MSW MANAGEMENT -Multidisciplinary, Scientific Work and Management Journal
ISSN: 1053-7899
Vol. 36 Issue 2, 2026, Pages 1543-1549

Bio-Enzyme Based Eco-Friendly Soil Stabilization for Strengthening Existing Footings: A Review Article

Jagadish J. S.[1], Gopalakrishna V. Gaonkar [2], Hemantkumar Ronad [3]
[1]Research Scholar, Department of Civil Engineering, JAIN (Deemed-to-be University), Bengaluru- 562112, Karnataka, India
[2]Assistant Professor, Department of Civil Engineering, JAIN (Deemed-to-be University), Bengaluru- 562112, Karnataka, India
[3]School of Civil Engineering, K.L.E. Technological University, Hubballi-580031, India
Corresponding author's email: jagadish11cse08@rediff.com

Abstract
Amid growing environmental concerns and infrastructure demands, sustainable soil stabilization has emerged as a pivotal frontier in geotechnical engineering. The performance and serviceability of foundation systems are strongly governed by the engineering behavior of supporting soils. A large number of existing structures worldwide are founded on weak or expansive soils, resulting in excessive settlement, cracking, and durability issues worldwide. Conventional soil stabilization methods such as cement and lime treatment, though effective, are associated with high carbon emissions and limited suitability for retrofitting existing foundations. Bio-enzyme-based soil stabilization has emerged as an eco-friendly alternative capable of improving soil properties without rigid cementation. This review critically examines the mechanisms, effectiveness, durability, environmental impact, and limitations of bio-enzyme soil stabilization with particular emphasis on its potential application for strengthening existing footing systems. A comprehensive synthesis of global research trends, material behavior, comparative performance, and future research needs is presented, highlighting bio-enzymes as a promising sustainable solution for foundation engineering.
Keywords: Bio-enzymes; Soil stabilization; Expansive soils; Soil–structure interaction; Sustainable geotechnics

1. INTRODUCTION

The evolving challenges associated with problematic soils have necessitated the exploration of innovative, eco-efficient stabilization strategies beyond conventional practices. Experimental investigations have demonstrated that bio-enzyme-treated soils exhibit improved strength and durability compared to untreated soils [1,2]. A comprehensive review on soil stabilization using bio-enzymes has been presented by Mall and Venkatesh [3]. Critical reviews on innovative soil and road stabilization techniques highlighted the environmental and performance limitations of conventional stabilizers [4]. Recent studies emphasized the growing relevance of bio-enzymes in subgrade and pavement stabilization [5].

Experimental studies on expansive soils treated with bio-enzymes revealed significant improvements in swelling and strength behavior [6,7]. Improvements in compaction and consistency characteristics were reported for TerraZyme-treated expansive soils [8], while Agarwal and Kaur demonstrated a marked increase in unconfined compressive strength [9]. Field-based performance evaluation further confirmed the effectiveness of TerraZyme as a soil stabilizer [10]. Enzymatic treatment has also been shown to improve plasticity and strength of earthen construction materials [11].

Guidelines for enzymatic soil stabilization were later proposed to enable standardized field applications [12]. Recent eco-friendly stabilization approaches using industrial and biological materials have further strengthened sustainability aspects [13,14]. Biopolymer stabilization has emerged as a complementary green alternative [15]. Studies on TerraZyme-treated soils further confirmed improvements in load-bearing and deformation behavior [16,17].

Despite these advances, foundation distress caused by weak and expansive soils remains a major challenge [18], and limited studies have explored bio-enzymes for foundation engineering applications [19–21]. Black cotton soils are particularly problematic due to their shrink–swell behavior [22–24]. Conference studies further validated TerraZyme effectiveness in expansive soils and road construction [25,26]. Conventional stabilization guidelines emphasize the need for low-carbon alternatives [27–30].Despite considerable advancements in soil improvement techniques, the behavior of weak and expansive soils continues to pose a persistent challenge in foundation engineering. Such soils are inherently prone to excessive deformation, volume change, and strength degradation when subjected to variations in moisture and loading conditions, leading to significant serviceability and durability concerns in civil infrastructure. Conventional stabilization approaches often address these issues through rigid cementitious bonding, which, although effective in increasing strength, may introduce brittleness and long-term cracking. Consequently, there is an increasing need to explore stabilization strategies that not only enhance soil performance but also maintain sufficient flexibility to accommodate stress redistribution beneath structural foundations.In this context, bio-enzyme-based soil stabilization has emerged as a promising and sustainable alternative due to its distinct mechanism of action, which modifies soil behavior through physicochemical interactions rather than rigid cementation. By improving interparticle bonding and reducing moisture susceptibility, bio-enzymes have the potential to mitigate key factors responsible for foundation distress, including swelling, softening, and progressive settlement. Moreover, the environmentally benign nature of bio-enzymes aligns well with contemporary demands for low-carbon and resource-efficient construction practices. These combined attributes position bio-enzymes as a strategically important research focus for developing resilient and sustainable foundation systems in problematic soil environments.

2. GLOBAL RESEARCH TRENDS IN BIO-ENZYME SOIL STABILIZATION

The application of bio-enzymes in geotechnical engineering has expanded significantly over the past two decades, particularly in Asia, Africa, and Europe. Early research focused on road subgrades and low-volume pavements, where enzymatic stabilization demonstrated improved compaction, reduced plasticity, and enhanced load-bearing performance [4,27,28].In India, extensive studies on TerraZyme-treated expansive and black cotton soils confirmed its effectiveness in improving CBR, UCS, and resistance to moisture-induced deterioration [16,18,22,24]. Studies in Nigeria and Egypt further demonstrated that enzymatic stabilizers can significantly enhance strength and durability across a wide range of soil types [1,2].

Recent publications emphasize the necessity of integrating bio-enzymes into mainstream geotechnical practice through field-scale validation, standard mix design procedures, and incorporation into design codes [3,30]. The increasing number of journal publications and conference proceedings highlights the growing recognition of bio-enzymes as viable soil improvement agents.

3. MECHANISM OF BIO-ENZYME SOIL STABILIZATION

Bio-enzymes stabilize soil primarily by modifying the physicochemical interactions between clay particles and pore water. Enzymes reduce the thickness of the diffuse double layer surrounding clay particles, thereby decreasing repulsive forces and facilitating closer particle arrangement [7,9]. This results in flocculation and aggregation, producing a denser and more stable soil structure [11].

