A Machine Learning Driven Performance Prediction of MICP and EICP Treated Organic Soils

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Abstract: Stabilizing organic clay soils is pretty tough in geotechnical engineering because these soils are highly plastic, have low strength, and using common stabilizers like cement and lime often brings environmental concerns. This paper takes a close look at two new ways to stabilize soil using biological processes: Microbially Induced Calcite Precipitation (MICP) and Enzyme Induced Calcite Precipitation (EICP). This research looks closely at existing studies and experimental data to compare how well different sustainable options improve organic clay soil. The research uses supervised machine learning methods, like Random Forest, to build predictive models for soil stabilization. These models are based on key factors such as soil type, treatment concentration, curing time, and microstructural features. The results show that both MICP and EICP clearly improve the mechanical properties of soil. MICP can boost Unconfined Compressive Strength (UCS) by anywhere from 10% to 66% depending on the soil type, while EICP helps bring down the liquid limit from 79% to 58.It goes up by 8% and increases the plastic limit from 30% to 47.8%Putting biochar into MICP (MICP-BIN) really changed things, increasing shear strength by 389.It was 5% higher than soil that hadn't been treated. Using SEM, EDX, and XRD to look at the microstructure, it was clear that calcium carbonate precipitation was the main way the soil got stabilized. The crystals form and clump the soil particles together, which reduces the spaces between them. The machine learning models were able to predict pretty accurately how effective the treatments would be. Looking at which features mattered most, it turned out that calcium carbonate content, curing time, and the soil's initial plasticity were the key factors. This study offers a basic framework for choosing and improving bio-cementation methods based on data to stabilize cohesive soil. It focuses on a sustainable way to reduce carbon emissions while improving geotechnical performance in infrastructure projects.

Keywords: *MICP, EICP, Organic Clay Soil, Bio-Cementation, Soil Stabilization, Machine Learning, Calcium Carbonate Precipitation, Sustainable Geotechnics.*

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I. INTRODUCTION

Subgrade soil's insufficient stiffness and strength, which may lead to challenges including uneven settlement (Luan et al., 2023). Besides this, ground water contamination, carbon emission, contamination of carcinogens like hexavalent chrome are also seen in the manufacturing process of some conventional stabilizers like cement, lime etc. (Tavala & Tabaroei, 2025) (Lee & Kim, 2020). This carbon emission generates about 1 to 1.2 ton carbon-di-oxide, nitrogen and sulfer oxides (Nox, SOx) which is a serious threat for human body (Islam et al., 2020) (Almajed et al., 2020).The natural residual clay soil shows a high plasticity index (PI) of 49% which exceeds the maximum plasticity index value of 30% for compacted clay liner rendering it unsuitable for civil engineering purposes (Zango et al., n.d.). There can be seen inadequate amount of nucleation cites even if we use EICP (Yuan et al., 2020). Heavy rainfall harms the plant development on the slope surface and affects the bearing capacity of the slope on the side of railroads, highway and other engineering structures because topsoil is poor in water stability, strength and erosion resistance (Liu et al., 2011).

Biopolymer is lately being used in some development areas to stabilize the soil.

Nanomaterials and biopolymer produced from xanthan gum enhancing the strength and durability of clayey soil

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(Tavala & Tabaroei, 2025). In terms of generating carcinogens and carbon emissions, EICP don't have such type of hazardous consequences. Furthermore, it doesn't negatively impact the environment (Lee & Kim, 2020). Some research indicates that the EICP and UCS of soil treated with fast-hardening Portland cement are quite similar (Lee & Kim, 2020). For treating large ground volume, chemical grouting method is not applicable because the effective treatment distance of chemical grouting is only 1-2m from the injection point. There is a need for alternative soil improvement methods that are more sustainable, environmentally friendly, and cost-effective which can be solved by a promising technique MICP (Cheng & Shahin, n.d.). Comparing with tradition stabilizer like 10% OPC, EICP can achieve impressive mechanical properties with minimal treatment cycles (Almajed et al., 2020). Additives like skim milk powder applying on EICP can increase the UCS of soil approximately 10 times (Yuan et al., 2020). Considering its resource availability and environmental friendliness, MICP has been widely used in soil consolidation, seepage control, anti-liquefaction, slope protection, coastal sedimentation inhibition, fugitive dust prevention, underground cultural relic repair, metal stability in contaminated soil, etc. (Yuan et al., 2020). The reduced thickness of the diffused double layer caused by the replacement of hydrogen ions with calcium from the precipitation of calcium carbonate accounts for the decline in LL, PI, and LS (Zango et al., n.d.).

Fly ash, cement, lime, granulated blast furnace slag, granite-cutting waste (G-CW) and cemented slurry waste (CSW) are just a few of the chemical and physical techniques used for a long time to improve clayey soils, which decreases soil's plasticity index and amplifies its UCS (Islam et al., 2020) (Tavala & Tabaroei, 2025). MICP demonstrated promise in lowering seismic-induced liquefaction, increasing unconfined compressive and shear strength, and decreasing permeability and compressibility (Tavala & Tabaroei, 2025). Prior research on the biotreatment of clays, which include bentonite, marine clay, and kaolin, has shown significant increases in strength, with increases of 400% for marine clay and 150% for kaolin. (Tavala & Tabaroei, 2025). In addition to non-traditional stabilizers have also been studied, including a variety of chemical agents like salts, ionic compounds, enzymes, lignosulfonates, polymers, and resins (Luan et al., 2023). Various mechanical approaches have been applied to protect slope surfaces, including geotextiles, wire mesh, cable nets, and various membrane structures (Liu et al., 2011). Regarding a poor soil to be used, it must either be strengthened or replaced with a more appropriate deposit. In a low concentration the EICP has a little effect on the soil (even if the curing time was 28 days). But in high concentration of the solution, it has an exponential rise in strength of soil (Lee & Kim, 2020). Applying additives, like organic materials, in EICP increases soil strength. Furthermore, the strengthened soil progressively gains strength. The organic debris improves the size and structure of the precipitated calcium carbonate crystals, indicating nucleation sites and templates.(Yuan et al., 2020)

