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Assessing The Impact Of Micro-Fibrillated Cellulose (MFC) On The Flexural Strength And Toughness Of The Reinforcement Concrete

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Abstract

The construction industry heavily relies on concrete material which provides durable performance but deals with three crucial drawbacks of micro-cracking and brittleness alongside environmental sustainability issues. Researchers explore the addition of Micro-Fibrillated Cellulose (MFC) which stems from plant fibers as a nanomaterial for reinforced concrete to boost mechanical performance along with sustainability. MFC shows excellent bonding properties along with high surface area which leads to better strength levels and toughness and enhanced durability performance. The research investigates MFC concentrations from 0% to 0.5% and 1% and 1.5% and 2% to determine optimal performance levels. Experimental testing encompassing compressive strength and flexural strength testing as well as toughness evaluation and durability assessment and microstructural analysis through SEM occurred at ages of 7, 14, 28, 56, 90, and 180 days. The combination of 1.5% MFC created the optimal reinforcement effects resulting in a 40% increase of flexural strength reaching 6.3MPa alongside a 62.5% growth of toughness reaching 195kN-mm at 180 days. The maximum compressive strength of 40.4MPa occurred with 1.5% MFC and water absorption decreased to 3.8% while chloride penetration fell to 700 Coulombs. Results indicate that MFC proves as an effective sustainable material because it delivers promising characteristics to enhance mechanical properties and durability for high-performance concrete applications. The analysis delivers new sustainable construction materials which demonstrate better resistance to damage.

Keywords: MFC, Reinforcement Concrete, SEM, Flexural strength, Toughness

1. Introduction

Concrete is the most popular building material because of its long lifespan and excellent structural resilience [1,2]. All over the world, concrete has been positioned as the second most-used material [3], with three tons utilized per year for each living on Earth [4]. Concrete has many benefits but has certain mechanical and morphological limits, such as a lack of strength under strain and the ability to contain micro-cracks and capillaries [5]. Conversely, there are environmental disadvantages and risks associated with concrete manufacturing, according to both academics and businesses. As an example, it contributes to about 7-8% of the mentioned proportion [7], which means that it is primarily responsible for 9% of the world's greenhouse gas emissions [6], namely CO_2. The high energy [8,9] and water [10,11] requirements of concrete manufacturing are another previously mentioned environmental danger. The extraction and use of many raw minerals and materials—including clay, natural sand, gravel, fibers, and other additives—is an additional environmental cost of making concrete [12].

A promising new path in concrete technology including carbon nanostructures, silicon oxides, titanium, iron, and other metals is receiving a lot of attention [13-15]. Microfibrillar cellulose (MFC) is one of the modifying additives that is now the subject of intensive research for usage in cement composites. Beet pulp, a byproduct of the sugar industry, has just found its way into the market as a biopolymer addition to concrete [16,17]. MFC, which is made from plant fibers, has great mechanical qualities, a nano-scale structure, and a large surface area, all of which make it an attractive material for improving concrete's performance (Figure 1) [18].

Figure 1.1: Schematic structures of MFC [19].

The features and qualities of these goods, which typically fall within the nanometric-micrometric size range, are superior to those of natural cellulose fibers [20]. MFCs are three-dimensional networks composed of aggregated cellulose chains [21]. Each chain is composed of several glucose molecules that are connected by hydrogen bonds and van der Waals interactions (Figure 2). It consists of long, slender cellulose microfibrils that have a high length-to-width ratio [22].

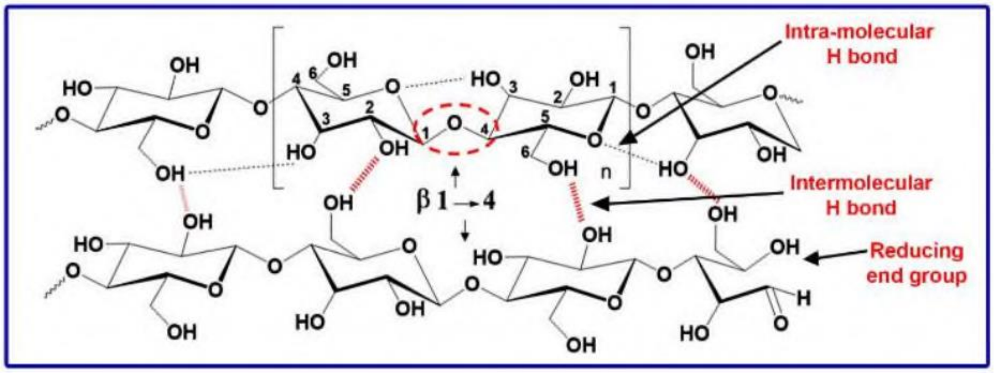


Figure 1.2: The molecular structure of MFC [23].

This study investigates the effect of micro-fibrillated cellulose on the flexural strength and toughness of reinforced concrete. It consisted of four different percentages of MFC gel (0.5wt%, 1wt%, 1.5wt%, and 2wt% concerning water). Thereafter, a study of the microstructure, mechanical and durability behavior, porosity, and absorption tests was made. Thus, the implications of the present work concerning the design optimization of a concrete mix will further provide insights into the development of more sustainable and high-performance construction materials. The results will lead to significant advancements in concrete technology and contribute to the delivery of efficient and durable infrastructure materials. Here the potential research objectives are:

- To investigate the influence of MFC on the flexural strength of reinforced concrete.
- To assess the impact of MFC on the toughness and energy absorption characteristics of reinforced concrete.
- To optimize the proportion of MFC in reinforced concrete for maximum mechanical performance.
- To compare the mechanical properties of MFC-reinforced concrete with conventional reinforced concrete.
- To evaluate the potential for using MFC as a sustainable additive in reinforced concrete.

