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Original Article

Study of Bacterial Concrete Corrosion Resistance in Marine Environment

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Abstract *- Concrete is a major building material. This study looked at Bacterial Concrete (BC), which is created by mixing a bacterial solution with a cell concentration of 10^7 CFU/ml. This amount is equivalent to 8% of the cement weight and helps to improve the performance in marine environments. Adding bacterial culture significantly enhanced the concrete's mechanical properties, durability, and self-healing ability. As a result, it showed better compressive strength than regular concrete. The major aim of this study is to see how the bacterial concrete could reduce the harmful effects of environmental stressors on marine structures. It also evaluated the economic feasibility and sustainability of Bacterial Concrete before use. During testing, Bacterial concrete beams were soaked in seawater for 365 days and showed no rebar corrosion, which is a common problem in normal concrete. Durability tests included water absorption, sorptivity, bulk diffusion, and sulphate resistance. Rice husk ash is utilized for the purpose of strengthening the M40-grade concrete, while adding 5 to 10 percent corn starch improved flowability and the setting time without losing strength. Furthermore, 0.5 percent silica fume is included to boost strength and durability. The study wraps up by discussing sustainability challenges and offering insights to promote the use of bacterial concrete in strong and lasting marine applications*.

Keywords *- Durability, Marine environments, Self-healing concrete, SEM, RHA.*

1. Introduction

Generally, Concrete is an artificial *(consolidated)* material, and it has properties that are similar to natural stone. Also, it is used as the construction material, which is the mixture of cement, fine aggregates- sand, and the coarse aggregates-crushed rock or gravel, and water. Then this mixture hardens (cures) with time to make the strong, versatile, durable, and reflective materials, which are used in the construction [1].

The Concrete with the bacteria, called the bio-self-healing concrete, utilizes the dormant bacteria that are embedded in the mix to repair cracks automatically. The Bacterial concrete usually seeks to repair the flaws. As a result, the service life of concrete structures is significantly increased. Self-healing concrete has emerged as an innovative material capable of addressing many issues commonly found in traditional concrete. In this process, *Bacillus Subtilis* bacteria, along with calcium lactate and nutrient broth, are incorporated into the concrete mix to enable autonomous crack repair [2, 3].

Concrete is considered the most commonly utilized construction material in the world. Nowadays, concrete has become an indispensable building material in the rapidly developing construction era [4]. The sustainable concrete structures have been designed to reduce the societal impact throughout their complete life cycle. In recent times, the sustainability of concrete has become the main focus in the construction sector to mitigate the environmental impacts and to verify the long-term viability [5]. The concrete's carbon footprint and resource consumption have raised many concerns [6]. In marine environments, concrete structures are exposed to chemical deterioration caused by reactions with chloride ions, sulfate ions, and magnesium ions present in seawater. They are also vulnerable to biodeterioration, which occurs mainly due to biological activity that produces acids. These two types of corrosion were observed and evaluated to predict the level of deterioration caused by each mechanism. The Chemical (abiotic) corrosion is more severe in splash zone of coastal structures, whereas as the evidence shown that the biodeterioration was the more dominant in tidal zones [1].

Generally, the seawater environment is mostly aggressive for the concrete, due to the presence of magnesium, chloride, and sulfate levels [7]. This aggressive nature has increased biofouling and marine macroorganisms and microorganisms on the surface and in concrete [8, 9].

The particular microorganisms, which are involved in concrete deterioration, resulted in the phenomenon known as the MICC (Microbial Induced Concrete Corrosion). Also, reinforced concrete structures are built around and in the coastal areas or the backwaters, and they have been highly affected by several microbial groups in the MICC form. The Change in the concrete materials by integration of the chemical and the mineral admixture showed good resistance against the MICC. Study [10] evaluated the performance of antimicrobials and the corrosion protection of the altered cement composites for the coastal areas. In the initial stage, four categories of the altered cement composite cube specimens were cast to calculate their compressive strength. In order to find the microorganism that is responsible for the concrete corrosion, microbial samples have been collected from the seashore, isolated and sequenced, and then the BLAST analysis is used for identification. The Bacterium was found to be *Serratia marcescens,* and a phylogenetic tree was built to show the *isolated bacterium's* evolutionary relationship. To evaluate the *antimicrobial* performance, four categories of the semi-circular altered cement composite specimens were exposed in the isolated microbial culture, and the total viable count was calculated. treated

Application of the MICP through the bio-mineralization process is considered the better method to increase the durability. In this research [11], the durability performance of microbial concrete was evaluated after exposure to both physical and chemical sulfate environments, specifically 5% sodium sulfate and 5% magnesium sulfate solutions. The results showed that untreated concrete specimens experienced significant deterioration and structural failure due to expansion caused by sulfate attack, whereas the microbial-treated concrete exhibited improved resistance under the same conditions. In the case of physical sulfate attack, the untreated mortar showed heavy salt efflorescence and severe surface scaling. However, the specimens treated with *Bacillus sp. CT5* demonstrated a significant improvement in resistance to sulfate penetration. The study findings suggest that the microbial concrete technology can greatly increase the concrete's durability, which is exposed to sulfate-rich environments.

Generally, Fibers are the most utilized reinforcement in concrete to increase the concrete's tensile strength, energy absorption, and cracking resistance [12]. The study [13] evaluated the bacterial concrete's mechanical performance and longevity in terms of density, compressive strength, split tensile strength, and water absorption capacity. Experimental results with normal concrete (without bacteria) were correlated with specimens containing bacteria. According to data, high percentage of bacteria has identified as 3.5 percent, and this amount has shown highest values in density, split tensile strength, and compressive strength. Hence, concrete's durability is increased by the bacterial growth. [14], used four different mixes, such as the bacterial concrete, basalt fibre bacterial concrete, fibre-reinforced concrete, and fibres in the regular concrete. Compressive strength and electrical resistivity of the concrete on samples are already cracked and then healed and utilized for assessing the efficiency of the concrete at healing and the mending. Moreover, there has the connection between results and microscope and spectrometer analysis. The future scope of the research is that the marine construction depends on the advances of CRISPR modified strains and climate adapted microbes that has been supported by AI enables profiling. These innovations aims to self heal the effectiveness and prolong marine infrastructure.

The construction industry needs durable and stronger structures, and the traditional repairing mechanisms, like the provision of extra reinforcement and motor injection, are time-consuming and expensive, so a self-healing mechanism has been preferred. The present study incorporated the bacterial concrete. Depending on the principle of biomineralization, which defines a biologically induced precipitated formula where the organism develops a localized microenvironment with the optimal conditions for precipitating mineral phases. When the crack appears, the bacteria release the healing products within the concrete and flow to the cracks for sealing.

