

Experimental Study on the Strength Enhancement of Carbon Fiber Reinforced GGBS Concrete

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Abstract

This study provides an in-depth analysis of the experimental investigation conducted on carbon fiber reinforced GGBS concrete (CFRGC). The primary objective of the research was to evaluate the effects of carbon fibers on various mechanical properties of concrete, with a particular focus on strength parameters. In this study, the carbon fiber content was systematically varied from 0.5% to 1.5% by weight of cement, in increments of 0.5%, to determine the optimal fiber percentage that yields the best performance. The strength properties analyzed include compressive strength, split tensile strength, and flexural strength. For the compressive strength tests, concrete cubes of 150 mm were cast, while for split tensile strength, cylinders with a diameter of 150 mm and a height of 300 mm were used. Flexural strength was evaluated using concrete beams of 100 mm × 100 mm × 500 mm dimensions. All concrete specimens were subjected to a curing process in water for periods of 7 and 28 days before being tested for their respective strengths. In addition to mechanical strength, the workability of the CFRGC was also assessed using the slump cone test. This test provided insights into how the addition of carbon fibers affects the ease of handling and placing the concrete. A thorough comparison of the experimental results between carbon fiber reinforced GGBS concrete and conventional concrete revealed significant improvements in the mechanical properties of the CFRGC, particularly in terms of compressive strength. The inclusion of carbon fibers was found to enhance the material's ability to resist compressive loads, making it a more robust option for structural applications. Moreover, the study also showed that the addition of carbon fibers positively influenced the split tensile and flexural strengths, indicating an overall improvement in the concrete's durability and performance. The enhanced mechanical properties of CFRGC suggest its potential use in high-performance structural applications, especially where greater load-bearing capacity, improved crack resistance, and better long-term durability are required.

Keywords: Carbon fibers, FRC, Workability, Compressive Strength, Flexural strength, Split tensile strength Superplasticizer, etc.

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INTRODUCTION

Concrete is a vital material in structural engineering, composed of cement, fine aggregate, coarse aggregate, and water mixed in defined proportions. Each component plays a critical role in the performance of the concrete. Coarse aggregates provide compressive strength, while fine aggregates fill the gaps between coarse particles, resulting in a denser and more durable structure with reduced permeability. Water, when combined with cement, initiates a chemical reaction that produces calcium silicate hydrate (C-S-H) gel, the primary source of concrete's strength.

Cement functions as the binding agent, ensuring the cohesion of all ingredients to create a homogeneous mixture with the necessary structural strength, workability, and durability. The chemical reaction between cement and water, known as hydration, is exothermic, releasing a considerable amount of heat. This heat can elevate the concrete's internal temperature, leading to water loss, thermal cracking, and a potential decrease in mechanical performance. These cracks, if formed, can compromise structural integrity by reducing strength, durability, and water resistance.

To prevent the adverse effects of rapid temperature increases during the hydration process in structural applications, the following strategies are commonly employed:

Utilize low-heat cement that minimizes heat release during hydration.

Lower the content of tricalcium aluminate (C3A), a compound that contributes to heat generation.

Adjust the fineness of cement grinding to reduce heat build-up.

Introduce pozzolanic materials or mineral admixtures that reduce the heat of hydration and improve long-term durability.

Pozzolanic materials, which are siliceous or aluminous in nature, may not have inherent binding capabilities, but when finely ground and combined with water, they chemically react with calcium hydroxide produced during hydration to form compounds with cementitious properties. The use of pozzolans in structural concrete enhances performance, reduces the risk of thermal cracking, and increases the durability and strength of structures, making them an effective solution in modern structural engineering projects.

OBJECTIVES

The primary objectives of this research are:

1. To investigate the behavior of carbon fiber-reinforced concrete incorporating Ground Granulated Blast Furnace Slag (GGBS).
2. To evaluate the strength properties of carbon fiber-reinforced GGBS concrete at varying percentages of GGBS and carbon fibers.

LITERATURE REVIEW

Chung (2000) investigated the use of short carbon fibers in concrete and found that they enhance tensile and flexural strength, reduce drying shrinkage, and improve thermal conductivity [1]. Additionally, carbon fibers provide cathodic protection to steel reinforcement embedded in concrete. Buell and Saadatmanesh (1995) explored the application of carbon fiber reinforcement for wooden bridge beams. Wrapping the beams with carbon fibers significantly increased their bending capacity, stiffness, and shear strength, compensating for defects in the wood such as knots and splits [2].

Gull and Tantray (2017) studied the influence of carbon fibers on the mechanical and fresh properties of self-compacting concrete. Their findings indicated that up to a saturation limit of 1.5%, carbon fibers enhanced the fresh and hardened properties of concrete. However, beyond this limit, both workability and strength started to decline [3]. Raza et al. (2018) experimented with reactive powder concrete using different fiber types, including steel, glass, and carbon fibers, to examine compressive strength, tensile strength, flexural strength, and modulus of elasticity [4].