2. Literature Review

The properties of different materials can benefit significantly from MFC additions especially in cementitious materials and hybrid composites and biopolymers. Research shows that cementitious matrices gain improved hydration behavior together with better mechanical properties by using MFC as an ingredient. The research conducted by Bilcati et al. (2024) examined CP V ARI cement that received cellulose microfibers and microparticles as additions. Composites containing crystalline micro-cellulose (MCC) with MFC achieved superior hydrational levels which resulted in stronger compressive strength compared to ordinary composites. The research by Aramburu et al. (2023) [25] confirmed that treated MFC contributed to better workability performance while decreasing water requirements and strengthening cement pastes during their initial development phase. Research demonstrates MFC performs as an agent that generates nucleation events during cement hydration resulting in better short-term and long-term mechanical behavior.

MFC demonstrates its ability to go beyond cementitious material by effectively improving hybrid materials including geopolymers. Zheng et al. (2023) [26] investigated MFC reinforcement of geopolymer composites through a green mechanochemical production method. The research showed MFCs have a notable positive impact on geopolymer material compressive strength because the capillary compression method achieved an 85.1% strength increase beyond pure geopolymer materials after 30 days of curing. MFC demonstrates strong promise in increasing the strength of hybrid organic-inorganic materials which shows its capacity to enhance composite material performance.

Further research by Siqueira et al. (2020) [27] investigated cement paste hydration with MCC and MFC as components in their research. When MFC influences hydration it reduces the total water content significantly during the first hydration period while maintaining reduced water content levels at day 28 compared to MCC pastes. Some evidence indicates that MFC technology operates as a unique element during cement hydration which can cause enhanced long-term strength and durability outcomes in cement-based products. MFC exhibits modifying abilities within the hydration process which enhances its potential as a concrete additive since it enables better long-term cement-based material performance.

Laboratory investigations demonstrate that MFC increases the properties of the biopolymer family including PLA and PBSA films along with films made from MFC. The research conducted by Apicella et al. (2024) [28] revealed that MFC added at 0.75 wt.% content elevated the mechanical strength along with barrier performance and sealing characteristics in these films. Research indicates MFC expands its usage potential to biopolymer applications that include the packaging sector. Irianto et al. (2024) [29] researched rice husk MFC extraction which showed that alkaline treatment improved crystallinity to boost MFC performance by enhancing composite properties such as dispersibility and strength characteristics. Extraction procedures together with modification methods establish critical ways to enhance MFC efficiency within different material applications.

MFC potential is extended up to enhancing the properties of composite materials, like particleboards and nanocomposites. According to Pawlak et al. (2018) [30], it has been proved that addition of MFC improves water resistance of particleboards, without changing their mechanical strength. It helps in water resistance for application in construction and furniture industries. In addition, Deng et al. (2018) [31] used functionalized MFC in nanocomposites, particularly with poly(ε-caprolactone) (PCL), where tensile strength and elongation at break significantly improved even at very low concentrations. This, therefore, signifies the potential of functionalized MFC to improve the mechanical properties of biopolymer composites and its versatility in a wide range of applications.

Overall, these studies show the flexibility and potential of MFC as it improves mechanical strength, hydration behavior, water resistance, and the overall performance of a large material variety. Promising to serve as an additive in cementitious materials, hybrid composites, biopolymers, and particleboards, MFC stands to offer new opportunities to upgrade the durability and performance of several materials. MFC emerges as a vital material for upgrading the properties of diverse materials from various industries that is sustainable and effective as an additive, thereby offering significant performance and environmental benefits.

3. Problem Statement

The study examines the potential advantages of incorporating MFC into concrete reinforcements. The main challenge to be addressed is that of enhancing the mechanical properties of the concrete, particularly flexural strength and toughness, for improved resistance to crack propagation and structural durability. Traditional methods of reinforcement like fiber reinforcement and chemical admixtures have their limitations in terms of fulfilling the cost and the environmental promise. MFC is, moreover, a bio-based nanomaterial that offers great promise with its high surface area and excellent interfacial bonding to improve crack-bridging mechanisms. However, not much work has been done to explore the effect of MFC on mechanical performance in concrete. The present study aims to offer a total study on improving the flexural strength and toughness of concrete and looks at the possible costs it may bring as a sustainable and efficient material for concrete-based applications.

4. Research Methodology

Figure 3 illustrates the assessment procedure of MFC effects on reinforced concrete flexural properties and toughness. The research process starts with problem definition and then requires reviewing existing literature about the topic. The experimental materials consist of cement and fine aggregates along with coarse aggregates measuring 10mm and 20mm and MFC forms the central part of this investigation. The experimental procedures shift focuses to preparing concrete mix proportions after choosing materials. Researchers mix materials accordingly during this phase to satisfy their selected research objectives. The testing facility receives prepared samples to conduct multiple examinations that measure concrete properties. The concrete evaluation consists of durability tests and measures of toughness followed by flexural strength tests and analysis of concrete microstructure dependent upon Scanning Electron Microscopy (SEM). The results from these tests lead to an analysis of MFC's impact on concrete flexural strength properties and toughness results. The evaluation program studies MFC's implementation potential into reinforced concrete materials for advanced performance characteristics.

