A review of Bacteria based self-healing concrete

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Abstract - *The characteristics and uses of bacterial concrete are thoroughly examined in this essay, with an emphasis on the material's capacity for self-healing. It starts by treating the microcracks that are naturally present in concrete, which cause toxic elements to seep in and cause structural damage. Concrete regeneration is essential, and bio-mineralization methods hold promise for closing these microcracks through continuous hydration processes. Microbiologically induced calcite precipitation (MICP), which is well-known for its ability to reinforce concrete integrity, is the most used technique for this. The study emphasizes how encapsulation techniques are preferable to direct application for better concrete restoration results. It highlights the function of urease-producing bacteria, such Bacillus Pasteurii and Bacillus Subtilis, which, when paired with a calcium supply, promote calcite precipitation ($CaCO_3$). By encouraging a strong pore structure, this response aids in the efficient sealing of concrete fractures. The study highlights that the flexibility of bacterial concentrations is crucial for improving concrete's durability and that including such bacteria enhances the material's overall strength and toughness in addition to helping it self-heal. Finally, it examines the various uses of bacterial agents in concrete healing and the variations in performance based on the application technique thereby outlining the benefits of incorporating bacterial technologies in concrete engineering.*

Key Words: *Bacterial Concrete, Self-healing Concrete, Bacteria, Self-healing, Micro-cracks, $CaCO_3$ precipitation,*

1. INTRODUCTION

1.1 Concrete: Concrete is a prevalent construction material, known for its strength in compression but weakness in tension, leading to inevitable cracking that diminishes structural lifespan. Traditional repair methods are costly and labor intensive. An innovative solution involves self-healing concrete that incorporates bacteria nourishing on calcium. These bacteria promote calcium carbonate precipitation to effectively seal cracks, enhancing both strength and durability. Specifically, cracks larger than 0.8mm pose repair challenges, yet bacterial reinforcement shows promise. Lightweight aggregates can substitute fine aggregate, boost bacterial mortar strength while facilitate better healing efficiency. The application of Rice husk ash and fly ash with bacteria further improves mechanical properties and reduces porosity, with strength gains up to 24% and 22%, respectively. Recent self-healing techniques, including hydrogel encapsulation and vascular systems, demonstrate significant potential for early-stage crack remediation. This study aims to review the influence of bacteria on concrete properties and the various bacterial types utilized for calcium carbonate precipitation.

1.2 Self-healing approach and ways of applying bacteria in concrete

a. **Self-healing approach:** When damage is detected, a healing agent is released by an ideal self-healing concrete system. Microorganisms that precipitate calcium carbonate are used in self-healing treatments, including autogenous healing, to successfully mend microcracks. In the very alkaline conditions of concrete, bacteria like Bacillus Sphaericus flourish. They convert urea into ammonium and carbonate, which generates CaCO3, which fills fractures and binds concrete ingredients like sand and gravel. Larger fissures require bacterial activation from hibernation in order to heal over time, but cracks less than 0.2 mm can be fixed by the concrete itself. This process, called Microbiologically Induced Calcium Carbonate Precipitation (MICP), uses bacteria as a persistent remedy. various metabolic routes are used by various microorganisms to create calcium carbonate; heterotrophic methods produce more precipitate than autotrophic ones. In essence, the breakdown of urea by bacterial urease catalyzes the conversion required for the creation of calcium carbonate, improving pH and carbonate levels in the surrounding environment and eventually promoting concrete's ability to heal itself.

The negative charge of the bacterial cell wall makes it easier for cations, such as Ca2+, to be absorbed. This causes calcium carbonate to precipitate at the cell surface, which serves as a nucleation site. Through urealysis, a variety of microorganisms may precipitate calcium carbonate, improving the qualities of concrete. Bacillus aerius enhances the endurance of rice husk ash concrete, whereas Bacillus subtilis boosts concrete strength using lightweight particles and graphite nanoplatelets. Bacillus sphaericus increases the durability of concrete, whereas Bacillus megaterium increases compressive strength by 24%. Through bacterial carbonate precipitation, Sporosarcina pasteurii adds to surface treatment choices and exhibits self-healing properties in fly ash and silica fume concretes.

