

Self-Healing Concrete for Durability Enhancement in Marine Environment

Marine Concrete Including ICCP

James Rajan B¹, Sujithra G², Vijaya B³
^{1,2}*Sivaji College of Engineering Technology*
³*MET Engineering College-INDIA*
doi.org/10.64643/IJRTV12I11-201243-459

Abstract—Concrete structures in marine environments are exposed to aggressive conditions such as chloride ingress, carbonation, and cyclic wetting and drying, which lead to cracking and reinforcement corrosion. This study focuses on the application of self-healing concrete as an advanced and sustainable material to enhance durability in marine conditions. The self-healing mechanism, primarily based on bacterial-induced calcium carbonate (CaCO₃) precipitation, enables autonomous crack repair and significantly reduces permeability. An experimental program was conducted to evaluate the performance of self-healing concrete using durability assessment tests including rapid chloride penetration, water permeability, and carbonation evaluation. The results indicate a substantial reduction in chloride ingress and improved resistance to environmental degradation compared to conventional concrete. The study demonstrates that self-healing concrete is a promising solution for improving the service life and durability of marine infrastructure.

Index Terms—Bacterial self-healing concrete; marine environment; durability; calcium carbonate (CaCO₃) precipitation; chloride ingress; rapid chloride penetration test (RCPT); carbonation; corrosion resistance.

I. INTRODUCTION

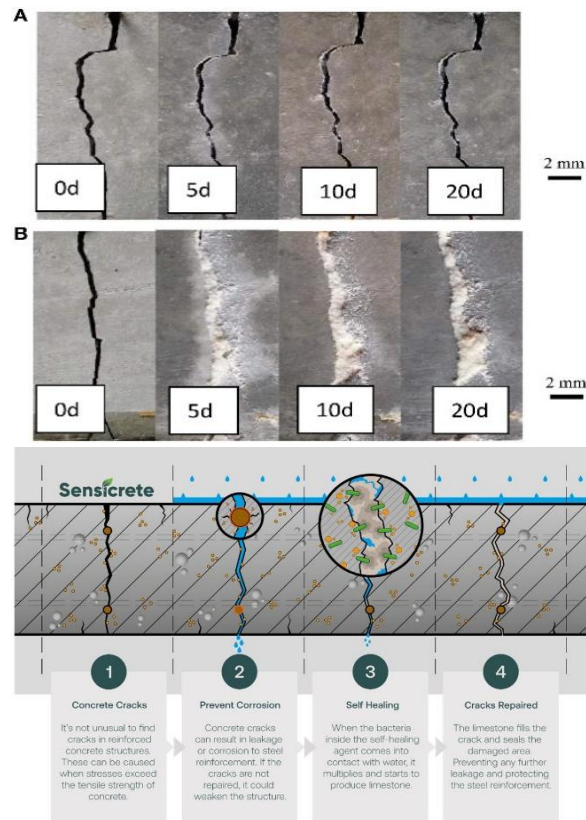
Self-Healing Concrete in Marine Environment
Concrete structures in marine environments are continuously exposed to aggressive conditions such as chloride ingress, carbonation, and cyclic wetting and drying, which lead to the formation of microcracks and deterioration of concrete. These cracks act as pathways for the ingress of seawater, chloride ions, and dissolved oxygen, ultimately resulting in reinforcement corrosion and reduction in structural durability.

Crack formation in concrete is inevitable due to shrinkage, thermal stresses, and external loading. In marine conditions, these cracks significantly accelerate the penetration of harmful agents, leading to progressive damage. Therefore, controlling crack propagation and sealing microcracks is a critical requirement for enhancing the service life of marine infrastructure.

Self-healing concrete has emerged as an innovative solution to address this challenge. In bacterial self-healing concrete, specific microorganisms such as *Bacillus* species remain dormant within the concrete matrix and become active when water enters through cracks. These bacteria induce the precipitation of calcium carbonate (CaCO₃) through biochemical reactions. The formed CaCO₃ crystals deposit within cracks, voids, and pores, effectively filling the gaps and restoring the integrity of the material.

