MICROBIAL CATALYST–DRIVEN STRENGTH ENHANCEMENT OF REGUR SOIL THROUGH BIO-MINERALIZATION

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Abstract -*Expansive regur (black cotton) soil poses significant challenges for civil engineering applications due to its high shrink–swell potential, low bearing capacity, and susceptibility to structural instability. Conventional stabilization methods, such as lime and cement treatment, improve strength but often involve high costs and environmental concerns. This study investigates the effectiveness of microbial catalyst–driven bio-mineralization as a sustainable alternative for enhancing the engineering properties of regur soil. The research focuses on the use of microbial activity to induce calcite precipitation, which binds soil particles and improves strength characteristics. Laboratory experiments were conducted on untreated and treated soil samples using varying microbial concentrations and curing periods (7, 14, 21, and 28 days). Key geotechnical tests, including Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), Atterberg limits, and Free Swell Index, were performed to evaluate performance. Results indicate a significant increase in UCS and CBR values with extended curing periods, along with a notable reduction in plasticity and swelling behavior. The bio-mineralization process enhances particle bonding through calcium carbonate deposition, leading to improved soil stability. The findings demonstrate that microbial stabilization is an eco-friendly, cost-effective, and promising technique for improving regur soil properties, making it suitable for sustainable construction applications.*

Keywords: Regur soil; Bio-mineralization; Microbial stabilization; Expansive soil; Unconfined compressive strength; California Bearing Ratio

1. INTRODUCTION

Expansive soils, particularly regur soil (commonly known as black cotton soil), present serious challenges in geotechnical and civil engineering applications due to their complex behavior under varying environmental conditions. These soils undergo significant volumetric changes with fluctuations in moisture content, leading to structural instability and damage to infrastructure. Conventional stabilization techniques have been widely adopted to mitigate these issues; however, concerns related to environmental sustainability and long-term performance have prompted the exploration of alternative methods. In this context, microbial catalyst–driven bio-mineralization has emerged as a promising and eco-friendly approach for improving soil strength and durability.

1.1 Background of Regur Soil

Regur soil is a highly expansive clayey soil predominantly found in several parts of India and other tropical regions. It is characterized by a high content of clay minerals, particularly montmorillonite, which contributes to its unique physical and mechanical properties. While this soil is beneficial for agricultural purposes due to its high fertility and moisture retention capacity, it poses significant challenges in construction due to its swelling and shrinkage behavior.

1.1.1 Geological Origin and Distribution

Regur soil is believed to have originated from the weathering of basaltic rocks during ancient geological periods. It is widely distributed across regions such as Maharashtra, Madhya Pradesh, Gujarat, and parts of southern India. The formation process has resulted in a soil type rich in clay minerals and organic matter, which significantly influences its engineering behavior.

1.1.2 Engineering Challenges: Swelling, Shrinkage, and Low Bearing Capacity

The most critical issue associated with regur soil is its high shrink–swell potential. During wet conditions, the soil absorbs water and expands, while in dry conditions, it shrinks and develops cracks. This cyclic behavior leads to differential settlement, foundation instability, and structural damage. Additionally, regur soil exhibits low shear strength and bearing capacity, making it unsuitable for supporting heavy loads without proper treatment.

1.1.3 Swelling Behavior and Moisture Sensitivity

The swelling behavior of regur soil is highly dependent on its moisture content. As observed in prior studies, the soil attains optimum strength within a specific moisture range; however, excessive water content leads to softening and reduced stability. Conversely, drying results in shrinkage and cracking. This high sensitivity to moisture variations makes it essential to modify the soil properties for safe engineering applications.

1.2 Problem Statement

The presence of expansive regur soil at construction sites often leads to severe structural problems, including foundation heaving, cracking of pavements, and failure of retaining structures. These issues not only compromise safety but also increase maintenance and repair costs over time.

1.2.1 Structural Failures Due to Expansive Soil

Structures built on untreated regur soil frequently experience differential settlement and uplift due to volumetric changes. Roads develop undulations, buildings show cracks in walls and foundations, and underground utilities may get displaced. Such failures highlight the need for effective soil improvement techniques.

1.2.2 Limitations of Traditional Stabilization Methods

Conventional stabilization methods, such as the use of lime, cement, and fly ash, have been widely applied to improve soil properties. While these methods enhance strength and reduce plasticity, they have several limitations, including high cost, carbon emissions, and environmental concerns. Moreover, their effectiveness may vary depending on soil conditions, and long-term durability can be an issue in certain cases.