The existing papers have only strengthening factors like crack healing behaviour and absorption of water of the bacterial concrete when compared with traditional concrete. Further, there are no studies associated with the determination of bacterial optimum dosage and the durability of the bacterial concrete, particularly in the marine environment. The studies concerned with the cost reduction of concrete by the complete or partial replacement of the ingredients are found to be rare. Further, the studies correlated in the utilization of eco-friendly material as the prominent workability agents in the concrete were also not found in the existing studies. The results of the existing studies can only be utilized for minor works, maintenance works such as tunnel works or crack repair works, and the greatest limitation of the existing studies is that they are not made aware to the public regarding the handling and innovation.

The major objective of the study is to identify bacterial concrete's durability in the marine environment, to identify bacterial concrete's strength, in comparison with normal concrete, to enhance the bacterial concrete's cost-effectiveness, and to compare the durability and sustainability performance of M40-grade bacterial concrete with its enhanced strength and durability characteristics.

The innovative feature of bacterial concrete in marine construction is the biologically inspired self-healing ability that functions even under constant saline exposure. Such a mechanism enables the minimization of chloride ingress, strengthens resistance to corrosion, natural crack closure, and improves prolonged durability. Considerably, this obtains these characteristics without depending on chemical additives, which provides a sustainable and low-maintenance-solution for marine infrastructure.

The marine structures are more susceptible to deterioration due to chloride penetration, cracks, and reinforcement corrosion. The traditional chemical admixtures provide only minimal protection for the short term and raise environmental concerns. The bacterial concrete with the biologically strong preventive measures for cracks limits the chloride ingress for the long term under saline exposure.

Table 1. Comparison of studies regarding the construction in the marine environment with the bacterial concrete

Study (Year)	Marine Exposure Conditions	Microbial/Technical Approach	Findings on Corrosion & Durability	Key Limitations/Remarks
[15]	Marine service conditions with chloride ingress focus	Microbially induced $CaCO_3$ precipitation	Reduced crack connectivity, lower chloride penetration, stronger corrosion resistance, improved durability	Field performance varies; there is a need for standardized long-term testing.
[16]	General concrete strength evaluation (not marine-specific)	Bacillus subtilis inoculation across grades M20–M30	Enhanced strength (destructive & non-destructive), cost–benefit discussed	No saline exposure; requires validation in chloride-rich marine settings
[17]	Harsh environments, including marine-like conditions	Bio-carriers with immobilized marine bacteria	Higher self-healing efficiency and mechanical strength	Needs translation to real marine field trials and scale-up
[18]	Cyclic seawater immersion (3.5% NaCl) with wet–dry cycles	Bacillus spp. MICP	Lower corrosion current density, improved crack sealing	Shelf-life and carrier stability remain challenges
[1]	Harbor slab exposure in tidal splash zone	Multi-strain consortia (Bacillus + Sporosarcina)	Slower chloride diffusion, delayed corrosion initiation	Competition with native microbes reduced persistence
[19]	Accelerated chloride diffusion tests	Bacillus sphaericus (ureolytic pathway)	Higher resistivity, reduced permeability	Ammonia by-products pose environmental concerns
[20]	Continuous saline spray chamber	Encapsulated spores in silica gel	Sustained healing for 6–12 months, improved surface integrity	Carrier compatibility and cost issues
[21]	Artificial cracks cured in seawater	Bacillus subtilis with nutrient capsules	Faster closure of cracks ≤0.4 mm	Larger cracks (>0.6 mm) showed reduced healing; nutrient depletion was noted.
[22]	Seawater plus carbonation exposure	MICP combined with low-dose inhibitors	Lower rebar mass loss compared to the single approach	Balancing biogenic and chemical inputs remains a challenge
[23]	Splash zone prisms in a coastal climate	Sporosarcina pasteurii	Denser $CaCO_3$ deposits, reduced microcrack growth	Short monitoring period; lacks long-term corrosion data
[23]	Saline immersion with temperature cycling	Alginate vs. lightweight aggregate carriers	Alginate maintained microbial viability and provided more consistent healing.	Mechanical strength impact of carriers needs optimization.
[23]	Batch production assessment	Standardized spore counts, QC protocols	More consistent performance, improved reproducibility	Contractor training and supply chain reliability remain hurdles

The study suggested that the bacterial concrete improved with genetically modified strains, multi-strain microbes, and climate-resilient organisms supported by AI-based profiling that delivers a superior self-healing process and hence maintains cost-effective, prolonged solutions.

2. Materials and Methods

2.1. Materials Used

The study used Cement, coarse aggregate, and fine aggregate for the concrete preparation, and it met the IS specifications. In the experimental study, *Bacillus subtilis* bacteria are used, and they are collected from a government-approved agency. Also, Ordinary Portland cement is used for the creation of specimens.

2.2. Methodology

In this study, the bacterial concrete specimens were prepared by integrating the bacterial solution with the cell concentration of 10^7 CFU/ml in a dosage equivalent to 8 percent of cement weight. This bacterial culture is uniformly mixed with the cementitious matrix to ensure the efficient distribution and activation of the bacterial spores in concrete. The Standard curing procedures were followed to enable the bacterial viability and the subsequent calcium carbonate precipitation.

An experimental study is to specify the maximum strength of every concrete type. It also aimed to test the sustainability and durability of normal concrete vs. bacterial concrete. Also, the study utilizes cubes, cylinders, beams, and slabs for the purpose of conducting the durability tests on normal and bacterial specimens. These samples have gone through the seawater submersion for some time periods, and then were tested after days to monitor the changes. Also, this study gives significant importance to the crack healing. It conducted many tests, like the slump test, compression test, durability test, ultimate load tests, and the breaking load tests, to determine the impact on concrete.

3. Results and Discussion

3.1. Durability Test

It is vital to prevent cracks and limit crack widths, and to verify the durability and functionality of concrete structures. Also, developing a reliable method to repair the concrete cracks in an automatic way can save costs and conserve materials, and also reduce the necessity for regular repairs. Durability of bacterial concrete can be assessed by utilizing the standard tests, which measure its resistance to environmental degradation, such as water, chlorides, sulfates, and the freeze-thaw cycles, and its self-healing efficacy, mostly compared with the conventional concrete [26]. The integration of the bacteria in the concrete has been shown to increase its durability by decreasing the permeability and increasing resistance to aggressive conditions in the environment [27]. These improvements stem from reductions in water absorption and chloride ion diffusion, which can contribute to the overall longevity of the bacterial concrete [28].

It used two concrete types, namely M30 normal and bacterial concrete, and M40 normal and bacterial concrete. The durability tests include water absorption, sorptivity, bulk diffusion, sulphate attack, corrosion inspection, and strength. The study used 3 numbers of cubes each for the Water absorption and 6 numbers each for the sulphate attack resistance, 2 numbers of cylinders each (10 cm X 5 cm) for the sorptivity, and 2 numbers of cylinders each (10 cm X 20 cm) for the Bulk diffusion. It also used the reinforced concrete beams of 4 numbers each (100 cm X 20 cm X 25 cm) and the reinforced concrete slabs of 4 numbers each (50 cm X 40 cm X 10 cm).