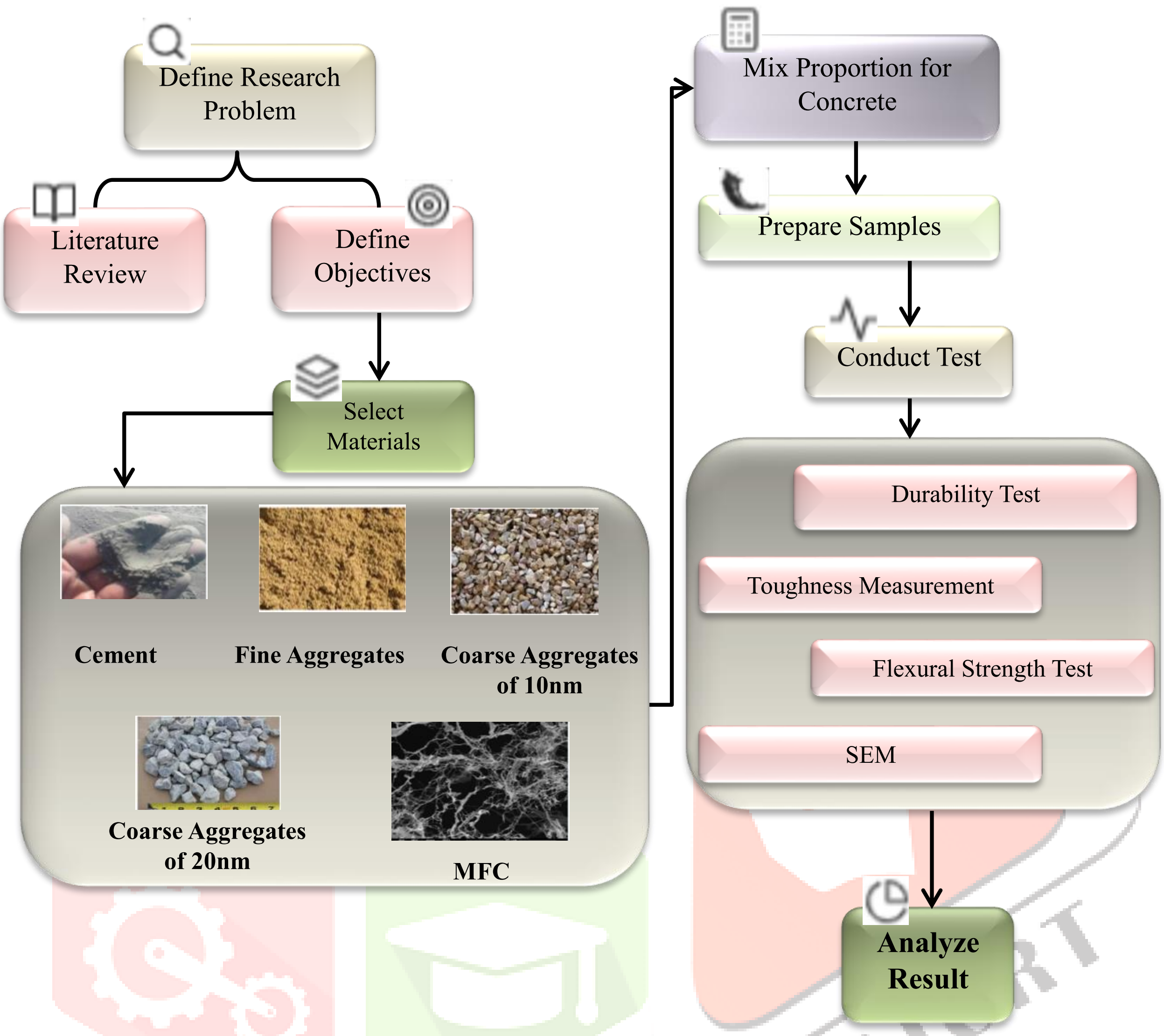


Figure 3: Framework of Proposed work

4.1 Materials and Mix Proportions

a) Cement

The project work makes use of Pozzolana Portland cement (PPC), which is easily accessible in the local market. The cement that was used for the project has been subjected to testing in accordance with IS: 4031-1988 and has been determined to meet several requirements outlined in IS: 1489-1991. Particular gravity was 3.6.

b) Fine aggregate

River sand that is readily accessible in the area and meets the requirements of IS: 383-1970 Grade 2. The local, clean river sand that is accessible will be used. For the casting of all specimens, sand will be passed through an IS 4.75mm sieve.

c) Coarse aggregate

Aggregate for the project was crushed annular granite that was mined in the area. The coarse aggregate used in the project work consisted of 60% for 20mm aggregate, with a specific gravity of 2.7.

d) Micro-fibrillated Cellulose

Research by Da Silva [32] has established MFC as a nano-scale biopolymer derived from cellulose fibers extracted from wood or plants. The unique combination of biodegradable features with superior mechanical performance and large surface area distinguishes MFC as a significant material for many industries. The bio-industry employs MFC as both a reinforcement element for composites and for food product thickening while it also produces biodegradable films and coatings.

4.2 Mix Proportion for Concrete

The components and their quantities for the concrete mix utilized in the current investigation are explained in this section. All mixtures of PPC have been tested and found to comply with IS: 4031-1988 and IS: 1489-1991. Clean, locally accessible Grade-II river sand is utilized as fine aggregate, and its qualities meet IS: 383-1970 standards. Coarse aggregates are made from locally available properly graded granite aggregates with a maximum size of 20mm and 10mm. The current research uses chemical admixtures, namely super-plasticizers, to ensure workability, if necessary. The mix proportions were determined using the BIS design approach. Position the specimens in a curing tank and allow them to cure for 7, 14, 28, 56, 90, and 180 days. Concrete mix designs will be developed following standard codes for various MFC dosages (e.g., 0%, 0.5%, 1%, 1.5%, and 2% by weight of cement). Mix proportions will be optimized to ensure sufficient workability and mechanical properties.

4.3 Conduct Testing

a) Compressive Strength

The compressive strength was measured by utilizing 150 mm concrete cubes. Cubes of cast concrete are submerged in water to cure after 24 hours of casting. The specimens are subjected to compression testing at 7, 14, 28, 56, 90, and 180 days. The specimens undergo a series of progressively heavier loads until they rupture, reaching their ultimate capacity at a rate of 140 kg/cm2 per minute [33]. Dividing the load at failure by the specimen's cross-sectional area provides the concrete's compressive strength.

$$\text{Compressive Strength} = \frac{\text{Load}}{\text{Cross-sectional Area}} \tag{1}$$

b) Flexural Strength

The flexural strength was used to assess the bending behaviour of the foamed concrete specimens at the maximum failure load [34]. At 7, 14, 28, 56, 90, and 180 days, the test was conducted. Over the rollers, the specimen was placed on the bottom plate. The specimen was subjected to a two-point force in the center until it broke. The formula for determining flexural strength is [35]:

$$F = PL/bd^2 \quad (2)$$

In this equation, F stands for the concrete's flexural strength in MPa,

P for the failure load in N,

L for the beam's effective span in mm, and

b for the beam's width in mm.

c) Toughness test

Test procedures based on toughness evaluate materials' energy-absorbing ability and their suitability to deform plastically before fracturing occurs. A material's total toughness becomes probeable by integrating both its strength behavior with its ductile properties [36]. Materials that undergo structural or engineering applications need toughness as a critical feature for performing under impact conditions without structural failure. The test procedure involves applying controlled stress or impact loads to materials while measuring their energy consumption until breakage or cracking happens. To measure toughness researchers mostly perform Charpy impact tests by applying a pendulum hammer to a specimen with a prepared notch to record the breaking force [37].

