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COMPARATIVE EVALUATION OF EXPANSIVE SOIL STABILIZATION USING BACILLUS SUBTILIS, BASALT FIBER, AND THEIR SYNERGISTIC COMBINATION

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ABSTRACT

Expansive and problematic soils can exhibit inadequate strength and volume instability, creating challenges for foundations and transportation infrastructure. This study compares three stabilization strategies—basalt fibre reinforcement, Bacillus subtilis-based microbial treatment, and their combined application—using unconfined compressive strength (UCS) as the principal performance indicator. The research records a baseline UCS of 0.68 kg/cm² for untreated soil. The average UCS increased to 1.12 kg/cm² with 0.80% basalt fibre and to 1.45 kg/cm² with 6% Bacillus subtilis. The combined treatment of 0.80% basalt fibre and 6% bacterial dosage achieved 3.87 kg/cm², a reported improvement of 469.1% over untreated soil. Dosage trials identified 0.80% as the best tested basalt fibre content and 6% as the best tested bacterial dosage. Baseline characterization reported specific gravity 2.178, natural water content approximately 33.53%, optimum moisture content (OMC) 17.24%, and maximum dry density (MDD) 1.28 g/cm³. The findings indicate that the combined treatment performed best within the tested laboratory programme. The interpretation remains limited by the small experimental matrix, lack of reported inferential statistics, and an inconsistency between the report's black-cotton/expansive-soil description and its sieve-based SW classification. Further replicated testing, swelling and durability measurements, microstructural verification, and field validation are needed before engineering deployment.

Keywords: Expansive soil, Bacillus subtilis, Microbially induced calcite precipitation, Basalt fibre, Unconfined compressive strength, Soil stabilization

I. INTRODUCTION

Soil is a primary load-bearing material in foundations, roads, embankments and earth structures. Where natural soil has low strength, high compressibility or moisture-sensitive volume change, treatment may be needed to meet engineering requirements. Expansive clays are particularly challenging because changes in water content can produce swelling and shrinkage, potentially causing differential movement and distress to structures. Conventional stabilizers such as lime and cement are widely used, but material production and treatment

processes can carry environmental and cost burdens. This motivates investigation of reinforcement and biological alternatives.

The research examines basalt fibre as a mechanical reinforcement and Bacillus subtilis with urea–calcium chloride reagents as a microbial treatment route associated with microbially induced calcite precipitation (MICP). It then evaluates whether combining these approaches improves UCS more than either treatment alone.

1.1 Research objectives and contribution

The objectives of the study are to characterize untreated soil; measure UCS at several basalt fibre contents; evaluate bacterial dosage; and compare untreated soil, individual treatments and the combined optimum treatment. The principal contribution is a direct comparison of the three stabilization strategies using the project's laboratory results. The study does not claim field performance or prove a particular microstructural mechanism, because field outcomes are not directly measured.

II. BACKGROUND AND LITERATURE CONTEXT

MICP is a biological ground-improvement approach in which microbial activity can promote carbonate precipitation. Where calcium carbonate forms at particle contacts, it may cement grains and improve stiffness or strength. Performance depends on bacterial activity, reagent concentration, pH, temperature, curing and the soil's pore structure. Reviews by Mujah et al. and Fu et al. identify MICP as a promising approach for soil strengthening, while also noting challenges such as non-uniform precipitation, process optimization and scale-up [1,2].

Research on Bacillus subtilis-treated soils reports strength improvements that depend on bacterial dosage and curing. Fuadah et al. found an optimum bacterial concentration in their organic-soil programme, while Harianto et al. reported improvements in shear strength and cohesion for treated sedimentary soil [3,4]. These studies provide context rather than directly comparable benchmarks because their soils, preparation procedures and test conditions differ from those in the present project.

Fibre reinforcement offers a complementary mechanical mechanism. Fibres can bridge developing cracks, distribute stress and increase resistance to localized deformation. Liu et al. investigated the combined use of MICP and basalt fibre in aeolian sand and reported that fibre dosage and length affected performance; excessive fibre can cause agglomeration and impede uniform treatment [5]. Boruah et al. similarly reported benefits from combining MICP with natural fibres, although fibre type and soil conditions differed [6]. These findings support testing a hybrid strategy, but do not independently validate the mechanism in the present specimens.

