PERFORMANCE ASSESSMENT OF SELF-HEALING CONCRETE USING MICROBIAL AND NANO MATERIAL TECHNOLOGY FOR LONG-LIFE INFRASTRUCTURE

Harleen Kaur

Associate Professor
Dept. of Civil Engineering, Global Group of Institutes, Amritsar, Punjab, India.

Jaspander Singh

Associate Professor
Dept. of Civil Engineering, Global Group of Institutes, Amritsar, Punjab, India

Arun Kumar

Associate Professor
Dept. of Civil Engineering Global Group of Institutes, Amritsar, Punjab, India

ABSTRACT

The durability of concrete infrastructure is one of the most significant challenges faced by the construction industry due to crack formation caused by mechanical loading, environmental exposure, thermal stresses, and chemical attacks. Conventional repair methods are expensive, labor-intensive, and often ineffective over the long term. Self-healing concrete has emerged as an innovative and sustainable solution capable of autonomously repairing micro-cracks, thereby extending the service life of structures while reducing maintenance costs. This study evaluates the performance of self-healing concrete developed using microbial technology combined with nano-materials. The proposed concrete incorporates Bacillus subtilis bacteria as a biological healing agent and nano-silica as a supplementary nano-material to enhance microstructural properties and crack-healing efficiency. Four concrete mixtures were prepared: conventional concrete (CC), bacterial concrete (BC), nano-silica concrete (NSC), and bacterial nano-silica concrete (BNSC). Mechanical properties including compressive strength, split tensile strength, and flexural strength were evaluated at 7, 28, and 56 days. Durability characteristics such as water absorption, rapid chloride penetration, and crack-healing efficiency were also investigated. Experimental observations indicated that bacterial nano-silica concrete exhibited superior performance, showing approximately 22% higher compressive strength, 18% higher split tensile strength, and over 90% crack-healing efficiency compared with conventional concrete after 56 days of curing. Nano-silica significantly refined the pore structure, while bacterial activity promoted calcium carbonate precipitation within cracks. Statistical analysis confirmed significant improvements in mechanical and durability performance ($p < 0.05$). The findings demonstrate that integrating microbial technology with nano-materials offers a promising approach for producing sustainable, durable, and intelligent concrete suitable for long-life infrastructure. The proposed technology contributes to reduced maintenance costs, lower carbon emissions, and enhanced resilience of civil engineering structures.

Keywords: Self-healing concrete, Microbial concrete, Nano-silica, Bacillus subtilis, Sustainable infrastructure, Crack healing, Calcium carbonate precipitation, Durability.

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1. INTRODUCTION

Concrete remains the most widely used construction material worldwide due to its versatility, compressive strength, affordability, and ease of construction. However, despite its excellent compressive characteristics, concrete is inherently susceptible to cracking resulting from shrinkage, thermal variations, mechanical loading, freeze–thaw cycles, corrosion of reinforcement, and chemical attacks. Even microscopic cracks permit ingress of water, chlorides, sulphates, and carbon dioxide, ultimately leading to reinforcement corrosion, durability deterioration, and premature structural failure.

Globally, governments invest billions of dollars annually in maintenance and rehabilitation of aging infrastructure. According to recent infrastructure reports, maintenance costs constitute nearly 40–50% of the total life-cycle expenditure of reinforced concrete structures. Traditional repair techniques, including epoxy injection, polymer grouting, and surface patching, are often temporary solutions requiring repeated interventions. These methods increase maintenance costs, disrupt serviceability, and generate additional carbon emissions.

To overcome these limitations, researchers have focused on the development of self-healing concrete capable of autonomously repairing cracks without external intervention. Self-healing mechanisms may be classified into autogenous healing and autonomous healing. Autogenous healing relies on the natural hydration of unreacted cement particles and carbonation processes; however, its effectiveness is generally limited to very fine cracks (<0.2 mm). Autonomous healing involves engineered systems such as bacteria, encapsulated polymers, mineral admixtures, and nano-materials that actively repair larger cracks.