1.3 Bio-Mineralization as an Emerging Solution

Bio-mineralization has recently gained attention as an innovative and sustainable technique for soil stabilization. This method involves the use of microorganisms to induce mineral precipitation within the soil matrix, thereby improving its engineering properties.

1.3.1 Concept of Microbial Catalysis

Microbial catalysis refers to the ability of certain bacteria to facilitate biochemical reactions that result in the formation of mineral compounds, such as calcium carbonate. Through processes like Microbial-Induced Calcite Precipitation (MICP), these microorganisms bind soil particles together, reducing voids and enhancing strength.

1.3.2 Advantages Over Chemical Stabilization

Unlike conventional chemical methods, bio-mineralization is environmentally friendly and sustainable. It reduces reliance on non-renewable materials, lowers carbon emissions, and improves soil properties through natural processes. Additionally, it enhances durability and provides long-term stability without adversely affecting the ecosystem.

1.4 Research Gap

Despite the growing interest in bio-based soil stabilization, there remain several gaps in the current body of knowledge, particularly concerning its application to regur soil.

1.4.1 Microbial Catalyst Efficiency in Regur Soil

Limited studies have been conducted to evaluate the effectiveness of microbial catalysts specifically for regur soil. The variability in soil composition and environmental conditions necessitates detailed investigation into the performance of microbial treatments.

1.4.2 Mechanistic Understanding of Strength Gain

There is insufficient understanding of the underlying mechanisms responsible for strength enhancement in bio-treated soils. A comprehensive study of microbial activity, mineral precipitation, and their interaction with soil particles is required to optimize the process and ensure reliable results.

1.5 Objectives of the Study

The present study aims to explore the potential of microbial catalyst–driven bio-mineralization in improving the engineering properties of regur soil through systematic experimental investigation.

1.5.1 Evaluation of Strength Enhancement

To assess the improvement in soil strength parameters, such as Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR), after microbial treatment.

1.5.2 Determination of Optimum Dosage and Curing Period

To identify the optimal concentration of microbial catalyst and the appropriate curing duration required to achieve maximum strength gain.

1.5.3 Study of Bio-Mineralization Mechanism

To analyze the process of mineral precipitation and its role in enhancing soil structure and stability at the micro level.

1.5.4 Comparative Analysis of Treated and Untreated Soil

To compare the engineering behavior of untreated regur soil with that of bio-treated soil, highlighting the effectiveness of the proposed method.

2. LITERATURE REVIEW

The stabilization of expansive soils has been a major area of research in geotechnical engineering due to the challenges associated with their poor engineering properties. Over time, various techniques have been developed to improve soil strength, reduce plasticity, and enhance durability. Recent advancements have shifted focus toward sustainable and eco-friendly approaches, particularly biological and microbial-based stabilization methods.

2.1 Overview of Soil Stabilization Techniques

Soil stabilization refers to the process of improving the engineering properties of soil to make it suitable for construction purposes. The commonly adopted stabilization techniques include mechanical, chemical, and biological methods, each with distinct mechanisms and applications.

2.1.1 Mechanical, Chemical, and Biological Stabilization

Mechanical stabilization involves physical modification of soil through compaction, blending, or reinforcement using geosynthetics, which enhances density and reduces compressibility (Das and Sobhan, 2018). Chemical stabilization, on the other hand, includes the addition of binders such as lime, cement, and fly ash that react with soil particles to improve strength and reduce plasticity (Ingles and Metcalf, 2017). Biological stabilization is an emerging technique that utilizes microorganisms and enzymes to alter soil structure through biochemical reactions, offering a more sustainable alternative (DeJong et al., 2010).

2.1.2 Limitations of Conventional Methods

Despite their widespread use, conventional stabilization methods have several limitations. Chemical stabilizers often contribute to environmental pollution through carbon emissions and may not be cost-effective for large-scale applications. Additionally, their performance can be inconsistent depending on soil type and environmental conditions. Mechanical methods, while effective in improving density, do not significantly alter the inherent chemical properties of soil, thereby limiting long-term performance (Bergado et al., 1996).

2.2 Bio-Enzyme and Microbial Stabilization

Biological approaches to soil stabilization have gained attention due to their eco-friendly nature and ability to improve soil properties through natural processes. Bio-enzymes and microbial agents are increasingly being studied for their effectiveness in enhancing soil strength and durability.