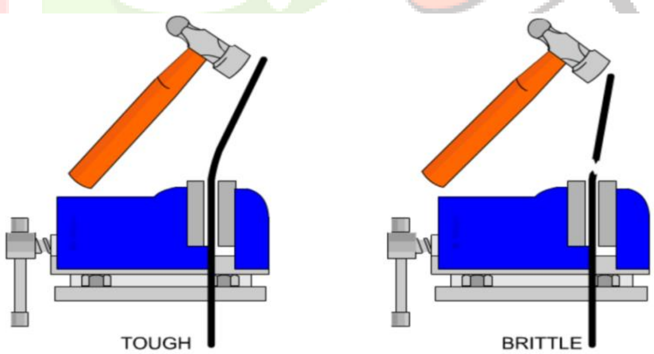


Figure 4: Toughness Test

d) Durability

The durability of concrete refers to its capacity to resist the damaging impacts of the environment that it will encounter over its lifespan, preventing it from deteriorating to an unacceptable degree. A minimum grade of concrete, an upper limit on the water-to-cement ratio, and the structure's exposure to the environment are all factors that contribute to the material's durability.

4.4 Microstructural Analysis

a) Scanning Electron Microscopy (SEM)

SEM is one of the most important techniques for evaluating the surface and microstructure of material at high resolution [38-40] (Figure 5). Stating that in SEM, a narrow beam of electrons is used the technique enables to visualize and measure a material's surface morphology, roughness, and particle size. This technique is very useful for the observation of surface defects, porosity, and grain boundaries in superconducting materials such as YBCO or polymer-based composites [41,42]. SEM can also demonstrate the dispersion of various phases in a composite where knowledge of dispersion is critical to the material's superconducting and mechanical characteristics. Energy-dispersive X-ray spectroscopy (EDS) is combined with SEM and allows for an analysis of the elemental distribution across the material and proves that the material is of high purity [43]. The resolution R of an SEM can be expressed as:

$$R = \frac{\lambda}{2.\sin(\theta)} \quad (3)$$

Where,

λ is the wavelength of the electrons and θ is the angle of the electron beam concerning the surface.

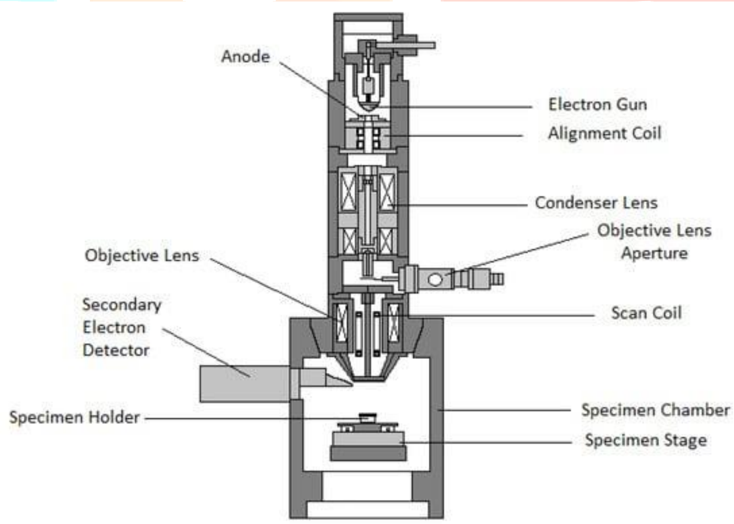


Figure 5: Scanning electron microscope [44].

5. Test Result and Discussion

The test findings derived from the experimental studies are provided as follows:

5.1 Result of RC Beams with Varying MFC Content

a) Flexural Strength (FS)

The FS results from concrete specimens containing different MFC amounts by weight of cement appear in Table 1. A control sample consisting of 0% MFC yielded a FS measurement of 4.5MPa and was used to establish baseline metrics. Adding 0.5% MFC elevated the FS to 5.1MPa which represented a 13.3% rise in performance. The FS reached 5.8MPa when MFC content reached 1.0% which resulted in a significant 28.9% improvement. A maximum flexural strength value of 6.3MPa occurred with 1.5% MFC addition which revealed a 40.0% improvement compared to the control sample. The FS of the material gradually declined to 6.0MPa when MFC reached 2.0%, producing a 33.3% enhancement over the control baseline but falling shorter than the highest peak at 1.5% MFC. These results suggest that the optimal MFC content for enhancing FS lays around 1.5%, beyond which the strength tends to diminish. Figure 6 shows the bar graph of FS vs. MFC Content.

Table 1: FS of RC Beams with Varying MFC Content

MFC Content (% by weight of cement)	FS (MPa)	% Increase Compared to Control
0% (Control)	4.5	--
0.5% MFC	5.1	13.3%
1.0% MFC	5.8	28.9%
1.5% MFC	6.3	40.0%
2.0% MFC	6.0	33.3%

