

Modeling And Experimental Validation Of Stress–Strain Behavior In Self-Healing Bacterial Concrete

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Abstract

Concrete is a widely utilized material in construction due to its versatility and availability; however, its inherent limitations—such as low tensile strength, limited ductility, and susceptibility to cracking—pose significant challenges to structural integrity and service life. These deficiencies are further aggravated by environmental and anthropogenic factors, including weathering, seismic activity, and land subsidence. Recent research has focused on developing self-healing concrete as a sustainable solution to enhance durability and performance. One promising approach involves **Microbiologically Induced Calcite Precipitation (MICP)**, a biomineralization process facilitated by *Bacillus* species, notably *Bacillus pasteurii*. Through microbial activity, calcium carbonate (CaCO_3) is precipitated within cracks, effectively sealing fissures without external intervention. MICP has demonstrated potential in consolidating fractures in granite and stabilizing sandy substrates, offering an environmentally benign and pollution-free method for improving concrete resilience. This study explores the mechanisms, applications, and sustainability implications of microbial self-healing systems in cement-based materials.

Keywords: Bacillus bacteria, Concrete properties, Encapsulation, Microbiologically Induced Calcite Precipitation, pH

1. Introduction

Concrete is the most widely used construction material globally, prized for its high compressive strength and versatility. However, it exhibits inherent weaknesses in tension, necessitating the incorporation of embedded steel reinforcement bars. These bars absorb tensile loads when cracks occur, while the surrounding concrete shields the steel from environmental exposure and corrosion.

Despite this synergy, cracks in concrete remain a critical challenge. They permit the ingress of water and aggressive ions, initiating corrosion of steel reinforcement and accelerating structural deterioration.

Biological Approach to Crack Remediation

Recent advancements in bioengineering have introduced self-repairing concrete capable of autonomously sealing surface cracks. This is achieved through the biological production of calcium carbonate (CaCO_3) crystals, facilitated by spore-forming, alkali-tolerant bacteria from the *Bacillus* genus. These bacteria, suspended in the mixing water and supplied with calcium-based nutrients, are incorporated into the concrete matrix. Remarkably, the bacterial spores can remain dormant within the concrete for up to **200 years**.

When cracks develop and water infiltrates the structure, the dormant spores are activated by moisture and oxygen. Through microbial metabolism—specifically via the nitrogen cycle—soluble nutrients are converted into insoluble calcium carbonate. The resulting calcite precipitates within the cracks, effectively sealing them.

This biomineralization process mirrors the natural healing of bone fractures, where osteoblast cells mineralize to regenerate bone tissue. Additionally, the microbial reaction consumes oxygen, a key driver of steel corrosion. By reducing oxygen availability, the process helps arrest corrosion, thereby enhancing the durability of reinforced concrete structures.

Microbiologically Induced Calcite Precipitation (MICP)

The technique employed—Microbiologically Induced Calcite Precipitation (MICP)—is a subset of biomineralization, a process by which living organisms produce inorganic solids. Common soil bacteria such as *Bacillus pasteurii* and *Bacillus subtilis* are frequently used due to their ability to precipitate calcite naturally. This environmentally friendly method offers a promising solution for sustainable infrastructure maintenance and longevity.

1.1 Introduction to Bacillus

In microbiology, the term *bacillus* (lowercase) refers broadly to any rod-shaped microorganism, whereas *coccus* denotes a spherical form. However, *Bacillus*—capitalized and italicized—designates a specific genus within the family **Bacillaceae**. Members of this family are characterized as Gram-positive, rod-shaped bacteria capable of forming endospores.

The Bacillaceae family is primarily divided into two major genera based on oxygen requirements:

1. **Clostridium** – Anaerobic spore-forming bacteria
2. **Bacillus** – Aerobic or facultatively anaerobic spore-forming bacteria

Cultures of *Bacillus* species typically exhibit Gram-positive staining in their early growth stages, although they may appear Gram-negative as they age. These bacteria are aerobic, spore-forming, and rod-shaped, and are widely distributed in natural environments. The genus *Bacillus* is notably diverse, encompassing numerous species with varied ecological and industrial significance.

