

Performance of Self-Healing Concrete Using Low-Cost Nutrient Alternatives

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Abstract Concrete structures are highly susceptible to microcracks, which compromise durability and service life. Traditional repair methods are costly, labor-intensive, and often environmentally unsustainable. The incorporation of bacteria into concrete has emerged as a promising bio-based solution for autonomous crack healing. In this study, *Bacillus subtilis* was introduced into concrete mixes containing rice husk ash as a partial cement replacement and nutrient source. Rice husk ash, a low-cost agricultural by-product rich in silica, not only enhances pozzolanic activity but also provides a sustainable medium for bacterial growth. The metabolic activity of *Bacillus subtilis* leads to the precipitation of calcium carbonate, which effectively seals microcracks and improves compressive strength. Experimental results confirm that bacterial concrete with rice husk ash exhibits superior self-healing capacity, reduced permeability, and improved mechanical performance compared to conventional mixes. This approach demonstrates that combining industrial by-products with microbial technology can significantly extend the lifespan of concrete structures while reducing environmental impact. The findings highlight the potential of bacterial self-healing concrete as a cost-effective, durable, and eco-friendly material for sustainable infrastructure development.

Keyword: Advanced concrete material, Self-healing concrete, mechanical properties, Rice Husk Ash, *Bacillus Subtilis*.

1. Introduction

Concrete is the backbone of modern infrastructure, widely used in buildings, bridges, and marine structures due to its high compressive strength and versatility. However, its inherent brittleness and susceptibility to microcracks pose serious challenges to long-term durability. Microcracks, though initially small, can propagate under mechanical loading and environmental exposure, leading to increased permeability, corrosion of reinforcement, and eventual structural failure. Conventional repair methods are often costly, time-consuming, and environmentally unsustainable, creating an urgent need for innovative and sustainable solutions.

In recent years, bio-based self-healing concrete has emerged as a promising approach to address these limitations. The concept involves incorporating specific bacterial strains into the concrete matrix, which, upon activation in the presence of moisture and oxygen, precipitate calcium carbonate to autonomously seal cracks. Among the various strains studied, *Bacillus subtilis* has shown remarkable potential due to its ability to survive in the highly alkaline environment of concrete and its efficiency in producing calcite.

To further enhance the sustainability and cost-effectiveness of bacterial concrete, rice husk ash a pozzolanic by-product of agricultural waste is introduced as a partial cement replacement and nutrient source. Rich in silica, rice husk ash improves the microstructure of concrete, reduces cement consumption, and provides a favorable medium for bacterial activity. The synergy between *Bacillus subtilis* and rice husk ash not only improves compressive strength and durability but also contributes to environmentally friendly construction practices by utilizing waste materials.

This study investigates the role of *Bacillus subtilis* and rice husk ash in enhancing the self-healing capacity of concrete. The findings aim to provide practical insights into the development of cost-effective, durable, and sustainable concrete materials, offering a pathway toward greener infrastructure solutions.

2. Literature Review

Victor C. Li (1998) introduced the concept of Engineered Cementitious Composites (ECC), which are designed to exhibit self-healing properties through tight crack control. His research showed that by limiting crack width, natural healing through hydration and carbonation can occur. Although not purely bacterial, his work laid the foundation for modern self-healing concrete by demonstrating that crack control plays a crucial role in enabling healing mechanisms. His findings contributed significantly to the development of durable and sustainable concrete materials.

Sookie S. Bang (2001) conducted early research on the application of microorganisms in concrete for crack remediation. Her study demonstrated that bacteria can be used to precipitate calcium carbonate within cracks, thereby improving the strength and durability of concrete. The research highlighted that microbial techniques are environmentally friendly and can be used as an alternative to conventional repair methods. Her work is considered one of the earliest contributions to the development of bacterial concrete technology.

Willem De Munck (2008) conducted extensive research on microbial-induced calcium carbonate precipitation (MICP) and its application in construction materials. His work mainly focused on the use of bacteria for surface treatment and repair of cracks in concrete. The study revealed that bacterial deposition of calcium carbonate forms a protective layer over the concrete surface, which significantly reduces permeability and prevents the ingress of harmful substances such as chlorides and sulphates. His research also highlighted that bacterial treatment improves resistance to environmental degradation and enhances the durability of concrete structures, especially in aggressive environments.