The precipitation of CaCO₃ not only seals visible cracks but also blocks micro-pores, reducing permeability and preventing further ingress of chloride ions. This process significantly limits corrosion of reinforcement and enhances durability, particularly in aggressive marine environments. The ability of CaCO₃ to fill cracks and create a dense microstructure plays a vital role in improving the long-term performance of concrete structures.

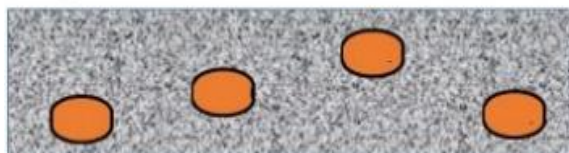
Therefore, the application of bacterial self-healing concrete presents a promising approach for mitigating crack-related deterioration and improving the durability and sustainability of marine infrastructure.



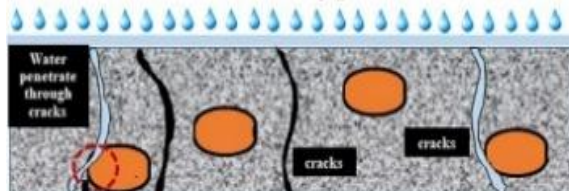
1. Make pellets of urease positive endospore forming bacteria



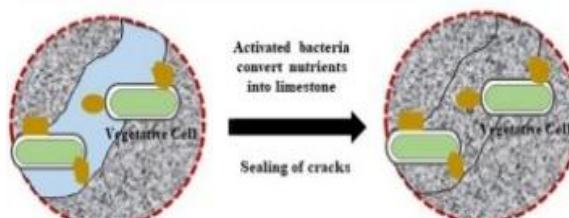
2. Mix pellets with concrete mix and make the structure



3. Crack in the concrete structure and seepage of water



4. Activation of bacteria, nutrient utilization, and healing of cracks



II. MARINE ENVIRONMENTAL EXPOSURE

Concrete structures in marine environments are exposed to highly aggressive conditions that significantly influence their durability and service life. The severity of deterioration depends on the exposure zone, which governs the extent of moisture variation, oxygen availability, and chloride penetration.

Marine structures are generally classified into the following exposure zones:

- **Splash Zone:**

This is the most critical zone, subjected to continuous wetting and drying cycles due to wave action. It experiences high oxygen availability and chloride concentration, leading to severe corrosion risk.

- **Tidal Zone:**

This zone undergoes periodic immersion and exposure due to tidal variations. The cyclic nature of exposure accelerates chloride ingress and promotes corrosion processes.

- **Submerged Zone:**

Structures in this zone remain continuously immersed in seawater. Although chloride concentration is high, the limited oxygen availability reduces the rate of corrosion compared to the splash zone.

- **Atmospheric Zone:**

This zone is exposed to marine air containing moisture and carbon dioxide (CO₂). Carbonation occurs in this region, reducing the alkalinity of concrete and increasing the vulnerability of reinforcement to corrosion.

Among these factors, chloride ingress is the primary cause of reinforcement corrosion in marine environments, as chloride ions penetrate through cracks and pores, breaking down the protective passive layer around steel reinforcement. Therefore, controlling permeability and sealing cracks are essential for improving the durability of marine concrete structures.

III. SELF-HEALING

A. Bacterial Self-Healing Process

In bacterial self-healing concrete, specific microorganisms such as *Bacillus* species are

incorporated into the concrete matrix in a dormant state. These bacteria can survive in the highly alkaline environment of concrete by forming spores. When cracks develop and water penetrates into the concrete, the bacteria become active and initiate metabolic processes.

The activated bacteria utilize nutrients such as urea and calcium sources present within the concrete to produce calcium carbonate (CaCO_3) through biochemical reactions. The precipitated CaCO_3 crystals are deposited within cracks, voids, and capillary pores, effectively sealing them. This process not only closes visible cracks but also reduces permeability by blocking micro-pores, thereby preventing further ingress of chloride ions and moisture.

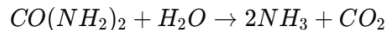
The formation of CaCO_3 within cracks enhances the density of the concrete matrix and restores its durability, which is particularly beneficial in marine environments where chloride-induced corrosion is a major concern.