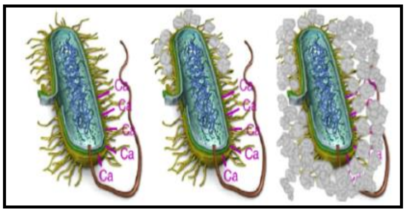


Fig. 1. Calcium carbonates formation on bacterial cell wall.

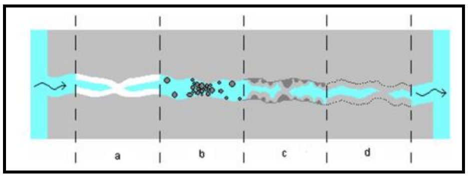


Fig. 2. Potential cementitious material self-healing processes

2. LITERATURE REVIEW:

- **Pui Yan Wong et al. (2024)** studied **the** healing mechanism of bacterial concrete using Microbial-Induced Calcium Carbonate Precipitation. They found that healing depends on pH (9–11), moisture, and oxygen, and identified nutrient depletion as a limitation. They suggested using bacteria + fungi systems.
- **Nirakar Pradhan et al. (2024)** focused on durability. Their results showed a reduction in water permeability (up to 60%), less chloride penetration, and better long-term performance. However, they noted a lack of real-world (field) studies.
- **Ajitanshu Vedrtnam et al. (2025)** studied carbon capture in bio-concrete. They found that some bacteria can absorb CO_2 during calcite formation, making concrete more eco-friendly. They introduced the idea of carbon-negative concrete.
- **Abeer M. Eisa et al. (2025)** developed rubberized bacterial concrete using recycled rubber and *Bacillus subtilis.* They found better crack healing, but a slight decrease in strength. This supports waste material use in construction.
- **P. Ingle, M. Shrestha, R. Potdar (2017)** this paper has presented the bio concrete with and without risk husk and also permeability compressive strength tests they are did by introducing of B. pasteurii. They use 2%, 4% and 6% rise husk replacing cement and used several bacterial solutions like 103, 105 and 107cells/ml I production of concrete. Finally, they concluded that compressive strength rise, permeability and porosity of rice husk concrete is decrease by the introduction of B. pasteurii and also enhances durability.
- **S. Sanjay, S. Neha, and R. Jasvir (2016),** This paper was presented the experimental investigation on bacterial concrete to increase the strength of bio concrete and to inform the process involved in the bacterial concrete to know the calcite crystals formed in bacterial concrete analysis of microstructure has been done that is used for the potential to recovery the cracks in bacterial concrete and also to inform the biological reaction in concrete. As a result, has been got because of good adaptability of nutrient broth medium of bio concrete at 28 days attained better strength when compare to conventional concrete.
- **Kunal R. Patil, B. Waghere, B. K. Ahire, et al (2016),** This research has been informed that an experiment on bio concrete with the several type of bacteria B. pasteurii and bacillus sharicus to enhancing durability and strength of concrete with the mechanism of MICP at age of 7,28 days. They found that when bacteria are added to the concrete its gives less compressive strength than nutrient broth solution by bacillus sphaericus and B. pasteurii.
- **Prof. M. Manjunath, A. A. Kalaje, Santosh A. Kadapure, (2014),** This paper was presented the observation they are did the tests on the mechanical properties of concrete, chloride permeability and water absorption and also fly ash replacing cement by 10% and 20% with bacterial solutions of 103,105,107 using B. Sphaericus at age of 28 days. Generally, they concluded that mechanical properties are improved by the presence of bacteria and decrease water absorption and permeability. The better results gain at bacterial solution of 105cells/ml.
- **N. Chahal and R. Siddique (2008)** this study has been presented that with use of Sporosarcina pasteurii which would make it, self-healing. They observed that newly formed cracks healed by the presence of bacteria. In the concrete mix 10%, 20% and 30% and also 5% and 10% dosage of fly ash and silica fume respectively replacing cement in the bacterial solution of 103, 105 and 107 cells/ml. They did tests on the water absorption and porosity, chloride permeability and compressive strength by using up to age 91 days. They concluded that by the presence of S. pasteurii increase compressive strength, cut downs the permeability and porosity of silica fume and fly ash concrete.
- **N. Ganesh and Dr. S. Siddiraju,** this paper has been informed using calcium lactate and bacteria to repair the cracks percentages of bacteria selected for the study are 3.5% and 5% with mass of cement. The cement replacing with 10% and 5 % of calcium lactate was used in concrete in this experiment B. pasteurii bacterial species is used with different

