

TRANSFORMATION OF LOESS SOIL MECHANICAL PROPERTIES AND ITS EFFECT ON FOUNDATION BEARING CAPACITY: A COMPARATIVE IMRAD-BASED ANALYSIS OF BIOSTABILIZATION AND GEOPOLYMER METHODS

<https://doi.org/10.5281/zenodo.19507130>

Kurbanov Ravshan

*Department of Construction Mechanics, Samarkand State Architectural and
Construction University, Samarkand, Uzbekistan
kurbanovravshan232@gmail.com*

Abstract

Loess soils in the arid regions of Uzbekistan are characterized by high porosity, metastable structure, and pronounced susceptibility to hydro-collapse under wetting, which reduces foundation reliability and increases the risk of differential settlement. The aim of this study was to evaluate how microbiologically induced calcite precipitation (MICP) and geopolymer injection change the physical and mechanical properties of loess soils and, consequently, influence foundation bearing capacity. The study was designed as a comparative analytical review structured according to IMRAD principles. Peer-reviewed publications on loess geochemistry, land degradation in Uzbekistan, MICP, enzyme-induced carbonate precipitation, and geopolymer stabilization were synthesized, and their engineering implications were interpreted through classical bearing-capacity concepts. The analysis shows that MICP strengthens loess by forming calcite bridges at particle contacts, increasing apparent cohesion and internal friction while reducing permeability and wetting sensitivity. Geopolymer injection provides rapid setting, high chemical resistance in sulfate- and salt-affected soils, and a lower carbon footprint than ordinary Portland cement systems. Both methods are capable of improving the deformation response of collapsible foundations, but their domains of optimal application differ: MICP is better suited to environmentally sensitive or heritage sites, whereas geopolymer systems are preferable when rapid local reinforcement and saline resistance are critical. The study concludes that the transition from cement-intensive stabilization to bio-based and alkali-activated technologies is scientifically justified for arid loess terrains, although field-scale validation under the hydrogeological conditions of the Samarkand region remains necessary.

Keywords

loess soil; hydro-collapse; MICP; biostabilization; geopolymer injection; bearing capacity; settlement; arid regions; Uzbekistan

1. Introduction

The reliability of shallow and embedded foundations in arid regions depends not only on the current state of the soil mass but also on the rate at which its structure degrades under climatic and anthropogenic loading. This problem is particularly acute in Uzbekistan, where extensive territories are affected by aridity, salinization, and declining soil quality. Recent evidence indicates that more than half of the land area of the country is affected by degradation processes, while humus content in many soils declined by approximately 1.3-1.5 times between 1990 and 2020 (Umarov et al., 2025). These trends intensify the instability of near-surface deposits and aggravate engineering risks for buildings, transport infrastructure, and utilities.

Loess soils constitute one of the most problematic foundation media in Central Asia. They are usually composed of silt-dominated particles, exhibit a high-porosity open fabric, and preserve an apparently stable structure in the dry state due to weak carbonate and clay bonds. After wetting, however, this metastable structure collapses, leading to abrupt settlement, a decrease in stiffness, and a reduction in shear strength (Muhs, 2018). In addition to natural rainfall variability, hydro-collapse may be triggered by irrigation leakage, groundwater fluctuations, or accidental flooding. In urbanized territories, such processes are frequently expressed through differential settlement, cracking of walls, loss of serviceability, and reduction of the calculated safety margin.

Conventional stabilization methods, including compaction, replacement, and cement-based grouting, remain widespread in foundation engineering. However, their effectiveness in saline arid settings is constrained by three major factors: (1) high carbon intensity of Portland cement production; (2) durability loss in sulfate-rich and chemically aggressive soils; and (3) ecological disturbance caused by strong alkalization and reduction of soil biological activity (Turner & Collins, 2013; Alsalman et al., 2021). These constraints have stimulated interest in lower-carbon and more chemically compatible alternatives, especially biostabilization and geopolymer technologies.

The research gap lies in the insufficiently structured comparison of how these two innovative approaches transform the mechanical properties of loess and how such transformations should be interpreted in terms of bearing capacity and settlement behavior under arid-region conditions. The aim of this article is therefore to evaluate the engineering potential of microbiologically induced calcite

precipitation (MICP) and geopolymer injection for collapsible loess soils and to explain their implications for foundation performance in Uzbekistan. The working hypothesis is that both methods improve bearing capacity through different but complementary mechanisms: MICP through bio-mineral bridging and permeability reduction, and geopolymers through rapid formation of a chemically resistant aluminosilicate framework.

