Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-459

Effects of EICP on vegetation growth and soil water retention in vegetated soils

Changbing Qin, Cheng Yuan
School of Civil Engineering, Chongqing University, Chongqing, China, changbingqin@u.nus.edu

Siau Chen Chian
Department of Civil & Environmental Engineering, National University of Singapore, Singapore.

ABSTRACT: Planting vegetation is widely recognized as an effective and sustainable method for slope reinforcement. However, in areas of heavy rainfall, plant seeds often have a low survival rate due to soil erosion. Enzyme-induced carbonate precipitation (EICP), a recently developed green soil stabilization technique, has been shown to effectively reduce rainfall-induced erosion and improve soil water retention, creating optimal conditions for plant growth. The combined application of vegetation and EICP demonstrates potential for slope reinforcement in high-rainfall areas, but the impact of this technique on vegetation growth remains uncertain. This study investigates the effects of EICP on alfalfa growth and soil water retention by reinforcing soil with varying urease and cementation solution concentrations. The results show that moderate EICP application during the early stages of plant growth enhances soil water retention without hindering root development. However, excessive EICP reinforcement can inhibit vegetation growth. These results highlight the importance of optimizing EICP solution concentrations to achieve a balance between soil stabilization and vegetation performance.

KEYWORDS: vegetation, EICP, water retention, plant growth, soil stabilization.

1 INTRODUCTION

Vegetation-based techniques are widely recognized as sustainable and environmentally friendly approaches for enhancing slope stability and controlling soil erosion. Through root reinforcement and evapotranspiration, vegetation improves soil shear strength, increases water retention, and reduces surface runoff, making it a key component of ecological slope engineering (Simon and Steinemann, 2000; Bordoloi and Ng, 2020). Among various plant types, herbaceous species such as *Medicago sativa* (alfalfa) are particularly promising due to their deep rooting systems, rapid growth, and strong soil-binding capacity. However, in regions experiencing intense rainfall, the establishment of vegetation is often hindered. Heavy precipitation can trigger rapid surface runoff and severe topsoil erosion, washing away seeds and seedlings before they become established. As a result, vegetation survival rates decline, limiting the long-term effectiveness of slope stabilization and ecological restoration (Ziadat et al., 2013; Wang et al., 2014). This challenge underscores the need for innovative reinforcement strategies that not only stabilize soil but also promote successful vegetation establishment under adverse environmental conditions.

Enzyme-induced carbonate precipitation (EICP) is an emerging biogeotechnical technique that catalyzes urea hydrolysis using urease enzymes, producing carbonate ions that react with calcium to form calcium carbonate ($CaCO_3$). The resulting precipitate binds soil particles and fills pores, thereby increasing strength and reducing permeability. Compared to traditional chemical stabilizers, EICP offers advantages such as environmental compatibility, ease of application, and suitability for near-surface treatments, making it especially relevant for erosion control (Gao et al., 2020; Miftah et al., 2022). While recent studies have demonstrated EICP's efficacy in improving unconfined compressive strength (Almajed et al., 2018), shear strength (Miftah et al., 2022), and permeability (Liu et al., 2024), its biological impacts remain largely unexplored. In particular, the effects of $CaCO_3$ precipitation on plant root development, water uptake, and overall growth are poorly understood. This raises concerns that pore clogging from excessive calcite formation could impede seedling emergence or root penetration, potentially undermining the ecological benefits of vegetation-based stabilization.

To address this gap, the present study examines the effects of EICP treatment on vegetation growth and soil water retention in soils. The soil column experiments were conducted using *Medicago sativa* as a model species, with soils treated at varying concentrations of urease and cementation solutions to simulate different levels of calcite precipitation. The study aimed to evaluate how EICP affects water retention and plant development during the critical early stages of germination and root establishment. Results indicate that moderate EICP levels enhance soil water retention without inhibiting root growth or shoot development. In contrast, excessive treatment reduced plant performance, likely due to restricted pore space and limited root expansion. These findings highlight the need to optimize EICP treatment parameters to achieve a balance between soil stabilization and healthy plant growth. The outcomes provide valuable guidance for developing integrated bio-geotechnical strategies for slope protection in rainfall-prone, erosion-susceptible environments.