concentrations of bacterial for an M40 concrete grade. Several tests are done in this investigation such as elastic modulus, flexural strength, and compressive strength the cubes of dimensions of 10x10x10 cm were used for the compressive strength test it was found that 40.53 MPa and 19.8 MPa for 28 and 7 days by using calcium lactate for normal concrete of compressive strength tests respectively and from this they observed reducing of compressive strength due to calcium lactate and also 10% is optimum dosage of calcium lactate by the introducing of bacteria in concrete they found enhancing of the properties of concrete and of concrete which is better than conventional concrete. Finally, they concluded that effective self-healing agent produced by using 5% of bacteria and 3.5% of calcium lactate.

- **Chintalapudi kartik** et all: Carried the work on bacterial concrete, the addition of urease producing bacteria along with calcium source results in calcium precipitation in concrete. Experiments showed that the cell concentration of 106 cells/ml of water in the cement paste and mortar specimens has higher compressive strength gain was up to 39.80%, 33.07% and 50%, 28.20% respectively.
- **G. Mohit and P. Krishna Chaitanya,** this paper has presented that, experimental investigation on bacterial concrete by B. pasteurii bacterial species and also compare the results with the normal concrete within this cement is replacing by 30% of GGBS and fly ash in M25 concrete grade. Different tests have been conducted in this investigation tests like X-Ray diffraction test, compressive strength, flexural strength, slump flow test and split tensile strength for several sample of 40ml, 50ml, and 60ml bacterial concentrations for each sample the compressive strength improved by 30% in bio concrete and bacterial concrete with fly ash by 15% and GGBS by 20%. It was found that bio concrete of 40ml and 50ml bacterial solution is attains extreme flexural strength and split tensile strength but it's not true for 60ml bacterial solution after 14 days when they did flexural tensile strength also, the optimum dosage of bacterial solution used in concrete is 50ml l it's the point of maximum improvement of mechanical properties of bacterial concrete. Generally, more $CaCO_3$ is produce in concrete because of bacteria species which has enhancing durability of structure due to reducing of voids by 10%.

3. AIM & OBJECTIVES

3.1 Aim & Objectives:

- To study the behavior of bacteria-based self-healing concrete using the concept of Microbial-Induced Calcium Carbonate Precipitation.
- Compare the effect of bacterial species such as Bacillus subtilis, Bacillus sphaericus, and Sporosarcina pasteurii on: Compressive strength durability and crack-healing efficiency
- To study the influence of different parameters such as: Bacterial concentration Nutrient content (e.g., calcium lactate) Environmental conditions (pH, moisture, oxygen)
- To study the use of waste materials (such as rice husk, rubber, fly ash, and GGBS) in bacterial concrete for sustainable construction.