The stabilisation of clayey soils, which are defined by limited permeability and complex surface chemistry, is largely understudied because coarse-grained sands are strongly preferred in the literature. A thorough understanding of MICP and EICP's relative efficiency is further hampered by the conspicuous absence of systematic comparison between them in identical settings. This is made worse by the absence of integrated data interpretation, which rarely integrates multi-scale microstructural analysis with mechanical performance. Lastly, there is still a lot of unrealised potential in AI and machine learning, especially when it comes to model reliability under the constrained data conditions typical of geotechnical testing. To create reliable, data-driven techniques for applying bio-cementation to cohesive soil profiles, these gaps must be filled.

In this work, a simplified bio-stabilization paradigm is presented, showing how small-scale experimental data can be used to predict immediate results. The study offers an adaptable approach to expand MICP and EICP applications towards larger, real-world geotechnical projects through quick, data-driven evaluation by creating this fundamental data input model.

II. METHODOLOGY

In this research work, a predictive model is developed with the help of supervised machine learning techniques, which can predict soil stabilization solutions for different conditions. The main reason for choosing ensemble learning models over traditional linear models is that geotechnical information is non-linear in nature. Here, we will discuss about Random Forest.

There is a technique of ensemble learning that is known as the Random Forest that develops many decision trees during the training process (Reis et al., 2019). In contrast to a decision tree model that easily suffers from overfitting problems, the RF algorithm is based on the "bagging" concept of Bootstrap Aggregating to build a reliable model.

The mechanism behind the Random Forest algorithm has two major sources of randomness or unpredictability. First, each individual tree in the forest is trained on a random sample of the training dataset with replacement, which is referred to as bootstrapping. Second, each node in the trees selects a random subset of the input features to find the optimum splitting point (Reis et al., 2019). This ensures that the model performs optimally on novel, unseen input datasets.#

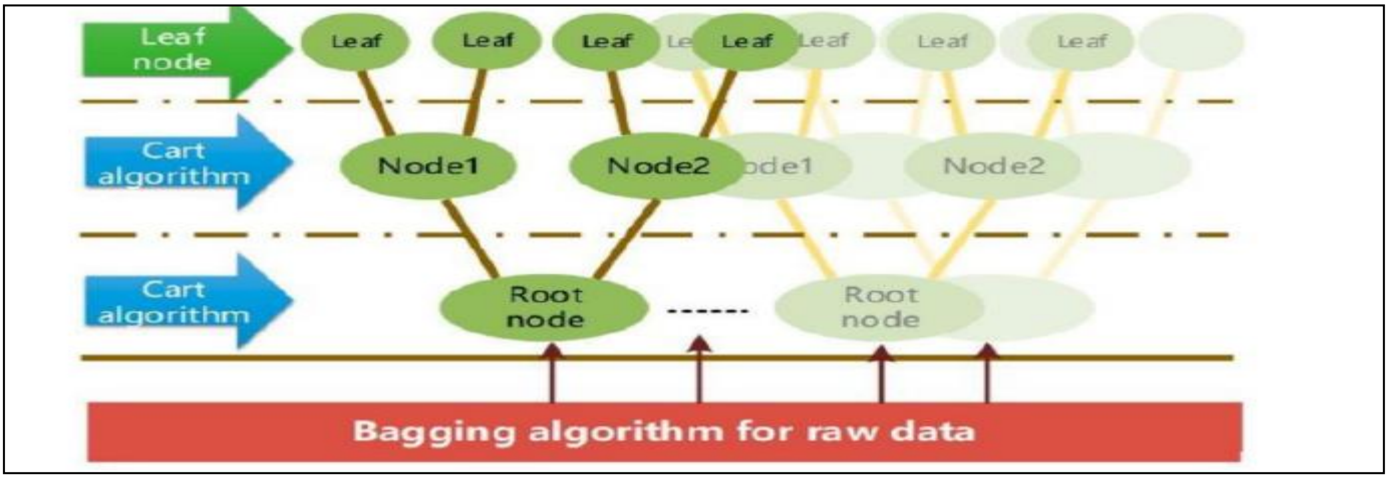

Fig 1 Schematic Diagram of Random Forest Model (View of Random Forest Algorithm Overview, n.d.)