Liu et al. (2019) prepared carbon fiber-reinforced concrete to investigate its flexural strength and toughness using a four-point loading test, identifying 1.5% carbon fiber content as the optimal dose [5]. Similarly, Liu et al. (2020) explored the mechanical properties of coral concrete with carbon fibers, finding improvements in cube compressive strength, axial compressive strength, split tensile strength, Poisson's ratio, and elastic modulus [6].

Venkat et al. (2018) examined the mechanical properties of concrete partially replaced with silica fume, metakaolin, and GGBS. Among these pozzolanic materials, silica fume provided the highest compressive and tensile strengths [7]. Elavarasan et al. (2020) investigated the partial replacement of cement with GGBS and metakaolin, concluding that maximum 28-day compressive strength was achieved with 20% metakaolin and 10% GGBS, while the highest splitting tensile strength occurred with 10% GGBS and 20% metakaolin replacement [8].

SYSTEM DEVELOPMENT

This study is based on experimental work designed to assess the effects of incorporating GGBS and carbon fibers in conventional concrete. Key properties such as compressive strength, flexural strength, and split tensile strength were investigated for concrete mix designs containing varying percentages of these materials.

For M50 grade concrete, the mix proportions were calculated according to the Indian Standard (IS 10262:2019). Prior to mixing, all materials were conditioned to room temperature, approximately $27^{\circ}\text{C} \pm 3^{\circ}\text{C}$. Each component, including cement, GGBS, aggregates, and carbon fibers, was weighed accurately using a digital electronic scale. The mixing was performed using a concrete mixer, ensuring that the cement and aggregates were thoroughly mixed in their dry state to achieve uniformity. Care was taken to avoid contamination and prevent the loss of water or other ingredients during the mixing process.

The prepared concrete mixture was compacted into molds using a vibrating table. The samples were demolded after 24 hours and subsequently submerged in a water curing tank maintained at $27^{\circ}\text{C} \pm 2^{\circ}\text{C}$ for 7 and 28 days. After the curing period, the specimens were subjected to compression, flexural, and tensile tests to assess their respective strength characteristics.

Compression Strength Test

The compressive strength of carbon fiber-reinforced GGBS concrete was evaluated using cube specimens with dimensions of $150\text{ mm} \times 150\text{ mm} \times 150\text{ mm}$, in accordance with IS 516: 1959. This test was conducted to assess the material's ability to resist compressive forces. During the test, a gradual load was applied until the cube specimen failed under compression. The failure patterns of the cubes, along with core details of the failed specimens, are illustrated in Figure 1 and Figure 2.



Figure 1. Chopped carbon Fiber.



Figure 2. Testing of Cube in Compression.

The compressive strength (F_{cu}) was calculated using the formula

$$F_{cu} = \frac{P_c}{A}$$

Where:

- P_c = Maximum load applied during the test (in kN)
- A = Cross-sectional area of the cube (in mm^2)
- F_{cu} = Compressive strength (in N/mm^2)

This formula helps determine the material's ability to withstand compressive loads, which is critical for evaluating its structural performance in real-world applications.

Flexural Strength Test

The flexural strength of carbon fiber-reinforced GGBS concrete was evaluated using beam specimens with dimensions of 100 mm × 100 mm × 500 mm. The specimens were tested using a two-point loading method, where the load was applied along two lines at the top surface, 200 mm apart. The beam was placed such that the axis of the specimen was aligned with the axis of the loading device. During the test, the load was applied gradually at a constant rate of 180 kg/min, ensuring there were no sudden impacts. The test setup for the flexural test and the failure pattern of the prisms are shown in Figure 3 and Figure 4, respectively.

The flexural strength F_{cr} of the concrete was calculated using the following equation:

$$F_{cr} = \frac{PL}{bd^2}$$

Where:

- P = Maximum applied load (in kN)
- L = Span length of the specimen (in mm)
- b = Measured width of the specimen (in mm)
- d = Measured depth of the specimen (in mm)

This test helps evaluate the flexural capacity of the concrete, which is crucial for assessing its ability to resist bending forces in structural applications.



Figure 3. Failure Pattern of Cube in Compression.



Figure 4. Test Setup for Flexure Test.

Split Tensile Strength Test

The split tensile test is an indirect method used to evaluate the tensile strength of concrete, as direct tensile testing is often difficult to perform. In this test, the concrete specimen is subjected to compressive loading until it fails due to tensile stress. For this study, cylindrical specimens were split along their central plane, parallel to the edges, to conduct the split tensile test. The compressive load was applied along the opposing edges of the cylinder.

