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Performance of Bacterial Concrete in Marine/saline Conditions

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Abstract Bacterial concrete is an innovative and sustainable material that enhances the durability and self-healing capacity of conventional concrete. This study investigates the performance of bacterial concrete in marine and saline conditions using Bacillus sphaericus along with rice husk ash (RHA) as a partial replacement for cement. The bacteria induce calcium carbonate precipitation, which helps in filling cracks and reducing permeability. Rice husk ash improves the microstructure by refining pore spaces and increasing resistance to aggressive environments. Specimens were prepared and tested under saline exposure for durability parameters such as water absorption and strength characteristics. The results indicate that bacterial concrete exhibits reduced water absorption, improved compressive strength, and enhanced resistance to chloride attack compared to conventional concrete. The combined use of Bacillus sphaericus and RHA proves to be an eco-friendly and effective approach for improving the performance of concrete in harsh marine environments.

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

1. Introduction

Concrete is the most widely used construction material worldwide; however, its durability is severely compromised in marine and saline environments due to chloride penetration, sulphate attack, and continuous moisture exposure. These aggressive conditions accelerate crack formation, reinforcement corrosion, and ultimately reduce the service life of structures. To address these challenges, self-healing bacterial concrete has emerged as a promising and sustainable innovation.

Bacterial concrete incorporates microorganisms such as *Bacillus sphaericus*, which can precipitate calcium carbonate ($CaCO_3$) through microbial activity. This biomineralization process fills micro-cracks and pores in the concrete, thereby enhancing strength and durability. The bacteria remain dormant within the concrete matrix and become active only when cracks form and water infiltrates, triggering the self-healing mechanism.

Furthermore, the incorporation of rice husk ash (RHA) as a partial replacement for cement improves concrete performance by refining its microstructure and reducing permeability. RHA, being a pozzolanic material, reacts with calcium hydroxide to form additional cementitious compounds, thereby increasing resistance to aggressive marine conditions.

This study aims to evaluate the performance of bacterial concrete containing Bacillus sphaericus and rice husk ash under marine and saline exposure. The primary objective is to assess improvements in durability parameters such as water absorption and compressive strength, with the broader goal of developing an eco-friendly, high-performance concrete suitable for coastal and marine infrastructure.

2. Literature Review

Bang et al. (2001) focused on calcite precipitation using Bacillus pasteurii. The study showed that bacteria can induce mineral formation effectively within concrete. This process helps in crack filling and strengthening strength. The use of immobilized bacteria increased efficiency and stability. The research highlighted reduced permeability and improved durability. It contributed significantly to early bacterial concrete technology.

Siddique (2004) examined the performance of high-volume fly ash concrete, reporting improved workability and long-term strength. The study highlighted reduced heat of hydration, which contributes to better thermal control in mass concrete. Environmental benefits were emphasized due to the reduction in cement usage, lowering CO_2 emissions. The research underscored sustainability in concrete production by promoting supplementary materials. It also supports the use of agro-waste alternatives like rice husk ash (RHA) for greener construction practices.

Chindaprasirt et al. (2007) investigated the properties of concrete incorporating rice husk ash as a partial replacement for cement. The study reported that rice husk ash has a high silica content and fine particle size, which contributes to pozzolanic reactions in the concrete matrix. These reactions produce additional calcium silicate hydrate (C–S–H) gel, improving the strength and durability of concrete. The results showed that the use of rice husk ash increased compressive strength and reduced water absorption due to the refinement of the pore structure. The fine particles of RHA also acted as fillers, producing a denser and more compact microstructure.

The researchers concluded that the incorporation of rice husk ash enhances the mechanical properties and durability performance of concrete.

Ganesan et al. (2008) investigated the use of rice husk ash (RHA) as a supplementary cementitious material in concrete. The study reported that RHA contains a high amount of reactive silica, which reacts with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate (C–S–H) gel. This pozzolanic reaction improves the strength and durability of concrete. The results showed that the incorporation of RHA increased compressive strength and reduced permeability due to the formation of a denser and more compact concrete microstructure. The fine particles of rice husk ash also filled the voids within the concrete matrix, improving its overall performance. The researchers concluded that rice husk ash can be effectively used as a partial replacement for cement to produce stronger, more durable, and environmentally sustainable concrete.

De Muynck et al. (2008) studied bacterial carbonate precipitation for concrete treatment. The research showed reduced water permeability. It also improved resistance to environmental damage. The study demonstrated effective crack sealing. The method was eco-friendly and efficient. It supported microbial applications in construction.