B. Chemical Reactions

The self-healing process in bacterial concrete is governed by a series of biochemical and chemical reactions that lead to the precipitation of calcium carbonate (CaCO_3), which fills cracks and pores.:

1. Urea Hydrolysis

Urea is hydrolyzed by bacteria to produce ammonia and carbon dioxide, initiating the healing reaction.



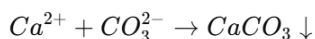
2. Formation of Carbonate Ions

Carbon dioxide reacts with water to form carbonate ions, which are essential for calcium carbonate formation.



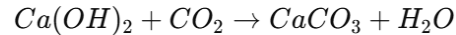
3. Calcium Carbonate Precipitation (Crack Healing)

Calcium ions react with carbonate ions to form calcium carbonate, which fills and seals cracks in concrete.



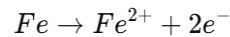
4. Carbonation Reaction (Natural Process)

Carbon dioxide reacts with calcium hydroxide to form calcium carbonate, reducing the alkalinity of concrete and increasing the risk of reinforcement corrosion if not controlled.



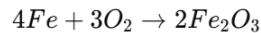
5. Corrosion Reaction of Reinforcement Anodic reaction:

Iron from the reinforcement loses electrons and forms ferrous ions, initiating the corrosion process.



Formation of rust:

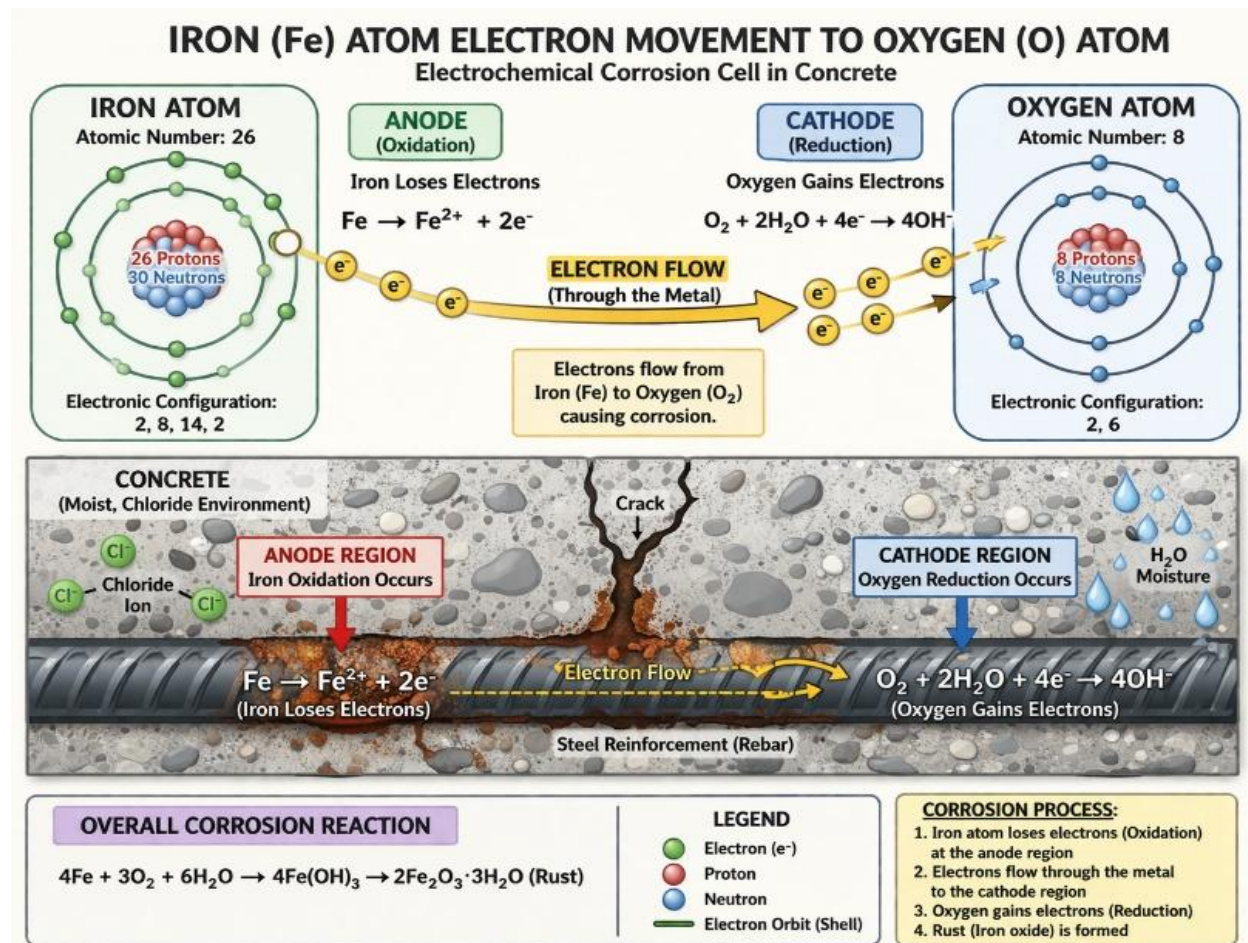
Iron reacts with oxygen to form iron oxide (rust), which leads to expansion and cracking of concrete.



