

Bio-Mediated Self-Healing Concrete: Experimental Investigation for Sustainable Infrastructure Systems

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Abstract

This is very important because there are a vast majority of construction material in infrastructure, and construction material is easily cracked by environmental stresses, shrinkage and mechanical loading. Such fissures enable the entry of water and chemicals that can enhance the corrosion of reinforced concrete and undermine structural stability. An approach to address this issue is a bacterial form of self-healing concrete, which repairs the cracks on its own and extends the longevity of concrete structure. This study investigates the experimental evaluation of a self-healing concrete containing *Bacillus subtilis*. Bacterial cultures and nutrients integrated into concrete were created and prepared. Conventional concrete was also made into control samples to allow comparisons. This included the casting of standard cube specimens (150 mm × 150 mm × 150 mm), at curing periods of 7, 14, and 28 days. Compressive strength tests of mechanical properties were performed and crack healing was checked through the formation of cracks artificially under moist conditions. Bacterial-infused concrete exhibited significantly better compressive strength than conventional samples during all curing intervals. In addition, crack closure found in bacterial specimens attributed to the generation of calcium carbonate from microbes was observed. The calcium mineralization process greatly alleviated the cracks and promoted the robustness of the concrete matrix. In this study, we demonstrate that bacteria-mediated self-healing concrete can function as a self-healing solution for fissures through superior mechanical properties and higher durability, providing an alternative for sustainable infrastructure construction through reduced maintenance needs.

Keywords: Self-healing concrete, bacterial concrete, calcium carbonate precipitation, sustainable construction, crack healing.

1.Introduction

1.1 Background : Concrete is the building material most commonly used in modern infrastructure because of its excellent compressive strength, durability, and economical performance. But cracks are also created due to a myriad of elements like thermal expansion/contraction, mechanical stresses, shrinkage processes, different environmental influences, and so on. Micro-cracks may also allow water ingress and exposure of chlorides and chemicals, leading to steel reinforcement corrosion and degrading its durability over time. Traditional repair methods such as epoxy injection or surface sealing are expensive and a challenge to assess and monitor. But new self-healing concrete technology that was introduced recently offers an innovative solution by enabling fault healing self-repair that is made internally to the structure itself. The approach of bacteria-based techniques which use microbial-induced calcium carbonate precipitation (MICP) serves to efficiently seal the cracks while improving their durability, and this has emerged as a notable method for attaining this healing effect [1–10].

1.2 Challenges : Despite the positive benefits, various barriers limit realization of the self-healing concrete technologies in practice. Another challenge is the poor strength of conventional concrete against crack propagation influenced by environmental factors. And traditional manual repair methods can be expensive and time-consuming when deployed across an extensive infrastructure system. Moreover, the long term effectiveness of crack healing and strength of the matrix used in the manufacturing of concrete should also be considered; the selection of the appropriate bacteria strains and sources of nutrients is really important for the calcium carbonate deposition needed for the cure-resistant crack sealing. Overcoming these challenges is crucial to propel performance metrics and sustainability in self-healing concrete applications [11–16].

1.3 Objectives of the Paper : To investigate the experimental investigation of bacteria-based self-healing concrete through *Bacillus subtilis*, this research is aimed at. This research is intended not only to characterize compressive strength, but also to assess how well this mix which contains bacterial-infused concrete heals cracks when compared with that of regular mixes. For example, how effective this mix, with bacteria in it, can be in breaking down cracks is examined.

1.4 Contributions: This work describes a brief experimental search of bacteria-fueled self-healing concrete for sustainable use cases in infrastructure. It includes *Bacillus subtilis*, which is used in the mix design to help to form calcium carbonate, the required for autonomous repairs to be made during service life. This is reflected through a range of test protocols examining compressive strengths and crack healing efficiencies during a diverse set of curing timeframes, all showing significant improvements compared to control specimens—indicating this novel approach has pragmatic implications for implementations where minimal maintenance is desired in tandem with improved structural integrity.

1.5 Paper Organization : This paper follows a structured introduction to literature in self-healing tech in Section 2; a list of materials used and research methodology in Section 3; results obtained from experiments and followed by analyses in Section 4; recommendations and suggestions in Section 5 of future research directions.