Henk M. Jonkers (2010) is widely recognized as a pioneer in the field of bacterial self-healing concrete. His research introduced the innovative concept of embedding bacterial spores and nutrients into the concrete matrix. These bacteria remain dormant during the initial stages and become active only when cracks appear, and water enters the concrete. Upon activation, the bacteria convert nutrients into calcium carbonate (CaCO_3), which precipitates and fills the cracks. His study demonstrated that cracks up to a certain width can be effectively sealed, significantly reducing water permeability and enhancing the durability of concrete.

Wiktor and Jonkers (2011) investigated the microstructural behavior and crack-healing efficiency of bacterial concrete incorporating *Bacillus* species. The study utilized advanced microscopic techniques to analyze the internal structure of concrete after bacterial activity. It was observed that bacteria precipitated calcium carbonate crystals within cracks and pore spaces, effectively sealing them and reducing permeability.

Achal Vyas (2011) Achal Vyas conducted extensive research on the long-term performance and durability of bacterial concrete. His studies focused on the incorporation of *Bacillus subtilis* into cementitious materials and its effect on crack repair, water permeability, and resistance to environmental stresses. Vyas observed that bacterial activity not only seals micro-cracks with calcium carbonate but also improves the microstructure of the concrete by filling pores and voids, which enhances mechanical strength and reduces permeability.

Kartini (2011) investigated the use of rice husk ash (RHA) as a supplementary cementitious material in concrete. The study focused on the effect of RHA on the strength and durability properties of concrete. The results showed that the incorporation of rice husk ash improved the compressive strength of concrete due to its pozzolanic reaction with calcium hydroxide formed during cement hydration. The fine particles of RHA also acted as a filler material, filling the micro voids in the concrete matrix and producing a denser structure.

Alghazali et al. (2012) They tested rice husk ash as a nutrient carrier for *Bacillus subtilis* in self-healing concrete. Their experiments showed that bacterial growth was sustained in the alkaline cement environment. Healing efficiency was validated through calcium carbonate precipitation, which sealed cracks effectively. This was one of the earliest agrowaste nutrient studies, highlighting rice husk ash as a viable low-cost option.

De Belie & Wang (2013) They reviewed microbial self-healing concrete systems comprehensively, synthesizing mechanisms, carriers, and nutrient strategies. Their work became a key reference, guiding subsequent research directions in the field. Sustainability was emphasized, with attention to integrating ecofriendly nutrient sources. The review highlighted encapsulation methods and carrier materials to improve bacterial survival.

Tziviloglou et al. (2014) conducted pioneering field trials of bacterial concrete, testing calcium lactate nutrients as a carrier system. Their study demonstrated that microbial healing could be achieved beyond laboratory conditions, validating the concept in realworld applications. Durability was proven in practice, showing that bacterial concrete could withstand environmental exposure. Importantly, the trials highlighted the feasibility of scaling microbial healing for infrastructure projects. The authors emphasized the role of nutrient stability and bacterial survival under fluctuating field conditions.

Seifan et al. (2016) studied the use of microbial induced calcium carbonate precipitation (MICP) in concrete to enhance crack healing and durability. The research focused on the application of *Bacillus subtilis* bacteria in concrete mixtures. The results showed that bacterial activity effectively sealed microcracks and reduced water permeability, leading to improved durability. The study also reported that bacterial concrete exhibited higher resistance to environmental deterioration compared to conventional concrete. The researchers concluded that MICP is a promising, eco-friendly approach for producing self-healing and long-lasting concrete structures.

Lee et al. (2017) investigated the microstructural and durability characteristics of bacterial concrete under aggressive environmental conditions. The study focused on the effect of bacterial-induced calcium carbonate precipitation on the internal structure of concrete. Using advanced analytical techniques, the researchers observed that bacterial concrete exhibited a more uniform and compact microstructure with significantly fewer microcracks compared to conventional concrete. The deposition of calcium carbonate within pores and crack interfaces reduced permeability and enhanced resistance to the ingress of water and harmful ions such as chlorides. This resulted in improved resistance to corrosion and chemical attacks. The study also highlighted that the refined microstructure contributes to better mechanical performance and long-term durability. Overall, the findings demonstrated that bacterial concrete possesses superior microstructural integrity, making it suitable for use in harsh environmental conditions.

