Experimental Evaluation Of Compressive Strength Of Fiber-Reinforced Concrete Using Destructive And Non-Destructive Testing Methods

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Abstract: This study investigates the impact of integrating several types of fibers—glass, carbon, polypropylene, and crimped steel—into standard concrete to create Fiber Reinforced Concrete (FRC) with improved mechanical qualities and durability. This study examines both destructive (compressive strength) and non-destructive (rebound hammer, core strength) test to determine the impact of each fiber type on conventional concrete at various curing times (7, 28, 90, and 360 days). The testing findings demonstrate that crimped steel fibers improved compressive strength the most, reaching 44.00 MPa after 360 days, followed by polypropylene, carbon, and glass fibers. Rebound Hammer tests indicate the better density and surface hardness of FRC made with steel and polypropylene fibers.The study emphasizes the importance of optimizing fiber type and dosage, revealing that a 1.5% content for steel and polypropylene fibers, and 1% for glass and carbon fibers, provides the best performance. This research supports the application of Non-Destructive methods in predicting the long-term strength, quality, and structural integrity of concrete in diverse construction environments.

Keywords: Fiber-Reinforced Concrete (FRC); Crimped steel fibers, polypropylene fibers, carbon fibers, and glass fibers; compressive and core strength; rebound hammer test; durability; and concrete mix design.

INTRODUCTION

The Bureau of Indian Standards (BIS) has developed standards for concrete mix design based on empirical relationships discovered through various trials with materials utilized in Indian settings. IS:10262 was designed in 1982 to guide the 'Mix design' of concrete; nevertheless, due to the demand for high strength concrete and economic manufacture, the addition of auxiliary elements has become necessary. Advanced technology has enabled the identification of additives that improve concrete quality while also making the process more cost-effective and environmentally friendly.

Concrete is classified as a brittle material because of its poor tensile strain capacity. However, it has been regarded as long-lasting because to its exposure to very aggressive settings such as polluted urban and industrial regions, aggressive marine environments, and toxic subsoil water in coastal locations. The latest revision of IS:456-2000 has focused on the durability aspects of concrete, recognizing that strength alone is not sufficient.

Cement is the main ingredient in concrete production, with an estimated global production of 1.3 billion tons in 1996. However, Normal Weight Concrete (NWC) can cause issues during design due to its high natural density relative to strength, leading to greater dead weight.

Concrete is an Artificial substance made of cement, aggregate, and water that solidifies and hardens when mixed with water and placed owing to hydration. This process joins the other components together, resulting in a stone-like substance. As technology advances and the field of concrete and mortar applications expands, the use of alternate materials is becoming an important solution.

Fibre reinforced concrete

Fiber reinforced concrete (FRC) is a form of concrete that incorporates fibers that add structural strength. Steel, glass, synthetic, and natural fibers are evenly scattered and randomly aligned. The fibers bridge cracks as they develop, resulting in post-cracking "ductility." The fibers contribute to the concrete's toughness under all loading conditions, enhance strain at peak load, and absorb energy in the post-peak area of the Load vs Deflection curve.

SFRC has a higher life cycle, reduced maintenance requirements, and lower costs compared to conventional steel reinforcement. When properly planned, it can replace traditional steel reinforcement and shorten construction time since steel fibers are incorporated directly as a component of the concrete mix. When equal levels of reinforcement are utilized, SFRC can perform similarly to conventionally reinforced concrete slabs, according to research. Steel fibers considerably increase the impact resistance of concrete, making it appropriate for use in constructions subjected to impact stresses.

Glass Fiber:

Glass fiber is formed by extruding thin silica-based or other glass strands into many threads with small diameters suitable for textile production. For thousands of years, Egypt and Venice have employed the process of drawing and heating glass to produce delicate fibers. Prior to its recent use in textile applications, all glass fiber was manufactured as staples, or bundles of short fiber lengths.

The mechanical properties of glass fiber are similar to those of carbon fiber and polymers. When used in composites, it is significantly less brittle and far less costly than carbon fiber, yet not as rigid. Glass fiber reinforced composites are widely used in the pipe and marine industries due to its high specific strength, stiffness, and better damage tolerance under impact loading.

Figure 1. Glass Fiber

Carbon Fiber:

Carbon fiber reinforced concrete (CFRC) was launched into the European market in the late 1970s as an alternative to secondary reinforcement in industrial floor slabs and prefabricated concrete products. It has since become a popular alternative to conventional reinforcement in various industries, including pavements, roads, foundation slabs, tunnel segments, and concrete cellars. Carbon fibers are added to fresh concrete during the batching and mixing process, producing a strong composite with superior crack resistance. CFRC can control tensile cracks and increase compressive strength, while conventional concrete loses tensile resistance after multiple crack formation If strong and attached to the material, randomly dispersed discontinuous fibers can bridge cracks and give "ductility" after cracking. Short discrete fibers function as stiff inclusions in the concrete matrix, analogous to aggregate inclusions.

