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

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Abstract - *Regur (black cotton) soil presents significant geotechnical challenges due to its high swelling–shrinkage behavior, low shear strength, and moisture sensitivity, which adversely affect the performance of civil infrastructure. Conventional stabilization methods using cement and lime, although effective, are associated with high carbon emissions and long-term environmental concerns. In recent years, microbial catalyst–driven bio-mineralization has emerged as a sustainable alternative for improving the engineering properties of problematic soils. This review critically examines the current state of research on bio-mineralization–based stabilization of Regur soil, with particular emphasis on microbial-induced and enzyme-induced carbonate precipitation mechanisms. The review synthesizes findings from laboratory and limited field studies addressing strength enhancement, swelling control, durability, and microstructural modifications. The influence of microbial activity, treatment protocols, and environmental conditions on performance is discussed in detail. Environmental, economic, and scalability aspects are also evaluated to assess practical applicability. The review identifies key research gaps and highlights future directions for advancing bio-mineralization as an eco-friendly ground improvement technique for expansive soils.*

Keywords: Regur soil; Bio-mineralization; Microbial-induced carbonate precipitation; Expansive soil stabilization; Sustainable ground improvement; Geotechnical engineering

1. INTRODUCTION

1.1 Engineering Challenges of Regur (Black Cotton) Soil

Regur soil, commonly referred to as black cotton soil, is a highly expansive clay soil predominantly found in central and southern regions of India. It is characterized by a high content of montmorillonite minerals, which impart pronounced swell–shrink behavior under varying moisture conditions. Seasonal moisture fluctuations cause significant volumetric changes, leading to differential settlement, cracking, and structural distress in pavements, embankments, and shallow foundations (Chen, 1988; Nelson and Miller, 1992).

From an engineering perspective, Regur soil exhibits high plasticity, low shear strength in saturated conditions, poor bearing capacity, and excessive compressibility. These properties pose serious challenges for infrastructure development, particularly for low-volume roads, residential foundations, and lightly loaded structures. The unpredictable nature of its volume change behavior necessitates soil improvement or stabilization prior to construction to ensure long-term serviceability and safety (Sivapullaiah et al., 2000).

1.2 Limitations of Conventional Stabilization Methods

Conventional stabilization techniques such as lime, cement, and fly ash stabilization have been widely adopted to improve the engineering properties of expansive soils. While these methods are effective in reducing plasticity and increasing strength, their application is associated with several technical, environmental, and economic limitations, particularly in the context of sustainable geotechnical engineering (Bell, 1996; Sherwood, 1993).

1.2.1 Environmental and Sustainability Concerns

The production of cement and lime is highly energy-intensive and contributes significantly to global carbon dioxide emissions. Cement manufacturing alone accounts for approximately 7–8% of global CO_2 emissions, raising serious concerns regarding the environmental sustainability of cement-based soil stabilization (Scrivener et al., 2018). In addition, excessive use of chemical stabilizers may alter soil chemistry and negatively impact surrounding ecosystems.

In expansive soils such as Regur soil, conventional stabilizers may not always provide durable long-term performance. The effectiveness of lime or cement treatment is influenced by factors such as mineralogy, sulphate content, curing conditions, and moisture ingress. Sulphate-induced heaving, leaching of stabilizing agents, and strength degradation under cyclic wetting and drying have been reported in several studies (Little, 1995; Puppala et al., 2006). Moreover, the brittle nature of cement-treated soils can lead to cracking, which compromises durability and increases maintenance requirements.

1.3 Emergence of Microbial Catalyst–Based Soil Improvement

In response to the limitations of conventional stabilization techniques, microbial catalyst–based soil improvement has emerged as an innovative and sustainable alternative within the field of bio-geotechnical engineering. This approach exploits the metabolic activity of microorganisms to induce the precipitation of cementitious minerals, primarily calcium carbonate, within the soil matrix—a process commonly referred to as microbial-induced carbonate precipitation (MICP) (DeJong et al., 2006; Ivanov and Chu, 2008).

