

# A Machine Learning Framework for Evaluating Mechanical Performance of MICP and EICP Treated Expansive Soils

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**Abstract:** Two most popular bio-stimulated methods of soil stabilization are Microbial Induced Calcium Carbonate Precipitation (MICP) and Enzyme Induced Calcium Carbonate Precipitation (EICP). These methods are more eco-friendly compared to conventional methods of stabilization of expansive soils using cement and lime. No models are available to combine different experimental results. This paper proposes the application of machine learning to evaluate and predict the behavior of MICP and EICP treated soils by combining different experimental results. We reviewed more than twenty papers to combine the results. Machine Learning models are built using properties of MICP and EICP treated soils. It concerns most important geotechnical, physicochemical, calcite content, curing time and admixtures such as Unconfined Compressive Strength (UCS), Splitting Tensile Strength (STS). We trained the model by using 20 samples based on the Random Forest (RF) algorithm. Finally, the machine learning model was evaluated with two techniques: coefficient of determination, RMSE and MAE for regression-based and classification models respectively. The RF model achieved 75% predicting accuracy. It also had a high precision (0.75) and recall (1.00) regarding the strength improvement based on calcite content, confirming that the strengthening occurred via calcite deposition. The fact that UCS, CaCO<sub>3</sub> content and microstructural properties (SEM/XRD) correlate very highly with each other was confirmed by correlation analysis. These results confirm the reliability of ensemble learning for stabilization trend identification and a scalable data-driven decision support system for soil engineering.

**Keywords:** MICP, EICP, Random Forest, Expansive Soil, UCS, STS, pH, Calcite Content, Curing Duration.

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## I. INTRODUCTION

Expansive soils present considerable challenges since they are very susceptible to encountering significant variations in volume in reaction to variations in the level of moisture. Due to low rainfall, these soils experience shrinkage or a decrease in volume due to water evaporation, resulting in increased hardness. Moreover, absorption of water results into increase in volume of soil or swell. When behavior of soils changes, it promotes severe land degradation. Thus, it is very important to stabilize expansive soil changes. [9] [12]

Expansive soil expansion leads to a potential risk to civil infrastructures constructed on expansive soil, a predominant cause to increasingly utilization of the soil improvement methods to treat soils for the sake of construction convenience [2][6]. Conventional stabilization techniques such as cement and lime, while effective, are associated with high carbon emissions, long-term durability concerns, adverse environmental effects, motivating the search for sustainable alternatives [4].

Recent advancements in soil treatment procedure have heavily focused on Bio-stimulated and Enzyme induced carbonate precipitation, primarily Microbial Induced Calcium Carbonate Precipitation (MICP) and Enzyme-Induced Calcium Carbonate Precipitation (EICP), either applied alone or both in addition to some additives e.g. fly ash, jute fibers [12], soyabean extracts [14], ureolytic bacteria (e.g. *Sporosarcina pasteurii*, *Bacillus magoterium*, *Bacillus cereus*), cementation reagents to induce calcite precipitation within expansive soil matrices [9] [15]. Several studies reported the integration of supplementary mineral admixtures, such as Fly ash (Class F), lime and eggshell powder (ESP) [20], to enhance nucleation efficiency, pore filling, creep damage control and supplementary pozzolanic reactions [13][17]. Natural fiber, such as jute fiber, have also been incorporated to improve mechanical interlocking and crack resistance while working with bio-cementation mechanism [12]. The precipitated calcite analysis – often rhombohedral or cubic- bridge adjacent soil particles, coat clay surfaces, fill macro pores, and reduce pore connectivity. It, therefore, changes the soil fabric from a dispersed to a dense, cemented, and flocculated structure [5]. The microstructural alteration has been consistently evidenced by SEM, XRD, EDX, and FTIR tests through identification of increased calcite content, reduced porosity/voids, reduced Free Swelling Index, and partial mineralogical alteration from high swelling montmorillonite to lower swelling phase [8][21][19]. The Engineering performances that have been reported involve significant enhancement in Unconfined Compressive Strength - often in the range from 1.8 times to 4.7 times of that of untreated soil - with noticeable corresponding enhancements in cohesion, friction angle, California Bearing Ratio, and other stiffness parameters [10]. Simultaneously, most studies reported significant reductions of free swell index, swelling pressure, permeability, and creep deformation [4] while the swelling suppression efficiency surpassed 80-99% for an optimized treatment condition. Durability performance from wetting-drying cycles, resistance to moisture fluctuation, and SWCC analyses showed that an increase in resistance to volume instability would be expected, along with an improved long-term performance especially when bio-cementation was combined with fillers and mineral additives [3] [14].