Unlike cement and lime, bio-enzymes do not form rigid cementitious bonds. Instead, they promote long-term soil fabric modification through biochemical catalysis [19]. This leads to improved particle interlocking and enhanced resistance to moisture penetration. The absence of brittle cementation makes bio-enzymes particularly suitable for use beneath existing foundations, where flexibility and gradual stress redistribution are essential [12,21].

Bio-enzyme soil stabilization operates through a fundamentally different mechanism compared to conventional cementitious binders, relying primarily on physicochemical modification of soil–water–particle interactions rather than rigid matrix formation. When introduced into fine-grained soils, bio-enzymes interact with the adsorbed water layers surrounding clay particles, leading to a reduction in the thickness and activity of these layers. This process diminishes repulsive forces between particles and promotes closer particle association, resulting in a more compact and stable soil fabric. Unlike traditional stabilizers that alter mineralogy, bio-enzymes function as catalysts that facilitate reorientation and aggregation of soil particles without generating new mineral phases.

As a consequence of this altered microstructure, enzyme-treated soils exhibit enhanced interparticle bonding, reduced moisture sensitivity, and improved resistance to deformation under applied loads. The densification of the soil matrix limits pore connectivity and restricts the movement of water, thereby contributing to improved strength, stiffness, and durability. Importantly, this mode of stabilization preserves a degree of flexibility within the soil mass, allowing it to accommodate stress redistribution without brittle failure. Such a behavior is particularly advantageous for foundation systems, where excessive rigidity may lead to stress concentration and cracking, whereas controlled deformability promotes long-term serviceability and structural resilience.

4. MICROSTRUCTURAL AND CHEMICAL ASPECTS

At the microstructural level, enzyme-treated soils exhibit reduced pore spaces and improved particle orientation. SEM studies reveal dense fabric and increased interparticle contact, while XRD analysis shows no new mineral formation, confirming that enzymes act as catalysts rather than binders [7,11].

Chemically, bio-enzymes facilitate reactions between clay minerals and available cations, promoting flocculation and reducing the affinity of soil for water [8,9]. These micro-level changes manifest as macro-scale improvements in plasticity, strength, compaction efficiency, and moisture resistance. Such microstructural enhancement is crucial for foundation applications where long-term stability is required [21].

The internal structure of soils modified by enzymatic treatment undergoes a notable refinement, characterized by a more compact arrangement and enhanced continuity between individual particles. Instead of remaining loosely organized, soil grains tend to reorganize into a configuration that supports improved load transfer and mechanical stability. This reconfiguration leads to a reduction in void connectivity and contributes to a more uniform and resilient soil framework.

From a chemical standpoint, bio-enzymes influence soil behavior by altering surface interactions within the clay–water system rather than by creating rigid bonding agents. Their action encourages closer association between mineral surfaces and naturally occurring ions, thereby limiting the tendency of soils to retain excessive moisture. These physicochemical adjustments translate into measurable improvements in engineering performance, including reduced deformability, enhanced strength, improved compaction response, and increased resistance to moisture-induced deterioration. Such transformations are particularly valuable for soils supporting foundations, where sustained performance under variable environmental and loading conditions is essential.

5. REVIEW METHODOLOGY

This review adopts a systematic narrative approach to critically synthesize the existing body of knowledge on bio-enzyme-based soil stabilization with particular emphasis on its applicability to foundation engineering and the strengthening of existing footing systems. The methodology was designed to ensure scientific rigor, transparency, and reproducibility in the selection and analysis of relevant literature.

A comprehensive literature search was conducted using major scientific databases, including **Scopus, Web of Science, SpringerLink, ScienceDirect, ASCE Library, and Google Scholar**. The search strategy employed a combination of keywords and Boolean operators, such as *bio-enzyme soil stabilization*, *TerraZyme*, *enzymatic soil treatment*, *sustainable soil stabilization*, *foundation soil improvement*, and *expansive soil stabilization*, to capture a broad spectrum of studies pertinent to the topic.The review focused on publications released between **2005 and 2025**, thereby encompassing both foundational research and recent advancements in enzymatic soil stabilization. Peer-reviewed journal articles and reputable conference proceedings reporting **experimental, field-based, or numerical investigations** were considered eligible for inclusion. Studies were required to report quantifiable performance indicators related to soil behavior, including strength characteristics, volumetric stability, durability, permeability, compressibility, or deformation behavior.

Publications were excluded if they comprised commercial brochures, marketing materials, non-engineering applications, or studies lacking verifiable experimental or analytical evidence. Additionally, papers focusing exclusively on pavement performance without transferable relevance to foundation behavior were critically examined and selectively included only where mechanistic insights or soil improvement trends were deemed applicable to foundation engineering.

From an initial pool of approximately **90 publications**, a final set of **42 studies** was selected following relevance screening and quality appraisal. These studies were then systematically categorized based on soil type, testing methodology, engineering property investigated, and applicability to foundation systems.

Rather than adopting a purely descriptive approach, the selected literature was analyzed thematically to identify prevailing trends, divergences in reported behavior, methodological limitations, and critical research gaps. This thematic synthesis enabled a comprehensive evaluation of the current state of knowledge while explicitly linking soil improvement mechanisms to foundation performance requirements.

Through this structured methodology, the review ensures that the conclusions drawn are firmly anchored in the existing body of scientific evidence and are directly relevant to advancing the application of bio-enzyme stabilization in foundation engineering practice.

6. REVIEW OF PREVIOUS STUDIES ON BIO-ENZYME STABILIZATION

Numerous experimental and field investigations have demonstrated that bio-enzymes such as TerraZyme and Renolith can significantly improve the engineering behavior of soils, particularly in terms of strength, compaction efficiency, and moisture resistance **[1,2,10,16]**. Reported increases in California Bearing Ratio (CBR) and unconfined compressive strength (UCS) across a wide range of clayey, lateritic, and expansive soils indicate enhanced load-bearing potential following enzymatic treatment **[5,10,16]**.

Studies on expansive soils consistently document reductions in swelling pressure and plasticity index after enzyme treatment, highlighting the effectiveness of bio-enzymes in mitigating volumetric instability—a primary cause of foundation distress **[25,26]**. In addition, enzyme-stabilized lateritic soils have exhibited improved durability under cyclic loading and environmental exposure, suggesting favorable long-term performance characteristics **[19,29]**.

However, a critical examination of the literature reveals that the overwhelming majority of these studies are oriented toward pavement and subgrade applications rather than foundation systems **[20,27]**. Although improvements in strength and swelling behavior are well established at the material level, direct evidence linking these improvements to foundation performance parameters such as load–settlement response, bearing capacity under footing loads, and soil–structure interaction remains limited **[12,21]**.