2.1 Research gap

The research addresses the practical comparison of basalt fibre, Bacillus subtilis treatment and their combination in the same laboratory programme. The available evidence is primarily UCS-based. Swelling pressure, free swell, CBR, permeability, durability, calcium-carbonate content and microstructure are not sufficiently documented as outcome measures in the reported comparison. These gaps limit a full assessment of suitability for expansive-soil applications.

2.2 Working hypothesis

The working hypothesis is that fibre reinforcement and biological bonding may act complementarily: basalt fibres provide tensile bridging and restraint, while mineral precipitation may improve interparticle bonding. This is a plausible interpretation, not a mechanism directly demonstrated by microscopy or mineralogical testing in the research.

III. MATERIALS AND EXPERIMENTAL METHODOLOGY

3.1 Materials

For this research usage of black cotton/expansive soil, basalt fibre, Bacillus subtilis bacterial suspension, urea and calcium chloride ($CaCl_2$) is done. The soil was air-dried, lumps are gently broken, and material passing the 4.75 mm sieve was used for specimen preparation. The research's treatment calculations use 500 g dry-soil portions. For the combined treatment, 0.80% basalt fibre corresponds to 4 g per 500 g soil, while 6% bacterial dosage corresponds to 30 mL of bacterial suspension as reported in the research methodology.

3.2 Baseline soil characterization

The research includes specific-gravity, sieve-analysis, natural-water-content and Standard Proctor compaction tests. These measurements are used as baseline descriptors and to guide specimen preparation. Table 1 summarizes the values reported in the research report; the classification issue is discussed in Section 6.

Table 1: Baseline soil properties

Property	Reported result	Use in this study
Specific gravity, G	2.178	Baseline index property
Natural water content	33.53%	Initial moisture condition
Optimum moisture content (OMC)	17.24%	Moisture reference for compaction
Maximum dry density (MDD)	1.28 g/cm³	Compaction reference
Particle-size descriptors	D_{10} = 0.24 mm; D_{30} = 0.64 mm; D_{60} = 1.65 mm	Gradation indices reported
Uniformity coefficient, C_u	6.875 (approx.)	Sieve-based descriptor
Coefficient of curvature, C_c	1.03 (approx.)	Sieve-based descriptor

3.3 Basalt fibre dosage series

Basalt fibre contents of 0.50%, 0.60%, 0.70%, 0.80%, 0.90% and 1.00% by dry-soil mass are tested. For each 500 g dry-soil portion, the fibre masses correspond to 2.5, 3.0, 3.5, 4.0, 4.5 and 5.0 g, respectively. The research reports that specimens are mixed with water and compacted in the UCS mould before testing.

3.4 Bacterial dosage series and MICP reagents

The bacterial dosage series comprised 4%, 5%, 6%, 7% and 8%. For 500 g dry soil, the reported bacterial suspension volumes are 20, 25, 30, 35 and 40 mL, respectively. The report describes 1 M urea and calcium chloride cementation solutions and gives reagent quantities adjusted across the dosage series to maintain a nominal liquid volume of 86.2 mL. Because the source describes the bacterial percentages in terms of research preparation, they are retained here as reported rather than reinterpreted as a standardized concentration unit.

3.5 Combined-treatment procedure

The combined treatment selected the best-performing individual dosages from the preliminary trials: 0.80% basalt fibre and 6% Bacillus subtilis. The research mixed 500 g prepared dry soil with 4 g basalt fibre, 30 mL bacterial suspension, and the specified urea–$CaCl_2$ reagents. The mixture was compacted in the UCS mould and tested using the research's unconfined compression procedure. Three readings are reported for the combined specimen series, with an average UCS of 3.87 kg/cm².

3.6 Unconfined compressive strength

UCS is used as the primary comparative response. The reported strength values are converted into percentage improvement relative to untreated soil using:

$$\textbf{Improvement (\%)} = [(\text{UCS treated} - \text{UCS untreated}) / \text{UCS untreated}] \times 100$$

The untreated average UCS of 0.68 kg/cm² was used as the reference. No independent significance test, confidence interval or between-specimen variance analysis is reported in the source; therefore, the numerical comparisons below are descriptive.

