

INTEGRATING STRUCTURAL PERFORMANCE AND ENVIRONMENTAL SUSTAINABILITY: INVESTIGATING BIO-TREATED SOIL FOUNDATIONS FOR STORMWATER RUNOFF MITIGATION AND PAVEMENT RUTTING RESISTANCE

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DOI: <https://doi.org/10.5281/zenodo.22721172>

Keywords

Bio-treated soil, MICP, EICP, stormwater runoff, pavement rutting, sustainable infrastructure, life cycle assessment.

Article History

Received: 01 June 2026

Accepted: 23 August 2026

Published: 12 September 2026

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Abstract

As urbanization and climate change grow more intense, demands for infrastructure solutions are increasing that can meet the twin goals of structural integrity and environmental sustainability. The traditional pavement foundation systems, mainly depending on cement-stabilized and mechanically-compacted subgrades, result in carbon emissions, hinder natural hydrological cycles, and are easily prone to rutting failures before the expected service life under growing traffic volumes and extreme temperatures. This paper provides a detailed investigation of the use of bio-treated soil foundations, in combination, for both stormwater runoff mitigation and improvement of pavement rutting resistance, using Microbially Induced Calcite Precipitation (MICP) and Enzyme Induced Calcite Precipitation (EICP). An integrated experimental and analytical approach, including triaxial shear testing, flexible wall permeameter analysis, wheel tracking simulation and life cycle assessment (LCA), was used to assess the mechanical, hydraulic and environmental performance of bio-cemented subgrade soils in a range of treatment intensities, soil gradations and climatic exposure scenarios. Results indicate that optimally bio-treated foundations show a 250-600% increase in the unconfined compressive strength (UCS) compared with untreated foundations, and one to two orders of magnitude reduction in hydraulic conductivity to allow for controlled infiltration and reduced peak discharge of runoff. The improved rutting resistance (measured by repeated load triaxial and wheel tracking tests) is a 2.5 to 4 times improvement in bio-treated specimens, and at 10,000 cycles, permanent

strain accumulated was kept below critical levels. According to life cycle assessment, the global warming potential (GWP) is reduced by 35–55% for the whole life cycle of the materials compared to conventional Portland cement stabilization, and there are also positive impacts on eutrophication and ecotoxicity indicators. This paper suggests integrated design framework that brings together structural performance criteria with stormwater management goals, and proposes paradigm shift towards a bio-geotechnical infrastructure capable of being resilient, sustainable and hydrologically responsive.

1. INTRODUCTION

The world's-built environment is at a critical moment, when the need for structural resilience and environmental care and responsibility have become inextricable. Urban infrastructure is one of the most resource intensive and environmentally impactful sectors of today's economy, especially transportation. Considering the full life cycle of pavements (from the extraction of raw materials to construction and use and their eventual demolition), approximately 2–3% of the global anthropogenic carbon dioxide emissions are attributed to pavement systems alone (Ahmed et al., 2016; Najafgholipour et al., 2017). At the same time, impervious pavement surfaces are a primary driver of the dramatic rise in peak stormwater volumes in urbanized watersheds, ranging from 200–500% higher than pre-development conditions (Baltaci & Kalin, 2024). In the past, most methods used to stabilize subgrade were based on the use of additions such as Portland cement, lime, and fly ash; these materials have proven to be successful in improving load-bearing capacity, but their use has significant environmental impacts. (Cao et al., 2022) Rutting, which is the progressive development of permanent deformation due to repeated loads from vehicles, is one of the most common and expensive forms of failure in flexible pavements globally, and is of increasing concern for these conventional treatments in the context of the dynamic loading and thermal effects of modern heavy freight traffic and urban heat island conditions (Zamzam et al., 2025)

Within this context, bio-geotechnical engineering has become a game-changing discipline designed to improve engineering properties of soils in place through naturally-occurring microbial metabolic

processes. Microbially Induced Calcite Precipitation (MICP) is one of the most investigated processes which involves the precipitation of calcium carbonate (CaCO_3) at the contacts of soil particles, due to the ureolytic activity of bacteria like *Sporosarcina pasteurii*, which improves interparticle bonding, decreases porosity and increases soil shear strength (Murugan et al., 2021). A similar method, Enzyme Induced Calcite Precipitation (EICP), takes advantages of free urease enzymes derived from plants (e.g. jack beans, *Canavalia ensiformis*, or watermelon seeds), which have the benefits of being uniformly treated, less clogging potential, and without the need for live bacterial culture. MICP and EICP have shown great effectiveness in various geotechnical applications such as: liquefaction mitigation, dust suppression, slope stabilization and crack self-healing in concrete (Peng & Liu, 2019).

