HFRC), they work together to provide better results than would be expected from the sum of their individual properties. The modulus of rupture increased at 0.5% fibers used GF is 10%, SF is 19.9% and Hybrid is 34.92%. With 1% fibers used GF is 14%, SF is 36.58% and Hybrid 44.88% while 1.5% use fibers GF is 19%, SF is 39.9 and Hybrid is 54.85. Before failure, a considerable amount of cracking was observed in the SFRC, HG100S100, and HG150S150 samples, while the control concrete and GFRC did not show significant crack formation. This indicates that the failure mode for the samples containing steel fibers (whether used alone or in combination) is ductile, which is a desirable characteristic for concrete.

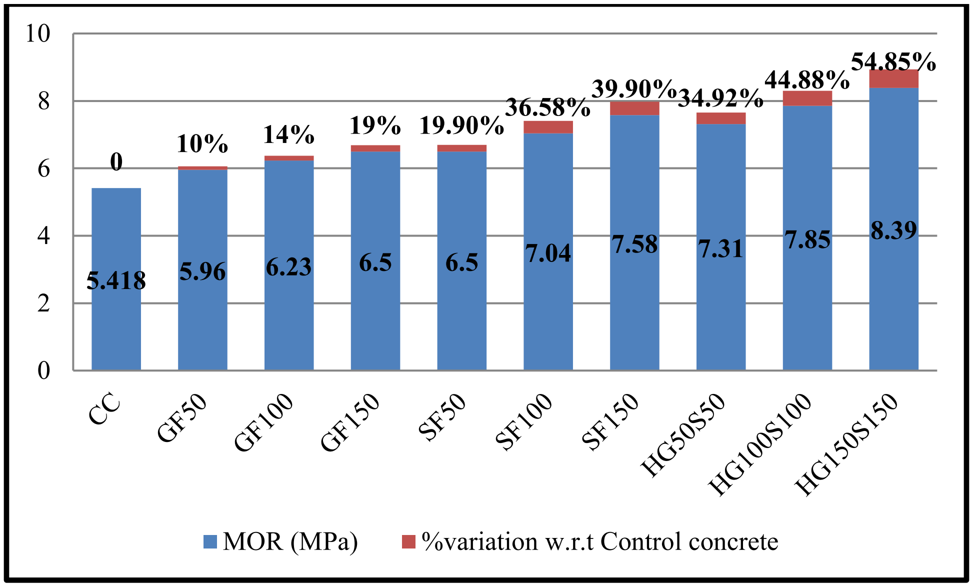
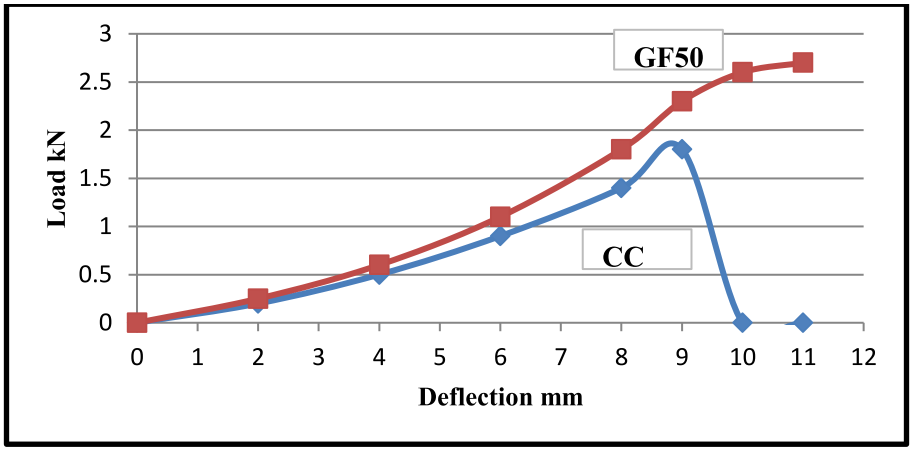