Figure 2. Carbon Fiber

Polypropylene Fiber:

Propene (also known as propylene) monomer is used to make polypropylene, a hard, stiff, and crystalline thermoplastic. Polypropylene is currently one of the most cost-effective polymers on the market.

Figure 3. Polypropylene Fiber

Polypropylene is one of the top three commonly utilized polymers in use today and a member of the polyolefin family. Polypropylene is used as a fiber and a plastic in the following industries: consumer goods, furniture, construction, automotive, and industrial applications.

Crimped Steel Fiber:

One of the most often utilized fibers is steel. Round fibers are often utilized. The range of the diameter is 0.25 to 0.75 mm. It is probable that the steel fiber will corrode and lose part of its strength. Nevertheless, studies have revealed that the fibers only rust at the surface. Steel fibers significantly increase the concrete's flexural, impact, and fatigue strength. They are widely employed in many different kinds of buildings, especially for bridge decks, airport pavements, and road overlays. Steel fibers have also been used to create thin plates and shells.

Figure 4. Crimpled Steel Fiber

REVIEW OF LITERATURE

Glass Fibers Reinforced Concrete (GFRC)

- **Agarwal & Shekhawat (2023)** investigated the incorporation of micro silica in GFRC. Their study found that adding glass fibers enhanced the compressive strength by 12% and flexural strength by 35% compared to normal concrete. However, the compressive strength decreased significantly at elevated temperatures.
- **Patel & Mehta (2022)** evaluated the influence of fiber volume fraction on the mechanical properties of GFRC. Their findings indicated that increasing fiber content up to 2% improved flexural strength and toughness but caused a reduction in workability.
- **Singh et al. (2021)** studied the durability of GFRC exposed to aggressive chemical environments. They reported that GFRC showed better resistance to sulfate attack and chloride penetration compared to conventional concrete, making it suitable for marine and industrial applications.
- **Zhao et al. (2020)** explored the effects of hybrid fiber reinforcement by combining glass fibers with polypropylene fibers. The hybrid GFRC exhibited enhanced impact resistance and energy absorption compared to GFRC with only glass fibers.
- **Alam et al. (2019)** investigated the thermal performance of GFRC panels. Their research showed that GFRC panels have lower thermal conductivity than traditional concrete panels, contributing to improved insulation properties in building envelopes
- **Kasagani & Rao (2018)** examined the effect of graded fibers on the stress-strain behavior of GFRC under tension. They found that the inclusion of graded fibers improved the tensile strength and ductility of the concrete.

Polypropylene Fiber-Reinforced Concrete (PFRC)

- **Kandasamy et al. (2023**) studied how permeable formwork affects the performance of polypropylene fiber-reinforced concrete. Their research discovered that the use of permeable formwork increased the performance of polypropylene fiber-reinforced concrete.
- **Wu et al. (2023)** investigated the effects of polypropylene fiber on the mechanical and physical parameters of pervious concrete. Their findings revealed that the use of polypropylene fibers improved the mechanical qualities of pervious concrete.
- **Murthi et al. (2023)** assessed the performance of PP fiber-reinforced pavement-quality concrete prepared from waste granite powder. Their research demonstrated the possibility of combining waste materials with polypropylene fibers to improve the performance of pavement-quality concrete.
- **Najaf and Abbasi (2022)** studied the impact resistance and mechanical characteristics of fiber-reinforced concrete made with string and fibrillated polypropylene fibers in a hybrid form. Their findings showed that using 1.5% fibrillated Forta fibers increased compressive strength by 18% and flexural strength by 58%. The hybrid use of fibers increased compressive strength by 32% and flexural strength by 85%.
- **Patel et al. (2021)** investigated the mechanical characteristics of PP fiber-reinforced concrete at high temperatures. Their findings suggested that when subjected to high temperatures, PP fibers increase concrete spalling resistance while having no negative impact on mechanical qualities.
- **Srinivasa Rao Naraganti (2021)** studied the durability of hybrid fiber reinforced concrete including polypropylene fibers. The study looked at water absorption, chloride permeability, and acid attack resistance and concluded that adding polypropylene fibers improves concrete durability.
- **Kaur and Singh (2021**) investigated the flexural strength of polypropylene fiber-reinforced concrete members. Their findings revealed that the use of polypropylene fibers increased the flexural strength of concrete elements.