The atomic structure of iron (Fe) contains outer shell electrons that are easily released during oxidation, initiating an electrochemical process in which electrons flow from iron to oxygen (O_2). This results in the formation of a corrosion cell, leading to the production of iron oxides (rust). The expansion of rust causes internal stresses, which ultimately lead to cracking and deterioration of reinforced concrete.

As cracks develop in concrete, they act as pathways for the ingress of oxygen, moisture, and chloride ions, particularly in marine environments where chloride concentration is high. These aggressive agents accelerate the corrosion process by breaking down the protective passive layer around the reinforcement, further weakening the structural integrity.

In self-healing concrete, bacterial activity is activated in the presence of water and induces the precipitation of calcium carbonate (CaCO_3) within the cracks. The deposited CaCO_3 fills cracks and pores, reduces permeability, and limits the ingress of harmful substances, thereby interrupting the corrosion cycle and enhancing the durability and service life of concrete structures.



C. Role of Calcium Carbonate in Crack Healing and Durability

The precipitation of calcium carbonate (CaCO_3) plays a critical role in the self-healing process of concrete. The CaCO_3 crystals formed through bacterial activity are deposited within cracks, voids, and capillary pores, effectively filling the discontinuities in the concrete matrix. This process leads to a significant reduction in permeability and restricts the ingress of harmful agents such as chloride ions, water, and dissolved oxygen. In marine environments, where chloride-induced corrosion is the dominant deterioration mechanism, the ability of CaCO_3 to block microcracks is particularly important. The deposited CaCO_3 not only seals surface cracks but also densifies the internal microstructure of concrete, thereby improving its resistance to aggressive environmental exposure.

Furthermore, the formation of CaCO_3 enhances the mechanical properties of concrete by restoring partial strength lost due to cracking. The healing efficiency depends on factors such as crack width, bacterial

concentration, and availability of nutrients. Typically, cracks up to 0.3–0.5 mm can be effectively healed through this mechanism.

D. Influence of Self-Healing on Marine Durability

Self-healing concrete significantly improves durability performance in marine conditions by mitigating the primary causes of deterioration. The sealing of cracks reduces water permeability and prevents chloride ingress, which is the main factor responsible for reinforcement corrosion.

In addition, the reduction in pore connectivity limits the diffusion of aggressive ions, thereby enhancing resistance to sulphate attack and carbonation. The maintenance of an alkaline environment within the concrete helps in preserving the passive layer around reinforcement, delaying the initiation of corrosion.

The combined effect of crack sealing and pore blocking results in improved long-term performance, reduced maintenance requirements, and increased service life of marine structures.

E. Microstructural Enhancement Due to CaCO_3 Formation

At the microstructural level, the deposition of calcium carbonate leads to the refinement of pore structure within the cement matrix. The CaCO_3 crystals act as fillers, reducing porosity and enhancing the density of the interfacial transition zone (ITZ) between aggregate and cement paste.

