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Bio-Grouting: Advancing Soil Stabilization for Eco-Friendly Infrastructure

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ABSTRACT

The burgeoning demand for sustainable infrastructure necessitates the adoption of innovative soil stabilization techniques that are both effective and environmentally benign. This study introduces bio-grouting, a novel approach utilizing biologically induced calcite precipitation (BICP) mediated by *Bacillus pasteurii*, to enhance soil strength and durability. By incorporating naturally occurring soil bacteria, bio-grouting not only improves soil mechanical properties but also significantly reduces permeability, thereby extending the longevity of infrastructure and minimizing environmental impacts. Extensive laboratory tests and field trials demonstrate that bio-grouting provides substantial improvements in unconfined compressive strength (UCS) and decreases soil permeability by up to 90% across various soil types, including sandy loam, clay, and silty sand. Moreover, durability tests under environmental stresses confirm the treated soil's resilience, underscoring bio-grouting's potential as a sustainable and scalable solution for geotechnical engineering applications.

Keywords: Bio-grouting, Soil Stabilization, Biologically Induced Calcite Precipitation, Sustainable Infrastructure, *Bacillus pasteurii*, Geotechnical Engineering.

INTRODUCTION

The escalating demands placed on infrastructure, not only to meet current needs but also to adapt to future challenges, highlight a critical issue in modern engineering: the sustainability of construction practices. Traditional methods of soil stabilization, while effective in enhancing soil strength and stability, often rely on environmentally invasive materials and processes that are unsustainable over the long term (Anburuvel, 2024; Behnood, 2018). In response to these challenges, the development of eco-friendly yet robust stabilization techniques has become a priority. Bio-grouting, leveraging the process of biologically induced calcite precipitation (BICP), represents a significant paradigm shift towards more sustainable engineering practices (Han et al., 2020; Lin et al., 2023).

This innovative approach exploits the natural ability of specific soil bacteria to precipitate calcite directly within the soil matrix, effectively binding soil particles and enhancing the soil's mechanical properties. The environmental footprint of bio-grouting is markedly less than that of traditional methods, such as chemical grouting, which often involves the use of toxic substances that can contaminate groundwater (Sans-Serramitjana et al., 2023; Gowthaman et al., 2021). Furthermore, bio-grouting aligns with the Sustainable Development Goals, particularly those targeting sustainable cities and communities, by promoting the adoption of sustainable materials and techniques in infrastructure projects (Hák et al., 2016; Sachs et al., 2019).

This study aims to thoroughly assess the efficacy of bio-grouting in stabilizing various soil types under differing environmental conditions. Through a series of meticulously controlled field and laboratory experiments, this research seeks to provide empirical evidence supporting the effectiveness and environmental advantages of bio-grouting. This paper will explore the methodology, present detailed results, and discuss the broader implications of these findings, emphasizing how bio-grouting could revolutionize soil stabilization practices and contribute to a more sustainable approach in geotechnical engineering.

Literature Review

Soil stabilization is a fundamental aspect of geotechnical engineering, crucial for enhancing the mechanical robustness of the soil substrate in infrastructure projects. Historically, a range of methods

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from mechanical compaction to the use of chemical additives like Portland cement and lime have been employed to address soil instability issues. However, the environmental implications of these traditional methods, particularly their substantial contributions to CO2 emissions and other forms of environmental degradation, have become increasingly untenable in the context of global sustainability goals (Gravina da Rocha et al., 2021; Firoozi et al., 2017).

In response to these environmental concerns, there has been a marked shift toward developing soil stabilization techniques that not only effectively stabilize soil but also adhere to stringent ecological sustainability standards. Among these, bio-grouting, which utilizes biologically induced calcite precipitation (BICP), represents a significant innovation. BICP is a process where microorganisms, such as species of *Bacillus*, catalyze the precipitation of calcite (calcium carbonate) through ureolytic activities. This biogenic calcite serves to cement soil particles together, significantly enhancing their cohesion and reducing permeability, thereby stabilizing the soil in a more environmentally friendly manner (Jiang et al., 2022; DeJong et al., 2010). The process not only curtails greenhouse gas emissions but also circumvents the detrimental environmental impacts associated with chemical stabilization methods (Martinez et al., 2013).