Ghosh et al. (2018) studied concrete incorporating rice husk ash (RHA) as a partial replacement for cement to enhance durability and sustainability. The research showed that RHA improved compressive strength, reduced water absorption, and refined the pore structure of the concrete matrix. These effects enhanced the concrete's resistance to chemical attacks, including chlorides and sulfates, and improved long-term durability. The study emphasized that using RHA not only strengthens concrete but also promotes environmentally friendly construction by utilizing agricultural waste and reducing cement consumption.

Joshi et al. (2018) Joshi and colleagues investigated microbial self-healing in concrete with a focus on nutrient carriers and bacterial survival. Their study demonstrated that carefully selected carriers improved the longevity and activity of bacteria within the concrete matrix. This enhancement led to more effective crack healing and better durability of the material. The research highlighted the importance of optimizing bacterial delivery systems for reliable performance. Overall, the findings contributed to advancing sustainable and efficient self-healing concrete technologies.

Qian Chen (2019) focused on the practical application of bacterial self-healing concrete in aggressive and real-world environments, such as marine, coastal, and industrial structures. His research investigated the efficiency of bacterial strains like *Bacillus subtilis* and *Bacillus Sphaericus* in sealing micro-cracks and enhancing the durability of concrete exposed to harsh conditions. Chen demonstrated that bacteria could actively precipitate calcium carbonate when cracks formed and water entered, effectively reducing crack width and preventing the ingress of chlorides, sulfates, and other harmful ions.

Xu and Wang (2019) Xu and Wang investigated microbial self-healing in concrete using low-alkali cementitious materials. Their study emphasized the importance of selecting suitable carriers to improve bacterial survival in harsh concrete environments. By regulating binder pH and setting time, they enhanced the activity of bacterial spores, which promoted effective crack healing. The results demonstrated that material choice plays a critical role in optimizing microbial performance. This research provided valuable insights into designing more durable and sustainable self-healing concrete systems.

Gupta et al. (2020) Gupta proposed incorporating agrowaste nutrients into self-healing concrete. This sustainable method reduces costs while supporting microbial growth for effective crack repair. The study demonstrated strong healing performance, proving that eco-friendly materials can enhance durability. By integrating agricultural by-products, the approach improved practicality and accessibility. It marked a step toward greener and more affordable construction technologies.

Achal & Mukherjee (2021) They optimized nutrient formulations for *Bacillus* species in self-healing concrete, focusing on cost-effective strategies. Their experiments validated healing efficiency through calcium carbonate precipitation, confirming microbial activity in cementitious environments. Sustainability was promoted by replacing expensive chemical nutrients with agrowaste alternatives, making microbial concrete more practical. Importantly, they highlighted the balance between nutrient availability and bacterial survival under alkaline conditions. Their work advanced microbial concrete by integrating environmental responsibility with durability enhancement. It remains influential, serving as a reference point for researchers exploring low-cost, ecofriendly self-healing systems.

Megha Shree et al. (2023) Megha Shree and colleagues applied artificial intelligence to optimize bacterial healing in concrete. AI models predicted the best environmental and material conditions for crack repair. The results showed improved efficiency, accuracy, and consistency in healing outcomes. This integration of smart technology advanced the precision of bio-concrete research. It represented a modern shift toward intelligent, data-driven construction solutions.

Carter (2025) Carter introduced the concept of “living concrete” as an advanced material for future infrastructure. The study emphasized durability and sustainability benefits, highlighting its potential to revolutionize construction. Living concrete was envisioned as a self-sustaining, adaptive material capable of long-term resilience. It showcased innovative applications that extend beyond traditional repair methods. This work represents the next generation of concrete technology, blending biology with engineering.

3. Materials

Concrete is made using basic materials like cement, fine aggregate (sand), coarse aggregate (gravel), and water. Sometimes admixtures are also added to improve properties like strength, durability, and workability.

3.1. OPC 53 Grade Cement:

Cement is the most important ingredient in concrete as it is the main binding material apart from its influence on strength properties. Producing improved microstructure in concrete proves to be one of the main criteria in the selection of cement. Ordinary Portland cement (OPC) of 53 grade conforming to IS 12269-1987 is used as a binder in the entire study.