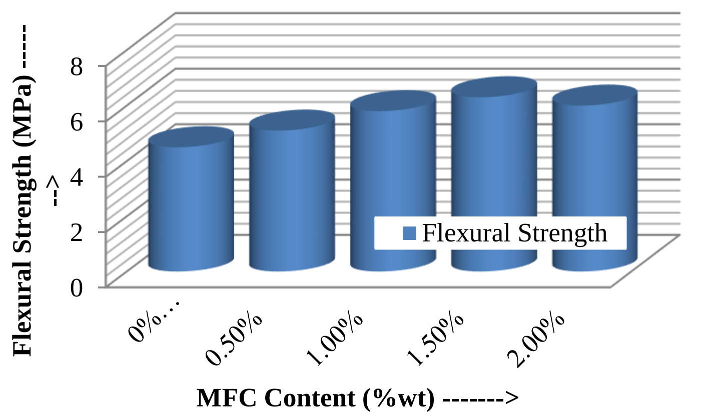


Figure 6: FS vs. MFC Content

b) Toughness Measurement

The calculated toughness measurement consisted of the area under the load-deflection curve. Table 2 displays the influence of MFC content on concrete toughness measured in kN-mm and shows relative percentage changes against the control. The control sample with no MFC showed 120kN-mm toughness used as the baseline measurement. The concrete sample achieved maximum toughness of 145kN-mm after receiving an additional 0.5% MFC treatment resulting in a 20.8% performance boost compared to untreated concrete. An increase in MFC content to 1.0% resulted in concrete toughness reaching 170kN-mm which represented a 41.7% improvement from the base value. A 1.5% MFC treatment resulted in peak toughness of 195kN-mm confirming a 62.5% improvement above the untreated sample. The toughness reached 190kN-mm with 2.0% MFC even though this was less than the best outcome at 1.5% MFC yet maintained a substantial 58.3% improvement compared to the control. The combination of materials at 1.5% MFC proved most effective for toughness enhancement with subsequent additions resulting in decreased properties. The integration of MFC Content into Figure 7 reveals a bar graph which displays the relationship of toughness and MFC Content.

Table 2: Toughness measurement of RC Beams with Varying MFC Content

MFC Content (% by weight of cement)	Toughness (kN-mm)	% Increase Compared to Control
0% (Control)	120	--
0.5% MFC	145	20.8%
1.0% MFC	170	41.7%
1.5% MFC	195	62.5%
2.0% MFC	190	58.3%

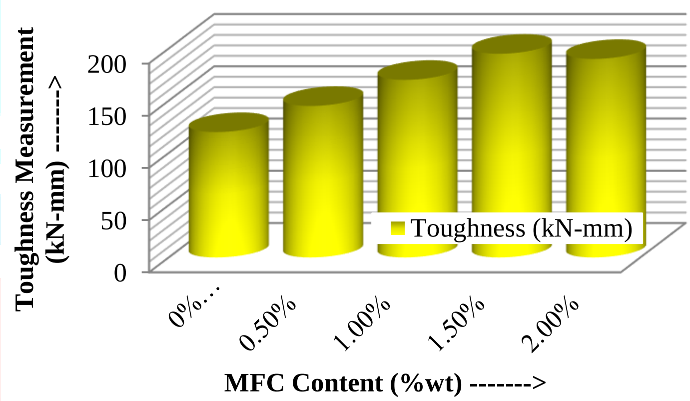


Figure 7: Toughness vs. MFC Content

c) Compressive Strength (CS)

Table 3 displays test results showing how different MFC concentrations affected concrete's compressive strength value in MPa and its relative MFC content measure compared to the control baseline. Analysis of the control condition without MFC showed a CS of 30.0 MPa as its reference standard. When adding 0.5% MFC to the concrete mix resulted in a CS strength increase of 34.5MPa which represented a 5.0% improvement over the baseline. An MFC addition of 1.0% enhanced the CS value to 41.3MPa resulting in a 10.0% improvement over the control sample. When concrete contained 1.5% MFC its strength reached 48.5MPa which marked an 18.2% increase when compared to the control sample. The 2.0% MFC composition showed slight variations in CS to 53.6MPa instead of 60.6MPa based on the control but it yielded greater strength than the baseline value. The experiments confirm that 1.5% MFC achieves optimal conditions for increasing CS while any dosage above this leads to diminished strength performance.

Table 3: CS of RC Beams with Varying MFC Content

MFC Content (% by weight of cement)	CS (MPa)	% Increase Compared to Control
0% (Control)	30.0	--
0.5% MFC	34.5	5.0%
1.0% MFC	41.3	10.0%
1.5% MFC	48.5	18.2%
2.0% MFC	53.6	13.3%

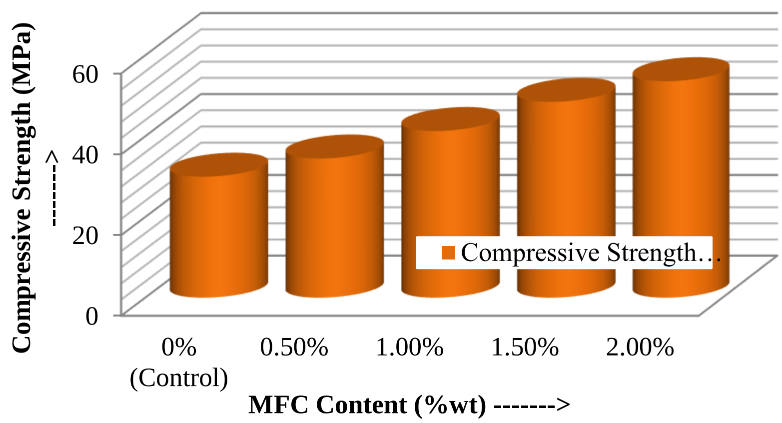


Figure 8: CS vs. MFC Content

d) Durability Test

The durability tests presented in Table 4 illustrate that MFC addition effectively enhances concrete performance. The moisture resistance capability of concrete improved significantly as the water absorption rate dropped from 5.2% in the control to 4.1% at the MFC rate of 1.5%. Testing showed chloride penetration decreased from 1250 Coulombs in the control to 800 Coulombs when using 1.5% MFC addition. The testing results indicate that concrete possesses reduced porosity while demonstrating enhanced durability at an MFC concentration of 1.5%. A 2.0% MFC treatment showed minimal reduction of test results while delivering results that exceeded control performance thus proving 1.5% MFC as the best addition concentration. The bar graph presented in Figure 9 illustrates chloride penetration behavior relative to MFC content addition.