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3.7 Experimental workflow

Experimental workflow

Stage	Procedure / decision
1. Soil preparation	Air-dry, break down lumps, remove debris, pass through 4.75 mm sieve
2. Baseline testing	Specific gravity, sieve analysis, natural water content and compaction
3. Fibre screening	Test 0.50–1.00% basalt fibre; select 0.80% based on highest reported UCS
4. Bacterial screening	Test 4–8% Bacillus subtilis; select 6% based on highest reported UCS
5. Combined treatment	Apply 0.80% fibre + 6% bacterial dosage with urea–$CaCl_2$ reagents
6. Performance assessment	Compare average UCS with untreated and single-treatment values

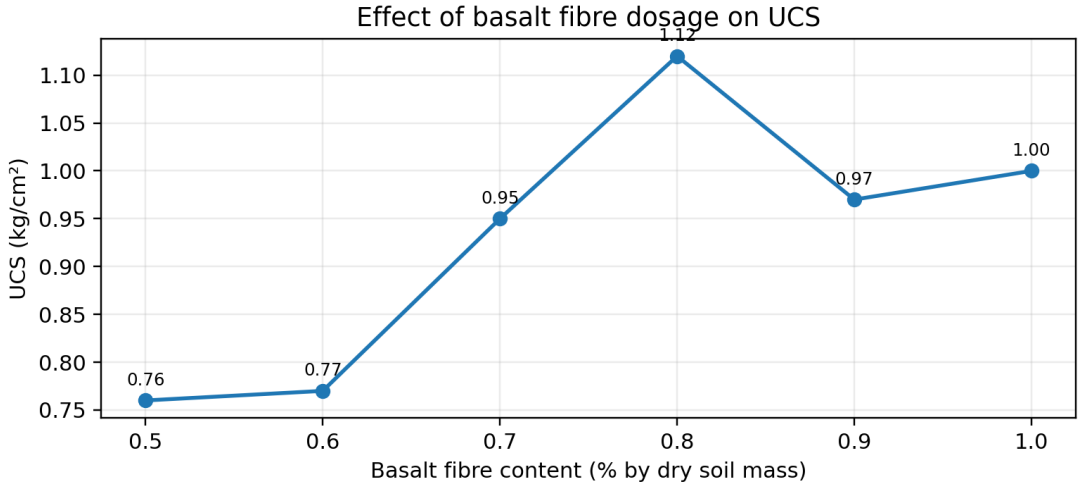
IV. RESULTS

4.1 Effect of basalt fibre content

The reported UCS increased from 0.76 kg/cm² at 0.50% fibre to a maximum of 1.12 kg/cm² at 0.80%. At 0.90% and 1.00%, the reported UCS values are 0.97 and 1.00 kg/cm², respectively. Thus, 0.80% was the best-performing dosage among the tested fibre contents; the data do not establish that it is a universal optimum for other soils or fibre geometries.

Table 2: Average UCS at different basalt fibre contents

Basalt fibre (% by dry soil mass)	Average UCS (kg/cm²)
0.50	0.76
0.60	0.77
0.70	0.95
0.80	1.12
0.90	0.97
1.00	1.00



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Figure 1. Reported UCS response to basalt fibre dosage.

4.2 Effect of Bacillus subtilis dosage

The bacterial dosage series produced average UCS values of 1.23, 1.30, 1.45, 1.20 and 1.17 kg/cm² at 4%, 5%, 6%, 7% and 8%, respectively. The maximum reported value occurred at 6%. Strength decreased at the two higher dosages in this experimental series. This pattern is consistent with the need to optimize bacterial/reagent conditions, but the research data alone do not identify the cause of the decline.

Table 3: Average UCS at different Bacillus subtilis dosages

Bacterial dosage (% as reported)	Average UCS (kg/cm²)
4%	1.23
5%	1.30
6%	1.45
7%	1.20
8%	1.17