All specimens have been cast and then immersed in the sea for curing. Then the Water absorption and the sorptivity tests were conducted after 28 days. Also, the Bulk diffusion test was conducted after 56 days in NaCl solution and after 365 days in seawater. Then the sulphate attack resistance test was held after 365 days in Na2SO4 solution and in seawater. After that, the Corrosion assessment and strength test were conducted at 28, 90,180, and 365 days. Finally, the SEM analysis was performed on the specimens, which were taken from the crack healing and the Reinforcement zone of both types of concretes.

3.1.1. Water Absorption Test

Generally, Water absorption can be defined as the amount of water that the concrete has absorbed under the atmospheric pressure. It is considered to be a specific concern in the applications, where the concrete is exposed to aggressive environments, particularly to the chloride and sulphate ions. The concrete's durability in aggressive environments depended on the transport properties that are impacted by the penetrability of the pore system. Also, many of the concrete elements were not completely water-saturated, and transport of water or other liquids is largely by absorption. The ingress of water by capillary suction could impact the rate of the chemical ingress, which affects the long-term durability and service life.

Then, after 28 days of curing in seawater, Normal Concrete and Bacterial Concrete cubes were taken out. The amount of water absorbed by the cube is calculated based on its initial weight. Then the Cubes are kept in an oven for drying for 24 hours. After that, the cubes are then weighed and submerged in seawater for an additional 24 hours. Then, after 24 hours, the cubes were removed from the water and weighed again.

$$Water\ Absorption = (wet\ weight - dry\ weight) / (dry\ weight)\ x\ 100 \quad (1)$$

Fig. 1 Cubes immersed in sea water

Fig. 2 Oven drying of cubes

Figure 1 above displays the cubes immersed in seawater. Figure 2 displays the oven drying of cubes. To verify the proper durability, the water absorption value must be within 4 to 6 percent, and when water absorption is below 5 percent, it can be considered as good quality concrete. The maritime code BS 6349 specified that the water absorption must not exceed 3 percent, or 2 percent in critical conditions, due to the highly aggressive chloride attack in the marine conditions.

Table 2. Concrete types and their water absorption level

Concrete Types	Water absorption (%)	
	M30	M40
NC	7.67%	6.21%
BC	4.85%	4.08%

Table 2 above displays the concrete types and their water absorption levels. The concrete types are normal and bacterial concrete. The water absorption level for the normal concrete M30 is 7.67% and M40 is 6.21%; then the bacterial concrete M30 is 4.85% and M40 is 4.08%.

3.1.2. Sorptivity Test

The Sorptivity is considered a common occurring phenomenon, where permeability occurs when the unsaturated pastes, concretes, or mortars come into contact with the water or moisture in the air. It is considered a durability property related to concrete. It is also the durability parameter characterized by simplicity of testing and sensitivity to concrete quality. The test represented a hindrance occurring in the path of water because of the capillary suction on the concrete specimen's surface. This property could be affected by the pore structure of concrete and the curing period. This test can be carried out on cylinders, each having a size of 10 cm X 5 cm, with the normal concrete and bacterial concrete. The specimens were oven-dried, and their weights were noted. Then these Specimens were sealed by the epoxy coating on the sides and immersed in the solution with 5mm height from the bottom immersed in the water. 2 non-conducting sticks were kept at the bottom of the tray to hold the specimens. Then, Care was taken to verify that the water penetration happens only by capillary rise. The Specimens were placed above the rod in such a way that the bottom surface touched the water. Then, they were weighed after 20, 40, and 60 minutes, and each weighing procedure was completed in thirty seconds.

$$I = S\sqrt{t} \tag{2}$$

Where,
S, sorptivity,
I, volume of absorbed water per unit cross-section at time t,
t, elapsed time in minutes.

$$I = \Delta w/Ad \tag{3}$$

Where,

$$\Delta \text{ w= change in weight} = W2 - W1 \tag{4}$$

W1, Oven dry weight of cube in grams
W2, Weight of cube after specified time minutes, capillary suction of water in grams
A is the surface area of the specimen through which water penetrated.

Fig. 3 Experimental test setup for sorptivity test

Table 3. Sorptivity test results

Type of concrete	Dry weight (kg)	Wet weight (kg) after			Sorptivity(10^{-5} g/mm^2/min$^{1/2}$)		
		20 min	40 min	60 min	20 min	40 min	60 min
M 30 NC	2.75	2.89	2.93	2.94	1.60	1.45	1.25
M 40 NC	2.81	2.82	2.92	2.96	1.29	1.04	1.01
M 30 BC	2.78	2.82	2.85	2.85	1.27	1.04	1.01
M 40 BC	2.75	2.82	2.82	2.82	1.21	1.03	0.90

Table 3 above displays the Sorptivity test results. It mentions the concrete types and their dry weight, wet weight after 20, 40, and 60 minutes. Then the sorptivity in 20, 40, and 60 minutes was measured as the time prolonged, resulting in lesser sorptivity and greater durability. Here, Bacterial Concrete exhibited greater durability as sorptivity is less than that of Normal Concrete.

3.1.3. Bulk Diffusion Test

This Test is mainly used to assess chloride attack on the concrete specimen by measuring the depth of chloride penetration into the concrete specimen. The bulk diffusion test is mainly conducted as per the ASTM C 1556-03. The cylinder (100mm diameter and 200mm length)is utilized as a test specimen. Then, after seven days of water curing, these concrete specimens were exposed to a 1.8 Molar NaCl solution for 56 days. Then, after this exposure, specimens were split by applying a splitting tensile force. To split face, 0.1 Molar Silver Nitrate ($AgNO_3$) solution was sprayed, and it was also observed that colour changes, i.e., up to penetrated depth of chloride ion, a white precipitation will form, and hence the depth of chloride ions was identified.

Fig. 4 Cylinders immersed in 1.8 Molar NaCl solution

Fig. 5 White precipitate after the application of AgNO3

The depth of diffusion (Xd) of a substance through concrete is proportional to the square root of the product of the diffusion coefficient (D) and time (t)

$$Xd = 4\sqrt{Dt} \quad (5)$$

Xd, Depth of chloride penetration

D, Diffusion coefficient

t, time in seconds

For the low permeability concrete, the value of D should be less than 1X 10^{-12} m^2/s, for medium permeability concrete, the value of D should be between (1to 5) X 10^{-12} m^2/s, and for high permeability concrete, the value of D should be greater than 5 X 10^{-12} m^2/s.

