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Research Article

A study on flexural behaviour and strengthening of fibre reinforced concrete beams using microorganisms

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Abstract

This study used microorganisms to investigate the flexural behavior of reinforced concrete beams with a cross-section of 150mm x 180mm and a length of 1500mm. The research focuses on the effects of these microorganisms on the mechanical properties and flexural behavior of the concrete. The study specifically investigated the mechanical properties of concrete by incorporating different ranges of Steel Fibers (SF): 0.2%, 0.4%, 0.6%, 0.8%, and 1.0%. Additionally, the research examined the flexural behavior of the RC beams, with incorporation of Bacillus Subtilis bacteria concentrations of 1%, 2% and 3% for both the control and optimum mix. Six concrete mixtures were designed with SF at the following percentages: 0.2%, 0.4%, 0.6%, 0.8%, and 1.0%. The study utilized M40-grade concrete. Bacillus Subtilis bacteria were incorporated into the concrete by the weight of the cement during the casting process. The specimens took on different shapes, such as cubes, cylinders, and prisms. The concrete specimens were cast and tested after 7, 14, and 28 days of curing. According to the experimental results, the optimal SF content was 0.8%. Finite Element Model (FEM) was developed using ANSYS to analyze the RC beams. The FEM approach proved helpful in predicting the experimental outcomes. Adding 0.8% of steel fibre and 2% microorganisms enhanced the compressive strength by 4.20% compared to the control sample. Similarly, the flexural behavior of the RC beams was increased by 19.98% and 24.40% compared to the conventional specimens. This study aims to provide the potential benefits of using microorganisms in concrete technology.

1. Introduction

Generally, concrete, while strong in compression, tends to be weak in tension. Fibres have been added to address this issue and enhance its overall performance. One standard method involves incorporating steel fibres of various geometries into the concrete mix. These steel fibres act as reinforcements, improving the materials tensile strength and ductility. Closed Steel Fibres (CSF) tend to improve the strength properties of the concrete. Unlike traditional open fibres, CSFs are designed to prevent fibre pull-out during tension, allowing for better utilization of their tensile capacity. The workability of fibre-reinforced concrete decreased with increasing steel fibre content. The mechanical properties were increased by 46% and 36% for tensile and flexural strength [1]. The effect of Recycled Steel Fibres (RSF) on concrete mechanical properties. Notably, RSF had a negligible impact on durability but significantly enhanced mechanical properties. These findings highlight the potential of RSF as a sustainable reinforcement option for concrete structures [2]. The effects of varying SF content and length on concrete strength properties. Parameters studied included slump, pore structure, CS, STS, flexural toughness, and impact resistance. The study provides valuable insights into optimizing steel fibre reinforcement in concrete [3]. The

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comparative studies of steel and hybrid fibre-reinforced concrete: While compressive strength showed slight effects, the hybridization increased the mechanical properties of the concrete by adding mixed fibres. Overall, fibre-reinforced concrete exhibited improved strengths with fibre reinforcement [4].

Fibre-reinforced concrete (FRC) is a composite material that integrates the advantages of conventional concrete with the enhanced strength and durability embedded fibres provide. Steel fibres, in particular, play a crucial role in enhancing the mechanical properties of concrete. Steel fibres act as tiny reinforcements within the concrete matrix, effectively bridging cracks and improving tensile strength. Including steel fibres significantly enhances the concrete ability to withstand tensile forces, making it more resistant to cracking and structural failure. Steel fibres improve ductility, allowing the concrete to absorb more energy during deformation. Steel fibres reduce crack widths and prevent crack propagation [5]. The mechanical performances of concretes and RC beams increased using steel fibres. Steel fibre RC concrete flexural strengths have increased significantly [6]. The addition of SF to concrete can substantially enhance its performance. Steel fibre-reinforced has gained popularity due to several advantages, including hindrance in macro crack propagation, prevention of micro-crack growth to macroscopic levels, improved ductility and residual strength after the first crack formation and high toughness [7]. Combining steel and polypropylene fibres offers a promising approach to enhancing concrete structure's strength, durability, and high-temperature performance [8,9]. Adding steel fibres improves the mechanical properties of concrete. SF enhanced the concrete's ability to withstand impact loads, making it more resistant to sudden forces. SFRC exhibits improved toughness, preventing brittle failure and enhancing durability. Including steel fibres enhances flexural strength, which is crucial for resisting bending stresses. SFRC shows increased tensile strength, reducing the risk of cracking and improving overall performance. Steel fibres contribute to ductility, allowing the concrete to deform plastically before failure. Moreover, SFRC resists cracking and spalling, making it suitable for various construction applications. Researchers continue to explore optimal fibre content and geometry to maximize these benefits [10].

The main disadvantages of concrete include low tensile strength when subjected to external loads and the formation of micro-cracks, which can lead to structural corrosion. Nowadays, concrete structures are protected from micro-cracks and corrosion by using Bacillus subtilis bacteria in the concrete [11–15]. Bacillus Subtilis bacteria make cement mortar more hydrated, which makes it safe to use and improves concrete performance [16–18]. The microorganisms fill the existing gaps in the concrete, so they propagate to increase the strength properties of the concrete, such as CS, STS and FS [19–22]. Bio concrete, which incorporates microorganisms, aims to enhance the strength properties of traditional concrete. This research contributes valuable insights into sustainable construction materials. The microorganisms actively fill existing voids within the concrete matrix. This process contributes to the enhancement of overall strength. Using concrete reduces the environmental footprint associated with traditional concrete production. Using microorganisms promotes sustainability and contributes to environmental protection [23]. Self-healing properties are at the core of this novel construction material, promising longevity and reduced maintenance costs. Bioengineered concrete incorporates microorganisms that actively repair cracks and fissures. These tiny agents play a crucial role in maintaining structural integrity over time. By promoting self-healing, bioengineered concrete contributes to environmental conservation. Reduced need for repairs translates to less material consumption and waste. The study emphasizes the long-term durability of bioengineered concrete. It withstands ecological stressors, making it an attractive choice for sustainable infrastructure. Bioengineered concrete represents a paradigm shift in construction practices. Its self-healing capabilities align with sustainability principles, making it a promising solution for resilient and eco-conscious infrastructure [24].

Soft computing methods, especially Artificial Neural Networks (ANN) and Gene Expression Programming (GEP), present considerable benefits in assessing the flexural strength of T-shaped concrete beams reinforced with FRP. These approaches yield more precise and dependable predictions than conventional empirical models, establishing them as essential resources in structural engineering [25]. Bacterial bio composite concrete presents a sustainable and efficient approach to improving concrete structures' strength and self-repairing properties, especially in environments exposed to soil. Incorporating bacteria like Bacillus flexus and Bacillus paramycoides has demonstrated considerable promise in enhancing the durability and lifespan of concrete, positioning it as a noteworthy advancement in civil engineering [26]. Wavelet transform methods, especially for modal excitation responses, provide a reliable and precise approach to identifying damage in reinforced concrete beams. Their capability to identify localized irregularities and variations in modal characteristics renders wavelet transform an essential instrument in structural health monitoring [27]. Using effective microorganism solutions in sustainable self-curing concrete presents a valuable approach to improving the durability and functionality of concrete structures.