The test was conducted according to IS 5816: 1999 to determine the tensile strength of carbon fiber-reinforced GGBS concrete. Cylindrical specimens with a diameter of 150 mm and a height of 300 mm were tested after curing periods of 7 and 28 days. The test setup is shown in Figure 5, and the failure pattern due to tensile stress is displayed in Figure 6.

The split tensile strength F_t was calculated using the following formula:

$$F_t = \frac{2P_t}{\pi dL}$$

Where:

- P_t = Maximum applied load (in kN)
- d = Diameter of the cylinder (in mm)
- L = Length of the cylinder (in mm)
- F_t = Split tensile strength (in N/mm^2)

This test is crucial for assessing the tensile strength of concrete, which is important for understanding its behavior under tensile stresses, especially in structural applications.



Figure 5. Failure Pattern of Prism in Flexure.



Figure 6. Test Setup for Split Tensile Test.



Figure 7. Failure pattern of Specimen in Split Tensile Test.

RESULTS AND DISCUSSION

The results from the tests conducted on both conventional concrete and carbon fiber-reinforced GGBS concrete at 7 and 28 days have been systematically recorded and tabulated. The experimental work involved compression strength, flexural strength, and split tensile strength tests on hardened concrete, following the appropriate standards and procedures. All strength tests were performed on concrete specimens cured in water for 7 and 28 days. In addition, the workability of the concrete was assessed using tests on the fresh concrete mix.

Workability of Concrete

The workability of fresh concrete was evaluated using the slump cone test for three types of concrete: conventional concrete, concrete with partial replacement of cement by GGBS, and carbon fiber-reinforced GGBS concrete. The test results, presented in Tables 1 and 2, show a decline in slump values as the percentage of GGBS and carbon fibers increased. This decrease in workability becomes more significant with higher GGBS and carbon fiber content. The variation of slump values with respect to fiber content for M50 grade concrete has been plotted and is shown in Figure 8.

This reduction in slump can be attributed to the stiffening effect of the fibers and GGBS, which limit the free movement of particles in the fresh concrete mix. Lower workability may necessitate the use of plasticizers or other admixtures to achieve the desired consistency when using higher percentages of GGBS and carbon fibers in the mix (Figure 9).

Table 1. Workability of concrete (percentage of GGBS).

S.N.	Mix Designation	GGBS content (%)	Workability (mm)
1	M0	0	120
2	M10	10	114
3	M20	20	107
4	M30	30	98
5	M40	40	89
6	M50	50	80

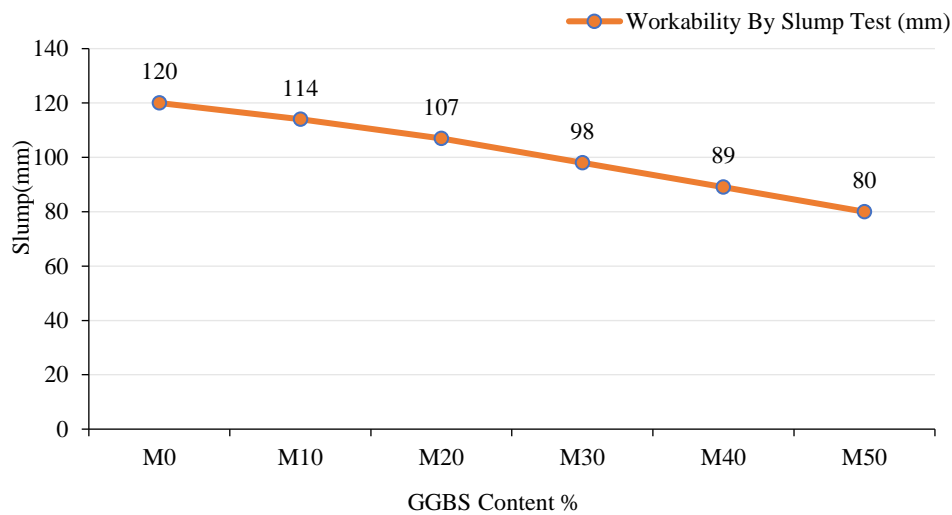


Figure 8. Workability of concrete with variation of GGBS.

Table 2. Workability of concrete (percentage of carbon fiber).