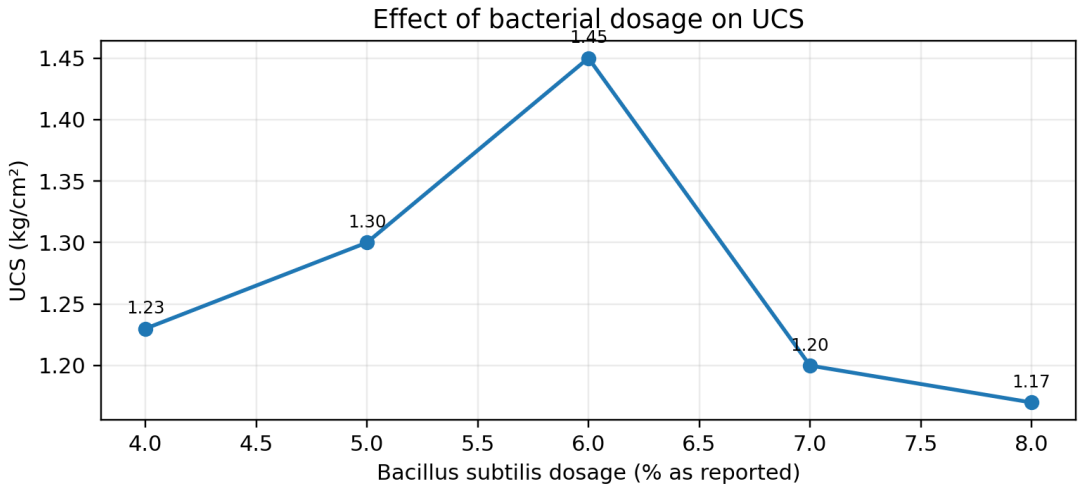


Figure 2. Reported UCS response to Bacillus subtilis dosage.

4.3 Comparison of stabilization strategies

The combined treatment gave the highest reported UCS. Table 4 compares untreated soil with the two individual treatments and the combined treatment. Percentage improvements are those reported in the research report, with small rounding differences possible from the baseline value.

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Table 4: Comparison of stabilization strategies

Treatment	Average UCS (kg/cm²)	Improvement over untreated
Untreated soil	0.68	Reference
0.80% basalt fibre	1.12	64.7%
6% Bacillus subtilis	1.45	113.2%
0.80% basalt fibre + 6% Bacillus subtilis	3.87	469.1%

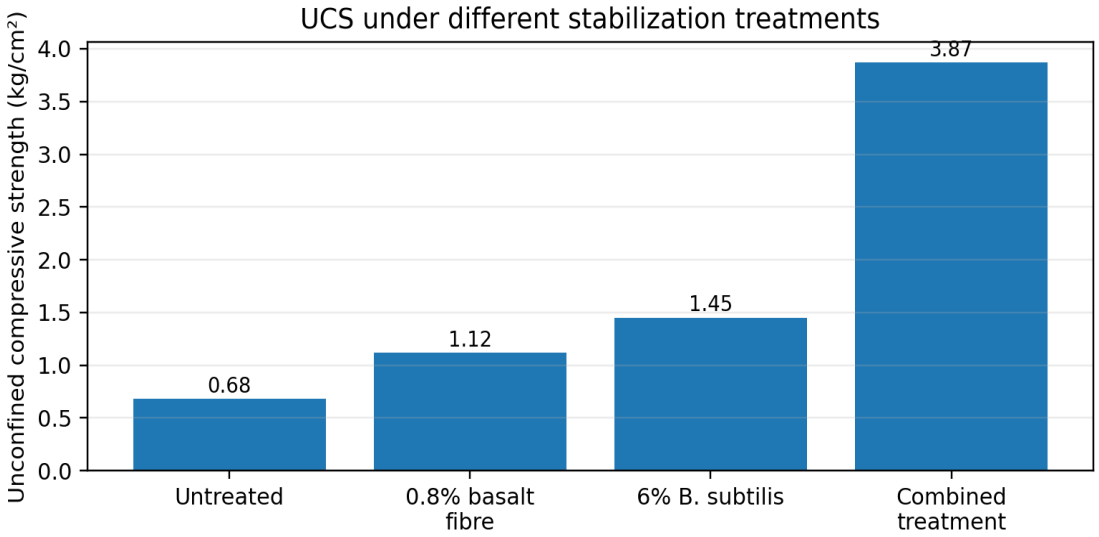


Figure 3. Comparison of average UCS for the four treatment conditions.

4.4 Quantitative comparison

Relative to untreated soil, the basalt-fibre treatment increased UCS by 0.44 kg/cm² and the bacterial treatment by 0.77 kg/cm². The combined treatment increased UCS by 3.19 kg/cm². The combined value was approximately 3.46 times the fibre-only value and 2.67 times the bacterial-only value. These ratios describe the reported means; they should not be interpreted as statistical interaction effects without a replicated factorial design and uncertainty estimates.

