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Innovative use of microbially induced calcite precipitation and zeolite for enhanced self-healing concrete

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ABSTRACT
Concrete, the cornerstone of modern building, has certain intrinsic shortcomings, such as poor tensile strength and crack susceptibility. Thus, biomineralization appears to be a promising strategy for repairing concrete construction defects through microbial activity. The most advanced use of this novel approach is Microbiologically-Induced Calcite Precipitation (MICP). Microbial urease enzyme-catalyzed calcium carbonate precipitation is a phenomenon that can be produced in concrete mixes containing zeolite by adding bacteria. This promotes calcite formation, sealing fissures and enhancing longevity. Our study compares M25 Bacterial Concrete (BC) and Conventional Concrete (CC) for optimal mix design and performance. We show by thorough experimentation that adding zeolite and bacteria does not affect the workability of concrete mixtures. In addition, BC has better compressive strength at different curing ages because of the sealing action of calcite precipitation and the synergistic improvement of zeolite. Results show MICP boosts concrete durability and cuts maintenance costs. Our research also looks into the flexural behaviour of beams made of reinforced concrete produced by microbes, offering insights into the structural performance of these novel materials in real-world applications. Materials support SDGs by fostering sustainable production and industrial innovation.

Keywords: Biomineralization; Green Construction Materials; Zeolite Additives; Sustainable Construction.

1. INTRODUCTION
With an emphasis on overcoming the shortcomings of concrete a material that is widely used in modern construction but is mechanically exposed this study explores the crucial role that building materials play in promoting sustainable constructions. We seek to maximise the performance of concrete while reducing its environmental impact by examining the mechanical and durability characteristics of bacterial concrete as well as the effects of adding natural zeolite as an additive. Concrete's low cost, abundant availability, and ease of usage all contribute to its indispensable nature in building. Unfortunately, the lifetime and structural integrity of built environments are compromised by its proneness to cracking under tension and exposure to extreme weather conditions. Remedial actions are required to maintain structural soundness because of the numerous variables that lead to these cracks, including temperature changes, settlement disparities, shrinkage during curing, and corrosion of reinforcement [1].

By adding bacteria that may precipitate calcium carbonate to seal cracks and increase strength and stiffness, a technique known as Microbiologically-Induced Calcite Precipitation (MICP) presents a viable means of reducing the likelihood of concrete breaking. With its potential uses in structural restoration and concrete crack treatment, this natural, pollution-free solution has drawn attention as a viable substitute for conventional repair techniques. Bacterial concrete offers a novel approach to self-healing concrete buildings since it continuously precipitates calcite. Numerous bacterial strains, including as Pseudomonas, Bacillus subtilis, and Escherichia coli, have proven to be useful in catalysing the synthesis of calcite within concrete matrices, hence filling and sealing cracks to improve durability. The integration of bacteria into concrete mixtures is further optimised using encapsulation processes, which guarantee compatibility with other material qualities and promote long-term structural robustness [2]. The combination of bacterial additives and natural zeolite in concrete formulations shows promise in overcoming the traditional limitations of concrete. These advancements not only enrich the

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strength and durability properties of concrete but also contribute to more sustainable construction practices by reducing environmental impacts and improving the longevity of concrete structures.

Furthermore, adding zeolite powder to concrete mixtures has several advantages because it can reduce carbon dioxide emissions and act as a powerful absorber of hazardous substances. Because of their high surface areas and porous architectures, natural zeolites have pozzolanic activity and help create denser microstructures in concrete, which improves mechanical strength and durability. Using Bacillus subtilis, Escherichia coli, Pseudomonas, and zeolite, our research aims to clarify the ideal mix design for conventional and bacterial concrete blends. By using in-depth mechanical and durability tests, we want to verify the effectiveness of zeolite and microbially induced concrete compared to their traditional counterparts. Furthermore, we evaluate the flexural behaviour of reinforced concrete beams, elucidating self-healing capabilities by sophisticated characterization approaches and experimental data validation. By utilising the potential of biomineralization and natural admixtures to improve the longevity and performance of concrete structures while reducing their environmental impact, this study ultimately advances sustainable construction techniques. This study aims to explore the advancements in sustainable concrete through zeolite and bacterial additives, demonstrating their potential to enhance durability, minimize environmental impact, and advance structural engineering practices.

2. EXPERIMENTAL PROCEDURES

2.1. Study participants

Scale samples are collected from K. S. Rangasamy College of Technology, Tiruchengode's Biotechnology lab. Conical flasks are used to transfer the obtained sample to the civil laboratory, where it is incubated. The laboratory's expertise in biotechnology ensures the availability of high-quality bacterial cultures for this study.

2.2. Methodology

Using the Indian Standard mix design approach, this study investigated the strength and durability features of bacterial concrete with and without zeolite for M25 grade concrete. Bacillus subtilis, Pseudomonas, and Escherichia coli were used to make bacterial concrete specimens, which were then evaluated for freshness, durability, and microstructural characteristics. It was determined which bacterial concrete mix was best. The ideal mix was used to cast structural members, and the results of this process were examined. Durability over time was assessed. The aim of this study is to evaluate the effectiveness of bacterial concrete, particularly through Microbiologically-Induced Calcite Precipitation (MICP), and to explore the impact of using zeolite as an admixture. This research seeks to address the challenges of conventional concrete by enhancing its properties through the self-healing abilities of bacterial additives and the environmental benefits of incorporating zeolite. The ultimate goal is to contribute to more durable and sustainable construction practices. The experimental structural behaviour results were validated through analytical study utilising Abaqus software. FTIR and UV spectroscopy were used to characterise the calcite precipitation [3].

2.3. Materials used

The primary materials utilised in this study were produced sand in accord with IS 383-2016, crushed stonework coarse aggregate with a nominal size of 20 mm in accordance with IS 383:1993, and Ordinary Portland Cement (OPC) of grade 53 in accordance with IS 1489:1993. The cement's standard consistency was 32%, its relative density was 3.1, and its 28-day compressive strength was 58.83 MPa. The relative density, fineness index, and water absorption of the fine aggregate (M-sand) were 2.63, 3.17, and 1.24%, respectively. The bulk density of 1695 kg/m^3, the relative density of 2.63, the fineness index of 7.0, the water absorption of 0.45%, and the crushing value of 20.67% were all observed in the coarse aggregate. Concrete was mixed and allowed to cure using potable water that complied with IS 456-2000 for building purposes. To make bacterial concrete, three different strains of bacteria were used: Bacillus subtilis, Bacillus pseudomonas, and Escherichia coli. To cultivate and grow these bacteria, a broth medium rich in nutrients was made [4]. The hatching process in the civil laboratory involves incubating bacteria at 30−37°C, maintaining neutral to slightly alkaline pH, providing nutrient-rich media, ensuring proper aeration, and maintaining sterility to promote growth and calcite precipitation for bacterial concrete.

In bacterial concrete mixtures, natural zeolite, an aluminosilicate mineral, was utilised in part substitute of cement. The zeolite had a relative density of 2.20, a fineness index of 3.278, and a water absorption percentage of 0.23%. Its principal constituents were oxides, comprising 67.75% SiO2, 13.68% Al2O3, 1.46% Fe2O3, and other oxides. Using the discovered material parameters, the Indian Standard approach was followed in designing the concrete for M25 grade. For conventional concrete, bacterial concrete with varied doses of bacteria, and bacterial concrete with different percentages of zeolite replacement, the proper mix proportions were determined.

Zeolite can lower carbon dioxide emissions from buildings and is a great absorber of hazardous substances. Concrete gains strength and durability from its pozzolanic activity and capacity to densify the microstructure. The purpose of adding zeolite to bacterial concrete is to improve its mechanical qualities and durability even further.

3. EXPERIMENTAL INVESTIGATION

This chapter describes the comprehensive programme of experiments conducted to assess the mechanical, microstructural, renewed, and durability possessions of bacterial concrete through and without zeolite addition [5]. The mix IDs and descriptions for the various concrete mixes made with bacterial additions are shown in Table 1.

