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Review Article

Effect of Enzyme-Based Soil Stabilization: A Review

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Abstract *- Soil stabilization is crucial to modern construction and infrastructure development. Among different stabilizers, using enzymes is one of the alternatives to improve soil stability and offer a sustainable alternative to traditional soil stabilization methods. In the present study, enzyme-based soil stabilization techniques have been studied using various enzymes, and it was found that the enzymes are effective in improving the strength of the soil. Terrazyme, the most common, is very effective in all soil types. It increases the cohesion of sandy soils, increases slope stability, mitigates the swelling and shrinkage of clayey soils, decreases Optimum Moisture Content, increases Maximum Dry Density, and improves California Bearing Ratio and Unconfined compressive strength (UCS). The study shows that Bio-enzymatic improves UCS strength up to 4.5 times and shear strength to 104.32% to 463.50%, reducing soil permeability by 0.4 to 0.16 times than the parent strength. It increases the strength through particle aggregation and cementation, forming calcium silicate hydrate and improving soil properties. Enzymes are natural, non-toxic, and biodegradable biocatalysts, making them an environmentally sustainable choice to enhance their strength and durability. The findings in this study represented sustainable solutions for soil stabilization, which engineers or researchers can use for future development and construction.*

Keywords *- Enzyme, Terrazyme, Soil stabilization, Unconfined Compressive Strength, Agriculture.*

1. Introduction

Soil stabilization is a recent innovative technique researchers use to increase soil strength in an environmentally friendly way. This technique is used for construction in developing countries. These are also used in the agricultural sector [11,17]. Soil stabilization is also done with the help of some chemicals and additives. Unlike soil stabilization, using enzyme offers a sustainable solution that does not negatively impact the environment. Specific enzymes are employed to improve soil properties. These enzymes break down the organic matter, increase the soil cohesion and enhance load-bearing capacity. However, these enzymes aid in reducing soil erosion and improving water retention, which are valuable in drought or excessive rainfall regions.

The advantage of using enzymes for soil stabilization is eco-friendly [5,10,12,20]. The chemicals used for long-term soil stabilization harm the environment while the impact on the environment using enzymes is minimal. Enzyme-based soil stabilization exhibits high adaptability and can be directed toward solving any particular soil problem. While clayey soils may require improved drainage, sandy soils may exhibit enhanced cohesion, thus calling for selecting and utilizing specific types of enzymes [6].

With its associated versatility, it serves to cover a wide range of soil conditions and engineering works. Enzyme-based soil stabilization is a promising new frontier in geotechnical engineering and agriculture. [9].

Regarding soil stabilization, some enzymes are used to improve soil properties. They are very specific biological catalysts involved in chemical reactions in living organisms. They do this by degrading organic matter, which increases soil cohesion while developing its load-bearing capacity. Other ways enzymes help with soil stabilization include preventing soil erosion and promoting water retention in arid two- or seasonal rainfall-prone areas. [5,20].

This paper discusses soil stabilization through various enzymes with a great focus on Terrazyme, the one in most common use. It improves soil strength by promoting soil particle aggregation and cementation. Organic cations derived from Terrazyme react with soil clay, forming calcium silicate hydrate and strengthening the soil. When the dosage of terrazyme is increased, the strength of the soil is markedly increased. Compaction and strength characteristics are discussed before and after soil enzyme addition. [12,21].

2. Soil Stabilization Using Enzyme

Soil stabilization through enzymes presents an innovative and eco-friendly approach for enhancing soil properties within civil engineering and construction. This overview will discuss the incorporation of specific enzymes into soil and their subsequent effects.

Enzymes are natural biocatalysts that play a crucial role in this stabilization process. When integrated into the soil structure, these enzymes initiate chemical reactions that provide numerous benefits. A primary advantage is the enhancement of soil cohesion, which effectively counters erosion while increasing load-bearing capacity. This adaptability makes enzyme-based soil stabilization suitable for various applications such as road building, foundation support, and slope reinforcement.