2. Literature Review

In recent years, however, self-healing concrete has brought much research attention in the process of development, owing to its ability to make civil infrastructure more durable and sustainable. Various biological, chemical, and material-based approaches have been researched to realize autonomous crack repair in concrete and other construction sites. Differently, it has been investigated for bacteria-induced calcium carbonate precipitation (MICP) as a capable mechanism during crack healing. Mahmood et al. (2022) studied the self-healing features of bio-concrete by encapsulating *Bacillus subtilis* into iron oxide nanoparticles. The approach entailed embedding bacterial spores within the concrete matrix and then activating them (moisture exposure). Experimental studies showed successful micro and nano crack healing by precipitation of calcium carbonate. The study noted better durability and crack closure efficiency. It cost more and was a more complex process for the concrete production owing to the encapsulation process.

Similarly, Yamasmit et al. (2023) analyzed the effect of *Bacillus subtilis* on the mechanical and healing capacity of the mortar containing various crack widths. This methodology entailed the preparation of mortar samples by cultures of the bacteria and followed the crack healing under controlled curing conditions. Cracks of about 0.5 mm of diameter were successfully sealed by the use of microbial calcite precipitation after 28 days, according to study results. The primary benefit was enhanced durability and recovery of the strength, the efficiency of healing was strongly governed by environmental factors (moisture and nutrient availability).

A study by researchers in 2023 of a bacterial concrete, *Bacillus licheniformis* isolated from agricultural soil, was also conducted. The research used microbial isolation techniques and subsequent addition of bacterial cultures to the concrete mixture. Mechanical and microstructural examinations (SEM and XRD) were used to confirm the formation of calcite crystals that were responsible for crack sealing. Compared to conventional concrete, the concrete of these was found to have more compressive and tensile strength. However, the study noted that bacterial survival in highly alkaline concrete environments is a significant drawback. Durga et al. (2023) performed a comparative experimental investigation and compared various *Bacillus* species such as *Bacillus subtilis*, *Bacillus licheniformis* and *Bacillus cereus*. Different bacterial concentrations were chosen, and permeability and durability qualities of concrete were determined using methods. Bacteria integrated into the concrete increased impermeability and resistive capacity, as calcium carbonate was deposited in pores that reduce water infiltration ability. This technique significantly improved durability performance, but it was necessary to calibrate the optimal bacterial concentration, so that the workability of concrete did not suffer. In a different experiment, researchers studied bacterial concrete bearing different percentages of bacterial solution and calcium lactate as a source of nutrients. Concrete samples were cast containing various concentrations of bacteria and subjected to compression and flexural strength studies. Moderate bacterial concentrations had a remarkable enhancement on the mechanical strength and crack-healing power, according to the findings. However, high amount of bacterial content led to inconsistent outcomes as a result of the change in the concrete microstructure. Hybrid material strategies for increasing bacterial self-healing efficiency are also investigated recently. In 2024, a study was conducted to study the self-healing concrete which incorporated *Bacillus* bacteria alongside rice husk ash, as a partial cement substitute. The techniques are replacing a part of cement with waste from agriculture and adding bacterial spores to the concrete matrix. The experiment showed higher compressive strength and crack sealing, achieved under simultaneous interaction of pozzolanic reaction and microbial carbonate precipitation. Despite the improvement in sustainability based on waste materials introduced as a sustainable option, the lack of long-lasting activity of the bacteria in concrete matrix proved to be a challenge.