Table 4 above displays the results of the bulk diffusion test. It mentions the type of concrete, the diffusion coefficient after 56 days of immersion in the NaCl solution, and the diffusion coefficient after 56 days of seawater immersion. Then another set of specimens was immersed in seawater for 56 days and tested for bulk diffusion.

Table 4. Results of bulk diffusion

SI. No	Type of concrete	Diffusion coefficient after 56 days of immersion in NaCl solution (m^2/s)	Diffusion coefficient after 56 days of immersion in seawater (m^2/s)
1	M30 NC	5.321 x 10^{-12} m^2/s	9.321 x 10^{-12} m^2/s
2	M40 NC	4.229 x 10^{-12} m^2/s	6.932 x 10^{-12} m^2/s
3	M30 BC	0.976 x 10^{-12} m^2/s	1.276 x 10^{-12} m^2/s
4	M40 BC	0.826 x 10^{-12} m^2/s	0.902 x 10^{-12} m^2/s

Fig. 6 Specimens prepared for seawater immersion for bulk diffusion test

(a)

(b)

Fig. 7 White precipitate formed after the application of AgNO3 in, (a) Normal concrete, and (b) Bacterial concrete.

3.1.4. Sulphate Attack Resistance

Sulphate attack resistance tests have indicated that the bacterial concrete exhibited significantly increased resistance to the sulphate attack [29]. The final test is the Sulphate attack tests, and they were mainly conducted to observe durability and the hardened properties of the concrete. This test was performed to measure the resistance of Normal concrete and Bacterial concrete to sulphate attack.

The Samples for the tests were immersed in the five percent Na_2SO_4 solution for 365 days, then they were cured in the water for 28 days, and they were closely monitored to observe the changes in the physical appearance, mass, and loss of compressive strength.

Fig. 8 Cubes immersed in 5% Na2SO4 solution for 365 days

Fig. 9 Deteriorated bacterial concrete cubes taken out from Na2 SO4 solution after 365 days

Table 5. Sulphate attack resistance test results

Sl. No	Type of concrete	Characteristic compressive strength (N/mm^2)	Compressive strength after 365 days of immersion in Na_2SO_4 solution (N/mm^2)	Percentage loss in compressive strength (%)
1	M30 NC	40.78	6.51	84.0
2	M40 NC	45.38	9.25	79.6
3	M30 BC	54.44	23.12	57.5
4	M40 BC	60.01	31.26	47.9

The above Table 5 presents the sulphate attack resistance results of the concretes, along with their characteristic compressive strength and the compressive strength after 365 days of immersion in a Na_2SO_4 solution. It defined the percentage loss in the compressive strength.

3.1.5. Corrosion Assessment

This study used two concrete types, such as M30 and M40, for the purpose of creating the Normal concrete and Bacterial Concrete specimens. Specimens are 3 (100 cm x 20 cm x 25 cm) RC beams and 3 (50 cm x 40 cm x 10 cm) RC slabs of each type. The above-mentioned specimens have gone through seawater submersion. Then these specimens are subjected to thorough testing and examinations at 28, 90, 180, and 365 days by assessing corrosion and the strength parameters. Then the samples taken from the reinforcing and the crack-healing zones of the concrete types are broadly analyzed, and, by utilizing the SEM (Scanning Electron Microscopy), a broad and thorough evaluation of their durability is conducted.

(a) **(b)**

Fig. 10 (a) Normal concrete beams before immersion in seawater, and (b) Corroded bars in normal concrete beams.

Figures 10(a) and (b) display the normal concrete beam in seawater submersion for 365 days. Also, clear corrosion is displayed on the rebar.

Figures 11(a) and (b) display the bacterial concrete beams inspected before 365 days of seawater immersion. There is no evidence of rebar corrosion.

(a) **(b)**

Fig. 11 (a) Bacterial concrete beams before immersion in seawater, and (b) Corroded bars in bacterial concrete beams.

(a) **(b)**

Fig. 12 (a) Normal concrete slabs during casting, and (b) Corroded bars in normal concrete slabs.

The above Figures 12(a) and (b) display the normal concrete slabs before 365 days of seawater immersion. And the reinforcement bars are corroded.

(a) **(b)**

Fig. 13 (a) Bacterial concrete slabs before immersion in seawater, and (b) Corroded bars in bacterial concrete slabs.

The above Figures 13(a) and (b) display the images of the concrete slabs with the bacteria before the seawater submersion for one year. In the comparison, the slabs' rebars did not show signs of corrosion.

3.2. Ultimate and Breaking Load Test

The following Figures 14(a) and (b) display the picture of beam and slab testing. This UTM is used for the evaluation of Mechanical attributes and the performance traits of several materials and constructions.

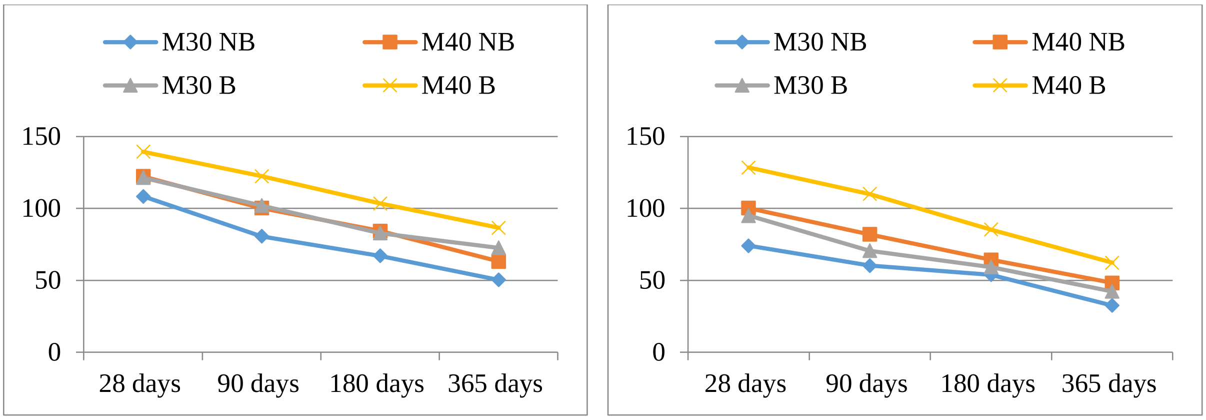
(a) **(b)**

Fig. 14 Testing of (a) RC beam, and (b) RC slab in UTM.