Additionally, employing enzymes for soil stabilization leads to a significant reduction in permeability. As enzymes decompose organic materials, they improve soil compaction and decrease water infiltration and swelling susceptibility. As a result, this method enhances both durability and resilience in the soil.

A key highlight of enzyme utilization in soil stabilization is its environmentally friendly nature. In contrast to conventional stabilizing agents that may pose hazards to environmental health, enzymes are biodegradable and do not adversely affect ecosystems.

In conclusion, utilizing enzymes for soil stabilization is a progressive solution that bolsters soil characteristics while fostering sustainable construction practices. Its ability to strengthen soils, reduce erosion risk, and lower permeability positions it as a beneficial technique vital to contemporary civil engineering projects and infrastructure development efforts. [14, 21].

3. Types of Enzymes Being Used

3.1. Terrazyme

Terrazyme was an advanced biotechnological solution that brought about revolutions in soil stabilization in civil engineering and building. It utilized natural enzymes to enhance soil properties, thus improving soil strength and durability. Introducing refrigerated enzymes directly into the matrix of soils catalyzes a set of chemical reactions that waters interface to enhance cohesion, water retention and bearing capacity. It prevents erosion and reduces the amount of traditional stabilizers from being used, which could be harmful to the environment. The application of Terrazyme offers innovative, sustainable, and forward-looking alternatives to resilient and environmentally friendly building activities. [12,20,22]

3.2. Alkazyme

Alkazyme is an enzyme-based brand used for soil stabilization processes. It mainly contains alkaline enzymes, which are targeted at solving some of the soil-related challenges. Its main function is to alter the pH and enhance the soil properties, thus rendering it ideal for construction, agriculture, and environmental remediation. When alkazyme acts on soil stabilization, it works by the enzymatic process of neutralizing the soil's acidity or alkalinity, thus adjusting the soil pH to a more optimal value for the intended applications. The pH adjustment makes for good soil cohesion, load-bearing capacity, and nutrient availability, benefiting its overall quality and functionality [9]. Thus, alkazyme can be recommended for treating soils with extreme pH, such as highly acidic or alkaline. Also, it is environmentally friendly as it does not react with harmful soil chemicals. This makes it a sustainable solution to soil improvement projects while decreasing ecological impacts. Thus, alkazyme is an enzyme-based product vital for soil stabilization. It changes soil pH and enhances its properties, resulting in better soil management practices with more activities that respect the environment. [19].

4. Mechanism of Stabilization with Enzymes

The role of the enzyme in soil stabilization is an innovative and novel process that requires its alkaline enzymes to modify pH and build properties in soils. The enzymatic approach constitutes a key part of soil enhancement for various uses. This triggers the growth of beneficial microorganisms in the soil, favoring the long-term stability of nutrients [20]. The enzymes act as natural biocatalysts that trigger important chemical reactions. They act by targeting the organic compounds in the soil and converting them into simpler forms. They form calcium carbonate crystals. Dressing thus reduces permeability and swelling and enhances soil compaction, thus forming stable soil, which increases soil cohesion and load-bearing capacity [1,8,16].

These enzymes work optimally in a variety of environmental conditions. When added to the soil, they first neutralize soil acidity or alkalinity, depending on the pH of the soil, in the case of highly acidic soils. Alkazyme's enzymes work to take the pH closer to neutral. If the soils are more alkaline, the processes help lower the pH toward the desired levels. This pH adjustment has great significance due to its impact on various other aspects of soil performance. For one, the change in pH enhances soil cohesion, which is important for construction stability. Improved cohesion reduces potential soil erosion and increases load-bearing capacity for applied use in infrastructure development. Secondly, adjusting the pH by Alkazyme promotes the availability of nutrients in the soil. This is particularly beneficial for agriculture, as it ensures that essential nutrients are more readily accessible to plants. As a result, crops grow healthier and more productively [7,9].