As the control mix, the mix ID "CC" stands for the regular concrete mix that hasn't had any bacterial additions. The remaining mix IDs show that different kinds of bacteria were added to the M25 grade concrete mix in varying proportions. The three types of bacteria that are employed are Escherichia coli (BEC), Bacillus Pseudomonas (BPC), and Bacillus Subtilis (BSC). Each type of bacteria is added at three different percentages: 0.1%, 0.2%, and 0.3%. The mix IDs and descriptions for the bacterial zeolite concrete mixtures are displayed in Table 2. These mixtures include zeolite and microorganisms as concrete additives. The mix IDs show the percentage of zeolite replacement (10%, 20%, or 30%), the kind of microbes employed (Bacillus Subtilis), and the amount of bacteria added (0.1%, 0.2%, or 0.3%) [6]. For instance, the mix ID "B1Z10" denotes a concrete mix that contains 0.1% Bacillus Subtilis and 10% replacement zeolite, whereas the mix ID "B3Z30" denotes a mix that contains 0.3% Bacillus Subtilis and 30% replacement zeolite. Using zeolite as a partial cement substitute can enhance the mechanical properties and durability of concrete while significantly reducing carbon dioxide emissions and absorbing hazardous substances.

Table 1: Mix ID and the description.

SL.NO.	MIX ID	DESCRIPTION
1.	CC	CC-M25
2.	BSC-01	M25 concrete with 0.1% of Bacillus Subtilis, (30 mL)
3.	BSC-02	M25 concrete with 0.2% of Bacillus Subtilis (60 mL)
4.	BSC-03	M25 concrete with 0.3% of Bacillus Subtilis (90 mL)
5.	BPC-01	M25 concrete with 0.1% of Bacillus Pseudomonas (30 mL)
6.	BPC-02	M25 concrete with 0.2% of Bacillus Pseudomonas (60 mL)
7.	BPC-03	M25 concrete with 0.3% of Bacillus Pseudomonas (90 mL)
8.	BEC-01	M25 concrete with 0.1% of Escherichia Coli (30 mL)
9.	BEC-02	M25 concrete with 0.2% of Escherichia Coli (60 mL)
10.	BEC-03	M25 concrete with 0.3% of Escherichia Coli(90 mL)

Table 2: Mix ID and the description for microbially induced concrete using zeolite.

SL.NO.	MIX-ID	DESCRIPTION
1.	B1Z10	0.1% of Bacillus Subtilis with 10% of Zeolite
2.	B2Z10	0.2% of Bacillus Subtilis with 10% of Zeolite
3.	B3Z10	0.3% of Bacillus Subtilis with 10% of Zeolite
4.	B1Z10	0.1% of Bacillus Subtilis with 10% of Zeolite
5.	B2Z10	0.2% of Bacillus Subtilis with 10% of Zeolite
6.	B3Z10	0.3% of Bacillus Subtilis with 10% of Zeolite
7.	B1Z10	0.1% of Bacillus Subtilis with 10% of Zeolite
8.	B2Z10	0.2% of Bacillus Subtilis with 10% of Zeolite
9.	B3Z10	0.3% of Bacillus Subtilis with 10% of Zeolite

3.1. Fresh concrete properties

According to IS: 1199-1959 requirements, the workability of fresh conventional concrete, bacterial concrete, and bacterial concrete with zeolite was evaluated using the slump test, compaction factor test, and Vee-Bee consistometer test [7]. These examinations gauge the new concrete mixes' workability and consistency. Slump values are displayed in Figure 1. According to IS: 456-2000, the standard drop of concrete is 108 mm; however, when bacteria are introduced, the slump decreases and stays within the range of 90–95 mm, suggesting medium workability and the compaction factor values are displayed in Figure 1.

Conventional concrete has a compaction factor of 0.93. It stays at 0.93 for various Bacillus Subtilis proportions, rises to 0.94 for Bacillus Pseudomonas, and rises even higher to 0.95 for E. Coli. The compaction factor rises to 0.95 and, in certain cases, reaches 0.96 to 0.98 when zeolites are added to Bacillus Subtilis. Values for the compaction factor are shown in Figure 2. It is discovered that typical concrete has a compaction factor value of 0.93. With varying proportions, the value stays the same for Bacillus Subtilis and is determined to be 0.94 for Bacillus Pseudomonas [8]. For E. Coli, the score rises even further to 0.95. The addition of zeolite to Bacillus Subtilis results in a compaction factor value of 0.95, reaching 0.96 for two proportions.

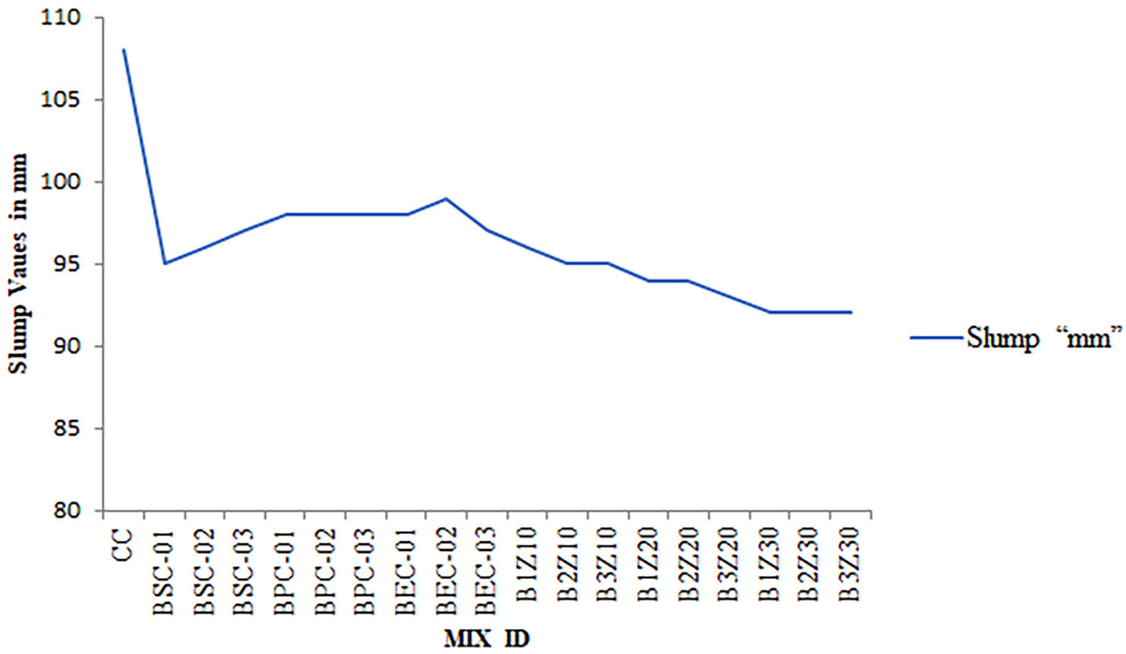

Figure 1: Slump values.

Figure 2: Compaction factor values.

3.2. Tests on bacteria

Escherichia coli (E. coli), Pseudomonas, and Bacillus subtilis were the three species of bacteria whose growth circumstances and performance in concrete were studied. The broth medium for bacterial culture contains glucose as a carbon source, peptone or yeast extract for nitrogen, essential minerals, phosphate buffers to maintain pH, and water for bacterial hydration and nutrient dissolution.

3.2.1. pH variation

By cultivating the bacteria in LB broth medium at different pH levels from 4 to 9 using 1N HCl and NaOH solutions, the ideal pH range for each type of bacteria's development was ascertained [9]. The growth of Bacillus subtilis was highest at pH 8, whereas the growth of E. coli and Pseudomonas was best at pH 7.

3.2.2. Temperature variation

The development of bacteria was investigated at several temperatures, ranging from 4°C to 42°C. In a lab setting, E. Coli develops between 20 and 37°C, Pseudomonas endures between 4 and 42°C, and Bacillus subtilis flourishes at 34°C.

3.3. Mechanical properties

Compressive strength on 15 cm cube specimens in accordance with IS 10086-1982, split tensile strength on cylinders measuring 150 mm in diameter and 300 mm in length, and flexural strength on 100 mm × 100 mm × 500 mm prisms were among the mechanical qualities assessed. Under two-point static loads, the flexural behaviour of reinforced concrete beams of 1500 × 150 × 100 mm was also investigated. To determine the best bacterium and dose for the highest strength, mixes containing 0.1%, 0.2%, and 0.3% of each species of bacteria (Bacillus subtilis, Pseudomonas, and E. coli) were made and examined at 7, 14, 28, 56, and 90 days. The best bacterial concrete mix was chosen in light of the findings. To create additional mixes, 10%, 20%, and 30% zeolite was added to cement in place of some of the cement, using the best bacterial concrete. These zeolite mixtures' compressive force, split tensile, and flexural strengths were compared to those of regular concrete and bacterial concrete without zeolite.