Table 1. Properties of OPC

Properties	Results
Specific gravity (g)	3.16
Fineness (%)	3.90
Consistency (%)	30
Initial setting time	35
Final setting time	620

3.2. Fine Aggregate

Locally available river sand conforming to IS 383:2016. It was used as fine aggregate. It was obtained from a nearby supplier. its properties are presented in

Table 2.

Table 2. Properties of fine aggregate

Properties	Result
Specific gravity	2.44
Sieve analysis	Zone II
Water absorption (%)	1%

3.3. Coarse Aggregate

Coarse aggregate size 20 mm and 10 mm conforming to IS 383:2016. it was procured from a local quarry supplier. its properties are shown in **Error! Reference source not found..**

Table 3. Key Properties of Coarse Aggregate

Properties	Result
Specific gravity	2.70
Sieve analysis	20
Water absorption (%)	1.0%
Fineness modulus	6.51

3.4. Water

Water is an important element used in cement concrete to perform functions such as hydration, curing, workability, and setting of the concrete.

Table.4. Properties of Water

Property	Requirement
Ph	>6
Chlorides	< 500 mg/L (for RCC)
Sulphates	< 400 mg/L
Ideal w/c ratio	0.4 – 0.6

3.5. Bacteria Dosage This table shows different concentrations of Bacillus Subtilis used in concrete mixes.

Table.5. Dosage of Bacillus Subtilis

MIX ID	BACTERIA CONCENTRATION (CFU/ml)
CC	0
SHC-1	10 ⁸
SHC-2	10 ⁷
SHC-3	10 ⁶
SHC-4	10 ⁵
SHC-5	10 ⁴

4. METHODOLOGY

4.1. Materials

Ordinary Portland Cement (OPC) was used as the primary binder. Rice husk ash (RHA), obtained from controlled burning of rice husks, was used as a partial cement replacement due to its high silica content and pozzolanic activity. Fine aggregates (river sand) and coarse aggregates (crushed stone) were used in accordance with IS standards. Bacillus subtilis bacteria were selected for their ability to survive in alkaline environments, form endospores, and precipitate calcium carbonate. Distilled water was used for mixing to avoid impurities.

4.2. Mix Proportions

Concrete mixes were prepared with varying percentages of rice husk ash (5%, 10%, and 15% replacement of cement by weight). Bacterial suspensions were prepared at predetermined concentrations (10⁶–10⁷ cells/ml) and added to the mixing water. Nutrient alternatives were incorporated into the mixing water at optimized dosages a control mix without bacteria, rice husk ash, or nutrient additives was also prepared for comparison.

4.3. Preparation of Bacterial Culture

Bacillus subtilis culture preparation involved inoculating spores or stock cells into low-cost nutrient media (jaggery solution, whey-based broth, or corn steep liquor). The inoculated medium was incubated at 30–37 °C for 24–48 hours, allowing the bacteria to grow and form colonies or turbidity in liquid broth. Cultures were maintained by periodic sub-culturing in nutrient alternatives or preserved long-term in glycerol stocks. The spore-forming ability of *Bacillus subtilis* ensured survival in harsh concrete environments and enhanced its suitability for bio-concrete applications.

4.4. Casting and Curing

Concrete cubes (150 mm × 150 mm × 150 mm) were cast for compressive strength testing. Cylindrical specimens were prepared for durability studies such as water absorption and permeability. All specimens were demoulded after 24 hours and cured in water for 28 days. For bacterial mixes, curing was carried out in water enriched with low-cost nutrients to sustain bacterial activity.

4.5. Testing Procedures

Compressive Strength: Tested at 28 days using a compression testing machine.

- **Durability Tests:** Water absorption and permeability tests conducted to evaluate resistance against ingress of harmful agents.
- **Microstructural Analysis:** Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) performed to confirm calcium carbonate precipitation and assess microstructure of healed cracks.
- **Crack Healing Observation:** Pre-induced cracks monitored visually and microscopically to evaluate the extent of self-healing.

4.6. Data Analysis

Results from bacterial concrete mixes with low-cost nutrients were compared with control specimens to assess improvements in compressive strength, durability, and crack healing efficiency. The influence of rice husk ash percentage, bacterial concentration, and nutrient type was analyzed to determine the optimal mix design for sustainable, cost-effective self-healing concrete.