The strength mechanism of soil enzyme is based on the cation exchange mechanism. The clay particle possessing the negative charge attracts the ions, reducing the double diffuse layer [6]. The clay minerals absorb the enzymes, which leads to the relaxation of the minerals. This relaxation leads to moisture retention and leads to the reduction in the double layer [9]. The clay minerals' ability to absorb water reduces, resulting in the rearrangement of the soil structure. This rearrangement leads to a change in the properties of the soil.[13]

Enzyme's action improves soil structure and porosity. This aids in better water retention and drainage by adjusting the soil pH, enhancing soil cohesion, improving nutrient availability, and improving soil structure. Its environmentally friendly nature makes it a promising solution for soil stabilization while minimizing harm to the ecosystem.

5. Effect of Enzyme on Soil Properties

Enzyme, an innovative biotechnological soil stabilization solution, significantly affects various soil properties and engineering parameters, including California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), consistency limits, compaction, permeability, and density.

5.1. CBR (California Bearing Ratio)

Terrazyme enhances CBR values by improving soil cohesion and load-bearing capacity. It strengthens the soil's resistance to deformation under traffic loads, making it suitable for road construction and pavement applications [20].

As the dosage of the enzyme increases, the CBR value, which measures soil's load-bearing capacity, correlates with its concentration increases and decreases with the addition of the enzyme. As CBR increased, soil strength also increased, and an increase was seen in more than double the parent soil. Providing valuable insights for engineering and construction projects [5,15].

5.2. UCS (Unconfined Compressive Strength)

Enzyme treatment increases the UCS of soil, making it more resilient to vertical stresses. The increase in the result is due to increased cohesion and formation of the cementitious compound [22]. This effect is particularly advantageous for foundations and retaining walls, ensuring their stability and durability. After treatment, the soil showed a great increase in its UCS value compared to the untreated soil [9]. Alkazyme's pH modification enhances soil cohesion, making the soil more stable, especially for construction projects. It reduces the risk of soil erosion and enhances load-bearing capacity [1,8,20].

5.3. Consistency Limits

Enzymatic action can alter the Atterberg limits of soil. It affects the soil's water content, hence affecting the consistency limit. It reduces plasticity and shrink-swell potential, making the soil more stable and less susceptible to changes in moisture content. This is vital for construction in regions with varying weather conditions. From compaction results, it can be perceived that the change in OMC/MDD governs the efficacy of the additive and that the addition of enzymes creates a denser material with a decrease in the affinity for water [20].

5.4 Compaction

Enzyme-treated soil exhibits increased density due to improved compaction. This higher density translates into improved load-bearing capacity, reducing settlement and enhancing the longevity of structures [15]. Terrazyme and alkazyme promote better compaction by enhancing soil structure and reducing permeability. Compacted soil treated with Terrazyme achieves higher densities, improving stability and load-bearing capacity [9,20].

5.5 Permeability

Terrazyme and Alkazyme contribute to enhanced soil structure and porosity, affecting permeability. It reduces soil permeability by breaking down organic matter and improving compaction. Improved soil structure is vital for better water retention and drainage. This is valuable for preventing excessive water infiltration, which can undermine the integrity of construction projects. Alkazyme contributes to enhanced soil structure and porosity. Improved soil structure is vital for better water retention and drainage [6,13,14].

The various researchers performed soil stabilization using different enzymes (e.g., Terrazyme, Alkazyme, and other enzymes). A summary of the terrazyme and other enzymes taken by different research studies is given in Tables 1 and 2.