The control, optimal, and bacterial concrete with optimum zeolite % beams underwent flexural testing of reinforced concrete. Crack patterns and load-deflection behaviour were investigated. Abaqus software was utilised for analytical study to validate the experimental results. The study examined the compressive force of several concrete mixtures, such as regular concrete, bacterial concrete containing varied amounts of bacteria (Bacillus subtilis, Bacillus pseudomonas, and Escherichia coli), and bacterial concrete with zeolites added. The data were combined and visually displayed, demonstrating that bacterial concrete mixes outperformed conventional concrete in terms of compressive force. The mix that contained 20% zeolite and Bacillus subtilis (B2Z20) had the highest strength [10]. The consolidated compressive strength of various combinations is revealed in Figure 3.

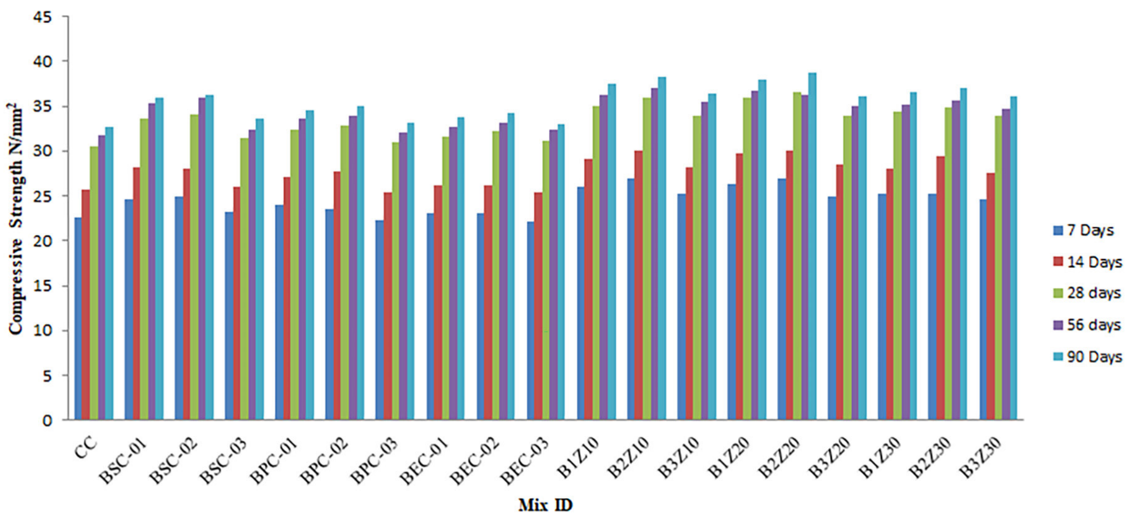

Figure 3: Consolidated Compressive strength of different mixes.

This figure displays the graphical progression of the compressive strength of the M25 grade microbial concrete mix proportions that contain different kinds of bacteria. It has been noted that the strength has increased and that Bacillus subtilis, Bacillus pseudomonas, and Escherichia coli outperform standard concrete. The various concrete mixtures' split tensile strengths were evaluated, and the findings were visually combined. When compared to normal concrete, the bacterial concrete mixes and those with additional zeolites showed higher split tensile strength; the B2Z20 mix performed the best [11]. The consolidated split tensile strength of the various combinations is shown in Figure 4.

The consolidated split tensile strength values of several concrete mixes—conventional concrete, bacterial concrete with varying amounts of bacteria, and bacterial concrete with additional zeolites—at various curing ages are shown in this figure. The flexural strength of the various concrete mixtures was tested in this test, and the combined results were shown visually [12]. When compared to normal concrete, the bacterial concrete mixes and those with additional zeolites showed improved flexural strength; the B2Z20 mix had the highest flexural strength. The combined flexural strength of various prism mixtures is shown in Figure 5.

The consolidated flexural strength values of several concrete mixes conventional concrete, bacterial concrete with varying amounts of bacteria, and bacterial concrete with additional zeolitesat various curing ages are shown in this Figure 5.

3.4. Load vs deflection test

To ascertain their load versus deflection behaviour, beam specimens of both bacterial concrete mixes (BSC-01, BSC-02) and conventional concrete were investigated. In comparison to traditional concrete beams, the bacterial

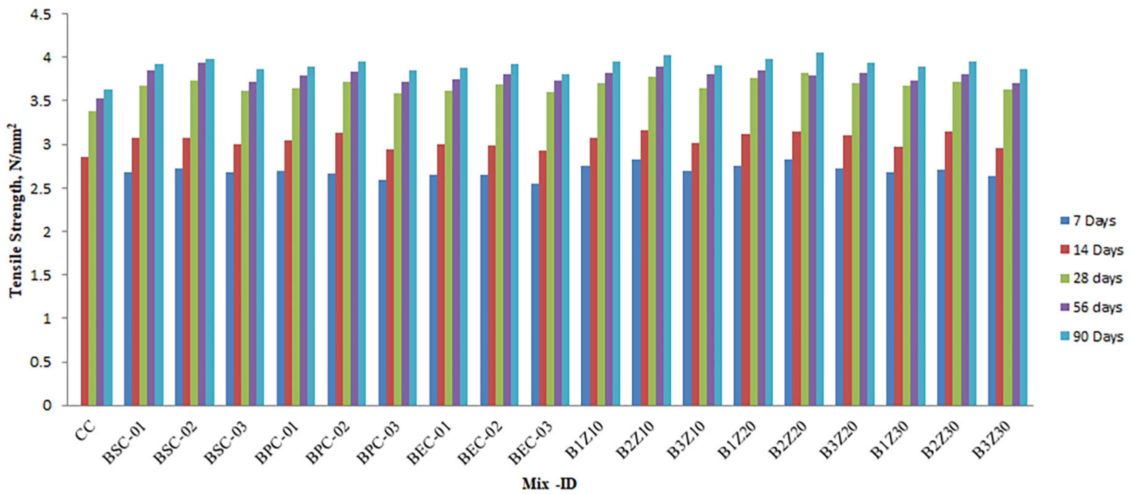

Figure 4: Consolidated Split tensile Strength of different mixes.

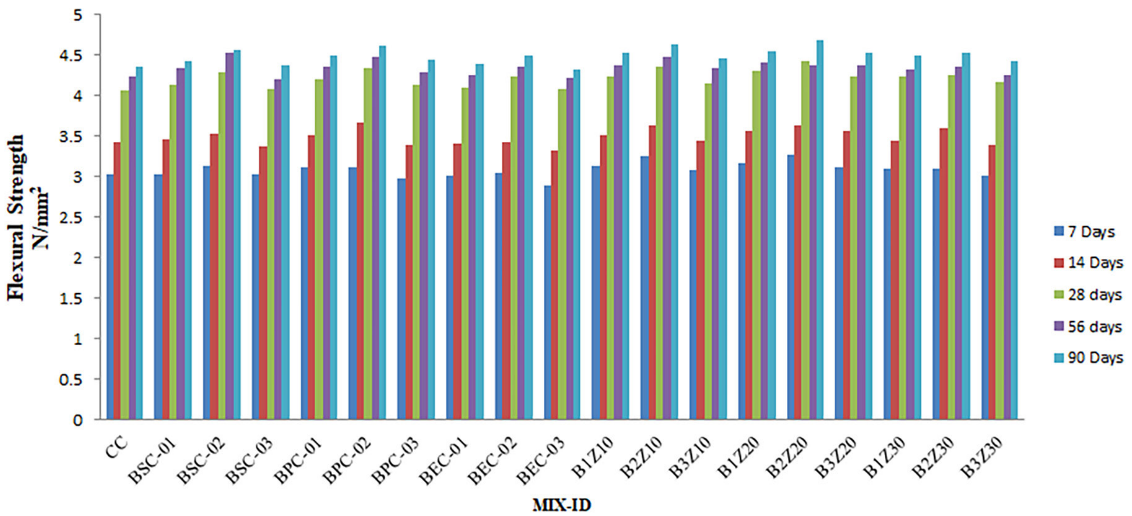

Figure 5: Consolidated Flexural Strength of different mixes of the prism.

concrete beams showed a greater load-bearing capability and a lower deflection rate. The load vs. deflection curve for the CC vs. BSC-01 beam is shown in Figure 6.

The load versus deflection curve for standard concrete beams and BSC-01 (Bacillus Subtilis with 0.1% percentage) beams is shown in this figure. In comparison to ordinary concrete, the BSC-01 beam exhibits a lower deflection rate and an improved load-bearing capability, with an ultimate failure load of 57 kN and a deflection of 9.5 mm, compared to the traditional beam's 48 kN and 8.8 mm deflection [13]. The load vs. bend curve for the CC vs. BSC-02 beam is shown in Figure 7.