Figure 4.5: Modulus of Rupture Results with and without Fibers

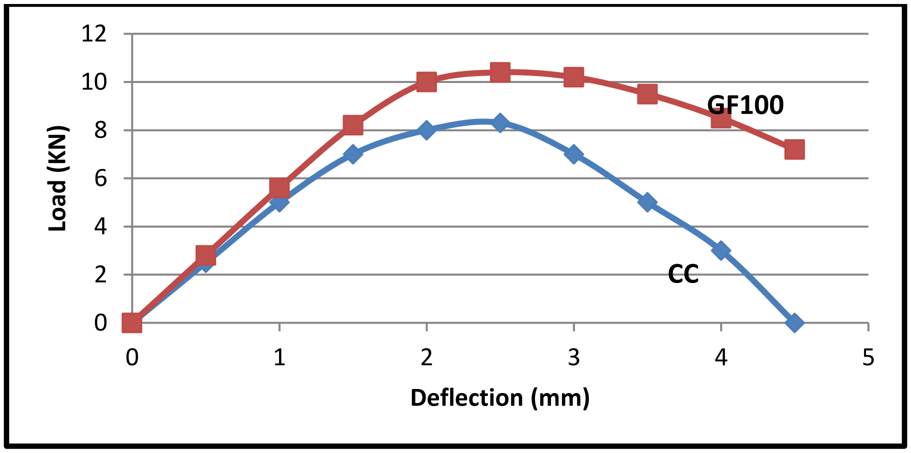
4.6 Load Deflection Curve and Ductility Characteristics

The concrete prisms were tested using two-point loading to see how flexible and strong they were. The way the specimens bent under the load was recorded in graphs (Figures 4.5 to 4.7). Based on the tests, we made the following observations:

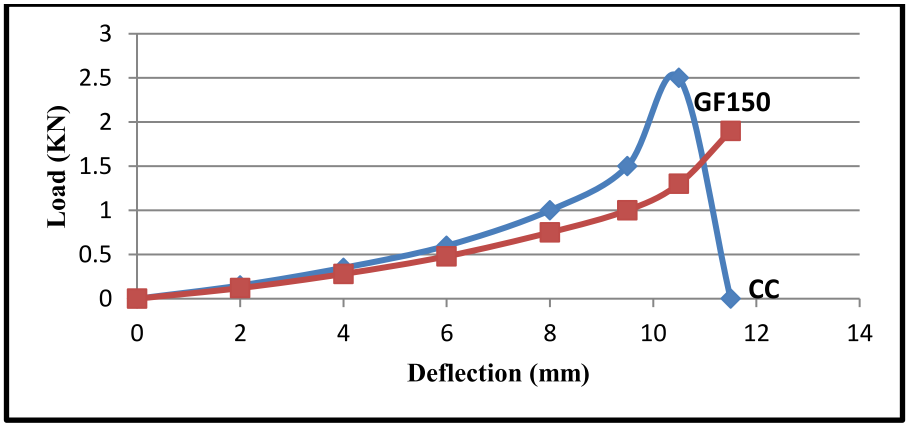
Both normal concrete and the concrete with glass fibers (GFRC) broke suddenly and completely when too much force was applied. However, the GFRC was able to handle a higher load before breaking. This shows that the glass fibers helped resist small cracks in the concrete for a while. But once the fibers broke, the concrete failed all at once in a brittle way. The sudden failure in GFRC happened because the glass fibers snapped quickly. The concrete without any fibers broke suddenly after reaching its maximum strength, bending less than 3 mm before it failed. But the concrete with steel fibers bent more up to 10 mm before breaking, showing that it was tougher and didn't fail right away. The concrete samples that had both glass and steel fibers (HG100S100 and HG150S150) bent more before breaking, showing they were more flexible and durable. This happened because the crumpled steel fibers helped stop cracks from spreading. In comparison, normal concrete and the ones with only glass fibers bent just a little (around 3 mm), while the ones with steel fibers bent over 10 mm, also showing better flexibility. No large cracks developed in the control concrete or GFRC samples. However, the steel fiber and hybrid fiber samples showed small cracks developing across their surfaces, indicating a more ductile failure behavior.



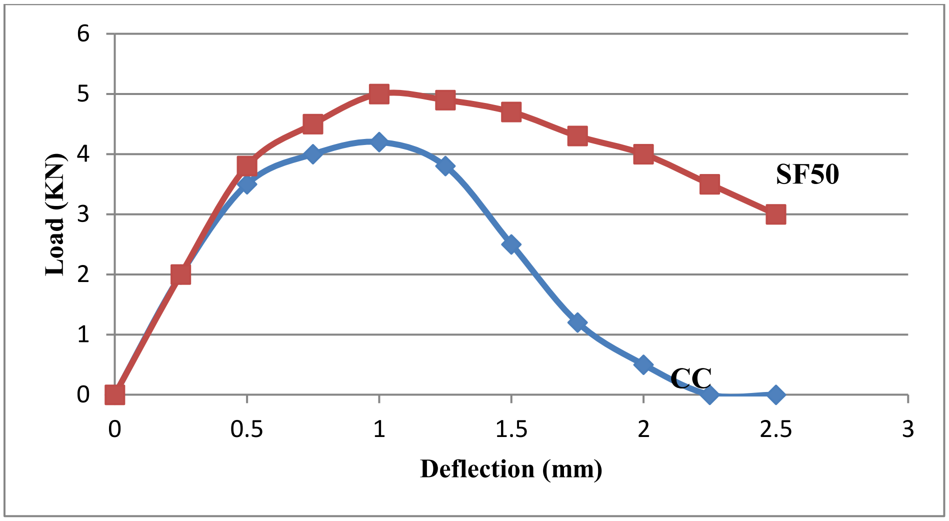
4.6(A) Load Deflection Curves of Control concrete CC and GF Glass Fiber with 0.5%