Steel Fiber Reinforced Concrete (SFRC)

- **Spadea et al. (2023**) investigated the performance of steel fiber reinforced concrete and conventional reinforced concrete cast-in-place half-scale concrete bridge decks under bending. Their findings suggested that steel fiber reinforced concrete decks had higher bending strength and ductility than conventional reinforced concrete decks.
- **Kafaji and Azzawi (2023)** Compared the bending performance of half-scale concrete bridge decks reinforced with SFRC and conventional reinforcement.
- **Inayat Ullah Khan et al. (2022)** Investigated the effect of steel fiber dosage and length on the compressive, splitting tensile, and flexural strengths of concrete.
- **Zhang et al. (2022)** Examined the effects of steel fiber content and aspect ratio on the mechanical properties of concrete.
- **Amin et al. (2022)** The review highlighted advancements in fiber types, dosages, and their effects on concrete properties, providing a comprehensive understanding of SFRC applications.

Carbon Fiber Reinforced Concrete (CFRC)

- **Patchen et al. (2023**) studied the mechanical characteristics of recycled carbon fiber reinforced ultra-high-performance concrete. The researchers discovered that integrating recycled carbon fibers improved the mechanical qualities of ultra-high-performance concrete.
- **Saini and Shafei (2023**) investigated the combined use of ultra-high-performance fiber-reinforced concrete and carbon fiber-reinforced polymer to improve the impact resistance of concrete-filled steel tubes. The study found that combining these materials improved the impact resistance of the constructions.
- **Alzamili and Elsheikh (2023**) investigated the performance of reinforced concrete components enhanced with carbon fiber reinforced polymer at high temperatures. Their findings showed that CFRP strengthening improved the heat resistance of concrete parts.
- **Zhang et al. (2023)** conducted an experimental study on the mechanical properties of CFRC under high temperatures. The study concluded that carbon fibers effectively mitigated the degradation of concrete's mechanical properties at elevated temperatures.
- **Wang et al. (2022)** examined the thermal conductivity and fire resistance of CFRC. Their research found that the inclusion of carbon fibers improved the thermal conductivity and fire resistance of concrete.
- **Kan et al. (2022)** investigated the frost resistance of CFRC. Their findings revealed that adding carbon fibers increased concrete's frost resistance, making it more durable in cold locations.
- **Zhan et al. (2021)** studied the mechanical characteristics of CFRC after exposure to high temperatures. Their investigation discovered that the inclusion of carbon fibers increased the residual compressive and flexural strengths of concrete under higher temperatures.
- **Alhassnawi and Alfatlawi (2018)** evaluated the effect of high temperatures on reinforced concrete columns enhanced with carbon fiber reinforced polymer products. The study found that CFRP strengthening increased the fire resistance of concrete columns.

Rebound Hammer Test:

- **Sbartaï et al. (2023)** investigated the use of rebound hammer tests to predict in-situ strength of concrete incorporating recycled aggregates. The study explored the influence of mix composition on rebound hammer readings and proposed machine learning models for strength prediction.
- **Zhang (2023)** examined the application of rebound hammer tests in assessing fire-damaged concrete. The research highlighted the method's effectiveness in evaluating surface hardness and estimating compressive strength in compromised structures
- **El-Hassan et al. (2023**) utilized the rebound hammer test to predict the in-situ strength of concrete including recycled aggregates, brick chips, and stone chips. The study aimed to

examine the effect of mixture composition and concrete age on the coefficient of variation of the rebound hammer index when applied to different types of concretes.

- **El-Mir et al. (2023**) used rebound hammer tests to assess the strength of concrete using recycled aggregate. The study's goal is to investigate the effect of mix composition and concrete age on the coefficient of variation of the rebound hammer index when applied to different types of concrete.
- El-Zahab et al. (2023) used rebound hammer tests to determine the in-situ strength of concrete with recycled particles. The study aimed to examine the effect of mixture composition and concrete age on the coefficient of variation of the rebound hammer index when applied to different types of concretes.
- **Scaria et al. (2023**) compared the rebound hammer and pullout techniques for evaluating concrete. The study discovered that rebound hammer readings had a correlation value of 0.695, showing a moderate relationship with compressive strength.

MATERIALS AND METHODOLOGY

Materials

Cement

This investigation used ordinary Portland Cement (OPC) of grade 53, as specified in IS 12269:2013. The cement was tested according to IS 4031:1988. Its physical properties, such as a specific gravity of 3.14 and a fineness of 4%, demonstrate its quality and appropriateness for high-strength applications. The usual consistency was determined to be 30%, with an initial setting time of 110 minutes and a final setting time of 440 minutes. These qualities guarantee optimal workability and strength development in concrete.