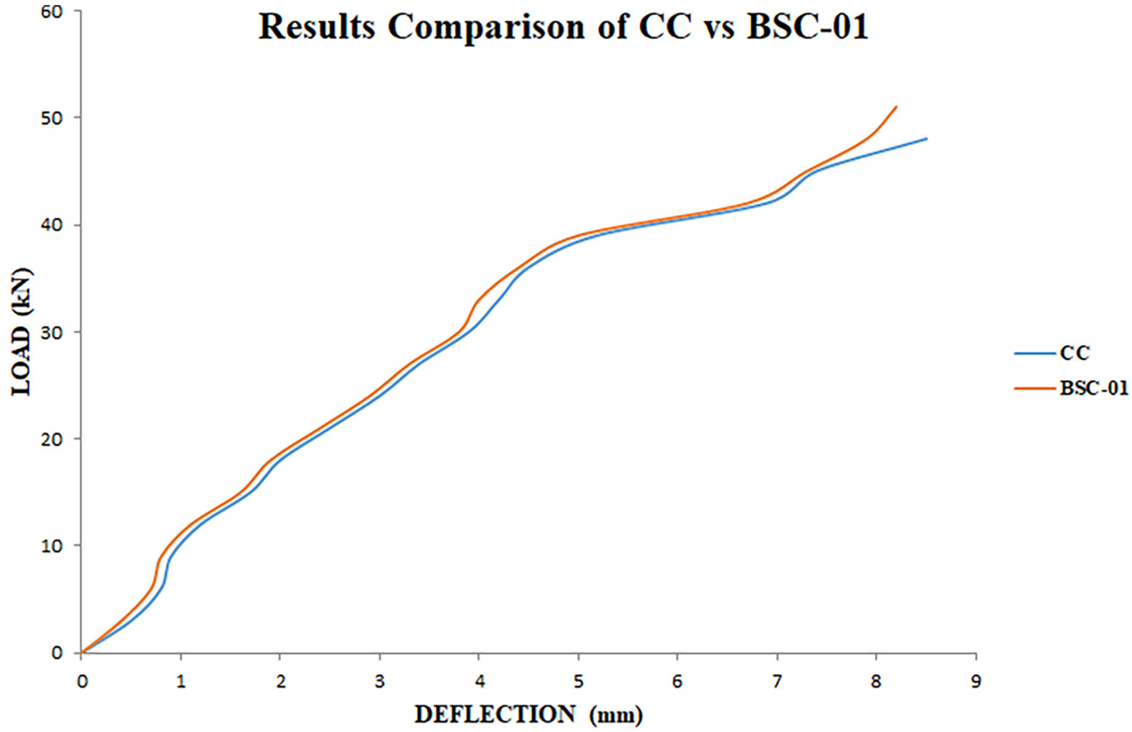

Figure 6: Load vs Deflection curve for CC vs BSC-01 beam.

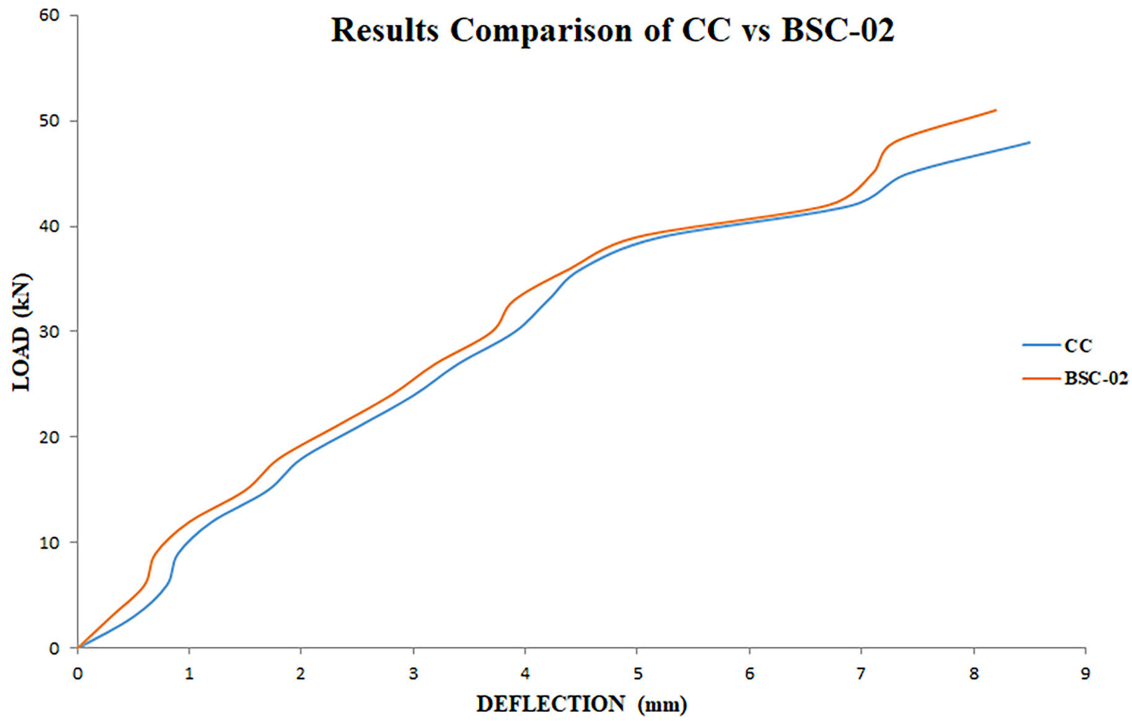

Figure 7: Load vs Deflection curve for CC vs BSC-02 beam.

The load versus deflection curve for standard concrete beams and BSC-02 (Bacillus Subtilis with 0.2% percentage) beams is displayed in this figure. When compared to ordinary concrete, the BSC-02 beam exhibits a lower deflection rate and an improved load-bearing capability, with an ultimate failure force of 60 kN and a bend of 9.4 mm, compared to the traditional beam's 48 kN and 8.8 mm deflection.

3.5. Durability properties

Using a variety of experiments, the durability properties of the best bacterial concrete and bacterial zeolite concrete mixes were thoroughly evaluated [14]. The three concrete mixes' water absorption properties were assessed at different curing ages (28, 56, and 90 days). Reducing water absorption in concrete is beneficial to its durability because it minimizes the risk of internal damage due to freeze-thaw cycles, decreases the likelihood of chemical reactions that can weaken the concrete, and helps prevent the ingress of harmful substances that could degrade its structural integrity [15]. Figure 8's graphic representation of the data demonstrated that the bacterial concrete mixes absorbed less water than regular concrete.

The sorptivity values of the various concrete mixes at various curing ages were evaluated using the sorptivity test. Figure 9 shows the Sorptivity behaviour of the mixtures based on the graphic presentation of the results.

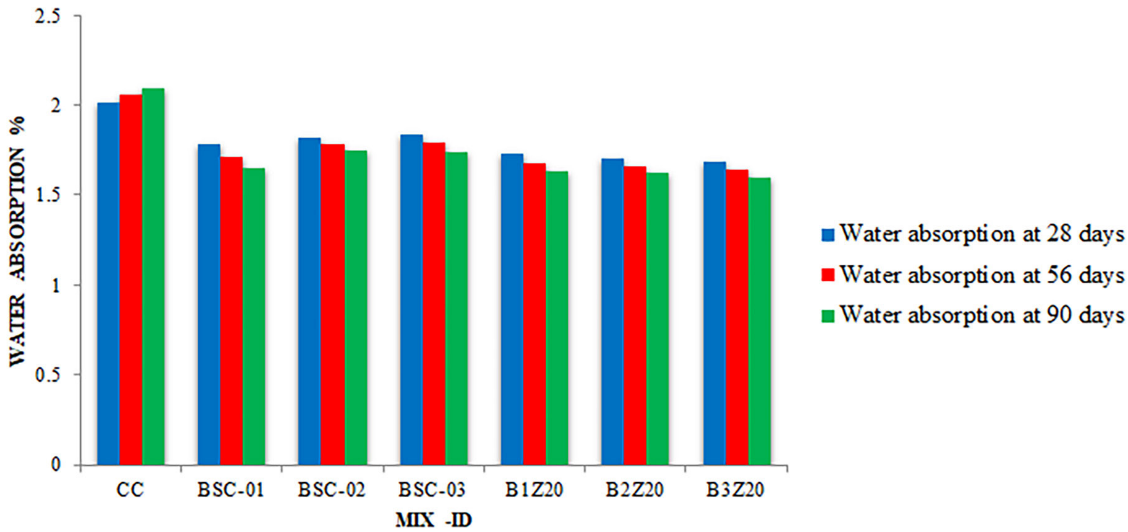

Figure 8: Graphical Representation of Water Absorption.