Table 6. Results of the breaking test of the beam

Number of days of curing	Non-bacterial concrete beam				Bacterial concrete beam			
	Ultimate load kN		Breaking load kN		Ultimate load kN		Breaking load kN	
	M30	M40	M30	M40	M30	M40	M30	M40
28 days	74.05	100.3	108.43	122.30	95.03	128.42	121.39	139.48
90 days	60.21	82.01	80.64	100.25	70.65	110.02	102.08	122.42
180 days	53.97	64.32	67.04	84.32	59.29	85.32	82.90	103.45
365 days	32.52	48.22	50.31	63.2	42.34	62.31	72.61	86.55

Table 6 above displays the results of the beam-breaking test. This data can define the performance of bacterial concrete beams and the normal concrete beams, and it describes the Ultimate Load of the beam and the breaking load of the beam, after exposure to marine environments to a great extent.



(a) **(b)**

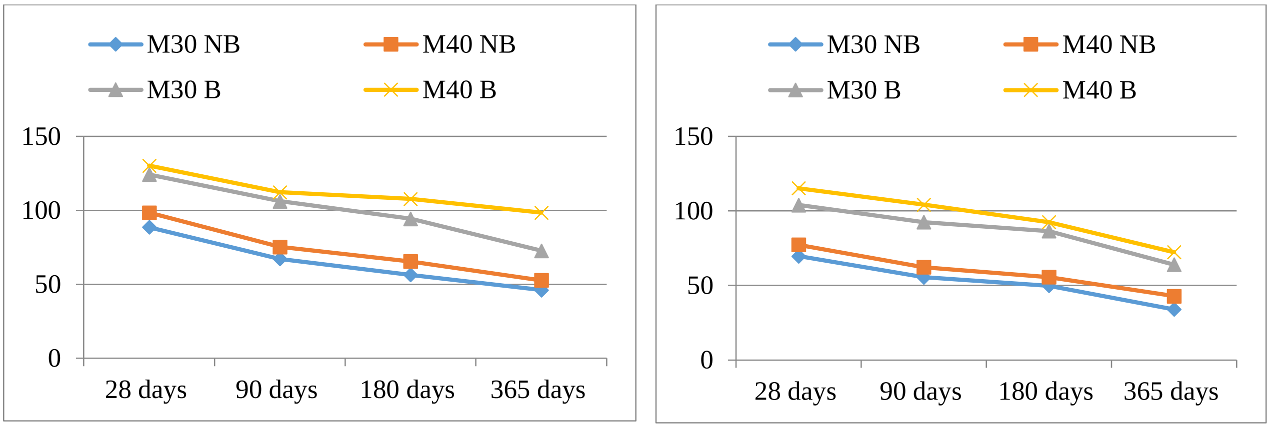
Fig. 15 RC beam, (a) Ultimate load, and (b) Breaking load.

Figures 15(a) and (b) display the breaking load of the beams and the graph of the beams' ultimate load. Also, this data can be used to know about the load-bearing capacities of beams, and it allows for informed decision-making in the construction and structural design.

Table 7. Results of the breaking test of the slab

Number of days of curing	Non-bacterial slab				Bacterial slab			
	Ultimate load kN		Breaking load kN		Ultimate load kN		Breaking load kN	
	M30	M40	M30	M40	M30	M40	M30	M40
28 days	69.66	77.32	88.63	98.43	104.04	115.23	124.25	130.21
90 days	55.55	62.31	67.18	75.32	92.51	104.23	106.27	112.29
180days	49.88	55.65	56.42	65.47	86.56	92.54	94.32	107.77
365days	34.01	42.89	46.18	52.74	64.02	72.36	72.72	98.42

Table 7 displays the results of the breaking test of the slab. It also displays the analysis of the normal slab and the bacterial slab, and gives the specific data of the ultimate load and the breaking load of the slabs.



(a) **(b)**

Fig. 16 RC slab, (a) Ultimate load, and (b) Breaking load.

Figure 16 above displays the ultimate and breaking load graph of the slabs. The mentioned data in the graph is most important because it provides a better understanding of the exact load-bearing capacities.

3.3. SEM Analysis

The SEM is prepared with the Energy Dispersive X-ray analysis, and it can be used to assess the concrete, whether deteriorated or new. Also, it is used to examine the concrete's microstructure. It enhances the capabilities of the optical microscope, making it easier to analyze the material's composition, porosity, and flaws.

In concrete quality assurance, the SEM is considered to be important, and it gives detailed information in the following areas:

- There is a need to measure the cement, to interact with the water for the hydration
- The dispersion and development gives valuable insights into the structure and the makeup of compounds that are created in the hydrating cement process.
- Mortar mixture consistency is significant for the overall strength of concrete, and it can be evaluated by recognizing its homogeneity.

Also, the SEM is a vital tool in forensic investigations, and it includes degraded concrete, and it also gives vital information on the cause and type of observed deterioration.

SEM-EDX examination and its information are given below:

- The Phase morphology, presence of the secondary and primary mineral phases in the paste, micro-cavities, pores, and fractures, and phase assemblage analysis.
- Determining the location of mineral phases' deposition and the source.
- The optical microscope has difficulty in detecting minute phases of micron-sized minerals.
- The Chemical variation or the zoning of the material's crystals.

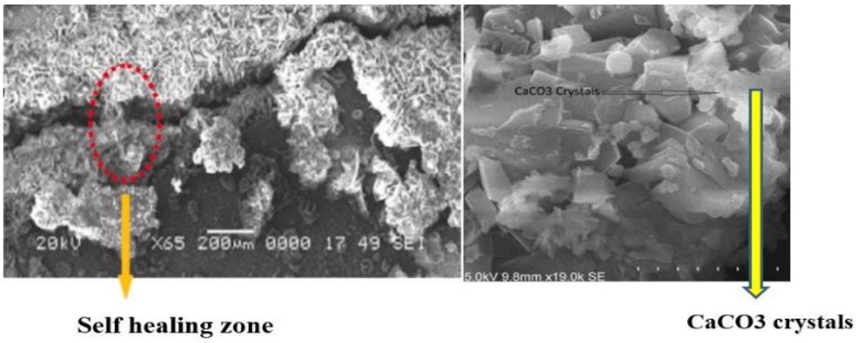
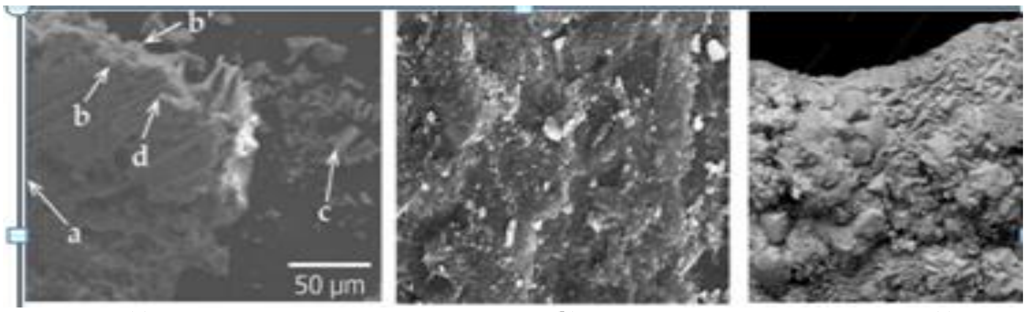