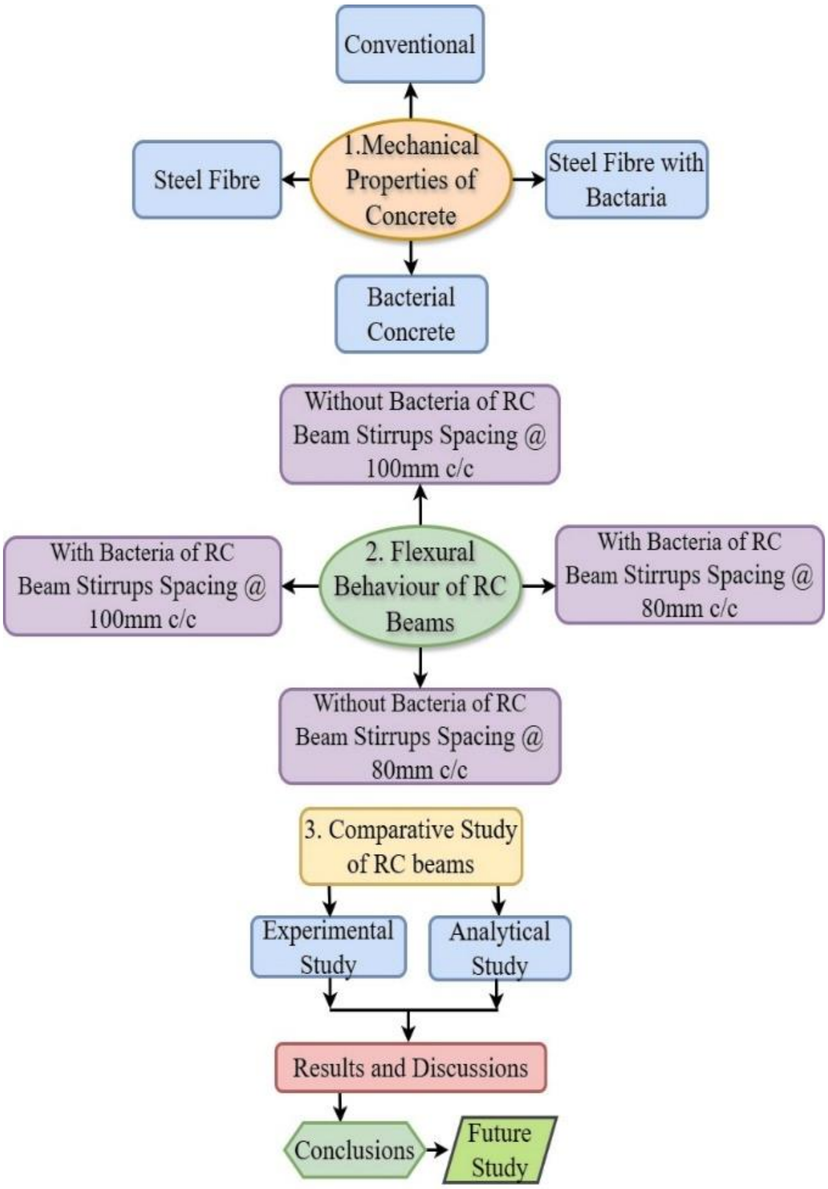


Fig. 1. Graphical abstract for this study

This innovative concrete reduces sorptivity, drying shrinkage, and expansion while enhancing microstructure and strength, marking notable progress in sustainable construction materials [28,29]. Soft computing methods, especially Genetic Programming (GEP) and ANN, present considerable benefits in assessing the load-carrying capacity of reinforced concrete beam-column joints. These approaches yield more precise and dependable predictions than conventional empirical models, establishing them as essential resources in structural engineering [30,31].

Concrete is widely used in construction due to its versatility and applications. Combining different types of fibres within a concrete mixture has been shown to enhance the strength properties of cementitious materials by monitoring crack initiation and propagation. In this study, we focus on the impact of integrating steel fibres ranging from 0.2% to 1% on the mechanical properties of concrete. Steel fibres play a crucial role in enhancing the strength and performance of concrete. The research continues to explore the optimal fibre content of 0.8% and the microorganism dosages of 1%, 2%, and 3%. The optimum steel fibre and microorganisms' content was 0.8% and 2%, respectively. This optimum mix is recommended for the flexural behavior of the RC beams investigation with various shear reinforcement spacing. The research underscores the potential of bio-concrete as an eco-friendly alternative. Further exploration and implementation of bio concrete in real-world construction projects are recommended. The significance of this study lies in its exploration of self-healing concrete, which addresses one of the major challenges in concrete structures: cracking. Cracks in concrete can arise from various factors, such as plastic shrinkage, drying shrinkage, thermal contraction, and structural loads. These cracks compromise the structural integrity and reduce the longevity of concrete structures by allowing external agents to penetrate and cause further damage. The graphical abstract gives details of the present study, as shown in (Fig. 1).

2. Research Methodology

The present study investigated steel fibre-reinforced concrete (SFRC) beams by adding steel fibres and microorganisms in various percentages. The research methodology of this study includes the collection of materials, mix design of concrete, preparation of the specimens, casting of the specimens, testing (mechanical properties and flexural behavior), experimental analysis, finite element analysis, and data analysis.

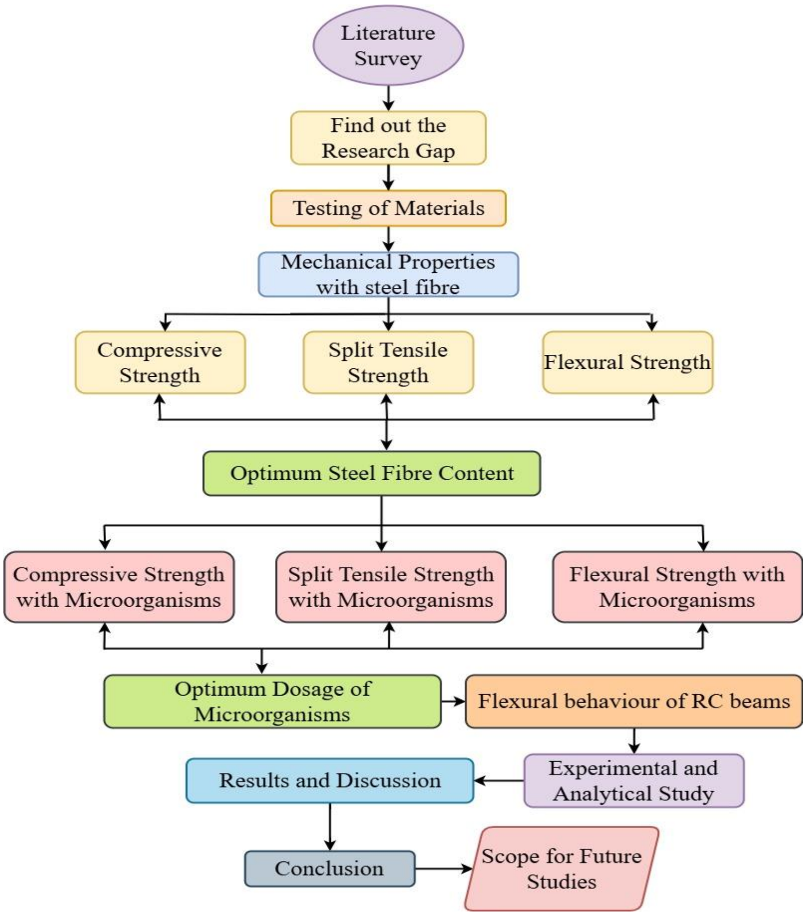


Fig. 2. Flow chart for the research methodology

The experimental results were compared to the FEM predictions. The addition of 0.8% steel fiber and 2% microorganisms showed an enhancement in compressive strength by 4.20% and the flexural behavior of RC beams by 19.98% and 24.40% compared to conventional specimens. This research methodology provides a comprehensive approach to investigating the effects of steel fibers and Bacillus Subtilis bacteria on self-healing concrete's mechanical properties and flexural behavior. The operating conditions of structures, such as moisture level, temperature, pH level, exposure to chemicals, structural load, maintenance, and monitoring, can significantly impact the effectiveness of bacterial hardening in concrete. The long-term effectiveness of bacterial hardening in concrete can be influenced by various factors, including the operating conditions of the structures and the impact of negative temperatures. A detailed investigation of the present study in different phases and the research methodology is shown in (Fig. 2).

3. Experimental Study

3.1. Materials

The study used 53-grade Ordinary Portland Cement (OPC), which conforms to IS 12269-1987 [32]. The fine aggregate was collected from the local market and adheres to grading zone II as specified in IS 383 – 2016 [33]. Natural crushed rocks were employed for the coarse aggregate, and the angular coarse aggregate also adheres to IS 383 – 2016 [33]. This study used a water-reducing or chemical admixture (Conplast SP430) to reduce the water content and increase the strength properties of the concrete. The initial tests were conducted, and the physical properties of the cement, fine aggregate, coarse aggregate and superplasticizer are provided in Table 1.

Table 1. Physical properties of cement

Properties	Test values			
	CE	FA	CA	SP
Specific gravity (g/cm^3)	3.14	2.65	2.69	1.08
Final setting time (min)	258	-	-	-
Initial setting time (min)	36	-	-	-
Fineness modulus (%)	3.56	-	-	-
Consistency (%)	34.15	-	-	-
Water absorption (%)	-	1.68	0.62	-
Fineness modulus (%)	-	2.94	6.28	-
Crushing values (%)	-		9.74	-
Impact value (%)	-		10.16	-

Note: CE- Cement; FA – Fine aggregate; CA – Coarse aggregate; SP – Superplasticizer

Bacillus subtilis microorganisms were cultivated in the laboratory, enhancing concrete's mechanical properties and reinforcing the concrete beam's flexural behaviour. Bacillus subtilis was added to the concrete mix based on the weight of the cement. Adding bacteria to concrete under production conditions involves a few key steps to ensure the bacteria remain viable and effective. Incorporated the bacterial suspension into the concrete mix during the mixing process and also ensured the bacteria were evenly distributed throughout the mix. Introducing bacterial additives into concrete can lead to significant changes in its structure and the hydration conditions of clinker minerals. Bacteria such as Bacillus Subtilis can precipitate calcium carbonate (CaCO3) within the concrete matrix. This process fills the pores and cracks, enhancing the density and reducing the permeability of the concrete. Incorporating bacterial additives can significantly enhance the concrete structure, leading to improved mechanical properties and durability.