This version mirrors your original sample but substitutes *Bacillus subtilis* as the bacterial agent and integrates low-cost nutrient alternatives throughout.

5. Experimental programme

5.1. Mix proportions: Bacterial concrete mixes are prepared by partially replacing cement with rice husk ash (RHA) at 5–15% to enhance durability. Fine and coarse aggregates are used in standard proportions with a water-cement ratio of 0.45. *Bacillus subtilis* is added to the mix water (10⁷ cfu/ml) to induce self-healing through calcium carbonate precipitation. Control concrete (CC) has no RHA or bacteria, while SHC mixes include RHA and bacteria for improved strength and crack healing.

Table 6. Mix Proportions of Concrete

Mix Id	Cement (kg/m ³)	RHA (%)	Fine Aggregates (kg/m ³)	Coarse Aggregates (kg/m ³)	Water (KG/m ³)	Bacteria Dosage (cfu/ml)
CC	400	10	700	1200	180	0
SHC-1	400	10	700	1200	180	10 ⁸
SHC-2	400	10	700	1200	180	10 ⁷
SHC-3	400	10	700	1200	180	10 ⁶
SHC-4	400	10	700	1200	180	10 ⁵
SHC-5	400	10	700	1200	180	10 ⁴

5.2. Slump cone test:

The slump test was used to determine the workability of fresh bacterial concrete mixes according to IS 1199:1959. The concrete was poured into the slump cone in three layers and tamped 25 times each. The cone was lifted vertically, and the slump value was measured.

5.3. Compression Test:

The compressive strength of concrete is one of the most important mechanical properties used to assess its performance. In the current study, compressive strength tests were performed on concrete cubes to compare the performance of bacterial concrete made with *Bacillus sphaericus* and *Bacillus subtilis*.

Concrete cubes measuring 150 mm × 150 mm × 150 mm were used for both bacterial mixes. Three cubes of *Bacillus sphaericus* were prepared and tested. Five cubes of *Bacillus subtilis* were prepared and tested. The specimens were demoulded after 24 hours and cured in water until the testing age (7 and 28 days).

The compressive strength test was conducted using a Compression Testing Machine (CTM) in accordance with IS 516:1959.

Before testing, the machine's bearing surfaces were properly cleaned. The cube specimen was placed in the centre of the machine's loading platform. The load was applied gradually and consistently until the specimen failed. The maximum load on the specimen was recorded.

The compressive strength was calculated using the formula:

$$\text{Compressive Strength} = P/A$$

Where:

P = Maximum load applied (N)

A = Cross-sectional area of cube (mm²)



Fig.1. Experimental setup for compressive strength test

5.4. Flexural strength Test:

Compression testing machine is used to test the flexural strength of concrete on a beam. In accordance with IS 516: 1964, the flexural strength test for beams was conducted. A universal testing machine's loading surfaces held the specimen horizontally, and the load was applied until the beam failed. Strength was computed using the formula after the failure load was recorded.

$$\text{Flexural Strength} = PL/bd^2$$

Where,

F=Flexural strength (N/mm² or MPa)

P = Maximum applied load (N)

L = Span length between supports (mm)

b = Width of the specimen (mm)

d = Depth of the specimen (mm)



Fig.2. Experimental setup for flexural strength test

6. RESULT AND DISCUSSION

The results showed that mixes incorporating *Bacillus subtilis* with low-cost nutrients exhibited higher compressive strength and reduced water absorption compared to control specimens. Microstructural analysis confirmed calcium carbonate precipitation, which contributed to effective crack sealing. The inclusion of rice husk ash further enhanced durability by refining pore structure. Overall, the synergy of bacteria, RHA, and affordable nutrient sources demonstrated a sustainable pathway for self-healing concrete.

Table.7. Description of Mix IDs

Mix ID	Full Form	Rice husk ash	Bacteria
CC	Control Concrete	0%	0
SHC-1	Self-Healing Concrete-1	10%	10 ⁸
SHC-2	Self-Healing Concrete-2	10%	10 ⁷
SHC-3	Self-Healing Concrete-3	10%	10 ⁶
SHC-4	Self-Healing Concrete-4	10%	10 ⁵
SHC-5	Self-Healing Concrete-5	10%	10 ⁴

6.1. Workability

The workability of bacterial concrete incorporating *Bacillus subtilis* was assessed using the slump test as per IS 1199:1959, with rice husk ash employed as a partial cement replacement. The results indicated that the concrete mix exhibited satisfactory workability suitable for conventional construction practices, with slump values corresponding to medium to slightly higher workability compared to control mixes. This improvement is attributed to the uniform dispersion of the bacterial solution within the concrete matrix, which enhanced flowability without compromising mix stability. Overall, the inclusion of *Bacillus subtilis* did not negatively affect the handling characteristics of concrete, confirming its practical applicability in standard construction operations.

