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Large-scale soil bio-cementation: insights into homogeneity, quality control, and waste handling

Sur l’effet des paramètres et des techniques d’injection pour obtenir une bio-amélioration homogène des sols: aperçus d’une expérience à grande échelle

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ABSTRACT: This paper deals with challenges in large-scale soil bio-cementation. Introducing a novel treatment strategy with ex-situ hydrolysis in a 1000 L bioreactor, the study employs a state-of-the-art installation to inject hydrolyzed solutions into a 40 m^2 area of 0–4 mm sand. A comprehensive multilevel quality control system monitors chemical and hydraulic processes across cycles, resulting in reaction efficiencies exceeding 80%. The paper discusses the gradual increase in pressure at the injection inlet, correlating with higher calcification levels. Findings indicate improved resistance in zones with higher injection pressure, demonstrating the efficacy of ex-situ bio-cementation. The study also explores the mechanical improvements, suggesting comparable results to traditional in-situ methods. Additionally, the paper addresses the monitoring of microbially induced calcium precipitation (MICP) at the geotechnical scale, highlighting the issue of residual ammonium reaching absorbed quantities of 4 mol/L.

RÉSUMÉ: Cet article traite des défis liés à la bio-cimentation des sols à grande échelle. Introduisant une nouvelle stratégie de traitement avec l'hydrolyse ex-situ dans un bioréacteur de 1000 L, l'étude utilise une installation de pointe pour injecter des solutions hydrolysées dans une zone de 40 m2 de sable de 0 à 4 mm. Un système complet de contrôle de la qualité à plusieurs niveaux surveille les processus chimiques et hydrauliques à travers les cycles, aboutissant à des efficacités de réaction dépassant 80%. L'article discute de l'augmentation graduelle de la pression à l'entrée de l'injection, corrélée à des niveaux de calcification plus élevés. Les résultats indiquent une résistance améliorée dans les zones avec une pression d'injection plus élevée, démontrant l'efficacité de la bio-cimentation ex-situ. L'étude explore également les améliorations mécaniques, suggérant des résultats comparables aux méthodes traditionnelles in-situ. De plus, l'article aborde le suivi de la précipitation calcique induite par les micro-organismes (MICP) à l'échelle géotechnique, mettant en lumière le problème de l'ammonium résiduel atteignant des quantités absorbées de 4 mol/L.

Keywords: MICP; upscaling; quality control; dynamic penetrometer; field testing.

1 INTRODUCTION

Nearly two decades since its inception, Microbially Induced Calcium Carbonate Precipitation (MICP) has gained attention as a sustainable alternative for ground improvement. Utilizing urease-bearing microorganisms, urea hydrolysis induces carbonate ion creation, leading to solid calcium carbonate precipitation. This biochemical process enhances soil properties, impacting permeability, stiffness, compressibility, and shear strength. The technique has been explored in controlled setups and natural environments, addressing diverse geotechnical challenges (Terzis & Laloui, 2019).

2 MATERIALS & METHODS

To validate the ex-situ treatment strategy, a bench-scale campaign was conducted. Sand columns, representing the tank's porosity, underwent treatment with hydrolyzed and calcium-rich solutions. Analysis of liquid samples assessed precipitation efficiency through calculations involving influent and effluent reactant concentrations. The laboratory-scale investigation provided insights into the chemical efficiency of the treatment strategy, microstructural comparisons, and its potential for improving soil mechanics.

A reinforced concrete container, 8.0 m × 10.0 m × 2.5 m, was constructed with two compartments for repeated experiments (Harran et al., 2022).

Figure 1. Testing set-up.

Unlike previous impermeable setups, this design incorporated draining tubes in the tank's bottom, preventing reactant accumulation. This setup allowed control over water table levels, simulating real environmental conditions. Eight injection wells (Figure 1) per compartment facilitated the bio-cementation protocol's implementation. The design prioritized preventing ammonium leaching and maximizing liquid circulation.