Though bio-stimulation based soil stabilization using MICP and EICP has been studied extensively through lab tests like UCS, Atterberg limits, pH, and Micro-Structural analysis (SEM, EDX, XRD, FTIR), most research is typically remote or experimental, thus having limited broader applicability. The integration of machine learning (ML) approaches to compile and study experimental data aggregated from various publications on related research is almost entirely absent, especially when it comes to exploring mechanical, physio-physical, and micro-structurally related variables. There therefore exists a study gap on using ML-Driven approaches to compile prior experimental evidence on bio-stimulation related soil MICP/EICP stabilization performance.

The paper proposes a novel approach using data-driven methods for bio-stabilized soil stabilization processes via MICP and EICP, thus exemplifying a viable means of leveraging micro-experimental and literature-based dataset information for predictive purposes. Through combining

machine learning algorithms and geotechnical and physicochemical factors like UCS values, Atterberg limits, pH, SEM images, EDX spectra, XRD images, and FTIR spectra, this research exemplifies a novel and holistic method of going past singular experimentation for MICP and EICP processes while forming a foundation for a bio-stabilization lab scale solution extended for practical geo tech applications.

## II. METHODOLOGY

In order to establish a strong data set to this study, more than twenty published researches papers were reviewed. With a focus on high impact journals such as, Soils and Foundations, Journal of Cleaner Production, Acta Geotechnica and Scientific Reports these articles were extracted from different academia websites; Google Scholar and ResearchGate. From MICP and EICP successful testing, the key mechanical results collected were Unconfined Compressive Strength (UCS) and stiffness parameters. Data preprocessing was executed after retrieval to pre-process the datasets and scale the input features for maintaining consistency across labs. Soil type was one of ensuring the independent factors isolated during feature selection (e. g., grain size initial dry density) as well as bio-cementation parameters (e.g., CaCO<sub>3</sub> content number of treatment cycles and curing time)

The pre-processed data were split by Train-Test Data Split technique and the greater part of the data was used for training 20 samples and rest for testing reserved for validation.

For ML model training, the Random Forest algorithm was used in this work. In this study, Random Forest (RF), popular and well-accepted machine learning model formed the prognostic model. RF is a joint machine learning model, which sums over a set of decision trees to obtain the outcome and provide stable predictions. The model uses Bagging which is a technique of generating multiple training sets by repeatedly drawing small samples (with replacement) from the original data. This process, combined with the random selection of features for each node split, significantly reduces the correlation between individual trees and mitigates the problem of overfitting. For the regression tasks in this study (predicting strength and modulus), the final result is obtained by averaging the individual forecasts of every tree in the forest [22]. Data segmentation enhances the efficacy of algorithms involved in data analysis and RF forecasting, thereby magnifying their overall performance. The ease of analysis is enhanced when data is sufficiently partitioned, as this allows for easier appreciation of patterns and trends and by making use of these concepts to divide time intervals, algorithms can be enhanced, leading to more precise and effective predicted outcomes that, in turn, lubricate a more exact appreciation and prediction of RF frequencies [22].

Flow Chart of Machine Learning Integrated with MICP/EICP Based Soil Stabilization:

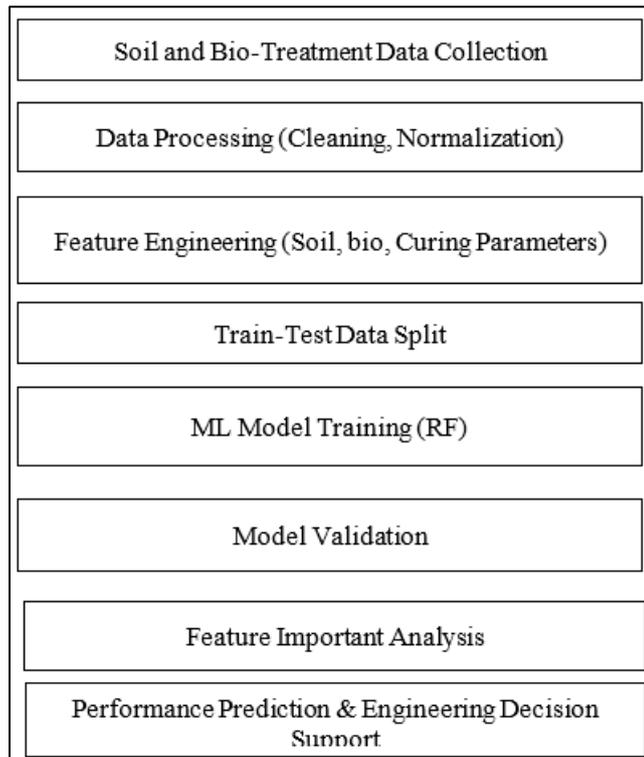


Fig 1: Flow Chart of Machine Learning Integrated with MICP/EICP based Soil Stabilization

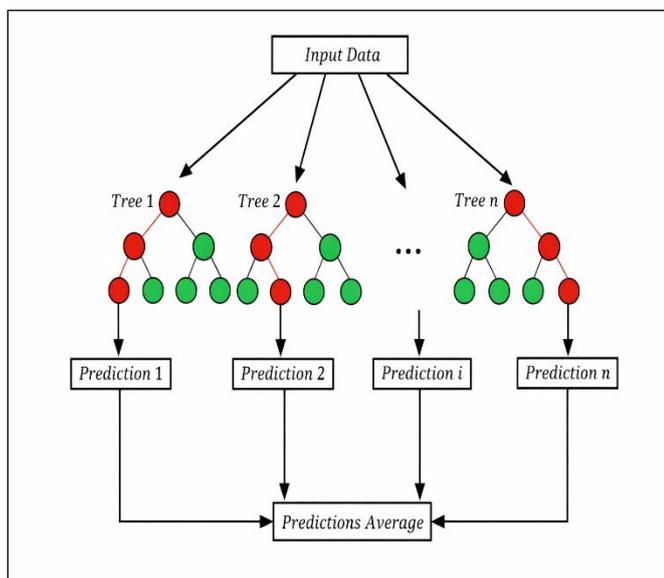


Fig 2: Schematic Representation of the Random Forest Ensemble Learning Process

For the model validation, the standard statistical metrics considered were the coefficient of determination, Root Mean Square Error (RMSE), and Mean Absolute Error (MAE). The metrics provided an unbiased estimation of the model's accuracy in predicting the mechanical response of stabilized sand.

Finally, a Feature Importance Analysis was done using the in-built capabilities of the RF algorithm. This analysis ranked, in order of their relative importance, each input attribute such as amount of precipitated vs initial.

### III. MECHANISM

In MICP, precipitates of calcium carbonate are produced by a combination of dissolved calcium ions and urea produced by the urease bacteria after hydrolysis [1]. MICP technology is a biotechnological method that utilizes bacteria to secrete urease, which subsequently decomposes urea into carbon ate ions [18]. These ions then react with calcium ions to produce calcium carbonate crystals, which help bind soil particles and fill soil pores [4]. The enzyme-mediated precipitation of calcite is achieved without any bacterial activity. The EICP method is used to improvise the geotechnical properties of soils by using an aqueous chemical solution that precipitates calcite within soil voids.[16] The precipitates help in roughening and binding soil grains and even in pore filling, thereby improving the strength and stiffness of the soils [8] [3].

The process before the precipitation of CaCO<sub>3</sub> in soil voids in biotreatment starts from urea hydrolysis initiated by the urease enzyme. During urea hydrolysis, the decomposition of urea leads to the formation of carbon dioxide and ammonia. The water in the system helps ammonia to dissolve and form hydroxide and ammonia ions. These ions create an environment that allows an increase in the solution's pH. Simultaneously, carbon dioxide dissolves in water and develops ions of bicarbonates and hydrogen due to the increased pH of the environment; carbonates are formed due to the reaction between bicarbonate and hydroxide ions, forming carbonate ions and calcium carbonate in the presence of calcium ions; the calcium carbonate formed is precipitated because of its low dissolution rate in water [4] [11] [12]