More recent studies have been dedicated to computational and machine learning to optimize bacterial healing efficiency. Meghashree et al. (2025) proposed a paradigm that merges bacterial self-healing concrete with the learning optimization based on Random Forest models and Kuhn–Tucker conditions. The approach was taken from the crack healing behavior of bacterial concrete and non-bacterial concrete specimens. The results of experiments showed that bacterial concrete could completely heal cracks within approximately 21 days under optimal curing conditions. Although the research offered important findings about the optimal healing process, there is still limited indication of how it can contribute to optimization of this model in large construction. Research on self-healing concrete has attracted considerable attention in the past few years because it works in the service of making civil facilities more durable. Different biological, chemical and material-based approaches have been studied by scientists focusing on enabling automated and self-repairive crack healing methods in concrete. Corresponding to this study, Yamasmit and colleagues have proposed the following study [36]. *Bacillus subtilis* had also significantly influence mechanical properties and healing abilities of mortar of various crack sizes are studied (2023). That meant getting mortar samples with bacterial cultures out and watching them cure in controlled curing conditions. Through precipitation of microbial calcite, cracks as long as ~0.5 mm are successfully closed in 28 days. Although the durability improvement and strength recovery were obtained using this measure, environmental factors, particularly moisture and nutrient supply, were shown to influence the healing. Durga et al. (2023) conducted a comparative experimental study among the different *Bacillus* species including *Bacillus subtilis*, *Bacillus licheniformis*, *Bacillus cereus*. Their approach was for different concentrations of bacteria with the examination of permeability and durability properties of concrete material. Results showed that if bacteria contained were integrated, it has not only increased the impermeability and resistance to water penetration, as a result of calcium carbonate deposition in the pores, but also achieved higher concentration of bacteria but a significant improvement in workability had to be achieved by careful calibration. An additional experimental investigation further assessed bacterial concrete supplemented with calcium lactate together with calcium lactate mixed with a different percentage of bacterial solution as a source of nutrients. Different bacterial proportions of concrete were prepared in the test sites and were used for test for compressive and flexural strength. It was determined that the medium bacterial concentrations enhance the mechanical strength and crack-healing efficacy, but the effects were contradictory when an excess of the bacterial solution were carried out in order to develop different microstructure modifications in the concrete. Recent studies have investigated hybrid material approaches in order to increase bacterial self-healing effectiveness. A 2024 study investigated self-healing concrete co-utilised *Bacillus* bacteria with rice husk ash, as a partial substitute for cement in 2024. This process consisted of mixing the mixture of agricultural produce with rice husk ash while embedding bacterial spores into the matrix by replacing some of the cement content. The experimental results showed that the compressive strength increased and crack sealing improved in accordance with synergistic effects of pozzolanic reacting with microbial carbonate precipitation, which are however still associated with difficulties in preserving long-term bacterial function in concrete matrix.

3. Materials and Methods

3.1 Research Methodology Overview

The research is carried out using an experimental approach and studies the behaviour of bacteria-based self-healing concrete for sustainable infrastructure projects. This study includes the preparation of bacterial cultures, concrete mix design, specimen casting, curing, and mechanical testing. Conventional concrete specimens were used as control samples to evaluate the capability of the bacterial self-healing process. The study concentrates on investigating the crack healing performance and mechanical properties of bacterial concrete using laboratory testing. The system developed in this study was based on microbial-induced calcium carbonate precipitation (MICP), during which bacteria embedded in the concrete matrix produce calcium carbonate when exposed to moisture and nutrients. This mineral precipitation fills the cracks and restores the structural integrity.



Figure 1: Overall experimental methodology

3.2 Materials Used

3.2.1 Cement. This material, Ordinary Portland Cement (OPC) grade 53, was used as the main binding material. The cement meets the requirements for IS 12269, and the early strength is highly suitable for structural materials.

3.2.2 Fine Aggregate. Fine aggregate was collected as natural river sand passing through a 4.75 mm sieve. The sand was cleaned and free from impurities.

3.2.3 Coarse Aggregate. Granite aggregates (maximum of 20 mm) were crushed. The aggregates were tested for specific gravity and water absorption as per the IS standards.

3.2.4 Water. Potable water suitable for concrete mixing and curing was utilized for the purposes of the entire test.

3.2.5 Bacterial Culture. This study employed a bacterium called *Bacillus subtilis*, a gram-positive, alkali-resistant bacterium that makes calcium carbonate via various metabolic pathways. Our choice of this bacterium was based on the high survival rate it has in an alkaline environment (concrete).

3.2.6 Nutrient Source. Calcium lactate was added as a nutrient source to induce bacterial growth and calcium carbonate precipitation within cracks.