Microorganisms act as natural biochemical catalysts, facilitating mineral precipitation under ambient conditions without the need for energy-intensive industrial processes. The precipitated minerals bind soil particles, reduce pore spaces, and enhance mechanical strength while potentially improving durability and resistance to environmental loading. Due to its eco-friendly nature and low carbon footprint, microbial soil improvement has gained increasing attention as a sustainable ground improvement technique.

1.4 Need for a Focused Review on Bio-Mineralization of Regur Soil

Although extensive research has been conducted on bio-mineralization in granular soils such as sands, the application of microbial techniques to fine-grained and expansive soils remains relatively limited. Regur soil presents unique challenges for microbial treatment due to its low permeability, high surface activity, and complex clay–microbe interactions (Mitchell and Santamarina, 2005).

Existing studies on microbial treatment of Regur soil are scattered, often limited to laboratory-scale investigations, and vary widely in terms of microbial species, treatment protocols, and reported performance outcomes. A comprehensive and critical synthesis of this literature is therefore necessary to evaluate the true potential, limitations, and applicability of microbial catalyst–driven bio-mineralization specifically for Regur soil. Such a focused review can help bridge the knowledge gap between laboratory research and practical field implementation.

1.5 Objective of the Review

The primary objective of this review is to critically examine existing literature on microbial catalyst–driven bio-mineralization techniques for strength enhancement of Regur soil. The review synthesizes findings related to microbial mechanisms, treatment methodologies, strength improvement, durability, and sustainability aspects.

2. REGUR SOIL: ENGINEERING CHARACTERISTICS AND STABILIZATION REQUIREMENTS

2.1 Origin, Mineralogy, and Physico-Chemical Properties

Regur soil, commonly known as black cotton soil, is derived primarily from the weathering of basaltic rocks of the Deccan Trap formation. It is extensively distributed across central and southern India, particularly in Maharashtra, Madhya Pradesh, Gujarat, Karnataka, and parts of Andhra Pradesh. The soil develops under semi-arid to sub-humid climatic conditions and is characterized by dark coloration due to the presence of iron and titanium oxides (Murthy, 2002; Gidigasu, 1976).

2.1.1 Mineralogical Composition

The dominant clay mineral present in Regur soil is montmorillonite, a member of the smectite group, which is responsible for its high swelling potential. Minor proportions of illite, kaolinite, quartz, feldspar, and calcite are also commonly reported (Grim, 1968; Sivapullaiah et al., 2000). The high specific surface area and weak interlayer bonding of montmorillonite enable significant water adsorption, making the soil highly sensitive to moisture variations.

From a physico-chemical standpoint, Regur soil exhibits high cation exchange capacity (CEC), typically ranging between 40 and 80 meq/100 g, which contributes to its strong interaction with pore fluids and stabilizing agents. The soil generally shows alkaline to neutral pH values and contains exchangeable cations such as calcium, magnesium, sodium, and potassium. These properties strongly influence its response to chemical and bio-mediated stabilization techniques (Mitchell and Soga, 2005).

2.2 Swell–Shrink Mechanisms and Strength Limitations

The swell–shrink behavior of Regur soil is primarily governed by the hydration and dehydration of montmorillonite minerals. During wet seasons, water molecules enter the interlayer spaces of the clay minerals, leading to volumetric expansion. Conversely, moisture loss during dry periods causes shrinkage and the formation of deep surface cracks (Chen, 1988; Nelson and Miller, 1992).

This cyclic volumetric change adversely affects the mechanical strength of the soil. In saturated conditions, Regur soil exhibits low shear strength and bearing capacity due to reduced effective stress and increased pore water pressure. Unconfined compressive strength (UCS) values are typically low, and significant strength loss is observed upon repeated wetting–drying cycles. These inherent limitations necessitate stabilization prior to its use as a foundation or subgrade material (Holtz and Kovacs, 1981).