Fine Aggregate

The fine aggregate utilized was locally available river sand that satisfied the IS 383:2016 standards. It was from Zone II, with a specific gravity of 2.58 and a fineness modulus of 2.74, suggesting high grading. The bulk density of the sand was 1618 kg/m³. Fine aggregate improves the mix's compactness and cohesiveness, making it easier to deal with.

Coarse Aggregate

Crushed angular coarse aggregate with a nominal maximum size of 20 mm was utilized, as per IS 383:2016. With a specific gravity of 2.73, a bulk density of 1430 kg/m³, and a low water absorption of 0.23%, it is ideal for constructing solid, durable concrete. Coarse particles add volume and improve the mechanical properties of concrete.

Water

Potable water from the laboratory was utilized for mixing and curing. The water quality was suitable for concrete usage, with a pH of 7.76, chloride concentration of 160 mg/L, sulphate concentration of 110 mg/L, and total dissolved solids (TDS) of 1000 mg/L. It also included 100 mg/L of organic solids and 900 mg/L of inorganic solids, which were all within acceptable levels to prevent undesirable reactions in the cement matrix.

Glass Fibers

Alkali-resistant (AR) glass fibers supplied under the brand name CEM-Fil were incorporated to improve concrete's crack resistance and toughness. These fibers had an elastic modulus of 72 GPa, filament diameter of 0.014 mm, and a specific gravity of 2.68. The fiber length was 12 mm, with a zirconia content of 16.7%, giving an aspect ratio of 857.1 and a specific surface area of 105 m²/kg. These characteristics are critical in enhancing both tensile and impact resistance.

Carbon Fibers

Carbon fibers were used to further improve concrete’s mechanical performance. Known for their high stiffness and durability. The specific gravity was 1.75, and the fiber length ranged from 6 to 12 mm, with an aspect ratio between 500 and 1000, making them effective at crack control and load transfer.

Polypropylene Fibers

Polypropylene fibers were used to enhance the toughness and crack resistance of concrete. These fibers, with diameters ranging from 30 to 50 microns and cut lengths of 6, 12, and 20 mm, had exhibited no water absorption. Their aspect ratios ranged from 400 to 667, making them suitable for improving concrete ductility and resistance to shrinkage cracking.

Crimped Steel Fibers

Crimped steel fibers were employed to improve the concrete's mechanical qualities, such as tensile strength, impact resistance, and ductility. The fibers ranged in diameter from 0.5 to 1.2 mm and length from 30 to 60 mm. With tensile strengths ranging from 800 to 1500 MPa, an elastic modulus of 200 GPa, and a specific gravity of 7.8, they significantly contributed to the structural integrity of the fiber-reinforced concrete. Water absorption was found to be low.

Admixture

The blend included a high-range water-reducing additive, Conplast SP430, which is made up of sulphonated naphthalene polymers. This additive enhanced the workability of the concrete without increasing the water content, decreased permeability, and allowed for better early strength, which added to the total durability of the concrete mix.

Destructive Tests

Compressive Strength:

The ability of a material or structure to withstand or resist compression is known as compressive strength. Compressive strength is determined by a material's capacity to tolerate failure in the form of cracks and fractures.

This test determines the maximum compression that concrete can bear without failure, as well as the push force given to the specimen's two faces. Concrete testing measures the concrete's resistance to stress, allowing us to focus on its compressive strength.

Figure 5: Test for Compressive Strength

Non-Destructive Tests

Core strength

Concrete core testing is a common method for determining the compressive strength of hardened concrete. It enables visual inspection of the internal regions of concrete members, as well as the assessment of strength and evaluation of other attributes of reinforced concrete-framed structures. The test is important to evaluate the true strength of concrete in structural components. Core samples should be collected with diamond-studded bits that are at least three times the maximum nominal size of coarse material (50 mm). Cores should be at least twice as long as their diameter. The core should not include reinforcing steel, and the amount, quantity, and position of steel reinforcement should be evaluated using magnetic equipment or radiographic ground-penetrating radar examination.A minimum of three cores are needed to examine a specific challenge. The placement of the core in vertical concrete elements, such as walls and deep beams, is critical owing to differences in concrete characteristics with elevation. The curing history of a structure is difficult to assess, and the direction of drilling influences core strength. The cores are visually examined for aggregate dispersion, compaction, and steel content.