3.3 Preparation of Bacterial Culture: Nutrient broth medium was taken for growing the bacterial culture needed in the experiments. From scratch the nutrient broth was made under laboratory conditions to make it environment optimal for bacterial reproduction. Subsequently *Bacillus subtilis* bacteria were inoculated in this prepared medium. Incubation of culture was done at approximately 30°C for about 24 hours to permit adequate growth and concentration of bacterium. The culture became a bacterial suspension after its incubation period. The bacterial solution, as above was poured into the concrete mixing water during the concrete mix preparation process to obtain a uniform distribution of the bacteria in the concrete.



Figure 2: Laboratory preparation of bacterial culture

3.4 Concrete Mix Design: The concrete mix was designed for M30 grade concrete following the guidelines specified in IS 10262. Typical mix proportion used in this study:

Material	Quantity (kg/m ³)
Cement	380
Fine Aggregate	650
Coarse Aggregate	1200
Water	180

Two types of concrete were prepared:

1. Conventional concrete (control sample)
2. Bacteria-based self-healing concrete

The bacterial solution was added to the mixing water in controlled proportions.

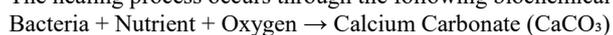
3.5 Specimen Preparation: Concrete cube specimens of 150 mm × 150 mm × 150 mm were prepared for compressive strength study. The concrete ingredients were first mixed well to give a homogeneous mix. The bacterial solution was subsequently added to the concrete during the mixing to ensure its proper distribution. The fresh concrete was then placed into cube moulds and compacted using a vibrating table to remove air voids and to have a good compacted state of the concrete. Following casting, the specimens were left undisturbed for 24 hours and then carefully demoulded. Later, cubes were placed in a water curing tank, cured for 7, 14, and 28 days, then compressive strength test.



Figure 3: Concrete specimen casting process

3.6 Crack Induction and Healing Mechanism: To evaluate the self-healing capability, controlled cracks were induced in selected concrete specimens using mechanical loading. After crack formation, the specimens were exposed to a moist curing environment to activate bacterial activity.

The healing process occurs through the following biochemical reaction:



The precipitated calcium carbonate fills the cracks and restores the structural integrity of the concrete.

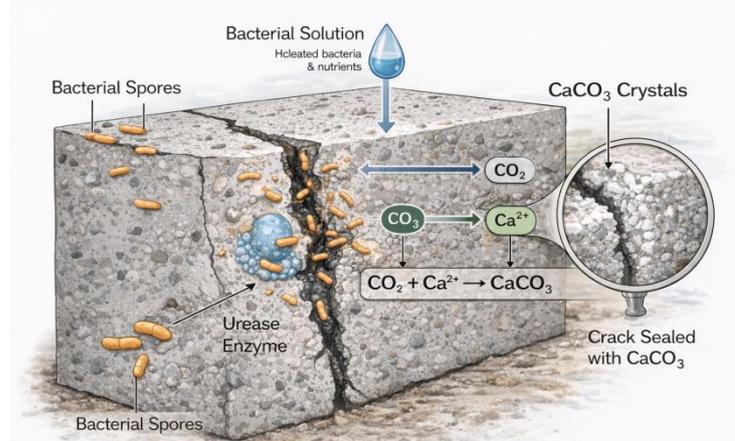


Figure 4: Mechanism of bacterial crack healing

3.7 Experimental Testing: The compressive strength tests were carried out following IS 516 by using a Universal Testing Machine (UTM). After the curing period, the concrete cube specimen was carefully brought to the center of the testing machine. Gradual and continuous load was then applied until the specimen failed. During the testing of the material, the maximum load at failure was recorded. This was then calculated in terms of maximum load divided by the cross-sectional area of the cube specimen to find the compressive strength of the concrete.

$$\text{Compressive Strength} = \left(\frac{\text{Load}}{\text{Area}} \right)$$

where Load is the maximum load applied at failure and Area is the cross-sectional area of the concrete cube. This is the value which is associated with the strength of a concrete.

3.7.1 Crack Healing Observation: Crack widths were measured using a digital microscope before and after the healing process. The reduction in crack width indicates the effectiveness of bacterial self-healing.