2.3 Performance Requirements for Infrastructure Applications

For safe and durable infrastructure performance, soils used in subgrades, embankments, and foundation systems must satisfy minimum criteria related to strength, stiffness, volume stability, and durability. In the case of pavement subgrades, parameters such as California Bearing Ratio (CBR), resilient modulus, and resistance to moisture-induced softening are critical (IRC:37, 2018).

Regur soil in its natural state rarely meets these performance requirements due to excessive swelling pressure, low soaked CBR values, and high compressibility.

For lightly loaded foundations, differential settlement and heave pose serious serviceability concerns. Consequently, regulatory guidelines and design standards recommend soil stabilization or replacement when expansive soils are encountered at construction sites (IS:1498, 1970; Bell, 1996).

Table 1. Typical Engineering Properties of Regur (Black Cotton) Soil

Property	Typical Range	Reference
Liquid limit (%)	50–100	Chen (1988); Sivapullaiah et al. (2000)
Plasticity index (%)	25–60	Murthy (2002)
Free swell index (%)	50–120	IS:2720 (Part 40), 1977
Cation exchange capacity (meq/100 g)	40–80	Mitchell and Soga (2005)
Soaked CBR (%)	1–4	Bell (1996)
Dominant clay mineral	Montmorillonite	Grim (1968)

2.4 Suitability of Bio-Mineralization for Expansive Clay Soils

Bio-mineralization techniques, particularly microbial-induced carbonate precipitation (MICP), have emerged as promising alternatives for improving problematic soils. In expansive clays like Regur soil, bio-mineralization offers potential advantages by inducing calcium carbonate precipitation that binds clay particles, reduces pore space, and modifies soil fabric (DeJong et al., 2006; Ivanov and Chu, 2008).

Unlike conventional stabilizers, microbial processes operate under ambient conditions and have a lower carbon footprint. Additionally, bio-mineralization has been reported to reduce swelling potential by limiting water ingress and altering the diffuse double layer surrounding clay particles (Soon et al., 2013). However, challenges such as low permeability, nutrient transport, and uniform distribution of precipitates must be addressed to ensure effective application in fine-grained soils. Despite these limitations, the inherent physico-chemical properties of Regur soil make it a viable candidate for bio-mediated stabilization, warranting focused investigation and critical review.

3. FUNDAMENTALS OF MICROBIAL CATALYST–DRIVEN BIO-MINERALIZATION

3.1 Concept and Classification of Bio-Mineralization Processes

Bio-mineralization refers to the process by which living organisms induce the formation of mineral phases through metabolic activities or enzymatic reactions. In geotechnical engineering, microbial catalyst–driven bio-mineralization exploits these natural processes to improve soil properties by precipitating cementitious minerals within the pore spaces of soils (DeJong et al., 2006). The microorganisms act as biochemical catalysts, accelerating mineral formation without being consumed in the reaction.

3.1.1 Classification Based on Biological Control

Bio-mineralization processes are broadly classified into biologically controlled mineralization (BCM) and biologically induced mineralization (BIM). In BCM, organisms regulate mineral nucleation and growth through cellular mechanisms, whereas BIM involves indirect mineral precipitation driven by metabolic by-products such as carbonate ions (Lowenstam and Weiner, 1989).

3.2 Microbial-Induced Carbonate Precipitation (MICP)

Microbial-induced carbonate precipitation (MICP) is the most extensively studied bio-mineralization technique for soil stabilization. It relies on ureolytic bacteria capable of hydrolyzing urea to produce carbonate ions, which subsequently react with calcium ions to form calcium carbonate ($CaCO_3$) precipitates (Stocks-Fischer et al., 1999).