1.2 Properties of Bacteria

This project utilizes two bacterial species: *Bacillus pasteurii* (now reclassified as *Sporosarcina pasteurii*) and *Bacillus odyseyi*. These microorganisms play a pivotal role in the bio-mediated enhancement of concrete through calcite precipitation.

Sporosarcina pasteurii (formerly Bacillus pasteurii)

Sporosarcina pasteurii is a well-studied, ureolytic bacterium known for its ability to induce the precipitation of calcium carbonate (CaCO_3) when supplied with urea and a calcium source. This process, termed **Microbiologically Induced Calcite Precipitation (MICP)** or biological cementation, enables the bacterium to solidify granular materials such as sand. Due to its natural and non-toxic mechanism, *S. pasteurii* has been proposed as an environmentally sustainable agent for biological construction and self-healing concrete applications.

Cellular Characteristics

- Prokaryotic organism lacking a membrane-bound nucleus and organelles
- Microscopic size: typically $<1 \mu\text{m}$ to $>10 \mu\text{m}$ in length
- High surface-area-to-volume ratio for efficient nutrient exchange
- Rapid growth rates under optimal conditions, sometimes outpacing DNA replication

These properties make *Sporosarcina pasteurii* an ideal candidate for bioengineering applications in construction, particularly in the development of self-healing concrete systems.

2. Objectives of the Present Work

- **Evaluate Mechanical Properties:** Investigate compressive strength, split tensile strength, and flexural strength of bacterial concrete.
- **Analyze Stress-Strain Behavior:** Examine stress-strain characteristics of bacterial concrete across standard mix grades (M40, M50).
- **Develop Predictive Modeling:** Formulate a mathematical model capable of predicting the stress-strain response of bacterial concrete.
- **Validate Theoretical Predictions:** Compare model-derived theoretical stress values with experimental results for accuracy and reliability.

3. Scope of the Present Investigation

The investigation is structured into three distinct phases:

1. **Phase I – Mechanical Characterization**
Assessment of compressive strength, split tensile strength, and flexural strength of bacterial concrete across standard mix grades.
2. **Phase II – Stress-Strain Analysis**
Detailed study of stress-strain behavior, including development of a predictive mathematical model.
3. **Phase III – Validation and Comparison**
Comparison of theoretical stress predictions with experimental data to validate accuracy and reliability.

3.1 First Phase Investigation

The initial phase of this study focuses on evaluating the **mechanical properties** of bacterial concrete, specifically its **compressive strength, split tensile strength, and flexural strength**. The investigation includes both conventional cement concrete mixes and bacterial concrete mixes, the latter incorporating a *Bacillus pasteurii* solution at a concentration of **10⁵ cells/ml**.

Two mix designs corresponding to standard concrete grades have been selected for comparative analysis between normal and bacterial concrete. All mix proportions are formulated in accordance with **IS: 10262–2009** guidelines.

To assess compressive strength development, specimens are cured and tested at **7 and 28 days**. For flexural and split tensile strength evaluations, curing durations of **7, 14, and 28 days** are considered. This phased approach provides a comprehensive understanding of the performance enhancements offered by bacterial concrete over conventional mixes.

3.2 Second Phase Investigation

The second phase focuses on analyzing the **stress-strain behavior** of bacterial concrete in comparison with conventional concrete. Both types of concrete are prepared using standard mix grades—**M40 and M50**—with bacterial concrete incorporating a *Bacillus pasteurii* solution at a concentration of **10⁵ cells/ml**. Mix designs adhere to **IS: 10262–2009** specifications.

Key activities in this phase include:

- **Mix Design Implementation:** Two mix cases are considered for each grade, representing both normal and bacterial concrete compositions.
- **Curing Protocol:** Cylinder specimens are cured for **28, 60, and 90 days** to capture the evolution of stress-strain characteristics over time.

- **Empirical Modeling:** Based on experimental data, empirical equations are developed to represent the uniaxial stress-strain behavior of both controlled and bacterial concrete mixes.
- **Theoretical Validation:** Theoretical stress values derived from the empirical models are compared against experimental results to assess model accuracy and predictive capability.