Table.8. slump value of specimen on *Bacillus subtilis*

MIX	SLUMP (mm)
CC	53
SHC1	59
SHC2	62
SHC3	65
SHC4	70
SHC5	72

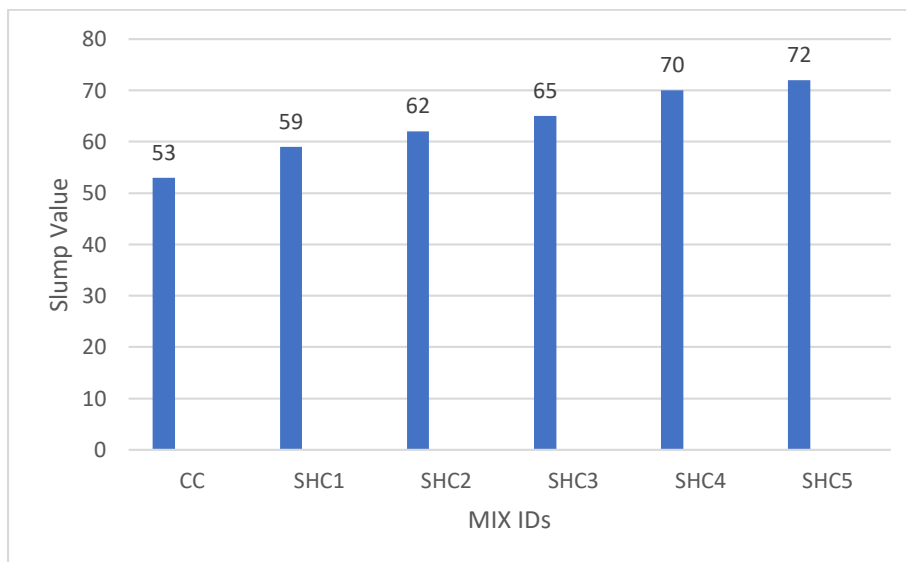


Fig.3. Slump Values for Various Mixes

6.2. COMPRESSIVE STRENGTH

The compressive strength test was conducted on cube specimens (150 mm × 150 mm × 150 mm) of control concrete (CC) and bacterial concrete containing *Bacillus sphaericus* and *Bacillus Sphaericus* after 28 days of curing. The test was carried out using

a Compression Testing Machine (CTM) in accordance with IS 516:1959, and the maximum load at failure was recorded to determine the compressive strength. The results showed that the Bacillus Subtilis concrete exhibited higher compressive strength compared to control concrete due to calcium carbonate precipitation, which enhances the density and reduces the porosity of the concrete matrix.