Figure 6: Concrete Core Test

Rebound hammer Test:

The Rebound Hammer test is a non-destructive way to determine the compressive strength of concrete. A spring-controlled mass slides along a plunger inside a tubular casing, causing the concrete to bounce back.The rebound index measures surface hardness, with low strength and stiffness resulting in lower rebound values. The test tries to measure the compressive strength, homogeneity, and quality of concrete using specified parameters. It can be used to distinguish between acceptable and questionable structural components, as well as to compare the strength of two structures.

Figure 7: Rebound Hammer

Figure 8: Rebound Hammer Test

EXPERIMENTAL INVESTIGATION

Optimum Fiber Content for Maximum Compressive Strength

From the experimental findings, the optimum fiber content for achieving maximum compressive strength varies for different fiber-reinforced concretes. CSFRC achieves the highest strength at 1.5% fiber content (40.80 MPa), while PFRC also performs best at 1.5% (36.60 Mpa). In the case of CFRc and GFRC, the best results are observed at 1% fiber content, with compressive strengths of 28.56 Mpa and 24.23 Mpa, respectively. These results indicate that an optimum fiber percentage is necessary to balance strength enhancement and workability. Beyond this limit, excessive fiber addition results in reduced compaction, fiber clumping, and decreased overall strength.

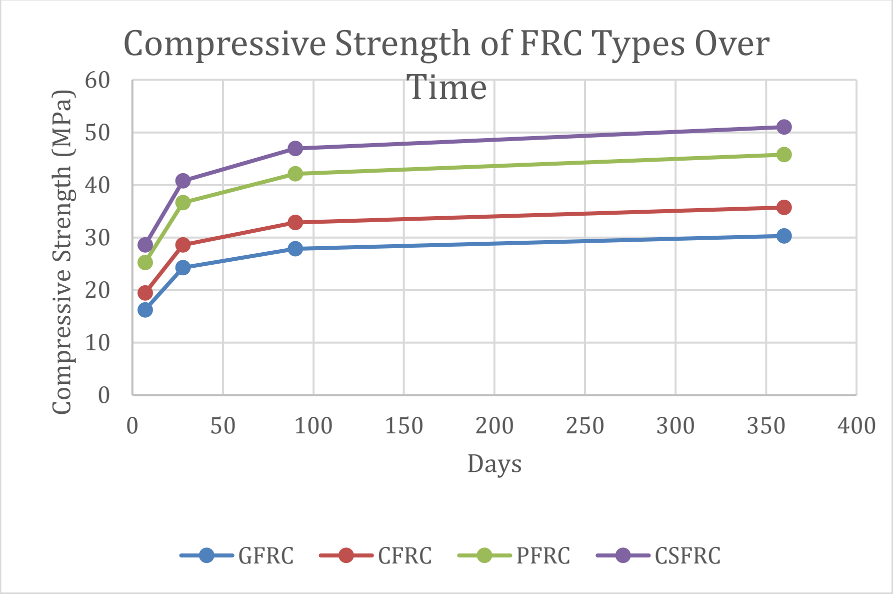
Table 1: Optimum Fiber Content for Maximum Compressive Strength of FRCs.

Fiber Type (FRC)	Concrete Grade	Optimum Fiber Content (%)	Maximum Compressive Strength (MPa)	Age at Maximum Strength
GFRC	M20	1.0	24.23	28 Days

CFRC	M25	1.0	28.56	28 Days
PFRC	M30	1.5	36.60	28 Days
CSFRC	M35	1.5	40.80	28 Days

Table 2 : Compressive Strength of FRCs at Optimum Fiber Content

Fiber Type (FRC)	Concrete Grade	OptimumFiber Content (%)	7-Day Strength (MPa)	28-Day Strength (MPa)	90-Day Strength (MPa)	360-Day Strength (MPa)
GFRC	M20	1.0	16.23	24.23	27.84	30.29
CFRC	M25	1.0	19.42	28.56	32.84	35.70
PFRC	M30	1.5	25.25	36.60	42.09	45.75
CSFRC	M35	1.5	28.56	40.80	46.92	51.00



Graph 1: Compressive Stength vs Different curing periods

Here is the graph illustrating the compressive strength of Fiber-Reinforced Concretes (FRCs) at optimum fiber content over different curing periods (7, 28, 90, and 360 days).