Both compartments were filled with 0–4 mm sand from the Catellani quarry (Switzerland), exhibiting a diverse grain size distribution and composed of 70% quartz and 30% natural carbonate minerals. The sand is labelled SP according to ASTM D2487 but still covers a range of contents from fine (2.9% < 0.1 mm diameter) to coarse (15.9% > 2 mm diameter). (Figure 2). The bio-cementation protocol involved 11 days of successive cycles injecting hydrolyzed carbonate solution followed by immediate cementation solution injection. Sporosarcina pasteurii was used for urea hydrolysis, and both solutions were prepared in 1000 L batches.(Table 1) The protocol aimed for full pore volume coverage, and drainage tubes simulated a draining bottom surface, collecting effluents for monitoring. This setup enabled control over injection pressure and offered insights into the bio-cementation process.

In-situ testing utilized an instrumented dynamic penetrometer (Panda, Solsolution) across treated and untreated sand volumes. Tests at various locations, chosen for spatial heterogeneity representation, assessed the bio-cementation effect on cone tip resistance. The results provided a detailed understanding of the treatment‘s impact on the soil‘s mechanical properties.

Mechanical performance assessment involved Unconfined Compressive Strength (UCS) tests on lab-treated samples. The samples were compared to conventionally bio-cemented ones. Testing included controlled axial strain rates and subsequent determination of calcium carbonate contents, offering insights into the treatment‘s impact on mechanical behavior.

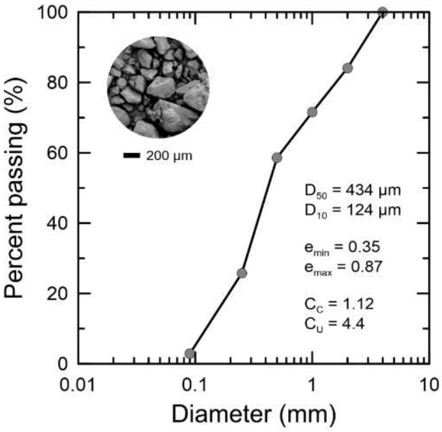

Figure 2. Particle size distribution and properties of the chosen sand.

Samples from both laboratory and large-scale experiments underwent Scanning Electron Microscopy (SEM) for textural and geometrical characterization of the precipitated calcium carbonate. This microscopic analysis provided visual insights into the structure and morphology of the cemented material.

Table 1. Treatment solution constituents.

	Bioreactor Solution (BS)	Cementation Solution (CS)
Peptone (kg/m^3)	1	-
Lyophilized bacteria (L/m^3)	1	-
Urea (kg/m^3)	50	-
Calcium chloride (kg/m^3)	-	200

3 RESULTS

The precipitation efficiencies were computed based on the excess reactant species found in each injection cycle, using either calcium or TIC excess. For each injection cycle, two effluent samples were taken. Remarkably, high completion rates exceeding 70% were achieved with reaction times as short as 4 hours between injections. The effluent predominantly exhibited a richness in calcium in five out of eight injection cycles.

The use of pre-hydrolyzed urea played a pivotal role in this efficiency, as calcium carbonate precipitated immediately upon the contact of BS and CS solutions. This process demonstrated comparable efficiency to conventional Microbially Induced Calcium Carbonate Precipitation (MICP). Notably, it boasted faster precipitation times and the advantage of introducing a solution into the ground with known characteristics, concentrations, and stability.

UCS (Figure 3) values increased with rising bond contents, reaching as high as 2.1 Mpa for 10% $CaCO_3$. Young's modulus (E) varied between 180 Mpa and 480 Mpa, increasing with higher bond content. Despite some observed scattering associated with the measured heterogeneity in gravimetric contents within the same sand column, the results were consistent. Generally, higher $CaCO_3$ contents resulted in a brittle response, characterized by distinctive peak strength followed by sharp softening.

SEM observations of precipitates formed in liquid batches after mixing the ex-situ BS and CS solutions are provided in Figure 4. The crystals exhibited a typical rhombohedral calcite morphology, reaching a size of 20 µm when precipitated without a sand matrix.