III. MECHANISM

Microbially induced calcite precipitation (MICP) as a set of biogeochemical processes in which microorganisms modify the chemical environment for the purpose of facilitate the precipitation of calcium carbonate ($CaCO_3$). (Das & Das Ringky, 2026) Considering many procedures, urea hydrolysis is the most popular for its high reaction efficiency, controlled kinetics, and compatibility with ureolytic bacteria such as Bacillus sp. and Sporosarcina pasteurii. (Das & Das Ringky, 2026) The hydrolysis of urea, producing carbonate (CO_3) and ammonium (NH_4^+) ions, is catalyzed by the enzyme urease. (Das & Das Ringky, 2026) $CaCO_3$ goes supersaturated in the presence of Ca^{2+} ions due to the increased pH and carbonate concentration. (Das & Das Ringky, 2026)

The hydrolysis of the compound urea, which produces carbonate (CO_3) and ammonium (NH_4^+) ions, is catalyzed by the enzyme urease. (Das & Das Ringky, 2026) The compound calcium carbonate becomes supersaturated when calcium ions (Ca^{2+}) are present because of elevated pH and carbonate concentration. (Das & Das Ringky, 2026) The negatively charged bacterial cell walls absorb calcium, which in turn act as a nuclei for crystal development and crystal growth of calcite. (Das & Das Ringky, 2026) The growing crystals then gradually attach to nearby soil particles, increasing the interparticle interaction. (Das & Das Ringky, 2026)

Apart from ureolysis, other microbial processes like photosynthesis, sulfate reduction, and denitrification also affect MICP. (Das & Das Ringky, 2026) In denitrification-based MICP, bacteria use nitrate as the final electron acceptor. (Das & Das Ringky, 2026) This produces carbonate species that combine with Ca^{2+} to form $CaCO_3$. (Das & Das Ringky, 2026) Similarly, sulfate-reducing bacteria convert sulfate (SO_4^{2-}) into sulfide, which produces bicarbonate that precipitates as calcium carbonate. (Das & Das Ringky, 2026) The type and shape of the resulting crystals, such as calcite, aragonite, or vaterite, depend on the bacterial strain, calcium supply, and factors like pH, temperature, and nutrient concentration. (Das & Das Ringky, 2026) These biogenic $CaCO_3$ deposits build up inside soil pores, reducing porosity, increasing stiffness, and creating a cemented matrix that significantly improves the mechanical and durability properties of low-cohesive soils. (Das & Das Ringky, 2026)

Table 1 MICP Mechanism Process

Microbial Process	Chemical Reactions	Reference
Urea Hydrolysis	$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{2-}$ $Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \downarrow$	
Denitrification	$1/2.6\ (C_2H_3O_2)_2 + 1.6/2.6\ Ca(NO_3)_2 \rightarrow CaCO_3$ $+ 1.6/2.6\ N_2 + 1.4/2.6\ CO_2$	(Das & Das Ringky, 2026)
Sulphate Reduction	$1/3\ (C_2H_3O_2)_2 + 2/3\ CaSO_4 \rightarrow CaCO_3$ $+ 1/3\ CO_2 + 2/3\ H_2O + 2/3\ H_2S$	

Enzyme Induced Calcite Precipitation (EICP) EICP is a bio-inspired soil treatment method that capitalizes on the catalytic function of the urease enzyme to create calcium carbonate ($CaCO_3$). (Das & Das Ringky, 2026) The free urease enzymes are indirect catalytic products, usually isolated from plant sources such as water melon seed, soyabean and jack bean (Canavalia ensiformis) for example, in comparison to MICP which is reliant on the metabolic activity of bacterial cells. (Das & Das Ringky, 2026) One possible benefit of this approach is the possibility of increased groutabilty in finer-grained soils as well as the potential to have higher treatment rates and better control over reaction conditions since biological viability does not need to be maintained. (Das & Das Ringky, 2026) In the course of EICP treatment, urease causes the hydrolysis of urea in aqueous solution, emanating carbonate and ammonium ions, as well as an increment in alkalinity. (Das & Das Ringky, 2026)

The high PH facilitate the transformation of dissolved carbon species into carbonate ions, which then reform with calcium ions from a soluble calcium to yield calcium carbonate. (Das & Das Ringky, 2026) The resultant $CaCO_3$ crystals help still further to consolidate, stiffen and toughen the soil by tying two adjacent soil particle contacts together. (Das & Das Ringky, 2026) Because EICP uses soluble, nanoscale enzymes instead of large bacterial cells, the treatment solution

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can penetrate any small pores that might be present in the soil matrix much more uniformly. (Das & Das Ringky, 2026) However, the absence of cell walls eliminates the natural sites that help crystals form in MICP. (Das & Das Ringky, 2026) Various additives such as non-fat milk, biopolymers, or calcite seed particles, can improve enzyme stability and ensure the production of $CaCO_3$ crystals. (Das & Das Ringky, 2026)

In its overall assessment, it was evident that when EICP is compared to traditional binders, the EICP method provides a regulated approach whereby bio-cementation is achieved, a process which is environmentally safe, produces less carbon emissions, yet retains its mechanical integrity as well as versatility in ground improvement applications. (Das & Das Ringky, 2026)

Table 2 EICP Mechanism Process

Microbial Process	Chemical Reactions	Reference
Urea Hydrolysis	$CO(NH_2)_2 + H_2O$ --(Urease Enzyme)→ $NH_3 + CO(NH_2)OH$ $CO(NH_2)_2 + OH^- \rightarrow NH_3 + HCO_3^-$ $NH_3 + HCO_3^- \rightarrow NH_4^+ + CO_3^{2-}$ $CaCl_2 + H_2O \rightarrow Ca^{2+} + 2Cl^-$ $Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3$	(Das & Das Ringky, 2026)