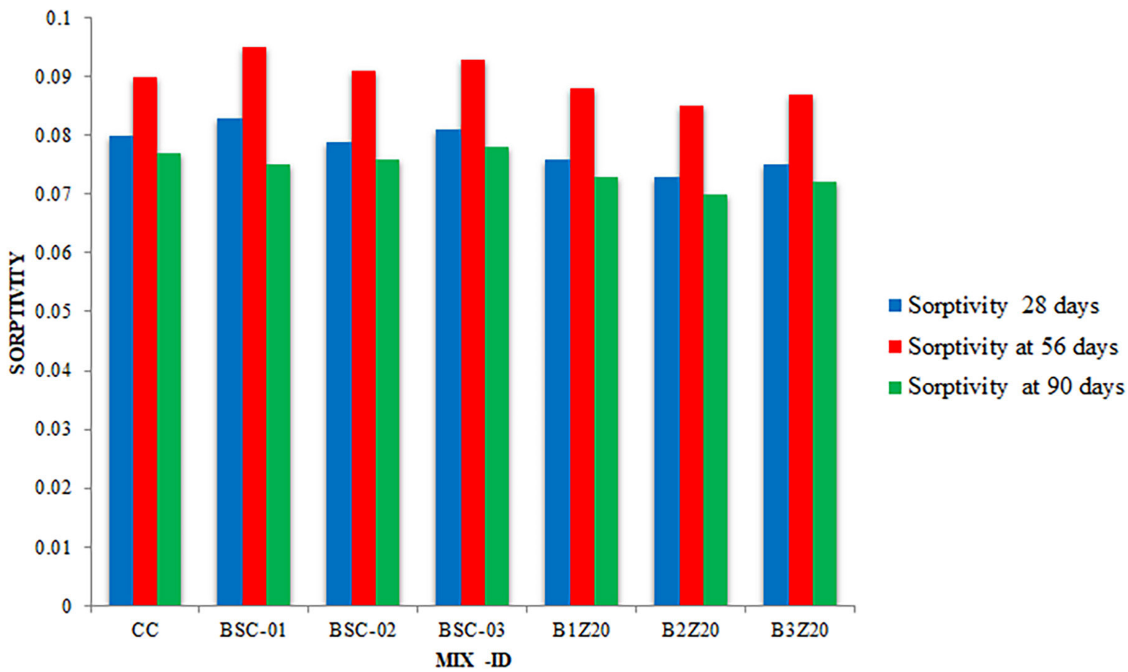

Figure 9: Graphical Representation of Sorptivity.

The findings of the Rapid Chloride Penetration Test (RCPT) on various concrete combinations are shown in Table 3. It shows the charges that are passed through each mix (measured in Coulombs) to show how resistant they are to the entry of chloride ions [16]. The concrete mixes compressive strength was assessed in the Acid Attack test following their exposure to acid attack, and the outcomes were visually displayed. In comparison to normal concrete, the bacterial concrete mixes and those including zeolites demonstrated superior resilience to acid attack.

The proportion of weight loss that various concrete mixes underwent at varying curing ages (28, 56, and 90 days) following a sulphate attack is displayed in Table 4.

This information sheds light on the mixtures' ability to withstand deterioration brought on by sulphate. The graphical depiction of compressive strength following acid assault is highlighted in Figure 10.

The compressive force values of several concrete mixes—conventional concrete, bacterial concrete with varying bacterial fractions, and bacterial concrete with additional zeolites—at various curing ages are displayed in this figure following acid assault [17]. The compressive force values of several concrete blends following

Table 3: Rapid Chloride Penetration Test results.

SL.NO.	MIX-ID	RAPID CHLORIDE ION PENETRATION – CHARGES PASSED (COULOMBS)
1.	CC	2075
2.	BSC-01	368
3.	BSC-02	345
4.	BSC-03	355
5.	B1Z20	340
6.	B2Z20	336
7.	B3Z20	378

Note. At 28 days, the effects of the mixes for quick chloride attack are evaluated.

Table 4: Weight loss after sulphate attack.

SL.NO.	MIX-ID	WEIGHT LOSS (%) 28 DAYS	WEIGHT LOSS (%) at 56 DAYS	WEIGHT LOSS (%) at 90 DAYS
1.	CC	6.2	10.25	12.34
2.	BSC-01	5.8	10.19	12.79
3.	BSC-02	4.9	9.09	10.89
4.	BSC-03	4.3	8.19	10.13
5.	B1Z20	7.9	9.99	13.79
6.	B2Z20	6.3	9.19	12.29
7.	B3Z20	6.2	9.29	11.79

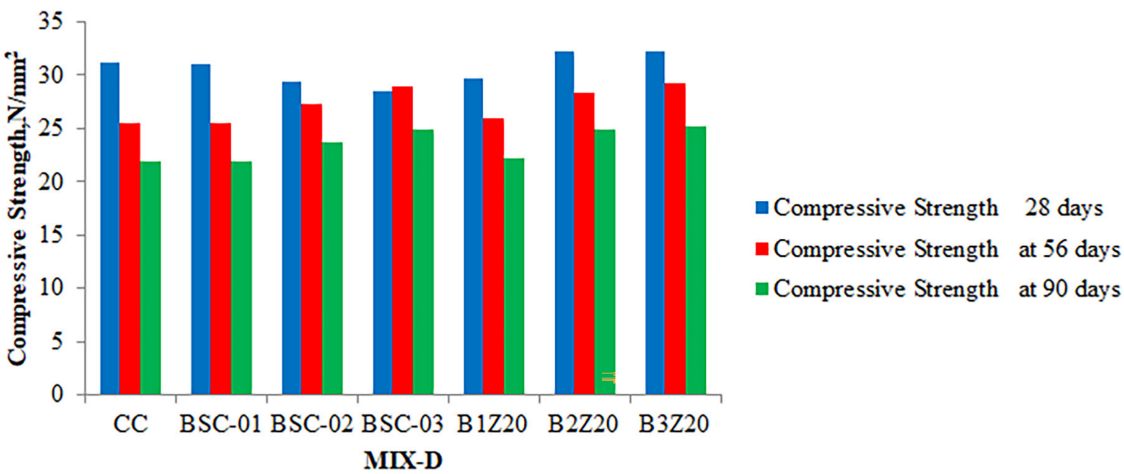

Figure 10: Graphical representation of Compressive Strength after Acid Attack.

exposure to a chloride attack are shown in Table 5. Three distinct curing ages (28, 56, and 90 days) are represented in the compressive strength data, which enables an assessment of the mixes' resistance to chloride-induced degradation over time.

3.6. Microstructural property

The presence of calcite crystals and Bacillus subtilis bacteria, which indicate the microbial healing features of bacterial concrete, was observed using Scanning Electron Microscopy (SEM) research [18]. The SEM picture of the bacterial concrete is shown in Figure 11.

The microbial repair properties of bacterial concrete are demonstrated by the Scanning Electron Microscope (SEM) image of the material in this figure, which shows the development of calcite crystals across the crack's surface and the presence of Bacillus Subtilis bacteria.

3.7. Chemical analysis

To describe the chemical components generated within the bacterial concrete, two sophisticated analytical methods were applied.

3.7.1. Fourier transform infrared spectroscopy (FTIR)

By analysing their distinct infrared absorption spectra, these spectroscopic methods were able to identify the organic and inorganic components—such as calcite (CaCO3) and calcium silicate hydrate (C-A-S-H)—found in the best bacterial concrete compositions [19]. FTIR spectroscopy was used to identify chemical bonds and functional groups in the calcite. Specific peaks in the FTIR spectrum signify the presence of carbonate ions, verifying calcite formation. The FTIR spectra of the CC is shown in Figure 12.

Table 5: Compressive strength after chloride attack.

