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Comparative Evaluation of Bio-Enzyme and Lime Stabilization on Black Cotton Soil Using Experimental and Literature Analysis

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Abstract: Black cotton soil exhibits significant swelling and shrinkage characteristics, making it unsuitable for construction without stabilization [1]. This study evaluates the effectiveness of bio-enzyme stabilization using experimental data and compares its performance with lime stabilization based on published literature. Laboratory tests including California Bearing Ratio (CBR), Liquid Limit (LL), Plastic Limit (PL), and permeability were conducted. Results indicate that bio-enzyme treatment improves soil strength and reduces permeability. Comparative analysis shows that while lime stabilization yields higher strength improvement due to pozzolanic reactions, bio-enzymes provide a sustainable and eco-friendly alternative [2], [3], [11]. The study highlights the suitability of bio-enzymes for environmentally conscious soil stabilization practices

Keywords: Black Cotton Soil, Bio-Enzyme, Soil Stabilization, Lime Stabilization, CBR, Atterberg Limits, Sustainable Engineering.

I. INTRODUCTION

Black cotton soil is commonly found and is noted for its high clay content, resulting in significant swelling and shrinking with changes in moisture levels. These characteristics pose significant difficulties in civil engineering applications like pavement and foundation construction [1]. Stabilization methods like lime and cement are often utilized to enhance soil properties. Lime stabilization improves soil strength via cation exchange and pozzolanic reactions, leading to better engineering performance [2]. Nonetheless, these conventional techniques possess environmental issues, such as elevated carbon emissions. Lately, bio-enzymes have appeared as a green alternative for stabilizing soil. Bio-enzymes are natural substances generated by fermenting organic materials such as fruit waste and molasses. They enhance soil characteristics by lowering water attraction and improving particle cohesion [3].

The goal of this research is to:
Assess bio-enzyme stabilization through experimental data analysis.
Evaluate its effectiveness against lime stabilization through existing literature.
Determine an eco-friendly method for enhancing black cotton soil

II. LITERATURE REVIEW

Soil stabilization has been extensively researched to enhance the engineering attributes of expansive soils like black cotton soil. Researchers have investigated different techniques, such as chemical and biological stabilization.

Conventional stabilization with lime has demonstrated significant effectiveness in increasing soil strength and decreasing plasticity. As stated in [2], lime interacts with clay minerals via cation exchange and pozzolanic reactions, leading to enhanced load-bearing capacity. Comparable results were observed in [12], where lime treatment notably decreased swelling and enhanced soil stability.

Research indicates that lime stabilization enhances California Bearing Ratio (CBR) values and reduces plasticity index, rendering soil better suited for pavement construction [1], [10]. Standard guidelines like IRC:37-2018 also suggest stabilization methods to enhance subgrade performance [7].

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In recent years, bio-enzyme stabilization has surfaced as a sustainable alternative. Bio-enzymes are natural substances created via fermentation that can change the physicochemical characteristics of soil. Study conducted by Rao and Ravindra [3] showed that bio-enzymes greatly enhance soil strength and decrease permeability.

Additional research [5], [6] shows that bio-enzymes improve compaction qualities and lower plasticity by diminishing the thickness of the water layer adsorbed around soil particles. Latifi et al. [11] also indicated that bio-enzyme treatment enhances soil strength and decreases moisture vulnerability.

Comparative research on bio-enzymes versus traditional stabilizers reveals that although lime enhances strength more significantly, bio-enzymes present benefits regarding sustainability and environmental effects [4], [11]. Bio-enzymes are especially appropriate for low-traffic roads and ecologically sensitive regions.

Moreover, standardized testing techniques like CBR and Atterberg limits are commonly employed to assess soil stabilization effectiveness [8], [9]. These techniques offer dependable signs of strength and plasticity performance.

Even with substantial investigation into individual stabilization techniques, few studies integrate experimental bio-enzyme findings with literature-based comparisons of lime stabilization. This research fills this void by combining both methods to deliver a thorough assessment.

III. MATERIALS AND METHODS

3.1 The materials used in this study include black cotton soil and bio-enzyme prepared from organic waste materials.

3.1.1 Black Cotton Soil

The soil sample was collected from a local site and air-dried before testing. The collected soil was pulverized and sieved to remove impurities. Black cotton soil is characterized by high clay content and exhibits swelling and shrinkage behavior due to moisture variation.

3.1.2 Bio-Enzyme

The bio-enzyme used in this study was prepared using natural organic materials. The ingredients include:

- Molasses (waste)
- Citrus fruit peels (orange/lemon waste)
- Water

Bio-enzymes are organic compounds produced through fermentation and are known to improve soil properties by enhancing bonding between particles and reducing water affinity.