S.N.	Mix Designation	GGBS content (%)	Carbon fiber (%)	Workability (mm)
1	M30	30	0	98
2	MF1	30	0.5	90
3	MF2	30	1.0	84
4	MF3	30	1.5	80

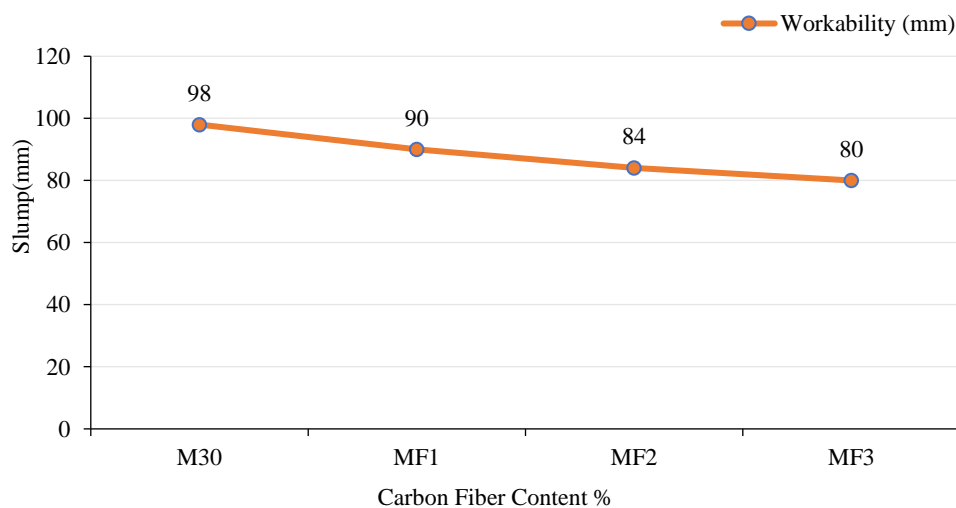


Figure 9. Workability of concrete with variation of carbon fiber.

Workability and Slump Value

Workability is assessed by measuring the slump value (in mm). Based on the results from Table 2, it was observed that for the same mix proportions, superplasticizer dosage, and fiber aspect ratio, an increase in fiber content (%) led to a gradual reduction in workability. The slump values decreased consistently as the fiber content increased, indicating a reduction in the flowability of the concrete mix (Figure 10).

Slump Loss

Tables 3 and 4 provide data on the workability and slump loss for various GGBS and carbon fiber contents in the M50 concrete mix. The water/cement (w/c) ratio for this mix designation was maintained at 0.34. As shown in Tables 1 and 2, increasing the percentage of GGBS and carbon fibers resulted in a

noticeable reduction in workability. This trend is further evidenced by the decreasing slump values and increasing slump losses in M50 grade carbon fiber-reinforced GGBS concrete (Figure 11).

This reduction in workability can be attributed to the densification of the concrete matrix, driven by the micro-filler effect of GGBS. The partial replacement of cement with GGBS, combined with the presence of carbon fibers, reduces the fluidity of the concrete, resulting in increased slump loss. This behavior highlights the need for careful consideration of fiber content and cementitious material replacement to maintain desired workability levels in high-performance concrete mixes (Figure 12).

Table 3. Slump loss of fresh concrete (percentage of GGBS).

S.N.	Mix Designation	GGBS Volume(%)	Workability	Slump Loss Using Eqn(2)
1	M0	0	120	0.00
2	M10	10	114	5.00
3	M20	20	107	10.83
4	M30	30	98	18.33
5	M40	40	89	25.83
6	M50	50	80	33.33

Table 4. Slump loss of fresh concrete (percentage of carbon fiber).

S.N.	Mix Designation	GGBS Volume(%)	Fiber Volume(%)	Workability	Slump Loss Using Eqn (2)
1	M30	30	0	98	0
2	MF1	30	0.5	90	8.16
3	MF2	30	1.0	84	14.28
4	MF3	30	1.5	80	18.36

Compressive Strength Test on Cubes

The compressive strength test was conducted on 150 x 150 x 150 mm cube specimens made from plain concrete, concrete with varying percentages of GGBS, and concrete containing 30% GGBS with carbon fibers. These specimens were tested after being immersed in curing water for 7 and 28 days. The compressive strength tests were carried out using a compression testing machine (CTM) to evaluate the strength characteristics of the concrete under load.

Table 5. Compressive strength of concrete (percentage of GGBS).

S.N.	Mix Designation	GGBS Content (%)	Avg. Comp. Strength (MPa)		% Variation in Compressive Strength Over Control Concrete	
			7 Day	28 Day	7 Day	28 Day
1	M0	0	39.86	54.86	00.00	00.00
2	M10	10	42.43	55.85	6.45	1.80
3	M20	20	45.48	56.64	14.09	3.24
4	M30	30	39.16	54.86	-1.75	0
5	M40	40	38.54	54.59	-3.31	-0.5
6	M50	50	37.59	54.25	-5.7	-1.11

The compressive strength increased with the addition of GGBS up to a certain percentage. For instance, the compressive strength rose from 54.86 MPa for plain concrete to 56.64 MPa with a 20% replacement of cement by GGBS. However, further increases in the percentage of GGBS beyond this point led to a decline in compressive strength, indicating that there is an optimal level of GGBS replacement for enhancing the strength of the concrete.