This phase aims to establish a robust mathematical framework for understanding and forecasting the mechanical response of bacterial concrete under axial loading conditions.

3.3 Third Phase Investigation

The third phase is dedicated to **validating the predictive accuracy** of the developed mathematical models. It involves a comparative analysis between the theoretical stress values—calculated from empirical equations—and the experimentally obtained stress data for both conventional and bacterial concrete mixes.

This phase is critical for assessing the reliability of the proposed models and confirming their applicability in forecasting the mechanical behavior of concrete under various loading conditions.

4. The Biological Self-Healing Process

The biological self-healing mechanism in concrete relies on the integration of specific bacterial strains capable of surviving within the concrete matrix and autonomously repairing micro-cracks. Understanding the **selection, activation, and functionality** of these bacteria is essential to optimizing their performance in enhancing the durability and service life of concrete structures.

The bacteria employed—typically spore-forming strains from the *Bacillus* genus—are incorporated into the concrete mix along with a suitable nutrient source, often calcium-based compounds. These bacteria remain dormant within the concrete until activated by environmental triggers, primarily the ingress of water and oxygen through newly formed cracks.

Upon activation, the bacteria metabolize the supplied nutrients, initiating a biochemical reaction that leads to the precipitation of **calcium carbonate (CaCO₃)**. This calcite formation fills and seals the cracks, adheres to the internal surfaces, and reinforces the structural integrity of the concrete. The process not only repairs existing damage but also contributes to the overall strength and longevity of the structure.

Remarkably, the healing process can begin within a few days of crack formation. The system is particularly effective for **micro- to nanometer-scale cracks**, which are common in concrete structures. Current construction standards typically permit crack widths up to **0.2 mm**, as such micro-cracks are not considered to compromise structural safety. Many concrete formulations exhibit an inherent capacity for autogenous healing, which is significantly enhanced through the incorporation of bio-based self-healing agents.

This innovative approach offers a **sustainable and efficient solution** for mitigating long-term deterioration, reducing maintenance costs, and extending the lifespan of critical infrastructure.

4.1 Mechanism and Efficacy of Biological Self-Healing in Concrete

Research indicates that the autonomous healing capacity of conventional concrete is primarily attributed to the presence of **unreacted cement particles** within the matrix. Upon crack formation, infiltrating water interacts with these residual particles, facilitating partial closure of micro-cracks. However, this natural healing process is inconsistent and often insufficient, particularly in critical applications such as tunnels and underground structures, where micro-crack-induced water leakage remains a persistent issue.

Experimental studies have shown that while self-healing of cracks up to **0.2 mm** occurred in only **30% of control (non-bacterial) samples**, bacterial concrete demonstrated **complete crack closure across all specimens**. Furthermore, bacterial concrete exhibited an extended healing capability, effectively sealing cracks up to **0.5 mm** in width.

The enhanced performance of bacterial concrete is driven by a targeted **bio-calcification process** involving specific bacterial strains—namely *Bacillus pasteurii* and *Bacillus odyseyi*. This process relies on the **enzymatic hydrolysis of urea**, catalyzed by the bacterial enzyme **urease**, which produces ammonia and carbon dioxide. These byproducts react with calcium ions to precipitate calcium carbonate (CaCO_3), forming a dense, impermeable calcite layer over the existing concrete surface.

This calcite deposition effectively seals cracks, impedes water ingress, and enhances corrosion resistance, thereby improving the structural integrity and longevity of the concrete. The efficiency of **Microbiologically Induced Calcite Precipitation (MICP)** is influenced by several factors, including bacterial cell concentration, ionic strength of the medium, nutrient availability, and pH levels.

This biologically driven approach offers a **robust and sustainable solution** for mitigating crack-related deterioration in concrete infrastructure.

5. Mechanism of Bacterial Crack Remediation in Concrete

The incorporation of *Bacillus pasteurii* into concrete introduces a biologically driven self-healing mechanism that significantly enhances structural resilience. Upon mixing, the bacterial spores enter a dormant state—similar to seeds awaiting favorable conditions—and remain inactive until triggered by environmental stimuli, primarily the ingress of air and moisture through newly formed cracks.