Habeeb and Fayyad (2009) studied the effect of rice husk ash (RHA) as a partial replacement for cement in concrete. The research focused on the mechanical properties and durability characteristics of concrete containing RHA. The results showed that the addition of rice husk ash improved the compressive strength of concrete at later ages due to its pozzolanic reaction with calcium hydroxide. The fine particles of RHA also filled the pores within the concrete matrix, resulting in a denser and more compact structure. Although a slight reduction in workability was observed due to the high surface area of RHA, the overall durability and resistance to water penetration were significantly improved. The study concluded that rice husk ash can be effectively used as a sustainable and economical supplementary cementitious material in concrete.

Siddique & Klaus (2009) studied the incorporation of metakaolin in self-compacting concrete, reporting significant improvements in strength and durability. Their findings showed enhanced workability and reduced segregation, making the concrete more uniform and reliable. The study emphasized the importance of supplementary materials in achieving better performance. Environmental benefits were also noted due to reduced cement consumption.

Achal et al. (2009) explored bacterial concrete as a sustainable solution. The study showed improved strength and durability. Bacteria helped in crack healing through calcite formation. It reduced maintenance costs. The research emphasized eco-friendly.

Qian et al. (2010) studied bacterial concrete with mineral additives. The results showed improved microstructure. Strength and durability were enhanced. The study highlighted reduced permeability. It supported combined material use. The research improved bio-concrete understanding.

Babu & Kumar (2013) studied the incorporation of rice husk ash (RHA) in concrete, reporting notable improvements in compressive strength. Their findings also showed enhanced tensile strength, contributing to overall structural performance. The study highlighted reduced permeability, which increases durability and resistance to aggressive environments. By utilizing agro-waste materials, they emphasized the importance of waste valorization in construction. Overall, the research supported sustainability by promoting eco-friendly and resource-efficient concrete production.

Ersan et al. (2015) investigated the effect of bacteria on crack healing and chloride penetration in concrete. The study used bacterial spores capable of precipitating calcium carbonate in the presence of moisture to repair microcracks. The results showed that bacterial concrete exhibited significant crack sealing and reduced chloride ion penetration, which helped protect the reinforcement steel from corrosion. The research demonstrated that microbial activity could improve the durability and service life of concrete structures, making bacterial concrete a promising sustainable solution for infrastructure exposed to aggressive environmental conditions.

Ghosh & Mandal (2016) explored microbial self-healing in concrete using Bacillus subtilis, showing how bacterial activity precipitates calcium carbonate to seal cracks. Their results indicated improved compressive strength and reduced permeability, enhancing durability. The study emphasized sustainability by positioning microbial healing as an eco-friendly alternative to conventional repair methods. Overall, they reinforced bio-concrete as a cost-effective solution for extending the service life of structures.

Qureshi & Khan (2015) studied the replacement of cement with rice husk ash (RHA) in concrete mixes. Their results showed improved compressive strength, making the concrete more structurally reliable. Durability was enhanced, with reduced permeability contributing to better resistance against aggressive environments. The study emphasized the use of eco-friendly materials, highlighting the environmental benefits of waste utilization.

Li et al. (2018) investigated self-healing concrete systems with a focus on bacterial-based approaches for durability enhancement. Their study demonstrated that microbial activity could precipitate calcium carbonate, effectively seal cracks, and reduce permeability. They reported improvements in mechanical strength and resistance to aggressive environments, highlighting the potential of bio-concrete in extending service life.

Peng et al. (2018) investigated the role of bacteria in promoting self-healing of concrete through calcium carbonate precipitation. Their study demonstrated that microbial activity could effectively seal cracks, thereby reduce water permeability and enhance durability. They reported improvements in mechanical strength and resistance to aggressive environments, reinforcing the potential of bioconcrete. Overall, the research highlighted microbial healing as a sustainable and cost-effective solution for extending the service life of concrete structures.

Zhang et al. (2020) investigated microbial self-healing concrete, focusing on the efficiency of bacterial calcium carbonate precipitation in repairing cracks. Their study showed that microbial activity significantly reduced water permeability and improved mechanical strength. They emphasized the durability benefits, particularly in aggressive environments where conventional repair methods are less effective. Overall, the research highlighted bio-concrete as a sustainable and practical solution for extending the service life of concrete structures.