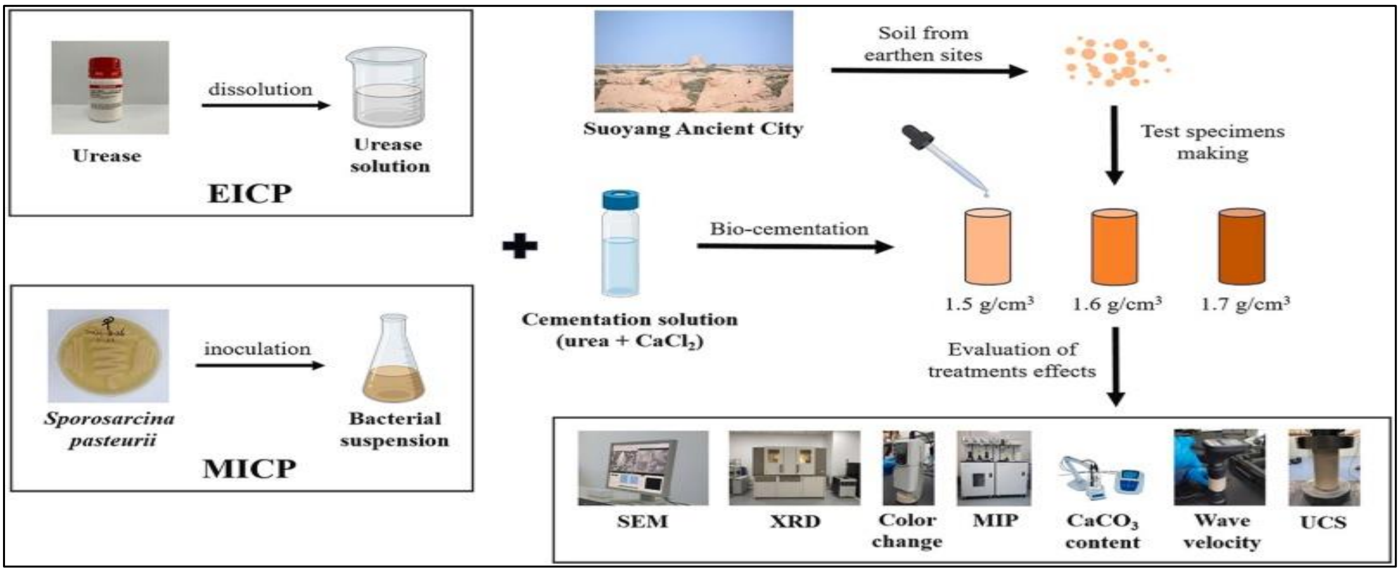

Fig 4 Procedure of Doing the Tests (Li et al., 2024)

IV. DATA COLLECTION

Table 3 Previous Studies on Bio-stimulated Soil Stabilization

SI NO	Authors	Bio Stabilized Element	Type of Materials	Strength test			Micro-structural Analysis			Atterberg limits
				UCS	STS	Flexure	SEM	EDX	XRD	
1	(Islam et al., 2020)	MICP(bio-stimulation)	natural soil	✓	✗	✗	✓	✓	✗	✓
2	(Zango et al., n.d.)	EICP	residual clay soil	✓	✗	✗	✓	✓	✓	✓
3	(Liu et al., 2011)	STW(organic polymer soil stabilizer)	topsoil of clayey	✓	✗	✗	✓	✓	✓	✓
4	(Luan et al., 2023)	liquid vinyl acetate-ethylene polymer	clay soil	✓	✗	✗	✓	✓	✓	✗
5	(Cheng & Shahin, n.d.)	MICP	Kaolin Clay	✓	✗	✗	✓	✗	✗	✗
6	(Wang et al., 2025)	MICP-BIN	Clay soil	✗	✗	✗	✓	✗	✗	✓

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Table 4 Comparative Findings of Bio-Stimulated Organic Clay Soil Stabilization Techniques

SI NO	Authors	Bio Stabilized Element	Stabilization Technique	Primary Materials	Mechanism of Improvement	Typical Strength Gains (UCS/Flexure)	Microstructural & Key Observation	Key Findings
1	(Islam et al., 2020)	MICP(bio-stimulation)	Indigenous bacteria to precipitate calcium carbonate	Natural soil	Calcite crystals bind soil particles, increasing strength and reducing swelling, while EPS contributes to changes in plasticity and may create a barrier against water molecules, further reducing swelling potential.	Natural Soils (UCS-a - re-compacted): GF soil: 66% increase BR soil: 10% increase DC soil: 51% increase MS soil: 6% reduction	Microstructural analysis using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray (EDX) confirmed the presence of calcite in biostimulated soils, visually demonstrating that calcite bridges soil grains	1.Biostimulated MICP is a promising method for treating problematic clayey soils 2.For natural soils (MS, GF, BR, DC), LL increased by 25%, 9%, 5%, and 7% respectively, and PI increased by 43%, 34%, 75%, and 47% respectively 3.Natural soils (GF, BR, DC) showed UCS-α increases of 66%, 10%, and 51%, and UCS-β increases of 24%, 32%, and 22%
2	(Zango et al., n.d.)	EICP	calcium carbonate ($CaCO_3$)	residual clay soil	Improving the plasticity and swelling behavior of residual clay soil was presented		1.XRD analysis was conducted on both untreated and EICP-treated residual soil to assess changes in mineral content 2.Scanning Electron Microscope (SEM) and Energy Dispersive X-ray (EDX) analyses confirmed the formation of calcium carbonate in the EICP-treated soil	1.EICP treatment improved the plasticity and swelling behavior of residual clay soil 2.The liquid limit (LL), plasticity index (PI), and linear shrinkage limit (LS) decreased with increasing concentration of the cementation solution and calcium carbonate content 3.The plastic limit (PL) increased .