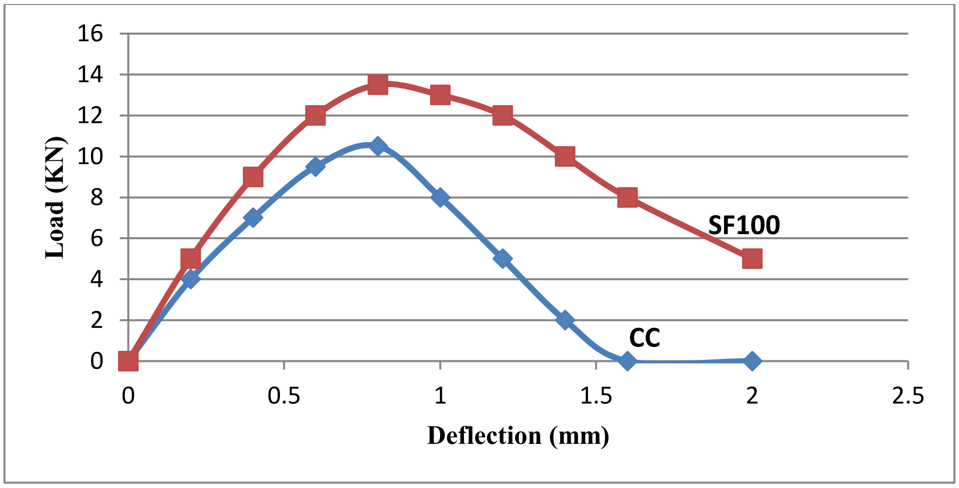
4.6(B): Load Deflection Curves of Control concrete CC and GF Glass Fiber with 1%



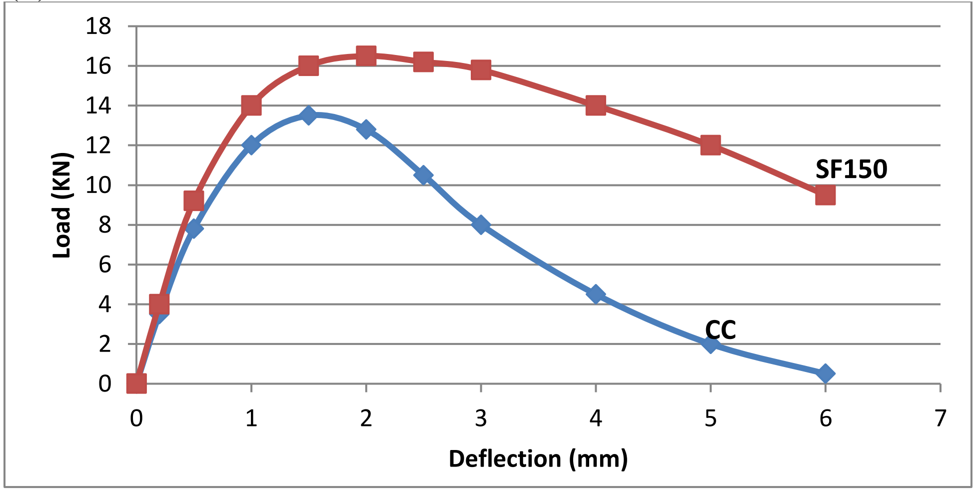
4.6(C) Load Deflection Curves of Control concrete CC and GF Glass Fiber with 1.5%