Table 5: Quantitative comparison of treatments

Comparison	UCS ratio / difference	Interpretation
Basalt fibre vs. untreated	+0.44 kg/cm²; +64.7%	Moderate improvement in tested series
Bacillus subtilis vs. untreated	+0.77 kg/cm²; +113.2%	Larger individual-treatment improvement
Combined vs. untreated	+3.19 kg/cm²; +469.1%	Highest measured average UCS
Combined vs. fibre only	3.46× UCS	Combined result exceeded fibre-only mean
Combined vs. bacterial only	2.67× UCS	Combined result exceeded bacterial-only mean

V. DISCUSSION

5.1 Fibre reinforcement

The increase in UCS up to 0.80% basalt fibre is compatible with a reinforcement mechanism in which fibres bridge developing cracks, redistribute stress and provide frictional resistance against relative movement. The lower values at 0.90% and 1.00% suggest that increasing fibre content beyond the best tested level did not provide further strength gain under the research conditions. Fibre clustering, reduced workability or non-uniform distribution are possible explanations discussed in the broader literature, but are not directly measured in this research.

5.2 Biological treatment

Bacillus subtilis treatment improved UCS over the untreated reference, with 6% giving the highest reported value in the dosage series. In MICP-related systems, carbonate precipitation may create bridges between particles and improve contact strength. The research used urea and calcium chloride reagents; however, no direct calcium-carbonate quantification, SEM imaging, XRD or other microstructural verification is reported as evidence for the specimens tested. The mechanism should therefore be presented as a plausible explanation rather than a confirmed observation.

5.3 Combined treatment

The combined treatment produced the largest UCS value in the research dataset. A complementary effect is plausible: fibre may improve crack bridging and post-cracking integrity, while biological mineral precipitation may strengthen particle contacts. The magnitude of the combined value warrants follow-up testing because no formal factorial analysis, uncertainty estimate or statistical interaction test is provided. Replicated specimens prepared across multiple soil batches are needed to establish the reproducibility of the result.

5.4 Engineering and sustainability implications

The findings suggest that a hybrid biological–fibre approach merits further study as a potential soil-improvement method. Basalt fibre can provide mechanical reinforcement, while biological treatment may offer particle bonding without relying solely on conventional cementitious additives. Nevertheless, sustainability cannot be concluded from UCS alone. A complete evaluation should consider reagent production, bacterial culture requirements, water use, curing time, cost, durability, possible ammonium by-products from ureolysis, and end-of-life impacts.

VI. DATA QUALITY, LIMITATIONS AND INTERPRETATION

Several limitations should be made explicit in any publication. First, the research report calls the material black cotton/expansive soil but also classifies it as well-graded sand (SW) from the sieve-analysis coefficients. Those descriptions are not readily consistent; the soil classification

should be verified using Atterberg limits, fines content and the applicable classification procedure before drawing expansive-clay-specific conclusions. This paper preserves the reported terminology and flags the inconsistency rather than silently resolving it.

Second, the natural water content (approximately 33.53%) differs from the reported OMC (17.24%), as expected for distinct natural and compaction conditions; sample conditioning should be carefully documented. Third, the available comparative dataset reports average UCS values but does not provide standard deviations or formal inferential tests. Although the combined-treatment table lists three measurements, the overall design is not described as a fully replicated factorial experiment across all treatment conditions. Consequently, the improvements are descriptive and should not be presented as statistically significant.

Fourth, the source does not provide direct evidence for carbonate amount, mineral distribution, swelling reduction, permeability changes, CBR improvement, long-term durability or field performance. These are important response variables for expansive-soil stabilization. Finally, bacterial dosage notation should be made unambiguous in future work by distinguishing volume fraction of suspension from cell density or culture concentration, and by documenting bacterial strain, growth conditions, reagent molarity, pH and curing conditions.

6.1 Recommended validation programme

Table 6: Recommended validation programme

Validation item	Recommended measurement	Reason
Soil identity	Atterberg limits, fines content, USCS classification	Resolve black-cotton vs. SW inconsistency
Replicates	At least 3–5 specimens per condition and soil batch	Estimate variability and confidence intervals
Volume-change behaviour	Free swell index, swell pressure, shrinkage	Directly assess expansive-soil performance
Load-bearing performance	UCS plus CBR and/or shear-strength tests	Broaden engineering relevance
Mechanism	SEM/EDS, XRD and $CaCO_3$ content	Verify mineral precipitation and bonding
Durability	Wet–dry cycles, soaking and strength retention	Assess service-condition robustness
Environmental assessment	Cost, reagent use, ammonium handling, life-cycle impacts	Evaluate practical sustainability

VII. CONCLUSIONS

This study compared basalt fibre, Bacillus subtilis-based treatment and their combined application for soil stabilization using the UCS results reported in the research report. The principal conclusions are:

- Untreated soil had a reported average UCS of 0.68 kg/cm².