Table1. Summary of the Terrazyme used as a soil stabilizer

Authors	Descriptions	Results
Venkatesh and Reddy (2017)	This study added Terrazyme to Black Cotton soil, and Shear strength and CBR tests were conducted. At different dosages, 1% - 4% of black cotton soil.	The shear strength of the soil increased, and the percentage increase was 410%. The curing shear strength of the soil is increased, and the percentage increase is 354.1%. CBR value increases from 3.9 to 8. Increase in 104.32%. Tri-Axial increase in the percentage of Terrazyme shear strength of the soil increases 6.4 kPa to 35.3 kPa, an increase of 451.87%. The best dosage was 4% Terrazyme, which gave the most favourable result.
Ramanjaneyulu et al. (2023)	This study conducted UCS and CBR tests on mixes of clay soil + Terrazyme+ marble dust. A marble proportion of 15% was constant	Use of 0.25 ml/kg and 15% Terrazyme and marble dust results in higher CBR and UCS for soil. Value-treated soil increases with MDD of 15% with 0.25ml/kg Terrazyme and 12%

	for all tests. Terrazyme used in this study were 0.125ml, 0.25ml and 0.5ml per kg of dry soil.	marble dust with original soil. OMC remains unchanged. UCS of untreated clay is 245 kPa increased to 44%, 111%, and 103% and CBR value to 13.13%, 21.46%, and 21.00% with 0.125ml/kg, 0.25ml/kg and 0.5ml/kg of Terrazyme dosages. The optimum is 0.25ml/kg of Terrazyme, along with 15% marble dust, which is effective in soil strength.
Zhang et al. (2013)	Stabilized soil mixed with TerraZyme was used to determine the relationship between UCS and microstructure. UCS and SEM tests were conducted on the sample.	UCS of treated soil increases. (SEM) show that the stabilized treated soil sample is denser than the untreated one. UCS tests are consistent with SEM analyses of stabilized soil with TerraZyme added.
Saini and Vaishnava (2015)	In this study, virgin soil (Dehradun) was mixed with various dosages of TerraZyme, and consistency limits, SPT, and CBR were obtained.	MDD value with TerraZyme was 1.8gm/cm^3 with an OMC of 17%. Consistency limits are reduced in the third dosage of an enzyme, and the soaked CBR increases after a curing period of two weeks.
Chaurasia et al. (2018)	This study shows that balancing performance and economic feasibility in infrastructure projects is paramount in developing nations like India. Traditional methods proved costly and time-consuming, leading to the exploration of alternatives. This paper examined the use of Terrazyme, a bio-enzyme, to enhance the properties of black cotton soil and red soil. Bio-enzyme application improved soil compaction, stability, and bearing capacity. Local materials were utilized, and in cases of limited granular resources, bio-enzyme-stabilized thin bituminous surfacing met pavement design requirements, reducing the thickness by 25 to 40 percent. Although bio-enzyme soil stabilization remained relatively underutilized due to limited awareness and standardized data, it held promise for cost-effective and efficient infrastructure development.	Bio-enzyme addition, particularly Terrazyme, demonstrated significant field performance improvements and ensured durable, maintenance-free pavements. Our research concluded that Terrazyme did not enhance red soil properties, as it is a non-cohesive soil. Terrazyme proved effective for cohesive soils, eliminating the need for granular sub-base, base, and surface courses in low-traffic areas, promoting eco-friendliness and resource savings. Terrazyme emerged as a smart, eco-friendly, and cost-effective construction material with great potential for future applications.

Table 2. Summary of other enzymes used as a soil stabilizer

Authors	Descriptions	Results
Carmona et al. (2016)	In this study, the strength and stiffness of sandy soil are improved using precipitated calcium carbonate ($CaCO3$), a Urease enzyme. With constant 4 kU/L urease, 0.25 mol/L urea-$CaCl2$ yields 90% precipitation, and compressive strength was boosted. XRD tests and UCS tests were also performed.	Urease enzyme helps urea break down, forming calcium carbonate and strengthening soil. The method leads to varied UCS test results. Higher urea-$CaCl2$ reduces precipitation and soil strength, possibly due to inadequate urease or enzyme inhibition.
Martínez and Tabatabai (2000)	In this study, Limed Agricultural soil was taken. L-glutaminase and L- aspartase	The lime application can increase soil pH, fostering microbial growth and diverse