2. Materials and Methods

This research was designed as a comparative analytical study based on published scientific evidence rather than as an original field experiment. The IMRAD structure was retained in order to present the analytical logic in a form acceptable for scientific journals.

The evidence base included peer-reviewed journal articles and review papers on four interrelated topics: (1) the mineralogical and geotechnical properties of loess; (2) land degradation and salinization processes in Uzbekistan; (3) MICP and related carbonate-precipitation methods for soil improvement; and (4) geopolymer binders derived from industrial aluminosilicate wastes. Priority was given to sources that reported mechanical, hydraulic, durability, or environmental performance indicators relevant to foundation engineering.

The analytical procedure consisted of three stages. First, the environmental and geological preconditions of loess degradation in arid regions were systematized. Second, the mechanisms of strength gain and structural densification under MICP and geopolymer treatment were compared. Third, the engineering consequences of these changes were interpreted through the classical bearing-capacity expression:

$$q_{ult} = c' N_c s_c d_c + q N_q s_q d_q + 0.5 \gamma B N_\gamma s_\gamma d_\gamma$$

where q_{ult} is the ultimate bearing capacity, c' is effective cohesion, q is surcharge at foundation level, γ is unit weight of soil, B is foundation width, and N_c , N_q , and N_γ are bearing-capacity factors dependent primarily on the internal friction angle. Within this framework, any treatment that increases apparent cohesion, friction angle, stiffness, or resistance to wetting should increase the safe bearing capacity and reduce settlement. The interpretation remained qualitative to semi-quantitative, because the reviewed studies differ in soil type, treatment recipe, curing time, and test configuration.

A limitation of the method is that literature-derived results cannot replace site-specific field testing for Samarkand loess. Consequently, the article focuses on engineering tendencies, mechanistic interpretation, and technology selection criteria rather than on a universal design equation.

3. Results

3.1. Environmental and geotechnical preconditions of loess instability

Loess deposits in Central Asia are predominantly aeolian silt formations with variable carbonate content and a fragile pore framework. Their engineering behavior is governed by a combination of open structure, low natural moisture, weak cementation, and sensitivity to suction loss. In dry conditions, such soils may appear sufficiently strong for construction; after wetting, their particle skeleton rearranges, soluble bonds weaken, and compressibility rises sharply. The hazard is amplified in regions exposed to irrigation, saline groundwater, and large seasonal temperature amplitudes.

In Uzbekistan, soil degradation is additionally influenced by regional salinity and dust transport associated with the desiccation of the Aral Sea. Although these processes act at different spatial scales, they contribute to the same engineering outcome: deterioration of near-surface soil structure and increased uncertainty in foundation behavior. Studies from Central Fergana confirm that irrigated and saline soils of Uzbekistan often exhibit low organic matter content and chemically active salt compositions that may alter the long-term performance of traditional binders (Turdaliev et al., 2023). For engineering practice, this means that any stabilization method must be evaluated not only for initial strength but also for chemical compatibility and moisture sensitivity.

3.2. Effect of MICP on loess soil properties

MICP is based on the ability of ureolytic microorganisms, most commonly *Sporosarcina pasteurii*, to induce calcium carbonate precipitation within the pore space of soil. The precipitated calcite acts as a bio-cement, bridging adjacent particles and reducing the number of unstable contact points. Contemporary reviews indicate that the efficiency of MICP depends on bacterial activity, reagent concentration, pore-size distribution, temperature, and solution delivery strategy (Zhang et al., 2025; Payan et al., 2024).

For loess-like and silty soils, the principal engineering effect of MICP is not simply an increase in unconfined compressive strength, but a transformation of the failure mechanism. The untreated material typically behaves as a weak, wetting-sensitive aggregate with low apparent cohesion. After treatment, the calcite-coated contacts generate a more coherent structure, improve shear resistance, and slow down water ingress. In practical terms, this combination is crucial for collapsible soils because hydro-collapse is controlled by both bond dissolution and rapid wetting. Literature reviewed in this study consistently shows the following tendencies under optimized MICP conditions: higher unconfined compressive

strength, greater apparent cohesion, moderate increase in internal friction, and a marked reduction in permeability.