Table 4: Durability Properties

Test Type	Control	0.5% MFC	1.0% MFC	1.5% MFC	2.0% MFC
Water Absorption (%)	5.2	4.8	4.5	4.1	4.3
Chloride Penetration (Coulombs)	1250	1150	950	800	850

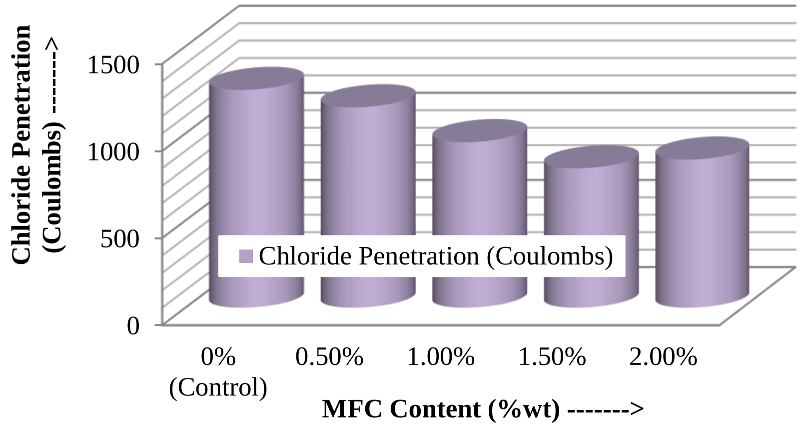
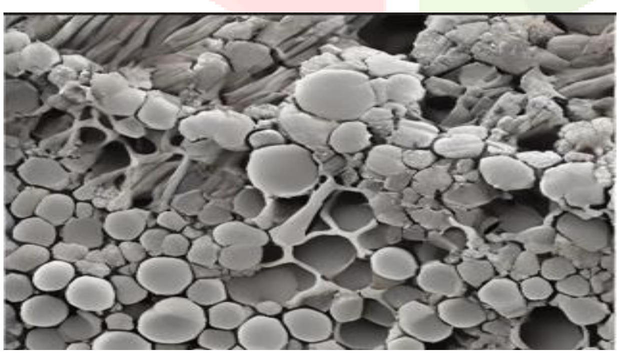


Figure 9: Chloride Penetration vs. MFC Content

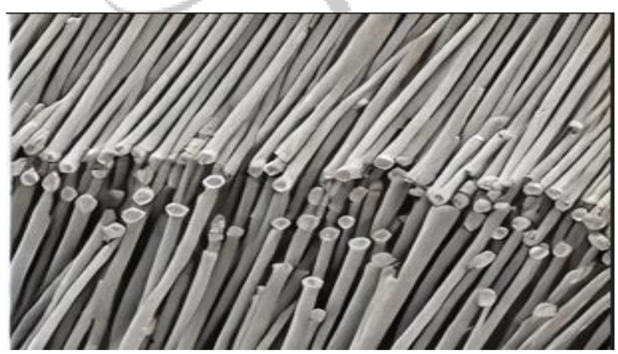
5.2 Microstructural Analysis

a) Scanning Electron Microscope (SEM)

Figure 10 presents the SEM micrograph sample. The data establishes the superiority of the 1.5% MFC sample through comprehensive images that depict effective fiber dispersion connected to crack bridging performance. The control sample shows a fragile and porous network structure containing multiple voids which makes the material prone to fluid penetration. The 1.5% MFC sample achieves superior fibril dispersion that improves the matrix densification and lowers its penetrable space. Strong interactions between fibers and matrix in MFC-modified concrete samples enhance mechanical properties combined with increased durability to produce superior compressive strength higher toughness and reduced water and chloride intrusion.



0% Control Sample



1.5% Microfibrillated Cellulose (MFC0

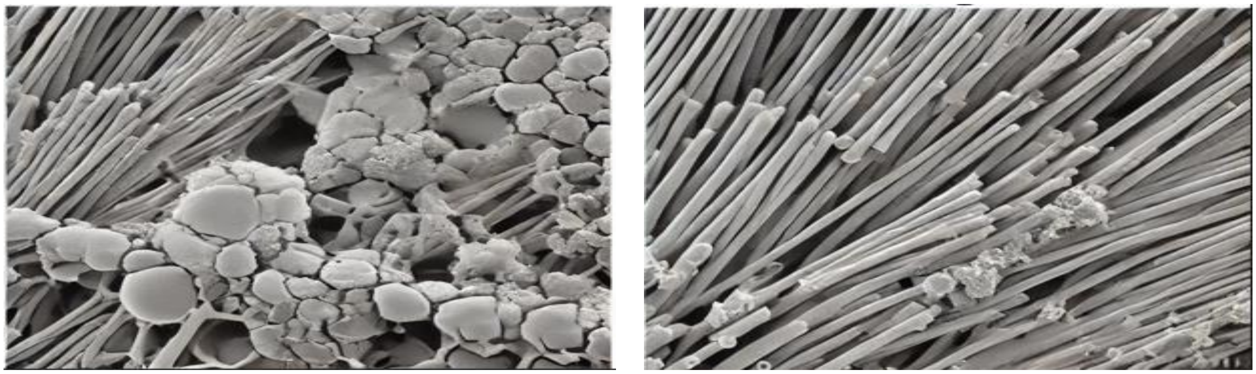


Figure 10: SEM images

5.3 Analysis of Mechanical Properties on Curing Ages

a) Flexural Strength

Table 5 shows the FS in MPa achieved by concrete specimens that integrated different MFC dosages across a curing period extending from 7 to 180 days. At 180 days the control group which contained no MFC reached a final FS value of 5.3MPa. The combination of 0.5% MFC content enhances strength performance across every age measurement resulting in 6.0MPa at 180 days. When the MFC content reaches 1.0% the mechanical strength of materials is enhanced to reach 6.9MPa after 180 days. Samples containing 1.5% MFC reach their best reinforcement outcomes by maintaining consistent strength growth from 4.3MPa at 7 days to 7.6MPa at 180 days. The increased strength at 2.0% MFC preserves a higher value than the control levels but presents marginally lower numbers than 1.5% MFC during 180-day tests reaching 7.2MPa in strength. Long-term tests reveal that MFC improves concrete strength performance with 1.5% MFC demonstrating the best results for extended behavior.