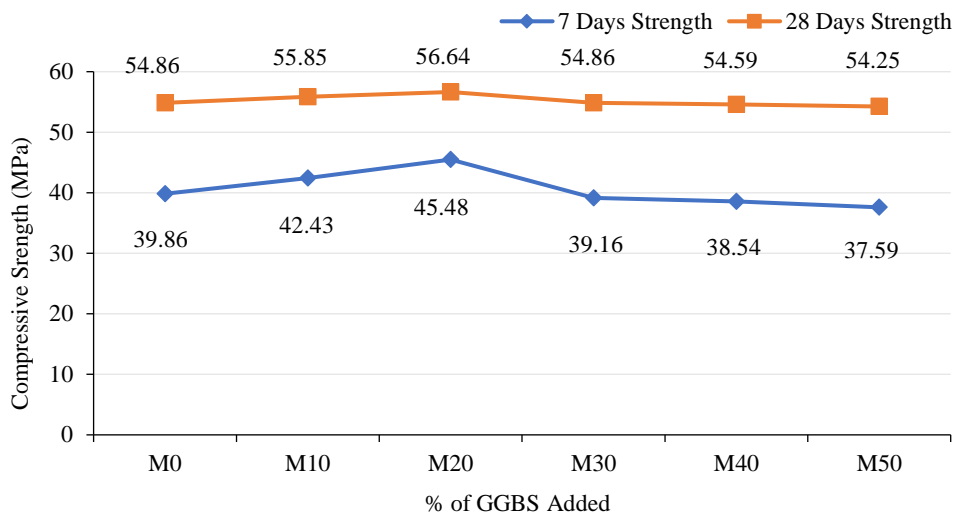


Figure 10. Compressive Strength of concrete with variation of GGBS.

The compressive strength results were calculated using the previously mentioned formula. Table 5 presents the test results for concrete with partial replacement of cement by GGBS. At 28 days of water curing, the compressive strength for the control mix (0% GGBS) was 54.86 MPa, which increased to 56.64 MPa with 20% replacement of cement by GGBS. Similarly, at 7 days of water curing, the compressive strength increased from 39.86 MPa for the control mix to 45.48 MPa with 20% cement replacement by GGBS. This indicates an improvement in early and long-term strength with partial GGBS replacement (Figure 11).

Table 6. Compressive strength of concrete (percentage of carbon fiber).

S.N.	Mix Designation	GGBS Content (%)	Fiber Content (%)	Avg. Comp. Strength (MPa)		% Variation in Compressive Strength Over Control Concrete	
				7 Day	28 Day	7 Day	28 Day
1	M30	30	0	39.16	54.86	0.00	0.00
2	MF1	30	0.5	40.53	60.79	3.49	10.81
3	MF2	30	1.0	42.01	63.01	7.28	14.85
4	MF3	30	1.5	41.63	59.58	6.30	8.60

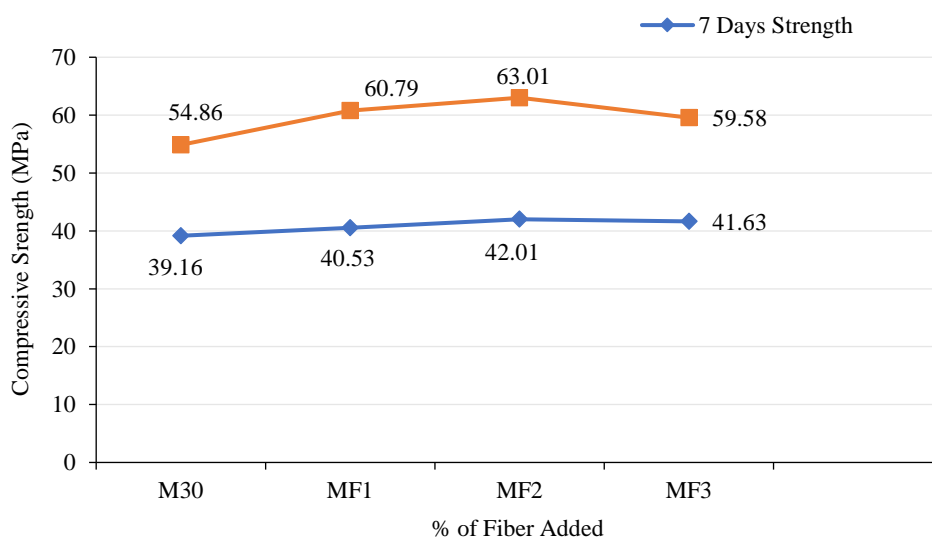


Figure 11. Compressive Strength of concrete with variation of carbon fiber.

The experiment shows that with addition of carbon fibers the compressive strength increased. The tests showed compression strength of 54.86 MPa with 0% carbon fibers and it increased to 63.01 MPa with addition of 1.00% carbon fibers by 14.85% (Table 6).