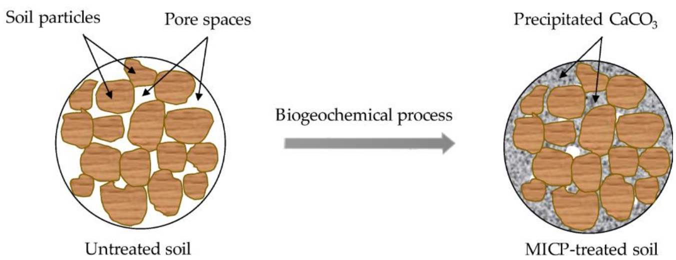

Figure-1: Microbial-Induced Carbonate Precipitation (MICP)

3.3 Enzyme-Induced Carbonate Precipitation (EICP)

Enzyme-induced carbonate precipitation (EICP) is a bio-inspired alternative to MICP that utilizes free urease enzymes rather than living microorganisms to catalyze urea hydrolysis. The absence of bacterial cells simplifies treatment protocols and reduces uncertainties related to microbial survival and transport in soil media (Whiffin et al., 2007).

3.3.1 Advantages over MICP

EICP offers improved control over reaction rates and uniformity of treatment, particularly in fine-grained soils where bacterial mobility is limited. Since enzymes are smaller than bacterial cells, they can more easily penetrate low-permeability clay soils such as Regur soil (Hamdan and Kavazanjian, 2016).

3.4 Other Microbial Mineral Precipitation Mechanisms

Beyond carbonate precipitation, other microbial processes capable of inducing mineral formation have been explored for soil improvement. These include microbial-induced calcium phosphate precipitation (MICPP), sulfate reduction–induced mineralization, and iron oxide precipitation (Achal and Pan, 2014).

3.4.1 Calcium Phosphate Precipitation

MICPP involves microbial metabolic pathways that release phosphate ions, which react with calcium to form calcium phosphate minerals. These precipitates exhibit higher chemical stability and lower solubility compared to calcium carbonate, making them attractive for long-term stabilization (Zhu and Dittrich, 2016).

4. LITERATURE REVIEW ON BIO-MINERALIZATION FOR SOIL STRENGTH ENHANCEMENT

4.1 Evolution of Bio-Geotechnical Engineering

Bio-geotechnical engineering emerged as an interdisciplinary field integrating microbiology, geochemistry, and geotechnical engineering with the objective of improving soil behavior using biologically mediated processes. Early research was primarily exploratory, focusing on understanding how microbial activity could influence mineral precipitation and soil fabric modification (Ivanov and Chu, 2008).

4.1.1 Early Developments in Microbial Soil Improvement

Initial studies on microbial soil improvement can be traced back to microbiological research on calcite precipitation by ureolytic bacteria. Stocks-Fischer et al. (1999) demonstrated that bacteria such as *Sporosarcina pasteurii* could induce calcite precipitation through urea hydrolysis. These findings were later translated into geotechnical applications by DeJong et al. (2006), who established microbial-induced carbonate precipitation (MICP) as a viable ground improvement technique.

4.2 Literature on Bio-Mineralization in Clayey and Expansive Soils

The application of bio-mineralization to clayey and expansive soils has been investigated to a lesser extent compared to granular soils. However, existing studies indicate that microbial treatments can effectively alter clay fabric, reduce swelling potential, and improve strength under controlled conditions (Soon et al., 2013).

4.2.1 Reported Challenges in Low-Permeability Soils

Low permeability in clayey soils significantly restricts the transport of bacteria, enzymes, and cementation solutions. Studies have reported uneven calcium carbonate distribution, localized clogging, and reduced treatment depth in expansive clays (Van Paassen, 2009). Additionally, the high surface charge and cation exchange capacity of clays can interfere with microbial activity and precipitation efficiency.

4.3 Studies on Microbial Treatment of Regur (Black Cotton) Soil

Research on microbial treatment of Regur soil is relatively limited but growing, with most investigations conducted at the laboratory scale. These studies primarily aim to evaluate the feasibility of MICP and EICP in mitigating the adverse properties of expansive black cotton soil.

4.3.1 Laboratory-Scale Investigations

Laboratory studies have employed mixing-based treatment methods to ensure uniform distribution of microbial solutions in Regur soil. Researchers have reported noticeable improvements in strength and reductions in swelling potential following microbial treatment (Gowthaman et al., 2019; Sharma and Reddy, 2021).