2 MATERIALS AND METHODS

2.1 *Basic soil properties and plants*

The soil used in this study was collected from the top 50 cm layer of a natural slope in Chongqing, China. Prior to testing, the soil was air-dried, mechanically crushed, and sieved through a 1 mm mesh. The particle size distribution of the sand fraction was determined by sieve analysis and is shown in Figure 1. Key physical properties are listed in Table 1.

Medicago sativa (alfalfa) was chosen as the model plant species due to its deep, fibrous root system, strong adaptability to varied soil conditions, and proven effectiveness in ecological slope stabilization. To promote germination, seeds were soaked in distilled water for 12 hours before sowing. A uniform seeding density of 30 seeds per soil column was applied, with seeds sown evenly across the soil surface.

Table 1. Basic properties of soil used in the study

Index property	Value
Specific gravity, G_s	2.57
Maximum dry density, ρ_{dmax}(g/cm^3)	1.807
Minimum dry density, ρ_{dmin}(g/cm^3)	1.437
Void ratio	0.61
dry density, ρ, (g/cm^3)	1.571
Optimum moisture content (%)	11.2

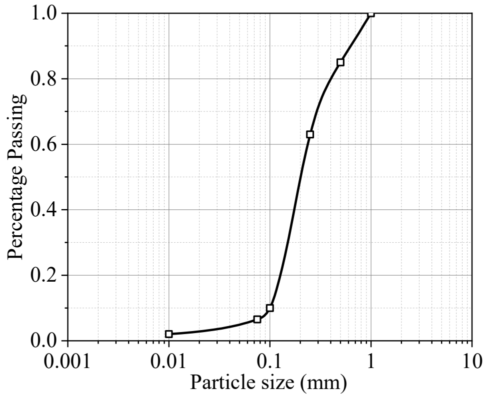

Figure 1. Distribution of particle sizes in the sand sample

2.2 *Soybean crude urease and cementation solution*

The urease enzyme used in this study was extracted from commercially available soybean powder. Specifically, 10 g of soybean powder was mixed with 100 mL of deionized water and stirred magnetically for 30 minutes. The mixture was refrigerated at 4 °C for 12 hours and then centrifuged at 10,000 rpm for 15 minutes. The supernatant was collected and filtered to obtain the crude soybean urease solution. Urease activity was determined using the electrical conductivity (EC) method proposed by Whiffin et al. (2007), yielding a value of 4.96 mM/min. This value falls within the typical range reported for EICP applications (Gao et al., 2020), confirming the enzyme's suitability for soil treatment.

The cementation solution contained equimolar concentrations of urea and calcium chloride ($CaCl_2$), a formulation commonly used in EICP research. To simulate different treatment intensities, three concentrations were prepared: 0.25 M, 0.5 M, and 1.0 M. Immediately before application, equal volumes of the urease and cementation solutions were mixed. The resulting solution was uniformly and rapidly sprayed onto the soil sample surfaces to initiate the precipitation process.

2.3 *Experimental setup and procedures*

Square polyvinyl chloride (PVC) columns (height: 15 cm; side length: 10 cm) with permeable base plates were used in this study. A geotextile layer was placed at the base of each column to allow drainage while preventing soil loss. Columns were uniformly filled with pre-treated soil to a dry density of 1.45 g/cm^3, reaching a height of 7 cm. The soil was compacted in three equal layers using a controlled procedure to ensure consistent packing. Volumetric water content (VWC) sensors (EC-5, METER Group, USA) and matric suction sensors (TEROS 21, METER Group, USA) were installed at a depth of 2 cm to monitor internal hydraulic conditions. Four treatment groups were established: (1) an untreated control, and (2) three EICP-treated groups receiving cementation solutions at concentrations of 0.25 M, 0.5 M, and 1.0 M, respectively. Each treatment was replicated three times (n = 12). Immediately before application, equal volumes of urease and cementation solutions were mixed and sprayed uniformly onto the soil surface. The control group received an equivalent volume of deionized water applied in the same manner.