Table 1: MICP Mechanism Process

Microbial Process	Chemical Reactions	Reference
Urea Hydrolysis	$\text{CO}(\text{NH}_2)_2 + 2\text{H}_2\text{O} \rightarrow 2\text{NH}_4^+ + \text{CO}_3^{2-}$ $\text{Ca}^{2+} + \text{CO}_3^{2-} \rightarrow \text{CaCO}_3 \downarrow$	[7]
Denitrification	$1/2.6 (\text{C}_2\text{H}_3\text{O}_2)_2 + 1.6/2.6 \text{Ca}(\text{NO}_3)_2 \rightarrow \text{CaCO}_3 + 1.6/2.6 \text{N}_2 + 1.4/2.6 \text{CO}_2$	
Sulphate Reduction	$1/3 (\text{C}_2\text{H}_3\text{O}_2)_2 + 2/3 \text{CaSO}_4 \rightarrow \text{CaCO}_3 + 1/3 \text{CO}_2 + 2/3 \text{H}_2\text{O} + 2/3 \text{H}_2\text{S}$	

Table 2: EICP Mechanism Process

Microbial Process	Chemical Reactions	Reference
Urea Hydrolysis	$\text{CO(NH}_2)_2 + \text{H}_2\text{O} \xrightarrow{\text{-(Urease Enzyme)-}} \text{NH}_3 + \text{CO(NH}_2)_2\text{OH}$ $\text{CO(NH}_2)_2 + \text{OH}^- \rightarrow \text{NH}_3 + \text{HCO}_3^-$ $\text{NH}_3 + \text{HCO}_3^- \rightarrow \text{NH}_4^+ + \text{CO}_3^{2-}$ $\text{CaCl}_2 + \text{H}_2\text{O} \rightarrow \text{Ca}^{2+} + 2\text{Cl}^-$ $\text{Ca}^{2+} + \text{CO}_3^{2-} \leftrightarrow \text{CaCO}_3$	[7]

IV. REVIEW OF TEST RESULTS

Table 3: Previous Studies on Bio-stimulated Soil Stabilization

Authors (Year)	Bio Solution (Bio cement) + Admixture	Strength Test		Durability	Micro-Structural Analysis		
		UCS	STS	Water Absorption test	SEM	XRD	FTIR
Mengmeng Li, Chaolin Fang, Satoru Kawasaki, Varenyam Achal (2018)	MICP+ Fly ash	✓	✗	✗	✓	✓	✓
Nitin Tiwari, Neelima Satyam & Meghna Sharma (2021)	MICP+ Bottom Ash (With Artificial Soil)	✓	✓	✗	✓	✓	✓
Mingdong Li, Wei Liu, Jingwu Zhang, Chaopeng Lang, Guizhong Xu, Liping Zhu, Qiang Tang (2024)	SICP/EICP	✓	✗	✗	✓	✗	✗
JianweiZhang, TiansaiZhang, YuhaoMa, KangjianYang, LeiShi, YangYang, YuanminZhang (2025)	EICP+ Fly ash	✓	✗	✗	✓	✓	✗
Shantanu Paul, Tisha Sikder, Mumtahmina Mim (2025)	MICP+ Jute fiber reinforcement (1.5% by dry soil mass)	✓	✓	✗	✓	✓	✓

Table 4: Comparative Findings of Bio-Stimulated Soil Stabilization Techniques

Authors (Year)	Stabilization Technique	Primary Material / Source	Mechanism of Improvement	Typical Strength Gains (UCS / Flexure)	Durability Performance	Micro structural & Key Observations	Key Findings
Mengmeng Li, Chaolin Fang, Satoru Kawasaki, Varenyam Achal (2018)	Bio cementation (MICP) with fly ash	Bio cement precipitated by <i>Bacillus megaterium</i> + fly ash	Ureolytic bacteria forms CaCO <sub>3</sub> which serve as bio cement and enhance the bonding in between soil and fly ash.	Increase with 719.4 kPa resulting in more than two-fold increase over control	Indicates long-term sustainability and robustness research are needed.	SEM verified bacteria and EDX/FTIR/XRD confirmed MICP.	Bio-cement with 25% fly ash offers optimum strength and minimum swelling