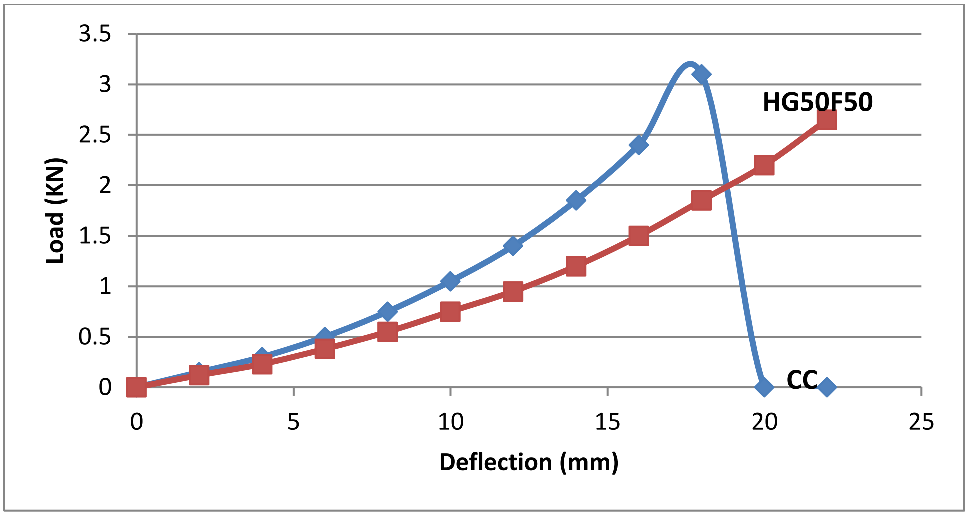
4.6(D): Load Deflection Curves of Control concrete CC and Steel Fiber SF with 0.5%



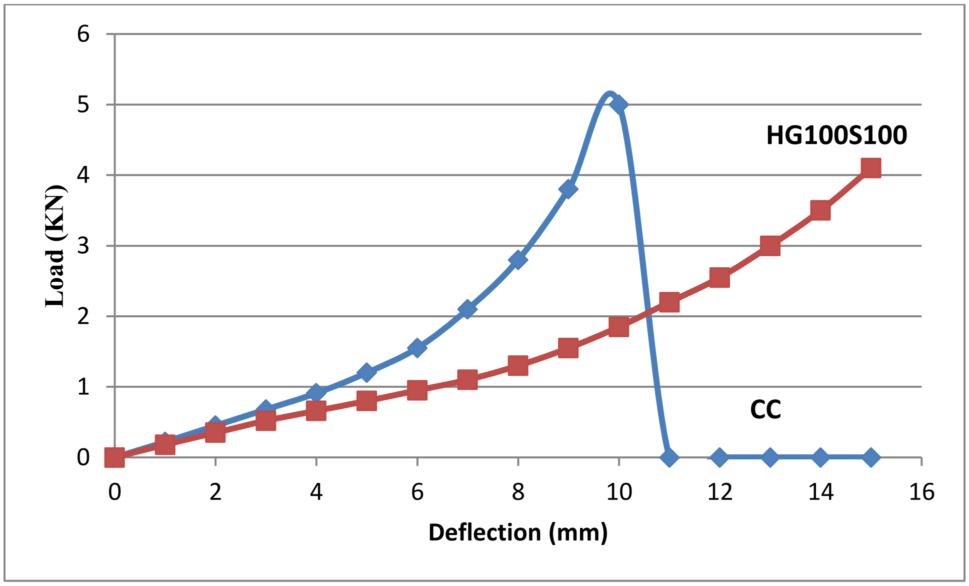
4.6(E): Load Deflection Curves of Control concrete CC and Steel Fiber SF with 1%



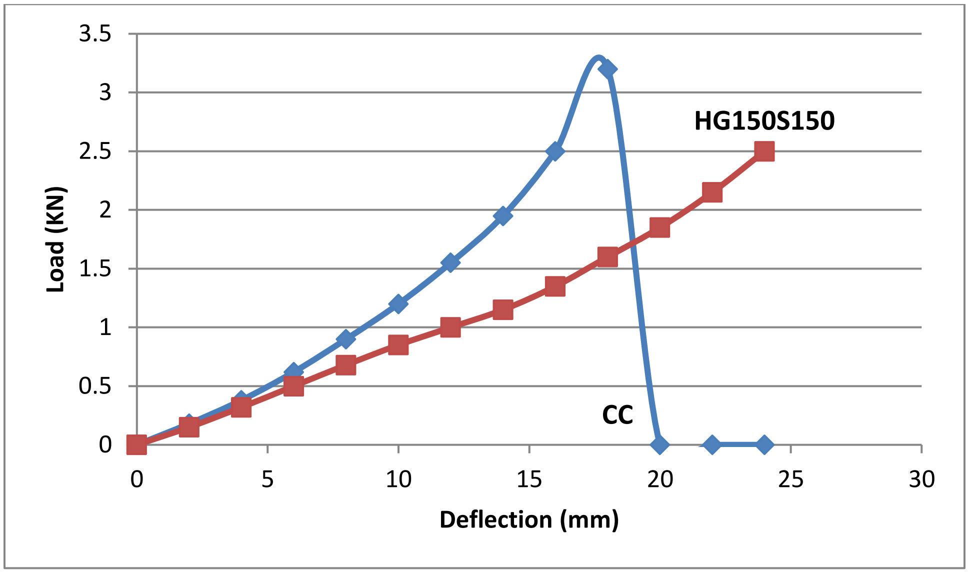
4.6(F): Load Deflection Curves of Control concrete CC and Steel Fiber SF with 1.5%