After treatment, columns were cured for 3 days at 25 ± 1 ° C. Soil water retention was then assessed by tracking VWC and matric suction during a drying phase. Prior to drying, all columns were saturated under the following conditions: (a) matric suction stabilized at 0 kPa, (b) VWC readings indicated saturation, and (c) a constant effluent flow was observed from the drainage outlet. This ensured a uniform initial saturated state across all columns. Columns were then exposed to constant temperature conditions (30 ± 1 ° C) for 5 days to allow evaporation, with drainage outlets kept open to permit free drainage. VWC and matric suction were continuously recorded throughout the evaporation phase.

Next, *Medicago sativa* seeds were sown at a uniform density of 30 seeds per column and covered with a 0.5 cm layer of dry soil. Columns were maintained under controlled environmental conditions (25 ± 1 °C) for 28 days. Plant growth parameters—including germination rate, plant height, and leaf area—were recorded at 7-day intervals. At the end of the experiment, root systems were carefully excavated for further analysis.

3 RESULTS AND DISCUSSION

3.1 *Soil water-holding capacity*

Figure 2 shows the drying paths of soil water retention curves (SWRCs) for soils treated with three concentrations of enzyme-induced carbonate precipitation (EICP) during a 5-day evaporation period. The curves were derived from volumetric water content (VWC) and matric suction measurements at a depth of 2 cm. EICP treatment markedly affected both the shape and position of the SWRCs, with clear distinctions among treatment groups. Across the entire suction range, soils treated with 1.0 M EICP consistently retained the most moisture, followed by the 0.5 M and 0.25 M treatments, while the untreated control exhibited the lowest water retention. These results indicate that EICP enhances soil moisture retention, with effectiveness increasing with cementation solution concentration. The likely mechanism is $CaCO_3$ precipitation, which fills pores, reduces connectivity, and limits vapor diffusion, thereby slowing evaporation.

Notably, the final matric suction values after five days reveal that EICP alters the soil's drying behavior. Soils treated with 1.0 M and 0.5 M EICP equilibrated at intermediate suction levels (10-300 kPa), whereas the 0.25 M and untreated soils advanced into the high suction range (>300 kPa). This suggests that higher EICP concentrations not only slow moisture loss but also delay the onset of high matric stress, potentially maintaining more favorable conditions in the root zone under drought or evaporative stress. From an applied perspective, improved water retention in EICP-treated soils could extend plant-available moisture during critical stages such as germination and early root growth. However, excessive EICP may cause pore clogging by $CaCO_3$, which could hinder root penetration and affect long-term soil structure and plant development.

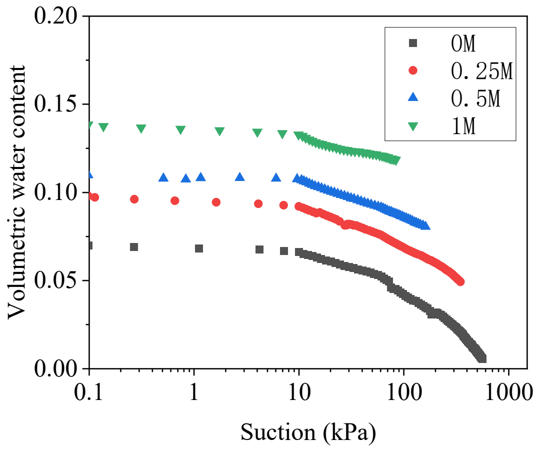

Figure 2. Comparative drying paths of SWCCs under different EICP treatment concentrations.