SL.NO.	MIX-ID	COMPRESSIVE STRENGTH 28 DAYS (N/mm^2)	COMPRESSIVE STRENGTH at 56 DAYS (N/mm^2)	COMPRESSIVE STRENGTH at 90 DAYS (N/mm^2)
1.	CC	27.9	25.73	23.75
2.	BSC-01	29.6	27.66	25.85
3.	BSC-02	30.8	28.91	27.18
4.	BSC-03	28.6	25.93	24.03
5.	B1Z20	31.1	28.57	26.74
6.	B2Z20	31.1	29.11	27.14
7.	B3Z20	27.9	25.73	23.75

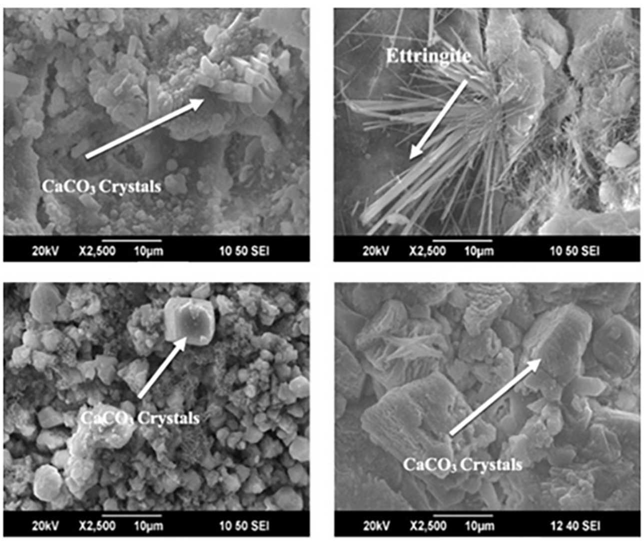

Figure 11: SEM image of Bacterial Concrete.

The presence of different functional groups and chemicals is depicted in the Fourier Transform Infrared Spectroscopy (FTIR) spectrum of typical concrete in this picture. The BSC-02's FTIR spectrum is shown in Figure 13.

The FTIR (Fourier Transform Infrared Spectroscopy) spectrum of the BSC-02 mix, a bacterial concrete containing 0.2% Bacillus subtilis, is shown in this picture. It reveals the presence of several functional groups and chemicals.

3.7.2. UV spectroscopy

Further confirmation of the presence of calcite and other mineral precipitates caused by bacterial metabolic activity within the concrete matrix was provided by the ultraviolet-visible spectrophotometric examination. UV-Vis spectroscopy was used to analyse the shift in absorbance peaks and characterise the development of nanoparticles in both standard concrete and the BSC-02 mix [20]. The absorption spectra provide insights into the specific carbonate species present and quantify the amount of calcite produced during precipitation [21]. The UV spectra obtained for the CC MIX are shown in Figure 14.

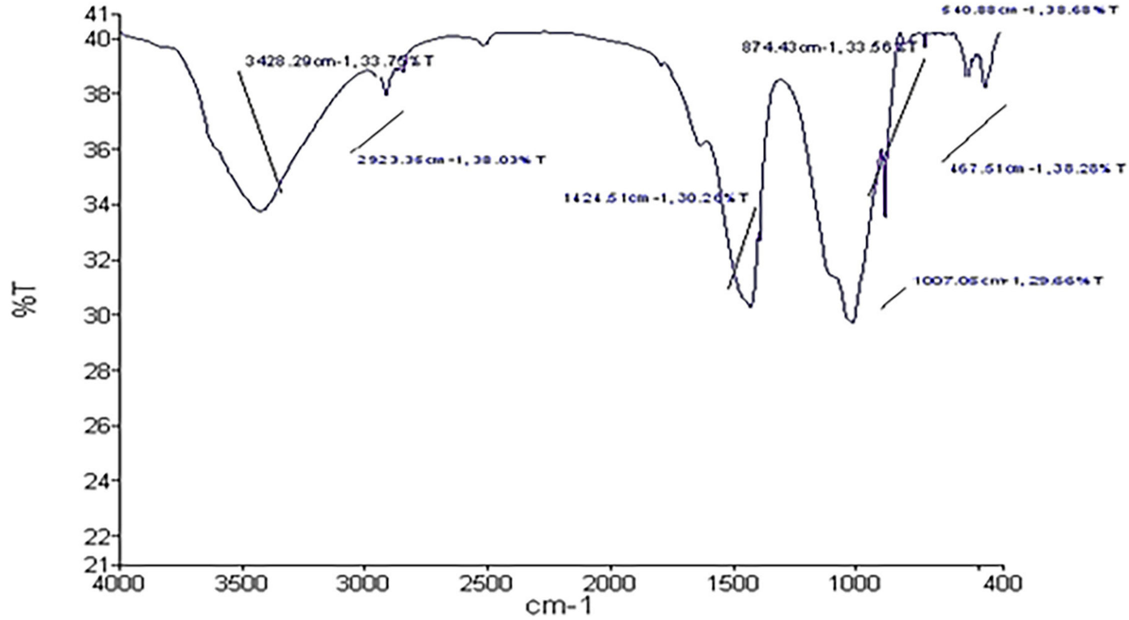

Figure 12: FTIR spectrum of the CC.

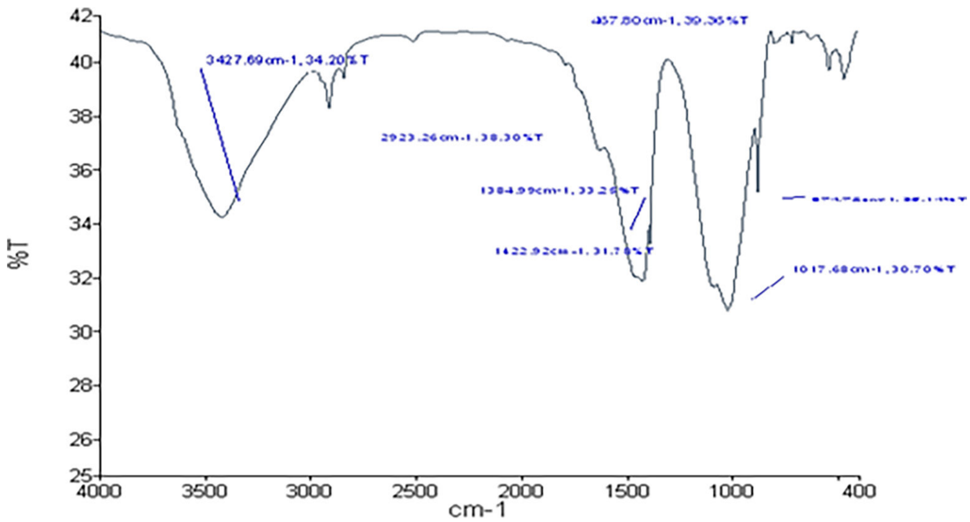

Figure 13: FTIR spectrum of the BSC-02.

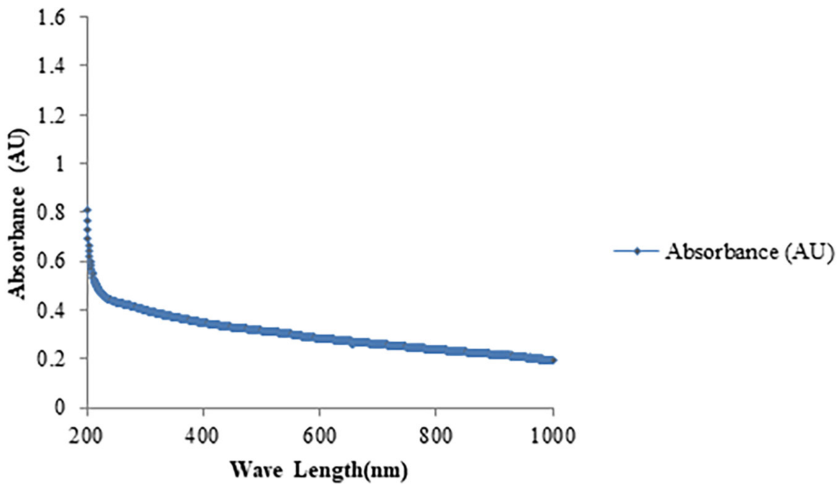

Figure 14: UV spectra obtained for CC MIX.