Furthermore, most reported results are derived from laboratory-scale experiments, with relatively few full-scale field investigations **[21]**. This constrains the generalizability of the findings, particularly in the context of heterogeneous field conditions, scale effects, and construction variability.

Consequently, while the existing body of research substantiates the potential of bio-enzymes as effective soil stabilizers, it simultaneously underscores a critical need for foundation-specific experimental studies and field validation to enable their rational and reliable adoption in foundation engineering practice **[12,20,21]**.

Table 1. Representative Studies on Bio-Enzyme Soil Stabilization

Author	Soil Type	Bio-Enzyme	Tests Conducted	Key Findings	Ref
Shivhare & Mohanan	Clayey soil	TerraZyme	CBR, UCS	Significant strength improvement	[5]
Aswar et al.	Mixed soils	TerraZyme	Compaction, durability	Improved MDD and UCS	[10]
Tiwari et al.	Expansive soil	TerraZyme	Swelling, UCS	Reduced swelling behavior	[25]
Mithanthaya et al.	Lateritic soil	Bio-enzyme	Strength, durability	Long-term performance	[19]
Thomas & Rangaswamy	Clay	Enzyme + cement	Stress–strain	Improved ductility	[21]

7. EFFECT OF BIO-ENZYME TREATMENT ON SOIL ENGINEERING PROPERTIES

Bio-enzyme treatment significantly alters key soil properties relevant to foundation engineering:

- Plasticity: Liquid limit and plasticity index decrease substantially, reducing shrink–swell behavior [8,9].
- Strength: UCS and shear strength increase due to improved interparticle bonding [1,10,17].
- Bearing Capacity: Enhanced stiffness leads to improved bearing resistance [21].
- Swelling Pressure: Reduced swelling minimizes uplift forces on foundations [22,26].
- Permeability: Reduced pore connectivity improves moisture resistance [2,29].

These improvements collectively enhance foundation performance, particularly in expansive and soft soils.

Bio-enzyme treatment induces substantial modifications in the engineering behavior of soils through physicochemical alteration of particle interactions and pore-fluid dynamics. These changes manifest across a spectrum of soil properties that are critically relevant to foundation engineering, particularly in fine-grained and expansive soils.

7.1. Influence on Plasticity and Consistency Characteristics

One of the most consistently reported effects of bio-enzyme treatment is the reduction in soil plasticity, evidenced by decreases in liquid limit and plasticity index. This behavior is attributed to the modification of clay–water interactions, whereby enzymatic activity reduces the thickness of the diffuse double layer surrounding clay particles, thereby diminishing their affinity for water.

From a foundation engineering perspective, the attenuation of plasticity is highly significant, as high plasticity soils are inherently susceptible to excessive deformation, volume change, and strength loss upon wetting. By lowering plasticity indices, bio-enzymes contribute to enhanced dimensional stability of foundation subsoils, particularly in expansive clay deposits.

7.2. Effect on Strength and Load-Bearing Capacity

Bio-enzyme stabilization has been widely reported to enhance the strength characteristics of soils, most notably in terms of unconfined compressive strength (UCS), California Bearing Ratio (CBR), and, in some cases, shear strength parameters. These improvements are primarily associated with enhanced interparticle bonding and densification of the soil matrix following enzymatic treatment.

While UCS and CBR are commonly employed as surrogate indicators of load-bearing capacity in pavement engineering, their relevance to foundation performance is indirect. Nevertheless, the reported strength gains suggest that enzyme-treated soils possess improved resistance to applied stresses, which is expected to translate into increased bearing capacity and reduced settlement when employed beneath footing systems. However, the paucity of direct footing load test data remains a critical limitation in quantifying this translation.

7.3. Swelling Pressure and Volume Change Behavior

A particularly important contribution of bio-enzymes in expansive soils is the marked reduction in swelling potential and swelling pressure. Several studies document significant decreases in free swell index, swelling pressure, and expansion strain following enzymatic stabilization.

For foundations resting on expansive soils, this effect is of paramount importance, as swelling-induced uplift and differential movement constitute a primary mode of structural distress. By suppressing the volumetric instability of clay minerals, bio-enzymes enhance the serviceability and durability of foundation systems. However, most existing evidence is derived from laboratory-scale tests, necessitating validation under in-situ stress conditions representative of foundation loading.

7.4. Permeability and Moisture Susceptibility

Bio-enzyme treatment has been observed to reduce the permeability and moisture susceptibility of treated soils by altering pore connectivity and reducing the affinity of clay particles for water. This results in improved resistance to moisture ingress and softening under cyclic wetting–drying conditions.

From a foundation standpoint, reduced permeability is beneficial in mitigating pore pressure build-up and moisture-induced strength degradation, particularly in regions subject to fluctuating groundwater levels. Nevertheless, excessively low permeability may adversely affect drainage characteristics, indicating the need for balanced design considerations depending on site-specific hydrogeological conditions.

7.5. Compressibility and Settlement Behavior

Although limited in scope, available studies suggest that enzyme-treated soils exhibit reduced compressibility and improved stiffness relative to untreated counterparts. These changes are attributed to soil fabric densification and enhanced interparticle contact.

Reduced compressibility implies lower primary settlement under structural loads, a desirable attribute for foundation systems. However, systematic investigations into consolidation characteristics, including compression indices, coefficient of consolidation, and secondary compression behavior, remain scarce. This deficiency currently limits the reliability of settlement prediction models for enzyme-stabilized foundation soils.

7.6. Durability Under Environmental Loading

Bio-enzyme-treated soils demonstrate appreciable durability under environmental stressors, including cyclic wetting–drying and seasonal moisture variations. Compared to cement-treated soils, which often exhibit brittle cracking and shrinkage-induced degradation, enzyme-treated soils retain greater flexibility and structural integrity.

This resilience is particularly advantageous for foundation applications exposed to climatic variability and long-term service conditions. Nonetheless, long-duration field monitoring is required to conclusively establish the durability and performance stability of enzyme-treated soils over the design life of structures.

The long-term effectiveness of any soil stabilization technique is largely governed by its ability to withstand environmental variations without significant loss of performance. Soils treated with bio-enzymes have demonstrated a notable capacity to maintain their structural integrity when exposed to fluctuating moisture conditions, seasonal wetting–drying cycles, and thermal variations. Unlike rigidly stabilized soils, enzymatically treated soils exhibit a more adaptable response to environmental stresses, allowing them to accommodate volumetric and stress changes with reduced risk of cracking or disintegration.