Fig. 17 SEM result showing self-healing zone

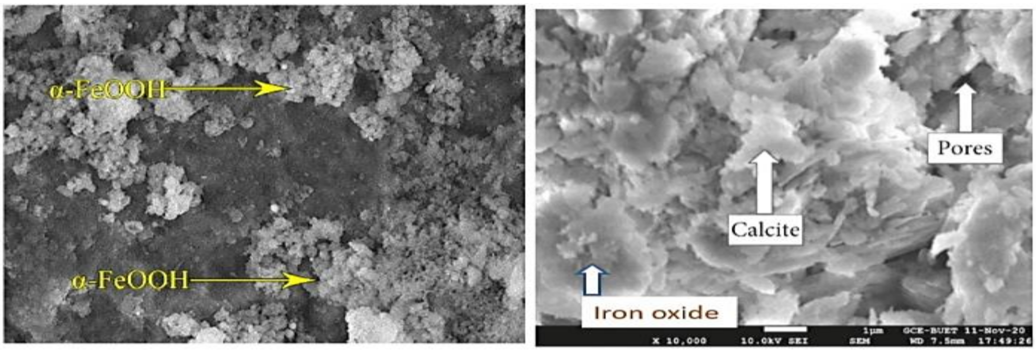
Figure 17 above displays the SEM result. Generally, four samples were taken from the zone of reinforcement and the crack in normal and bacterial concrete beams. Then it displays examination, which revealed the existence of the pores, minerals, chemicals, and other pertinent features. Also, the SEM report gave a wide analysis of the normal concrete specimens, which were taken from the zone of reinforcement. Also, this specimen is exposed to continuous seawater immersion for the duration of 365 days.



(a) (b) (c)

Fig. 18 Normal concrete beam specimens, (a) Reinforcement zone, (b) Layer of rust, and (c) Rust.

Figure 18 above displays the normal beam specimen from the reinforcement zone. (a) Displays the reinforcement area in the concrete. (b-b') displays the iron oxide layer. Then the (c) Displays the rust fragments. Then (d) displays the presence of the iron oxide crystal.

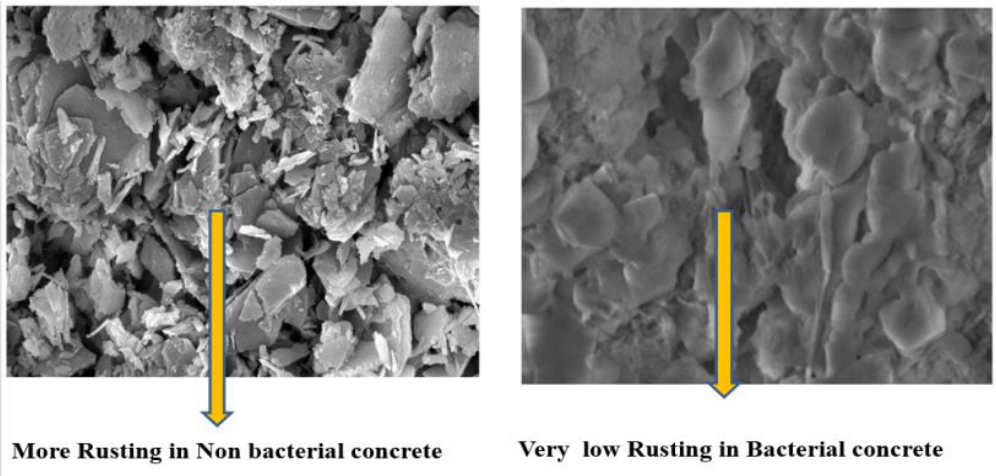


(a) (b)

Fig. 19 Iron oxide content in, (a) Normal concrete, and (b) Bacterial concrete.

Figure 19 above displays an image comparing the Iron Oxide content in normal and bacterial concrete. Additionally, it highlighted a stark contrast between normal and bacterial concrete, with significant effects for the construction sector.

Normal concrete can be characterized by its significantly prominent iron oxide hydroxide content, which is considered the major component of the compound. The comparison is held between the normal concrete and bacterial concrete, and SEM analysis revealed that bacterial concrete exhibited a high proportion of calcites and reduced iron oxide amount, which indicates substantial disparities in the mineral composition between the normal concrete and bacterial concrete. Although a lower pore count in the bacterial concrete suggested the possible microstructure variations, when it is contrasted with the normal concrete, it suggests the possible effects on the material's durability and strength.



(a) (b)

Fig. 20 Rusting in, (a) Normal concrete, and (b) Bacterial concrete.

Figure 20 above displays the images of rusting in normal concrete and bacterial concrete. It can be seen in the figure that more rusting occurs in the normal concrete and less rusting in the bacterial concrete. The results have highlighted the potential efficiency of bacterial intervention in minimizing corrosion in concrete infrastructures. It provides a hopeful prospect for the longevity and durability of concrete-based constructions.

Table 8. Comparative study of atom percentage in normal and bacterial concrete

Elements or compounds	Atom percentage in normal concrete (%)	Atom percentage in bacterial concrete (%)
Carbon	20.6	13.6
Chloride	22.92	0.06
Iron oxide	10.9	3.3
Oxygen	10.8	18.3
Aluminium oxide	3.42	0.25
Magnesium sulphate	11.47	0.8
Sulphur dioxide	7.43	0.1
Calcium carbonate	0.33	46.91

Table 8 above is a comparative study that describes the atomic percentages of compounds and elements in normal concrete and bacterial concrete. Normal concrete has manifested high carbon content, suggesting the augmented propensity for carbonation. Also, these phenomena have arisen from the reaction of the atmospheric CO_2 with concrete, and it has produced a reduction in the pH and consequent diminution in the concrete's durability.

Moreover, concrete has sodium carbonate, which led to significant outcomes, and included significant expansion that, under certain circumstances, can yield the complete disruption and the breakdown of the concrete structures.

Then the durability of the concrete is examined, and the issue of the chloride attack becomes a significant threat, which could lead to 40 percent failures in the concrete structure. With the presence of oxygen and water, the chloride aggression triggers the corrosion in the steel reinforcements, and it may weaken the structure significantly. Also, the chlorides may seem to be harmless to harden the concrete, but they increase reinforcement corrosion risks. Reinforcement corrosion initiates when the chloride ion concentration in steel exceeds the critical 'threshold level.' In the normal Portland cement concrete, with the cement content ranging from 254 to 446 kg/m3, the chloride threshold values were between 1.6 and 3.6 percent.