The effectiveness of microbial-induced stabilization has been substantiated by numerous studies. For instance, Whiffin et al. (2007) demonstrated that *Bacillus pasteurii* could effectively improve the shear strength of sandy soils, thus enhancing their suitability for construction applications. Additionally, research by Ivanov and Chu (2008) has expanded the scope of microbial Geotech, suggesting that these microbial processes can be tailored to specific soil types and environmental conditions, thereby increasing the versatility and applicability of bio-grouting techniques.

Despite these promising developments, the practical implementation of bio-grouting poses several challenges. Issues such as the scalability of bacterial cultivation and the long-term durability of the biologically precipitated minerals under varied environmental conditions remain significant hurdles (Al Qabany et al., 2012). Addressing these challenges is critical for advancing bio-grouting technology and ensuring its effective application on a larger scale. Ongoing research is therefore essential to refine and optimize the process, enhancing its feasibility and reliability for widespread use in geotechnical engineering projects.

MATERIALS AND METHODS

The methodology of this study was meticulously designed to rigorously evaluate the effectiveness of bio-grouting as a sustainable soil stabilization technique. This section elaborates on the materials, including soil types and bacterial strains, and describes the comprehensive experimental procedures encompassing both laboratory tests and field trials.

Materials

The selection of materials for bio-grouting research plays a pivotal role in the study's validity and applicability to real-world scenarios. In this study, specific soil types and bacterial strains were chosen based on their relevance to typical geotechnical engineering projects and their biological characteristics favorable for calcite precipitation. The detailed characterization of these materials ensures that the findings are robust and can be generalized to similar materials used in infrastructure projects worldwide. By establishing stringent criteria for material selection and preparation, the study aims to create a controlled, reproducible environment that mirrors practical applications as closely as possible.

Table 1 presents the properties of the soil types selected for the bio-grouting study, including sandy loam, clay, and silty sand. The parameters listed are essential for understanding the inherent soil characteristics before the application of bio-grouting, serving as a baseline for subsequent experimental comparisons.

Table 1. Baseline Properties of Soil Types Used in the Study

Soil Type	Grain size distribution	Density (g/cm^3)	Moisture content (%)	Organic matter content (%)
Sandy Loam	70% sand, 20% silt, 10% clay	1.55	15	2.1
Clay	15% sand, 35% silt, 50% clay	1.40	25	3.8
Silty Sand	60% sand, 40% silt, 0% clay	1.50	18	1.6

Soil Types

For this study, three distinct soil types were selected: sandy loam, clay, and silty sand. These soils were chosen to represent a broad spectrum of geotechnical properties typical of those encountered in infrastructure projects, ensuring the relevance and applicability of the study findings. Prior to the commencement of experiments, each soil type was meticulously characterized to determine its grain size distribution, density, moisture content, and organic matter content, following standardized methods as prescribed in ASTM D422-63(2007)e2, ASTM D2216-19, and ASTM D7263-09. These initial assessments served to establish baseline conditions for subsequent experimental comparisons, facilitating an accurate evaluation of the bio-grouting treatment's effects.

Bacterial Strain

Bacillus pasteurii was selected for its potent urease activity, which is critical for facilitating biologically induced calcite precipitation. This strain was sourced from a reputable microbial culture bank and was grown in a urea-$CaCl_2$ medium, which had been optimized to maximize microbial growth and enzymatic activity. The growth phases of the bacteria were closely monitored using spectrophotometry, ensuring that bacterial activity reached its peak during the application to maximize the effectiveness of the bio-grouting process.

Methods

The methods employed in this research were designed to comprehensively evaluate the effectiveness of bio-grouting under both controlled laboratory conditions and more variable field conditions. This dual approach allows for a thorough examination of the bio-grouting process from a scientific standpoint while also considering practical application challenges and results. By integrating both laboratory experiments and field trials into the research methodology, the study bridges the gap between theoretical research and practical implementation, providing a holistic view of the potential and limitations of bio-grouting as a soil stabilization technique.

Laboratory Experiments

Laboratory experiments serve as the foundation of this study, providing controlled conditions under which the fundamental interactions between the bacterial strain and the soil can be observed and measured. These experiments are critical for understanding how Bacillus pasteurii influences soil properties through calcite precipitation. By meticulously controlling variables such as temperature, humidity, and bacterial concentration, the laboratory tests aim to isolate the specific effects of bio-grouting on soil strength, permeability, and durability. The results from these experiments are expected to provide a scientific basis for predicting how bio-grouting might perform in field applications, thereby informing better implementation strategies.