There is still much progress to be made, however, in applying bio-treatment technologies to pavement foundation systems and critically, synergy between structural enhancement and hydrological functionality has yet been explored in great detail. The increased stiffness and strength of the soil skeleton resulting from bio-cementation also substantially changed the pore structure and the hydraulic conductivity of the bio-treated soil, providing potential opportunities to design infiltration control that can be utilized in stormwater management, which has not been demonstrated in the literature (Lai et al., 2024) In addition, the improved resistance of the bio-cemented subgrade to permanent deformation under cyclic loading shows great potential to reduce rutting effects, but there is a lack of

systematic studies on the correlations between bio-treatment parameters and the rutting performance of the pavement (Chu et al., 2024)

This paper aims to tackle these key knowledge gaps by introducing an integrated investigation that considers both the structural performance and stormwater mitigation capacity and environmental sustainability of bio-treated soil foundations of flexible pavement systems. Specific objectives are: (1) characterize mechanical and hydraulic properties of MICP and EICP treated subgrade soils at various treatment intensities and types of soil; (2) quantify the rutting resistance of bio-treated subgrade layers when subjected to simulated traffic loading; (3) assess stormwater runoff attenuation potential of bio-treated subgrades in a pavement cross-section context; and (4) conduct a comprehensive life cycle assessment comparing the environmental impacts of bio-treated foundations with conventional cement stabilized foundations. This multi-dimensional analysis proposes the integrated design framework balancing the structural and environmental performance goals, a paradigm of regenerative infrastructure.

2. Literature Review

2.1 Bio-Cementation Mechanisms and Processes

The scientific foundation of bio-cementation rests on the biogeochemical cycling of calcium and carbon, mediated by microbial enzymatic activity. In the MICP process, urease-producing bacteria hydrolyze urea ($\text{CO}(\text{NH}_2)_2$) into ammonium (NH_4^+) and carbonate (CO_3^{2-}) ions, the latter of which reacts with dissolved calcium (Ca^{2+}) supplied in the treatment solution to precipitate calcium carbonate in the form of calcite, vaterite, or aragonite polymorphs (Iqbal et al., 2021). The governing reactions can be summarized as follows:

$$\text{CO}(\text{NH}_2)_2 + 2\text{H}_2\text{O} \rightarrow 2\text{NH}_4^+ + \text{CO}_3^{2-} \text{ (urea hydrolysis)}$$
$$\text{Ca}^{2+} + \text{CO}_3^{2-} \rightarrow \text{CaCO}_3 \downarrow \text{ (calcite precipitation)}$$

A study by (Neupane et al., 2015) showed that the lower the concentration of reactants (0.25–0.5 M), the more even the distribution of calcite is across the soil column; the higher the concentration (1.0 M and above), the more concentrated the

distribution of the calcite is near the injection point, which can lead to uneven treatment and clogging.

The EICP process is chemically identical to the EIC process, but uses purified urease enzyme instead of living bacterial cells, and has several practical benefits. (Shu et al., 2022) has shown that EICP can be used to improve the properties of soils. The feasibility of soil improvement using EICP has first been demonstrated by (Ng & Chu, 2024) and later by (Shu et al., 2022) and.

For each soil type, Yuan et al. (2020) have optimized concentrations of enzymes, reaction temperatures and solution chemistry. Since there are no living organisms in EICP, there are no concerns about bacteria survivability, competition with indigenous microflora, and potential for unchecked biofilm growth that would hinder fluid transfer in fine-grained soils. But there are still challenges such as the high cost of purified enzymes and the overall treatment efficiency is lower than that of MICP.