3.8 Data Analysis Techniques: Statistical and comparative analyses were performed on the experimental results for the performance of bacterial concrete. Factors such as compressive strength, reduction of the crack width, healing efficiency percentage, and durability performance were looked at to assess the effectiveness of bacterial action on the concrete matrix. Data were visualized through graphical analysis to notice differences and trends of the data produced in the experiment. Graphs were produced with Microsoft Excel and MATLAB and the results were calculated for the performance of conventional concrete/bacterial concrete samples. The overall patterns showed an improvement in strength and crack-healing characteristics with bacteria. However, certain practical limitations, including the need for a controlled environment for bacterial activity, and the challenge of implementing the technique on a large construction scale, were also identified.

4. Results

In this section, the research findings of tests on compressive strength and crack-healing results due to bacteria-induced self-healing concrete are described. The results are shown in terms of tables, graph results presented in figures and data set and descriptive analysis so as to be able to express effectively the performance of bacterial concrete against conventional concrete. The compressive strength of the concrete specimens was measured after curing periods of 7, 14, and 28 days. The data are shown in Table 1.

Table 1. Compressive Strength Results of Concrete Specimens

Curing Period	Conventional Concrete (MPa)	Bacterial Concrete (MPa)
7 Days	22	24
14 Days	28	31
28 Days	35	39

We report that bacterial concrete has superior compressive strength to ordinary concrete during all curing periods. Bacterial concrete has a compressive strength of around 9% higher than traditional concrete after curing for 7 days. Within 14 days, it increased to about 10.7%, while after 28 days, the improvement approached 11.4%. Such improvement in compressive strength can be attributed to calcium carbonate (CaCO₃) precipitation via bacterial activity. Calcite crystals help to seal pores and microcracks in the concrete matrix, thus the microstructure and load-bearing capacity are improved.

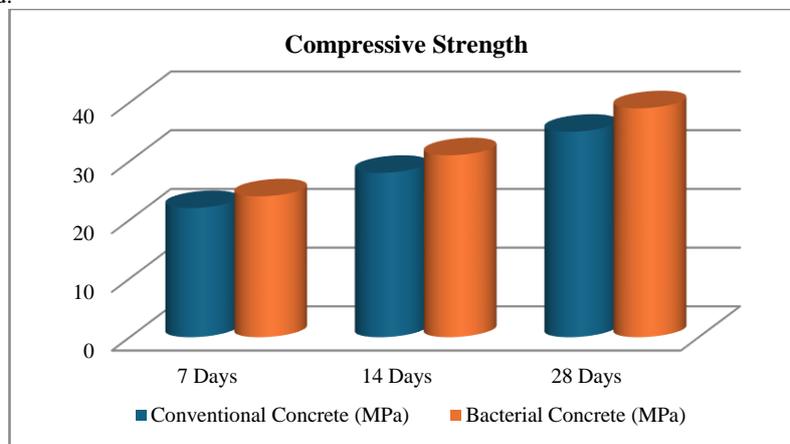


Figure 5: Compressive strength comparison between conventional and bacterial concrete.

The graph demonstrates a consistent increase in compressive strength with curing time for both concrete types. However, bacterial concrete consistently outperforms conventional concrete, highlighting the positive influence of microbial mineralization on structural performance.

4.2 Crack Healing Performance: Crack healing capability was evaluated by inducing small cracks in the concrete specimens and monitoring the crack closure over time under moist curing conditions.

Table 2. Crack Healing Observation

Initial Crack Width (mm)	Crack Width After Healing (mm)	Healing Efficiency (%)
0.40	0.05	87.5
0.35	0.04	88.6
0.30	0.03	90

The results show that bacterial concrete achieved crack healing efficiency between 87% and 90% within the observation period. This significant crack closure is attributed to microbial-induced calcium carbonate precipitation, which effectively seals the cracks and restores the continuity of the concrete matrix.