	enzymes were taken, and their activities were noted. Lime was also added as a soil stabilizer.	enzymes, impacting nutrient cycling. Most enzymes grew more active as soil pH increased, except acid phosphatase. Sensitivity to pH varied, with L-glutaminase being the most sensitive and L-aspartase the least. These findings highlight potential early indicators of soil health and stress.
Venkatesh and Mall (2023)	In this study, Soil stabilization enhances soil properties for better pavement performance. India employs bio enzymes like DZ-1X, Terrazyme, Permazyme, and Renolith, especially in clay-rich soils. Lab tests confirmed their effectiveness and affordability, with the bonus of environmental friendliness.	Applying bio enzymes in soil stabilization presents a promising solution for improving soil properties in various regions, particularly where swelling and shrinking characteristics pose challenges for construction. These enzymes have demonstrated their effectiveness in enhancing soil strength, reducing water content, and controlling dust, offering sustainable pavement construction and soil management alternatives. Their potential benefits make bio enzymes valuable in soil stabilization and geotechnical engineering.
Thomas et al. (2018)	Compared to conventional OPC, this study explores the effectiveness of non-traditional soil stabilizers, namely alkali-activated GGBS and enzymes. Different tests like OMC and UCS were performed. It focussed on soil from Chhattisgarh, India, noting moisture content, density, strength, and cohesion improvements with these eco-friendly stabilizers, making them promising alternatives to OPC for soil stabilization.	Higher stabilizer dosages decrease MDD while increasing OMC, UCS, and shear strength. A dosage of 20% GGBS with 1M NaOH, 12% OPC, or 645 ml/m3 enzyme is optimal. Alkali-activated GGBS outperforms OPC, with UCS 1.15 times higher and 5.5 times higher than enzyme-stabilized soil, suggesting its superior strength development for this soil type.
Renjith et al. (2020)	This research explores the effectiveness of the enzyme-based soil stabilizer, Eko Soil, in constructing unpaved roads in Australia and worldwide. It aims to identify the ideal mix proportions for this additive by understanding its stabilization mechanism, reducing costs, and improving road construction efficiency.	This study explores the soil stabilization effects of a new enzyme-based additive for global unpaved road construction. Key findings include temperature sensitivity, reduced water demand, pore densification as the mechanism, and substantial strength improvements, especially when using optimal moisture levels. For fine-grained soil, a 1% application of the additive at a 1:500 (DMR) ratio is recommended, along with a 7% AMR for consistent mixing, offering a sustainable and cost-effective road construction solution.
AbouKhadra et al. (2018)	This study explores how environmentally friendly enzyme-based materials can strengthen weak soils, reducing the need for costly replacements. Various doses of two commercial enzyme products were tested on five different soils, assessing strength, density, and permeability. The findings revealed a notable increase in soil strength, especially in fine soils, with a more substantial effect in soils with higher clay content. Additionally, X-ray fluorescence analysis detected a slight rise in silica ion content in treated soils.	Enzymatic stabilization significantly improved unconfined compressive strength and California bearing ratio. Fine soil showed a remarkable enhancement compared to sandy soil, with improvements ranging from 2.75 to 4.5 times those of untreated soil. The optimal enzyme concentration for fine soil was found to be 0.25%. Bio-enzymatic stabilization also greatly improved soil permeability, with treated soil exhibiting values from 0.4 to 0.16 times that of untreated soil. The increase in soil strength and permeability

		was more pronounced with higher clay content. Maximum dry density showed minor improvement in fine soil and negligible changes in coarse soil. While lab results are promising, the real-world application of enzymatic stabilization should be verified to confirm its effectiveness, especially concerning forming new chemical bonds between soil particles or water.
Silva et al. (2017)	In this study, Enzymes, natural catalysts, excel in physiological conditions but differ from industrial needs. Extracting enzymes from extremophiles can help, but it does not always meet industrial demands. Ensuring enzyme stability in extreme environments is crucial. This review provides practical insights into commonly used methods for enzyme stabilization, supported by case studies.	Enzymes designed for physiological environments face challenges in industrial settings. Extracting enzymes from extremophiles offers solutions but does not cover all needs. Enzyme stability is vital, and this review offers practical insights with case studies.