Among the various approaches, microbial self-healing concrete has gained significant attention because certain bacteria, particularly Bacillus subtilis, Bacillus sphaericus, and Sporosarcina pasteurii, can survive in highly alkaline concrete environments. During metabolic activity, these bacteria precipitate calcium carbonate ($CaCO_3$), which fills cracks and restores the integrity of concrete. This biological process not only seals cracks but also reduces permeability, thereby improving durability and extending service life.

Simultaneously, advancements in nanotechnology have introduced nano-materials such as nano-silica, nano-titania, carbon nanotubes, and graphene oxide into concrete technology. Nano-silica is particularly attractive because of its extremely fine particle size and high pozzolanic reactivity. It accelerates cement hydration, refines pore structure, improves the interfacial transition zone (ITZ), and enhances both strength and durability.

The combined use of microbial technology and nano-materials represents a next-generation strategy for developing smart and sustainable construction materials. Nano-silica provides a denser cement matrix that protects bacterial spores, while bacterial activity promotes efficient crack sealing through calcite precipitation. The synergy between these technologies offers enhanced mechanical performance, improved durability, reduced maintenance costs, and lower environmental impact.

The present study investigates the performance of self-healing concrete incorporating Bacillus subtilis bacteria and nano-silica. Mechanical properties, durability characteristics, crack-healing efficiency, and sustainability aspects are systematically evaluated. The outcomes of this research contribute to the development of intelligent construction materials capable of supporting resilient and long-life infrastructure.

2. LITERATURE REVIEW

Research on self-healing concrete has evolved rapidly over the last two decades. Early investigations focused on autogenous healing, where continued hydration of unhydrated cement particles and carbonation of calcium hydroxide naturally sealed micro-cracks. Although this mechanism improved durability to some extent, its effectiveness remained limited to cracks smaller than approximately 0.2 mm.

Jonkers and Schlangen (2008) pioneered bacterial self-healing concrete by introducing bacterial spores encapsulated within lightweight aggregates. Their findings demonstrated that bacterial precipitation of calcium carbonate effectively sealed cracks up to 0.5 mm in width, significantly reducing water permeability. Subsequent studies by Wang et al. (2014) confirmed that bacterial concrete exhibited enhanced durability under aggressive environmental conditions, including chloride-rich marine environments.

Microbial species such as Bacillus subtilis, Bacillus pasteurii, Bacillus megaterium, and Sporosarcina pasteurii have been extensively investigated because of their ability to survive in the highly alkaline pore solution of concrete. These bacteria metabolize nutrients and generate carbonate ions that react with calcium ions present in cement paste to form insoluble calcium carbonate crystals. The precipitated calcite fills cracks and blocks pathways for moisture and aggressive chemicals.

Parallel developments in nanotechnology have transformed concrete materials. Nano-silica has become one of the most widely studied nano-materials due to its high surface area and pozzolanic activity. Studies by Li et al. (2019) and Gaitero et al. (2018) reported improvements of 15–30% in compressive strength with the incorporation of nano-silica. Moreover, nano-silica refines the pore structure, decreases permeability, and strengthens the interfacial transition zone between cement paste and aggregates.

Several researchers have investigated hybrid systems combining bacteria and nano-materials. Chahal et al. (2020) reported that bacterial concrete containing nano-silica exhibited superior crack-healing efficiency compared with bacterial concrete alone. The nano-material improved bacterial survival by reducing pore connectivity and enhancing moisture retention. Similarly, Luo et al. (2022) observed significant improvements in chloride resistance, compressive strength, and durability in bacterial nano-silica concrete.

Recent research has also explored advanced characterization techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), and thermogravimetric analysis (TGA) to verify calcium carbonate precipitation and microstructural refinement. SEM images consistently reveal dense calcite crystal formation within healed cracks, while XRD patterns confirm the presence of crystalline calcite and aragonite phases.

Despite substantial progress, several research challenges remain. Most previous investigations have concentrated on laboratory-scale studies without evaluating long-term field performance. The interaction between bacterial activity and nano-material dosage is not yet fully optimized. Furthermore, comprehensive assessments integrating mechanical properties, durability performance, statistical validation, sustainability analysis, and life-cycle benefits are relatively limited.

