Analytical Framework for Predicting Stress–Strain Characteristics in Bacterial Concrete

Chappidi Manikanta Reddy[1], R.S.Ravichandran[2], J. Saravanan Professor[3]
[1]*Ph.D. scholar Annamalai University Tamil Nadu*
[2]*Assistant Professor, Annamalai University, Tamil Nadu*
[3]*Annamalai University, Tamil Nadu*

***Abstract*—Concrete remains a fundamental material in the construction of infrastructure and buildings due to its versatility and widespread availability. However, despite its utility, conventional concrete exhibits notable limitations, including low tensile strength, limited ductility, and minimal resistance to cracking. These vulnerabilities are exacerbated by natural phenomena such as weathering, seismic activity, land subsidence, and anthropogenic factors, all of which contribute to the formation of fractures and fissures that compromise structural integrity and reduce service life.**

To address these deficiencies, extensive global research has led to the development of innovative solutions aimed at enhancing the durability and performance of cement-based materials. One such advancement is the concept of self-healing concrete—an autonomous mechanism that enables the material to repair cracks without external intervention.

A promising approach in this domain is the biomineralization of calcium carbonate through microbial activity, particularly using Bacillus species. This process, known as Microbiologically Induced Calcite Precipitation (MICP), falls under the broader scientific field of biomineralization, wherein living organisms facilitate the formation of inorganic solids. Bacillus pasteurii, a common soil bacterium, has demonstrated the ability to precipitate calcite ($CaCO_3$), effectively acting as a microbial sealant.

The application of MICP has shown significant potential in selectively consolidating simulated fractures and surface fissures in granite, as well as in stabilizing sandy substrates. Its appeal lies in the environmentally benign nature of the calcite precipitation, which is both natural and pollution-free, making it a sustainable solution for enhancing the longevity and resilience of concrete structures.

***Index Terms*—Bacillus bacteria, Concrete properties, Encapsulation, Microbially induced calcium precipitate, pH**

I. INTRODUCTION

Bioengineered Self-Healing Concrete: A Sustainable Innovation

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

Despite this synergy, cracks in concrete pose a significant challenge. They allow the ingress of water and aggressive ions, initiating corrosion of the 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 the presence of 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, which is 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 their 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 odysseyi*. 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

- *S. pasteurii* is a prokaryotic organism, meaning it lacks a membrane-bound nucleus and organelles.
- The cells are microscopic, typically ranging from less than 1 µm to over 10 µm in length, making them difficult to observe under standard light microscopy.
- Their small size results in a high surface-area-to-volume ratio, which facilitates rapid exchange of nutrients and waste products.
- Under optimal conditions, these bacteria can exhibit rapid growth rates, sometimes outpacing their ability to replicate DNA, due to efficient nutrient uptake and metabolic activity.

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

II. OBJECTIVES OF THE PRESENT WORK

- Evaluate Mechanical Properties: To investigate the compressive strength, split tensile strength, and flexural strength of bacterial concrete.
- Analyze Stress-Strain Behavior: To examine the stress-strain characteristics of bacterial concrete across standard mix grades (M20, M25, M30).
- Develop Predictive Modeling: To formulate a mathematical model capable of predicting the stress-strain response of bacterial concrete.
- Validate Theoretical Predictions: To compare the model-derived theoretical stress values with experimental results for accuracy and reliability.

3. Scope of the Present Investigation

In alignment with the outlined objectives, the present investigation is structured into three distinct phases to ensure a comprehensive evaluation:

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 the stress-strain behavior of bacterial concrete, including the development of a predictive mathematical model.
3. Phase III – Validation and Comparison Comparison of theoretical stress predictions with experimental data to validate the accuracy and reliability of the proposed model.

3.1 First Phase Investigation

The initial phase of this investigation focuses on evaluating the mechanical properties of bacterial concrete, specifically its compressive strength, split tensile strength, and flexural strength. The study encompasses both conventional cement concrete mixes and bacterial concrete mixes, the latter incorporating a *Bacillus pasteurii* solution at a concentration of 10^5 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 the guidelines specified in IS: 10262–2009.

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

3.2 Second Phase Investigation

The second phase of this investigation 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—M20, M25, and M30—with bacterial concrete incorporating a *Bacillus pasteurii* solution at a concentration of 10^5 cells/ml. Mix designs are formulated in accordance with IS: 10262–2009.

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 durations of 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 of this investigation is dedicated to validating the predictive accuracy of the developed mathematical models. Specifically, 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.

IV. 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 such as those 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 ($CaCO_3$). 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. In fact, 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 the 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 odysseyi*. 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.

V. 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—analogous 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.

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.

VI. 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: The maximum stress a material can withstand before failure.
- Yield Strength / Yield Point: The stress level at which permanent deformation initiates.
- Percent Elongation & Reduction of Area: Indicators of a material's ductility and deformation capacity.

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

- Elastic Modulus (E): A measure of stiffness in the elastic region.
- Yield Strength: The onset of plastic deformation.
- Ultimate Tensile Strength: The peak stress prior to necking or failure.
- Fracture Strain: The strain value at the point of rupture.