When ammonium concentrations exceed the water's natural self-purification capacity, it triggers various environmental concerns, notably eutrophication. Eutrophication, in turn, leads to the decline of aquatic life, such as fish, degradation of water quality, and disturbance of biodiversity. Therefore, it is crucial to monitor and mitigate ammonium concentrations arising from the bio-cementation process, to maintain them below acceptable thresholds. The recirculation of ammonium, combined with the levels produced with every new hydrolyzed batch, led to an increase in influent NH4+ concentrations throughout the treatment, as illustrated in Figure 5. At the end of the 20,800 L treatment, the effluent NH4+ concentration stabilized at around 1 mol/L.

Considering the average NH4+ concentration in the 11 cycles, accounting for dilution, the residual recorded ammonium aligned with the theoretical value. This suggests that to bring NH4+ within acceptable limits, substantial volumes and pumping times are needed in large-scale projects. The potential retention of NH4+ on soil particles and dissolution in groundwater observed in previous literature works further underscores the challenges associated with NH4+ elimination through MICP-induced ureolysis. Hence, the study postulates that byproduct extraction from treatment solutions prior to injection into the ground using ex-situ hydrolysis remains a promising alternative. This approach aims to enable NH4+ elimination and minimize operational constraints, ultimately producing soil admixtures or grouts for bio-cementation that align with environmental norms.The results of dynamic penetrometer tests revealed varying heterogeneity in the treated section. Figure 6 presents a typical penetrogram result with a discrepancy at a depth of 1.2m attibuted to the well's outlet.

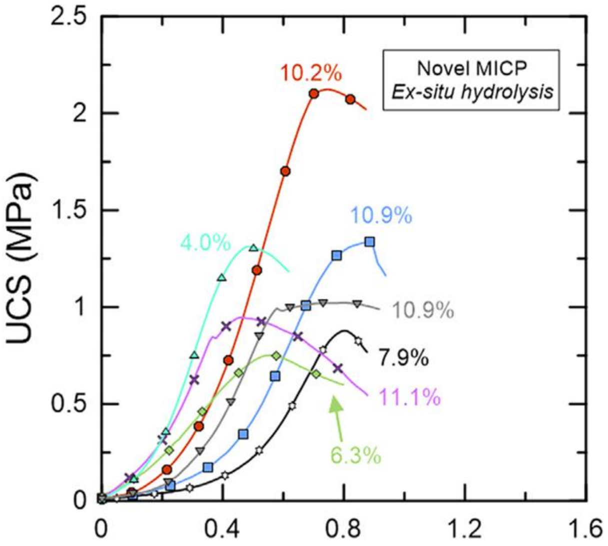

Figure 3. UCS determination on samples produced using ex-sity hydrolysis.