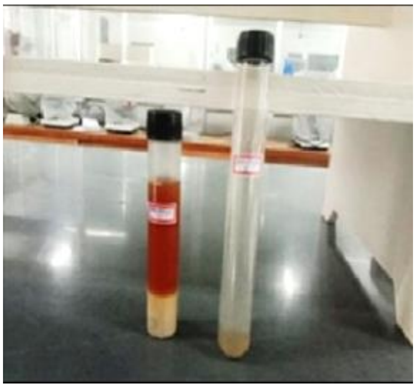
Table 2. Physical properties of steel fibre

Properties	Test values
Diameter (mm)	0.72
Length (mm)	50
Aspect ratio (L/D)	69.45
Tensile strength (MPa)	1100
Modulus of elasticity (MPa)	204
Unit weight (kg/m^3)	7850

The hydration conditions of clinker minerals are also optimized, resulting in a more stable and resilient concrete matrix. Additionally, steel fibres were procured from the Chennai fibre region, and their physical properties are detailed in Table 2. The percentages of steel fibres and microorganisms were added to the concrete mix concerning the weight of the cement in the concrete mix, and the materials are shown in (Fig. 3).

(a)

(b)



(c)

Fig. 3. Materials of the study(a) Steel fibre, (b) Concrete mix, and (c)Bacillus subtilis

3.2 Mix Design

According to IS 10262 - 2019 [34], the mix design used M40-grade concrete with a concentrated w/c of 0.40. The mix proportions ratio in this study is 1:1.57:2.84. A total of six mix proportions were designed: M40-SF0, M40-SF0.2, M40-SF0.4, M40-SF0.6, M40-SF0.8, and M40-SF1.0 is reported in Table 3. SFs were added to the concrete mix based on the weight of the cement. These SF were incorporated at various percentages (0.2%, 0.4%, 0.6%, 0.8%, and 1.0%). After the mix design, the material quantities were calculated: cement 416 kg/m^3, fine aggregate 654 kg/m^3, coarse aggregate 1182 kg/m^3, water content 147 kg/m^3 and a w/c of 0.40. The mechanical properties, including CS, STS and FS, were examined after curing periods of seven, fourteen, and twenty-eight days. One hundred sixty-two samples were cast and tested for these properties: 54 for CS, 54 for STS, and 54 for FS.

Table 3. Materials required for concrete 1M^3 in kg/m^3

Mix ID	CE	FA	CA	Water	SP	W/C	SF (%)
M40-SF0	416	654	1182	147	2.08	0.4	0
M40-SF0.2	416	654	1182	147	2.08	0.4	0.2
M40-SF0.4	416	654	1182	147	2.08	0.4	0.4
M40-SF0.6	416	654	1182	147	2.08	0.4	0.6
M40-SF0.8	416	654	1182	147	2.08	0.4	0.8
M40-SF1.0	416	654	1182	147	2.08	0.4	1.0

3.3 Mechanical Properties of Concrete

3.3.1 Compressive, Split Tensile and Flexural Strength of Concrete

The mechanical properties of Steel Fibre-Reinforced Concrete (SFRC), including CS and FS are examined as per IS 516 - 516 [35], and STS, are evaluated according to IS 5816 - 1999 [36]. The steel moulds used for testing have the following dimensions: compressive strength mould: 150 mm x 150 mm x 150 mm, split tensile strength mould: 150 mm diameter x 300 mm height and flexural strength mould: 150 mm x 150 mm x 750 mm. The waste oil is applied to the interior faces to prevent concrete adhesion to the steel moulds.

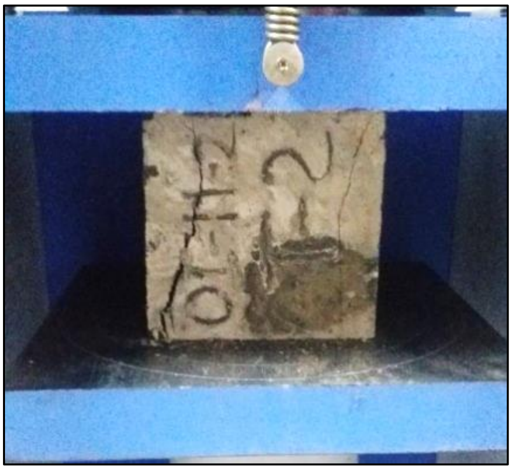


Fig. 4. Compressive strength test

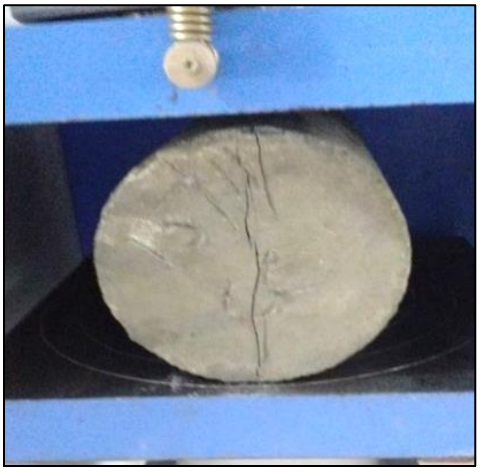


Fig. 5. Split tensile strength test

The concrete mix is prepared using a machine mix and poured into the steel moulds in three layers, compacting each layer twenty-five times. Excess concrete is then removed with a trowel. The steel moulds are placed at room temperature for 24 hours. After demolding, the samples are cured in a water tank. The CS and STS tests are conducted using a Compressive Testing Machine (CTM) with a capacity of 3000 kN, as shown in (Figs. 4 and 5). Similarly, the FS of SFRC is evaluated using a Universal Testing Machine (UTM) with a capacity of 400 kN under two-point loading, illustrated in (Fig. 6). The calculated CS, STS, and FS values follow the recommended equations from IS 516 - 1959 [35,36].

Fig. 6. Flexural strength test

3.3.2 Optimum Steel Fibre and Dosage of Microorganisms Content

Based on the experimental test results, the optimum SF content was examined by 0.8%, listed in Table 4. The microorganisms' content (0%, 1%, 2%, and 3%) was added by the weight of the cement to the optimum content mix M40-SF0.8, which is reported in Table 5. The Bacillus Subtilis bacteria are added to the concrete with the required quantity of water while pouring the concrete casting. Three mix proportions were designed, and it's recommended that the reinforced concrete beams be cast. The optimal steel fibre content and dosage of microorganisms were found to be 0.8% and 2%, respectively. The optimum mixes performed better than the other concrete mixes, as presented in Table 6. Beyond the optimum mix, the bond behavior between aggregates and cement paste becomes inadequate, reducing strength.

Table 4. Mechanical properties of the SFRC at various ages

Mix ID	Mechanical properties at 28 days (MPa)									Increased strength (%)		
	CS			STS			FS			CS	STS	FS
	7	14	28	7	14	28	7	14	28	28	28	28
M40-PF0	30.53	42.16	46.78	3.08	4.28	4.68	3.92	5.42	5.98	-	-	-
M40-PF0.2	31.42	43.48	48.25	3.46	4.68	5.12	4.36	5.98	6.58	3.14	9.40	21.40
M40-PF0.4	33.08	45.98	51.06	3.62	5.12	5.64	4.98	6.87	7.62	9.15	20.51	40.59
M40-PF0.6	33.89	46.87	52.18	4.17	5.72	6.32	5.27	7.38	8.17	11.54	35.04	50.74
M40-PF0.8	35.52	49.43	54.87	4.53	6.28	6.89	5.86	8.02	8.96	17.29	47.22	65.31
M40-PF1.0	34.64	47.92	53.16	4.25	5.34	6.27	5.34	7.43	8.42	13.64	33.97	55.35

Table 5. Mechanical properties of the SFR bacterial concrete at various ages

Mix ID	Mechanical properties at 28 days (MPa)									Increased strength (%)		
	CS			STS			FS			CS	STS	FS
	7	14	28	7	14	28	7	14	28	28	28	28
M40-SF0.8	35.62	49.42	54.87	4.52	6.28	6.89	5.74	7.93	8.79	-	-	-
M40-SF0.8-B1	36.24	50.12	55.64	4.68	6.46	7.12	5.98	8.26	9.14	1.40	3.34	4.70
M40-SF0.8-B2	37.24	51.38	57.18	5.18	7.12	7.84	6.76	9.28	10.28	4.21	13.79	17.75
M40-SF0.8-B3	36.72	50.82	56.42	4.92	6.53	7.38	6.21	8.74	9.68	2.82	7.11	10.88

Table 6. Optimum steel fibre, microorganisms' content and CS of concrete at 28 days

Mix ID	Bacteria content (%)	Optimum steel fibre (%)	CS (MPa)
M40-SF0.8-B0	0	0.8	54.87
M40-SF0.8-B1	1	0.8	55.64
M40-SF0.8-B2	2	0.8	57.18
M40-SF0.8-B3	3	0.8	56.42

4. Experimental Study on RC Beams

4.1. Fabrication and Experimental Setup of the RC beams

In this study, RC beams were cast with a cross-section of 150 mm x 180 mm and a length of 1500 mm, and the fabrication of the RC beam is shown in (Fig. 7). The RC beam was designed according to IS 456 – 2000 [37]. Two 10 mm diameter and two 8 mm diameter deformed steel bars were provided for tension and compression reinforcement. Shear reinforcement was uniformly placed at 100 mm and 80 mm c/c throughout the length. Four RC beams were cast and tested under four-point loading, with various shear reinforcement spacing of 100 mm and 80 mm, respectively. Geometric details of the specimens are reported in Table 7. The RC beams were fabricated in two proportions: M40-SF0.8-B0 and M40-SF0.8-B2%. The reinforcement was cut to 1450 mm, and shear reinforcement was placed at 100 mm and 80 mm c/c.