4. METHODS

4.1 Working of Bio concrete as a repair material: Self-healing concrete is a biologically engineered material designed to repair cracks in concrete structures. It incorporates specific bacterial species, such as bacillus, along with calcium lactate and nutrients like nitrogen and phosphorus. These self-healing agents remain viable within the concrete for up to 200 years. When water and nutrients penetrate the porous surface of the concrete, the bacterial spores germinate. The bacteria then feed on calcium lactate, leading to the consumption of oxygen and the conversion of soluble calcium lactate into an impenetrable calcareous compound. This process results in granite-like solidification over the cracks. Furthermore, the consumption of oxygen mitigates corrosion of the embedded steel reinforcement, enhancing the structural integrity of the concrete. The reaction between CO2 and calcium hydroxide in the concrete matrix produces calcium carbonate, contributing to the self-healing properties of the material. Water (H2O) and calcium carbonate (CaCO3) are the products of the reaction between CO2 and calcium hydroxide (Ca(OH)2). Because Ca(OH)2 is soluble, it can seep into cracks when water enters. By breaking down calcium nutrients, bacteria in concrete promote a self-healing mechanism that improves fracture rehabilitation. For example, calcium carbonate, carbon dioxide, and water are produced when calcium acetate reacts with oxygen. This demonstrates how autogenous healing mechanisms aid in the closing of fractures in concrete buildings and how microbial activity directly contributes to the creation of calcium carbonate.

4.2 Self-healing measurement methods: This document discusses various techniques for determining the width of sealed cracks in concrete, predominantly utilizing image surveillance and microscopy. Key technologies include optical imaging, high-pixel camera photography, and X-ray computed tomography, revealing average crack dimensions of 60 μm with polymer filling reaching up to 138 μm. Auxiliary cementing materials have been shown to effectively plug cracks of 200 μm width, while encapsulating microorganisms in concrete can heal wider cracks up to 970 μm, representing a highly effective approach. The combination of chemicals and microorganisms has demonstrated efficacy, extending the self-healing capability to cracks up to 0.22 m wide. The literature indicates that many researchers focus primarily on large-scale mechanical properties to evaluate self-healing effectiveness, with additional assessments of macrostructures highlighting improved results. However, some studies have shown less accuracy in crack analysis when utilizing only microscopy. While microstructure tests are also performed along with durability tests, the reliability of self-healing based solely on durability metrics has been questioned as less effective. Certain researchers have conducted nano-scale effectiveness tests, but evidence suggests that self-curing, macro-mechanical, micro-structure, and nano-structure tests have not been measured in parallel. Future research is urged to adopt a systematic method for evaluating self-healing efficacy in concrete.

4.3 Mechanism of applying the healing agents in concrete: According to research, there are two primary ways to apply healing chemicals to concrete: encapsulation and direct application. The best bacterial concentration was determined by direct application entails adding bacteria to lightweight aggregates and employing graphite nanoplates as carriers. To improve self-healing, encapsulation entails covering aggregates with a polymer after impregnating them with a bacterial solution. This technique has better healing quality, allowing for a wider spectrum of cracks and a quicker response to cracking. Bacterial spores encapsulated in hydrogel have also demonstrated enhanced healing efficacy. After 28 days, the direct application of Shewanella bacteria increased the cement mortar's compressive strength by 25%. By improving the dispersion and defense of bacteria in alkaline settings, these techniques increase the effectiveness of self-healing.

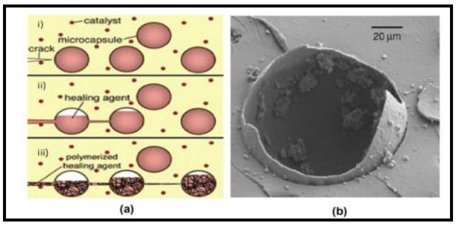
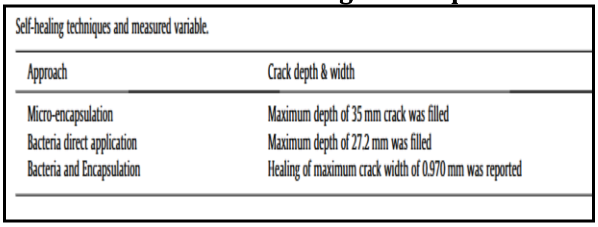