4.6(G): Load Deflection Curves of Control concrete CC and Hybrid Fiber HG50S50 with 0.5%



4.6(H): Load Deflection Curves of Control concrete CC and Hybrid Fiber HG100S100 with 1%



4.6(I): Load Deflection Curves of CC and Hybrid Fiber HG150S150 with 1.5%

Testing Pictures

The results picture are shown Control Concrete, Steel Fiber prism, Glass Fiber Prism and Hybrid Fiber Prism in figure 4.14

Figure 4.7: CC, SF, GF and Hybrid Fiber Prism Respectively in Figures

Compressive Strength results of Glass Fiber with 0.5%, 01% and 0.5% respectively as shown in Figure 4.15

Fig. 4.8 Compressive Strength results of Glass Fiber

Compressive Strength results of Steel Fiber with 0.5%, 01% and 0.5% respectively as shown in Figure 4.16

Fig. 4.9 Compressive Strength results of Steel Fiber

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

In large-scale projects such as long-span bridges, highways, high-rise buildings, and military structures, there is a growing need for concrete with enhanced mechanical properties especially improved tensile and compressive strength, ductility, durability, and serviceability. The inclusion of fibers in concrete has shown promising results in achieving these improvements.

Fiber-reinforced concrete (FRC) has proven its value globally, and the future of concrete technology is increasingly tied to both mono and hybrid fiber-reinforced systems. Many international projects have successfully incorporated various types of fibers to strengthen their structures. However, the construction industry in Pakistan has been relatively slow to adopt this innovation, despite clear evidence of its benefits. As awareness grows, the use of mono and hybrid FRC is expected to become.

Analysis of the findings of the study and do the following: -

1. The maximum compressive strength was observed in the HG150S150 mix, showing a 18% increase over the control. Among the single-fiber mixes, steel fiber-reinforced concrete showed a greater improvement in compressive strength compared to glass fiber-reinforced concrete.

2. Tensile strength improved significantly with the inclusion of fibers, with steel fibers contributing more effectively than glass fibers.

3. In terms of flexural strength, the HG150S150 mix (a hybrid of steel and glass fibers) achieved a notable 54.85% increase in modulus of rupture (MOR) compared to the control concrete. In comparison, concrete with only glass fibers showed an increase of about 19%, while steel fiber concrete showed a 39.9% improvement. The addition of crimped steel fibers also altered the failure behavior of the concrete. These fibers resisted cracking more effectively due to their textured surface, and failure occurred primarily due to fiber pullout rather than brittle fracture. On the other hand, glass fibers improved compressive strength, tensile strength, and MOR, but they did not affect the failure mode. Concrete with glass fibers failed suddenly after peak loading, producing a smooth fracture surface without noticeable crushing.

4. Specimens containing steel fibers displayed multiple cracks before failure and continued to carry load even after initial cracking, demonstrating enhanced post-crack behavior. However, the incorporation of steel fibers significantly reduced the workability of fresh concrete, and this reduction worsened as the fiber volume increased. Mixing challenges such as balling were observed with steel fibers, though these issues were managed with the use of plasticizers.

5. Corrosion of steel fibers was also noted in some samples. In contrast, alkali-resistant glass fibers did not exhibit any signs of corrosion, making them more durable in that regard. However, using glass fibers alone was not effective in altering the failure mode of concrete, making them more suitable for use in combination with other fibers. Overall, the results suggest that increasing the content of glass fibers can improve concrete properties, but this must be balanced against their negative impact on workability.

5.2 RECOMMENDATIONS

During the investigation, it became clear that there are several additional aspects of fiber use that deserve further exploration. The following topics are recommended for more in-depth study in future research:

1. Concrete with high strength often exhibits brittleness. Improving its ductile behavior requires additional studies on the use of hybrid fibers within high-strength concrete formulations.

2. It's important to develop effective techniques within the concrete matrix to minimize the corrosion of steel fibers when exposed to environmental conditions. This will help extend the service life of structures.

3. Additional research can explore the effects of using a higher percentage of fiber content to further improve concrete performance.

4. Shake table testing should be carried out on prototype frames reinforced with fibers to better understand their behavior under dynamic loading.

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