Flexure Strength Test on Beams

Flexure strength is achieved for different GGBS percentage & results are represented in Table 7. Variation of flexural strength with respect to fiber % is shown in Table 8. This test was conducted on a beam specimen of size 100 × 5100 × 500 mm after curing the specimen for 7 days and 28 days. Universal testing machine was used to perform this test.

Table 7. Flexural strength of concrete (percentage of GGBS).

S.N.	Mix Designation	GGBS Content (%)	Avg. Flexural Strength (MPa)		% Variation in Flexural Strength Over Control Concrete	
			7 Day	28 Day	7 Day	28 Day
1	M0	0	4.53	6.8	00.00	00.00
2	M10	10	5.13	7.5	13.24	10.29
3	M20	20	7.00	9.2	54.52	35.29
4	M30	30	6.78	8.6	49.67	26.47
5	M40	40	6.08	8.4	34.21	23.53
6	M50	50	6.21	8.2	37.08	20.59

The flexural strength was increasing with the partial replacement of cement with GGBS. Upto 20% cement replacement by GGBS, the flexural strength was increased upto 9.2 MPa. After 20% cement replacemnt flexural strength was seen decreasing (Figure 12).

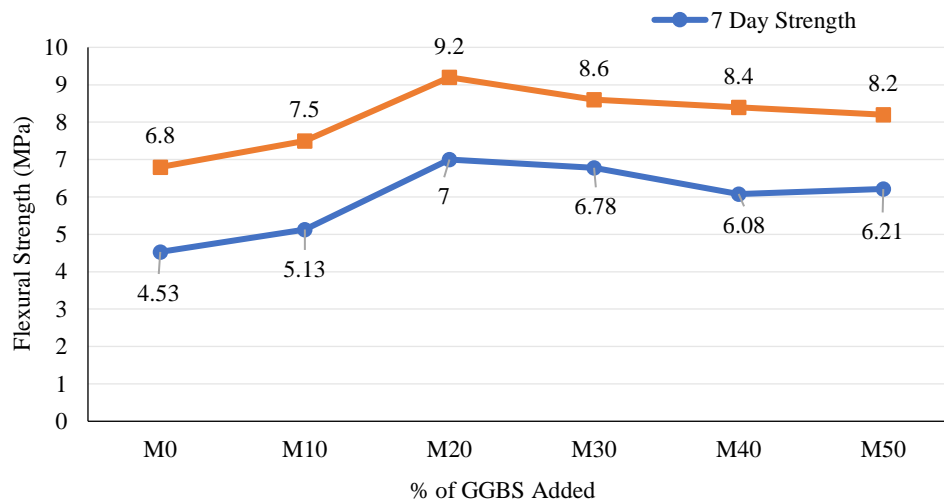


Figure 12. Flexural Strength of concrete with variation of GGBS.

The flexural strength performed on concrete beams of size 100 × 100 × 500 mm. It has been observed that flexural strength was 6.8 MPa of normal concrete with 0% GGBS fraction which increased to 9.2 MPa with 30% cement replacement with GGBS. After 30% GGBS replacement with cement in concrete, the flexural strength has been seen decreasing.

As the carbon fiber content increased in the concrete mix, the flexural strength improved. Up to 1% carbon fiber inclusion, the flexural strength increased by 20%. However, further increases in carbon fiber dosage resulted in a decline in flexural strength, indicating an optimal fiber content for enhancing flexural performance (Figure 13).

Table 8. Flexural strength of concrete (percentage of carbon fiber).

S.N.	Mix Designation	GGBS Content (%)	Fiber Content (%)	Avg. Flexural Strength (MPa)		% Variation in Flexural Strength Over Control Concrete	
				7 Day	28 Day	7 Day	28 Day
1	M30	30	0	7.00	9.2	0.00	0.00
2	MF1	30	0.5	7.52	9.93	7.42	7.93
3	MF2	30	1.0	8.03	11.04	14.71	20.00
4	MF3	30	1.5	7.76	10.65	10.85	15.76