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								4.Liquid limit decreased from 79% to 58.8% Plastic limit increased from 30% to 47.8%
3	(Liu et al., 2011)	STW(organic polymer soil stabilizer)	Acetic-ethylene-ester	topsoil of clayey	Improves soil properties through a multi-faceted mechanism that includes filling voids, engaging in chemical reactions, and forming an elastic and viscous membrane structure around soil aggregates	The maximum value of the strength as 241 KPa is observed at 30% STW concentration with 72-hour of curing time	1.Scanning electron microscopy (SEM) analysis was used to discuss the stabilization mechanisms of STW in clayey soil 2.SEM images revealed interactions between the STW soil stabilizer and the soil, which significantly alter the soil fabric and improve strength, water stability, and erosion resistance	1.Unconfined compressive strength increased with curing time, with the most significant changes occurring within the first 24 hours 2.Increasing STW concentration from 5% to 30% gradually improved strength for specimens cured for 24, 48, and 72 hours, but strength remained almost unchanged for uncured specimens 3.Water stability index (K-value) increased with STW concentration: from 90.8% at 5% STW to 100% at 30% STW, compared to 28% for untreated aggregates
4	(Luan et al., 2023)	liquid vinyl acetate-ethylene polymer	liquid polymer soil stabilizer composed of vinyl acetate-ethylene copolymer	Clay soil	primarily involves a pore-filling effect, the formation of physicochemical bonds, and surface wrapping of clay particles by the polymer	3 days curing: 0.71 MPa 7 days curing: 0.91 MPa 14 days curing: 1.10 MPa 21 days curing: 1.24 Mpa	Higher stabilizer content and longer curing times result in a dense agglomeration structure and a homogeneous skeleton structure	1.Rapid strength growth occurs before 14 days, reaching approximately 89% of the final strength, with a decreasing growth rate

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								thereafter. Strength is largely stable between 21 and 28 days 2.Involves pore-filling, physicochemical bonds, and surface wrapping of clay particles by the polymer
5	(Cheng & Shahin, n.d.)	MICP	**Calcium Carbonate ($CaCO_3$) **Urease Active Strain: MCP-11 (Bacillus sphaericus. DSM 23526, Germany)	Kaolin Clay	1. MICP utilizes ureolytic bacteria to form calcium carbonate precipitates throughout the soil matrix, which increases soil strength and stiffness 2.The calcite formation binds soil particles together, leading to enhanced soil strength and stiffness	Maximum UCS values for soils with 10% and 20% clay samples were about 280 kPa and 400 kPa, respectively, after 21 days of curing. These values are about 2.5 and 1.6 times higher than benchmark soil samples (bacteria-free samples submerged in cementation solution)	Produced relatively small crystals (about 2-5 µm in diameter) that fully covered the surface of sand grains. Most of these crystals did not significantly contribute to strength development	1.Applicable for treating sand columns with less than 5% clay content, showing an exponential relationship between UCS and calcite content 2.Can produce high strength in bio-cemented soil samples with up to 5% clay content 3.Effective for soils with up to 20% clay content, increasing UCS by up to 70% after 21 days, but with limited cementation depth
6	(Wang et al., 2025)	MICP-BIN	corn stover biochar and the S. pasteurii (CGMCC 1.3687) strain	Clay soil	1.The shear strength of treated soil increased by 22.4%, $CaCO_3$ content by 30%, and shear strength improved by 389.5% compared to remoulded soil 2.The internal friction angle increased by		macroscopic observations revealed that a substantial amount of calcium carbonate crystals formed on the surface of the clay soil reinforced using the MICP-BIN method.	1.The MICP-BIN method significantly enhances the shear strength, internal friction angle, and cohesion of clay soil. 2.The method increases the calcium carbonate content in the soil

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					22.7% and 405.2%, while cohesion improved by 9.4% and 344.3%			3.Both MICP treatment and biochar incorporation increase suction in clayey soil

V. RESULT AND DISCUSSION

The distribution of experimental indicators, presented in Figure 2, demonstrates that strength tests and microstructural analyses constitute the dominant evaluation approaches in MICP/EICP-treated expansive soil studies. The prevalence of these parameters reflects the central role of calcite precipitation in governing mechanical performance enhancement. The comparatively lower frequency of swell and plasticity-based tests suggests that volumetric stability, although important, is less consistently quantified across studies.

The inter-parameter relationships illustrated in Figure 3 reveal meaningful correlations between strength gains and microstructural observations. The moderate positive association between mechanical improvement and microstructural descriptors supports the mechanistic understanding that $CaCO_3$ precipitation enhances particle bonding and densifies soil fabric. These findings align with established bio-cementation theory, wherein mineral bridging reduces pore connectivity and increases load-bearing capacity.

Model performance is evaluated through the normalized confusion matrix in Figure 4, which indicates that the Random Forest classifier reliably identified the dominant strength-test category, achieving an overall accuracy of 75%. While minority-class prediction was limited due to dataset imbalance, the model demonstrates strong discriminative capability for the primary stabilization indicator. This suggests that ensemble learning effectively captures dominant performance trends from compiled experimental data.

Further validation is provided by the numeric correlation structure in Figure 5, which confirms interdependency among strength gains, microstructural characteristics, and reported findings. The consistency between statistical correlations and mechanistic expectations reinforces the robustness of the machine learning framework.

Collectively, the figures demonstrate that the Random Forest model not only achieves satisfactory predictive performance but also reflects physically meaningful relationships within bio-stabilized expansive soils. This convergence between data-driven outcomes and established geotechnical mechanisms strengthens the credibility of the proposed ML-based evaluation framework.