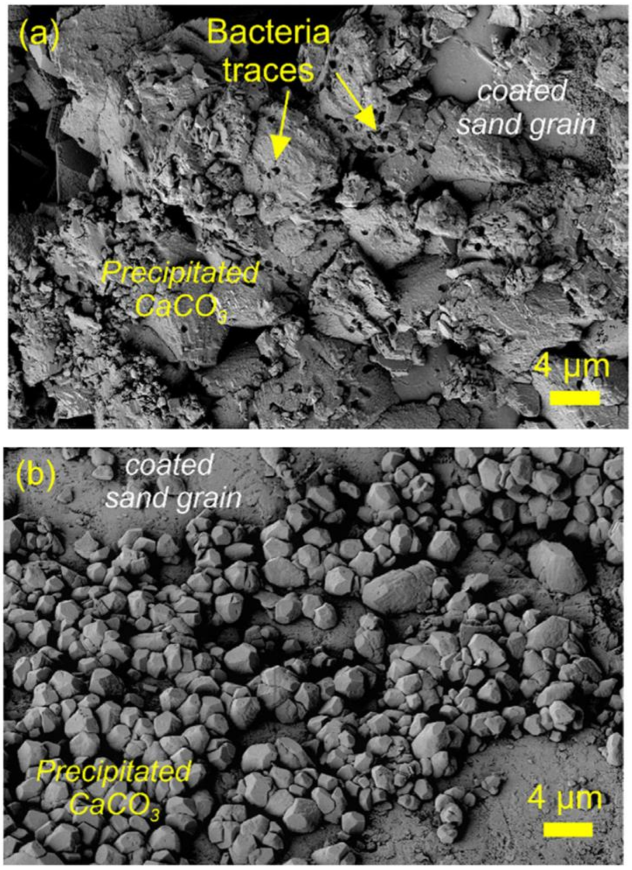

Figure 4. SEM observations of calcium carbonate precipitated on the surface of sand grains using (a) traditional MICP with in-situ hydrolysis and (b) novel MICP with ex-situ hydrolysis.

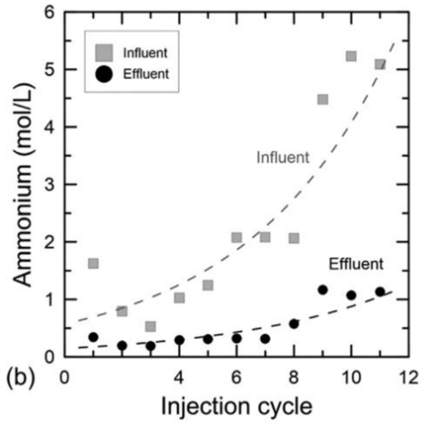

Figure 5. NH4+ concentrations during recirculation of enriched treatment batches.

All tests in the untreated compartment demonstrated overall homogeneity in cone resistance (qd) across depth, with values ranging between 0.5 and 1 MPa. A follow-up experiment using a slited pipe, i.e. without outlets every 50cm across the well‘s depth, yielded more homogenous results (Figure 7).

4 CONCLUSIONS

The ex-situ hydrolysis approach demonstrated high precipitation efficiencies and comparable mechanical properties to traditional MICP. The microscopic analysis revealed changes in mineralization processes at the pore scale. Chemical monitoring confirmed the efficiency of the precipitation reaction, with implications for the treatment of residual ammonium. The dynamic penetrometer campaign provided spatial insights into the effectiveness of bio-cementation, highlighting areas of significant improvement. Overall, the study contributes to bridging laboratory advancements with large-scale implementation of bio-cementation, providing a comprehensive multi-level quality monitoring system for real-world applications.

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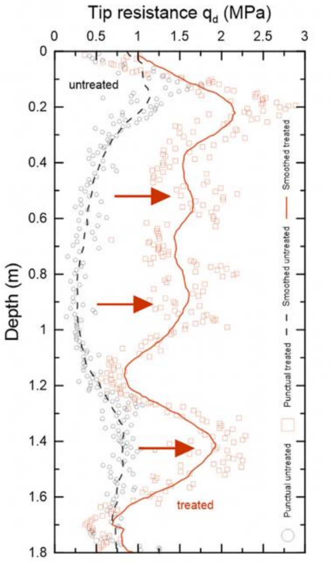

Figure 6. Penetrograms for both treated and untreated states using a sleeved tube.

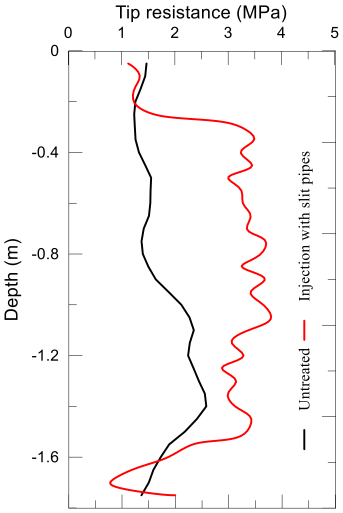

Figure 7. Penetrogram for both treated and untreated states using a slit tube.

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