(a)

(b)

(c) (d)

Fig. 7. Fabrication of the RC beams (a) Cross-section and longitudinal reinforcement details, (b) Steel mould, (c) Steel mould with reinforcement cage, and (d) Casting RC beams

The compression, tension, and shear reinforcement were bonded with steel wire. The steel mould for the RC beam is cleaned, and waste oil is applied to serve as a lubricant. Once the reinforcement steel cage is aligned correctly within the mould, machine-mixed concrete is poured into it. The concrete is thoroughly compacted using a vibrator machine to prevent the formation of honeycomb structures. After compaction, the concrete is levelled and left at room temperature for 24 hours. The following day, the steel mould is carefully removed from the RC beam without causing any damage. After a curing period of 28 days, the RC beams are removed from the curing tank, and their outer surfaces are cleaned. Additionally, the beams are white-washed and marked with a grid.

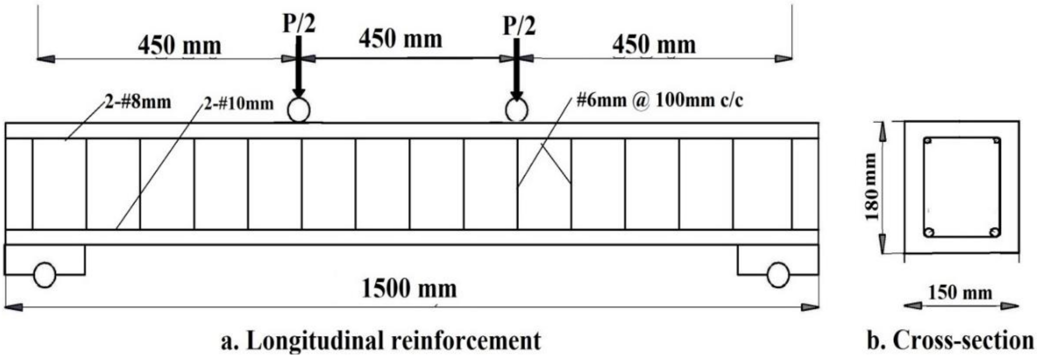


Fig. 8. Loading positions, cross-section and longitudinal reinforcement details of the RC beam

Each specimen is placed on a 50T capacity loading frame, with deflection meters positioned at marked locations. The graphical representation and experimental setup of the RC beam are shown in (Fig. 8). loading is gradually applied to the RC beams until they fail, and axial load and deflection are recorded at initial cracks, ultimate load, and failure load. The loading rate for all specimens is maintained at 0.5 mm/minute. This facilitates a more consistent stress distribution throughout the beam, which is essential for analyzing the material's flexural behavior. Four-point loading is commonly employed in flexural testing to accurately assess the beam's flexural strength and stiffness, as illustrated in (Fig. 9).

Fig. 9. Experimental setup of RC beam

Table 7. Geometric properties of the RC beams

Specimen ID	Details of Specimen (mm)			Reinforcement		Shear reinforcement
	B	D	L	Bottom	Top	
M40-SF0.8-B0	150	180	1500	2#10mm	2#8mm	#6mm @ 100mm c/c
M40-SF0.8-B0	150	180	1500	2#10mm	2#8mm	#6mm @ 80mm c/c
M40-SF0.8-B2	150	180	1500	2#10mm	2#8mm	#6mm @ 100mm c/c
M40-SF0.8-B2	150	180	1500	2#10mm	2#8mm	#6mm @ 80mm c/c

5. Analytical Study

5.1. Finite Element Model

The Finite Element Model (FEM) was developed using ANSYS software. The experimental test results were compared and examined against the analytical results. The 3D model was created, and the FEM analysis was conducted on the RC beam with various mesh sizes (fine, medium, and coarse). Based on the sensitivity analysis, the coarse mesh size yielded better results and saved time than the remaining mesh sizes. The finite element model helps predict experimental test results and correlates highly with experimental data. The 3D model of the RC structure developed in ANSYS software is shown in (Fig. 10). The meshing of the 3D model and the loading arrangement of the RC beam are illustrated in (Fig. 11 and 12).

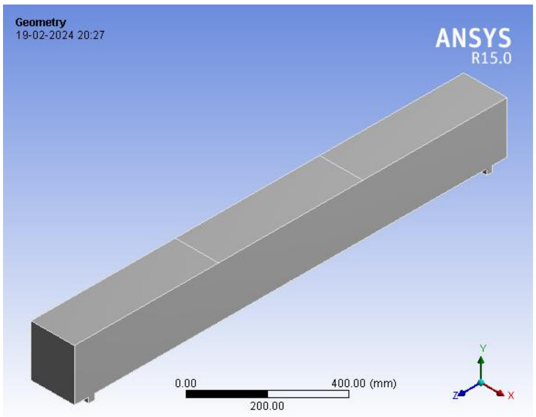


Fig. 10. D model of RC beam

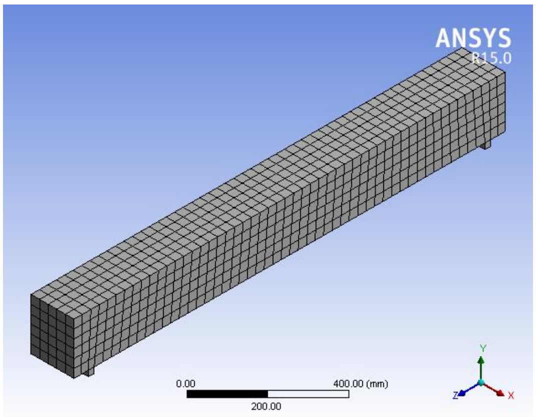


Fig. 11. Meshing of RC beam

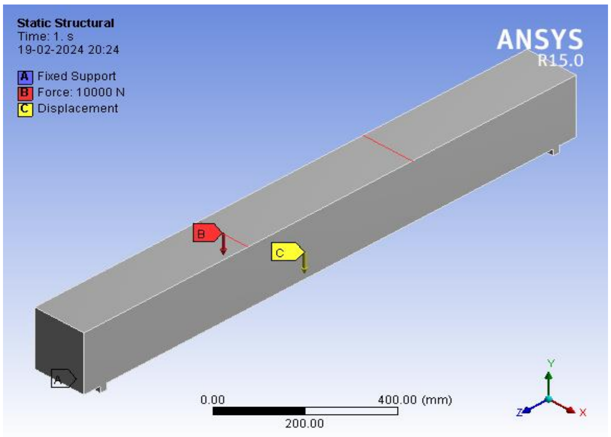


Fig. 12. Load and support arrangement of RC beam

5.2. Boundary Condition of RC beam

The boundary condition of the RC beam was considered as one end being roller support, and the other is supported for the analysis in ANSYS. The roller support restricts movement in the x and z directions while allowing movement in the y direction where the load is applied. Similarly, in the simple support condition, the beam's y direction is also restrained to prevent the free rotation of the RC beam.

6. Results and Discussion

6.1. Steel Fibres and Microorganisms Influence in CS of Concrete

The CS of steel fibre-reinforced concrete was examined at seven, fourteen, and twenty-eight days, respectively, as depicted in (Fig. 13). The CS of the concrete is enhanced with the addition of SF by 3.14%, 9.15%, 11.54%, 17.29%, and 13.64% for M40-SF0.2, M40-SF0.4, M40-SF0.6, M40-SF0.8, and M40-SF1, compared to the conventional concrete mix M40-SF0. Based on the experimental study, the optimum SF content is 0.8%. Additionally, the CS of the concrete was studied with the optimum SF content of 0.8%. Furthermore, microorganisms (at concentrations of 0%, 1%, 2%, and 3%) were added to the optimum SF content of 0.8%, resulting in mixes such as M40-SF0.8-B1, M40-SF0.8-B2, and M40-SF0.8-B3.