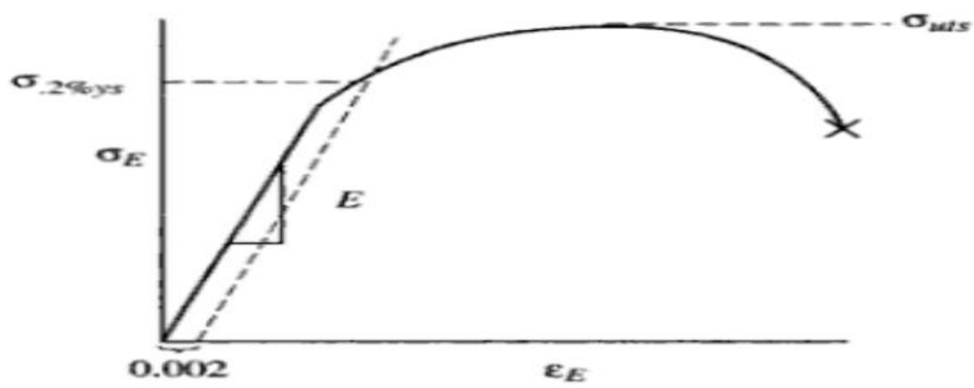
📐 Material-Specific Behavior

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*: Capable of yielding 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

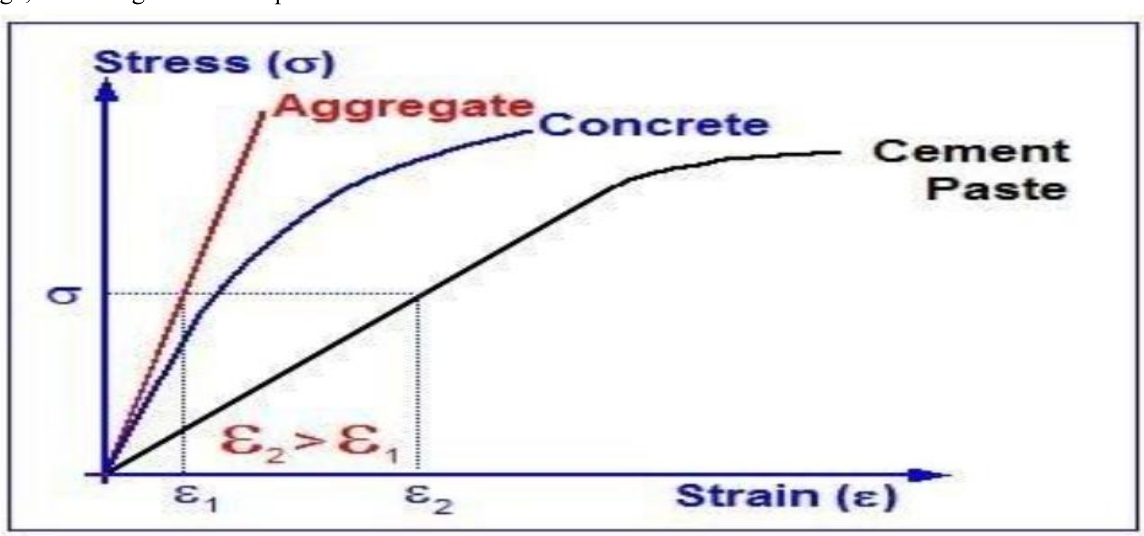
The stress–strain relationship for normal-strength concrete exhibits distinct characteristics that reflect its composite nature and internal microstructure. Initially, the curve displays a linear response, typically up to 30–40% of the ultimate load. This linear region corresponds to the elastic behavior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



Stress-Strain curve of Concrete

6.2 Post-Peak Stress–Strain Behavior of Concrete

The descending portion of the stress–strain curve, commonly referred to as the post-peak response, provides critical insight into the failure characteristics of concrete. This segment of the curve can be accurately captured using displacement-controlled or strain-controlled testing machines. Unlike load-controlled systems—which apply a constant rate of load and often result in sudden, catastrophic failure beyond the ultimate load—displacement-controlled machines allow for incremental deformation, enabling the recording of stress reduction after peak load.

