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Editorial

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Editorial: Use of biopolymers in environmental geotechnics

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Soils are fundamental to infrastructure development, yet their inherent geotechnical attributes often fail to meet the stringent performance requirements of modern construction activities. Soil stabilisation using cementitious binders, particularly cement and lime, has been extensively employed to improve the mechanical properties of problematic soils, offering a proven and generally effective solution for addressing soil-related challenges in geoen지니어링 applications. However, growing concerns over the significant energy demands and carbon footprint associated with the production and application of these conventional binders have driven the search for more environmentally responsible alternatives, prompting a paradigm shift towards more sustainable ground improvement practices.

Among the many alternatives explored to mitigate the environmental drawbacks of cement and lime, bio-inspired solutions, such as biopolymer admixtures, microbially induced calcium carbonate precipitation (MICP) and enzyme-induced carbonate precipitation (EICP), are garnering increasing attention. These emerging techniques offer a sustainable and environmentally responsible approach to soil stabilisation, with their multifaceted soil-amending benefits positioning them as promising candidates for next-generation ground improvement strategies. Despite encouraging developments, the existing literature reveals numerous inconsistencies, and a thorough understanding of the stabilisation mechanisms and performance of bio-inspired methods presently remains somewhat elusive (Mohamed *et al.*, 2024a). This is not unexpected, particularly for clay-rich soils, where the stabilisation process, among other factors, is governed by intricate physicochemical interactions between the stabilising agent and the reactive clay

particles. Evidently, a systematic compilation of high-quality laboratory data – encompassing a diverse array of soil types/attributes, as well as different stabilisation methodologies, tested under a variety of controlled and representative environmental conditions (e.g. simulated pore-water chemistry, field moisture fluctuations and climatic stressors) – is necessary to support the development of reliable frameworks/standards capable of guiding bio-inspired ground improvement solutions in practice.

This themed issue of *Environmental Geotechnics* brings together seven research articles that investigate the efficacy of different bio-inspired ground improvement solutions across diverse geoen지니어링 applications. The main focus of the themed issue is on biopolymer-based admixtures, which are the subject of four of these articles (Babatunde *et al.*, 2025; Cai *et al.*, 2025; Nakayenga and Hata, 2025; Pitso *et al.*, 2025), plus two investigating MICP (Wang *et al.*, 2025; Xu *et al.*, 2025), and one exploring the application of lignocellulose-degrading enzymes (Mugula *et al.*, 2025).

Collectively, these research studies not only advance state-of-the-art knowledge, but also align with several United Nations Sustainable Development Goals (SDGs) by promoting: (i) innovative ground improvement technologies (SDG 9: Industry, Innovation and Infrastructure); (ii) valorisation of waste materials (SDG 12: Responsible Consumption and Production); (iii) bio-inspired engineering solutions as low-impact alternatives to conventional, energy-demanding and ecologically disruptive geoen지니어링 practices (SDG 13: Climate Action); and (iv) responsible waste management practices to mitigate environmental contamination risks and promote ecosystem resilience (SDG 15: Life on Land). Their findings highlight

the potential of bio-inspired ground improvement techniques as a transformative approach to geotechnical engineering in an era of environmental accountability.

Biopolymers can effectively reduce soil permeability, rendering them attractive admixtures for constructing landfill barrier systems. However, their long-term performance under environmental stressors must be rigorously evaluated to ensure sustained effectiveness. Addressing this imperative, in the first article of this themed issue, Cai *et al.* (2025) investigate the evolution of permeability in biopolymer-stabilised low-plasticity clay when subjected to intermittent drying and wetting cycles. Focusing on xanthan gum (XG) biopolymer and benchmarking its efficacy against bentonite, their experimental findings demonstrate that XG is more effective in mitigating desiccation-induced macro- and micro-cracking, thus offering superior leakage prevention. Considering cyclic drying and wetting, the minimum admixture dosages required to meet the $\leq 10^{-10}$ m/s permeability coefficient threshold are 1.35% and 7.5% (by dry mass of soil) for XG and bentonite, respectively. Additionally, it is worth mentioning that two recently published articles in this journal have investigated (i) the wetting and drying behaviour of sand and sand–clay mixtures modified with XG biopolymer additive (Chang *et al.*, 2024), and (ii) employing XG biopolymer to stabilise mine tailings for dust control (Chen *et al.*, 2021).

Soil erosion, often manifesting as piping, is a major cause of failure in geo-infrastructure, including for levees, embankments and bridge foundations. In this context, Babatunde *et al.* (2025) examine the efficacy of zein biopolymer treatment on the erosion behaviour of poorly-graded sandy soils using laboratory hole-erosion testing (HET), further supporting and discussing their results using rheological and shear-wave analyses. Their HET findings highlight that zein biopolymer enhances soil stability by significantly reducing the rate of particle loss (detachment) and hence the hydraulic erosion rate. Their study also reveals that the biopolymer gel transitions from shear-thickening to shear-thinning behaviour after a 4-hour curing period, with a strengthening of the soil structure produced over time, and hence improved erosion resistance; more pronounced effects noted in sands with larger particle sizes.