4.4 Comparative Review of MICP and EICP in Regur Soil

Comparative assessments of MICP and EICP indicate that both techniques are capable of improving the strength characteristics of Regur soil, albeit with differing operational efficiencies and limitations.

4.4.1 Treatment Efficiency and Uniformity

MICP often results in higher peak strength due to sustained microbial activity; however, uniformity of treatment remains a challenge in clayey soils. In contrast, EICP provides more homogeneous mineral precipitation due to the smaller size and mobility of urease enzymes (Neupane et al., 2015).

4.5 Influence of Key Parameters Reported in Literature

The effectiveness of bio-mineralization in Regur soil is highly sensitive to several interacting parameters, as reported across the literature.

4.5.1 Bacterial Strain and Urease Activity

Ureolytic activity directly governs the rate of carbonate precipitation. Studies consistently report superior performance when using *Sporosarcina pasteurii* due to its high urease activity and alkalinity tolerance (Stocks-Fischer et al., 1999).

5. MECHANISMS OF STRENGTH ENHANCEMENT IN REGUR SOIL: A SYNTHESIS OF LITERATURE

5.1 Particle Bonding and Cementation Effects

One of the primary mechanisms responsible for strength enhancement in Regur soil treated through bio-mineralization is particle bonding induced by mineral precipitation. Microbial or enzyme-catalyzed reactions result in the formation of calcium carbonate crystals that act as cementing agents, creating interparticle bonds and reducing the degree of freedom of clay particles (DeJong et al., 2006).

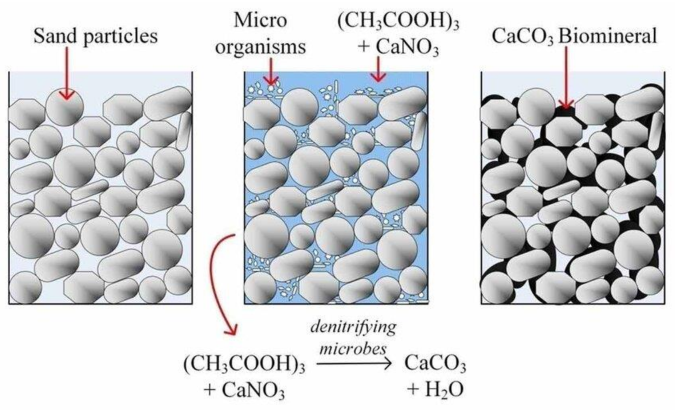

Figure-2: Soil Pore Filling and Cementation Mechanism

5.1.1 Nature of Cementation in Expansive Clay Soils

Unlike granular soils where calcite forms point-to-point contacts, in fine-grained soils such as Regur soil, precipitation occurs along clay plate surfaces and within micro-pores. This leads to surface coating, edge bonding, and partial pore filling, contributing to increased apparent cohesion and stiffness (Soon et al., 2013).

5.2 Alteration of Clay Fabric and Diffuse Double Layer

Beyond cementation, bio-mineralization induces fundamental changes in clay fabric and interparticle physicochemical interactions. The precipitation of calcium carbonate alters the electrical environment of clay particles, affecting the thickness of the diffuse double layer (DDL) (Mitchell and Soga, 2005).

5.2.1 Role of Multivalent Calcium Ions

The introduction of calcium ions during bio-mineralization promotes cation exchange, replacing monovalent ions such as sodium with divalent calcium. This process reduces repulsive forces between clay particles and encourages flocculation and aggregation (Grim, 1968).

5.3 Reduction in Swelling Potential and Moisture Sensitivity

Swelling control is a critical requirement for stabilizing Regur soil, and bio-mineralization has been shown to significantly reduce swelling potential by modifying both mechanical and physicochemical soil behavior.

5.3.1 Restriction of Water Ingress

Calcium carbonate precipitation reduces pore connectivity and forms protective coatings around clay particles, limiting water absorption. This restricts the entry of water into interlayer spaces of montmorillonite, thereby reducing swell pressure and free swell index (Soon et al., 2013).