3.2 *Soil evaporation*

To further investigate EICP's impact on soil moisture dynamics, volumetric water content (VWC) and matric suction at 2 cm depth were monitored during the 5-day drying period. Figures 4a and 4b show the temporal evolution of VWC and matric suction, respectively, across treatments. All treatments exhibited progressive VWC decline and accompanying matric suction increase during evaporation, but the magnitude differed markedly with EICP concentration. Relative to the untreated control, EICP-treated soils showed slower moisture loss and more gradual suction development. By day 5, matric suction in the control reached 561 kPa, exceeding the 1.0 M EICP treatment (84 kPa) by 6.68 times. Notably, the control exhibited a steep surge in suction starting on day 4, indicating rapid transition to a high-suction state. In contrast, the 0.25 M treatment had only marginal suction increase on day 4, with substantial rise delayed until day 5. Suction in the 0.5 M and 1.0 M treatments remained relatively stable through day 4, increasing markedly only on day 5. The delayed suction response in EICP-amended soils arises from two mechanisms: (a) Enhanced initial hydraulic state: EICP-induced pore filling and improved retention yielded higher initial VWC, extending the duration before critical drying thresholds. (b) Modified hydraulic properties: As shown by SWRCs (Figure 3), EICP reduced matric suction at equivalent water contents, indicating moisture retention at lower energy states.

Collectively, EICP fundamentally alters soil hydraulic behavior during drying, beyond merely increasing water-holding capacity. The moderated suction development promotes sustained hydraulic gradients potentially favorable for root water uptake and microbial processes, particularly during early growth. Furthermore, the delayed transition to high-suction regimes suggests that EICP moderates the soil's moisture response to evaporative demand, highlighting its potential for enhancing drought resilience in slope stabilization.

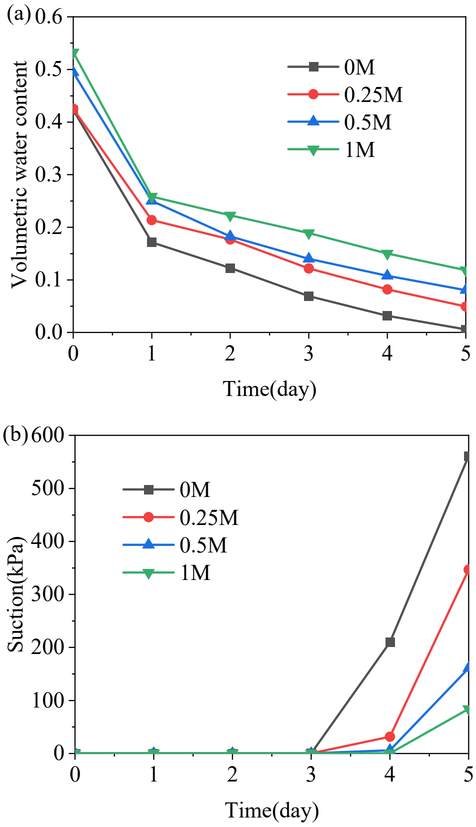

Figure 3. Measured test results: (a) VWC and (b) matric suction over time during evaporation.

3.3 *Plant growth characteristics*

Figure 4 shows weekly photographs of plant growth under different EICP concentrations. Visual assessment indicates that EICP application negatively impacts plant development, with severity increasing at higher concentrations. To quantify these effects, survival rate, plant height, and leaf area were evaluated. After the fourth week, root systems were extracted from soil (Figure 5). The cementation solution significantly inhibited root elongation. Untreated controls had the longest roots (7 cm), while increasing EICP concentrations progressively reduced root length to approximately 5 cm at 0.25M and 1 cm at 1M.

Leaf area in this study refers to the projected horizontal area, calculated from top-view images using ImageJ. Figure 6(a) shows plant survival rates over time. On Day 3, germination in untreated soil (0 M) reached 97%, significantly higher than in soils treated with 0.25 M, 0.5 M, and 1.0 M EICP (56%, 43%, and 10%, respectively). This suggests EICP treatment inhibits seed germination, with the effect increasing with concentration. By Day 7, germination was largely complete and surviving seedlings peaked. Over the next three weeks, all seedlings in untreated soil survived, while survival rates in EICP-treated soils declined. By Day 28, survival rates for the 0.25 M, 0.5 M, and 1.0 M groups dropped to 53%, 26.7%, and 6.7%, respectively. This continuous decline may be attributed to: (a) Phytotoxic ions (e.g., NH4+, Cl-) introduced by EICP exceeding plant tolerance thresholds; and (b) CaCO3 precipitates from the EICP reaction filling soil pore spaces, potentially impeding root penetration and development, leading to wilting or death.