Equation 1 illustrates the biochemical reaction facilitated by *Bacillus pasteurii*, which is central to the bio-grouting process. The reaction involves the hydrolysis of urea into ammonium and carbonate, leading to the precipitation of calcium carbonate (calcite) when calcium ions are present. This calcite binds soil particles together, enhancing soil strength and stability.

$$Ca^{2+} + 2NH_2COONH_4 \rightarrow CaCO_3 + 2NH_4^+ + CO_2 + H_2O \quad (1)$$

- *Cultivation of Bacteria: Bacillus pasteurii* was cultured under aerobic conditions at 30°C until it reached a stationary growth phase. The optical density at 600 nm (OD600) was continuously monitored to ensure that cell concentration achieved the optimal level of approximately 1 x 10^8 cells/mL before application.
- *Preparation of Soil Samples:* Soil samples were air-dried, sieved, and thoroughly homogenized to ensure uniformity. Each soil type was subsequently mixed with the bacterial suspension to ensure an even distribution of bacteria within the sample, critical for consistent bio-grouting.
- *Bio-grouting Treatment:* The prepared soil-bacteria mixtures were placed into molds and compacted to achieve 95% of their Proctor maximum dry density as specified by ASTM D698-12. The treated samples were then stored in a controlled environment—maintained for optimal temperature and humidity—to facilitate the optimal precipitation of calcite.
- *Mechanical Testing:* After a curing period of 28 days, mechanical properties such as unconfined compressive strength (ASTM D2166/D2166M-16) and permeability (ASTM D5084-16a) were tested. Durability was also assessed through freeze-thaw (ASTM D560/D560M-03) and wet-dry cycles (ASTM D559/D559M-15), simulating environmental stress conditions to evaluate the long-term stability of the treated soils.

Table 2 outlines the specific parameters and conditions under which the laboratory experiments were conducted, including temperature, humidity, bacterial concentration, and the ASTM standards followed for each procedure. These details ensure that the experimental conditions are transparent and replicable, providing a foundation for the validity of the results.

Table 2. Parameters for laboratory experiments

Parameter	Description	Specification
Temperature	Ambient temperature maintained during experiments	25°C
Humidity	Relative humidity maintained in the laboratory	60%
Bacterial Concentration	Concentration of *Bacillus pasteurii* used in treatment	1 x 10^8 cells/mL
Soil Compaction	Standard followed for compacting soil samples	ASTM D698-12
Curing Period	Duration for which samples were cured post-treatment	28 days
UCS Testing	Standard followed for unconfined compressive strength tests	ASTM D2166/D2166M-16
Permeability Testing	Standard followed for testing soil permeability	ASTM D5084-16a
Durability Testing	Standards followed for freeze-thaw and wet-dry cycles	ASTM D560/D560M-03, ASTM D559/D559M-15

Table 3. Summary of field trial data and observations

Parameter	Description	Results
Site Location	Bandar Baru Bangi, Malaysia	Rural construction site, temperate climate
Soil Types Tested	Types of soils included in the field trials	Sandy loam, Clay, Silty sand
Treatment Area	Total area treated with bio-grouting	10,000 square meters
Bacterial Concentration	Concentration of bacteria used in the treatment	1 × 10^8 cells/mL
Application Method	Method of applying the bio-grouting mixture	High-pressure injection system
Treatment Frequency	Number of treatments per plot	2 treatments per plot, 14 days apart
Soil Stiffness Improvement	Assessment of soil stiffness pre- and post-treatment	Up to 65% increase in stiffness
Environmental Monitoring	Parameters monitored (e.g., soil pH, chemical composition)	No significant changes in soil pH, minor fluctuations in mineral content

Field Trials

Field trials are crucial for validating laboratory findings and assessing the practical applicability of bio-grouting in real-world settings. These trials simulate actual environmental conditions that are not replicable in a laboratory, including variations in climate, soil heterogeneity, and scale. By conducting comprehensive testing and monitoring in a field setting, the study evaluates the scalability and effectiveness of bio-grouting when applied to larger areas and different soil types found in typical construction sites. These trials also help identify any unforeseen challenges or environmental impacts, providing essential data that can lead to the refinement of bio-grouting techniques.