Nitin Tiwari, Neelima Satyam & Meghna Sharma (2021)	MICP bio stimulation	Indigenous bacteria present in the soil	Bio cementation via ureolysis	UCS and Split tensile strength (STS) were increased	reduction in swelling pressure and swell strain	Calcite content 205%, SEM-calcite fills cavities, XRD confirmed CaCO <sub>3</sub> formation	cost-effective and ecofriendly method to stabilize the road pavement subgrades
Mingdong Li, Wei Liu, Jingwu Zhang, Chaopeng Lang, Guizhong Xu, Liping Zhu, Qiang Tang (2024)	EICP using Soybean Urease (SICP)	Soybean Powder Extraction, Equimolar Urea-CaCl <sub>2</sub> Solution; Expansive Soil	Bio mineralization (SICP) of calcite	UCS, cohesion, and internal friction angle increased		Optimum moisture content < 2%, max dry density reduced swelling pressure (39 kPa)	Eco-friendly for expansive soil; roll at OMC.
JianweiZhang ,TiansaiZhang ,YuhaoMa, KangjianYang, LeiShi, YangYang, Yuanmin Zhang (2025)	EICP	Silt clay, Class F fly ash	Carbonate	UCS increased by 129%, friction angle increased by 68%	Freeze thaw durability causing deterioration	SEM causes dense matrix	Optimum mix: Soil:ash = 1:1, w/c = 0.52, CCS = 0.8 mol/L
Shantanu Paul ,Tisha Sikder, Mumtahmina Mim (2025)	MICP Combined with jute fiber	Expansive Bacteria, Jute fiber, Cemented Solution	Bio stimulation with ureolysis and Jute fiber helps mechanical interlocking and friction	UCS increment up to 186% increase at 1.5% fiber	Significant reductions in swell strain (85%) and swell pressure (90%)	CaCO <sub>3</sub> content increased (163% to 176%), SEM indicated cohesion and reducing deformability	Eco-friendly, sustainable and efficient

**V. RESULTS & DISCUSSION**

The Random Forest (RF) model developed for expansive soil stabilization achieved an overall accuracy of 75% with a balanced accuracy of 0.50, indicating reasonable predictive capability despite limited sample size. The model correctly classified all Calcite Content cases (precision = 0.75, recall = 1.00, F1-score = 0.857), confirming that calcite precipitation is a dominant indicator of mechanical improvement in bio-stimulated stabilization. However, performance for the minority class was limited due to class imbalance, which affected balanced accuracy. Feature importance analysis revealed that strength criteria and admixture-related parameters significantly influenced predictions, while correlation analysis demonstrated strong relationships between calcite content, UCS, and microstructural tests (SEM/XRD). Overall, the results indicate that the RF framework can effectively capture key stabilization trends and provides a promising data-driven approach for predicting the performance of MICP and EICP treated expansive soils.