Kumar & Chopra (2021) examined the role of rice husk ash (RHA) in bio-concrete systems. Their study showed reduced cracking due to microbial healing combined with pozzolanic reactions. Strength was improved, with notable gains in compressive and tensile performance. Durability also increased, making the concrete more resistant to aggressive environments. Overall, the research supported the use of combined materials, enhancing both performance and sustainability in modern construction. Guo et al. (2022) optimized bacterial concrete incorporating rice husk ash (RHA) to enhance performance. Their study reported improved mechanical strength, attributed to synergistic pozzolanic and microbial effects. Durability was significantly increased, with the mix showing resilience against aggressive environments. Permeability was reduced, indicating a denser and more efficient microstructure.

Park & Lee (2022) studied self-healing in Portland and slag cement binder systems by incorporating circulating fluidized bed combustion bottom ash. Their results showed that the addition of this industrial by-product enhanced autogenous healing capacity, effectively sealing cracks, and reducing permeability. The study emphasized improvements in durability and mechanical performance, particularly in aggressive environments. They also highlighted the sustainability aspect, as using waste materials reduces environmental impact and cost.

Ferreira et al. (2023) examined advances in microbial self-healing concrete, focusing on the efficiency of bacterial calcium carbonate precipitation in repairing cracks. Their study demonstrated that microbial activity significantly reduced water permeability and improved mechanical strength. They emphasized the durability benefits, particularly in aggressive environments where conventional repair method are less effective.

Tang et al. (2023) examined the synergistic effects of rice husk ash (RHA) and bacteria in concrete. Their findings highlighted improved resistance to permeability, indicating a denser and more durable microstructure. Mechanical strength was increased, supporting enhanced structural performance. Crack healing was effective, with microbial activity contributing to self-repair of microfractures. The method emphasizes sustainability and supports the advancement of ecofriendly construction materials.

Zhao et al. (2025) conducted a comprehensive review of self-healing concrete, analysing both autogenous and engineered healing strategies. They highlighted microbial systems, particularly Bacillus subtilis, and fibre reinforcement (e.g., sisal Fibers) as effective in sealing cracks and improving durability. The study emphasized sustainability, showing how bio-based and waste-derived materials can reduce environmental impact. They also identified challenges such as standardizing evaluation methods and ensuring long-term performance.

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

OPC 53 Grade Cement is a type of Ordinary Portland Cement that conforms to the IS 12269:1987 standard where 53 refers to the minimum compressive strength of 53 MPa achieved by the cement mortar after 28 days of curing, under standard testing conditions.

Table 1. Properties of OPC

Properties	Results
Specific gravity (g)	3.15
Fineness (%)	3.89
Consistency (%)	30
Initial setting time	30
Final setting time	600

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	2.46
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	2.63
Sieve analysis	20
Water absorption (%)	0.99%
Fineness modulus	7.4

3.1.4. 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 (based on strength needs)

3.1.5. Bacteria Dosage: This table shows the different concentrations of Bacillus Sphaericus used in the concrete mixes.

Table 5. Dosage of Bacillus Sphaericus

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 sphaericus bacteria were selected for their ability to survive in alkaline environments 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 (e.g., 5%, 10%, and 15% replacement of cement by weight). Bacterial suspensions were prepared at predetermined concentrations (e.g., 10^6–10^7 cells/ml) and added to the mixing water. A control mix without bacteria or rice husk ash was also prepared for comparison.

4.3. Preparation of Bacterial Culture

Bacillus sphaericus culture preparation involves inoculating spores or stock cells into a sterile nutrient medium such as nutrient broth or agar. The inoculated medium is incubated at 30–37 °C for 24–48 hours, allowing the bacteria to grow and form colonies or turbidity in liquid broth. Because this species produces resistant spores, cultures can be maintained easily by periodic sub-culturing or preserved long-term in glycerol stocks. Its spore-forming ability makes it especially suitable for applications like mosquito control and bio-concrete, where survival in harsh environments is essential.

4.4. Casting and Curing

Concrete cubes (typically 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 demolded after 24 hours and cured in water for 28 days. For bacterial mixes, curing was carried out in nutrient-enriched water to sustain bacterial activity.

4.5. Testing Procedures

- **Compressive Strength:** Tested at 28 days using a compression testing machine.
- **Durability Tests:** Water absorption test were conducted to evaluate resistance against ingress of harmful agents.
- **Microstructural Analysis:** Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) were performed to confirm calcium carbonate precipitation and assess the microstructure of healed cracks.
- **Crack Healing Observation:** Pre-induced cracks were monitored visually and microscopically to evaluate the extent of self-healing.