- Basalt fibre improved UCS to 1.12 kg/cm² at 0.80% fibre, corresponding to a reported 64.7% increase over untreated soil. This was the best result among the six fibre dosages tested.
- Bacillus subtilis treatment reached 1.45 kg/cm² at 6% dosage, corresponding to a reported 113.2% increase. Higher tested dosages of 7% and 8% produced lower average UCS values.
- The combined treatment of 0.80% basalt fibre and 6% Bacillus subtilis produced the highest reported UCS, 3.87 kg/cm², or a 469.1% improvement over untreated soil.
- The large combined-treatment response supports further investigation of hybrid stabilization, but does not by itself prove statistical synergy or confirm a specific microstructural mechanism.
- Before application to expansive soil, the soil classification inconsistency should be resolved and the treatment should be validated using replicated tests, volume-change measurements, durability evaluation and microstructural analysis.

VIII. FUTURE SCOPE

Future work could use a replicated factorial experimental design varying fibre content, bacterial dosage, reagent concentration and curing period. Testing should include free swell index, swell pressure, CBR, permeability, and wet–dry durability, alongside UCS. Soil classification should be confirmed before and after treatment. SEM/EDS and XRD, together with calcium-carbonate measurement, can examine whether the proposed mineral-bridging mechanism occurs. Longer-term work should compare the hybrid method with lime- and cement-treated controls and report cost and environmental burdens. Field trials should only follow after laboratory repeatability and practical handling of biological reagents and reaction by-products are demonstrated.

IX. STATISTICAL INTERPRETATION AND PROPOSED VALIDATION FRAMEWORK

The results show a clear descriptive ranking: the combined treatment produced the highest UCS, followed by bacterial treatment, basalt-fibre treatment and untreated soil. The magnitude of the combined-treatment response is substantial in the source dataset, but the present report does not provide specimen-level measurements, standard deviations or a formal factorial interaction test. The result should therefore be described as a strong observed improvement, not as statistically proven synergy. Replicate testing is needed to distinguish a reproducible treatment effect from specimen variability.

For a follow-up study, a factorial or response-surface design would allow the independent and interactive effects of fibre content, bacterial dosage and curing time to be estimated. At least three independently prepared specimens per condition should be considered as an initial design target; the final number should be justified by pilot-test variability and a power analysis. Specimen preparation order should be randomized, and testing should be performed using the

same loading rate, specimen geometry, moisture-conditioning procedure and curing environment.

Table 7. Suggested experimental design for validating the reported optimum

Factor / control	Suggested levels or procedure	Purpose
Basalt fibre content	0.0, 0.5, 0.7, 0.8, 0.9, 1.0% of dry soil	Resolve the strength peak near 0.8%
Bacterial suspension	0, 4, 5, 6, 7, 8% by the research definition	Confirm the observed optimum at 6%
Replicates	At least 3 independently prepared specimens per condition as a starting point	Estimate repeatability and uncertainty
Controls	Untreated soil; reagent-only control; bacteria-only; fibre-only; combined treatment	Separate biological, chemical and fibre effects
Reporting	Individual UCS values, mean, standard deviation and confidence interval	Support transparent comparison

For each treatment, report both absolute UCS and percentage change relative to the untreated control. The percentage improvement formula used in this paper is appropriate for descriptive comparison, but statistical inference should use the specimen-level observations rather than only treatment averages. A one-way analysis may compare treatment groups, while a factorial model can test whether the fibre-by-bacteria interaction is distinguishable from the separate main effects. If assumptions are not met, use suitable robust or non-parametric alternatives and report the chosen method explicitly.

Quality assurance should include calibration records for the loading frame, dimensional checks, soil moisture measurements at testing, documented mixing times and a consistent curing protocol. Raw data should be retained in a spreadsheet with specimen ID, soil batch, fibre mass, bacterial volume, reagent volume, curing age, dimensions, peak load and calculated UCS. This will allow another laboratory to reproduce the calculations and help identify outliers without selectively removing inconvenient results.