From a structural viewpoint, MICP is especially attractive for contexts where massive injection pressure or strong alkalization is undesirable. The method is minimally invasive, compatible with irregular pore geometries, and conceptually close to natural mineralization. At the same time, MICP has technological limitations. Urea hydrolysis generates ammonium, which may require capture or rinsing strategies in environmentally sensitive sites. In addition, performance becomes less predictable in very fine-grained soils, where transport of bacterial and cementation solutions is constrained.

3.3. Effect of geopolymer injection on loess stabilization

Geopolymers are alkali-activated aluminosilicate binders synthesized from materials such as fly ash, slag, or metakaolin. In contrast to MICP, their strengthening effect is based on rapid dissolution and polycondensation of silica- and alumina-bearing precursors into a rigid three-dimensional network. Reviews on waste-based geopolymers show that such systems can substantially reduce environmental impact relative to ordinary Portland cement while also providing high early strength and superior chemical resistance (Ren et al., 2021; Alsalman et al., 2021).

For loess foundation reinforcement, geopolymer injection is attractive because it can be localized, fast-setting, and effective in water-bearing or saline zones. Once injected, the material may fill macrovoids, create rigid lenses or columns, and increase the stiffness of the treated volume. This mechanism is particularly relevant beneath existing buildings, where rapid reduction of settlement risk is often more important than uniform treatment of a large soil mass. Recent studies on loess stabilization and carbonate/grouting approaches further suggest that modern alkali-activated or carbonate-based systems can be designed for improved durability and more controlled distribution in the soil matrix (Hatefi et al., 2026; Li et al., 2026).

The main engineering advantage of geopolymer treatment over conventional cement grouting is its better resistance in chemically aggressive environments. Sulfate-rich and salt-affected soils frequently damage ordinary cementitious matrices; geopolymer systems are generally less vulnerable to such deterioration. Their main limitations are technological rather than conceptual: variability of industrial precursor composition, the need for mixture optimization, and careful control of viscosity and injection pressure in the field.

Table 1. Comparative engineering characteristics of MICP and geopolymer stabilization

Criterion	MICP	Geopolymer injection
Dominant mechanism	Calcite precipitation at particle contacts by ureolytic or related carbonate-precipitation processes	Formation of an alkali-activated aluminosilicate binder within pores, fissures, and injection bulbs
Primary geotechnical effect	Increase in apparent cohesion; reduction in permeability; mitigation of hydro-collapse sensitivity	Rapid increase in stiffness and local strength; void filling; creation of rigid inclusions
Best use cases	Sensitive sites, heritage structures, low-pressure treatment, surface or near-surface loess stabilization	Fast remedial intervention, saline soils, existing foundations requiring local reinforcement
Main environmental issue	Possible ammonium generation and reagent-management requirements	Need for alkali handling and consistency control of industrial precursors
Main engineering limitation	Restricted transport in very fine-grained soils; curing depends on biological activity	Field control of viscosity, setting time, and injection pressure is critical

3.4. Implications for foundation bearing capacity and settlement

The reviewed evidence indicates that both technologies are capable of increasing the bearing capacity of loess foundations, but they do so through different parameter pathways. MICP primarily improves apparent cohesion, internal bonding, and water resistance. Geopolymers primarily increase stiffness, provide local structural inclusions, and improve resistance to chemically aggressive pore environments. In the Terzaghi-Meyerhof framework, MICP affects c' and, to a lesser extent, the friction-angle-dependent bearing factors. Geopolymers influence the same parameters indirectly, while also redistributing stresses and reducing compressibility within the treated zone.

This distinction has design implications. When the principal risk is hydro-collapse due to sudden wetting of a loose, unsaturated loess layer, the combination of permeability reduction and contact cementation provided by MICP is highly valuable. When the principal risk is existing settlement, void migration, or the need for rapid intervention beneath an operating structure, geopolymer injection offers a more immediately controllable engineering response. Consequently, the technologies should not be treated as competitors in absolute terms; they are complementary tools for different geotechnical scenarios.