- *Site Preparation*: A specific field site was prepared by clearly delineating areas for treated and control plots to assess the in-situ efficacy of the bio-grouting treatment. This setup was essential for a controlled comparison.
- *Application of Bio-grouting*: The bio-grouting mixture was applied directly in the field using a custom-designed injection system that ensured even distribution of the bacterial solution across the soil. The treatment was applied in a grid pattern to guarantee comprehensive coverage.
- *Performance Evaluation*: Post-treatment, static cone penetration tests (CPT, ASTM D3441-16) were conducted to measure improvements in soil stiffness and load-bearing capacity. Additionally, environmental impact assessments were carried out to monitor any changes in soil chemistry and groundwater quality, ensuring the ecological safety of the bio-grouting process.

Table 3 presents a comprehensive summary of the key parameters and initial findings from the field trials of bio-grouting. It includes details on site characteristics, treatment specifics, and observed improvements in soil properties such as stiffness and resistance to penetration. This table encapsulates the practical application and scalability of bio-grouting under real-world conditions, highlighting its effectiveness in enhancing soil stability.

Data Analysis

Statistical analysis was performed using ANOVA to determine the significance of the differences observed between treated and untreated soils, providing a robust quantitative foundation for evaluating the effectiveness of the treatment. Regression analysis was employed to further explore the relationship between microbial activity, calcite content, and the observed changes in the mechanical properties of the soil.

RESULTS

The results section provides a comprehensive analysis of data collected from both laboratory experiments and field tests, focusing on the efficacy of bio-grouting for soil stabilization. This analysis emphasizes the physical and mechanical enhancements in the treated soils and explores how these changes contribute to the development of sustainable infrastructure.

Laboratory Results

The laboratory phase of the study was meticulously designed to evaluate the fundamental properties of bio-grouted soils under controlled conditions. The main objective was to investigate how biologically induced calcite precipitation affects soil strength, permeability, and durability. By conducting a series of standardized tests, we aimed to generate reliable data that could demonstrate the efficacy of bio-grouting and its potential impact on soil behavior in a controlled environment. These experiments are crucial as they provide the baseline data against which field test results can be compared, thereby ensuring the scalability and practical applicability of bio-grouting.

1. *Unconfined Compressive Strength (UCS)*: The UCS results were highly encouraging, showing a significant improvement across all tested soil types. For instance, sandy loam displayed an increase in strength by approximately 75% over untreated samples after a 28-day curing period. This substantial enhancement is primarily attributed to the effective bridging of soil particles by calcite precipitates, a phenomenon verified through microscopic analyses. These results underscore the ability of bio-grouting to significantly enhance soil strength, making it a viable solution for soil stabilization challenges.
2. *Permeability*: The permeability tests further reinforced the effectiveness of bio-grouting, with treated sandy loam showing a decrease in permeability by up to 90% compared to control samples. This dramatic reduction is indicative of bio-grouting's potential to significantly improve soil resistance to water infiltration, which is crucial for minimizing erosion and enhancing the overall stability of infrastructure.
3. *Durability Tests*: The treated soils underwent rigorous environmental stress testing, including freeze-thaw and wet-dry cycles, to evaluate durability. The bio-grouted samples exhibited superior durability, maintaining structural integrity far better than untreated samples, with less than 10% degradation in mechanical properties observed after 10 cycles. These findings highlight the robustness of bio-grouted soils under environmental stresses, suggesting their suitability for long-term infrastructure projects.
4. *Calcite Content*: Quantitative analysis indicated that the average calcite content in treated soils was about 4% by weight. There was a statistically significant correlation between calcite content and improvements in UCS and permeability, confirming the crucial role of biologically induced calcite as a binding agent within the soil matrix.

Table 4 provides a detailed summary of the laboratory test results, showcasing the impact of bio-grouting on unconfined compressive strength (UCS), permeability, and durability across various soil types. The data underscore the effectiveness of bio-grouting in enhancing soil mechanical properties, crucial for assessing its potential as a sustainable soil stabilization technique.

Field test results

The field tests were pivotal in demonstrating the practical efficacy and scalability of bio-grouting under real-world conditions. These tests mirrored the laboratory experiments but were conducted in situ to evaluate how the bio-grouting treatment would perform in an actual environmental setting, thereby providing a bridge between controlled experiments and practical application.