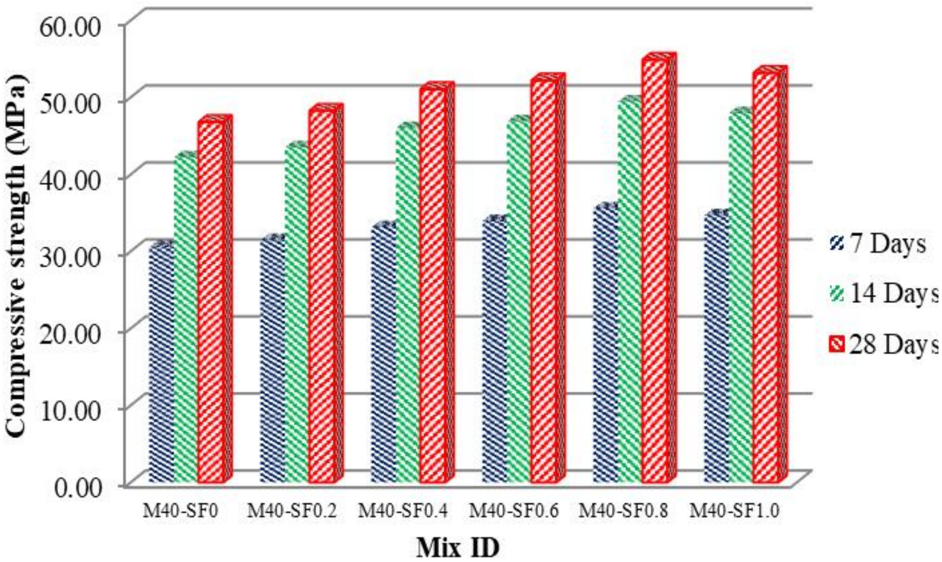


Fig. 13. Compressive strength of SFC at various ages

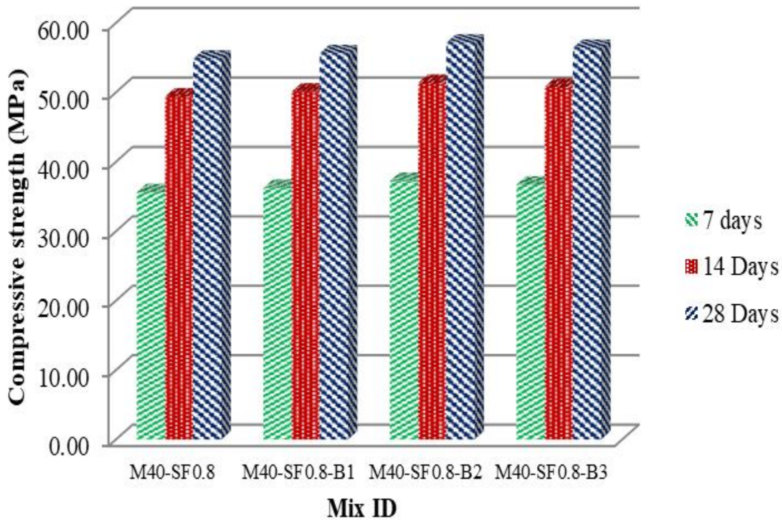


Fig. 14. CS of SFC with microorganisms at various ages

The strength properties of the concrete also increased by 1.40%, 4.21%, and 2.82% compared to the control mix M40-SF0.8-B0, as presented in (Fig. 14). The experimental study achieved the optimum strength properties with 17.29% enhancement for M40-SF0.8 and 4.21% enhancement for M40-SF0.8-B2. The CS of the SFRC was increased by with the addition of microorganism's content by 2%. The microorganisms fill the existing voids, which is the reason the strength properties of the concrete have been increased.

6.2. Steel Fibres and Microorganisms Influence the STS Of Concrete

The strength properties of the concrete, precisely the split tensile strength, were evaluated using various steel fibre ranges (0%, 0.2%, 0.4%, 0.6%, 0.8%, and 1%) and microorganisms (0%, 1%, 2%, and 3%) at different ages 7, 14 &28 days, respectively. In the first portion of the study, the STS properties of the concrete increased by 9.40%, 20.51%, 35.04%, 47.22%, and 33.97% for mixes M40-SF0.2, M40-SF0.4, M40-SF0.6, M40-SF0.8, and M40-SF1, compared to the conventional concrete mix M40-SF0 as depicted in (Fig. 15). Adding steel fibre enhanced split tensile strength properties, with the optimum content identified as 0.8% steel fibre compared to the other mixtures. In the second part, microorganisms were incorporated at concentrations of 0%, 1%, 2%, and 3% into the optimal fibre content of 0.8%.

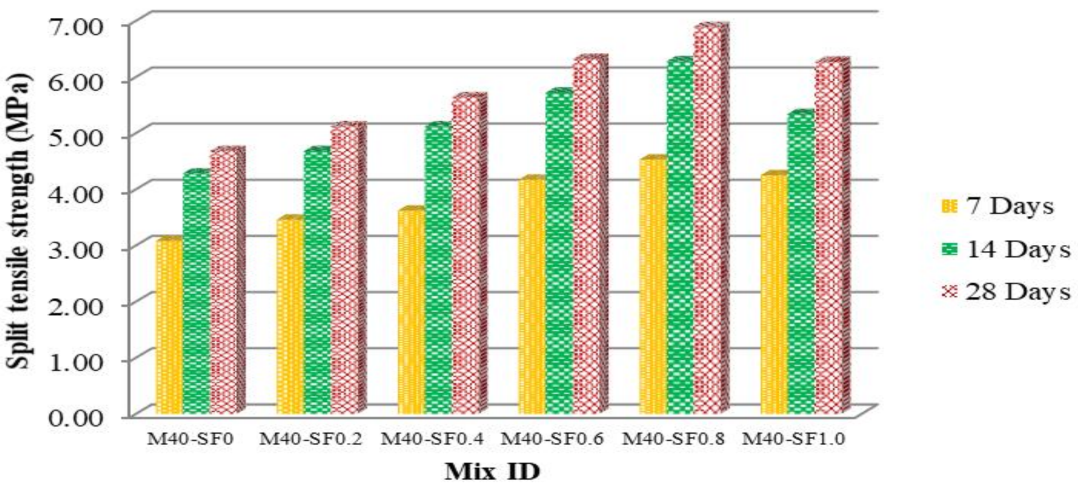


Fig. 15. Split tensile strength of steel fibre concrete at various ages

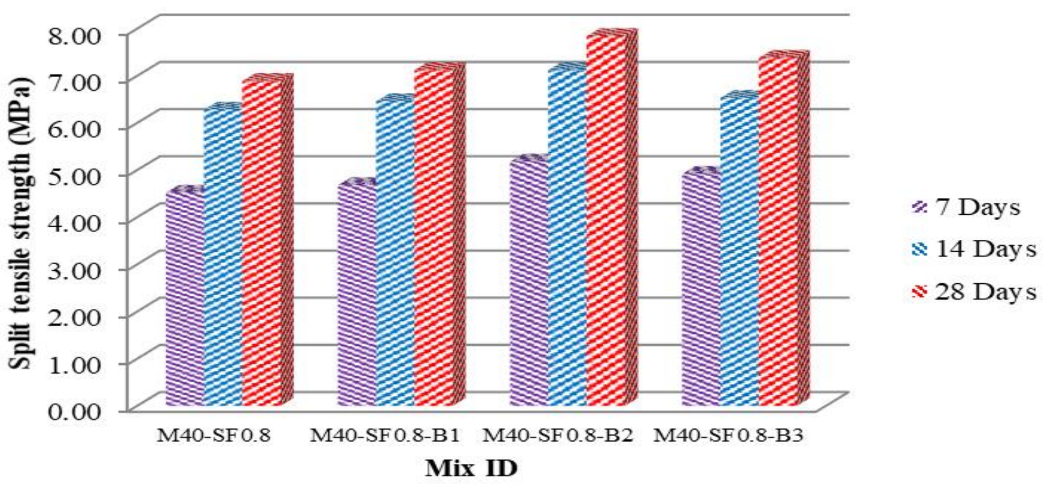


Fig. 16. STS of steel fibre concrete with microorganisms at various ages

The mechanical properties of concrete were enhanced by adding SF and microorganisms for M40-SF0.8-B1, M40-SF0.8-B2, and M40-SF0.8-B3. Notably, the strength properties of the concrete exhibited improvements of 3.34%, 13.79%, and 7.11% when compared to the control mix M40-SF0.8-B0, as illustrated in (Fig. 16). Based on the experimental study, the STS increased by adding 2% microorganisms' content to the optimum steel fibre content of 0.8%. It is clearly shown that the STS of concrete mix M40-SF0.8-B2 exceeds that of the M40-SF0.8 concrete mix. The 0.8% steel fibre and 2% microorganisms content improved the split tensile strength. The steel fibre interconnects with the cement paste and aggregates, while the microorganisms fill the existing voids [38]. Overall, the mechanical properties of the split tensile strength were enhanced by using steel fibre and microorganisms.

6.3. Steel Fibres and Microorganisms Influence the FS of Concrete

Similarly, the FS of the concrete was determined using steel fibre and microorganisms at the ages of 7, 14 &28 days, respectively. (Fig. 17) depicts the effect of SFs on concrete's flexural behavior at those ages.