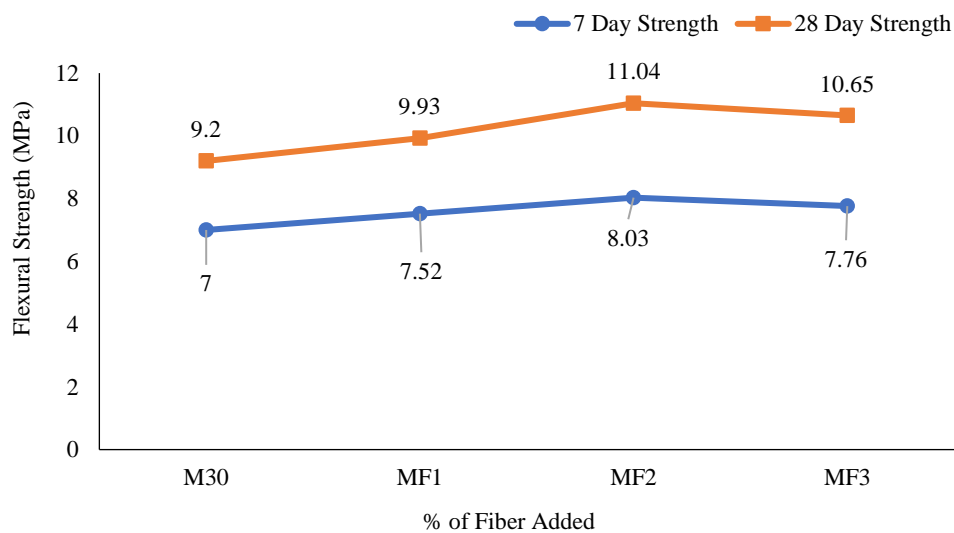


Figure 13. Flexural Strength of concrete with variation of carbon fiber.

Split Tensile Strength Test on Cylinders

The split tensile strength test was conducted on concrete with partial replacement of cement by GGBS. The test results for both 7-day and 28-day strengths are provided in Table 9. Additionally, the split tensile strength results after the inclusion of carbon fibers are presented in Table 10 for the same curing periods. This test was performed using a universal testing machine (UTM) on cylindrical specimens with a diameter of 150 mm and a height of 300 mm, following standard testing procedures to assess the tensile strength characteristics of the concrete (Figure 14).

The split tensile test was performed on concrete cylinder of diameter 150 mm and height 300 mm. The test showed that the tensile strength was 3.18 MPa with 0% GGBS and it increased to 3.52 MPa with 20% GGBS replacement with cement. After 20% GGBS cement replacement, strength started to decrease.

Table 9. Split tensile strength of concrete(percentage of GGBS).

S.N.	Mix Designation	GGBS Content (%)	Avg. Split Tensile Strength (MPa)		% Variation in Split Tensile Strength Over Control Concrete	
			7 Day	28 Day	7 Day	28 Day
1	M0	0	1.89	3.17	00.00	00.00
2	M10	10	2.75	3.49	45.50	10.09
3	M20	20	2.31	3.52	22.22	11.04
4	M30	30	2.17	2.84	14.81	-10.41
5	M40	40	1.92	2.61	1.58	-17.66
6	M50	50	1.83	2.36	-3.17	-25.55

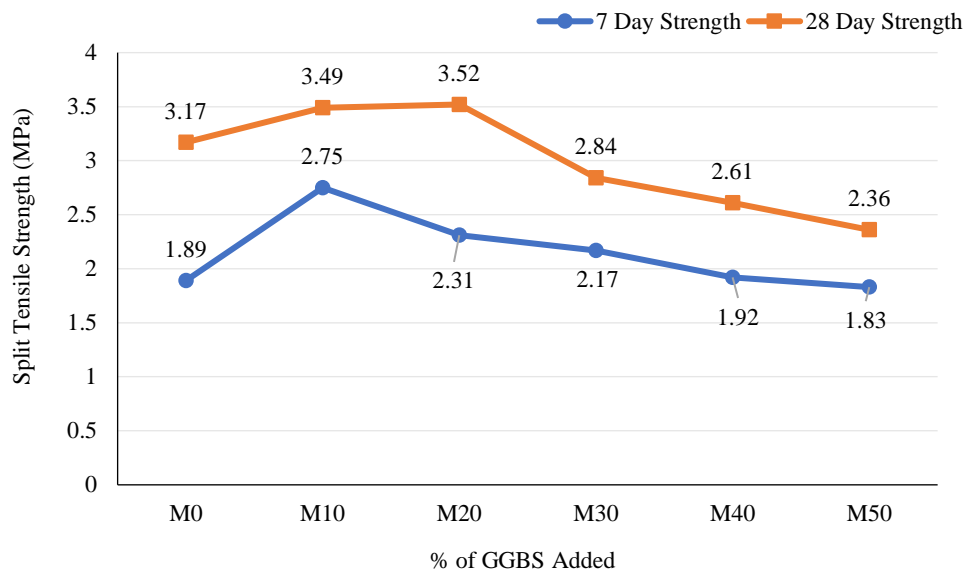


Figure 14. Split Tensile Strength of concrete with variation of GGBS.

Table 10. Split tensile strength of concrete(percentage of carbon fiber).