This densification improves the resistance of concrete to fluid transport mechanisms such as capillary suction and diffusion. As a result, the durability properties of concrete, including permeability, sorptivity and resistance to chemical attack, are significantly enhanced.

F. Practical Significance in Marine Structures

The application of bacterial self-healing concrete is particularly beneficial in marine infrastructure such as quay walls, offshore platforms, bridge piers, and breakwaters. These structures are subjected to continuous exposure to seawater and require high durability performance.

By reducing crack propagation and limiting chloride ingress, self-healing concrete minimizes the risk of reinforcement corrosion and structural damage. This leads to reduced maintenance costs and improved sustainability of marine infrastructure.

IV. EXPERIMENTAL PROGRAM

A. Materials

Concrete specimens were prepared using Ordinary Portland Cement (OPC), fine and coarse aggregates, potable water, and bacterial culture (*Bacillus* species). To enhance durability and microstructural properties, Ground Granulated Blast Furnace Slag (GGBS) and micro silica (silica fume) were incorporated as supplementary cementitious materials. GGBS improves resistance to chloride ingress, while micro silica enhances particle packing and reduces permeability. Nutrients such as urea and calcium sources were added to promote calcium carbonate (CaCO_3) precipitation for self-healing action.

B. Mix Proportion

- Water-cement ratio: 0.40–0.45
- Bacterial concentration: 10^5 – 10^7 cells/ml
- GGBS replacement: 20–40% of cement

- Micro silica (silica fume): 5–10% of cement
- Control mix and self-healing mix prepared for comparison

C. Specimen Details

- Cube: $150 \times 150 \times 150$ mm
- Cylinder: 150×300 mm

D. Crack Induction

Controlled loading was applied to generate cracks with widths ranging from 0.2 mm to 0.5 mm, suitable for evaluating self-healing efficiency.

E. Marine Simulation

Specimens were exposed to 3.5% NaCl solution and subjected to wet-dry cycles to simulate marine environmental conditions. This exposure accelerates chloride ingress and allows evaluation of durability performance under realistic service conditions.

F. Compressive Strength of concrete

The results indicate that self-healing concrete exhibits slightly higher compressive strength compared to conventional concrete. This improvement is attributed to the formation of calcium carbonate (CaCO_3), which fills microcracks and pores, resulting in a denser concrete matrix.

At 28 days, the strength gain is more significant due to continued bacterial activity and crystallization, which enhances the bonding within the concrete. The presence of GGBS and micro silica further contributes to strength development by improving particle packing and reducing porosity.

Age (Days)	Conventional Concrete (MPa)	Self-Healing Concrete (MPa)
7 Days	25–30	28–32
28 Days	35–40	40–45

G. Phenolphthalein Indicator Test for Concrete (CaCO_3 / Carbonation Test)

The Phenolphthalein indicator test is a simple and effective method to evaluate carbonation depth and self-healing performance in concrete.

In self-healing concrete, this test plays a crucial role in verifying the formation of Calcium Carbonate (CaCO_3)

due to healing mechanisms such as bacterial action or chemical reactions.

Relevance to Self-Healing Concrete

Self-healing concrete uses:

- Bacteria (e.g., Bacillus species)
- Healing agents (calcium lactate, urea, etc.)

These react to produce CaCO_3 , which:

- Fills cracks
- Blocks pores
- Reduces permeability

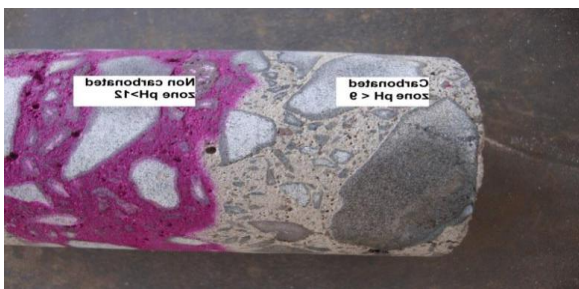
This process reduces pH locally in healed zones (similar to carbonation), making the phenolphthalein test highly useful.