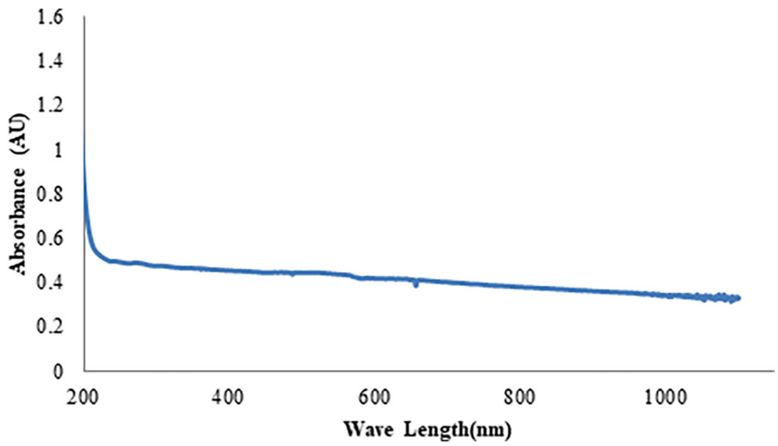

Figure 15: UV spectra obtained for BSC-02 MIX.

The UV-visible spectrum obtained for the conventional concrete mix is depicted in this figure, which reveals that there are no notable peak values in the UV-visible region. The UV spectra acquired for the BSC-02 MIX are shown in Figure 15.

The UV-Visible spectrum for the BSC-02 mix, which is bacterial concrete containing Bacillus subtilis at a 0.2% proportion, is shown in this figure. It shows a particular absorbance peak between 200 and 300 nm that corresponds to the amino group.

3.8. Regression analysis

Regression analysis was used to determine relationships between compressive force and splitting tensile strength as well as compressive force and flexural force for the BSC-02 and B2Z20 mixes. The goodness of fit was evaluated by calculating the correlation coefficients (R2). The relationship between BSC-02's split tensile and compressive strong point is seen in Figure 16. The relationship between the splitting tensile and compressive strengths of the BSC-02 mix, a bacterial concrete containing 0.2% of Bacillus Subtilis, is depicted in this image [22]. The experimental values fit a quartic polynomial expression with a 95.3% correlation, according to the value of $R^2 = 0.95$. The relationship between BSC-02's compressive and flexural forces is shown in Figure 17.

The affiliation between the flexural and compressive force of the BSC-02 mix, a bacterial concrete containing 0.2% Bacillus Subtilis, is shown in this figure. The experimental values fit a quartic polynomial expression with a 98.7% correlation, according to the value of $R^2 = 0.98$.

3.9. Beam deformation analysis

Analysing the deflection and failure patterns under loads, the deformation behaviour of ordinary concrete beams and beams constructed with 0.2% Bacillus bacterium concrete were examined [23]. The conventional beam's distortion is emphasised in Figure 18.

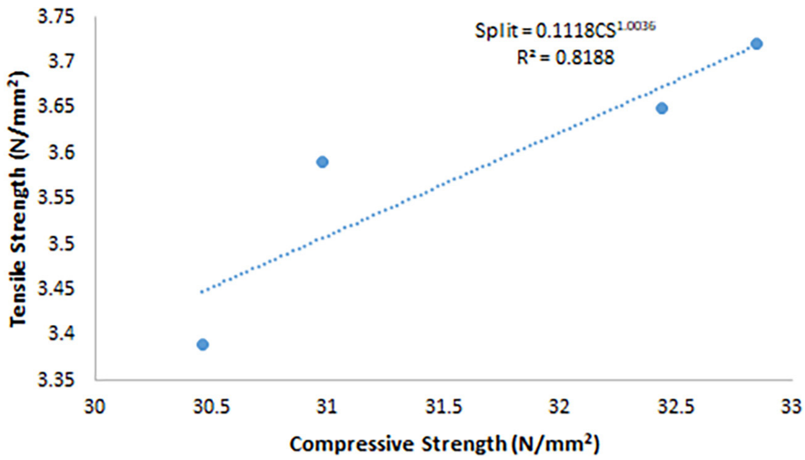

Figure 16: Relationship between the compressive and split tensile strengths of BSC-02.

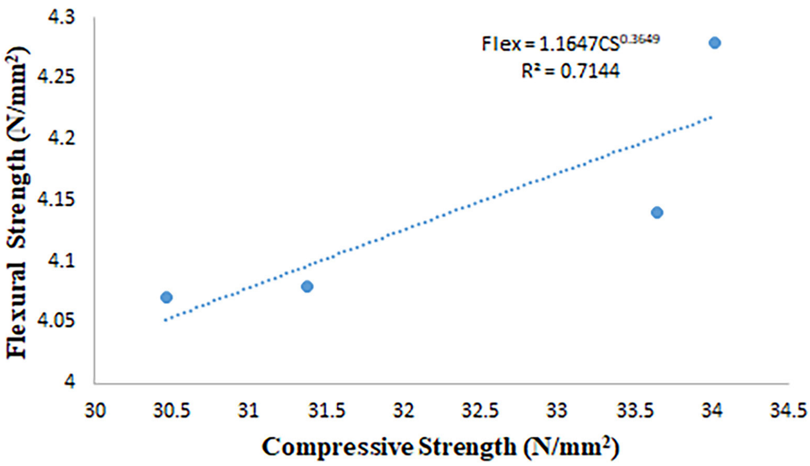

Figure 17: Relationship between compressive vs flexural strength of BSC-02.

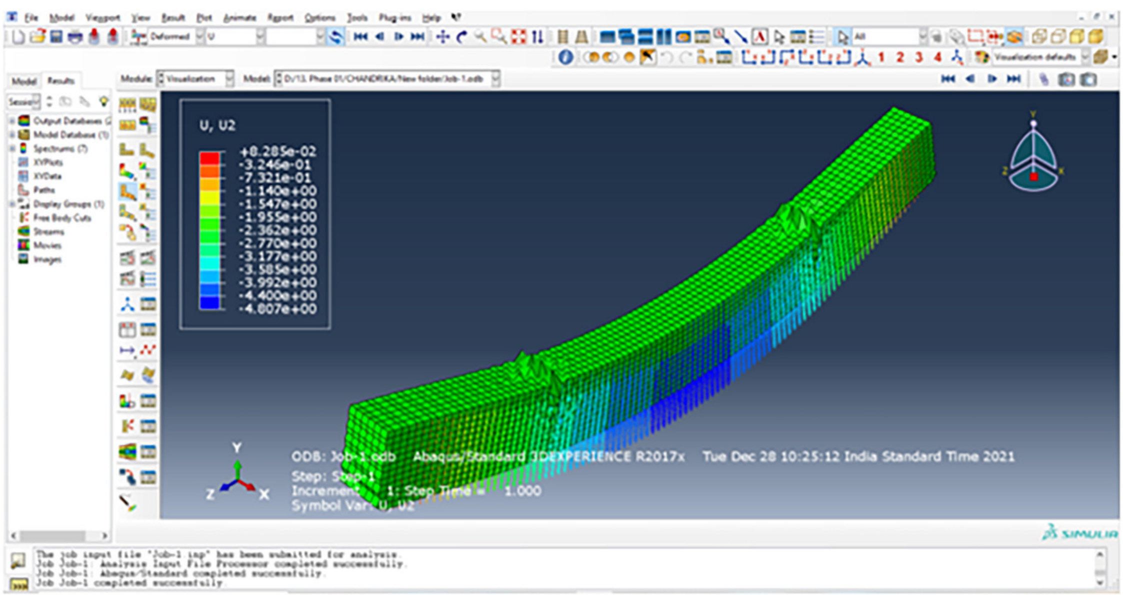

Figure 18: Deformation of the conventional beam.

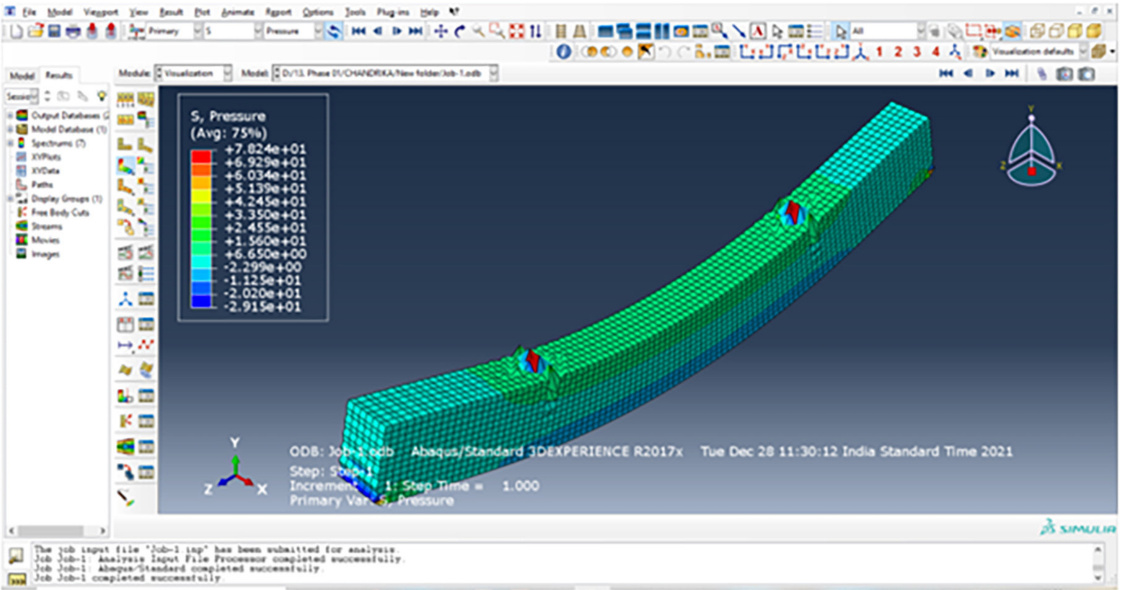

Figure 19: Deformation of the beam with 0.2% of bacillus bacteria.