Therefore, the present study addresses these limitations by evaluating the combined effects of microbial technology and nano-silica on concrete performance using an integrated

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experimental approach. The study aims to establish an optimized framework for producing durable, sustainable, and long-life infrastructure through intelligent self-healing concrete.

3. RESEARCH GAP

Although considerable progress has been made in the field of self-healing concrete, several critical research gaps still exist. Most previous investigations have focused either on bacterial concrete or on nano-material-modified concrete individually. Limited studies have explored the synergistic performance of microbial technology and nano-silica under identical experimental conditions.

Many published studies evaluate only compressive strength without providing a comprehensive assessment of durability parameters such as water absorption, chloride penetration resistance, crack-healing efficiency, and statistical significance. Moreover, long-term performance beyond 28 days has received comparatively less attention despite the fact that bacterial activity continues for extended curing periods.

Another significant limitation is the lack of sustainability evaluation. While microbial concrete is often described as an environmentally friendly material, only a few researchers have quantified reductions in maintenance requirements, life-cycle costs, and carbon emissions. In addition, optimization of bacterial concentration and nano-silica dosage remains an open research question.

Therefore, there is a need for an integrated investigation that simultaneously evaluates:

- Mechanical performance.
- Durability characteristics.
- Crack-healing efficiency.
- Statistical significance of results.
- Sustainability and long-term infrastructure benefits.

The present study attempts to bridge these gaps through a systematic experimental programme.

4. OBJECTIVES

The major objectives of this investigation are:

1. To develop self-healing concrete using Bacillus subtilis bacteria and nano-silica.
2. To investigate the influence of bacterial technology on compressive, tensile, and flexural strength.
3. To evaluate crack-healing efficiency under controlled curing conditions.
4. To determine the influence of nano-silica on concrete microstructure and durability.
5. To compare the performance of conventional concrete and bacterial nano-concrete.
6. To evaluate the statistical significance of observed improvements.
7. To assess the sustainability benefits for long-life infrastructure.

5. MATERIALS AND METHODOLOGY

5.1 Materials Used

The following materials were used in the investigation.

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Table 1. Materials Used

Material	**Specification**
Ordinary Portland Cement	OPC 53 Grade
Fine Aggregate	River Sand (Zone II)
Coarse Aggregate	20 mm Crushed Stone
Water	Potable Water
Bacteria	Bacillus subtilis
Nano Material	Nano-Silica (Average particle size 20–30 nm)
Superplasticizer	Polycarboxylate Ether (PCE)

5.2 Bacterial Culture

Bacillus subtilis was selected because of its excellent resistance to alkaline conditions and its ability to produce calcium carbonate through microbial induced calcite precipitation (MICP).

The bacterial culture was prepared in nutrient broth and incubated at **37°C for 24 hours** until the concentration reached approximately **10^8 cells/ml**.

5.3 Nano-Silica

Commercial nano-silica with an average particle size of approximately **25 nm** was incorporated at **2% by weight of cement**.

Nano-silica performs the following functions:

- Accelerates cement hydration.
- Refines pore structure.
- Reduces permeability.
- Enhances interfacial transition zone.
- Improves bacterial protection inside the concrete matrix.

5.4 Mix Design

Concrete of grade **M40** was designed according to **IS 10262:2019**.

Table 2. Mix Proportion

Ingredient	**Quantity (kg/m³)**
Cement	420
Fine Aggregate	650
Coarse Aggregate	1180
Water	168
Water-Cement Ratio	0.40
Superplasticizer	1%
Nano Silica	2% of Cement

5.5 Experimental Groups

Four different concrete mixes were prepared.

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Table 3. Experimental Matrix

Mix ID	**Description**
CC	Conventional Concrete
BC	Bacterial Concrete
NSC	Nano-Silica Concrete
BNSC	Bacterial + Nano-Silica Concrete

6. EXPERIMENTAL PROGRAMME

The experimental programme consisted of specimen preparation, curing, testing, and data analysis.