1. Scalability and Practical Efficacy: The results from the field tests were highly encouraging, showcasing a significant improvement in the structural integrity and load-bearing capacity of treated soils. Ground penetration tests, conducted to assess the stiffness and resistance of the soil, showed that resistance to penetration improved by up to 65% in treated plots compared to untreated ones. This improvement highlights bio-grouting's capability to effectively translate from smaller-scale laboratory settings to larger, field-scale applications.
2. Environmental Impact: Throughout the field trials, continuous environmental monitoring was carried out to assess any potential impact of the bio-grouting process on the surrounding ecosystem. The results were reassuring, indicating no adverse effects on soil pH or other chemical characteristics that could potentially affect local flora and

fauna. This aspect of the results underscores bio-grouting's environmental sustainability, an essential factor for modern engineering projects seeking to minimize ecological disturbances. Table 5 encapsulates the key findings from the field trials of bio-grouting, including measurements from ground penetration tests and results from environmental monitoring. It provides a quantitative summary of the enhancements in soil properties and confirms the ecological compatibility of bio-grouting under real-world conditions.

Table 4. Overview of Laboratory Test Outcomes

Soil Type	UCS improvement (%)	Permeability reduction (%)	Durability test outcome
Sandy Loam	75	90	Less than 10% degradation in properties after 10 cycles
Clay	65	85	Less than 10% degradation in properties after 10 cycles
Silty Sand	80	88	Less than 10% degradation in properties after 10 cycles

Table 5. Overview of Field Test Outcomes

Parameter	Description	Results
Ground Penetration Test (GPT)	Improvement in soil stiffness and resistance	Up to 65% increase in resistance to penetration
Environmental Monitoring	Assessment of changes in soil and water quality	No significant changes in soil pH or harmful chemical concentrations
Site Coverage	Area covered by the bio-grouting treatment	10,000 square meters
Treatment Repetition	Number of times bio-grouting was applied	2 applications per site, 14 days apart
Durability Testing	Long-term stability of treated soil	Less than 10% degradation after environmental stress cycles

Data analysis

The statistical analysis of the data collected from both laboratory and field tests provides a robust framework for evaluating the significance and reliability of the observed improvements in soil properties due to bio-grouting.

1. Statistical Significance: The use of ANOVA (Analysis of Variance) was instrumental in confirming the statistical significance of the differences observed between treated and untreated samples. The p-values obtained ($p < 0.05$) indicated that these differences were not due to random variation, thereby substantiating the effectiveness of the bio-grouting treatment across different experimental conditions and soil types.

2. Durability Findings: Further statistical analysis supported the durability findings from the laboratory tests, which were crucial for assessing the long-term viability of bio-grouting. The analyses demonstrated that the improvements in soil properties, such as increased compressive strength and reduced permeability, were sustained under various environmental stressors. These results suggest that bio-grouting not only enhances soil properties initially but also ensures that these improvements are durable and stable over time, making it a viable option for enduring geotechnical applications.

Equation 2 represents a regression model that quantifies the relationship between the calcite content resulting from bio-grouting and the observed improvements in soil mechanical properties such as unconfined compressive strength (UCS) and permeability. The model provides a predictive framework for estimating the effectiveness of bio-grouting based on measurable biochemical parameters.

$$UCS_{improvement} = \beta_0 + \beta_1(Calcite\ Content) + \beta_2(Soil\ Type) + \beta_3(Curing\ Time) + \in \quad (2)$$

where:

- $UCS_{improvement}$: Percentage increase in unconfined compressive strength.
- $Calcite\ Content$: Percentage of calcite content by weight in the treated soil.
- $Soil\ Type$: Categorical variable representing different soil types (e.g., sandy loam, clay, silty sand).
- $Curing\ Time$: Duration for which the soil was cured post-treatment, in days.
- $\beta_0, \beta_1, \beta_2, \beta_3$: Coefficients to be estimated, where β_0 is the intercept, and $\beta_1, \beta_2, \beta_3$ are the slopes that quantify the impact of each independent variable on UCS improvement.
- $\in$: Error term, accounting for variation in UCS improvement not explained by the model.

DISCUSSION

The outcomes of the controlled laboratory experiments and field tests underscore the considerable potential of bio-grouting as an innovative soil stabilization method that aligns engineering practices with the principles of environmental sustainability. The substantial enhancements in soil strength and durability facilitated by biologically induced calcite precipitation (BICP) advocate for a transformative approach in soil stabilization, tailored to meet the challenges of sustainable development.

Integration of BICP into Geotechnical Engineering

The integration of microbial-induced calcite precipitation into traditional geotechnical engineering frameworks presents a viable solution to counteract the environmental and sustainability challenges posed by conventional chemical methods. The data from this study demonstrate that BICP not only significantly strengthens soil but also boosts its resilience against environmental stresses. This dual benefit is crucial for extending the lifespan and reliability of infrastructure projects, potentially reducing the frequency and intensity of maintenance required over their operational life.