Once activated, the spores germinate and initiate metabolic activity by consuming the embedded **calcium lactate nutrient**. This biochemical process results in the enzymatic conversion of calcium lactate into **insoluble calcium carbonate (CaCO_3)**, commonly referred to as limestone. The reaction also consumes oxygen, a critical factor in the corrosion of steel reinforcement.

The precipitated CaCO_3 accumulates within the crack, adhering to its surfaces and effectively sealing the damage. This not only restores the structural integrity of the concrete but also prevents further penetration of water and corrosive ions. The reduction in oxygen availability due to bacterial metabolism further mitigates the risk of steel corrosion, thereby enhancing the durability of reinforced concrete structures.

A notable feature of *Bacillus pasteurii* is its robust spore structure, which enables the bacteria to remain viable within the concrete matrix for up to **200 years**, ready to activate when conditions permit. Experimental evidence supports the superior performance of bacterial concrete, demonstrating reduced water and chloride permeability and improved strength recovery compared to conventional surface-applied bacterial treatments.

This biologically induced crack remediation process presents a **sustainable, long-term solution** for maintaining and extending the service life of concrete infrastructure.

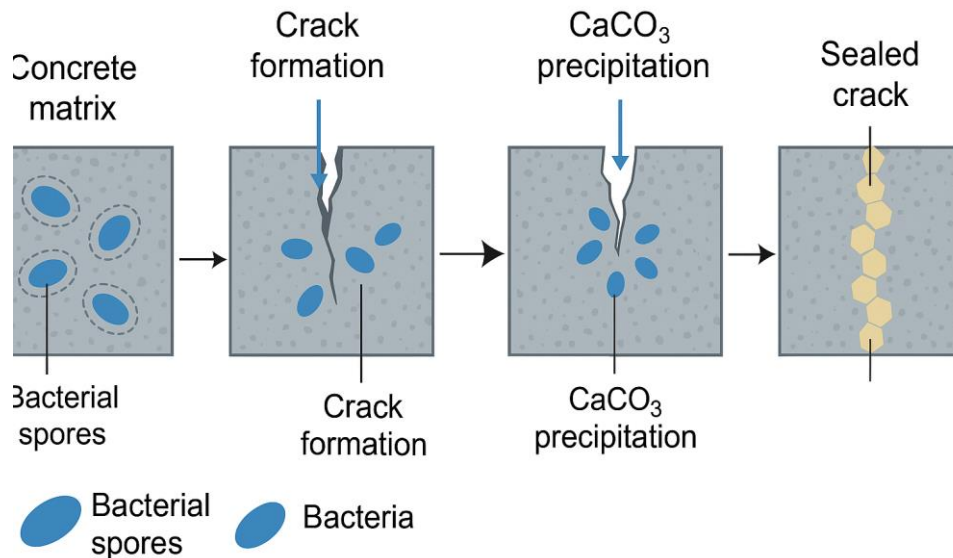
Selection of Bacterial Strains

A pivotal element in the formulation of self-healing concrete is the careful selection of bacterial strains capable of thriving within the material's highly alkaline environment. The most effective candidates for this application are **alkali-tolerant, spore-forming bacteria** that can remain viable over extended periods and activate in response to environmental stimuli.

For the present study, *Bacillus pasteurii*, a well-documented member of the *Bacillus* genus, has been selected due to its demonstrated ability to induce calcite precipitation. This bacterium is particularly suited for self-healing applications because of its resilience and capacity to remain dormant until triggered by moisture and oxygen infiltration—conditions typically associated with crack formation in concrete.

From a safety standpoint, *Bacillus pasteurii* is considered **non-pathogenic** and poses no risk to human health. As a naturally occurring soil bacterium, it is safe for use in construction environments. Although questions have been raised regarding the regulation of bacterial activity, these microorganisms do not possess autonomous behavior. Their metabolic functions are strictly dependent on the presence of specific environmental conditions and nutrient sources.

The integration of such biologically active agents into concrete represents a **transformative advancement in sustainable construction practices**. By enabling autonomous crack remediation, bacterial concrete offers improved durability, reduced maintenance requirements, and extended structural lifespan.