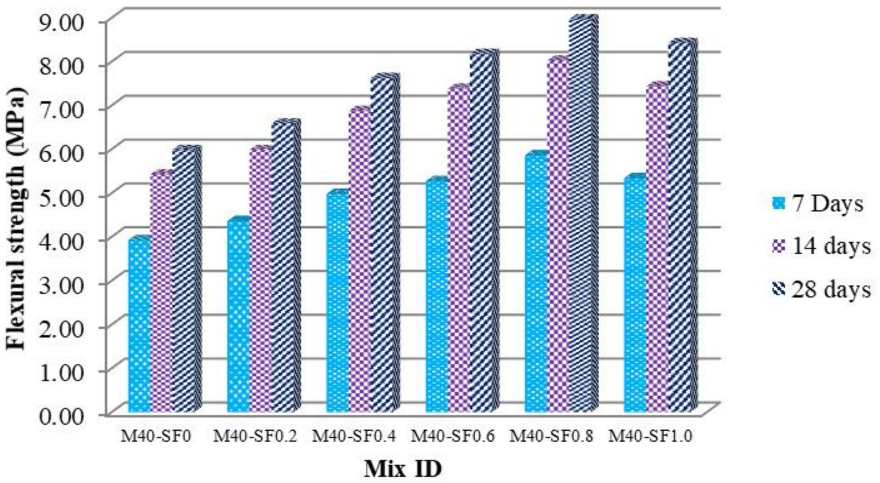


Fig. 17. Flexural strength of steel fibre concrete at various ages

The flexural strength increased by 21.40%, 40.59%, 50.74%, 65.31%, and 55.35%, with the addition of steel fibre in the range from 0.2% to 1%. The optimum flexural strength concrete mix was found to be M40-SF0.8. Additionally, the flexural strength increased when incorporating microorganisms (at 1%, 2%, and 3%). According to the experimental test results, the FS of the concrete improved by 4.70%, 17.70%, and 10.88% for M40-SF0.8-B1, M40-SF0.8-B2, and M40-SF0.8-B3, as shown in (Fig. 18). The experimental study observed that the FS of the concrete increased with the addition of 0.8% steel fibre and 2% microorganisms. The recommended combination for further investigation of RC beams is 0.8% fibre content and 2% microorganisms.

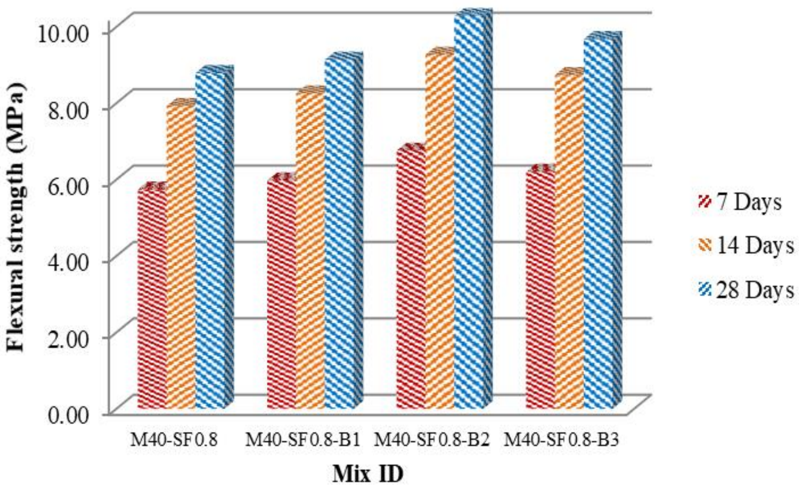


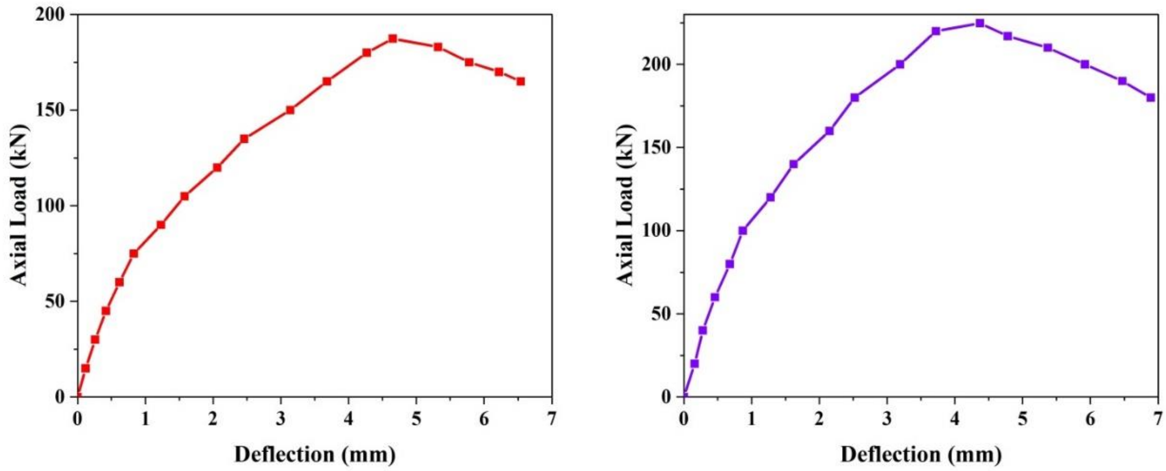
Fig. 18. FS of steel fibre concrete with microorganisms at various ages

6.4. Flexural Behavior of RC Beams

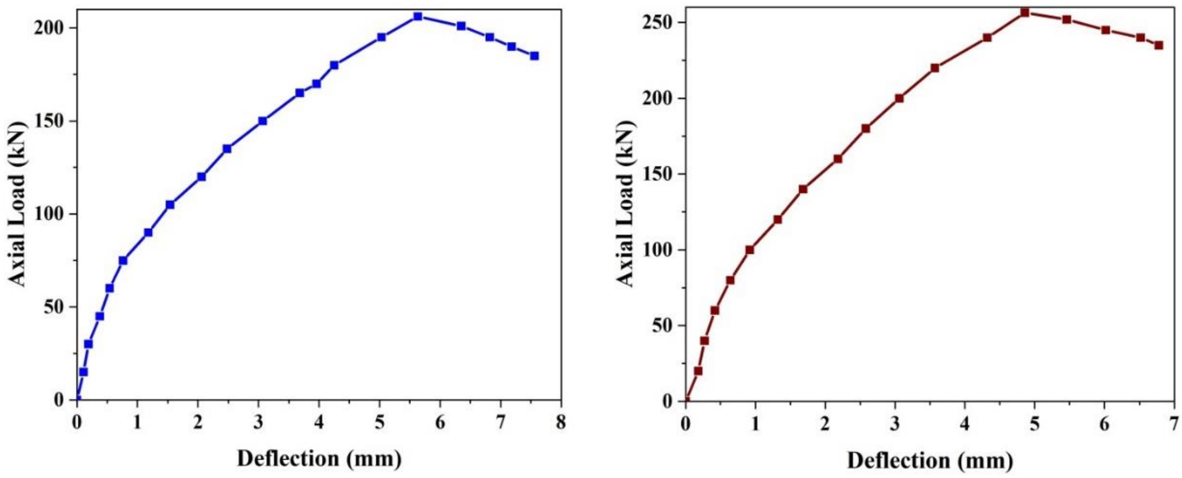
This study investigated the flexural behavior of RC beams by combining steel fibres and microorganisms. They cast and tested four RC beams after a 28-day curing period, varying the shear-reinforced spacings to 100 mm and 80 mm. Incorporating SF and microorganisms led to improved mechanical properties and enhanced flexural behavior in the RC beam. The study's main objective was to investigate parameters such as axial load versus deflection, failure mode, peak ductility, stiffness, and energy absorption. In past studies, bacteria such as Bacillus Subtilis, Bacillus Sphaericus, and Sporosarcina Pasteurii have been frequently used for self-healing concrete. The current study also uses Bacillus Subtilis, aligning with established research. Compressive strength studies have shown varying levels of improvement, typically ranging from 5% to 15%. The previous study reported a 10% increase in compressive strength by incorporating Bacillus Subtilis [23]. Improvements in flexural strength have also been reported, ranging from 10% to 20%. Another study found a 12% increase in flexural strength with bacteria-induced self-healing [39]. The current study reports an enhancement in compressive strength by 4.20%, incorporating 0.8% steel fiber and 2% microorganisms. This improvement is slightly lower than some previous studies but still demonstrates a significant positive impact [40]. Additionally, the study found an increase in the flexural behavior of RC beams by 19.98% and 24.40% compared to conventional specimens. This is higher than the improvements reported in earlier studies, indicating a notable enhancement in flexural properties [41].

6.5. Axial Load-Deflection Responses of RC Beams

A total of four reinforced concrete beams with dimensions 150mm x 180mm x 1500mm (labelled M40-SF0.8-B0-S100, M40-SF0.8-B0-S80, M40-SF0.8-B1-S100 and M40-SF0.8-B1-S80) were cast and tested after a curing period of 28 days. Axial load versus deflection was recorded, including the initial crack load, ultimate load, and failure load for all reinforced concrete beams, as reported in Table 8. The flexural behavior of the reinforced concrete beams was studied under axial loading, gradually increasing the axial load until the specimen failed. The initial crack loads were 94 kN, 116 kN, 103 kN, and 126 kN. The ultimate loads were 187.32 kN, 224.75 kN, 206.17 kN, and 256.48 kN. The failure loads were 183 kN, 217 kN, 201 kN, and 252 kN for the M40-SF0.8-B0-S100, M40-SF0.8-B0-S80, M40-SF0.8-B1-S100, and M40-SF0.8-B1-S80 reinforced concrete beams, respectively. The flexural behavior of the reinforced concrete beam axial load increased by 19.98% when reducing the shear reinforcement spacing for M40-SF0.8-B0-S80 reinforced concrete specimens, compared to the M40-SF0.8-B0-S100 RC specimens. Similarly, the axial load's flexural behavior showed a 24.40% increase when reducing the shear reinforcement spacing for M40-SF0.8-B2-S80 RC specimens compared to the M40-SF0.8-B2-S100 RC specimens. Based on experimental observations, flexural behavior performance is enhanced by incorporating steel fibres and microorganisms into reinforced concrete beams. The axial load versus deflection response of the M40-SF0.8-B0-S100, M40-SF0.8-B0-S80, M40-SF0.8-B1-S100, and M40-SF0.8-B1-S80 reinforced concrete beams are shown in (Fig. 19).