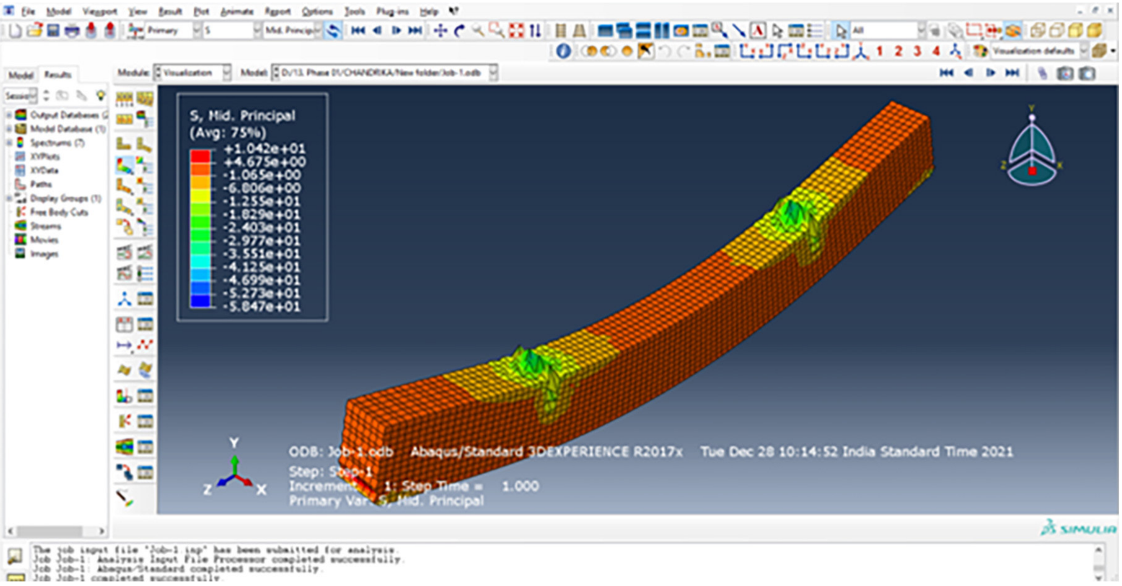

Figure 20: Deformation of the beam with 0.2% of bacillus bacteria with 20% of Zeolite.

The deformation behaviour and failure pattern of a standard concrete beam under load are depicted in this image. The deformation of the beam with 0.2% of Bacillus bacteria is shown in Figure 19.

The deformation behaviour of the beam constructed with 0.2% Bacillus bacteria concrete under loading is shown in T Figure 20, which also shows the failure pattern and deflection.

The Young's Modulus values (in N/mm^2) for various concrete mixtures are shown in Table 6.

The mixes include CC (conventional concrete), BSC-01, BSC-02, and BSC-03 (bacterial concrete containing variable percentages of Bacillus bacteria), and B1Z20, B2Z20, and B3Z20 (bacterial concrete induced with varying concentrations of zeolite).

3.10. Failure load comparison

To assess how accurate the analytical techniques for forecasting the failure behaviour were, the experimental and analytical failure loads of the concrete beams were compared [24]. The comparison of experimental and analytical failure loads is shown in Figure 21.

Table 6: Young's Modulus values.

SL.NO.	MIX-ID	E (N/mm²)
1.	CC	27.595 × 10^3
2.	BSC-01	28.722 × 10^3
3.	BSC-02	28.322 × 10^3
4.	BSC-03	28.140 × 10^3
5.	B1Z20	29.600 × 10^3
6.	B2Z20	29.781 × 10^3
7.	B3Z20	29.327 × 10^3

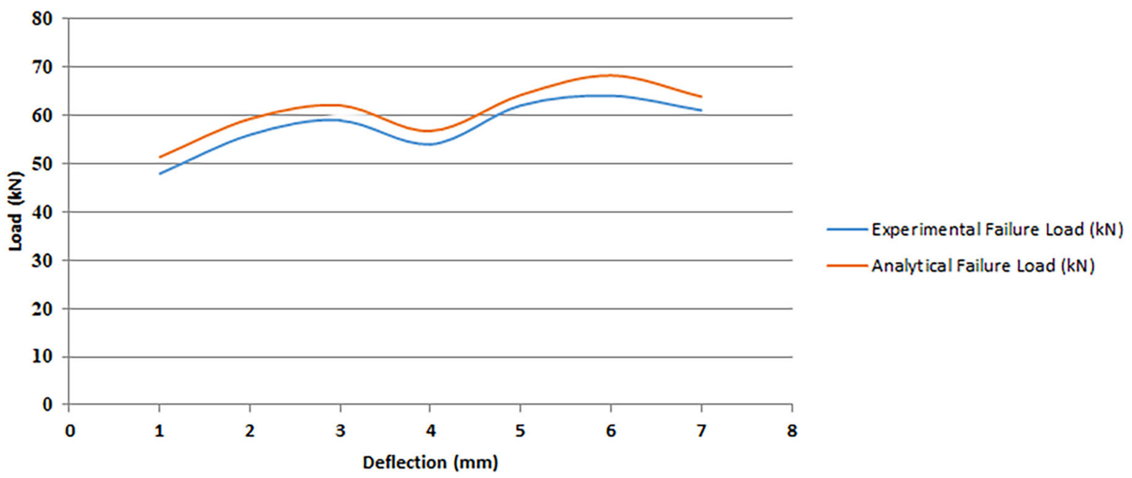

Figure 21: Comparison of Analytical and experimental failure loads.

Table 7: Comparison of Deflections.

SL.NO.	TYPE OF BEAM	EXPERIMENTAL DEFLECTION (mm)	ANALYTICAL DEFLECTION (mm)
1.	CC	12.5	8.285
2.	BSC-01	9.5	9.667
3.	BSC-02	9.4	10.18
4.	BSC-03	9.7	9.321
5.	B1Z20	9.2	8.904
6.	B2Z20	9	9.191
7.	B3Z20	9.3	11.05

This image sheds light on the precision of the analytical techniques used to forecast the failure behaviour by contrasting the experimental and analytical failure loads of the concrete beams [25]. The experimental and analytical deflections (in millimetres) for the identical set of concrete mixes are contrasted in Table 7.

The deflections are listed for the standard concrete (CC) beam, the beams with different proportions of Bacillus bacteria (BSC-01, BSC-02, and BSC-03), and the beams with zeolite-induced bacterial concrete (B1Z20, B2Z20, and B3Z20).

4. CONCLUSIONS

The study showed that adding zeolite and Bacillus bacteria to concrete can greatly improve its durability and mechanical qualities [26]. The addition of bacteria and zeolite increased the concrete's flexural, split tensile, and compressive strengths. The mixture containing 0.2% bacteria and 20% zeolite (B2Z20) showed the greatest strength gains, surpassing normal concrete by up to 20%. The microstructure's densification and pore filling caused by calcite precipitation were credited with the increased strengths.

When compared to ordinary concrete, the bacterial and zeolite concrete mixes also significantly improved the durability traits such water permeability, acid resistance, and chloride ion penetrability. The enhanced performance was attributed to strong silicate/aluminate bonding and the positive impacts of calcite deposition, as proven by SEM and FTIR investigations.

Overall, it was discovered that the best combination for bacterial concrete with M25 grade concrete was B2Z20, which contains 0.2% bacillus and 20% zeolite [27]. This economical, environmentally beneficial method can be used for both new building construction and structure rehabilitation.

5. ACKNOWLEDGMENTS

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