5.4 Correlation between Calcite Content and Strength Gain

A strong correlation between calcium carbonate content and mechanical strength improvement has been consistently reported in the literature. Calcite content is often quantified using acid digestion or thermogravimetric analysis and is considered a key indicator of treatment effectiveness.

5.4.1 Quantitative Relationships Reported in Literature

Studies indicate that strength gain increases with calcite content up to an optimum level, beyond which additional precipitation may lead to brittleness or localized clogging. For expansive soils, relatively lower calcite content is often sufficient to achieve significant improvements due to enhanced clay–mineral interactions (DeJong et al., 2013).

6. REVIEW OF TREATMENT TECHNIQUES AND APPLICATION METHODS

6.1 Mixing-Based Laboratory Treatment Methods

Mixing-based treatment is the most commonly adopted approach in laboratory-scale studies on bio-mineralization of clayey and expansive soils, including Regur soil. In this method, soil is thoroughly mixed with bacterial or enzyme solutions along with cementation reagents to achieve uniform distribution of reactants (Gowthaman et al., 2019).

6.1.1 Rationale for Mixing-Based Approaches

Due to the low permeability and high surface activity of expansive clays, direct percolation or injection of microbial solutions is often ineffective at the laboratory scale. Mixing ensures intimate contact between soil particles, microbes or enzymes, and calcium sources, thereby enhancing precipitation efficiency and repeatability of results (Soon et al., 2013).

6.2 Injection and Percolation Techniques

Injection and percolation techniques are more representative of field-scale bio-mineralization and involve delivering bacterial or enzyme solutions into soil through injection wells or surface percolation systems.

6.2.1 Injection-Based Delivery Methods

Injection methods typically involve low-pressure injection of microbial and cementation solutions into the subsurface. These techniques have been successfully applied in sandy soils; however, their effectiveness in expansive clays is limited by low hydraulic conductivity and rapid clogging near injection points (Van Paassen, 2009).

6.3 Curing Regimes and Environmental Control

Curing conditions play a critical role in governing the kinetics of bio-mineralization and the stability of precipitated minerals. Temperature, moisture content, and curing duration directly influence microbial activity and enzyme efficiency.

6.3.1 Effect of Temperature and Moisture

Most ureolytic bacteria exhibit optimal activity in the temperature range of 25–35 °C and alkaline pH conditions. Insufficient moisture restricts reactant mobility, whereas excessive moisture may dilute reactants and reduce precipitation efficiency (Stocks-Fischer et al., 1999).

7. DURABILITY AND LONG-TERM PERFORMANCE: LITERATURE INSIGHTS

7.1 Wet–Dry and Cyclic Durability Studies

Durability under cyclic environmental loading is a critical performance criterion for stabilized expansive soils, particularly in regions experiencing seasonal moisture variations. Several studies have investigated the response of bio-mineralized soils to repeated wetting and drying cycles to assess the stability of microbial-induced cementation over time (DeJong et al., 2010).

7.1.1 Effects of Wet–Dry Cycling on Bio-Treated Soils

Wet–dry cycling induces volumetric changes, microcracking, and degradation of bonding in untreated expansive soils. In contrast, bio-mineralized soils exhibit improved resistance due to the presence of calcium carbonate cementation, which restricts particle movement and reduces moisture ingress (Soon et al., 2013). However, partial strength loss after multiple cycles has been reported, particularly when cementation is non-uniform.

7.2 Resistance to Environmental Degradation

Environmental degradation mechanisms such as chemical leaching, temperature fluctuations and microbial activity loss can adversely affect the long-term performance of bio-mineralized soils. Understanding these factors is essential for evaluating the feasibility of bio-based stabilization in real-world applications.

7.2.1 Chemical Stability and Leaching Resistance

Calcium carbonate precipitates formed during bio-mineralization are generally stable under neutral to alkaline conditions. However, acidic environments can dissolve calcite, leading to a reduction in cementation and strength. Laboratory leaching studies indicate that bio-treated soils exposed to mildly acidic conditions may experience gradual strength reduction, highlighting the importance of site-specific chemical assessment (Van Paassen, 2009).