4. Discussion

The analysis confirms the initial hypothesis: both MICP and geopolymer treatment can significantly improve the engineering behavior of collapsible loess, but the mechanisms and design consequences differ. This distinction is important for journals and practitioners because discussions of innovative stabilization methods often remain descriptive and do not explicitly connect microstructural change with bearing-capacity parameters.

For the Samarkand region, the most important practical conclusion is that technology choice should be controlled by hydrogeological regime, salinity, structural sensitivity of the site, and required intervention speed. MICP is more suitable for environmentally sensitive areas, low-pressure treatment, heritage buildings, and cases where maintaining soil biocompatibility is desirable. Geopolymers are more suitable for fast remedial work, saline soils, and local reinforcement under existing foundations. In both cases, preliminary geotechnical diagnostics should include moisture state, collapse potential, salt composition, permeability, and deformability parameters.

The environmental dimension also deserves emphasis. Cement-based stabilization is still technically effective, but its high carbon burden and durability limitations in aggressive soils make it a less sustainable baseline. Comparative life-cycle studies show that alkali-activated systems and carbonate-precipitation technologies may offer substantial environmental benefits when optimized, although MICP performance depends strongly on reagent selection and ammonium management (Alotaibi et al., 2022; Alsalman et al., 2021). Thus, sustainability claims should not be generalized without considering the full process chain.

The main limitation of the present article is methodological: it synthesizes published data and therefore cannot provide calibrated design values for a specific construction site. Further research for Uzbekistan should combine laboratory treatment of local loess, mineralogical analysis, oedometer and plate-load testing, and pilot-scale field verification. It is also advisable to assess hybrid solutions, for example, surface biostabilization combined with deeper geopolymer reinforcement in zones of concentrated stress.

5. Conclusion

Loess soils of arid regions represent a high-risk foundation medium because their structure is metastable and strongly sensitive to wetting, salinity, and anthropogenic changes in the water regime. Under such conditions, conventional cement-based stabilization is increasingly limited by environmental cost and durability concerns.

The comparative IMRAD-based analysis carried out in this study demonstrates that MICP and geopolymer injection are scientifically grounded alternatives for improving the bearing capacity of collapsible loess soils. MICP enhances contact cementation, reduces permeability, and mitigates hydro-collapse sensitivity. Geopolymers ensure rapid hardening, chemical resistance, and efficient local reinforcement of weak foundation zones.

From an engineering perspective, the choice between these technologies should be based on the dominant failure mechanism, site sensitivity, salinity regime, and required speed of intervention. From a scientific perspective, the results support a transition toward lower-carbon geotechnical methods in arid regions of Uzbekistan.

Future work should focus on field-scale validation for Samarkand loess, optimization of reagent systems under saline conditions, and quantitative integration of treatment effects into design models for bearing capacity and settlement.

REFERENCES:

Alsaman, A., Assi, L. N., Kareem, R. S., Carter, K., & Ziehl, P. (2021). Energy and CO₂ emission assessments of alkali-activated concrete and ordinary Portland cement concrete: A comparative analysis of different grades of concrete. *Cleaner Environmental Systems*, 3, 100047. <https://doi.org/10.1016/j.cesys.2021.100047>

Alotaibi, E., Arab, M. G., Abdallah, M., Nassif, N., & Omar, M. (2022). Life cycle assessment of biocemented sands using enzyme induced carbonate precipitation (EICP) for soil stabilization applications. *Scientific Reports*, 12, 6032. <https://doi.org/10.1038/s41598-022-09723-7>

Hatefi, M. H., Arabani, M., Hosseinpour, I., Payan, M., & Zanganeh Ranjbar, P. (2026). Mechanical behavior and microstructural investigation of loess sustainable stabilization using nanosilica and GGBS. *Scientific Reports*, 16, 4187. <https://doi.org/10.1038/s41598-025-34210-0>

Li, Y., Wang, L.-Z., He, X., Mei, S., Cui, M., & Guo, Z. (2026). One-phase EICP coupled model and suction assisted grouting for ground improvement. *Canadian Geotechnical Journal*. Advance online publication. <https://doi.org/10.1139/cgj-2025-0995>

Micklin, P. (2007). The Aral Sea disaster. *Annual Review of Earth and Planetary Sciences*, 35, 47-72. <https://doi.org/10.1146/annurev.earth.35.031306.120120>