Test Procedure (Adapted for Self-Healing Concrete)

- Prepare cracked concrete specimens.
- Allow healing under controlled conditions (water curing / marine exposure).
- Break the specimen to expose internal surface.
- Spray phenolphthalein solution (1%).
- Observe color variation across healed and unhealed regions.



Carbonation Depth Measurement Test



Carbonation Penetration Depth



Self-Healing Concrete CaCO_3 Test

V. DURABILITY ASSESSMENT TESTS

The durability performance of self-healing concrete in marine conditions was evaluated using a series of standardized tests to assess resistance to chloride ingress, carbonation, permeability, and moisture absorption.

A. Rapid Chloride Penetration Test (RCPT)

This test measures the amount of electrical charge passing through concrete, which indicates its resistance to chloride ion penetration.

Self-healing concrete shows lower Coulomb values, which means reduced permeability. This improvement is due to the formation of calcium carbonate (CaCO_3) that seals cracks and blocks pores, preventing chloride ingress.

B. Carbonation Test

This test is carried out using a phenolphthalein indicator to determine the depth of carbonation. Carbonation may begin within 1 to 5 years, depending on exposure conditions and concrete quality.

Self-healing concrete shows reduced carbonation depth because crack sealing limits the entry of carbon dioxide (CO_2) and helps maintain the alkalinity of concrete.

C. Alkalinity (pH) Test

This test is used to measure the pH level of concrete. A decrease in pH indicates carbonation and loss of the protective layer around steel reinforcement.

Self-healing concrete maintains a higher pH level by reducing permeability and preventing CO_2 penetration, thereby protecting reinforcement from corrosion.

D. Water Permeability Test

This test evaluates the resistance of concrete to water penetration under pressure.

Self-healing concrete shows lower permeability because CaCO_3 fills cracks and pores, blocking the flow of water and improving durability.

E. Sorptivity Test

This test measures the rate of capillary water absorption in concrete.

Self-healing concrete exhibits lower sorptivity values, indicating reduced capillary pores and improved resistance to moisture ingress.

VI. RESULTS AND DISCUSSION

Table 1 Durability Comparison

Sl. No	Durability Comparison		
	Property	Conventional Concrete	Self-Healing Concrete
1	RCPT (Coulombs)	3000–4000	800–1500
2	Permeability	High	Low
3	Carbonation Depth	High	Reduced
4	Crack Width	0.3 mm	mm

A. Discussion

The results clearly indicate that self-healing concrete performs significantly better than conventional concrete in terms of durability. The Rapid Chloride Penetration Test (RCPT) values are considerably lower, indicating improved resistance to chloride ion ingress. This reduction is primarily due to the precipitation of calcium carbonate (CaCO_3), which seals cracks and blocks pore pathways.

Carbonation depth is also reduced in self-healing concrete, as the crack-sealing mechanism limits the penetration of carbon dioxide into the concrete matrix. This helps in maintaining the alkalinity required to protect steel reinforcement.