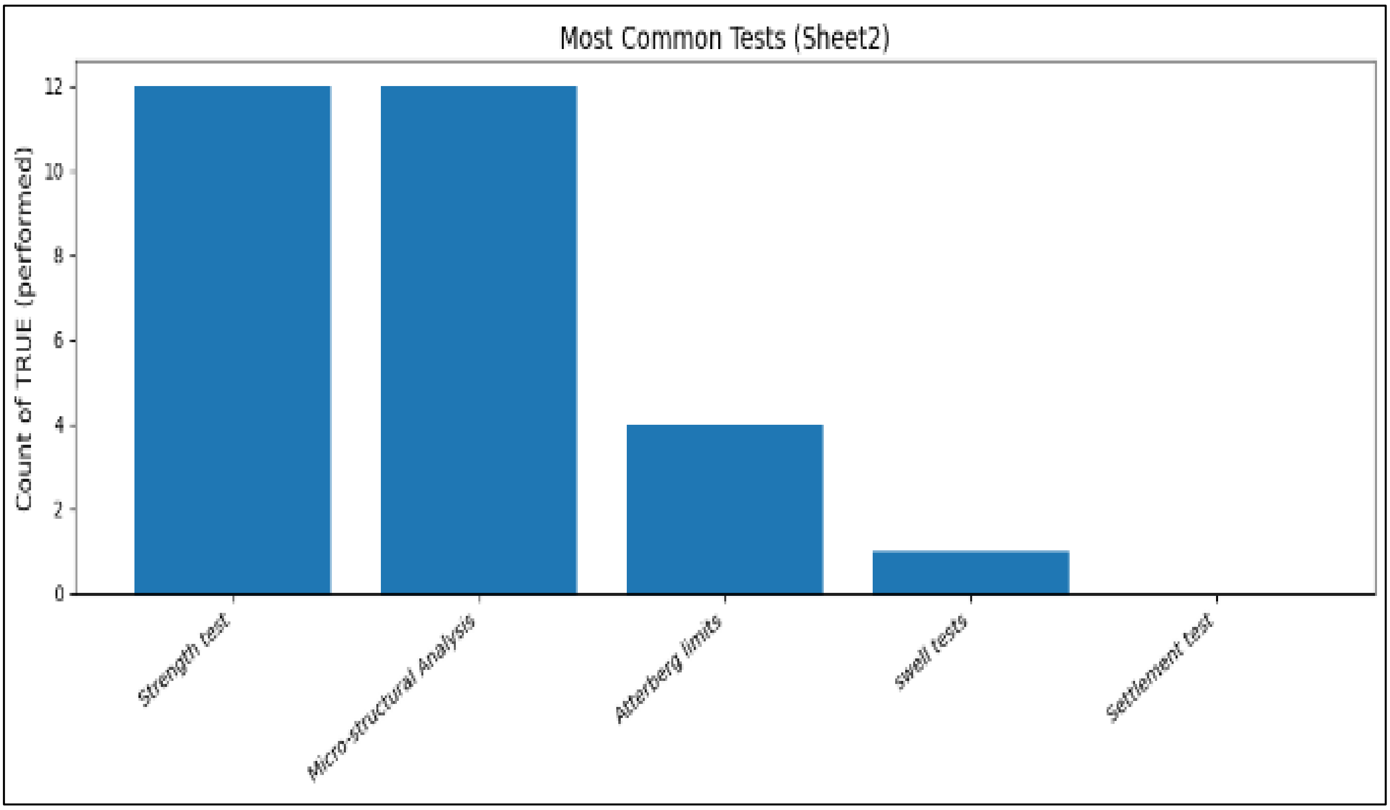

Fig 2 Classification Test Frequency

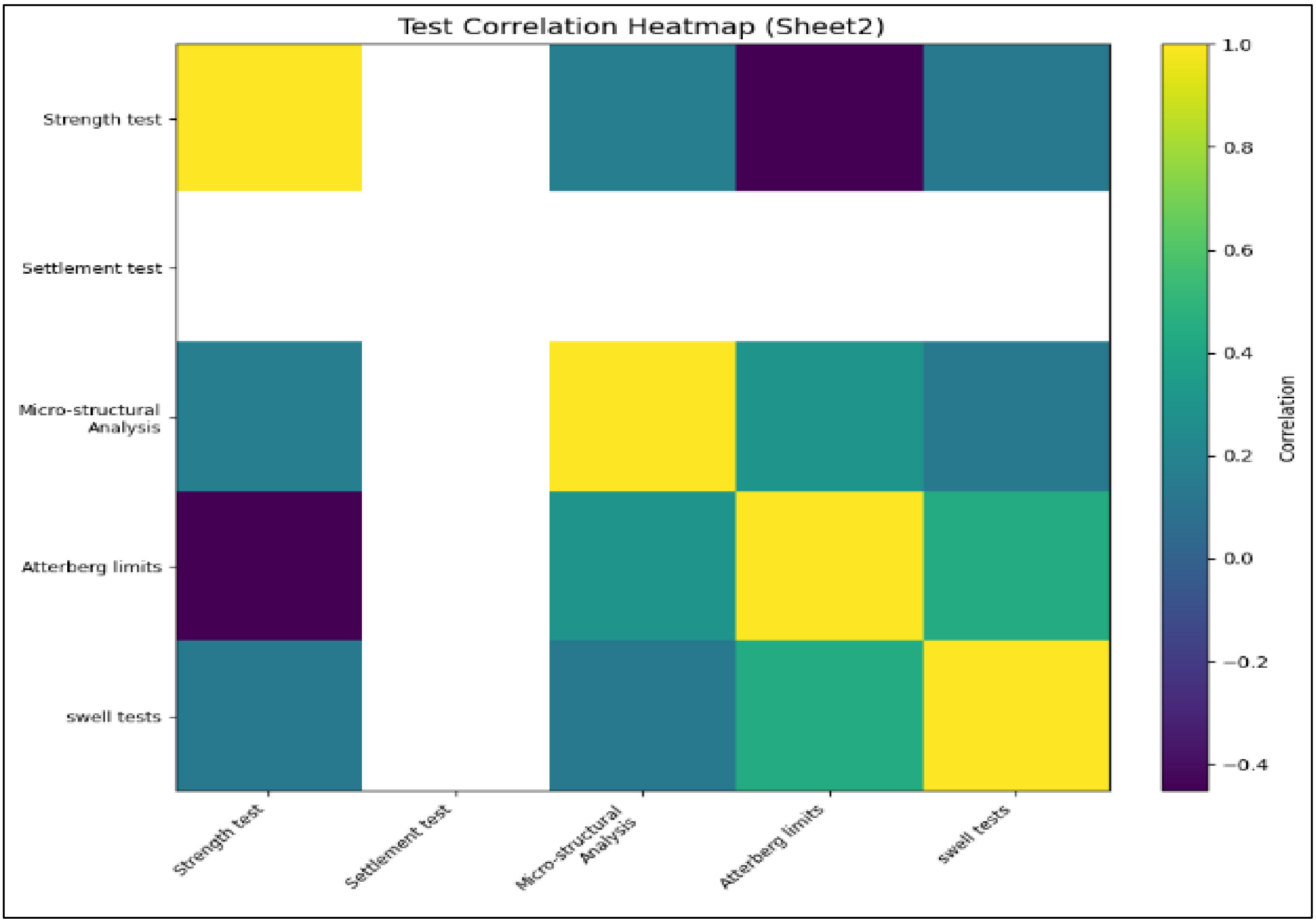

Fig 3 Test Correlation Heatmap

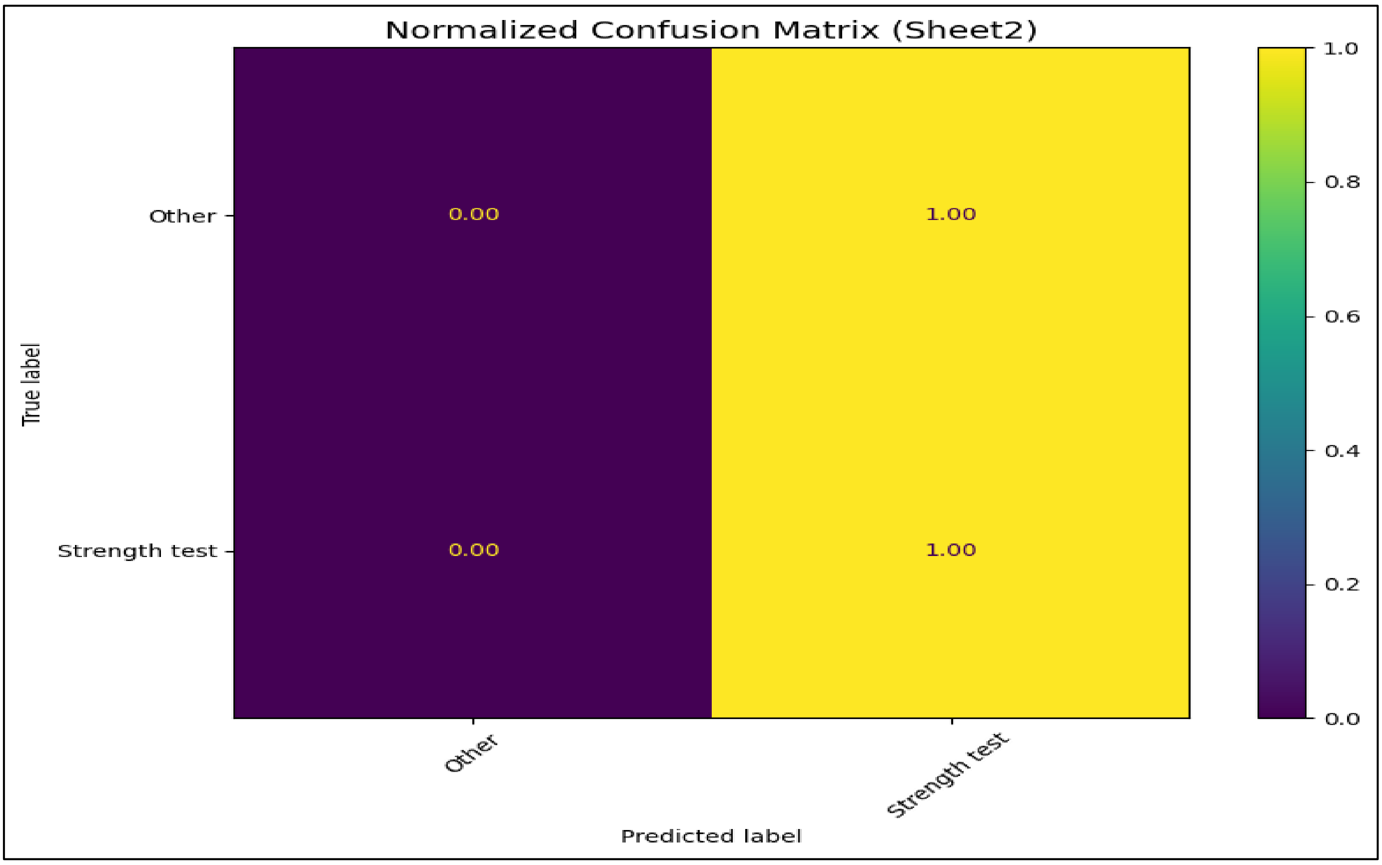

Fig 4 Normalized Confusion Matrix

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VI. CONCLUSION

This research shows that MICP and EICP provide a practical and eco-friendly way to stabilize organic clay soils, serving as a good alternative to traditional binders that have a large carbon footprint. Improvement basically happens because $CaCO_3$ crystals form and stick to soil particles, creating tiny mineral bridges. These bridges tighten up the soil and help it hold more weight. Data shows that bio-stabilization can boost mechanical strength a lot—sometimes the UCS increases by up to ten times when certain EICP additives are used. It also helps with volumetric stability by cutting down the liquid limit and plasticity index quite a bit. Using the Random Forest machine learning model worked well, reaching about 75% accuracy in handling the complex, non-linear patterns found in geotechnical datasets. This study shows that machine learning can reliably predict bio-cementation results by checking that statistical correlations match what we already know about how the process works. In the end, combining data-driven modeling with biochemical analysis offers a straightforward way to apply sustainable bio-stabilization methods in real-world geotechnical engineering projects.

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➢ *Author Contribution*