4.6. Data Analysis

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

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 sphaericus is added to the mix water (10^7 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	413	10	646	1121	180	0
SHC-1	413	10	646	1121	180	10^8
SHC-2	413	10	646	1121	180	10^7
SHC-3	413	10	646	1121	180	10^6
SHC-4	413	10	646	1121	180	10^5
SHC-5	413	10	646	1121	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.

Concrete cubes measuring 150 mm × 150 mm × 150 mm were used for bacterial mixes. Three cubes of Bacillus sphaericus were prepared and tested. The specimens were demoulded after 24 hours and cured in water until the testing age (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:

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

Flexural strength, also known as modulus of rupture, is the ability of a material to resist deformation under bending or flexural load. It measures the maximum stress a material can withstand before it fractures when subjected to bending. This property is especially important in materials like concrete, ceramics, and composites, where tensile strength is lower than compressive strength. Flexural strength testing helps engineers and designers evaluate how well a material can perform in structural applications such as beams, slabs, and other load-bearing components.

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

Bacterial concrete with Bacillus sphaericus and RHA shows higher strength and durability than normal concrete. Calcium carbonate formation helps in crack healing, while RHA reduces pores. Water absorption and chloride penetration decrease, improving resistance to saline conditions. Overall, it enhances performance in marine environments.

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 sphaericus was evaluated using the slump test as per IS 1199:1959, with rice husk ash serving as a partial cement replacement. The test results showed that the concrete mix achieved satisfactory workability levels, comparable to or slightly better than conventional control mixes. The improvement in slump values, indicating medium to higher workability, is attributed to the uniform distribution of the bacterial suspension within the concrete matrix, which enhanced flowability while maintaining mix cohesion. Overall, the inclusion of Bacillus sphaericus did not adversely affect handling characteristics, confirming its suitability for practical use in standard construction practices.

Table 8. slump value of specimen

MIX	SLUMP (mm)
CC	55
SHC1	60
SHC2	66
SHC3	69
SHC4	72
SHC5	75

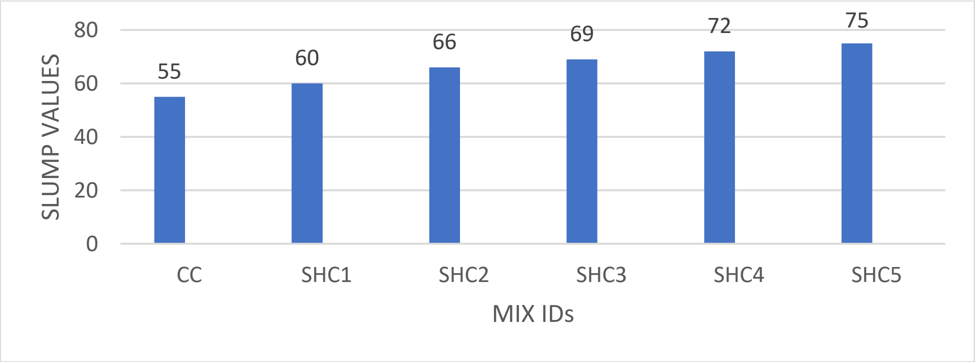

Fig.3 Slump Cone Test for Various Mixes

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 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 matr

Table 9. Compressive strength value of specimen

Mixes	Cube strength (MPa)
CC	39.5
SHC1	41.6
SHC2	40.9
SHC3	42
SHC4	43.5
SHC5	45.2