3.2 Preparation of Bio-Enzyme

The bio-enzyme was prepared using a fermentation process as follows:
The raw materials were mixed in a fixed proportion:

- 1 part molasses
- 3 parts citrus peels
- 10 parts water

The mixture was placed in an airtight plastic container.
The container was opened periodically during the initial days to release gases formed during fermentation.
The mixture was allowed to ferment for a period of 21 days until a stable solution was obtained.
After fermentation, the solution was filtered and used as bio-enzyme for soil stabilization.

3.3 Experimental Methodology

The experimental work was carried out in two stages:

3.3.1 Testing of Untreated Soil

Initially, the natural soil was tested to determine its engineering properties. The following tests were conducted:

- Liquid Limit (LL)
- Plastic Limit (PL)
- California Bearing Ratio (CBR)
- Permeability test

These tests help in understanding the strength, plasticity, and water flow characteristics of the soil.

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3.3.2 Preparation of Treated Soil

The soil sample was mixed with the prepared bio-enzyme solution. Proper mixing was ensured to achieve uniform distribution of the enzyme throughout the soil.

The treated soil was then allowed to cure under controlled conditions to allow interaction between soil particles and the bio-enzyme.

3.3.3 Testing of Bio-Enzyme Treated Soil

After curing, the treated soil was tested using the same procedures:

- Liquid Limit (LL)
- Plastic Limit (PL)
- California Bearing Ratio (CBR)
- Permeability

The results were compared with untreated soil to evaluate improvement in properties.

3.4 Comparative Methodology (Lime Stabilization)

Since laboratory testing for lime stabilization was not conducted, data from previously published studies were used for comparison.

The comparison was based on:

- Strength improvement (CBR values)
- Plasticity characteristics
- Liquid characteristics
- Permeability behavior

This approach allows evaluation of bio-enzyme performance against conventional stabilization methods.

IV. RESULT AND DISCUSSION

4.1 Experimental Results

Property	Untreated Soil	Bio-Enzyme Treated Soil
CBR (%)	8.89	11.56
Liquid Limit (%)	46.67	41.25
Plastic Limit (%)	29	22.90
Permeability (cm/s)	2.12×10^{-3}	3.42×10^{-4}

Table 01: Result of untreated and treated soil

4.2.1 Strength Characteristics (CBR Analysis)

The California Bearing Ratio (CBR) value increased from 8.89% to 11.56%, indicating a significant improvement in the load-bearing capacity of the soil.

This improvement can be attributed to the modification of inter-particle bonding caused by the bio-enzyme. The enzyme reduces the thickness of the adsorbed water layer surrounding clay particles, leading to closer particle packing and increased frictional resistance. As a result, the soil exhibits enhanced shear strength and stiffness.

4.2.2 Plasticity Behavior (Atterberg Limits)

The reduction in Liquid Limit (LL) and Plastic Limit (PL) indicates a decrease in soil plasticity. This behavior suggests that the treated soil becomes less sensitive to moisture variation.

The modification takes place as a result of bio-enzymes influencing the electrochemical properties surrounding clay particles, thereby decreasing their hydrophilic tendencies. As a consequence, the soil undergoes a shift towards a more consolidated and less prone to swelling condition.

4.2.3 Permeability Characteristics

The permeability of the soil decreased from approximately 2.12×10^{-3} cm/s to 3.42×10^{-4} cm/s, indicating a reduction in

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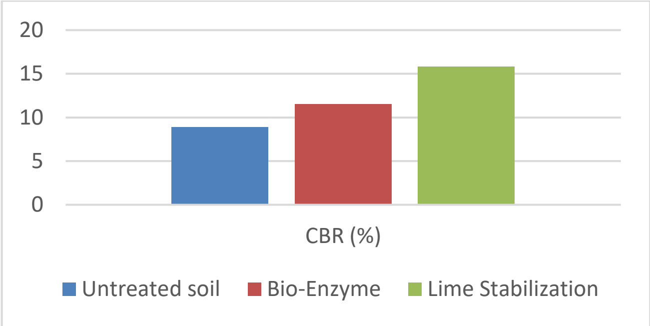
water flow through the soil mass.
This reduction is due to:

- Improved particle arrangement
- Reduced void spaces
- Enhanced bonding between soil particles

The formation of a denser soil matrix limits water infiltration, thereby improving durability and resistance to moisture-induced damage.