(a) (b)



(c) (d)

Fig. 19. Axial load-deflection response from an experimental study (a) M40-SF0.8-B0-S100, (b) M40-SF0.8-B0-S80, (c) M40-SF0.8-B2-S100, and (d) M40-SF0.8-B2-S80

Table 8. Experimental results for RC beam with steel fibre and microorganisms

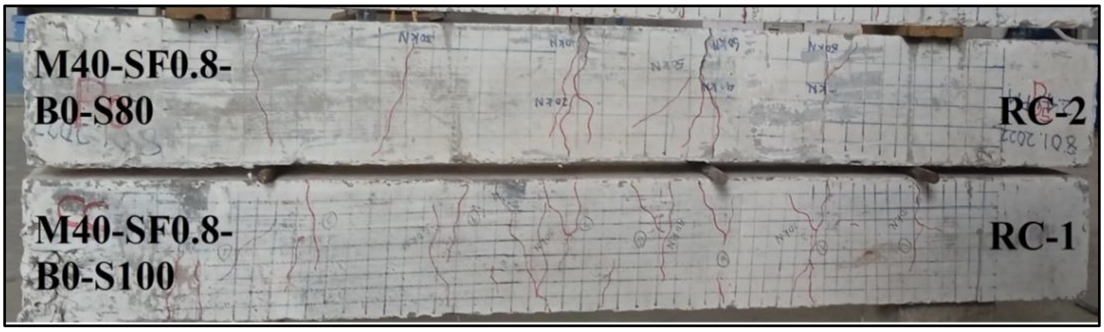
Specimen ID	Experimental load (kN)			Ultimate deflection (mm)
	Initial cracks	Ultimate	Failure	
M40-SF0.8-B0-S100	94	187.32	183	4.65
M40-SF0.8-B0-S80	116	224.75	217	4.37
M40-SF0.8-B2-S100	103	206.17	201	5.63
M40-SF0.8-B2-S80	128	256.48	252	4.86

6.6. Mode of Failure of the RC Beams

The flexural behaviour of the RC beams was tested, and all RC beams commonly exhibited flexural failure and fibre pull-out. Axial load was applied to the RC beams, forming initial cracks at loads of 94 kN, 116 kN, 103 kN, and 126 kN. The load was incrementally increased to the ultimate load, reaching values of 187.32 kN, 224.75 kN, 206.17 kN, and 256.48 kN. During this process, the cracks propagated throughout the specimens. Subsequently, the RC beams failed as further load was applied, with failure loads of 183 kN, 217 kN, 201 kN, and 252 kN. The ductility index increased when the shear reinforcement spacing was reduced from 100mm to 80mm by ductility factors of 3.52, 3.70, 3.43, and 3.80. Similarly, the stiffness also increased, with values of 40.28 kN/mm, 51.43 kN/mm, 36.62 kN/mm, and 52.77 kN/mm for the M40-SF0.8-B0-S100, M40-SF0.8-B0-S80, M40-SF0.8-B1-S100, and M40-SF0.8-B1-S80 RC beams, respectively is reported in Table 9. Adding steel fibres and microorganisms enhanced the FS of the RC beams. (Fig. 20) depicts the mode of failure of the RC beams. The mechanism of action for bacteria in self-healing concrete involves a fascinating process that helps repair cracks and enhance the longevity of concrete structures [42].

Table 9. Experimental results for RC beam with steel fibre and microorganisms

Specimen ID	Experimental test results				Ductility	Stiffness (kN/mm)	Failure mode
	Initial load(kN)	Deflection (mm)	Ultimate load(kN)	Deflection (mm)			
M40-SF0.8-B0-S100	94	1.32	187.32	4.65	3.52	40.28	FF+FP
M40-SF0.8-B0-S80	116	1.18	224.75	4.37	3.70	51.43	FF+FP
M40-SF0.8-B2-S100	103	1.64	206.17	5.63	3.43	36.62	FF+FP
M40-SF0.8-B2-S80	128	1.28	256.48	4.86	3.80	52.77	FF+FP



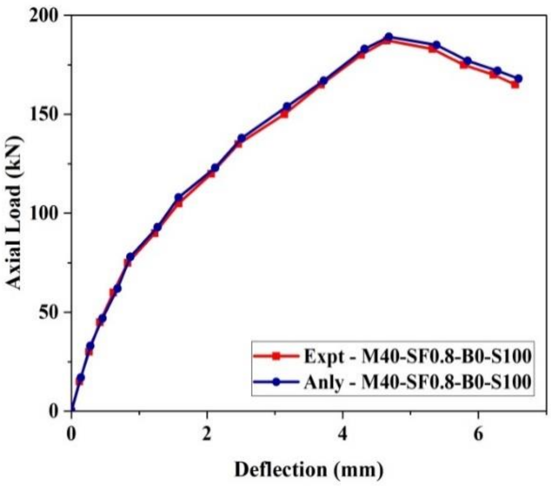
(a)

(b)

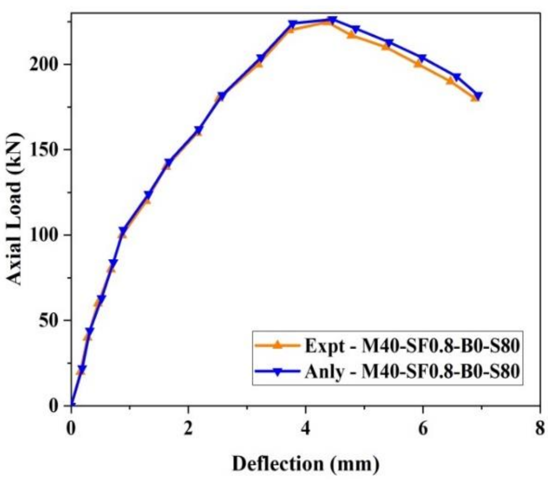
Fig. 20. Tested RC beams (a) M40-SF0.8-B0-S100 and M40-SF0.8-B0-S80 and (b) M40-SF0.8-B2-S100 and M40-SF0.8-B2-S80

6.7. Comparison of Experimental and Analytical Study

The experimental test results were compared to the analytical results regarding flexural behavior. (Fig. 21) illustrates the axial load-deflection curves for both analytical and experimental responses. Up to 70% of the load, the axial load versus deflection curve exhibits linear behavior [40]. After that, the RC beams reach to elastic to plastic behavior. The experimental ultimate load for the RC beams was 187.32 kN, 224.75 kN, 206 kN, and 256.54 kN, respectively. The corresponding experimental deflection values were 4.65 mm, 4.37 mm, 5.63 mm, and 4.68 mm. Similarly, the ultimate load and deflection from the analytical results were compared to the experimental results. The mean, standard deviations, and coefficient of variation were 0.99, 0.04, and 0.45 for the ultimate load and 0.99, 0.007, and 0.69 for the deflection. These results are reported in Table 10. The finite element analysis deflection of the RC beams (M40-SF0.8-B0-S100, M40-SF0.8-B0-S80, M40-SF0.8-B1-S100, and M40-SF0.8-B1-S80) is presented in (Fig. 22).



(a)



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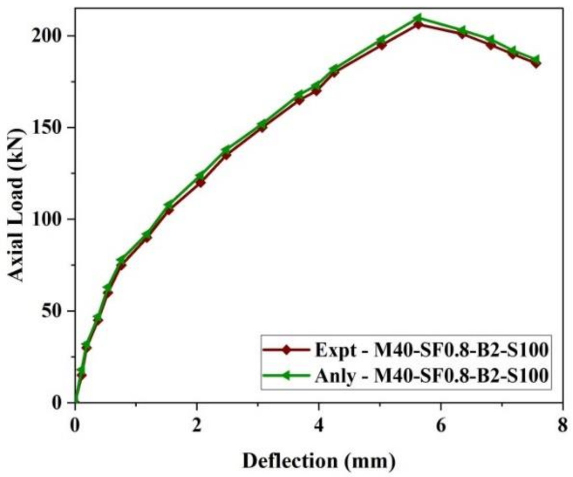