Figure 6(b) presents plant height variation over time. Plants in untreated soil consistently exceeded those in EICP-treated soils in height, which generally decreased with increasing EICP concentration. This trend aligns with the physiological stress imposed by EICP, hindering vertical growth. Notably, control group plant height slightly declined after Day 14, not due to physiological deterioration but to stem curvature from vigorous leaf growth causing shoot apex bending. Figure 6(c) illustrates leaf area changes under different treatments. A clear inverse relationship was observed: higher EICP concentrations resulted in smaller leaf areas. This finding aligns with the survival and height data (Figures 6(a) and 6(b)), further confirming the adverse effects of EICP on plant development.

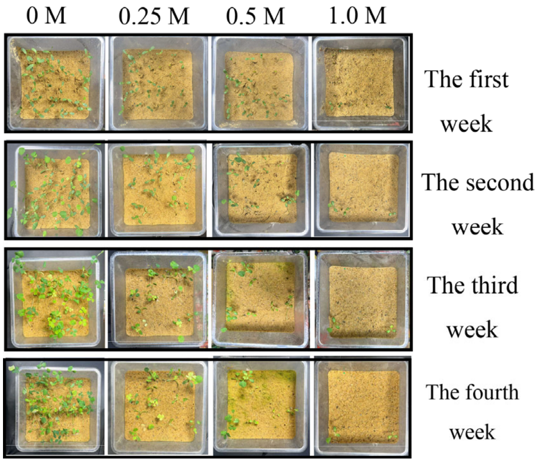

Figure 4. Pictures of alfalfa seedlings treated with cementation solutions at varying concentrations.

Figure 5. Effect of Cementation Solution Concentration on Root Length of Plants

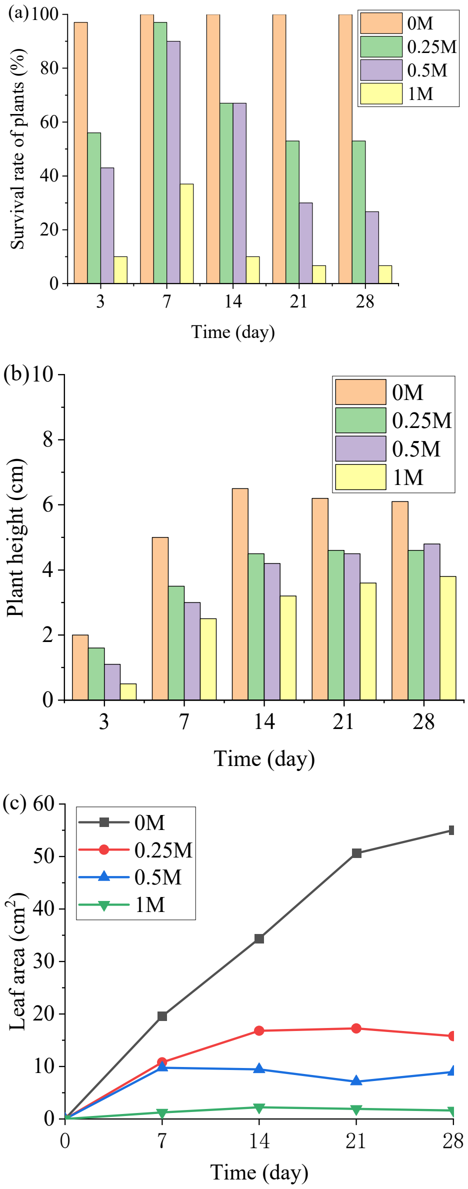

Figure 6. Response of seed germination and seedling growth characteristics to varying cementation solution concentrations:(a) Survival rate; (b) Plant height; (c) Leaf area