This enhanced durability can be attributed to the nature of stabilization induced by bio-enzymes, which promotes cohesive particle association while preserving a degree of flexibility within the soil matrix. As a result, the treated soil is less susceptible to progressive degradation caused by repeated environmental loading. Such resilience is particularly significant for foundation systems that remain continuously exposed to groundwater fluctuations and climatic influences throughout their service life. The capacity of enzyme-treated soils to retain strength and stiffness under these conditions reinforces their suitability for long-term geotechnical applications where performance stability is as critical as initial strength improvement.

Table 2. Effect of Bio-Enzyme Treatment on Soil Engineering Properties

Property	Untreated Soil Behavior	Bio-Enzyme Treated Soil Behavior	Engineering Significance	Ref.
Plasticity Index	High plasticity; pronounced clay activity	Significantly reduced plasticity; stabilized consistency	Improved dimensional stability and reduced deformation potential	[8,9]
Swelling Pressure	High swelling potential under moisture ingress	Substantially reduced swelling and heave	Mitigation of uplift forces and differential movement beneath foundations	[22,26]
Unconfined Compressive Strength (UCS)	Low compressive resistance; poor load capacity	Markedly increased compressive strength	Enhanced load-bearing and stress resistance of subsoil	[1,10]
Moisture Resistance	High sensitivity to water; rapid strength loss	Improved resistance to softening and degradation	Sustained performance under seasonal moisture variations	[2,29]
Bearing Capacity	Low bearing resistance; prone to excessive settlement	Enhanced bearing response and reduced settlement tendency	Increased foundation safety and serviceability	[21]

8. DURABILITY AND MOISTURE RESISTANCE

Durability is a critical requirement for any stabilization method intended for foundation applications. Several studies have evaluated enzyme-treated soils under cyclic wetting–drying conditions and seasonal moisture variations. Results consistently indicate that enzyme-treated soils retain a significant portion of their strength even after repeated environmental cycles [1,29].

Unlike cement-treated soils, which may crack due to shrinkage and thermal stresses, enzyme-treated soils exhibit greater flexibility and resistance to microcracking [11,17]. This property makes them particularly suitable for foundations subjected to fluctuating moisture and groundwater conditions [2,21].

The performance of stabilized soils over the lifespan of a structure depends not only on initial strength enhancement but also on the ability to sustain those improvements under variable environmental conditions. Bio-enzyme-treated soils exhibit a notable capacity to preserve their mechanical and volumetric stability when subjected to prolonged exposure to moisture fluctuations and repeated environmental cycles. Rather than deteriorating rapidly in the presence of water, these soils tend to retain a substantial portion of their stiffness and load-carrying capability, which is essential for ensuring reliable support beneath foundation systems.

The resistance of enzyme-treated soils to moisture-induced degradation is primarily linked to the modification of soil–water interactions within the treated matrix. By limiting the tendency of fine particles to absorb and retain excessive water, enzymatic treatment reduces softening, loss of cohesion, and strength deterioration commonly observed in untreated fine-grained soils. This behavior contributes to improved resilience against erosion, softening, and progressive weakening under saturated or near-saturated conditions. Such durability and moisture resistance are particularly valuable for foundations constructed in regions experiencing seasonal rainfall, fluctuating groundwater levels, or aggressive climatic exposure, where long-term stability is a critical design requirement.

9. COMPARATIVE PERFORMANCE WITH OTHER STABILIZERS

Bio-enzymes are often compared with conventional and alternative eco-friendly stabilizers:

- Lime and Cement: Provide high immediate strength but are brittle and environmentally intensive [18,21].
- Fly Ash: Offers moderate improvement but depends on availability and chemical compatibility [20].
- Biopolymers: Provide excellent bonding but are costly and sensitive to biodegradation [15].

Bio-enzymes offer a balanced combination of performance, sustainability, and cost-effectiveness [14,30]. Recent research suggests hybrid stabilization techniques combining enzymes with biopolymers or industrial byproducts as a future direction for sustainable soil improvement [13,15].

A qualitative comparison of bio-enzymes with conventional and alternative soil stabilizers is essential for assessing their relative technical merit, environmental compatibility, and applicability to foundation engineering, particularly in the context of strengthening existing footing systems. The comparison presented in Table 3 highlights the distinct advantages and limitations associated with commonly used stabilizers.

Table 3. Comparison of Bio-Enzymes with Other Stabilizers

Stabilizer	Strength Gain	Sustainability	Suitability for Existing Footings	Ref
Lime	High	Moderate	Limited	[18]
Fly Ash	Moderate	Moderate	Limited	[20]
Biopolymers	High	High	Moderate	[15]
Bio-Enzymes	Moderate–High	High	Excellent	[14,30]

Lime stabilization is widely recognized for its ability to induce substantial strength improvement in fine-grained soils; however, its relatively brittle behavior and carbon-intensive production process limit its sustainability and suitability for applications beneath existing foundations. Fly ash offers moderate strength enhancement and promotes waste reutilization, yet its performance is highly dependent on soil chemistry and curing conditions, which restricts its reliability for foundation retrofitting.

Biopolymers represent an emerging class of environmentally benign stabilizers capable of producing significant strength gains while maintaining ductility. Nevertheless, concerns regarding long-term durability and cost constrain their widespread adoption for foundation applications. In contrast, bio-enzymes provide a balanced combination of mechanical performance and environmental compatibility. Their non-cementitious stabilization mechanism enables moderate to high strength improvement while preserving soil flexibility, making them particularly suitable for in-situ treatment beneath existing footing systems where structural disturbance must be minimized.

10. APPLICATION IN STRENGTHENING EXISTING FOOTINGS

Strengthening existing footings requires improving subsoil properties without extensive excavation or structural disturbance. Bio-enzymes can be applied through in-situ mixing or injection beneath footings, enhancing soil stiffness, reducing compressibility, and improving load transfer [12].

Reduced swelling pressure minimizes uplift forces [22,24], while increased strength improves bearing capacity and reduces settlement [17,21]. Field guidelines for enzymatic stabilization provide practical insights into mixing depth, curing, and moisture control, which are directly transferable to foundation retrofitting [12,27].

These characteristics position bio-enzymes as a viable in-situ solution for strengthening existing foundations, especially in urban environments.

11. ECONOMIC AND ENVIRONMENTAL CONSIDERATIONS

From an environmental perspective, bio-enzymes significantly reduce greenhouse gas emissions associated with soil stabilization. Cement production alone contributes nearly 8% of global CO_2 emissions, whereas bio-enzymes require minimal energy for production and application [30].