X. PRACTICAL IMPLEMENTATION, SUSTAINABILITY AND REPORTING RECOMMENDATIONS

The combined treatment may be relevant to preliminary ground-improvement research, but laboratory UCS improvement alone is insufficient to approve field use. Expansive-soil performance depends on moisture variation, swell pressure, seasonal wetting and drying, drainage, confinement and the thickness of the treated zone. Before field deployment, the soil identity and classification must be verified, especially because the source report describes the material as black cotton/expansive soil while also reporting a well-graded sand (SW) classification. These descriptions imply different engineering behaviour and should not be treated as interchangeable.

A staged validation pathway is recommended. First, confirm classification using the relevant index tests, including Atterberg limits and particle-size distribution. Second, repeat the UCS programme with replicates and controlled curing. Third, evaluate swell-related behaviour and bearing performance using tests suited to the intended application. Fourth, investigate durability under wet–dry cycles and leaching, and document any change in pH or soluble constituents associated with the bacterial and cementation reagents. Finally, conduct a small controlled field trial only after laboratory acceptance criteria have been defined.

Table 8. Additional tests recommended before practical application

Test / assessment	Question answered	Why it matters
Atterberg limits and classification	Is the material truly expansive clay / black cotton soil?	Resolves the classification inconsistency
Free swell / swell pressure	Does treatment reduce expansion under wetting?	Critical for expansive-soil applications
CBR or application-specific bearing test	Does the treated soil meet the intended pavement or foundation requirement?	Connects laboratory strength to design use
Wet–dry durability	Does strength persist through moisture cycling?	Assesses service-life robustness
Permeability and leachate / pH checks	Does treatment alter water movement or pore-water chemistry?	Supports environmental and drainage assessment
Microstructural / carbonate confirmation	Is mineral precipitation present and distributed?	Tests the proposed MICP mechanism rather than assuming it

The sustainability case should be evaluated alongside engineering performance. Basalt fibre and biological reagents have material, transport and processing requirements, and bacterial treatment should not automatically be described as impact-free. A future comparison with conventional stabilizers should account for material quantities, energy and water use, labour, curing time, durability, maintenance and end-of-life handling. The research expenditure should be presented only as the cost of the reported laboratory work, not as a validated unit cost for field construction.

XI. ACKNOWLEDGMENT

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XII. DATA AVAILABILITY

The experimental values presented in this paper are taken from the authors' laboratory research report. No additional experimental observations or simulated data were generated for this study.

XIII. REFERENCES

1. D. Mujah, M. A. Shahin, and L. Cheng, “State-of-the-Art Review of Bio-cementation by Microbially Induced Calcite Precipitation (MICP) for Soil Stabilization,” 2016.
2. T. Fu, A. C. Saracho, and S. K. Haigh, “Microbially induced carbonate precipitation (MICP) for soil strengthening: A comprehensive review,” 2023.
3. N. Fuadah, A. Djamaluddin, and A. Muhiddin, “Design Engineering Study of the Unconfined Compressive Strength Characteristics of Organic Soil Stabilized with Bacillus subtilis Bacterial,” Design Engineering, 2023, pp. 358–370.
4. T. Harianto, M. A. Walenna, and M. C. P. A. Torano, “Shear Strength Characteristics of Stabilized Sedimentary Soil with Bacillus subtilis Bacteria,” IOP Conference Series: Earth and Environmental Science, vol. 1117, no. 1, 012022, 2022, doi: 10.1088/1755-1315/1117/1/012022.
5. J. Liu, X. Li, G. Li, and J. Zhang, “Experimental Study on the Mechanical Behaviours of Aeolian Sand Treated by Microbially Induced Calcite Precipitation (MICP) and Basalt Fibre Reinforcement,” 2023.
6. R. P. Boruah, B. Mohanadhas, and J. Kamalanathan, “A comparative study of the shear strength of a poorly graded soil using Bacillus subtilis, vetiver fibre and bamboo fibre,” 2025.
7. Y. Shu et al., review of fibre-reinforced MICP for sustainable soil stabilization, 2024.
8. R. T. and N. T., “Stabilization of Clay Soil by MICP using Ureolytic / Non-Ureolytic Bacteria,” 2021.