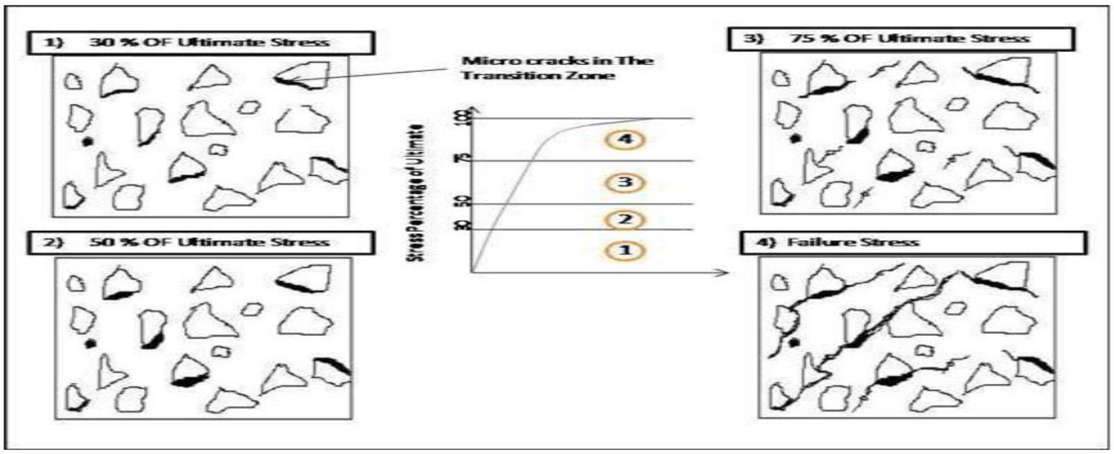
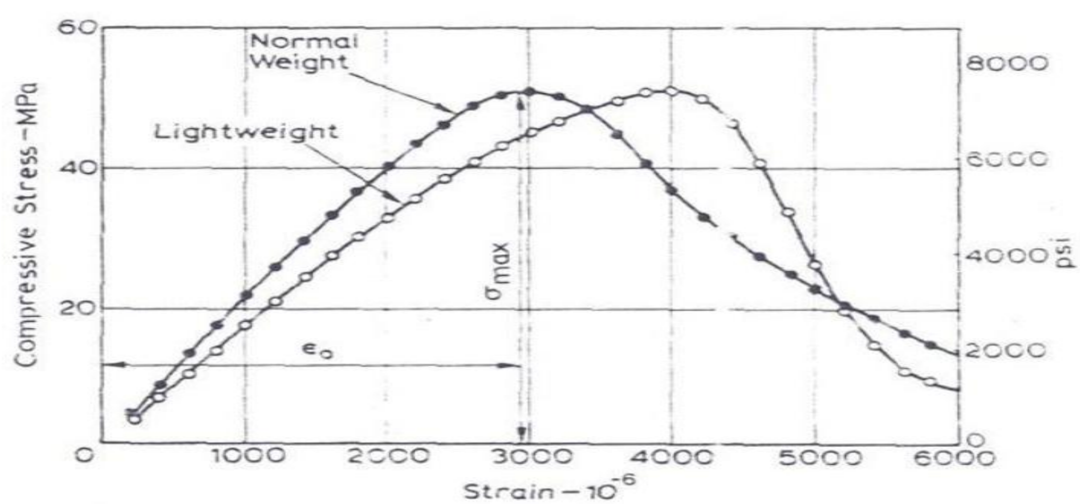


Figure 6 Stress-strain relationship for ordinary concrete

For normal-strength concrete, the strain at failure typically reaches approximately 0.005. The nature of the post-peak response is influenced by several factors, including the relative stiffness between the testing apparatus and the specimen, as well as the rate at which strain is applied. As the compressive strength of concrete increases, its brittleness also tends to rise, evidenced by a corresponding decrease in strain at failure.

It is noteworthy that while cement paste and aggregates individually exhibit linear stress–strain behavior, the composite response of concrete is distinctly non-linear. This non-linearity arises from the mechanical mismatch and micro-cracking phenomena occurring at the interfacial transition zone between the paste and aggregate particles.

Understanding the complete stress–strain profile, including the post-peak region, is essential for evaluating the ductility, toughness, and failure mechanisms of concrete, particularly in structural applications where energy absorption and crack propagation are critical considerations.



VII. 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.

VIII. 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.

REFERENCES

[1] Yasmeena Javeed [a], Yingxin Goh [b], Kim Hung Mo [a], Soon Poh Yap [a], Bey Fen Leo [c] “Microbial self-healing in concrete: A comprehensive exploration of bacterial viability, implementation techniques, and mechanical properties”

[2] Sumbly Maqbool, Khushpreet Singh “Effect of bacterial encapsulation in concrete: A review on applications and effects”

[3] J.Y. Wang et al.Application of hydrogel encapsulated carbonate precipitating bacteria for approaching a realistic self-healing in concrete Constr. Build. Mater.(2014)

[4] S. Jena, B. Basa, K.C. Panda, N.K. Sahoo Impact of Bacillus subtilis bacterium on the properties of concrete

[5] K. Vijay, M. Murmu Effect of calcium lactate on compressive strength and self-healing of cracks in microbial concrete

[6] Z.B. Bundur, M.J. Kirisits, R.D. Ferron Use of pre-wetted lightweight fine expanded shale aggregates as internal nutrient reservoirs for microorganisms in bio-mineralized mortar

[7] H. Kim, H.M. Son, S. Park, H.K. Lee Effects of biological admixtures on hydration and mechanical properties of Portland cement paste
[8] Nuaklong, P. Jongvivatsakul, V. Phanupornprapong, J. Intarasoontron, H. Shahzadi, W. Pungrasmi, S. Thaiboonrod, S. Likitlersuang Self-repairing of shrinkage crack in mortar containing microencapsulated bacterial spores
[9] T. ShanmugaPriya, N. Ramesh, A. Agarwal, S. Bhusnur, K. Chaudhary Strength and durability characteristics of concrete made by micronized biomass silica and Bacteria-Bacillus sphaericus