The graph and table show that the addition of fibers greatly increases the compressive strength of concrete, with considerable benefits occurring as the curing age advances. Among the many forms of fiber-reinforced concrete, CSFRC (Concrete with Steel Fibers) and PFRC (Concrete with Polypropylene Fibers) show the most significant improvements, particularly after 360 days, emphasizing the long-term benefits of fiber reinforcing. GFRC (Glass Fiber Reinforced Concrete) demonstrates a steady but modest improvement over time, reaching a 28-day strength of 24.23 MPa, with only a slight increase thereafter. Similarly, CFRC (Carbon Fiber Reinforced Concrete) mirrors this trend, showing marked enhancement from 7 to 28 days, followed by a gradual rise beyond 90 days. PFRC, on the other hand, shows a more pronounced strength development, particularly evident at 360 days where it attains a strength of 45.75 MPa, suggesting that polypropylene fibers contribute significantly during both early and long-term curing stages. Most notably, CSFRC consistently records the highest compressive strengths at all ages, culminating in a peak value of 51.00 MPa at 360 days, indicating that steel fibers offer the greatest enhancement in structural strength and durability. These findings affirm that the type of fiber used plays a critical role in determining the performance of fiber-reinforced concrete, with long-term curing further amplifying the benefits provided by fiber inclusion.

Rebound Hammer Test:

The data presented in the table for Fiber-Reinforced Concrete (FRC) at optimum fiber content demonstrates varying compressive strength development across different fiber types and concrete grades over several curing periods (7, 28, 90, and 360 days). The rebound hammer test results reflect the effectiveness of different fibers in enhancing the mechanical properties of concrete at various stages of curing. The comparison highlights how fiber type, dosage, and concrete grade influence the material's ability to gain strength over time.

Glass Fiber Reinforced Concrete (GFRC), with a concrete grade of M20 and 1.0% fiber content, demonstrates a gradual increase in rebound strength over time. The strength begins at 14 MPa at 7 days and improves to 23 MPa at 28 days. It continues to rise to 26 MPa at 90 days, followed 28 MPa at 360 days. Although GFRC shows the lowest strength values compared to other fiber types, its steady progression indicates reliable long-term performance, making it suitable for applications where durability over time is a key consideration.

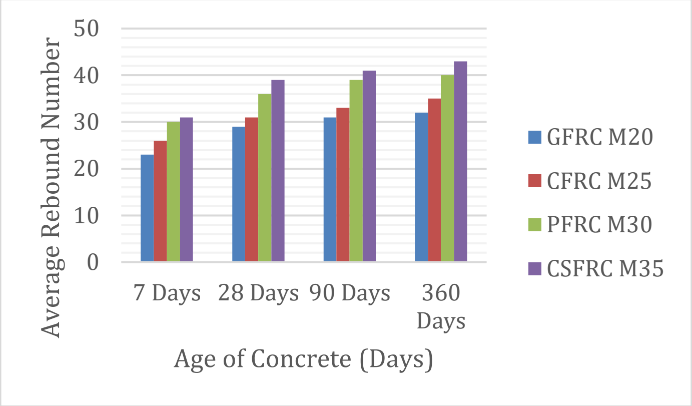
Carbon Fiber Reinforced Concrete (CFRC), corresponding to M25 grade with 1.0% fiber content, shows moderate and consistent strength development. Starting at 18 MPa at 7 days, the rebound strength increases to 26 MPa at 28 days, then to 30 MPa at 90 days, and finally to 34 MPa at 360 days. This fiber type provides a balanced performance, with a stable rate of strength gain over time. CFRC is ideal for applications requiring a reasonable mix of early and sustained strength, without demanding the highest performance.

Polypropylene Fiber Reinforced Concrete (PFRC), using M30 concrete with 1.5% fiber content, shows a strong and steady development in rebound strength. It begins with 24 MPa at 7 days and rises significantly to 35 MPa by 28 days. The strength continues to climb to 40 MPa at 90 days and slightly further to 42 MPa at 360 days. This consistent upward trend highlights PFRC's effectiveness in enhancing both early-age and long-term strength, making it an excellent choice for structures requiring quick load-bearing capacity as well as long-lasting performance.

Crimped Steel Fibers (CSFRC), at M35 grade and 1.5% fiber content, outperforms all other fiber types across all curing periods. The rebound strength starts at 26 MPa at 7 days, increases to 40 MPa at 28 days, reaches 44 MPa at 90 days, and peaks at 48 MPa at 360 days. CSFRC's high strength at both early and later stages reflects the superior reinforcing capability of steel fibers. Its performance makes it the most suitable option for heavy-duty applications and critical infrastructure where maximum strength and durability are essential.