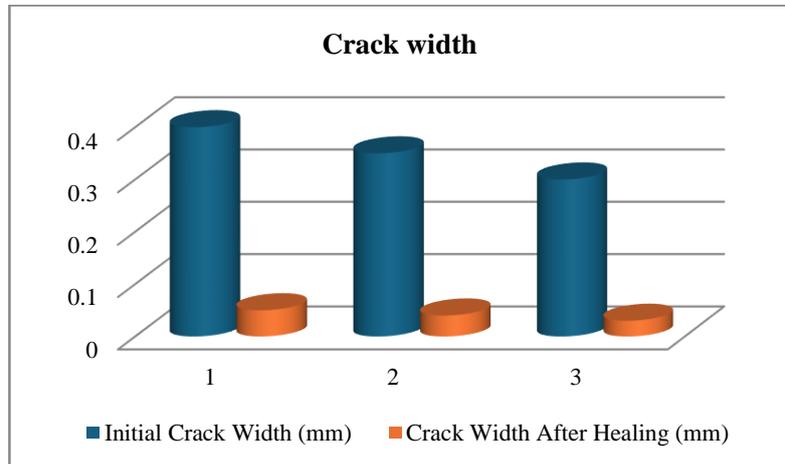


Figure 6: Crack healing process in bacterial concrete specimens.

The figure illustrates the crack before healing and the crack after healing. The reduction in crack width confirms the ability of bacterial concrete to autonomously repair structural damage.

4.3 Durability Performance: In addition to compressive strength and crack healing efficiency, bacterial concrete also demonstrated improved durability characteristics. The presence of calcite deposits within the concrete matrix reduced permeability and prevented water infiltration.

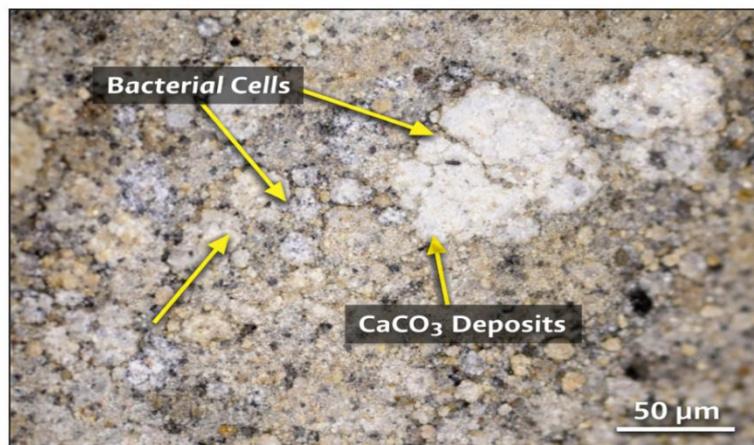


Figure 7: Microstructural observation of calcium carbonate precipitation in bacterial concrete. The formation of calcite crystals within pores and cracks enhances the overall durability of the material by reducing the penetration of aggressive chemicals.

5. Discussion

5.1 Summary of Key Findings. Their experimental results are consistent with conventional concrete showing inferior performance against the bacterial concrete. Mature *Bacillus subtilis* as part of concrete mixture promoted the microbial-induced calcium carbonate formation and enhanced the compressive strength and crack repair action. Significantly the bacterial concrete presented a compressive strength increase of as much as 11% after a 28 days curing period. Moreover, 87% to 90% efficiency were provided for healing cracks, indicating that the bacterial healing mechanism was effective for sealing microcracking in the concrete.

5.2 Results Interpretation. The increased compressive strength can be assigned to calcium carbonate crystals produced due to bacterial action. Such crystals are capable of filling internal cavities and microcracks and in doing so creating an increasingly dense concrete structure. During crack-healing, the water penetrates these cracks, and the dormant bacterial spores present in the mix are activated. As bacteria eat up nutrients, they secrete calcium carbonate that gradually fills the gaps, thus returning the concrete to its useful function. The finding demonstrates that microbial-mediated precipitation of the calcium carbonate helps to increase the physical strength as well as durability of concrete system.

5.3 The study implications. The contribution of such a research is relevant for a sustainable infrastructure development in general. Self-healing concrete through the bacterial infill could reduce maintenance costs caused by the crack repairs in bridges, buildings, tunnels, and other structures. With automatic crack repairs, the technology would be a game-changer in increasing the lifespan of infrastructure with negligible environmental impacts. And bio-materials for construction are another promising example of adding biological processes, and thereby promising an approach to smart and sustainable construction.