Economically, bio-enzyme stabilization reduces material transportation costs, construction time, and equipment requirements [27]. The ability to treat soils in situ beneath existing structures eliminates costly demolition and reconstruction, making bio-enzymes particularly attractive for rehabilitation projects [20,30].

Lifecycle cost analyses suggest that enzyme stabilization becomes increasingly cost-effective in urban rehabilitation and remote regions [3,27].

Strengthening existing footing systems presents a complex geotechnical challenge, as any soil improvement technique must enhance subsoil performance without inducing excessive disturbance to the superstructure. In this context, bio-enzyme-based stabilization offers a practical and minimally invasive alternative for improving the engineering behavior of foundation soils, particularly in urban environments where excavation and reconstruction are often impractical.

The application of bio-enzymes beneath existing footings primarily aims to improve soil stiffness, reduce compressibility, and mitigate moisture-induced volume changes. Through in-situ treatment methods such as surface percolation, pressure injection, or controlled mixing, enzymatic solutions can be introduced into the subsoil to modify particle interactions and improve load transfer mechanisms. This leads to a more uniform stress distribution beneath the footing and contributes to reduced differential settlement and enhanced bearing response.

An important advantage of bio-enzymes in foundation rehabilitation lies in their ability to enhance soil performance without inducing excessive rigidity. Unlike cementitious grouting or rigid inclusions, enzymatic treatment preserves a degree of deformability within the soil mass, allowing it to accommodate structural movements and environmental variations without generating stress concentrations. This controlled flexibility is particularly beneficial for existing structures, where compatibility between the treated soil and the superstructure is critical to long-term serviceability.

Furthermore, the environmentally benign nature of bio-enzymes supports their application in sensitive or densely populated areas, where sustainability considerations and regulatory constraints increasingly govern construction practices. By enabling soil improvement with reduced carbon footprint and minimal material transportation, bio-enzyme stabilization aligns with contemporary objectives of sustainable foundation engineering. However, to fully realize its potential in strengthening existing footings, the development of standardized application procedures and performance-based design guidelines remains an essential future requirement.

12. RESEARCH GAPS AND LIMITATIONS

Despite extensive research on pavement applications [4,20,25,26], foundation-specific behavior remains underexplored. Major gaps include:

- Consolidation behavior under sustained loads [21]
- Load–settlement response beneath footings [12]
- Soil–structure interaction effects [21]
- Long-term creep and deformation behavior [30]
- Lack of standardized design guidelines [3,27]

These gaps limit widespread adoption in foundation engineering and highlight the need for targeted research.

Despite the growing interest in bio-enzyme-based soil stabilization and the encouraging improvements reported in soil engineering properties, several critical gaps and limitations remain that currently restrict its widespread adoption in foundation engineering practice.

A primary limitation arises from the disproportionate focus of existing studies on pavement and subgrade applications, with relatively little emphasis placed on foundation systems. As a result, key performance indicators relevant to foundations—such as load–settlement response, bearing capacity under footing loads, and stress redistribution mechanisms—have not been sufficiently explored. The absence of systematic model-scale and full-scale footing experiments restricts the ability to directly translate soil property enhancements into reliable foundation design parameters.

Another significant gap pertains to the long-term deformation behavior of enzyme-treated soils under sustained structural loading. Parameters governing consolidation, secondary compression, and time-dependent creep remain largely undocumented, thereby limiting confidence in predicting long-term settlement and serviceability performance of foundations resting on enzymatically stabilized soils.

The interaction between enzyme-treated soils and overlying structural systems also remains inadequately understood. Comprehensive soil–structure interaction analyses incorporating the modified mechanical and hydraulic characteristics of enzyme-stabilized soils are scarce, impeding the development of rational analytical and numerical models for foundation rehabilitation and retrofitting.

Furthermore, the lack of standardized mix design procedures, dosage recommendations, curing protocols, and quality control measures constitutes a major barrier to practical implementation. Current practices are often extrapolated from pavement engineering, which may not be directly applicable to the complex stress states and boundary conditions encountered in foundation systems.

In addition, most reported findings are derived from controlled laboratory environments, with limited long-term field monitoring data available under realistic service conditions. This constrains the assessment of durability, environmental compatibility, and performance variability associated with different soil types, groundwater chemistries, and climatic regimes.

Collectively, these limitations underscore the need for integrated experimental, numerical, and field-based investigations to advance bio-enzyme stabilization from a promising soil improvement technique to a validated and design-ready solution for foundation engineering applications.

13. RESEARCH GAPS IN BIO-ENZYME APPLICATIONS FOR FOUNDATION ENGINEERING

MSW MANAGEMENT -Multidisciplinary, Scientific Work and Management Journal
ISSN: 1053-7899
Vol. 36 Issue 2, 2026, Pages 1543-1549

Despite the growing body of literature demonstrating the efficacy of bio-enzyme-based soil stabilization in improving key engineering properties of soils, its application in foundation engineering remains inadequately developed. A critical synthesis of existing studies reveals several substantive research lacunae that currently constrain the rational and widespread adoption of bio-enzymes for strengthening existing footing systems.

Firstly, the overwhelming majority of investigations are confined to pavement and subgrade applications, with a conspicuous absence of model-scale and full-scale footing load tests on enzyme-treated soils. Consequently, the load–settlement response and ultimate bearing behavior of foundations resting on enzymatically stabilized soils remain largely undocumented.

Secondly, the consolidation behavior of enzyme-treated soils under sustained structural loading has not been systematically examined. Parameters governing primary consolidation, secondary compression, and time-dependent deformation (creep) are scarcely reported, thereby limiting the ability to predict long-term settlement and serviceability performance of foundations.

Thirdly, the interaction between enzyme-treated soils and overlying structural systems has received minimal scholarly attention. Soil–structure interaction analyses incorporating the modified mechanical and hydraulic properties of enzymatically stabilized soils are virtually absent, precluding the development of reliable design models for foundation retrofitting.

Furthermore, the lack of standardized mix design procedures and foundation-specific application guidelines presents a significant barrier to practical implementation. Existing recommendations are predominantly extrapolated from pavement practice and may not be directly transferable to foundation loading regimes, particularly in urban rehabilitation contexts.

In addition, long-term field performance data under real service conditions are exceedingly limited. There is a notable scarcity of documented case studies involving existing buildings or infrastructure retrofitted using bio-enzyme stabilization, which impedes confidence in its durability, reliability, and economic viability.