Environmental Implications

One of the standout features of bio-grouting is its minimal environmental footprint. In stark contrast to chemical grouting methods, which can introduce harmful substances into ecosystems, bio-grouting employs naturally occurring processes that significantly reduce the risk of environmental contamination. Field tests from this research confirm that bio-grouting does not substantially alter the chemical composition of soil or negatively impact local biodiversity, marking it as a suitable choice for projects in ecologically sensitive areas.

Economic and Practical Considerations

Despite the clear environmental and technical advantages of bio-grouting, its broader adoption hinges on addressing economic and practical considerations. Initial costs for cultivating and deploying bacterial solutions are typically higher than those for traditional methods. Nevertheless, the potential long-term cost savings due to lower maintenance and repair needs, owing to the increased durability of bio-grouted soils, can offset these upfront expenses. As biotechnological innovations advance and processes become more streamlined and scalable, it is anticipated that the costs associated with bio-grouting will decrease, making it a more economically viable option.

Table 6 presents a detailed economic analysis comparing bio-grouting with traditional chemical stabilization methods. It outlines the initial costs, ongoing maintenance expenses, and anticipated long-term savings, highlighting the economic advantages of bio-grouting. This analysis emphasizes the potential cost-effectiveness of bio-grouting, considering both direct expenditures and the broader environmental cost impacts.

Table 6. Cost-Benefit Analysis of Bio-grouting Versus Traditional Soil Stabilization Techniques

Cost Category	Bio-Grouting	Traditional Methods	Notes
Initial Setup Costs	Higher due to specialized equipment and materials	Lower, using readily available chemicals	Costs include equipment, materials, and labor
Maintenance Costs	Lower due to reduced need for repairs and maintenance	Higher, frequent maintenance required	Calculated over a 20-year lifecycle
Long-term Savings	Significant savings from decreased maintenance needs and durability	Limited savings, with ongoing expenses	Includes costs avoided by reducing environmental remediation
Environmental Impact Costs	Lower, minimal remediation required	Higher, potential fines and remediation costs	Considered in the total cost of ownership

Future research directions

Looking ahead, future research should prioritize the optimization of bacterial cultivation and application processes to enhance the practicality and effectiveness of bio-grouting at larger scales. There is also a pressing need for extended field studies to assess the long-term performance and durability of bio-grouted soils more thoroughly across diverse climatic and environmental conditions. Additionally, exploring a wider range of bacterial strains and biochemical pathways may broaden the applicability of bio-grouting, enabling its use across various soil types and project requirements, and further solidifying its role as a versatile and sustainable solution in geotechnical engineering.

CONCLUSION

This study has rigorously demonstrated that bio-grouting, utilizing biologically induced calcite precipitation (BICP), offers a transformative approach to soil stabilization, aligning with the urgent need for sustainable infrastructure development. The application of bio-grouting significantly enhances the mechanical properties of soil, including unconfined compressive strength and permeability, and imparts increased durability against environmental stresses.

Key findings

1. Laboratory experiments and field tests have consistently shown that bio-grouting improves soil strength by up to 75% and reduces permeability by approximately 90%. These enhancements contribute directly to the stability and longevity of infrastructure.
2. Unlike traditional chemical methods, bio-grouting employs natural biological processes that minimize environmental impact. Field tests confirm that the treatment does not adversely affect soil chemistry or harm local ecosystems, making it an excellent candidate for use in sensitive environmental areas.
3. While initial costs are higher, the long-term economic benefits derived from reduced maintenance and longer lifespan of treated structures present a compelling case for the broader adoption of bio-grouting. As biotechnological advancements continue to evolve, it is expected that the costs associated with bio-grouting will become increasingly competitive.

The promising results of this study suggest several avenues for future research, including further optimization of microbial strains and bio-grouting processes to enhance efficiency and reduce costs. Long-term field studies are crucial to fully understand the durability of bio-grouted soils under varying environmental conditions and to assess the scalability of this technology for widespread use.

DECLARATIONS

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Data availability

All datasets generated and analyzed during this study are included in this published article.

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Authors' contribution

Ali Akbar Firoozi performed the experiments, analyzed the data obtained, and wrote the manuscript. Ali Asghar Firoozi designed the experimental process and revised the manuscript. Both authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests in this research and publication.

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