Also, in normal concrete, the chloride content is 22.92 percent, and it has a significant risk. Also, the bacterial concrete exhibited a chloride content of 0.06 percent and indicated the unique resistance to the chloride attack, specifically in the marine environment. Hence, the bacterial concrete asserts its supremacy in durability over the normal concrete, and the chloride percentages are higher in normal concrete than in bacterial concrete.

Then the Iron oxide content, which is presented in the concrete products, should be restricted to three to four percent to prevent any compromise in the product's mechanical strength. In Table 8 above, the normal concrete has an iron oxide content of 10.9 percent, and the bacterial concrete has a low iron oxide content of 3.3 percent.

Generally, Oxygen is considered the basic and irreplaceable constituent of many construction materials, such as concrete, and it is also important in binding properties. Without oxygen, there is a significant loss of these properties, and it could cause chemical transformation. In Table 8, the bacterial concrete has the highest oxygen percentage compared with the normal concrete.

Too much aluminium oxide in the cement can lead to lower durability and less strength of the concrete. Aluminium oxide presence can trigger the formation of the mineral known as the ettringite, which leads to the cracking and expansion in concrete, and it damages its structural and durability integrity, although these excess aluminium oxide impacts the workability and setting time of the cement, and creates a challenging task. In Table 8, the bacterial concrete has a lower aluminium percentage, and provides a better solution, outperforms the normal concrete, and demonstrates the possibilities to enhance the situation.

There is complexity in the concrete sulfate attack process, and it involves physical salt attack and chemical sulfate attack. Finally, it has resulted in the concrete expansion, disintegration, and cracking, specifically in the reinforced structures. The Magnesium sulfate attack deteriorates the concrete and eventually leads to its degradation. The Magnesium sulfate presented in the normal concrete is higher than in the bacterial concrete.

The Sulfur dioxide in the concrete caused the electrochemical and chemical corrosion. Sulfur content in concrete should not exceed 2.75 percent. The bacterial concrete will be effective in marine conditions because of its low percentage of sulfur content. In Table 8, sulfur dioxide is more present in the normal concrete than in the bacterial concrete.

The Calcium carbonate in the concrete increases packing, workability, and early strength, and it also accelerates the hydration. The presence of high calcium carbonate content in Bacterial Concrete has provided a sustainable solution for marine conditions. In Table 8, the calcium carbonate percentage is higher in the bacterial concrete than in the normal concrete.

3.4. Bacterial Concrete's Cost-Effectiveness

The Bacterial concrete is possibly cost-effective in the long run because of its self-healing capacities, significantly decreases the future maintenance and repair costs, and extends the concrete's service life. But its initial costs are currently higher, due to the expensive bacterial strains and nutrients, improved durability, sustainability, and there is less need for human intervention in severe areas, and it is a better and economically viable material for the future sustainable infrastructure.

This study included a wide-ranging investigation of the bacterial concrete properties, and it aimed to optimize its performance and cost-effectiveness. Particularly, the study explored the impacts of replacing fine aggregate with the RHA, and also analyzed its effect on the density, compressive strength, and porosity of concrete.

[19, 30] included thorough addition of the high-quality corn starch and the silica fume to the concrete mix, and it aimed to optimize workability and strength. The Combination of these modifications can lead to major developments, and mark it as the best thing in the whole properties, sustainability, and durability of bacterial concrete.

3.4.1. Rice Husk Ash

RHA is considered the positive reactive material with the pozzolanic properties, and it is a better candidate to increase the interface between cement paste and the aggregate in the high-performance concrete [31-33].

The specific RHA sample is attained from local rice mills. The M40 grade concrete was selected for the study as it shows superior performance to the other. This study has shown detailed experiments by examining the effects of replacing fine aggregates with various RHA percentages % such as 3, 5, and 10 percent, with 8% bacterial solution. It also conducted the investigation of bacterial concrete properties, and it aims to optimize its cost-effectiveness and performance. Moreover, the major objective of this study is to create specimens for corrosion testing and for assessing concrete performance. Workability evaluation required the execution of slump tests, which revealed RHA inclusion, and it led to insufficient cohesion among the particles, as demonstrated by the resultant shear slump and the slump values.

Fig. 21 Slump test of bacterial concrete

The above Figure 21 displays the slump test of bacterial concrete. The shear slump is one of the types of deformation in concrete, and it is caused by the insufficient cohesion and the decreased water content that resulted from the water absorption by the RHA.

Fig. 22 Reinforced concrete beam with the bacteria and RHA

Table 9. Optimal % of RHA to be added

Type of concrete	% RHA added		
	0%	5%	10%
M40 grade normal concrete	45.38	48.9	32.3
M40 grade bacterial concrete	60.01	65.8	39.2

Beam was built using bacterial concrete that is reinforced with RHA for the purpose of increasing its strength and resilience. By this advanced method, the fine aggregate in concrete was substituted with the RHA, and it resulted in the significant improvement of the concrete's overall durability and strength. Also, this method contributed to the development of eco-friendly and sustainable construction practices.

Figure 22 above displays a beam cast using M40 grade bacterial concrete, which incorporates RHA.

The above Table 9 gives a thorough analysis of the concrete strength when fine aggregate is replaced by RHA. It gives the particular RHA (%) that needs to be added, and it also gives the comparison table showing the strengths of the M40-grade normal concrete and the bacterial concrete.

Then, it highlighted the impacts of 5 % RHA on concrete mixes and strength, and provided better insights for decision-making and analysis in concrete construction in the future.

Table 10. M40 grade concrete with RHA test results

Type of Concrete	Compressive strength (N/mm^2)	Flexural strength(N/mm^2)	Split tensile strength (N/mm^2)	Modulus of elasticity (GPa)	Ultimate load (kN)	Breaking load (kN)	Depth of chloride penetration (mm)
BC+ RHA	65.8	6.81	5.01	49.32	138.42	152.31	3
NC+RHA	48.9	4.45	3.92	37.63	108.56	130.41	8

Table 10 above displays the test results for the M40 grade normal concrete and the concrete with 8% bacteria and 5% RHA. The Bacteria and the addition of the RHA increased several concrete properties. These study findings are a symbol of hope, and they indicate that the integration of RHA and bacteria leads to significant enhancements in the sustainability, strength, and durability of the concrete. It did not achieve better results, which is a testament to the possible benefits of integrating the bacteria and RHA into the concrete mix. The addition of RHA to normal concrete and the Bacterial Concrete has decreased the workability due to water absorption. This is because of the highly porous nature of RHA, which allows it to absorb the water and then retain the water in the concrete mix, and affects its workability.

3.4.2. Corn Starch

From these chosen bio-admixtures and the corn starch, it has undergone a broad and rigorous study to determine the cement mortar effects. The analysis [34] found that adding five percent to ten percent of the corn starch to the cement content by weight led to major development of flowability and setting time of cement mortar. Finally, these developments have attained the results by verifying that strength, durability, and also shrinkage parameters remained well within a better range.