Table 5: FS (MPa) at Different Ages

MFC Content (% by weight of cement)	7 Ages	14 Ages	28 Ages	56 Ages	90 Ages	180 Ages
0% (Control)	3.2	3.8	4.5	4.8	5.0	5.3
0.5%	3.6	4.3	5.1	5.5	5.8	6.0
1.0%	4.0	4.9	5.8	6.3	6.7	6.9
1.5%	4.3	5.4	6.3	6.9	7.3	7.6
2.0%	4.1	5.0	6.0	6.6	6.9	7.2

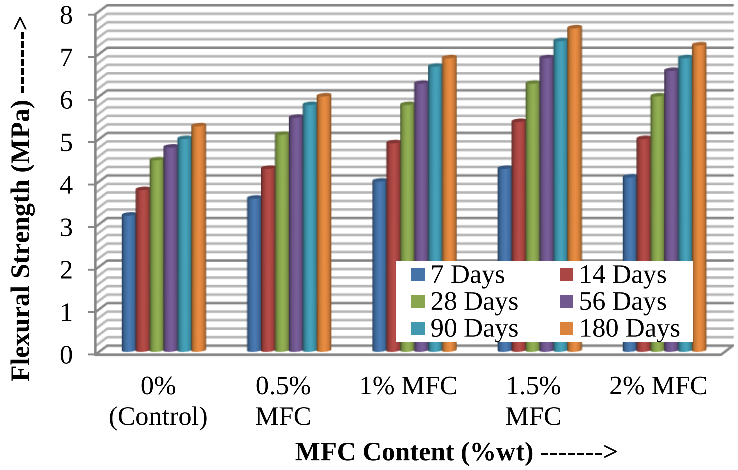


Figure 11: FS vs. Curing Age

b) Toughness Measurement

The toughness (kN-mm) measurements for concrete specimens with changing MFC levels show results at multiple curing durations spanning from 7 to 180 days in Table 6. Controls containing 0% MFC saw toughness values climb steadily from 90kN-mm on day 7 to reach 145kN-mm on day 180. A supplementation of 0.5% micro fibrillated cellulose boosts toughness in concrete at all ages up to 180 days to achieve 175kN-mm. The application of 1.0% MFC leads to the highest toughness level which reaches 210kN-mm during the 180-day testing period. Toughness measurements yield their highest level at 240kN-mm when samples include 1.5% MFC content after curing for 180 days demonstrating optimum reinforcement benefits. With 2.0% MFC addition strength testing shows toughness surpassed the untreated concrete measures while achieving 225kN-mm at 180 days. Long-term analysis indicates that MFC enhances concrete toughness effectively with 1.5% MFC proving to be the optimal dosage arrangement. Toughness values are presented in Figure 12 as a bar chart that depends on Curing Age.

Table 6: Toughness (kN-mm) at Different Ages

MFC Content (% by weight of cement)	7 Ages	14 Ages	28 Ages	56 Ages	90 Ages	180 Ages
0% (Control)	90	105	120	130	140	145
0.5%	105	125	145	160	170	175
1.0%	120	140	170	185	200	210
1.5%	135	165	195	215	230	240
2.0%	130	155	190	205	220	225

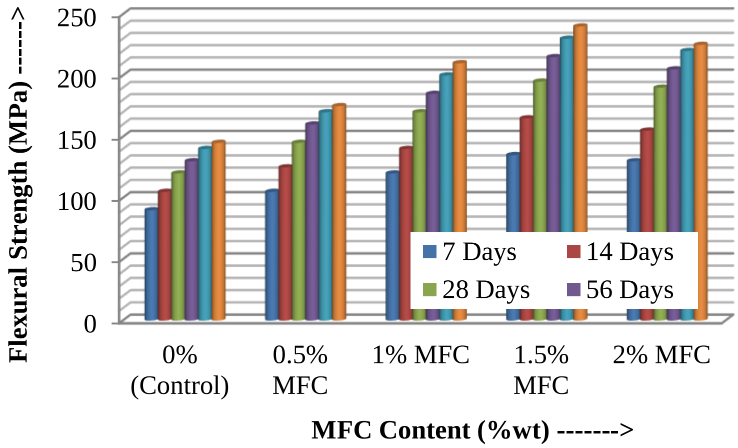


Figure 12: Toughness vs. Curing Age

c) Compressive Strength (CS)

CS (MPa) evaluation results for cement-based mixtures with different MFC percentages appear in Table 7 at multiple curing periods. The control mixture with 0% MFC achieved a compressive strength boost from 21MPa at 7 days to 34MPa at 180 days. The strength of MFC enhanced mixes accelerates from day 7 to day 180 where the 0.5% MFC material shows optimal results at 22MPa at 7 days and 35.9MPa at 180 days. The compressive strength values of 1.0% MFC mixes rise from their initial 23.5MPa measurement at 7 days to their maximum strength of 37MPa at 180 days. When MFC content increases to 1.5% and 2.0% the material strength develops more substantially. Compression tests reveal the strength progression of samples with 1.5% MFC starting at 25.7MPa at 7 days and reaching 40.4MPa at 180 days while the 2.0% MFC mix shows initial strength of 24.6MPa at 7 days increasing to 40MPa at 180 days. Samples with 1.5% MFC content displayed optimal compressive strength at all curing stages because higher MFC contents enhance long-term strength development. The bar graph of Figure 13 displays CS vs. curing age.