6. Stress–Strain Curves

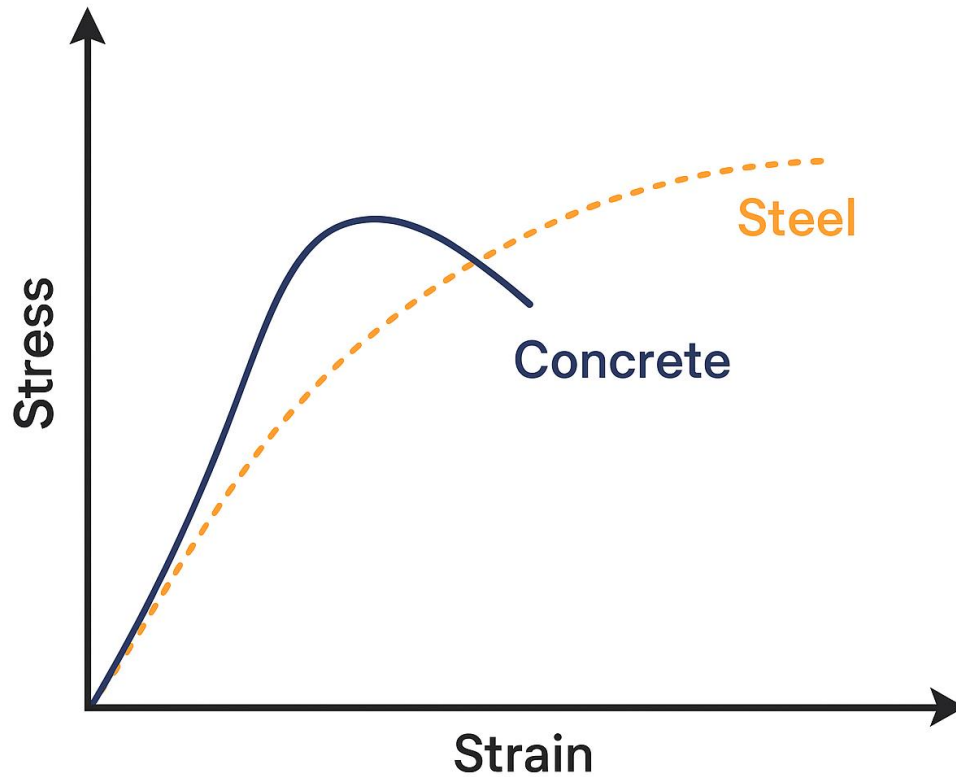
The **stress–strain curve** serves as a foundational tool for evaluating the mechanical behavior of materials under applied loads. Its profile—both in shape and magnitude—is influenced by several intrinsic and extrinsic factors, including chemical composition, heat treatment history, prior plastic deformation, strain rate, testing temperature, and the nature of the applied stress.

Key Parameters Derived from Stress–Strain Analysis

- **Tensile Strength:** Maximum stress a material can withstand before failure.
- **Yield Strength / Yield Point:** Stress level at which permanent deformation initiates.
- **Percent Elongation & Reduction of Area:** Indicators of ductility and deformation capacity.

These parameters collectively define the strength and ductility of a material. A well-constructed engineering stress–strain curve enables determination of critical mechanical properties such as:

- **Elastic Modulus (E):** Measure of stiffness in the elastic region.
- **Yield Strength:** Onset of plastic deformation.
- **Ultimate Tensile Strength:** Peak stress prior to necking or failure.
- **Fracture Strain:** Strain value at the point of rupture.



Material-Specific Behavior

Each material exhibits a unique stress–strain response, captured by measuring strain at incremental levels of tensile or compressive loading. These curves are essential for assessing material performance, informing design decisions, and ensuring structural integrity.

Stress–strain behavior can vary significantly depending on testing conditions such as temperature and loading rate. Despite these variations, materials are broadly categorized based on their stress–strain characteristics:

- **Ductile Materials**
Examples: Structural steel, aluminum alloys
Characteristics: Yield under normal conditions; exhibit significant plastic deformation before fracture
- **Brittle Materials**
Examples: Cast iron, glass, stone
Characteristics: Fracture occurs abruptly with minimal or no plastic deformation

Understanding these distinctions is essential for selecting appropriate materials in structural, mechanical, and civil engineering applications.