6. Implications of the Effectiveness of Terrazyme

The advent of Terrazyme, a bio-enzyme soil stabilizer, has brought significant advancements in soil engineering and road construction. Terrazyme enhances the soil's physical properties, producing strong and durable infrastructure at a minimum cost.

However, its effectiveness heavily depends on soil properties, affecting its applied practice and the possibility of global acceptance. Terrazyme functions by increasing the chemical bonding of the soil particles with a decrease in water retention capability.

However, sandy soils' efficiency is restrained because of their high permeability and low cohesion. In contrast, clay soils experience relatively more advantages. These tend to be characterized by high plasticity and water retention, which preserve clay soils' predictable load-bearing capacity development by reducing swelling and increasing shrinkage.

Loamy soils exhibit moderate improvements in their performance features; whereas Terrazyme shows full efficacy in these soils, their inherent stability mitigates the overall efficacy. For soils with high silt contents, the ability of the enzyme to couple and prevent sensitivity to water further makes these saliferous soils more viable construction options.

These performance disparities underscore the requirement for an exhaustive soil analysis before applying Terrazyme. This encompasses the requisite assessment of particle-size distribution, the Atterberg limits, and the moisture content in authenticity to get a pretty good view of the effectiveness of the enzyme. Furthermore, global consideration of these factors, namely climate conditions such as rainfall and temperature, considerably determines the long-term performance.

The implications of these differences are significant concerning infrastructure development. Hence, engineers and decision-makers must customize strategies for using Terrazyme according to soil types to optimize for cost against sustainability. Further research directed at enhancing the applicability of the enzyme may broaden the scope for its use, thus ushering in green projects across regional bases of the world.

7. Field Application and Limitations

Terrazyme brought a vast change in soil stabilization practices, offering a sustainable and efficient alternative to chemical processes. Improving soil strength and durability, this bioenzyme has been found to have applications in road construction, embankments, and other infrastructural projects. Even though there is immense potential for this biostabilizer, practical limitations in actual applications need to be considered.

In field conditions, Terrazyme demonstrates its most significant benefits in stabilizing clay-rich soils, which are prone to swelling and shrinkage due to water retention. Its ability to improve load-bearing capacity and reduce water sensitivity has made it a preferred choice in regions with expansive soils. Furthermore, Terrazyme's ease of application, requiring minimal specialized equipment, has contributed to its adoption in remote and resource-limited settings.

However, these advantages still remain to be challenging. The effectiveness of the enzyme is closely linked to the soil type, and a detailed preliminary investigation needs to be carried out before usage to ascertain acceptability. Sandy soils show less improvement because of the high degree of permeability, whereas soils containing organic substances can work in race with the enzyme, reducing its efficiency. Environments with extreme temperatures and high precipitation can also have an impact on the durability of Terrazyme-treated soils in the long term. Another limitation lies in a lack of standardized application protocols, which affect results inconsistently across project sites. Field trials and case studies are imperative for developing best practices for specific soil-climatic conditions. Further compromise would be needed before one weighed the economic viability of using Terrazyme in large-scale projects against other alternative stabilization methods. Further research and development to enhance applicability to various soil types and environmental conditions, coupled with the preparation of guidelines, thus unlocking its full potential for sustainable construction practices worldwide, are required to overcome the above-mentioned pitfalls.