Finally, the influence of soil mineralogy, groundwater chemistry, and climatic variability on the long-term performance of enzyme-treated soils has not been comprehensively investigated. This limits the ability to generalize the effectiveness of bio-enzymes across diverse geotechnical and environmental settings.

Addressing these research gaps through integrated experimental, numerical, and field-based investigations is essential to advance bio-enzyme stabilization from a promising soil improvement technique to a validated foundation engineering solution.

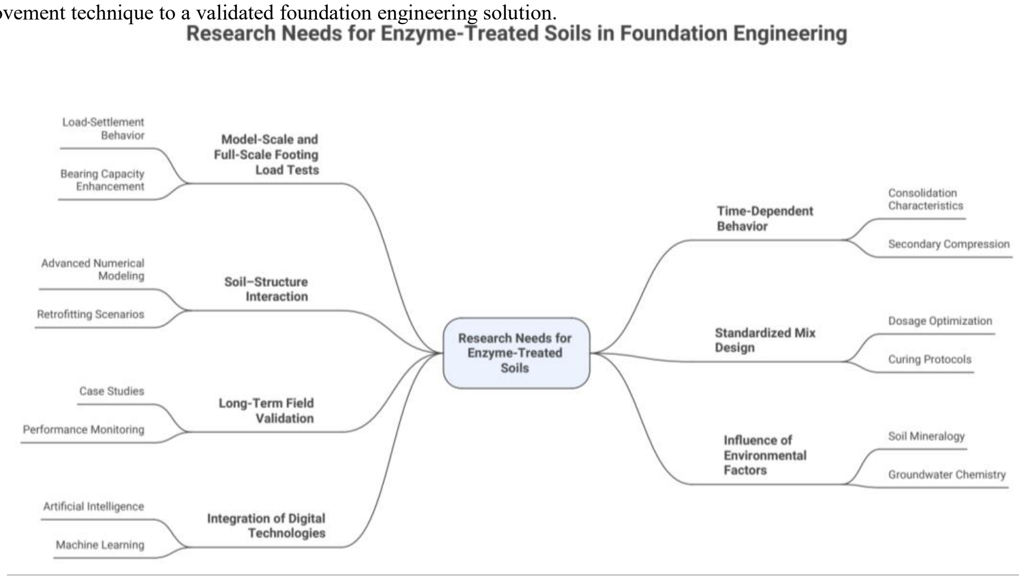

Figure 1 Research Needs for Enzyme Treated soils in Foundation Engineering -Flow Chart

14. QUALITATIVE COMPARISON OF BIO-ENZYMES WITH OTHER SOIL STABILIZERS

A qualitative comparison of bio-enzymes with conventional and alternative soil stabilizers is essential to assess their relative technical, environmental, and practical merits, particularly for applications involving existing foundation systems.

Cement Stabilization

Cement is widely recognized for its ability to induce substantial and rapid strength gain through hydration and pozzolanic reactions, resulting in a rigid cementitious matrix. While this provides high immediate load-bearing capacity, cement-treated soils often exhibit brittle behavior and are susceptible to shrinkage cracking under thermal and moisture variations. Furthermore, cement production contributes significantly to global carbon emissions, thereby limiting its appeal in sustainable geotechnical practice. For existing footings, cement stabilization is often impractical due to excavation requirements and the risk of inducing stress concentration beneath the structure.

Lime Stabilization

Lime stabilization is particularly effective in modifying plasticity and enhancing the workability of clayey soils through cation exchange and pozzolanic reactions. It provides moderate to high strength improvement and long-term durability. However, like cement, lime-treated soils tend to become relatively stiff and brittle, which may be undesirable beneath existing foundations requiring controlled deformability. Additionally, lime stabilization is sensitive to soil mineralogy and is less effective in non-clayey or organic soils.

Fly Ash and Industrial Byproducts

Fly ash and other industrial byproducts offer a sustainable alternative by utilizing waste materials and reducing reliance on virgin binders. These stabilizers can improve strength and reduce plasticity when favorable chemical conditions exist. However, their performance is highly dependent on soil chemistry and curing conditions. Moreover, the availability and consistency of such materials vary regionally, and their applicability for in-situ foundation retrofitting is often constrained by handling and curing requirements.

Biopolymers

Biopolymers have gained attention as environmentally friendly stabilizers capable of forming strong interparticle bonds and enhancing erosion resistance. They provide excellent initial strength and improved ductility compared to cementitious binders. However, biopolymers are often associated with higher material costs and potential long-term biodegradation, which raises concerns regarding durability in foundation applications exposed to moisture and microbial activity.

Bio-Enzymes

Bio-enzymes occupy a distinct position among soil stabilizers by improving soil behavior through physicochemical modification rather than rigid cementation. They enhance interparticle bonding by altering clay–water interactions, leading to reduced plasticity, swelling, and moisture susceptibility while imparting moderate to high strength gains. Their non-brittle stabilization mechanism makes them particularly suitable for subsoil improvement beneath existing footings, where excessive rigidity may compromise serviceability. From an environmental standpoint, bio-enzymes exhibit a significantly lower carbon footprint and enable in-situ application without extensive excavation or structural disturbance. However, their effectiveness is strongly soil-dependent, and standardized design guidelines remain underdeveloped.

Table 4. Qualitative Comparison of Soil Stabilizers

Stabilizer	Strength Gain	Brittleness	Sustainability	Suitability for Existing Footings	Key Limitations
Cement	Very High	High	Low	Limited	High CO_2 emissions, brittle behavior
Lime	High	Moderate	Moderate	Limited	Soil-specific effectiveness
Fly Ash	Moderate	Low–Moderate	High	Limited	Material variability, curing dependence
Biopolymers	High	Low	High	Moderate	Cost, biodegradation concerns
Bio-Enzymes	Moderate–High	Low	Very High	Excellent	Soil dependency, lack of design codes

15. FUTURE RESEARCH DIRECTIONS

Future studies should focus on:

- Model footing tests on enzyme-treated soils
- Long-term consolidation and creep studies [21,30]
- Numerical SSI modeling incorporating enzymatic soil parameters [12,21]
- Field-scale validation under real foundation conditions [12,27]
- Integration with AI-based soil behavior prediction models [3]

Addressing these aspects will facilitate the development of reliable design guidelines for foundation applications.

Although bio-enzyme-based soil stabilization has demonstrated promising improvements in soil behavior, its transition from a pavement-oriented soil improvement technique to a reliable foundation engineering solution necessitates focused and systematic future research. The following directions are identified as critical for advancing the scientific understanding and practical applicability of bio-enzymes in foundation engineering.