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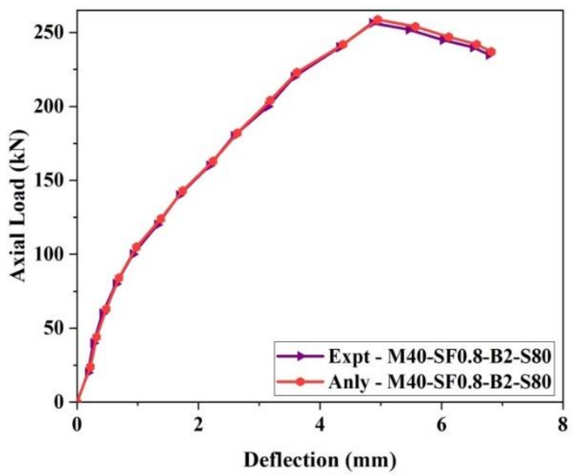
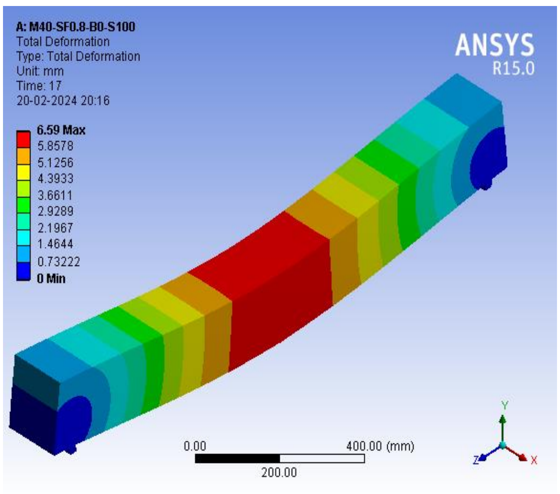
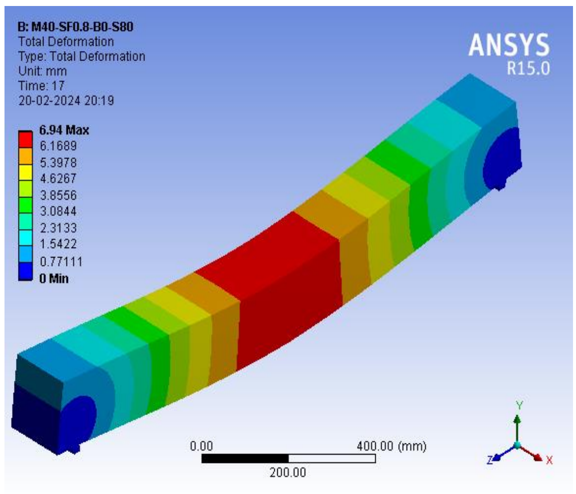


(d)

Fig. 21. Comparison of the experimental and analytical axial load-deflection response of all RC beams (a) M40-SF0.8-B0-S100, (b) M40-SF0.8-B0-S80, (c) M40-SF0.8-B2-S100, and (d) M40-SF0.8-B2-S80



(a)



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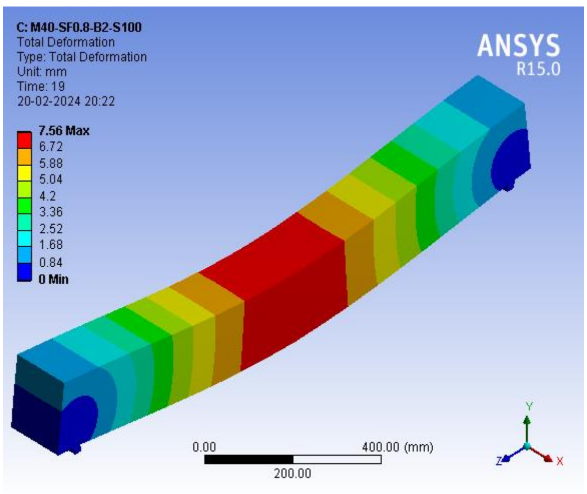

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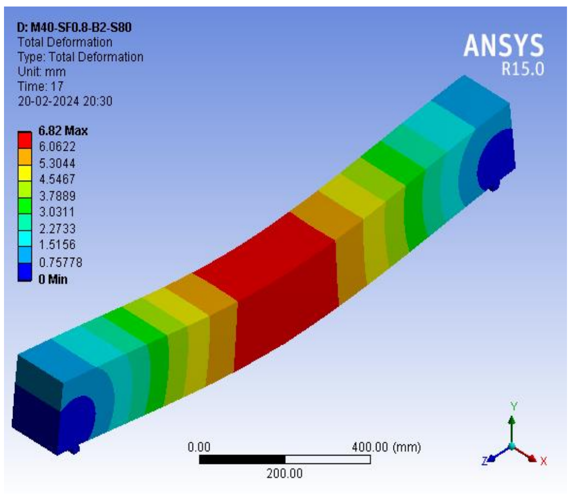

(d)

Fig. 22. Axial load-deflection response from the analytical study (a) M40-SF0.8-B0-S100, (b) M40-SF0.8-B0-S80, (c) M40-SF0.8-B2-S100, and (d) M40-SF0.8-B2-S80

Table 10. Comparative study between the experimental and analytical results

	Experimental values at the ultimate point		Analytical values at the ultimate point		P_{Expt} / P_{Anly}	
	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)	Load	Deflection
M40-SF0.8-B0-S100	187.32	4.65	189.16	4.68	0.99	0.99
M40-SF0.8-B0-S80	224.75	4.37	226.38	4.46	0.99	0.98
M40-SF0.8-B2-S100	206.17	5.63	209.74	5.68	0.98	0.99
M40-SF0.8-B2-S80	256.54	4.86	258.67	4.95	0.99	0.98
		Mean			0.99	0.99
		SD			0.004	0.007
		CV (%)			0.45	0.69

7. Conclusions

This study introduces a novel approach to enhancing concrete structures mechanical properties and flexural behavior by incorporating self-healing properties using microorganisms, specifically Bacillus Subtilis bacteria and steel fibers. By exploring the synergistic effects of steel fibers and Bacillus Subtilis bacteria on the mechanical properties of self-healing concrete, this study contributes to the advancement of concrete technology and offers new possibilities for constructing more resilient and sustainable structures. The present study investigated the experimental and analytical study on the flexural behavior of RC beams with the addition of various percentages of steel fibre (0%, 0.2%, 0.4%, 0.6%, 0.8%, and 1%) and microorganisms (0%, 1%, 2% and 3%). The experimental and analytical test results led to the following conclusions:

The strength properties of steel fibre concrete (CS, STS and FS) were studied with percentages ranging from 0%, 0.2%, 0.4%, 0.6%, 0.8%, and 1% at ages seven, fourteen, and twenty-eight days. According to the experimental study, the optimum SF content was 0.8%. Compared to the conventional concrete mix, the CS, STS and FS improved by 17.29%, 47.22% and 65.21%, respectively. The optimum SF content of 0.8% (in the concrete mix) was investigated by adding microorganisms at 0%, 1%, 2% and 3%.

The mechanical properties of steel fibre concrete were enhanced by adding microorganisms. The optimum dosage of microorganisms was found to be 2%. Compared to the conventional concrete mix, the CS, STS, and FS increased by 4.21%, 13.79% and 17.75%, respectively. Based on the experimental test results, the optimum SF and microorganism content were 0.8% and 2%, respectively. This optimum mix was recommended for studying the flexural behavior of RC beams.

Four RC beams (namely, M40-SF0.8-B0-S100, M40-SF0.8-B0-S80, M40-SF0.8-B1-S100, and M40-SF0.8-B1-S80) were studied with various shear reinforcement spacing of 100mm and 80mm. The axial load increased by 19.98% for M40-SF0.8-B0-S100 and 24.40% for M40-SF0.8-B1-S100, compared to M40-SF0.8-B0-S80 and M40-SF0.8-B1-S80 RC beams.

The modes of failure commonly observed in all RC beams are flexural failure and fibre pull-out. Adding steel fibre and microorganisms enhances the strength properties related to the flexural behavior of the RC beams. The ductility index and stiffness of the RC beams increased by 3.70 and 51.43 kN/m with the addition of steel fibres and microorganisms. Furthermore, the ductility index and stiffness were enhanced by 3.80 and 52.77 kN/m when shear reinforcement spacing was reduced from 100 mm to 80 mm. The experimental and analytical axial load versus deflection curves exhibit similar behavior. When comparing the experimental and analytical load and deflection, the mean, standard deviations, and coefficient of variation were 0.99, 0.04, and 0.45 for the ultimate load and 0.99, 0.007, and 0.69 for the deflection.

Finite element models were developed for RC beams, and the analytical study results were compared to the experimental test results. The finite element model helps predict the experimental test results, and the analytical results were highly correlated with the empirical findings.

8. Recommendation for the Future Studies

The present research examined the mechanical properties of concrete and the flexural behavior of RC beams with the incorporation of steel fiber and bacteria. Future studies can focus on implementing the current project in the actual field and comparing the experimental results with field test outcomes.

Acknowledgement

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List of Abbreviations

ANN	- Artificial neural networks	FA	- Fine aggregate
CA	- Coarse aggregate	FEM	- Finite element model
CE	- Cement	FRC	- Fibre-reinforced concrete
CS	- Compressive strength	FS	- Flexural strength
CSF	- Closed steel fibres	GF	- Steel fibre
CTM	- Compressive testing machine	IS	- Indian standard
CV	- Coefficient of variation	OPC	- Ordinary Portland cement
RC	- Reinforced concrete	RSF	- Recycled steel fibres
SD	- Standard deviation	SFRC	- Steel fibre-reinforced concrete
SP	- Superplasticizer		

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