Fig. 3. (a) Simple process of microcapsule approach: (i) Formation of cracks in matrix; (ii) process of releasing healing agent; (iii) process of crack healing and **(b) ESEM image displaying a ruptured microcapsule.**

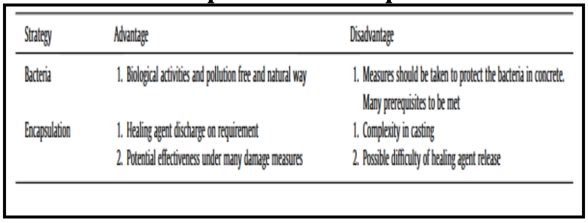
Table-1 Self-healing Technique



Self-healing techniques and measured variable.

Approach	Crack depth & width
Micro-encapsulation	Maximum depth of 35 mm crack was filled
Bacteria direct application	Maximum depth of 27.2 mm was filled
Bacteria and Encapsulation	Healing of maximum crack width of 0.970 mm was reported

Table-2 Summarized Contrast Between Specific Techniques.



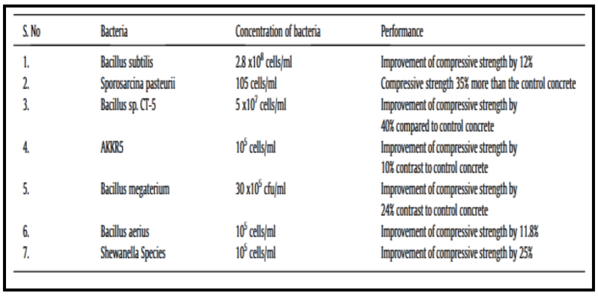
Strategy	Advantage	Disadvantage
Bacteria	1. Biological activities and pollution free and natural way	1. Measures should be taken to protect the bacteria in concrete. Many prerequisites to be met
Encapsulation	1. Healing agent discharge on requirement 2. Potential effectiveness under many damage measures	1. Complexity in casting 2. Possible difficulty of healing agent release

4.4 Effect of bacteria on properties of concrete

a. **Hydration kinetics:** Depending on the type of calcium source utilized, adding bacteria spore powder to concrete can either speed up or slow down its setting time. While calcium format and calcium nitrate speed up the setting time, calcium lactate tends to slow it down.

b. **Compressive strength**: The strength of structural concrete has been enhanced through a biotechnological method involving calcite precipitation. Microbial cells, particularly Bacillus megaterium, thrive in permeable cement mortar, adapting to the high pH during curing, leading to calcite precipitation on the cells and within the mortar matrix. This results in lower porosity and permeability. Higher grade concrete (50 MPa) shows a 24% increase in compressive strength when bacteria are introduced, compared to lower grades. Replacing 10% of cement with fly ash and including Sparcious pasteurii bacteria can enhance compressive strength by 20%. Other studies indicate that different fly ash concentrations improve mortar strength by 19%, 14%, and 10% with bacterial presence. Additionally, the use of nanomaterials like GNP for bacterial distribution further increases compressive strength through microbial calcium carbonate precipitation. Overall, the concrete's compressive strength can significantly improve due to the deposition of $CaCO_3$ from the bacterial activity.

Table-3 Different types of bacteria and their performance.