4.3 Comparative Analysis with Lime Stabilization

4.3.1 CBR%

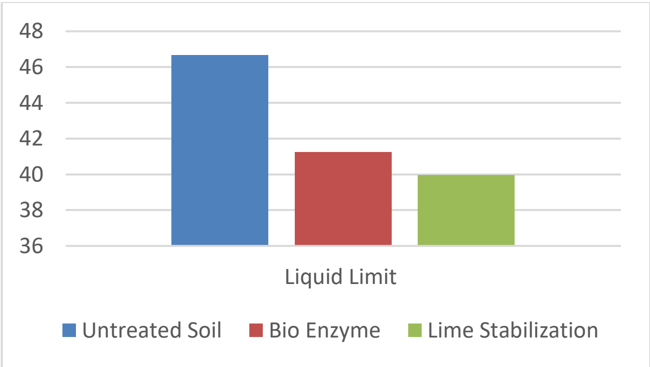


The California Bearing Ratio (CBR) value of untreated black cotton soil was found to be 8.89%, which increased to 11.56% after bio-enzyme treatment, indicating an improvement in load-bearing capacity.

In comparison, lime stabilization reported in literature shows higher CBR values 15.8%, due to strong pozzolanic reactions that form cementitious compounds.

Although lime provides greater strength enhancement, bio-enzyme treatment offers moderate improvement with the advantage of being environmentally sustainable. Therefore, bio-enzymes can be considered suitable for low to medium load applications, while lime is preferred for high-strength requirements.

4.3.2 Liquid Limit



The Liquid Limit of untreated black cotton soil was observed to be high, indicating significant water-holding capacity and compressibility. After bio-enzyme treatment, the Liquid Limit decreased, reflecting reduced affinity for water and improved soil stability.

In comparison, lime stabilization reported in literature shows a more significant reduction in Liquid Limit due to strong chemical reactions with clay minerals. While lime provides greater reduction, bio-enzyme offers sufficient improvement with better environmental compatibility.

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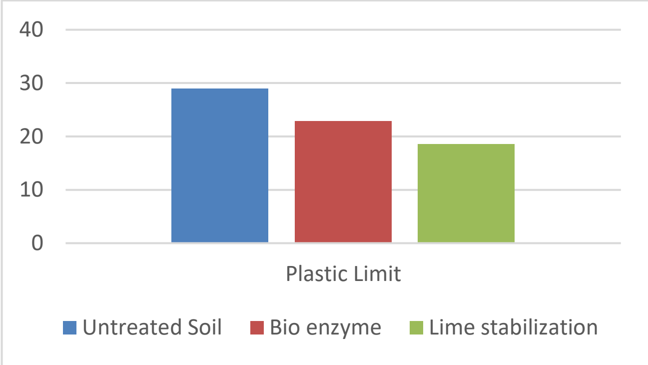
4.3.3 Plastic Limit



The Plastic Limit of the untreated soil decreased after bio-enzyme treatment, indicating reduced plasticity and improved workability. This change suggests that the soil becomes less deformable under varying moisture conditions.

Lime stabilization also reduces plasticity, often more effectively due to flocculation and cementation processes. However, bio-enzyme treatment achieves moderate improvement while maintaining eco-friendly characteristics.

4.3.4 More Analysis

Property	Bio-Enzyme	Lime Stabilization
CBR (%)	11.56	15.8
Liquid Limit	41.25	39.95
Plasticity	22.9	18.55
Permeability	Decreased	Decreased
Mechanism	Physical–chemical bonding	Pozzolanic reaction

4.3.5 Mechanism Comparison
Lime Stabilization:
Lime reacts chemically with clay minerals through cation exchange and pozzolanic reactions, forming cementitious compounds (C-S-H and C-A-H). This leads to a significant increase in strength and rigidity.

Bio-Enzyme Stabilization:
Bio-enzymes act by modifying the physicochemical interaction between soil particles, reducing water affinity and improving particle bonding without forming cementitious compounds.

V. CONCLUSION

This study evaluated the effectiveness of bio-enzyme stabilization on black cotton soil and compared its performance with lime stabilization using literature data. The results indicate that bio-enzyme treatment improves the engineering properties of soil by increasing the California Bearing Ratio (CBR), reducing plasticity, and decreasing permeability. The CBR value showed noticeable improvement, indicating enhanced load-bearing capacity, while reductions in liquid and plastic limits confirmed decreased soil plasticity and improved stability. The decrease in permeability demonstrated better resistance to water infiltration.

Comparative analysis revealed that lime stabilization provides higher strength improvement due to strong pozzolanic reactions. However, bio-enzyme stabilization offers a sustainable and environmentally friendly alternative with satisfactory performance.

Therefore, bio-enzyme stabilization can be effectively used for low to medium load applications such as rural roads and subgrade improvement, while lime stabilization remains more suitable for high-strength requirements.

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