4 CONCLUSIONS

This study systematically examined the effects of EICP treatment on soil hydraulic properties and alfalfa (*Medicago sativa*) growth using controlled soil column experiments. Results show that EICP significantly improves soil water retention by reducing evaporation and delaying the onset of high matric suction. These effects are attributed to $CaCO_3$ precipitation, which fills pores, impedes vapor diffusion, and modifies soil-water behavior, with efficacy increasing with cementation solution concentration (1.0 M > 0.5 M > 0.25 M > control). After five days of drying, soil treated with 1.0 M EICP retained a matric suction of 84 kPa, compared to 561 kPa in untreated soil, indicating sustained plant-available moisture.

However, EICP also imposed concentration-dependent stress on plant growth. Low-concentration treatment (0.25 M) modestly reduced germination and root length, yet allowed sustainable growth with a 53% survival rate after 28 days. In contrast, higher concentrations (≥0.5 M) drastically suppressed plant performance, reducing germination to 43% and 10% and survival to 26.7% and 6.7%, respectively. These adverse effects stem from (i) ionic stress due to elevated NH_4^+ and Cl^- from urea hydrolysis, and (ii) physical obstruction of root growth from excessive $CaCO_3$ clogging, with root lengths under 1.0 M treatment limited to 1 cm.

In conclusion, while EICP offers substantial potential for enhancing soil water retention and erosion control on rainfall-prone slopes, its application must be carefully optimized. A cementation solution concentration of ~0.25 M appears to strike a practical balance between hydraulic benefit and plant viability, mitigating the trade-off between soil stabilization and vegetation success.

5 ACKNOWLEDGEMENTS

The research was financially supported by the National Natural Science Foundation of China (Grant No.: 52108302).

6 REFERENCES

Almajed, A., Tirkolaei, H. K., and Kavazanjian, E. 2018. Baseline Investigation on Enzyme-Induced Calcium Carbonate Precipitation. *Journal of Geotechnical and Geoenvironmental Engineering* 144, 11.

Bordoloi, S., and Ng, C. W. W. 2020. The effects of vegetation traits and their stability functions in bio-engineered slopes: A perspective review. *Engineering Geology* 275, 24.

Gao, Y. F., Meng, H., He, J., Qi, Y. S., and Hang, L. 2020. Field trial on use of soybean crude extract for carbonate precipitation and wind erosion control of sandy soil. *Journal of Central South University* 27, 3320-33.

Liu, L. X., Gao, Y. F., Meng, H., Pan, Q. W., Wang, Z. B., Zhou, Y. D., Liu, B., and Cao, X. W. 2024. Pore-scale, mechanical, and hydraulic properties of EICP-treated sand using crude legume ureases with different protein contents. *Acta Geotechnica* 19, 47-63.

Miftah, A., Tirkolaei, H. K., Bilsel, H., and El Naggar, H. 2022. Erodibility improvement and scour mitigation of beach sand by enzymatic induced carbonate precipitation. *Geomechanics for Energy and the Environment* 32, 11.

Simon, K., and Steinemann, A., 2000. Soil bioengineering: challenges for planning and engineering. *Journal of Urban Planning and Development* 126 (2), 89–102.

Wang, N., Jiao, J. Y., Lei, D., Chen, Y., and Wang, D. L. 2014. Effect of rainfall erosion: seedling damage and establishment problems. *Land Degradation & Development* 25, 565-72.

Whiffin, V.S., Van Paassen, L. A., and Harkes, M. P. 2007. Microbial carbonate precipitation as a soil improvement technique. *Geomicrobiology Journa,* 24, 417-423

Ziadat, F. M., and Taimeh, A. Y. 2013. Effect of rainfall intensity, slope, land use and antecedent soil moisture on soil erosion in an arid environment. *Land Degradation & Development* 24, 582-590.