S.N.	Mix Designation	GGBS Content (%)	Fiber Content(%)	Avg. Split Tensile Strength (MPa)		% Variation in Split Tensile Strength Over Control Concrete	
				7 Day	28 Day	7 Day	28 Day
1	M30	30	0	2.17	2.84	0.00	0.00
2	MF1	30	0.5	2.23	2.92	2.76	2.81
3	MF2	30	1.0	2.37	3.04	9.21	7.04
4	MF3	30	1.5	2.30	2.96	5.99	4.23

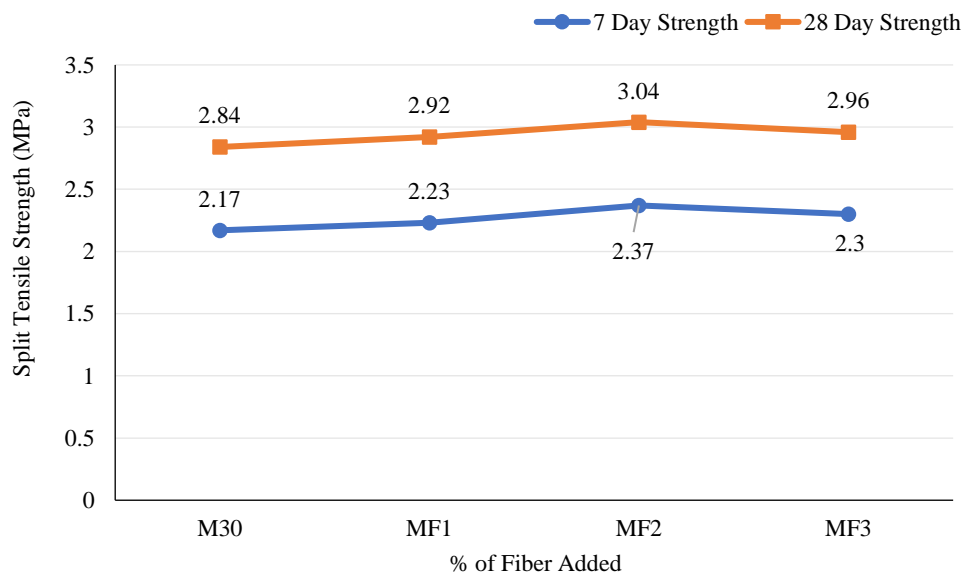


Figure 15. Split Tensile Strength of concrete with variation of carbon fiber.

The split tensile test results demonstrated that the tensile strength increased with the addition of carbon fibers, reaching a maximum of 3.04 MPa with 1% carbon fiber. Beyond this fiber content, the tensile strength started to decline, indicating an optimal fiber dosage for maximizing tensile performance (Figure 15).

CONCLUSIONS

This section summarizes the key findings and applications of carbon fiber-reinforced GGBS concrete based on the results of the study:

Workability: The workability of fresh concrete exhibited a decline as the proportion of ground granulated blast furnace slag (GGBS) and carbon fibers increased in the mix. For standard concrete, the maximum recorded slump value was 120 mm. However, this value dropped to 80 mm when 50% of the cement was replaced with GGBS. The addition of carbon fibers further reduced the workability of the mix, demonstrating the need for adjustments in mix design when incorporating these materials to maintain desired workability levels for structural applications.

Compressive Strength: The compressive strength of normal concrete was recorded at 39.86 MPa after 7 days and 54.86 MPa after 28 days of curing. When 20% of the cement was replaced with GGBS, the compressive strength remained similar at 39.16 MPa and 54.86 MPa after 7 and 28 days, respectively. However, the compressive strength increased to 42.01 MPa and 63.01 MPa with the addition of 1% carbon fiber after 7 and 28 days, representing an increase of 7.28% and 14.85%, respectively.

Flexural Strength: The maximum flexural strength achieved was 7.00 MPa at 7 days and 9.20 MPa at 28 days with 30% cement replacement by GGBS. The addition of 1% carbon fiber further increased flexural strength to 8.03 MPa and 11.04 MPa after 7 and 28 days, showing an approximate 20% increase.

Split Tensile Strength: The split tensile strength with 30% cement replacement by GGBS was 2.31 MPa at 7 days and 3.52 MPa at 28 days. With the addition of 1% carbon fiber, the tensile strength increased to 2.37 MPa and 3.04 MPa after 7 and 28 days, reflecting an improvement of 9.21% and 7.04%, respectively.

Optimal Fiber Content: The ideal carbon fiber content for enhancing compressive strength, flexural strength, and split tensile strength was determined to be 1%. At this level, the concrete exhibited optimal strength characteristics. However, increasing the fiber content beyond 1% resulted in a reduction in strength, indicating that excessive fiber dosage negatively affects the mechanical properties of the concrete. This highlights the importance of maintaining the appropriate fiber content to achieve the best structural performance.

These findings demonstrate that carbon fiber-reinforced GGBS concrete has enhanced mechanical properties, particularly at an optimal fiber content of 1%, making it a viable material for structural applications where higher strength and durability are required.

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