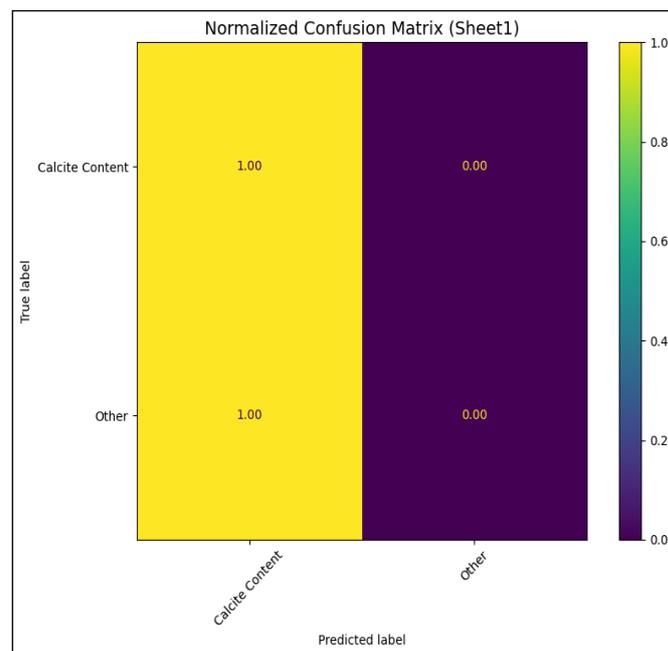


Fig 3: Confusion Matrix of RF Model

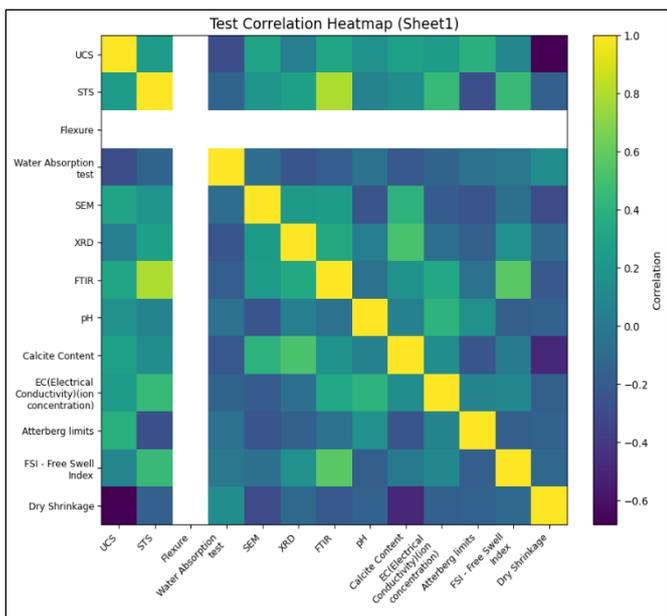


Fig 4: Correlation Heatmap of Stabilization Test Parameters

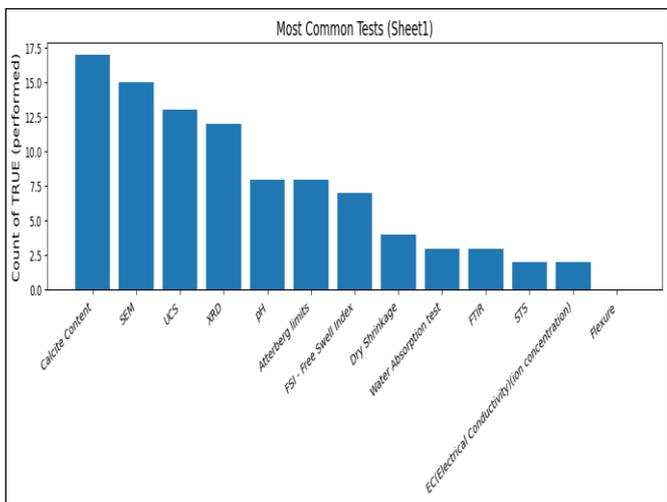


Fig 5: Most Common Stabilization Tests Performed in Expansive Soil Studies

Table 5: Random Forest Classification Performance Metrics

Class	Precision	Recall	F1-Score	Support
Calcite Content	0.7500	1.0000	0.8571	3
Other	0.0000	0.0000	0.0000	1
Accuracy	-	-	0.7500	4
Macro Average	0.3750	0.5000	0.4286	4
Weighted Average	0.5625	0.7500	0.6429	4

**VI. CONCLUSION**

A framework was developed using data to assess bio stimulated soil treatments. The soil can then be improved in terms of mechanical properties. The Random Forest models showed 75% accuracy after treatment. pH was found to be a

significant parameter in distinguishing between the effectiveness of bio solution treatments, and Unconfined Compressive Strength was found to be a significant figure. The data set shows a significant correlation between treatment efficiency and improved strength, which can be between 1.8 and 4.7 times that of untreated soil.

The database contains datasets, which include chemical parameters from pH measurements, mechanical parameters from UCS tests, and microstructural parameters from Scanning Electron Microscopy (SEM) and X-ray diffraction (XRD) tests. Microstructural observations confirmed calcite precipitation. The soil fabric is enhanced to a denser, cemented form, which accounts for the enhanced soil strength. The calcite content contributed moderately to model performance. A minimal contribution to predictive ability was observed using Fourier Transform Infrared Spectroscopy (FTIR). The addition of Fly Ash and Jute fiber enhanced mechanical interlocking in the soil. The research is focused on small-scale data analysis and heterogeneity in datasets. The small sample size and variability in experimental conditions impacted the generalizability of the models. The proposed model has good applicability. The predictive capability of the proposed model is likely to improve with larger and denser datasets.

It provides us with scalable database to include stabilization processes and geotechnical performance analysis. Future studies should focus on expanding key parameters - pH and UCS with an addition of multi scale datasets. It will improve model accuracy from lab experiments to real world applications

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**AUTHOR CONTRIBUTION**

- Author 1,2 was primarily involved in manuscript writing, revisions, and preparation of the final corrected version of the manuscript.
- Author 3\* 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.

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