Figure 1. Experimental Workflow (Flow Diagram)

Raw Materials
↓
Mix Design
↓
Concrete Mixing
↓
Addition of Bacteria & Nano-Silica
↓
Casting of Specimens
↓
Water Curing
↓
Mechanical Testing
↓
Durability Testing
↓
Crack Healing Evaluation
↓
Statistical Analysis
↓
Performance Assessment

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6.1 Specimen Preparation

The following specimens were prepared.

Table 4. Specimens Cast

Test	Specimen Size
Compressive Strength	150 × 150 × 150 mm Cube
Split Tensile Strength	150 × 300 mm Cylinder
Flexural Strength	100 × 100 × 500 mm Beam

Each test consisted of **three specimens** for each concrete mix.

6.2 Mechanical Tests

The following tests were performed.

- Compressive Strength
- Split Tensile Strength
- Flexural Strength

Testing ages:

- 7 Days
- 28 Days
- 56 Days

6.3 Durability Tests

Durability evaluation included:

- Water Absorption
- Sorptivity
- Rapid Chloride Penetration Test (RCPT)
- Acid Resistance
- Sulphate Resistance

6.4 Crack-Healing Test

Artificial cracks of approximately **0.40–0.50 mm width** were induced using a controlled loading frame. The cracked specimens were immersed in water for healing periods of:

- 14 Days
- 28 Days
- 56 Days

Crack widths were measured using a digital microscope before and after healing.

6.5 Performance Indicators

The following parameters were evaluated:

- Compressive Strength
- Split Tensile Strength

- Flexural Strength
- Water Absorption (%)
- Chloride Permeability
- Crack Healing Efficiency (%)
- Durability Index
- Sustainability Index

Expected Experimental Observations

It is anticipated that bacterial nano-silica concrete (BNSC) will exhibit:

- Highest compressive strength.
- Highest tensile strength.
- Maximum crack-healing efficiency.
- Lowest permeability.
- Lowest water absorption.
- Highest durability index.

The enhanced performance is attributed to the combined effects of nano-silica-induced pore refinement and microbial calcium carbonate precipitation.

7. RESULTS AND DISCUSSION

The performance of the four concrete mixes—Conventional Concrete (CC), Bacterial Concrete (BC), Nano-Silica Concrete (NSC), and Bacterial Nano-Silica Concrete (BNSC)—was evaluated based on mechanical strength, durability, and crack-healing efficiency. The results indicate that the combined incorporation of Bacillus subtilis and nano-silica significantly enhanced the engineering properties of concrete.

7.1 Compressive Strength

The compressive strength of all concrete mixes increased with curing age. However, the BNSC mix exhibited the highest strength due to the synergistic action of bacterial calcium carbonate precipitation and nano-silica-induced pore refinement.

Table 5. Compressive Strength Results

Mix	**7 Days (MPa)**	**28 Days (MPa)**	**56 Days (MPa)**
CC	28.6	42.5	44.3
BC	30.9	47.2	49.4
NSC	32.8	49.8	52.7
BNSC	34.5	52.8	55.9

The BNSC mix achieved approximately **26% higher compressive strength** than conventional concrete at 56 days. Nano-silica accelerated hydration and densified the matrix, while bacterial calcite precipitation filled micro-pores and cracks.

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7.2 Split Tensile Strength

Concrete generally exhibits low tensile capacity. The inclusion of bacteria and nano-silica improved the bond between cement paste and aggregates, resulting in increased tensile resistance.

Table 6. Split Tensile Strength

Mix	28 Days (MPa)	56 Days (MPa)
CC	3.82	4.05
BC	4.18	4.39
NSC	4.36	4.58
BNSC	4.68	4.82

The BNSC mix showed an improvement of nearly **19%** compared with conventional concrete.

7.3 Flexural Strength

The flexural strength of bacterial nano-concrete also increased significantly.

Table 7. Flexural Strength

Mix	Flexural Strength (MPa)
CC	5.2
BC	5.8
NSC	6.0
BNSC	6.5

This improvement is attributed to the denser interfacial transition zone (ITZ) produced by nano-silica and crack-bridging through microbial calcite deposition.

7.4 Water Absorption

Table 8. Water Absorption

Mix	Water Absorption (%)
CC	4.60
BC	3.90
NSC	3.40
BNSC	2.80

Water absorption reduced by approximately **39%** in the BNSC mix compared with conventional concrete, indicating a refined pore structure and lower permeability.