Firstly, there is an urgent need for **model-scale and full-scale footing load tests** on enzyme-treated soils. Such investigations should explicitly quantify load–settlement behavior, bearing capacity enhancement, and failure mechanisms under realistic foundation loading conditions, thereby bridging the gap between material-level soil improvement and structural performance.

Secondly, future studies must address the **time-dependent behavior** of enzyme-treated soils under sustained structural loads. Comprehensive evaluation of consolidation characteristics, secondary compression, and creep deformation is essential for predicting long-term foundation settlement and ensuring serviceability compliance in real-world applications.

Thirdly, the incorporation of bio-enzyme-modified soil properties into **soil–structure interaction (SSI) frameworks** represents a vital research frontier. Advanced numerical modeling, calibrated against experimental and field data, is required to simulate the interaction between enzyme-treated subsoil and superstructures, particularly for retrofitting scenarios involving existing buildings.

Fourthly, the development of **standardized mix design methodologies and foundation-specific application guidelines** is imperative. Unlike pavements, foundations are subjected to complex stress paths and boundary conditions; hence, dosage optimization, depth of treatment, curing protocols, and quality control measures must be tailored specifically for foundation systems.

Furthermore, **long-term field validation and performance monitoring** of bio-enzyme-stabilized foundation systems are critically needed. Documented case studies involving existing buildings, infrastructure retrofitting, and urban rehabilitation projects would significantly enhance confidence in the durability, reliability, and economic viability of enzymatic stabilization techniques.

The influence of **soil mineralogy, groundwater chemistry, and climatic variability** on the efficacy of bio-enzymes should also be systematically investigated to enable broader generalization across diverse geotechnical and environmental contexts.

Finally, emerging digital technologies offer substantial scope for innovation. The integration of **artificial intelligence and machine learning frameworks** for predicting the behavior of enzyme-treated soils based on soil type, environmental conditions, and enzyme characteristics can significantly accelerate design optimization and decision-making processes in sustainable foundation engineering.

In summary, advancing bio-enzyme stabilization from a promising soil improvement method to a design-ready foundation engineering solution requires coordinated experimental, numerical, and field-based research efforts focused explicitly on foundation performance rather than solely on soil property enhancement.

CONCLUSIONS

This review has critically evaluated the feasibility of bio-enzyme-based soil stabilization as an environmentally sustainable approach for improving the performance of existing footing systems. Based on a comprehensive synthesis of experimental and field-based investigations spanning several decades, the following conclusions are drawn:

1. Bio-enzymes consistently reduce plasticity, swelling potential, and moisture susceptibility in fine-grained soils, thereby addressing the dominant mechanisms responsible for foundation distress in expansive and soft soil deposits.
2. The improvement in strength characteristics, commonly quantified through unconfined compressive strength and California Bearing Ratio, has been widely demonstrated, indicating enhanced bearing resistance; however, these parameters alone are insufficient for direct application in foundation design without explicit correlation to load–settlement behavior.
3. Unlike cementitious stabilizers, bio-enzymes modify soil behavior through physicochemical reorganization of the soil matrix rather than through rigid cementation, rendering them particularly suitable for subsoil enhancement beneath existing footings where controlled deformability and stress redistribution are essential.
4. While substantial performance benefits have been established in pavement and subgrade applications, foundation-specific evidence remains limited, particularly with regard to consolidation characteristics, long-term settlement response, and soil–structure interaction mechanisms.
5. The absence of codified design provisions for enzyme-treated soils currently restricts their integration into routine foundation engineering practice.

Accordingly, although bio-enzymes represent a technically viable and environmentally responsible alternative for subsoil improvement beneath existing footing systems, their widespread adoption necessitates targeted experimental programs, comprehensive field validation, and the formulation of foundation-oriented design methodologies.

DECLARATIONS

Conflict of Interest: The authors declare no conflict of interest.

Funding: No external funding was received.

Ethical Approval: Not applicable.

REFERENCES

1. S. B. Raheem, G. F. Oladiran, D. A. Oke, and S. A. Musa (2020). Evaluation of Strength Properties of Subgrade Materials Stabilized with Bio Enzyme, Department of Civil Engineering, The Polytechnic Ibadan, Oyo State, Nigeria. EJERS, European Journal of Engineering Research and Science. DOI:10.24018/ejeng.2020.5.5.1329
2. Abdullah AbouKhadra, Ahmed F. Zidan & Yasser Gaber (2018). Experimental evaluation of strength characteristics of different Egyptian soils using enzymatic stabilizers. Cogent Engineering, https://doi.org/10.1080/23311916.2018.1517577
3. Niranjan Mall & Kumar Venkatesh (2023). Soil Stabilization Using Bio Enzyme, Springer jurisdictional. DOI:10.1007/s40009-023-01338-4
4. S. M. Lim, D. C. Wijeyesekera, A. J. M. S. Lim, I. B. H. Bakar (2015). Critical Review of Innovative Soil Road Stabilization Techniques. International Journal of Engineering and Advanced Technology (IJEAT). https://www.researchgate.net/publication/283616538_Critical_Review_of_Innovative_Soil_Road_Stabilization_Techniques.
5. Saurabh Shivhare, Harikumar Mohanan (2023). A review on subgrade soil stabilization using bio enzymes. Arabian Journal of Geosciences. https://doi.org/10.1007/s12517-023-11257-9