S. No	Bacteria	Concentration of bacteria	Performance
1.	Bacillus subtilis	2.8 x10^8 cells/ml	Improvement of compressive strength by 12%
2.	Sporosarcina pasteurii	105 cells/ml	Compressive strength 35% more than the control concrete
3.	Bacillus sp. CT-5	5 x10^7 cells/ml	Improvement of compressive strength by 40% compared to control concrete
4.	AKKR5	10^5 cells/ml	Improvement of compressive strength by 10% contrast to control concrete
5.	Bacillus megaterium	30 x10^5 cfu/ml	Improvement of compressive strength by 24% contrast to control concrete
6.	Bacillus aerius	10^5 cells/ml	Improvement of compressive strength by 11.8%
7.	Shewanella Species	10^5 cells/ml	Improvement of compressive strength by 25%

c. **Water permeability:** The durability of concrete under pressure gradients is fundamentally influenced by its permeability, which is linked to the characteristics of its pore network, including porosity, tortuosity, specific surface area, size distribution, connectivity, and micro cracks. These features are affected by the water/cement (w/c) ratio, particle size distribution, age of the materials, and the ingress of aggressive substances. Research indicates that the deposition of calcium carbonate ($CaCO3$) can reduce both the water absorption and permeability of concrete. For instance, studies show that the introduction of the bacteria S. Pasteurii into fly ash concrete significantly reduces porosity and permeability, with a fourfold decrease in water absorption observed at a concentration of 10^5 cells/ml. Similarly, concrete specimens mixed with Bacillus Megaterium demonstrated over three times less water absorption than controls due to microbial calcite deposition. The use of Bacillus Aerius further enhances durability by filling pores with calcite, thereby reducing water absorption and porosity. At 28 days of curing, control specimens exhibited high to moderate permeability, whereas AAKR5 bacterial concrete showed a significant reduction in permeability due to calcium carbonate filling pores. Additionally, microbial precipitation has been shown to improve the quality of recycled aggregates, thereby reducing their water absorption as well.

d. **Chloride ion permeability:** Corrosion of reinforcing steel caused by chloride ingress is a significant environmental threat to concrete structures. The permeability of concrete to chloride ions is influenced by its internal pore structure, which is affected by factors such as mix design, curing methods, hydration levels, the use of supplementary cementitious materials, and construction practices. The Rapid chloride permeability test measures the electrical current passing through concrete samples to assess their chloride permeability. Incorporating bacteria in concrete can enhance resistance to chloride permeation; studies show that concrete containing bacteria had an average reduction of 11.7% in chloride permeability compared to standard concrete. Specifically, Sparcious Pasteurii and Bacillus Subtilis effectively reduce chloride penetration and enhance sulfate exposure resistance. The inclusion of Bacillus Aerius also decreased total charge passed through both control and RHA concrete specimens, with reductions of 55.8%, 49.9%, and 48.4% compared to conventional concrete at 7, 28, and 56 days, respectively. Moreover, Sparcious Pasteurii at an optimal concentration of 105 cells/ml in 10% silica fume concrete demonstrated a significant reduction in rapid chloride penetration (380 coulombs). It was noted that fly ash concrete with Sporoscarcina pasteurii at the same bacterial concentration achieved maximum chloride ion reduction; however, concrete with 30% fly ash yielded only 762 coulombs of penetration, indicating its effectiveness. Thus, the service life of concrete structures, particularly those subject to de-icing salts or marine environments, is largely dependent on their ability to resist chloride ion penetration.

e. **Microstructure:** Calcite precipitation in mortar and concrete was characterized through SEM analysis, revealing rod-shaped bacteria associated with the calcite crystals. This deposition enhances concrete impermeability by acting as a barrier against harmful substances. The introduction of Bacillus Megaterium bacteria at a concentration of 30-105 cfu/ml resulted in a maximum calcium weight increase of 38.76% compared to other bacterial proportions and control samples. SEM, EDS, and XRD analyses confirmed the presence of calcite, primarily as calcium carbonate, thus improving concrete microstructure and durability. The SEM images demonstrated that bacterial concrete contained embedded calcite crystals, effectively filling voids and enhancing the strength of RHA concrete through calcium carbonate deposition. Microstructural results indicated that the calcium carbonate filled cracks, leading to reduced water absorption, chloride permeability, and acid ingress, as evidenced by increased ultrasonic pulse velocity signal transmission rates.