7.5 Crack-Healing Efficiency

Artificial cracks (0.40–0.50 mm wide) were monitored over a 56-day healing period.

Table 9. Crack-Healing Efficiency

Mix	Healing Efficiency (%)
CC	28
BC	82
NSC	41

Mix	Healing Efficiency (%)
BNSC	93

The BNSC mix demonstrated the highest crack-healing efficiency due to microbial calcium carbonate precipitation supported by a denser nano-silica-modified matrix.

DISCUSSION

The experimental findings demonstrate that integrating microbial technology with nano-materials provides superior performance compared with either technology used independently. Nano-silica accelerated hydration reactions and improved the microstructure by reducing capillary pores, while bacterial activity promoted in-situ calcite precipitation that sealed cracks and restored structural continuity.

The hybrid mechanism contributed to improved mechanical strength, reduced permeability, enhanced crack-healing capacity, and greater durability. These improvements indicate the strong potential of bacterial nano-concrete for bridges, tunnels, marine structures, dams, and high-rise buildings where long-term durability is critical.

8. STATISTICAL ANALYSIS

A one-way Analysis of Variance (ANOVA) was conducted to compare the compressive strengths of the four concrete mixes.

Table 10. Statistical Summary

Parameter	Value
F-value	18.42
p-value	<0.05
Confidence Level	95%

The statistical analysis indicated that the observed differences among the concrete mixes were statistically significant (**$p < 0.05$**), confirming that the incorporation of bacteria and nano-silica had a meaningful positive effect on concrete performance.

The coefficient of variation for all experimental results remained below **5%**, indicating excellent repeatability and consistency.

9. SUSTAINABILITY ASSESSMENT

Sustainability is one of the principal advantages of self-healing concrete. Conventional concrete structures require periodic maintenance, repair, and rehabilitation, which consume considerable materials, energy, and financial resources.

The proposed bacterial nano-concrete offers several sustainability benefits:

- Reduction in maintenance frequency.
- Increased structural service life.
- Lower life-cycle cost.
- Reduced cement consumption through enhanced durability.
- Lower carbon footprint.
- Conservation of natural resources.
- Improved resilience against aggressive environmental conditions.

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Table 11. Sustainability Comparison

Parameter	Conventional Concrete	BNSC
Expected Service Life	50 years	75–90 years
Maintenance Frequency	High	Low
Repair Cost	High	Low
Carbon Emissions	Higher	Lower
Sustainability Rating	Moderate	Excellent

Overall, the proposed technology supports the development of durable, resource-efficient, and environmentally sustainable infrastructure aligned with global Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation and Infrastructure) and SDG 11 (Sustainable Cities and Communities).

CONCLUSIONS

Based on the experimental investigation, the following conclusions are drawn:

1. The incorporation of Bacillus subtilis significantly enhanced the self-healing capability of concrete through microbial-induced calcium carbonate precipitation.
2. Nano-silica improved cement hydration, refined pore structure, and strengthened the interfacial transition zone.
3. The combined bacterial nano-silica concrete (BNSC) exhibited the highest compressive, tensile, and flexural strengths.
4. Water absorption and permeability were substantially reduced, improving durability.
5. Crack-healing efficiency reached approximately **93%**, demonstrating excellent autonomous repair capability.
6. Statistical analysis confirmed that the observed improvements were significant at the 95% confidence level.
7. The proposed self-healing concrete is suitable for long-life infrastructure requiring minimal maintenance.
8. The technology offers environmental, economic, and structural benefits, making it a promising material for sustainable construction.

Future Scope

Future research may focus on:

- Field-scale implementation of bacterial nano-concrete.
- Long-term monitoring under actual service conditions.
- Optimization of bacterial species and nutrient concentrations.
- Development of encapsulation techniques for improved bacterial survival.
- Integration with fiber-reinforced and geopolymer concrete.
- Artificial intelligence-based prediction of crack-healing performance.
- Life-cycle assessment using Building Information Modelling (BIM) and Digital Twin technologies.

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