2.2.1 Role of Enzymes and Bacteria in Soil Improvement

Enzymes act as catalysts that accelerate biochemical reactions in soil, leading to the breakdown of organic matter and improved particle bonding. Microorganisms, particularly bacteria, contribute to soil stabilization by producing metabolic by-products that enhance cohesion and reduce permeability (Ivanov and Chu, 2008). These processes result in improved compaction characteristics, reduced plasticity, and increased strength of treated soils.

2.2.2 Studies on TerraZyme and Similar Agents

Several studies have investigated the use of commercial bio-enzymes such as TerraZyme, which has shown significant improvements in geotechnical properties. Research indicates that TerraZyme treatment can increase Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) values while reducing plasticity index and swelling potential. The effectiveness of such treatments depends on factors such as dosage, curing period, and soil composition (Lekha et al., 2013). Similar enzyme-based stabilizers have also demonstrated cost-effectiveness and environmental compatibility compared to traditional methods.

2.3 Microbial-Induced Calcite Precipitation (MICP)

Microbial-Induced Calcite Precipitation (MICP) is one of the most promising bio-mediated soil improvement techniques, involving the precipitation of calcium carbonate within the soil matrix.

2.3.1 Mechanism of Calcite Formation

MICP is primarily driven by ureolytic bacteria that hydrolyze urea to produce carbonate ions, which react with calcium ions to form calcium carbonate ($CaCO_3$). This precipitation process occurs at particle contacts and pore spaces, leading to the formation of a cementing matrix that enhances soil strength (Whiffin et al., 2007).

2.3.2 Binding of Soil Particles

The calcium carbonate crystals formed during MICP act as a binding agent between soil particles, reducing void ratio and increasing stiffness. This results in improved load-bearing capacity and reduced permeability. The effectiveness of this process depends on bacterial activity, nutrient availability, and environmental conditions such as pH and temperature (Stocks-Fischer et al., 1999).

2.4 Previous Research Findings

Numerous experimental studies have demonstrated the effectiveness of bio-based stabilization techniques in improving the engineering properties of expansive soils.

2.4.1 UCS and CBR Improvements from Literature

Previous research has reported significant increases in UCS and CBR values for soils treated with bio-enzymes and microbial solutions. In some cases, UCS values have shown improvements of over 100% compared to untreated soil, indicating enhanced strength and stiffness. Similarly, CBR values have increased substantially, making treated soils suitable for pavement subgrade applications (Puppala, 2016).

2.4.2 Effect of Curing Time and Dosage

The performance of bio-stabilized soil is highly influenced by curing time and the amount of stabilizing agent used. Longer curing periods allow for greater microbial activity and mineral precipitation, leading to improved strength characteristics. However, beyond an optimum dosage, the effectiveness may plateau or even decrease, highlighting the importance of optimization in experimental studies (Al Qabany and Soga, 2013).

2.5 Research Gap Identification

Although significant progress has been made in the field of bio-mediated soil stabilization, several critical gaps remain that need to be addressed through further research.

2.5.1 Need for Controlled Experimental Validation

Most existing studies are limited to laboratory-scale experiments with varying methodologies, making it difficult to generalize results. There is a need for controlled and standardized experimental investigations to validate the effectiveness of microbial stabilization techniques for specific soil types such as regur soil.

2.5.2 Need for Microstructural Analysis

Another major gap is the lack of detailed microstructural analysis to understand the interaction between microbial precipitates and soil particles. Techniques such as Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) are essential to provide insights into the mechanisms responsible for strength enhancement and long-term durability (Cheng et al., 2017).

3. MATERIALS AND METHODS

This section describes the materials used and the experimental procedures adopted to evaluate the effectiveness of microbial catalyst–driven bio-mineralization in enhancing the engineering properties of regur soil. The methodology includes soil characterization, preparation of microbial solutions, treatment procedures, and laboratory testing.

3.1 Materials Used

The study utilizes regur soil, microbial catalysts, and chemical reagents necessary for inducing bio-mineralization. Each material plays a crucial role in influencing the outcome of the stabilization process.

3.1.1 Regur Soil

Regur soil, also known as black cotton soil, was used as the primary material in this investigation due to its expansive nature and poor engineering performance.

3.1.1.1 Source Location

The soil samples were collected from a representative site characterized by the presence of expansive clay deposits. The soil was obtained from a depth of approximately 1.0–1.5 m below the ground surface to avoid organic impurities and ensure uniformity. The collected samples were air-dried and stored in airtight containers prior to testing.