This study has indicated that the ten percent corn starch is considered the optimal dosage to attain the high compressive strength and the workability. It was concluded by the thorough assessments of the strength and workability, and it demonstrates the precise nature of the research findings.

In spite of the possible slight reduction in the compressive strength, the result of corn starch inclusion might cause changes in microstructure, reliability, and accuracy of the study.

Fig. 23 Slump test of bacterial concrete with corn starch

Also, to increase the performance of cement mortar, this study integrated 0.5 percent silica fume, and it reflected the wide approach. Upon integrating the corn starch, workable concrete highlighted true slump, and it represented concrete's ability to maintain shape and high slump value, which indicated an increase. These effects are demonstrated in Figure 23.

Table 11. Test results of sustainable M40 grade normal and bacterial concrete

Types of concrete	Compressive strength (N/mm^2)	Flexural strength (N/mm^2)	Split tensile strength (N/mm^2)	Modulus of elasticity (GPa)	Ultimate load (kN)	Breaking load (kN)	Depth of chloride penetration (mm)
BC with RHA+ corn starch	60.2	5.8	4.5	39.28	127.2	140.39	3
BC with RHA+ corn starch+silica fume	68.8	6.72	5.23	47.25	140.42	159.31	3
Normal concrete with RHA + corn starch	43.2	3.93	3.27	32.12	98.54	118.63	7
The Normal concrete with RHA + corn starch + silica fume	50.8	4.78	4.02	37.67	112.56	135.04	5

Table 11 above explains the complete test results for the M40-grade bacterial and normal concrete. This table contains their variants, which consist of five percent RHA, ten percent corn starch, and 0.5 percent silica fume.

Finally, the M40 grade bacterial concrete with bacterial solution concentration of 10^7 CFU/ml, corresponding to 8% of cement weight, 5% rice husk ash, 10% corn starch, and 0.5% silica fume, has shown better improvements in durability and mechanical properties. These increased compressive strength, and also reduced water permeability, and the evidence of self-healing by the calcium carbonate precipitation was observed, confirming the efficiency of the bacteria in integrating the overall performance of the concrete matrix.

4. Conclusion

This study used the bacterial concrete, which was developed by integrating the bacterial solution with the cell concentration of 10^7 CFU/ml, corresponding to 8 percent of cement weight. The integration of bacterial culture has significantly increased the concrete's mechanical performance and durability properties, signifying the superior self-healing capability and compressive strength compared to conventional concrete. The study is conducted to understand the bacterial concrete efficiency by repairing cracks and increasing concrete strength, especially in the harsh marine environments. It mainly focused on the distinct ability of the bacteria to produce calcium carbonate. It included the bacterial concrete beams in the seawater immersion for 365 days, without the rebar corrosion, which is the major issue in normal concrete, and it is a major development. This study compared the breaking loads and ultimate loads of the normal concrete and the bacterial concrete beams and slabs, and finally, it provides better insights into the strength differences. It analyzed the compound and elemental compositions of normal concrete and bacterial concrete, and revealed that normal concrete has a high carbon content, which is used to enhance its susceptibility to carbonation. Also, in the normal concrete, the iron oxide content is 10 percent, but in bacterial concrete, it is in an acceptable range. The role of atomic oxygen in many construction materials, such as concrete, is vital. It is considered key to bind concrete properties. Without oxygen, these properties can significantly diminish, and it can also lead to chemical transformation. The bacterial concrete, with the high oxygen content, suggested the possible increases in durability and strength. It then provides a better solution by outperforming normal concrete, because of its lower aluminium %. Also, the bacterial concrete is efficient in marine conditions because of its low sulfur content. Also, high CaCO3 content in Bacterial Concrete provided a better solution in marine environments.

The findings of this study are mentioned here: the bacteria Bascillus subtilis maintain the same pH as concrete. It has been found that Compressive strength, Flexural strength, and Split tensile strength of bacterial concrete are greater than those of normal concrete. The target strength of M30 and M40 conventional concrete is less than that of the corresponding bacterial concrete. Hence, the bacterial concrete can replace the normal concrete. There has been a reduction in pore size in the concrete structure. Also, the Cracks are inevitable in concrete, though the bacterial concrete has its crack healing or self-healing capacity, it can easily repair the cracks by lime precipitation. Then oxidation of iron causes rusting in the normal concrete, but the bacterial concrete prevents the reinforcement from being corroded due to its very low porosity and moisture consumption by the bacteria. The bacterial concrete has a greater bending stress compared with the normal concrete. The capacity of load carrying in the bacterial concrete is higher than that of Normal concrete, and it continues the service life of structures, specifically in Marine conditions. The cracks and corrosion are considered the major issues in the realm of durability of the concrete structures, and the Bacterial Concrete is one of the better solutions to that. It is a suitable natural, eco-friendly, organic material, and it can be utilized to prevent excessive corrosion in the marine environment than other methods and materials. Although the bacterial concrete cost is higher than conventional concrete, it could be balanced by replacing fine aggregate with RHA.

The RHA can act as a nutrient for bacterial growth, and it also exhibits high pozzolanic characteristics and contributes to the high impermeability of concrete. The RC beam with bacteria and the RHA is resistant to corrosion, and it has higher strength than conventional concrete. Also, the RHA causes a reduction in the water content of concrete. The water absorption property of the RHA can cause a negative effect on workability. But the eco-friendly and organic material, Corn starch, increases the workability of concrete. But the corn starch tends to decrease compressive strength. The silica fumes can solve this problem by increasing compressive strength. As these admixtures were added to the Bacterial Concrete, high-strength nonporous concrete was acquired. Because of its nonporous nature, the reinforced concrete has a longer lifespan, and corrosion is resisted. Bacterial concrete with silica and corn starch as admixtures provided a better result than the normal concrete. The bacterial concrete uses these admixtures in the construction near the marine areas or structures. Also, this mix can prevent the corrosion of reinforcement, and it provides good strength and life to the structure.

It examined the practical possibilities of the RHA to strengthen the endurance of M40-grade concrete. The study results indicated that an increase of more than 5% leads to decreases in the particle cohesion, which was indicated by the slump tests. Also, the findings of the study provide new possibilities to increase the strength of the concrete. Also, it revealed that integration of five to ten percent corn starch in the cement mortar has resulted in increased flowability and the setting time, while maintaining the shrinkage, strength, and durability parameters. Additionally, these significant discoveries have the potential to revolutionize the concrete manufacturing process. It also pinpointed that the optimum quantity of corn starch is ten percent. Moreover, to increase concrete's performance, this study introduced 0.5 percent silica fume and provided better solutions to increase the concrete's durability and strength.

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PMP: Conceptualization, experimental analysis, and writing, SP: Research Design and Supervision. All authors read and accepted the manuscript.

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