6.1 Stress–Strain Behaviour of Concrete

The stress–strain relationship for normal-strength concrete exhibits distinct characteristics that reflect its composite nature and internal microstructure. Initially, the curve displays a **linear response**, typically up to **30–40% of the ultimate load**. This linear region corresponds to the elastic behavior of the material, where stress and strain are proportionally related.

Beyond this point, the curve transitions into a **non-linear phase**, marked by increasing strain for relatively small increments in stress. This non-linearity is primarily attributed to the progressive development and coalescence of **micro-cracks**, particularly at the interface between the cement paste and aggregate particles.

As loading continues, these micro-cracks expand and merge, forming a widespread crack network throughout the concrete matrix. The material reaches its ultimate stress when this crack network becomes extensive, encompassing both the interfacial zones and the cement paste itself. For normal-strength concrete, the strain corresponding to ultimate stress typically approaches **0.003**.

The stress–strain behavior of concrete under **tensile loading** mirrors its compressive response, although tensile strength is significantly lower. In both cases, the formation and propagation of micro-cracks play a critical role in defining the material's mechanical performance.

Understanding this behavior is essential for accurate modeling, structural design, and durability assessment of concrete elements under various loading conditions.

7. Need for the Present Work

Traditional crack remediation techniques in concrete structures often rely on synthetic agents such as **epoxies and polymer-based compounds**. While these materials can offer temporary solutions, they introduce foreign systems with uncertain long-term performance and may pose **compatibility challenges** with the existing concrete matrix. Additionally, their application can compromise the **aesthetic integrity** of the structure.

Crack formation is an inevitable consequence of the **aging process in concrete**, particularly when exposed to environmental fluctuations. These fissures provide direct pathways for aggressive agents—such as **moisture, chlorides, and other corrosive substances**—to penetrate and initiate corrosion in embedded reinforcement, ultimately compromising structural durability.

In many industrial and infrastructural settings, repair operations are constrained by **safety concerns or operational limitations**, making conventional maintenance impractical. In such scenarios, the adoption of **self-healing materials** presents a promising alternative. **Bacterial concrete**, which incorporates bio-mineralizing microorganisms, offers an **autonomous crack-sealing mechanism** that activates upon exposure to moisture and oxygen.

Beyond its functional advantages, bacterial concrete enhances **mechanical properties** such as compressive and tensile strength, while also contributing to **environmental sustainability**. Its eco-friendly nature and ability to **extend the service life of concrete structures** underscore the relevance and necessity of the present investigation.

8. Conclusions

The experimental investigation, supported by comprehensive tabular and graphical analyses, confirms the **superior performance of bacterial concrete** and its variant incorporating fly ash when compared to conventional concrete. The integration of *Bacillus* bacteria has demonstrated a **marked improvement in strength parameters**, particularly during the early curing phase.

This enhancement in **compressive strength** is primarily attributed to the **microbial precipitation of calcium carbonate**, which effectively fills voids within the concrete matrix. The resulting densification produces a **more compact and impermeable structure**, thereby improving resistance to seepage and enhancing overall durability.

With continued development, **bacterial concrete presents a promising alternative to Ordinary Portland Cement (OPC)**, offering a **sustainable and environmentally responsible solution**. Its inherent resistance to corrosion further supports its suitability for **long-term structural applications**, especially in aggressive environmental conditions.

Moreover, the inclusion of *Bacillus pasteurii* has been shown to **refine the hydration structure of cement mortar**. Laboratory cultivation of this bacterium is both **safe and economically viable**. Optimal results were achieved using a **cell concentration of 10^5 cells per milliliter of mixing water**, a standard maintained throughout the study to maximize mechanical performance and durability.

These findings highlight the potential of **bacterial concrete as an innovative, self-healing material** capable of extending the lifespan of concrete infrastructure while reducing maintenance demands and minimizing environmental impact.

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