8. Critical Summary

The researchers studied and examined the soil stabilization effects of a novel enzyme-based additive, a material being utilized in constructing unpaved roads both in Australia and globally. The investigation unfolded in four distinct stages to ascertain the stabilization effects and the underlying mechanisms of this enzyme-based innovation, particularly tailored for common field soils found in Victoria, Australia. Here are the key findings:

- The addition of Terrazyme significantly improved the unconfined compressive strength, and the California bearing ratio (CBR) also increased both in soaked and unsoaked conditions of fine soil. It was remarkable, with enhancements ranging from 2.75 to 4.5 times compared to untreated soil.
- Bio-enzymatic stabilization greatly enhanced soil permeability. Treated soil showed coefficients ranging from 0.4 to 0.16 times that of untreated soil. The permeability reduces as the enzymes are added.
- Notably, the impact on soil strength and stability was more pronounced in soils. As the UCS of the soil increases, the subgrade used for construction also stabilizes. Soil shear strength exhibited remarkable percentage increases, ranging from 104.32% to 463.50%, particularly with higher Terrazyme percentages and longer curing periods.
- The improvement was seen in the case of cohesive soil, decreasing the moisture content of the parent soil. Tri-axial tests confirmed TerraZyme's effectiveness, showing a substantial increase in cohesion. Also, the treated soil affects the consistency limits of the soil.
- Enzyme-stabilized soils required less water for compaction, shifting the Optimum Moisture Content (OMC) towards the wetter side. Stabilized samples prepared at the OMC of control samples did not exhibit significant strength improvement.
- Analysis via XRD and EDS demonstrated no compositional changes in the treated samples compared to controls, indicating no chemical reactions or new compound formations. Micro-Computed Tomography (μCT) scans revealed distinct pore differences, highlighting that enzyme-based stabilization primarily worked through densification.
- Stabilizer efficiency notably increased (up to 500% in CBR strength) when stabilization was done at the stabilized OMC, as opposed to the reference OMC. Understanding this mechanism enhanced the optimized strength of stabilized soil, potentially increasing it from 15% to 500% compared to control samples.

It has been found that the Shear Strength of the soil increases with the addition of the enzyme, ranging from 200% to 410% in various soil types. CBR value to 13.13%, 21.46%, and 21.00% with 0.125ml/kg, 0.25ml/kg and 0.5ml/kg of Terrazyme dosages. UCS of untreated clay is 245 kPa increased to 44%, 111%, and 103%. CBR value increases from 3.9 to 8 in most of the soil.

Enzymes, in comparison with other additives, are less effective. UCS, and shear strength of dosage of 20% GGBS with 1M NaOH, 12% OPC, or 645 ml/m^3 enzyme with optimal the alkali-activated GGBS outperforms OPC, shows 1.15 times higher and 5.5 times higher than enzyme-stabilized soil, Tri-Axial increase in percentage of Terrazyme shear strength of the soil increases 6.4 kPa to 35.3 kPa, increase in 451.87%. These findings show a great change in the soil strength.

Enzymes, as natural, non-toxic and biodegradable biocatalysts, make it an environmentally sustainable choice to enhance their strength and durability. In the present study, enzyme-based soil stabilization techniques have been studied using various enzymes, and it was found that the enzymes are effective in improving the strength of the soil. Terrazyme, being the most common, is very effective in all soil types.

Ultimately, the study pinpointed that it facilitates ring valuable insights for the road construction industry seeking sustainable and cost-effective solutions using enzyme-based additives. These findings form a solid foundation for informed decision-making in employing this innovative approach in road construction. Bio-enzymatic stabilization holds immense potential for transforming construction practices, but its practical suitability demands further investigation in real-world conditions.

Author Contributions

All the authors contributed to the successful completion of this work. Dr. Ajanta Kalita and Miss. Nisha K. Singh spearheaded the review paper's conceptualization, outlining the review's scope, objectives, and structure. Mr. Dinken Paksok completed the final draft of the review paper before submission. Mr. Kunchok Tashi also helped in the final editing of the paper. Dr Ajanta Kalita and Mr Dinken Paksok assisted in finalizing the submission and ensuring that it met academic standards and formatting guidelines before submission.

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