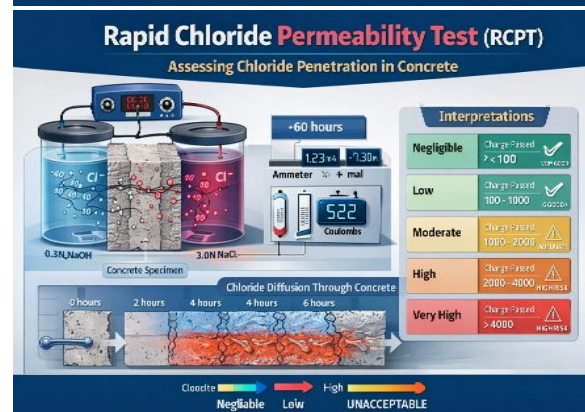
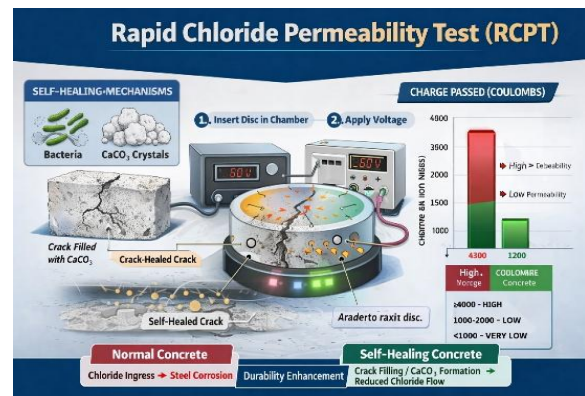
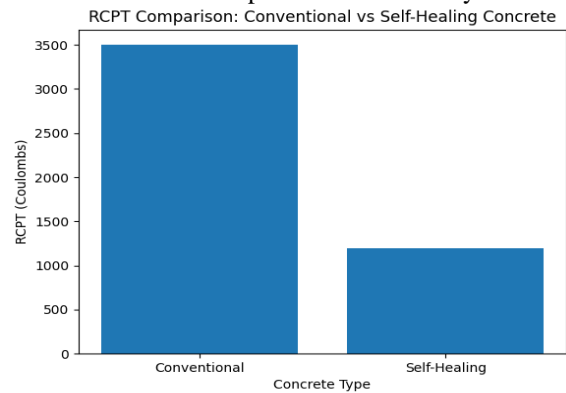
Furthermore, the permeability of self-healing concrete is significantly lower compared to conventional concrete. The formation of CaCO_3 within cracks and pores reduces the connectivity of capillary voids, thereby restricting the flow of water and aggressive agents.

Overall, the reduction in crack width and improvement in microstructure contribute to enhanced durability, making self-healing concrete highly suitable for marine environments.

B. Graph Explanation

The graphical results indicate a significant reduction in chloride permeability in self-healing concrete, as evidenced by lower RCPT values compared to conventional concrete. This improvement is attributed to the formation of calcium carbonate (CaCO_3), which effectively seals cracks and blocks pore pathways.

The carbonation depth is also reduced in self-healing concrete due to the crack-sealing mechanism, which limits the penetration of carbon dioxide into the concrete matrix and helps maintain alkalinity.



In addition, the overall permeability of concrete decreases as the deposited CaCO_3 blocks capillary pores, restricting the movement of water and

aggressive ions. This combined effect contributes to enhanced durability and improved performance in marine environments.

VII. COMPARISON WITH CONVENTIONAL CONCRETE

Self-healing concrete demonstrates superior performance compared to conventional concrete, particularly in terms of crack control, permeability reduction, and resistance to chloride ingress. In conventional concrete, cracks remain unsealed and act as pathways for the penetration of water, oxygen, and chloride ions, leading to progressive deterioration and reinforcement corrosion over time.

In contrast, self-healing concrete has the ability to autonomously repair cracks through the precipitation of calcium carbonate (CaCO_3). This crack-sealing mechanism reduces permeability, limits the ingress of aggressive agents, and helps maintain the alkalinity of the concrete matrix. As a result, the rate of corrosion is significantly reduced.

Overall, self-healing concrete enhances long-term durability, reduces maintenance requirements, and improves the service life of structures, making it a more sustainable and effective solution for marine environments.

VIII. INTEGRATION WITH ICCP SYSTEM

Self-healing concrete can be effectively integrated with Impressed Current Cathodic Protection (ICCP) systems to provide enhanced corrosion control in marine structures. While self-healing concrete offers passive protection by sealing cracks through calcium carbonate (CaCO_3) precipitation, ICCP provides active protection by supplying external current to the steel reinforcement, preventing oxidation.

The crack-sealing ability of self-healing concrete reduces the ingress of chloride ions, oxygen, and moisture, thereby minimizing the initiation of corrosion. At the same time, the ICCP system ensures that the steel reinforcement remains in a cathodic state by supplying electrons, which further inhibits corrosion reactions.

The combination of these two technologies creates a dual protection mechanism, where self-healing concrete improves the durability of the concrete matrix and ICCP actively protects the embedded steel. This

integrated approach is particularly effective in aggressive marine environments, where long-term durability and corrosion resistance are critical.