Author 1 was primarily involved in manuscript writing, revisions, and preparation of the final corrected version of the manuscript and Author-1* contributed to the research methodology, idea generation, machine learning modeling, data analysis, manuscript writing, editing, preparation of the final draft, and overall supervision of the study.

REFERENCES

[1]. Almajed, A., Abbas, H., Arab, M., Alsabhan, A., Hamid, W., & Al-Salloum, Y. (2020). Enzyme-Induced Carbonate Precipitation (EICP)-Based methods for ecofriendly stabilization of different types of natural sands. Journal of Cleaner Production, 274. https://doi.org/10.1016/j.jclepro.2020.122627

[2]. Cheng, L., & Shahin, M. A. (n.d.). Assessment of different treatment methods by microbial-induced calcite precipitation for clayey soil improvement.

[3]. Das, P., & Das Ringky, S. (2026). FROM CEMENT TO MICROBES: A COMPARATIVE REVIEW OF CONVENTIONAL AND BIO-STIMULATED SOIL STABILIZATION TECHNIQUES. In KUET.

[4]. Islam, M. T., Chittoori, B. C. S., & Burbank, M. (2020). Evaluating the Applicability of Biostimulated Calcium Carbonate Precipitation to Stabilize Clayey Soils. Journal of Materials in Civil Engineering, 32(3). https://doi.org/10.1061/(asce)mt.1943-5533.0003036

[5]. Lee, S., & Kim, J. (2020). An Experimental Study on Enzymatic-Induced Carbonate Precipitation Using Yellow Soybeans for Soil Stabilization. KSCE Journal of Civil Engineering, 24(7), 2026–2037. https://doi.org/10.1007/s12205-020-1659-9

[6]. Li, J., Zhu, F., Wu, F., Chen, Y., Richards, J., Li, T., Li, P., Shang, D., Yu, J., Viles, H., & Guo, Q. (2024). Impact of soil density on biomineralization using EICP and MICP techniques for earthen sites consolidation. Journal of Environmental Management, 363, 121410. https://doi.org/10.1016/J.JENVMAN.2024.121410