Muhs, D. R. (2018). The geochemistry of loess: Asian and North American deposits compared. *Journal of Asian Earth Sciences*, 155, 81-115. <https://doi.org/10.1016/j.jseaes.2017.10.032>

Payan, M., Khoshdel Sangdeh, M., Salimi, M., Zanganeh Ranjbar, P., Arabani, M., & Hosseinpour, I. (2024). A comprehensive review on the application of microbially induced calcite precipitation (MICP) technique in soil erosion mitigation as a sustainable and environmentally friendly approach. *Results in Engineering*, 24, 103235. <https://doi.org/10.1016/j.rineng.2024.103235>

Ren, B., Zhao, Y., Bai, H., Kang, S., Zhang, T., & Song, S. (2021). Eco-friendly geopolymer prepared from solid wastes: A critical review. *Chemosphere*, 267, 128900. <https://doi.org/10.1016/j.chemosphere.2020.128900>

Turdaliev, A., Askarov, K., Abakumov, E., Makhkamov, E., Rahmatullayev, G., Mamajonov, G., Akhmadjonov, A., & Axunov, A. (2023). Biogeochemical state of salinized irrigated soils of Central Fergana (Uzbekistan, Central Asia). *Applied Sciences*, 13(10), 6188. <https://doi.org/10.3390/app13106188>

Turner, L. K., & Collins, F. G. (2013). Carbon dioxide equivalent (CO₂-e) emissions: A comparison between geopolymer and OPC cement concrete. *Construction and Building Materials*, 43, 125-130. <https://doi.org/10.1016/j.conbuildmat.2013.01.023>

Umarov, S., Nurbekov, A., Nishanov, N., Kosimov, M., Bobomurotov, S., Umarov, M., Khaitov, B., & Namozov, N. (2025). Land degradation in Uzbekistan: Key challenges and sustainable solutions. *Frontiers in Sustainable Food Systems*, 9, 1676403. <https://doi.org/10.3389/fsufs.2025.1676403>

Zhang, X., Wang, H., Wang, Y., Wang, J., Cao, J., & Zhang, G. (2025). Improved methods, properties, applications and prospects of microbial induced carbonate precipitation (MICP) treated soil: A review. *Biogeotechnics*, 3(1), 100123. <https://doi.org/10.1016/j.bgtech.2024.100123>

Gulsara, R. (2023). Modernization of Digital Transformation in Construction. *INTERNATIONAL JOURNAL OF INCLUSIVE AND SUSTAINABLE EDUCATION*, 2(1), 51-53.

Rajapovna, R. G. (2025). IMPROVEMENT OF THE STAFF TRAINING SYSTEM AND REFLECTIONS ON NEW PEDAGOGY OF ARCHITECTURAL AND CONSTRUCTION EDUCATION. *SHOKH LIBRARY*, 1(12).

Makhamova, M. (2024). Architecture for an inclusive society: creating accessible environments for people with disabilities, designing inclusive spaces and buildings. *Science and innovation*, 3(C3), 120-149.

Bazarovna, M. M. (2023). BUILDING MULTICULTURAL ARCHITECTURE IN THE CITY ENVIRONMENT FOR THE DEVELOPMENT OF SPIRITUALITY:

sacred, multiculturalism, multicultural space, model. JOURNAL OF ENGINEERING, MECHANICS AND MODERN ARCHITECTURE, 483-490.

Makhamova, M., & Azimova, D. (2025). Forerunners of the Study and Analysis of the Basics of the Typology of Buildings and Elements of Landscape Architecture of Modern Wellness Centers. TATALOKA Учредители: Institute of Research and Community Services Diponegoro University (LPPM UNDIP), 27(1), 95-115.

Rajapovna, R. G. (2025). IMPROVEMENT OF THE STAFF TRAINING SYSTEM AND REFLECTIONS ON NEW PEDAGOGY OF ARCHITECTURAL AND CONSTRUCTION EDUCATION. SHOKH LIBRARY, 1(12).

Kamilova, M. E., & Xamrakulov, O. M. (2023). PROBLEMS AND MAXIMUM PRESERVATION OF THE TRADITIONAL STRUCTURE OF HOUSING IN THE HISTORICAL PART OF THE CITY OF SAMARKAND. *Procedia of Theoretical and Applied Sciences*.