IX. LIMITATIONS AND CHALLENGES

Despite its advantages, self-healing concrete has certain limitations that need to be considered for practical implementation. One of the primary challenges is the relatively high initial cost associated with the incorporation of bacterial agents and nutrients, which may increase the overall construction cost.

Another important limitation is the survival and effectiveness of bacteria in harsh environmental conditions, particularly in highly alkaline concrete and aggressive marine environments. The efficiency of the self-healing process may reduce over time if the bacterial activity is not sustained.

In addition, the crack-healing capability of self-healing concrete is generally limited to small crack widths, typically up to 0.5 mm. Cracks wider than this range may not be effectively healed, requiring additional repair methods.

Furthermore, long-term performance and field validation of self-healing concrete are still under investigation. More studies and large-scale applications are required to fully understand its durability and reliability over extended service periods.

X. CONCLUSION

Self-healing concrete provides an effective and sustainable solution for improving durability in marine environments. The bacterial-induced precipitation of calcium carbonate (CaCO_3) enables autonomous crack repair, which reduces permeability and limits the ingress of chloride ions and other aggressive agents.

The experimental results confirm significant improvements in durability performance, including lower RCPT values, reduced carbonation depth, and enhanced resistance to corrosion compared to conventional concrete. The ability of self-healing concrete to seal cracks and maintain the internal integrity of the concrete matrix plays a crucial role in extending structural service life.

Furthermore, the integration of self-healing concrete with systems such as Impressed Current Cathodic Protection (ICCP) offers a combined passive and active protection mechanism, providing a more

comprehensive approach to corrosion control. Overall, self-healing concrete represents a promising advancement for durable, sustainable, and long-lasting marine infrastructure.

REFERENCES

- [1] M. Jonkers, "Bacteria-based self-healing concrete," *HERON*, vol. 56, no. 1/2, pp. 1–12, 2011.
- [2] K. Van Tittelboom and N. De Belie, "Self-healing in cementitious materials—A review," *Materials*, vol. 6, no. 6, pp. 2182–2217, 2013.
- [3] V. Wiktor and H. M. Jonkers, "Quantification of crack-healing in novel bacteria-based self-healing concrete," *Cement and Concrete Composites*, vol. 33, pp. 763–770, 2011.
- [4] Wang, K. Van Tittelboom, N. De Belie, and W. Verstraete, "Use of silica gel or polyurethane immobilized bacteria for self-healing concrete," *Construction and Building Materials*, vol. 26, pp. 532–540, 2012.
- [5] S. Lular and G. Suthar, "A review paper on self-healing concrete," *Journal of Civil Engineering Research*, vol. 5, no. 3, pp. 53–58, 2015.
- [6] ASTM C1202-19, "Standard test method for electrical indication of concrete's ability to resist chloride ion penetration," ASTM International, 2019.
- [7] ACI Committee 224R, "Control of cracking in concrete structures," American Concrete Institute, 2001.
- [8] ACI Committee 318, "Building code requirements for structural concrete," American Concrete Institute, 2019.
- [9] Bureau of Indian Standards, *IS 456:2000: Plain and reinforced concrete – Code of practice*, 2000.
- [10] EN 206, *Concrete – Specification, performance, production and conformity*, European Standard, 2013.
- [11] P. K. Mehta and P. J. M. Monteiro, *Concrete: Microstructure, Properties, and Materials*. New York, NY, USA: McGraw-Hill, 2014.
- [12] M. Neville, *Properties of Concrete*, 5th ed. Harlow, U.K.: Pearson Education, 2011.
- [13] N. De Muynck, N. De Belie, and W. Verstraete, "Microbial carbonate precipitation in construction materials," *Ecological Engineering*, vol. 36, pp. 118–136, 2010.
- [14] S. Ramachandran, V. Ramakrishnan, and S. S. Bang, "Remediation of concrete using microorganisms," *ACI Materials Journal*, vol. 98, no. 1, pp. 3–9, 2001.
- [15] M. D. A. Thomas and P. B. Bamforth, "Modelling chloride diffusion in concrete," *Cement and Concrete Research*, vol. 29, pp. 487–495, 1999.