8. ENVIRONMENTAL, ECONOMIC, AND SUSTAINABILITY ASPECTS

8.1 Environmental Implications of Microbial Treatments

Microbial catalyst–driven soil improvement has attracted attention primarily due to its potential environmental advantages over conventional chemical stabilization techniques. Bio-mineralization processes rely on naturally occurring biochemical reactions operating at ambient temperature and pressure, thereby avoiding the energy-intensive manufacturing processes associated with traditional binders such as cement and lime (DeJong et al., 2006).

8.1.1 Environmental Benefits of Bio-Mineralization

The principal environmental benefit of microbial treatments lies in their reduced greenhouse gas emissions during material production and application. Calcium carbonate precipitation occurs in situ, eliminating the need for high-temperature calcination processes. Additionally, bio-mineralization can utilize locally available materials and indigenous microorganisms, further reducing transportation-related emissions (Ivanov and Chu, 2008).

8.2 Comparison with Cement and Lime Stabilization

Cement and lime stabilization have been widely adopted for improving expansive soils due to their rapid strength gain and well-established design practices. However, these methods are increasingly scrutinized due to their environmental and durability limitations.

8.2.1 Performance and Environmental Trade-Offs

While cement and lime treatments provide substantial short-term strength improvement, their production is associated with significant CO_2 emissions. Cement manufacturing alone contributes approximately 0.8–0.9 tonnes of CO_2 per tonne of cement produced (Scrivener et al., 2018). In contrast, bio-mineralization significantly reduces embodied carbon, albeit often with slower strength development.

8.3 Cost-Effectiveness and Carbon Footprint Considerations

Economic feasibility is a critical factor influencing the adoption of any soil improvement technique. At present, microbial treatments are generally more expensive at the laboratory scale due to costs associated with nutrients, enzymes, and controlled application procedures.

8.3.1 Life-Cycle Cost Perspective

Several authors argue that a life-cycle cost assessment provides a more realistic comparison between bio-mineralization and conventional stabilization. Although initial costs may be higher, potential savings can be achieved through reduced material usage, lower environmental compliance costs, and extended service life of treated infrastructure (DeJong et al., 2010).

9. CONCLUSIONS

This review critically synthesized the existing literature on microbial catalyst–driven bio-mineralization for strength enhancement of Regur (black cotton) soil. The findings indicate that bio-mineralization, particularly microbial- and enzyme-induced carbonate precipitation, offers a promising and sustainable alternative to conventional chemical stabilization methods. Reported studies consistently demonstrate improvements in strength, stiffness, and durability, along with significant reductions in swelling potential and moisture sensitivity. Microstructural evidence confirms that calcium carbonate precipitation alters clay fabric, enhances interparticle bonding, and restricts volumetric instability. Compared to cement and lime stabilization, bio-mineralization exhibits lower carbon footprint and improved environmental compatibility, making it attractive for sustainable geotechnical applications. Although challenges related to treatment uniformity and scalability remain, the reviewed literature highlights the strong potential of bio-mineralization for mitigating the engineering problems associated with Regur soil. With continued research and field-scale validation, microbial catalyst–based techniques can contribute meaningfully to eco-friendly ground improvement practices in expansive soil regions.

10. LIMITATIONS OF THE REVIEWED STUDIES

Despite encouraging outcomes, the literature on bio-mineralization of Regur soil exhibits several limitations. Most studies are confined to laboratory-scale investigations employing mixing-based treatment methods that do not fully replicate field conditions. Limited field trials and long-term monitoring data restrict the assessment of in-situ performance and durability. Variability in microbial strains, treatment protocols, curing regimes, and testing procedures makes direct comparison between studies difficult. Environmental concerns related to ammonium by-products are often acknowledged but rarely quantified or mitigated systematically. Additionally, economic feasibility and scalability under Indian field conditions remain insufficiently addressed. These limitations highlight the need for standardized methodologies, comprehensive life-cycle assessments, and pilot-scale demonstrations to enable reliable translation of bio-mineralization from research to practice.

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