Table 3 : Rebound Number of FRCs at Optimum Fiber Content

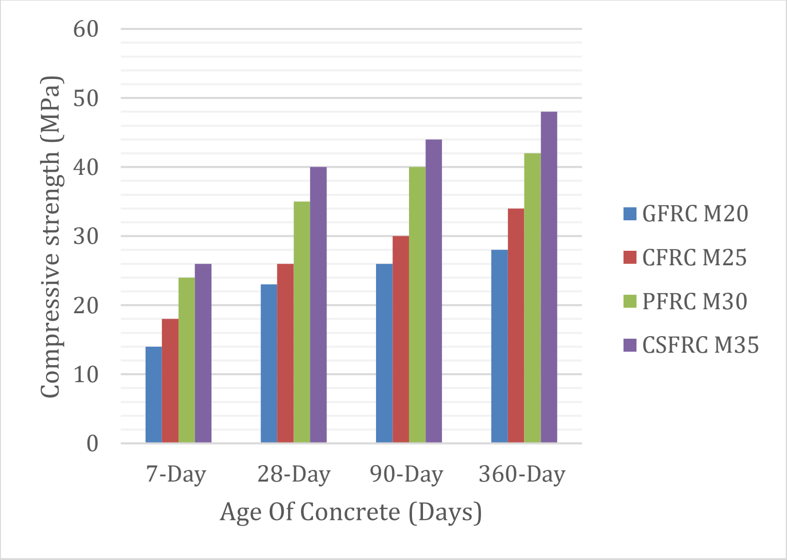
Fiber Type (FRC)	Concrete Grade	Optimum Fiber Content (%)	Average Rebound Number At 7 Days	Average Rebound Number At 28 Days	Average Rebound Number At 90 Days	Average Rebound Number At 360 Days
GFRC	M20	1	23	29	31	32
CFRC	M25	1	26	31	33	35
PFRC	M30	1.5	30	36	39	40
CSFRC	M35	1.5	31	39	41	43



Graph 2: Rebound Number vs. Age of Fiber Reinforced Concrete (FRC)

Table 4 : Equivalent compressive strength with Rebound Hammer of FRCs at Optimum Fiber Content

Fiber Type (FRC)	Concrete Grade	Optimum Fiber Content (%)	7-Day Rebound Strength (MPa)	28-Day Rebound Strength (MPa)	90-Day Rebound Strength (MPa)	360-Day Rebound Strength (MPa)
GFRC	M20	1	14	23	26	28
CFRC	M25	1	18	26	30	34
PFRC	M30	1.5	24	35	40	42
CSFRC	M35	1.5	26	40	44	48



Graph 3: Equivalent Compressive Strength Over Time

Concrete Core Test

The Core Strength Test results for Fiber-Reinforced Concrete (FRC) at optimum fiber content indicate significant improvements in compressive strength over time. Each fiber type—GFRC (Glass Fiber Reinforced Concrete), CFRC (Carbon Fiber Reinforced Concrete), PFRC (Polypropylene Fiber Reinforced Concrete), and CSFRC (Crimped Steel Fiber Reinforced Concrete)—shows good strength improvement, especially during the 28-day and 360-day curing periods.The data clearly reflects how different fibers interact with concrete matrices to influence strength gain throughout the curing process.

Glass Fiber Reinforced Concrete (GFRC), using M20 grade concrete and 1.0% fiber content, shows a steady improvement in core strength over time. Starting at 15.8 MPa at 7 days, it increases to 23.5 MPa at 28 days, continues to 26.03 MPa at 90 days, and finally reaches 29.38 MPa at 360 days. Although GFRC exhibits the lowest strength among the fiber types, the consistent growth pattern highlights its contribution to long-term performance and structural stability, especially in applications where gradual strength development is acceptable.

Carbon Fiber Reinforced Concrete (CFRC), with a concrete grade of M25 and a fiber percentage of 1.0%, has greater early and long-term strength than GFRC. The core strength starts at 18.5 MPa at 7 days and increases to 27.85 MPa at 28 days, 31 MPa at 90 days, and 34.81 MPa at 360 days.The performance shows CFRC's capability to deliver reliable strength gain, making it suitable for structures requiring improved durability and slightly faster strength development compared to GFRC.

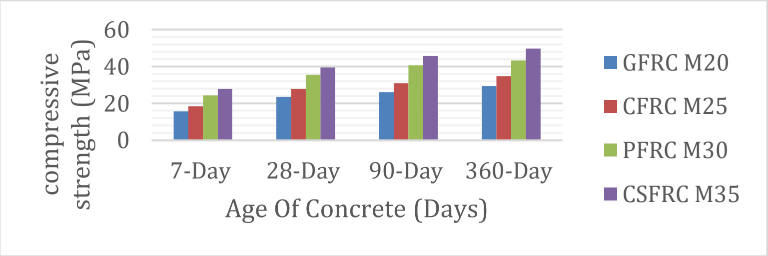
Polypropylene Fiber Reinforced Concrete (PFRC), composed of M30 grade concrete and 1.5% fiber content, compressive strength has increased significantly. At 7 days, the strength is 24.4 MPa, increasing dramatically to 35.4 MPa at 28 days, 40.71 MPa at 90 days, and 43.25 MPa after 360 days.This upward trend indicates PFRC's excellent balance of crack resistance and strength development, making it ideal for structural elements subject to dynamic loads and where early and sustained performance is critical.