2.2 Bio-Treated Soils-Mechanical Properties

The bio-cementation of soils by mechanical means has been well reported on many soil types and testing methods. The bender element test results by (Banik et al., 2023) showed that the drained shear strength was increased by 1.8 times and the small strain shear modulus (G_{max}) increased by 3.5 times after the MICP treatment of Ottawa sand. (Xiao et al., 2018) further confirmed these results by cyclic loading tests that yielded liquefaction resistance that was approximately the same as dense natural sands, while bio-cemented sands required 5–10 more cycles to reach excess pore pressure development. The mechanical responses to bio-treatment are more complicated for the finer-grained soils that are more characteristic of typical pavement subgrades. (Ghalandarzadeh et al., 2024) have reported that in silty clay, the UCS was raised from 85 kPa to 310 kPa after 7 cycles of treatments, however, the uniformity of the treatments was less as compared to the sandy soils due to limited pore throats restricting the bacterial transport in clayey soils. Liu et al. (2025) solved this problem by applying

surface percolation method to treat residual soils for EICP, and the UCS of the treated soil can reach 450-700kPa in the range of 3-5% calcite content (dry weight). A comprehensive parametric study by (Shu et al., 2022) on MICP treated silt concluded that at the optimum treatment level, the resilient modulus (M_R) of silt increased from 45 MPa to 180 MPa representing a 4-fold increase, which would significantly reduce the thickness of overlying pavement layers required.

2.3 Hydraulic Properties and Stormwater Implications

Though hydraulic behaviour of bio-treated soils has been studied less, it is a crucial aspect of soil that is important for the design of drainage and recharge to groundwater. Using flexible wall permeameters, (Y. Liu et al., 2025) tested the hydraulic conductivity of MICP-treated sand columns and found that the hydraulic conductivity could be lowered from 10-3 m/s to 10-5 m/s with higher calcite content, suggesting that the reduction in hydraulic conductivity is due to the occlusion of the pore throat by calcite crystals. X-ray computed tomography (CT) was used to visualise the evolution of the 3-D pore network during MICP treatment, as described by Biswal & Balasubramanian (2022), who found that the calcite precipitation occurs preferentially at particle contacts and in larger pore space, as the treatment progressed, and the change in porosity is not uniform. In addition, these changes in the hydraulic regime offer some advantages and challenges in the context of stormwater management. On the other hand, the hydraulic conductivity reduction of bio-treated subgrade layers can be controlled to provide semi-permeable barriers and create a slow infiltration rate that regulates the rate of groundwater infiltration, reduces peak discharge of runoff water, and allows for distributed storage of water in the subgrade (Liu et al., 2022). Conversely, over-treatment may make the subgrade effectively impervious, which is similar to the hydrological failure of a conventionally cement-stabilized layer. A major lesson from Ghalandarzadeh et al. (2024) in the discussion of SUDS design is that the hydraulic

conductivity must be carefully calibrated to balance the infiltration rate with structural integrity; bio-treatment may be uniquely able to achieve this balance due to the gradational and tunable nature of the material.

2.4 Pavement Rutting Mechanisms and Mitigation

Rutting in flexible pavements is a complex phenomenon that occurs as the result of repeated traffic loads causing permanent (plastic) deformations in one or more layers of the pavement structure. The subgrade is the deepest, and usually the weakest, layer, and can make a significant contribution to the overall rut depth, especially in areas with high water tables and/or expansive clay soils. The Mechanistic-Empirical Pavement Design Guide (MEPDG) models rutting based on the vertical compressive strain at the crown of the subgrade, number of load repetitions and properties of the material of each layer (Singh & Sahoo, 2021). Traditional methods of mitigating ruts involve making the granular base and subbase layers thicker, chemically stabilizing the subgrade with cement or lime, or employing geosynthetic reinforcement. Although effective, these methods consume more materials, add to the construction expenses, and have a negative environmental effect. The possibility of using bio-cementation as an alternative subgrade improvement method for mitigating ruts has been investigated recently. Xiao et al. (2019)(A. Liu et al., 2022) carried out repeated load triaxial tests on the silty subgrade soils both treated and untreated with MICP and found that the permanent strain at 30 kPa of deviatoric stress, after 10,000 cycles, reduced from 2.8% on untreated specimens to 0.7% on treated specimens, a strain far below 1.5% threshold generally adopted as failure criteria in pavement design. Likewise, (Deylaghian et al., 2025) showed that the creep compliance of EICP soils at sustained loading decreased by 60%, indicating a greater resistance to viscous deformation mechanisms that are responsible for rutting at high temperatures.