5.4 Comparison with Previous Studies. The results in this study correspond with previous studies to investigate bacterial self-healing concrete where improvements in compressive strength and crack healing efficiency have also been reported because of microbial-induced precipitation

of calcium carbonate. The observed crack healing efficiency here is in agreement with previous studies that revealed that bacterial concrete can effectively seal cracks of about 0.5 mm in width. The effectiveness of healing is affected, however, by bacterial content, nutrient availability, environmental settings, and the length of curing.

5.5 Limitations of the Study. As promising as these findings may have been, we identified several limitations. First, the experiments were conducted in controlled lab environments which do not correspond with what one would expect in real world environments where field applications are needed. Secondly and more importantly, studies are required to evaluate the durability and survival rates of bacteria in concrete over a period of time. As part of costs of preparing bacterial cultures, the current limitation of their scale could be incurred.

5.6 Perspectives for Future Work. Further work would be conducted to optimize the concentrations of bacterial species as well as the nutrient sources to improve healing effect and maintain the mechanical properties of the concrete. In addition, study designs should focus on the long-term response to an environmental condition, for example, heating of the concrete, or the effect of exposure to chemicals. Explore new techniques such as microencapsulation to enhance species viability and even improve healing when cracks begin to form.

5.7 General Effects of Results: In summary, this study demonstrates that bacteria-based self-healing concrete offers a feasible solution for improving durability and sustainability in construction practices. Thanks to autonomous repair mechanisms and also better mechanical strength profiles, this sort of concrete might revolutionize resilient infrastructure by removing the need for regular maintenance over the design life span.

6. Conclusion.

This research aimed at the development of microbial self-healing concrete made using *Bacillus subtilis* for increasing the life cycle reliability and sustainable cementitious material. The mechanical and crack-healing properties of bacillus-based concrete compared to traditional concrete under varied curing conditions were studied in our experimental study. The findings proved that a high percentage increase in mineralization that occurs spontaneously after bacteria are integrated in a matrix of a concrete is also achieved by embedding a beneficial microorganism to enhance the properties. For bacterial concrete, the results showed that there was an increase in the compressive strength after 28 days of curing.

The enhanced compressive strength was 9–11% higher after 28 days than those of normal concrete. This enhanced mechanical strength is largely due to the microbially induced precipitation of CaCO_3 (calcium carbonate) in the concrete matrix which in turn causes filling of internal pores and microcracks; results in a denser and more rigid microstructure of the concrete. Bacterial activity increased the cementitious matrix bonding and mechanical behavior. Additionally, it confirmed the autonomous healing of microbial concrete (crack-healing) by solid cell observation. Biological metabolic activity sealed the caused cracks in the samples and the healing efficacy was approximately 87–90%. As a result of precipitation of CaCO_3 in cracks, reduced permeability and restricted the free entry of harmful agents, like water and/or chlorides, resulting in a material's superior long-term durability. It is the overall results of the study that suggest bacteria-based self-healing concrete for sustainable infrastructure may result from an eco-friendly solution in a sustainable manner of concrete construction with a higher degree of durability and self-repairing ability, which is also known to increase significantly the structural life of concrete.

6.1 Future Work.

Results that have shown a relationship with bacterial self-healing mechanisms are promising — although more research is needed that shows how they can be employed in practice in subsequent studies. Ongoing exploration of the optimal concentrations & nutrient sources to maximize overall healability but also without compromising fundamental physical properties of the matrices themselves should then be incorporated with longer-term studies of spore viability/durability across climate modalities, including changes in moisture levels and chemical reactions.

Encapsulation innovations will also have to get explored that offer more protection of spores and more rapid release upon cracking events extending possible restorative activities into long service lives. Also, extensive field experiments testing broad-scale feasibility and practical performance in construction environments from bridges/tunnels/buildings constructed from environmentally friendly materials/industrial waste would contribute to knowledge of the ecological footprints generated by the adaptation of construction technologies.

Finally, interdisciplinary collaborations that bring together microbiology, materials science and civil engineering fields will expand advancement on ways toward the practical application of sustainable adoption and facilitate the full applications of modern infrastructures in global infrastructures due to the broad application of current systems.

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