The research article by Nakayenga and Hata (2025) proposes using casein biopolymer as an additive in cement-treated soils to produce lightweight embankment materials. Experimental variables include

casein dosage, cement content and mixing time, with performance evaluated in terms of dry density, compressive strength and permeability. The findings indicate that 5% casein (by dry mass of cement), applied with a mixing time of 10 min, produces lightweight embankment materials with complaint unconfined compressive strength (>300 kPa) and permeability ($\sim 10^{-6}$ m/s). Furthermore, the casein-modified cement-treated soil exhibits enhanced durability against cyclic wetting and drying, with the pH of its leachate closely resembling that of soil–cement without casein, suggesting minimal environmental impact.

Focusing on advancing sustainable soil stabilisation solutions, Pitso *et al.* (2025) investigate the individual and combined effects of guar gum (GG) and hydrated lime on the consolidation and shear strength properties of saturated sandy silt. Their findings suggest that GG can be employed to engineer the failure mode of soil–lime blends, effectively reducing their brittleness. At critical state, lime-treated samples retain a high frictional component of shear strength, although the cohesive component is significantly diminished. In contrast, samples primarily stabilised with GG continue to exhibit a notable degree of cohesion. Furthermore, partial substitution of lime with GG produced an increase in both the compression and swelling indices, while concurrently decreasing the consolidation coefficient and permeability. However, the authors of this editorial are of the view that improved stabilisation performance may be achieved by using alternative biopolymers. That is, given that lime is rich in calcium cations, it may be more appropriate to pair it with an anionic biopolymer agent (e.g. XG or sodium alginate), particularly in clay-rich soils, to promote enhanced clay–biopolymer cationic bridging during early stages, and to allow for the development of long-term complex pozzolanic reactions (Mohamed *et al.*, 2024b). Table 1 provides a comparative overview of potential interaction mechanisms and stabilisation outcomes in clay-rich soils stabilised with lime–biopolymer additives.

To enhance soft ground stability, Wang *et al.* (2025) introduces MICP–BIN, a novel soil reinforcement method that integrates MICP with biochar-induced nucleation (BIN) to enhance clay soil properties. By incorporating biochar derived from corn stover into clay and treating it with MICP, the researchers observed improved shear strength and water retention. Laboratory tests, including direct shear strength and drying experiments, confirmed the technique’s effectiveness compared to the untreated soil or soil treated with MICP alone. The study highlights MICP–BIN as a promising,

Table 1. Potential interaction mechanisms and stabilisation outcomes in clay-rich soils stabilised with lime–biopolymer additives

Biopolymer	Charge type	Interaction with lime (Ca ²⁺)	Soil stabilisation potential with lime
Guar Gum	Neutral	Weak	Low
Xanthan Gum	Anionic	Moderate	Moderate
Sodium Alginate	Anionic	Strong (Ca ²⁺ crosslinking)	High

sustainable solution for soft ground reinforcement. Future research should examine long-term field applications, biochar variations, and potential bioelectricity generation benefits.

Sustainable utilisation of natural resources is of prime importance to circular economy. To this end, Xu *et al.* (2025) explores an eco-friendly approach to improving mining waste, specifically tailings sands, through MICP. The study improves this technique by applying ultraviolet mutagenesis to enhance the calcium carbonate-producing ability of naturally occurring bacteria. Laboratory experiments demonstrated that the modified bacteria significantly improved the mechanical properties of tailings sands, such as their unconfined compressive and direct shear strengths, by forming effective calcium carbonate binding structures. The results highlight a promising, cost-effective solution for stabilizing tailings, addressing both environmental and safety concerns. Further investigation is recommended into the calcium carbonate nucleation process to optimize this method.

Finally, the sustainable utilisation of natural resources is further addressed by Mugula *et al.* (2025). They used naturally bio-cemented termite mound soils (TMS) as a sustainable alternative for highway construction. The study found that TMS outperforms surrounding soils (SS), with the former having finer particle size, lower organic content and shrinkage, and higher plasticity and specific gravity. TMS also exhibited twice the unconfined compressive strength and achieved approximately 34% higher California Bearing Ratio. Replacing traditional cement stabilisation with TMS could reduce CO₂ emissions by at least 34 tons per kilometre of highway construction. The study encourages further research into soil enhancement using lignocellulose-degrading enzymes to replicate the natural bio-cementation process found in termite mounds.

We thank all the researchers contributing to this themed issue. We hope that this collection inspires further research and collaboration in this area of study.

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