Table 7: CS (MPa) at Different Ages

MFC Content (% by weight of cement)	7 Ages	14 Ages	28 Ages	56 Ages	90 Ages	180 Ages
0% (Control)	21	25	30	32	33	34
0.5%	22	26	31.5	33.2	34.7	35.9
1.0%	23.5	28	33.6	35.1	36.4	37
1.5%	25.7	30.8	35.3	37.5	39.6	40.4
2.0%	24.6	29.8	34.2	36.8	37.5	40

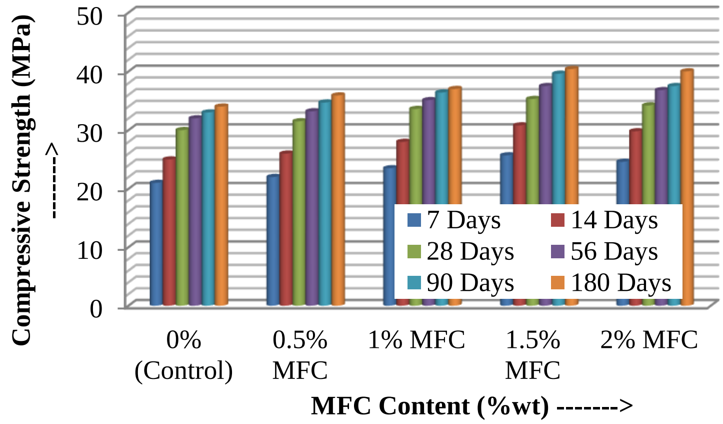


Figure 13: Compressive strength vs. Curing Age

d) Durability Properties

Table 8 shows the performance of cement mixtures containing different MFC contents in terms of water absorption and chloride penetration at 28 and 180 days. The water absorption values decrease as the percentage of MFC increases. Control (0% MFC) mix registered water absorption of 5.2% at 28 days when reduced to 4.8%-4.2% for specimens containing 0.5%, 1.0%, 1.5%, and 2.0% MFC. For 180-day water absorption values, further reduced across all mixtures as compared to the 28-day result, the control shows a 4.8% drop, and 0.5%, 1.0%, and 1.5% MFC mixes show cuts going down to 4.4%, 4.1%, and 3.8%, respectively. The 2.0% MFC mix is slightly increased to 4.0% as compared to 28 days, but a good value relative to the control mix shows up.

Coulombs of chloride penetration also improve with an increased MFC content. The control mix shows as much as 1250 Coulombs at 28 days whereas the MFC mixes show a significant reduction in chloride penetration: 1150, 950, 800, and 850 Coulombs for the 0.5%, 1.0%, 1.5%, and 2.0% MFC mixes, respectively. Improvement continued in all mixes until the 180th day, for the control mix it further reduced down to 1100 Coulombs. The MFC-containing mixes continue showing improvements with the best performance of the mixes being observed in the 1.5% MFC mix where the reduction recorded was 700 Coulombs. These results demonstrate that the incorporation of MFC improved durability through reduced water absorption and chloride penetration, thereby contributing to enhanced resistance against environmental degradation over time. Figure 14 gives the bar graph of chloride penetration over time.

Table 8: Durability Parameters at 28 and 180 Days

Test Type	Age (Days)	0% Control	0.5%	1.0%	1.5%	2.0%
Water Absorption (%)	28	5.2	4.8	4.5	4.1	4.2
	180	4.8	4.4	4.1	3.8	4.0
Chloride Penetration (Coulombs)	28	1250	1150	950	800	850
	180	1100	1000	850	700	750

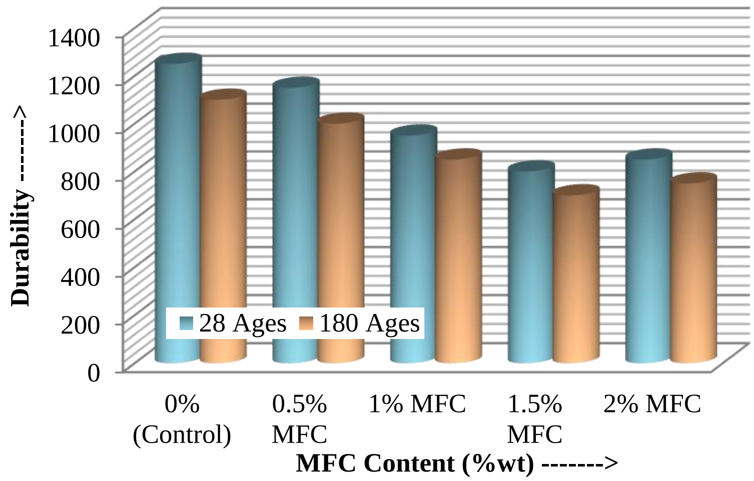


Figure 14: Chloride Penetration over Time

6. Conclusion

Concrete is the second most used material worldwide, which offers durability but faces mechanical and environmental limitations. To enhance its performance, MFC, a nanomaterial derived from plant fibers, has been explored. The interest in MFC is mainly due to its high surface area and superior mechanical properties, making it a promising additive in reinforced concrete. The methodology involved preparation of concrete samples with different MFC contents, like 0.5%, 1.0%, 1.5%, and 2.0% by weight of cement, and studying their mechanical properties at curing periods of 7, 14, 28, 56, 90, and 180 days. The following conclusions were made based on the experimental results:

- The flexural strength of reinforced concrete received its highest improvement of 40% when MFC content reached 1.5%. The strength assessment showed a minimal downtrend after optimal results were achieved. Measurements of toughness revealed a major enhancement reaching 62.5% at the MFC concentration of 1.5%. The energy absorption capacity together with crack resistance of concrete increase when MFC is added to the composition.
- MFC reinforced concrete achieved a 18.2% strength boost when it contained 1.5% MFC. Excessive MFC addition at 2.0% resulted in a minor reduction of strength but not as significant as other mechanical properties. Concrete durability improved based on both reduced water absorption and

decreased chloride penetration due to MFC addition. The mixture containing 1.5% MFC showed the best durability outcomes.

- MFC-enhanced concrete showed better fiber distribution and reduced porosity based on SEM analysis thus leading to better mechanical strengths according to research findings. Tests determined that using 1.5% MFC produced the best possible combination of strength along with durability enhancement and material toughness. The use of bio-based MFC material represents an environmentally friendly solution for concrete strengthening which could minimize the need for traditional reinforcing structures.

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