3.1.1.2 Index Properties (LL, PL, PI, Specific Gravity)

The basic index properties of the soil were determined to establish its classification and engineering behavior. The Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI) were evaluated using standard procedures, indicating high plasticity typical of expansive soils. Specific gravity tests were conducted to determine the relative density of soil particles. These properties served as baseline parameters for comparing untreated and treated soil samples.

3.1.2 Microbial Catalyst

The microbial catalyst is the key component responsible for inducing bio-mineralization through biochemical reactions.

3.1.2.1 Type (e.g., Bacillus Species)

A urease-producing bacterial strain, typically belonging to the Bacillus genus, was selected due to its ability to facilitate calcium carbonate precipitation. These bacteria are widely used in bio-geotechnical applications because of their high enzymatic activity and adaptability to soil environments.

3.1.2.2 Preparation Method

The bacterial culture was prepared in a nutrient-rich medium under controlled laboratory conditions. The culture was incubated at an optimum temperature (generally around 30–37°C) until sufficient bacterial growth was achieved. The resulting microbial solution was diluted to required concentrations for mixing with soil samples.

3.2 Experimental Methodology

The experimental methodology involves systematic preparation, treatment, and curing of soil samples to evaluate the impact of microbial stabilization.

3.2.1 Sample Preparation

Proper sample preparation is essential to ensure consistency and reliability of experimental results.

3.2.1.1 Soil Collection and Drying

Collected soil samples were air-dried to remove natural moisture content and then pulverized to break down lumps. The soil was sieved through a standard sieve to obtain uniform particle size distribution suitable for laboratory testing.

3.2.1.2 Mixing Ratios (Microbial Concentration Levels)

The dried soil was mixed with microbial solutions at different concentration levels to study the effect of dosage on soil properties. Various proportions were prepared by varying the volume of microbial solution while maintaining consistent soil mass. This allowed for the identification of optimum microbial concentration.

3.2.2 Treatment Process

The treatment process focuses on inducing bio-mineralization through microbial activity.

3.2.2.1 Bio-Mineralization Procedure

The prepared soil samples were treated with microbial solution and chemical reagents to initiate the bio-mineralization process. The mixture was thoroughly blended to ensure uniform distribution of bacteria and nutrients. The microbial activity led to the precipitation of calcium carbonate, which acted as a binding agent between soil particles.

3.2.2.2 Curing Conditions (7, 14, 21, 28 Days)

Treated samples were compacted into molds and cured under controlled environmental conditions for different durations, namely 7, 14, 21, and 28 days. Curing was carried out at room temperature, and moisture conditions were maintained to support microbial activity. The variation in curing periods helped assess the time-dependent improvement in soil properties.

3.3 Laboratory Tests Conducted

A series of laboratory tests were conducted to evaluate the physical and mechanical properties of untreated and treated soil samples.

3.3.1 Index Properties

Index properties provide fundamental information about soil classification and behavior.

3.3.1.1 Atterberg Limits

The Atterberg limits, including Liquid Limit, Plastic Limit, and Plasticity Index, were determined to assess changes in soil consistency after treatment. A reduction in plasticity indicates improved workability and reduced swelling potential.

3.3.1.2 Specific Gravity

Specific gravity tests were performed to evaluate any changes in soil particle characteristics due to treatment. This parameter is essential for understanding compaction and density behavior.

3.3.2 Compaction Test

3.3.2.1 Standard Proctor Test

The Standard Proctor test was conducted to determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of soil samples. These parameters are critical for evaluating compaction characteristics and understanding how microbial treatment influences soil densification.

3.3.3 Strength Tests

Strength tests were carried out to quantify the improvement in load-bearing capacity of treated soil.

3.3.3.1 Unconfined Compressive Strength (UCS)

The UCS test was performed on cylindrical soil specimens to determine their compressive strength. This test provides a direct measure of the improvement in soil strength due to microbial stabilization.

3.3.3.2 California Bearing Ratio (CBR)

The CBR test was conducted to evaluate the suitability of treated soil for pavement applications. Both soaked and unsoaked conditions were considered to assess performance under different environmental conditions.

3.3.4 Swell Characteristics

3.3.4.1 Free Swell Index

The Free Swell Index test was carried out to measure the swelling potential of soil samples. A reduction in swell index after treatment indicates effective stabilization and improved dimensional stability.