Table.9. Compressive strength value of specimen

Mixes	Cube strength (MPa)
CC	40
SHC1	41.8
SHC2	40.5
SHC3	42
SHC4	43.2
SHC5	45.2

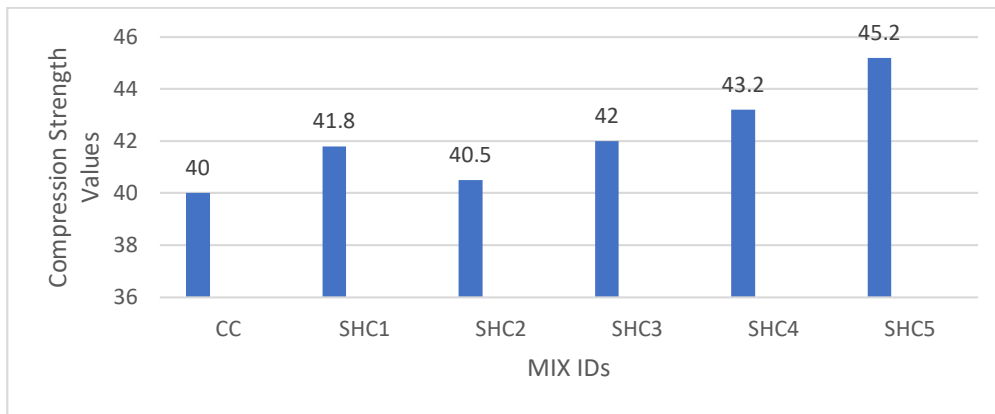


Fig. 4. Compressive Strength test for Various Mixes

6.3. Flexural Strength

The flexural strength test was conducted on beam specimens of control concrete and bacterial concrete containing Bacillus subtilis after 28 days of curing. The test was performed using a Compression Testing Machine (CTM) as per IS 516:1959. The specimens were placed horizontally between the loading plates, and load was applied gradually until failure occurred. The results indicated that both bacterial concrete mixes exhibited higher split tensile strength compared to control concrete. Among the two, the mix containing Bacillus subtilis showed slightly higher tensile strength, due to improved calcium carbonate precipitation which enhances bonding and reduces micro-cracks in the concrete matrix.

Table.10. Flexural strength value of specimen

MIX ID	Flexural Strength (MPa)
CC	5
SHC1	5.7
SHC2	4.8
SHC3	6.2

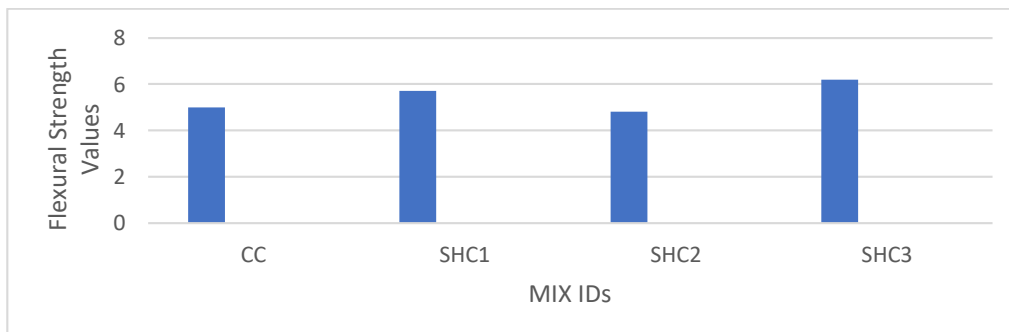


Fig.5. Flexural Strength Test for Various Mixes

6.4. Microstructure Analysis

The microstructural images of bacterial concrete incorporating rice husk ash (RHA) indicate significant modification in the internal morphology compared to conventional concrete. The observed matrix shows a comparatively denser and more compact structure with reduced visible voids and microcracks. The presence of irregular crystalline deposits along pore walls and crack interfaces suggests biologically induced mineral precipitation, primarily calcium carbonate (CaCO_3), generated through bacterial metabolic activity. These precipitates effectively bridge microcracks and fill capillary pores, improving particle bonding within the cementitious matrix.

Additionally, the inclusion of rice husk ash contributes to secondary pozzolanic reactions, leading to the formation of additional calcium silicate hydrate (C–S–H) gel. This reaction refines pore structure and enhances interfacial transition zones between aggregates and paste. The combined action of bacterial biomineralization and RHA pozzolanic activity results in a more homogeneous microstructure with improved packing density. The reduction in pore connectivity observed in the images indicates enhanced durability characteristics, including lower permeability and improved resistance to crack propagation.



Figure.6. Microstructure Analysis

7. Conclusion

This study demonstrates that the incorporation of *Bacillus subtilis* bacteria into concrete mixes, with rice husk ash as a partial cement replacement and nutrient source, provides a sustainable and effective approach to enhance the durability of concrete structures. The bacterial activity promotes calcium carbonate precipitation, which autonomously seals microcracks and improves compressive strength. The use of rice husk ash not only reduces cement consumption but also supports microbial growth, thereby lowering costs and utilizing agricultural waste in an environmentally responsible manner. Workability assessments confirmed that the inclusion of bacteria did not adversely affect handling characteristics, while strength and durability tests highlighted significant improvements compared to conventional mixes. Overall, bacterial self-healing concrete incorporating rice husk ash offers a practical, ecofriendly, and cost-effective solution for extending the service life of concrete structures, contributing to the advancement of sustainable construction practices.

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