6. Prof. Guruprasad Jadhav, Mr. Ganesh Panchal, Mr. Randhir Mane (2016). A study on experimental investigation of bio-enzyme stabilized expansive soil. 1Dept. of Civil Engineering, Parvati Bai Genba Moze College of Engineering Wagholi, Pune Maharashtra, (India). International Journal of Innovative Research in Science and Engineering. http://data.conferenceworld.in/PGMCOE/P1211-1220.pdf
7. Nway Nway Nilar Myint, Than Mar Swe (2014). Investigation into Soil Stabilization with Enzyme. Dept of Civil Engineering, Mandalay Technological University, Mandalay, Myanmar. International Journal of Scientific Engineering and Technology Research. http://ijsetr.com/uploads/154263IJSETR1079-253.pdf
8. Usha Patel, Shalini Singh, Shivani Chaudhari (2018). Effect of Bio enzyme – TerraZyme on Compaction, Consistency Limits and Strength Characteristics of Expansive Soil. International Research Journal of Engineering and Technology (IRJET). https://www.semanticscholar.org/paper/Effect-of-Bio-enzyme-%E2%80%93-TerraZyme-on-Compaction%2C-and-Patel-Singh/b0b37be7124c05de3d2f322e1a0fc56093d43881
9. Puneet Agarwal, Suneet Kaur (2014). Effect of bio-enzyme stabilization on unconfined compressive strength of expansive soil. International Journal of Research in Engineering and Technology. DOI:10.15623/ijret.2014.0305007
10. Aswar, D.S., Bajad, M.N. and Ambadkar, S.D. (2023) Performance Evaluation of Terrazyme as Soil Stabilizer. Civil Engineering Infrastructures Journal. DOI:10.14445/22315381/IJETT-V70I4P222
11. Sravan Muguda and H. B. Nagaraj (2019). Effect of Enzymes on Plasticity and Strength Characteristics of an Earthen Construction Material. Muguda and Nagaraj Geo-Engineering. https://doi.org/10.1186/s40703-019-0098-2
12. B. O'Donnell, A. Swarup, A. Sidiq, D. Robert, and S. Setunge (2022). Guidelines for Enzymatic Soil Stabilization. Editors Nanotechnology in Construction for Circular Economy Proceedings of NICOM7, 31 October–02 November, 2022, Melbourne, Australia. https://library.oapen.org/bitstream/handle/20.500.12657/75441/978-981-99-3330-3.pdf#page=371
13. Iiro Youn, Seongtaek, Yoseok Jeong and Sewook Oh (2023). Evaluating the Strength and Durability of Eco-Friendly Stabilized Soil Bricks Incorporating Wood Chips", MDPI- Materials for Civil Construction and Sustainability, Applied Sciences 2023, 13, 10929. https://doi.org/10.3390/app131910929
14. Souhila Rehab Bekkouche, Mohammed Benzerara, Umar Zada, Ghulam Muhammad and Zulfiqar Ali "Use of Eco-Friendly Materials in the Stabilization of Expansive Soils" (2022), MDPI- Materials for Civil Construction and Sustainability, Building, 2022, 12(10), 1770,DOI: 10.3390/buildings12101770
15. Mojtaba Jamshidi, Mehdi Mokhberi, Amir Hossein Vakili, Alireza Nasehi, "Bio-Polymer Stabilization of Soils" Elsevier-Transportation Geotechnics, Volume 42, September 2023, 101110, https://doi.org/10.1016/j.trgeo.2023.101110
16. Venika Saini And Priyanka Vaishnava, Soil Stabilization by Using Terrazyme, International Journal of Advances in Engineering & Technology, volume 8, issue 4, pg. 566-567. India, August 2015. https://www.ijaet.org/media/12I28-IJAET0828239-v8-iss4-566-573.pdf
17. C. Jairaj, M.T. Prathap Kumar, H. Muralidhara, (2019). "Shear Strength of BC-Soil Admixed with Lime and Bio-Enzyme", Material Science Forum, Trans Tech Publications Ltd, Vol. 969, Pg. 3327-334. India. 2019. https://doi.org/10.4028/www.scientific.net/MSF.969.327
18. Vijay Rajoria, Suneet Kaur, (2014) "A Review on Stabilization of Soil Using Bio – Enzyme", International Journal of Research in Engineering and Technology. Vol. 03, pg. 566-573, 2014. - https://www.ijaet.org/
19. Shankar, A U, Rai, H K, Mithanthaya, R, "Bio-Enzyme Stabilized Lateritic Soil as a Highway Material", Indian Roads Congress Journal, Vol. 70, Issue No. 2, 2012, http://worldcat.org/issn/0046905X
20. Shil T, Pradhan R, Nanda S, Mohapatra BG (2020) Strengthening of soil subgrade using bio-enzyme. In: Recent developments in sustainable infrastructure: select proceedings of ICRDSI 2019. Springer Singapore, Singapore, pp 13–25, https://link.springer.com/chapter/10.1007/978-981-15-4577-1_2
21. Thomas AG & Rangaswamy BK (2021), "Strength behavior of enzymatic cement treated clay", International Journal of Geotechnical Engineering, 2021, Vol. 15, No. 3, pp 259–272, https://doi.org/10.1080/19386362.2019.1622854
22. Sinha K, Waghmare S, Pachdhare ABK (2018), "Stabilization of black cotton soil using bio-enzyme". International Journal for Scientific Research and Development, 6(2):90–92, https://ijsrd.com/Article.php?manuscript=IJSRDV6I20159
23. Jamal SH, Kumar PS (2016) An experimental study on renolith treated black cotton soil for subgrade pavements. International Journal of Science and Research, 5(11):1240–1244, https://www.ijsr.net/getabstract.php?paperid=ART20163074.
24. Baby M, Gowshik A, Rajeshwar AK, Mohanasundram M (2016) "Experimental study of expansive soil stabilized with TerraZyme", International Journal of Engineering Research & Technology, 5(01):897–899. http://www.ijert.org.
25. Tiwari A, Sharma JK, Garg V (2021)," Stabilization of expansive soil using Terrazyme. In: Proceedings of the Indian geotechnical conference 2019: IGC-2019 volume III. Springer Singapore, Singapore, vol 3, pp 113–125, https://doi.org/10.1007/978-981-33-6444-8_10.
26. Chaurasia VS, Pandey PP, Mishra AV, Gupta SS, Pawar AU (2021) Stabilization of soil using terrazyme for road construction. In: Proceedings of the Indian geotechnical conference 2019: IGC-2019 volume III. Springer Singapore, Singapore, pp 671–683. https://doi.org/10.1007/978-981-33-6444-8_60
27. M. A. Kestler, "Stabilization selection guide for aggregate and native-surfaces low volume roads," U.S. Department of Agriculture, 2009. pp 204-211, https://www.fs.usda.gov/eng/pubs/pdf/hi_res/08771805hi.pdf
28. S. M. Lim, D. C. Wijeyesekera, A. J. M. S. Lim, I. B. H. Bakar, "Critical Review of Innovative Soil Road Stabilization Techniques" Blue Eyes Intelligence Engineering & Sciences Publication Pvt. Ltd. (International Journal of Engineering and Advanced Technology (IJEAT)), Volume-3 Issue-5, June 2014. https://www.ijeat.org/
29. Ramesh, H. N., & Sagar, S. R. (2015). *Effect of drying on the strength properties of Terrazyme-treated expansive and non-expansive soils*. Proceedings of the Indian Geotechnical Conference (IGC), India. https://igs.org.in/storage/proceedings-uploads/TH-08-117-160523094757.pdf?utm_source=chatgpt.com.
30. Mittal, A. (2020). *Soil stabilization using bio-enzyme: A review*. Proceedings of the Indian Geotechnical Conference (IGC), India. https://igs.org.in/