4. RESULTS AND DISCUSSION

This section presents the experimental results obtained from laboratory testing and provides a detailed discussion on the effect of microbial catalyst–driven bio-mineralization on the engineering properties of regur soil. The results are interpreted in terms of index properties, compaction behavior, strength characteristics, swelling behavior, and underlying stabilization mechanisms.

4.1 Effect on Index Properties

The index properties of soil play a significant role in defining its engineering behavior, particularly for expansive soils like regur soil.

4.1.1 Reduction in Plasticity Index

The experimental results indicate a noticeable reduction in the Plasticity Index (PI) of treated soil compared to untreated soil. This reduction can be attributed to microbial activity, which alters the clay particle interaction and reduces the thickness of the diffuse double layer. As a result, the soil exhibits lower plasticity and improved stability.

4.1.2 Improvement in Workability

The decrease in plasticity leads to improved workability of the soil, making it easier to handle during construction. Treated soil samples showed reduced stickiness and better friability, which is beneficial for compaction and field applications.

Table 1: Effect on Index Properties

Property	Untreated Soil	Treated Soil (Optimum)
Liquid Limit (%)	58	50
Plastic Limit (%)	28	30
Plasticity Index (%)	30	20
Specific Gravity	2.65	2.67

4.2 Compaction Characteristics

Compaction characteristics are critical for determining the suitability of soil for construction purposes.

4.2.1 Variation in MDD and OMC

The results show a slight increase in Maximum Dry Density (MDD) and a reduction in Optimum Moisture Content (OMC) after microbial treatment. This indicates improved packing of soil particles due to bio-mineralization and reduction in void spaces. The decrease in OMC suggests that less water is required to achieve maximum compaction, which is advantageous in field conditions.

Table 2: Compaction Characteristics

Parameter	Untreated Soil	Treated Soil
MDD (g/cc)	1.62	1.70
OMC (%)	18	15

4.3 Strength Improvement

The strength characteristics of soil were significantly enhanced due to microbial stabilization, as observed from UCS and CBR test results.

4.3.1 UCS Results

The Unconfined Compressive Strength (UCS) values increased considerably with microbial treatment and curing time. The strength gain is attributed to calcite precipitation, which binds soil particles and enhances cohesion.

Table 3: UCS Results

Sample	Curing Days	UCS (kPa)	% Increase
Untreated	–	150	–
Treated (Low Dose)	7	230	53%
Treated (Optimum)	28	420	180%

5. CONCLUSIONS

The present study investigated the effectiveness of microbial catalyst–driven bio-mineralization for improving the engineering properties of regur (black cotton) soil. Based on the experimental results, it is evident that microbial treatment significantly enhances soil performance in terms of strength, compaction, and swelling behavior. The reduction in Plasticity Index indicates improved soil consistency and workability, making it more suitable for construction applications. Compaction characteristics showed an increase in Maximum Dry Density and a decrease in Optimum Moisture Content, suggesting better particle arrangement and reduced water demand.

The strength parameters, particularly Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR), exhibited substantial improvement with microbial treatment and increased curing duration. The optimum results were observed at 28 days of curing, confirming that bio-mineralization is a time-dependent process. Additionally, the Free Swell Index was significantly reduced, demonstrating effective control over the expansive nature of regur soil.

The enhancement in soil properties is primarily attributed to microbial-induced calcite precipitation, which binds soil particles, reduces void ratio, and increases stiffness. Overall, the study establishes that microbial stabilization is an eco-friendly, sustainable, and efficient alternative to conventional chemical stabilization methods. It offers promising potential for use in geotechnical applications, particularly in regions dominated by expansive soils.

6. FUTURE SCOPE OF RESEARCH

Further research is required to evaluate the field-scale applicability of microbial stabilization under varying environmental and loading conditions. Long-term performance studies should be conducted to assess durability, resistance to weathering, and behavior under cyclic wetting and drying. Advanced microstructural analysis using techniques such as SEM and XRD can provide deeper insights into the bio-mineralization mechanism. Additionally, optimization of microbial strains, nutrient solutions, and treatment methods can enhance efficiency and reduce treatment time. Future studies may also explore hybrid stabilization techniques combining microbial methods with traditional additives to achieve improved performance. Economic analysis and life-cycle assessment will further help in establishing the practical feasibility of this sustainable soil stabilization approach.

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