[7]. Liu, J., Shi, B., Jiang, H., Huang, H., Wang, G., & Kamai, T. (2011). Research on the stabilization treatment of clay slope topsoil by organic polymer soil stabilizer. Engineering Geology, 117(1–2), 114–120. https://doi.org/10.1016/j.enggeo.2010.10.011

[8]. Luan, Y., Ma, X., Ma, Y., Liu, X., Jiang, S., & Zhang, J. (2023). Research on strength improvement and stabilization mechanism of organic polymer stabilizer for clay soil of subgrade. Case Studies in Construction Materials, 19. https://doi.org/10.1016/j.cscm.2023.e02397

[9]. Reis, I., Baron, D., & Shahaf, S. (2019). Probabilistic Random Forest: A Machine Learning Algorithm for Noisy Data Sets. The Astronomical Journal, 157(1), 16. https://doi.org/10.3847/1538-3881/aaf101

[10]. Tavala, A. N., & Tabaroei, A. (2025). Sustainable clay soil stabilization using constructions waste: Mechanical behavior, engineering parameters and microstructural analysis. Results in Engineering, 27. https://doi.org/10.1016/j.rineng.2025.106247

[11]. View of Random Forest Algorithm Overview. (n.d.).

[12]. Wang, Y., Li, S., Huang, L., Garg, A., & Bogireddy, C. (2025). Enhancing clay soil reinforcement using MICP-BIN method with biochar-induced nucleation. Environmental Geotechnics, 12(4), 327–340. https://doi.org/10.1680/jenge.23.00082

[13]. Yuan, H., Ren, G., Liu, K., Zheng, W., & Zhao, Z. (2020). Experimental study of EICP combined with organic materials for silt improvement in the yellow river flood area. Applied Sciences (Switzerland), 10(21), 1–19. https://doi.org/10.3390/app10217678

[14]. Zango, M. U., Kassim, K. A., Muhammed, A. S., Ahmad, K., Umar, M., & Makinda, J. (n.d.). Improvement in Plasticity Behavior of Residual Clay Soil via Bio-cementation Technique. Current Applied Science and Technology, 21(3). https://doi.org/10.14456/cast.2021.42