Crimped Steel Fiber Reinforced Concrete (CSFRC), the highest-performing among all the fiber types, uses M35 grade concrete with 1.5% fiber content. It starts with a strong 27.8 MPa at 7 days, increases to 39.5 MPa at 28 days, further to 45.66 MPa at 90 days, and achieves 49.63 MPa at 360 days. CSFRC's superior strength at every curing stage makes it particularly suitable for high-load or infrastructure projects requiring exceptional compressive performance and long-term reliability.

In conclusion, all FRC types show improved compressive strength with longer curing times, with CSFRC demonstrating the highest strength values, followed by PFRC, CFRC, and GFRC. These findings emphasize the importance of selecting appropriate fiber types and optimizing fiber content based on the specific performance needs of a project. Whether the priority is early strength, crack resistance, or long-term durability, fiber-reinforced concretes provide a tailored solution to meet varying structural demands.

Table 6: Concrete Core strength Test Results of FRCs at Optimum Fiber Content

Fiber Type	Concrete Grade	Optimum Fiber Content (%)	7-Day Core Strength (MPa)	28-Day Core Strength (MPa)	90-Day Core Strength (MPa)	360-Day Core Strength (MPa)
GFRC	M20	1	15.8	23.5	26.03	29.38
CFRC	M25	1	18.5	27.85	31.00	34.81
PFRC	M30	1.5	24.4	35.4	40.71	43.25
CSFRC	M35	1.5	27.8	39.5	45.66	49.63



Graph 4: Core Compressive Strength over Time

CONCLUSIONS

The Fiber-Reinforced Concrete (FRC) study revealed important information on the effect of fiber content on compressive strength, rebound hammer strength, and core strength in concrete.The findings demonstrated that the optimal fiber content for maximal compressive strength varied according to the kind of fiber utilized. For example, Concrete Strengthened with Steel Fibers (CSFRC) has the maximum compressive strength of 40.80 MPa at an ideal fiber percentage of 1.5%, making it the most effective in increasing the total strength of concrete.

In terms of long-term performance, CSFRC consistently achieved the highest compressive strength across all curing periods (7, 28, 90, and 360 days), demonstrating its superior contribution to the concrete's structural integrity.

PFRC showed significant strength gains over time, indicating the ability of polypropylene fibers to improve concrete's durability and long-term performance. In comparison, CFRC and GFRC demonstrated more consistent but lower strength increases, which may be useful in applications requiring lighter, more cost-effective solutions.

The Rebound Hammer test confirmed the compressive strength data, with CSFRC once again outperforming the other fiber types, reaching a strength of 48.00 MPa at 360 days. Core strength tests reinforced these findings, with CSFRC achieving the highest value of 49.63 MPa at 360 days, further validating the internal quality and robustness of the concrete. PFRC, CFRC, and GFRC also exhibited good core strength, highlighting their potential for specific applications that require high internal strength.

Polypropylene fibers in PFRC also showed strong results, especially in core strength and durability, while carbon and glass fibers offered lower but consistent performance, suitable for specialized applications where flexibility or crack resistance is prioritized. This research underscores the critical role of fiber selection in optimizing concrete mixtures for various construction needs, ensuring enhanced strength, durability, and sustainability.

The core strength test results clearly indicate that the inclusion of fibers significantly enhances the compressive strength of concrete over time, with Crimped Steel Fiber Reinforced Concrete (CSFRC) exhibiting the highest strength at all curing periods. CSFRC reached a peak core strength of 49.63 MPa at 360 days, followed closely by Polypropylene Fiber Reinforced Concrete (PFRC) at 43.25 MPa, demonstrating their superior reinforcing capabilities and long-term performance. Carbon Fiber Reinforced Concrete (CFRC) and Glass Fiber Reinforced Concrete (GFRC) also showed consistent strength gains, though at comparatively lower levels. The steady increase in core strength across all fiber types underscores the effectiveness of fiber reinforcement in improving concrete's internal structural integrity and durability, particularly with prolonged curing.

In conclusion, this study emphasizes the importance of selecting the appropriate fiber content to achieve the desired performance characteristics in FRC. Steel fibers, particularly in CSFRC, were found to be the most effective for enhancing both compressive and long-term strength, making them ideal for applications requiring high durability.

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