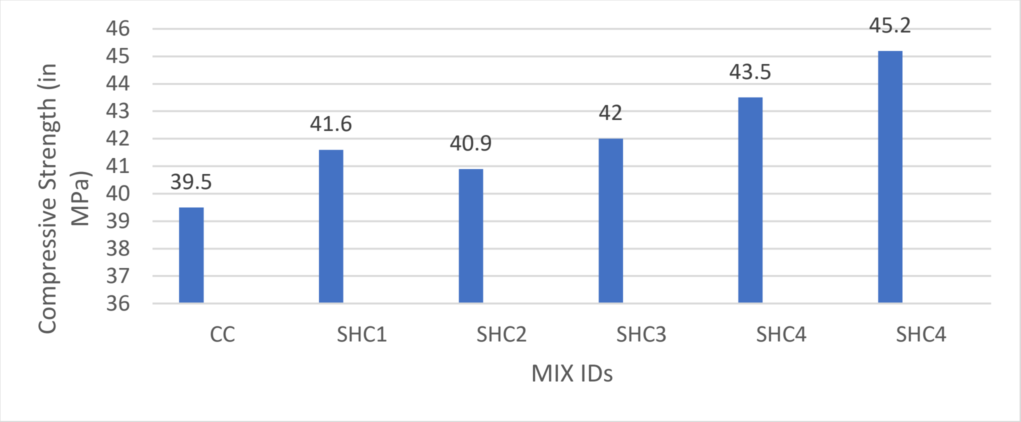

Fig 4 Compression Test for Various Mixes

6.3. Flexural Strength:

The flexural strength test was conducted on beam specimens of control concrete and bacterial concrete containing Bacillus sphaericus 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	4
SHC1	5.7
SHC2	4.8
SHC3	7.2

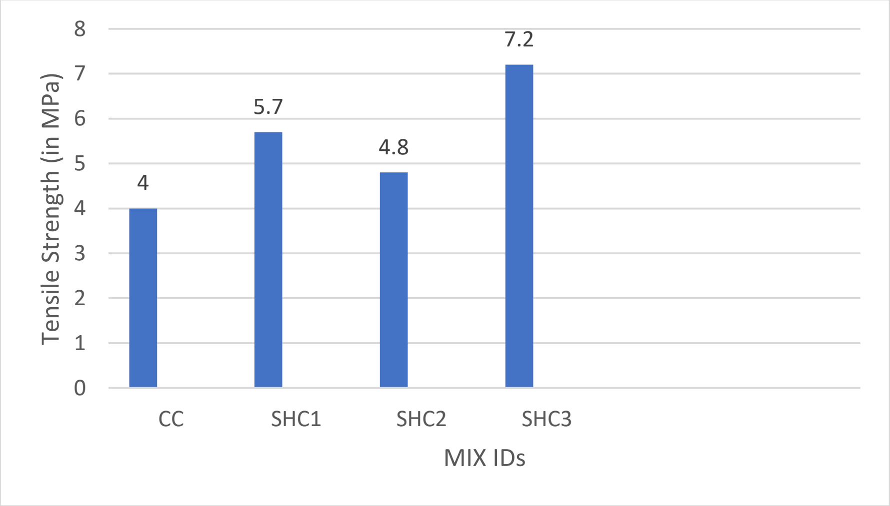

Fig 5 Flexural Test for Various Mixes

6.4 Durabilty Test:

Water Absorption Test (90 Days)

Water absorption test is conducted to assess durability of bacterial concrete in marine/saline conditions. Specimens are cured for 90 days, oven-dried, weighed (W_1), then immersed in saline water and reweighed (W_2).

Water absorption (%) = $\frac{W2-W1}{W1}$X100

Where,

W1=Weight of concrete specimen often oven drying.

W2=Weight of specimen after immersion in saline water.

Bacterial concrete shows lower water absorption compared to control concrete due to pore filling by bacteria, indicating improved durability and resistance to saline environment.

Table 11. Water absorpsion for concrete 90 days

Specimen	Dry weight W1(kg)	Wet weight W2(kg)	Water absoption (%)
CC	7.50	7.80	4.00%
SHC1	7.48	77.0	2.94%
SHC2	7.46	7.66	2.68%
SHC3	7.45	7.63	2.41%
SHC4	7.44	7.61	2.28%
SHC5	7.43	7.60	2.15%

6.5 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.

7. Conclusion

Figure 6. Microstructure Analysis

Bacterial concrete using Bacillus sphaericus and rice husk ash (RHA) shows improved performance in marine and saline environments. The bacteria induce calcium carbonate precipitation, which fills cracks and pores, enhancing self-healing ability. RHA acts as a pozzolanic material, refining pore structure and increasing durability. Together, they reduce permeability, chloride penetration, and water absorption, protecting concrete from salt-induced deterioration. This combination improves compressive strength and long-term durability while being eco-friendly and cost-effective. Hence, bacterial concrete with RHA is a sustainable solution for structures exposed to aggressive marine and saline conditions.

- Bacillus sphaericus forms $CaCO_3$ and heals cracks
- Rice husk ash reduces pores and densifies concrete
- Improves resistance to salt (chloride) attack
- Reduces water absorption
- Increases compressive strength
- Enhances durability in marine conditions
- Eco-friendly (uses waste RHA)
- Low maintenance and cost-effective

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