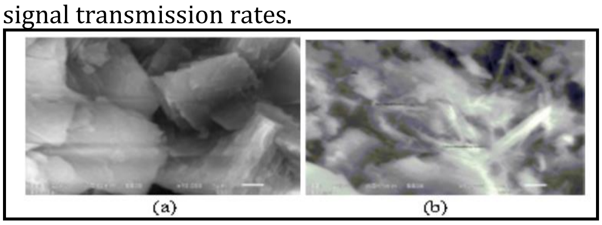

(a) (b)

Fig. 4. SEM Images (a) control concrete (b) Bacterial calcite precipitation in 10% silica fume concrete.

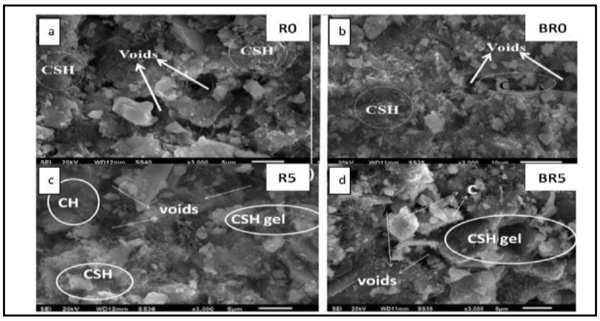


Fig. 5. SEM images of (a) Normal concrete (R0) (b) Bacterial concrete (BR0) (c) 5% of RHA Concrete (R5) (d) Bacterial concrete with 5% RHA (BR5).

5. CONCLUSION

5.1 The following conclusions can be drawn:

i. The study focuses on how urease-producing bacteria, such Bacillus subtilis and Bacillus pasteuri, may repair concrete fractures.
ii. It examines several bacteria that can be used in this way.
iii. The results of the study show that these bacteria have a beneficial effect on the compressive strength of concrete and Portland cement mortar.
iv. The use of bacteria decreases the permeability of chloride ions and water penetration.
v. The study promotes the use of "microbial concrete" as an economical and eco-friendly substitute for conventional concrete sealants, increasing the longevity of construction materials.
vi. The research focuses on the application of urease-producing bacteria, specifically Bacillus subtilis and Bacillus Pasteurii, for concrete crack healing.
vii. Various bacteria types were investigated for their effectiveness in repairing cracks in concrete.
viii. The study found that the compressive strength of concrete is positively influenced by the presence of bacteria.
ix. Bacteria contribute to reducing water penetration and chloride ion permeability in concrete.
x. The findings suggest that "microbial concrete" can serve as a cost-effective and environmentally friendly alternative to traditional concrete, enhancing the durability of building materials.
xi. It concludes that Bacillus Pasteurii and Bacillus subtilis are the most effective bacteria for healing concrete cracks.

6. LIMITATIONS AND FUTURE RESEARCH

- Bacterial concrete offers a promising self-healing solution, but faces challenges before large-scale use.
- The absence of standardized methods for evaluating self-healing efficiency limits comparability across studies.
- Most research occurs in labs, lacking assessments of long-term performance in real-world conditions, such as bacterial viability and nutrient depletion.
- Scalability remains a concern due to insufficient data on large-scale structural testing and healing kinetics modeling.
- Economic viability is questionable due to the costs of bacterial culture, encapsulation, and nutrient supply.
- Environmental impacts, specifically ammonium production from ureolytic bacteria, could affect reinforcement durability.
- Future research should focus on improving bacterial encapsulation and using innovative materials, such as nanomaterials and hydrogels, for enhanced bacterial survivability and spore-release control.
- Investigating novel microbial strains with better metabolic activity and environmental resilience could boost efficiency.
- Analysis of the bonding between cementitious matrix and microbially precipitated calcium carbonate is crucial for load transfer behavior understanding.
- The impact of cyclic loading on MICP-healed concrete needs exploration.
- Comprehensive assessments of life-cycle costs and sustainability are necessary to verify the long-term feasibility of bacterial concrete in structural applications.

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