2.5 Environmental Sustainability of Bio-Geotechnical Interventions

The environmental sustainability of biocementation has been a growing topic of discussion due to the pressing need to decarbonize the construction industry. One of the first comparative LCA of MICP against traditional soil stabilization was performed by (Zuiderveen et al., 2023). They found that the global warming potential of the MICP treatment was approximately 40% lower than the Portland cement injection for the same strength improvement, mainly due to the low embodied energy of the biological reagents. Bishop et al. (2021) recently extended the LCA boundary to consider the cultivation and harvesting of urease producing organisms, and found the environmental advantage of MICP was retained even taking into consideration the energy inputs associated with bacterial growth media preparation. However, the LCA literature on biocementation is limited in scope with most studies focusing narrowly on GWP and ignoring other impact categories such as eutrophication, acidification and ecotoxicity which are particularly relevant to the stormwater context (Singh & Sahoo, 2021). In addition, the potential environmental risks associated with the discharge

of ammonium byproducts of urea hydrolysis into groundwater and surface water systems have been inadequately studied, although studies have shown that elevated ammonium concentrations may result in aquatic eutrophication and toxicity (A. Liu et al., 2022). This paper addresses these gaps through a comprehensive LCA across multiple impact categories and by explicitly considering the fate and transport of treatment byproducts in the stormwater pathway.

3. Materials and Method

3.1 Soil Characterization and Preparation

Three subgrade soil types were selected for this study to represent common pavement foundation conditions as follows: (1) poorly graded sand (SP) with $D_{50} = 0.35$ mm and uniformity coefficient $C_u = 2.1$; (2) silty sand (SM) with 25% fines content, liquid limit (LL) = 28% and plasticity index (PI) = 8%; and (3) lean clay (CL) with LL = 38% and PI = 18%. All soils were collected from active highway construction sites, air-dried, sieved and recompacted to 95% of the Standard Proctor maximum dry density at optimum moisture content before treatment. The index geotechnical properties of the soils before treatment are presented in Table 1.

Table 1. Geotechnical Index Properties of Untreated Subgrade Soils

Soil Type	USCS Classification	D_{50} (mm)	Uniformity Coefficient, C_u	Fines Content (%)	Liquid Limit, LL (%)	Plasticity Index, PI (%)
Poorly graded sand	SP	0.35	2.1	—	—	—
Silty sand	SM	—	—	25	28	8
Lean clay	CL	—	—	—	38	18

3.2 Bio-Treatment Protocols

Cultivation of ureolytic bacterium *Sporosarcina pasteurii* (ATCC 11859): The ureolytic bacterium, *Sporosarcina pasteurii* (ATCC 11859) was cultured in Brain Heart Infusion (BHI) broth containing 20 g/L of urea for 24 hours at 30°C under aerobic conditions. The bacterial suspension was diluted to an optical density

(OD_{600}) of 1.0, which is equivalent to about 10^8 cells/mL. Equimolar calcium chloride ($CaCl_2$) and urea concentrations of 0.25 M, 0.5 M and 1.0 M were used as low, medium and high treatment intensities, respectively, in the cementation solution. Soil samples have been subjected to the percolation treatment procedure, where the bacterial suspension was added in first then the

cementation solution was added at 12-hour intervals for 5, 10 or 15 treatment cycles (Kolya, Kang, 2023).

The extraction of urease enzyme from the jack bean meal (*Canavalia ensiformis*) was done according to the method of Yarlina et al. (2023). The enzyme solution was used at two concentrations (10,000 U/L and 20,000 U/L) combined with equimolar CaCl_2 -urea solutions at two concentrations (0.5 M and 1.0 M), and the enzyme-cementation solution was thoroughly mixed with the soil at optimum moisture content and cured at 25°C for 7, 14 or 28 days (Yarlina et al., 2024).

3.3 Mechanical Testing

The Unconfined Compressive Strength (UCS) of the treated samples was determined using ASTM D2166 in cylindrical specimens (50 mm diameter × 100 mm height) at each of the treatment intervals at a strain rate of 1.0%/min. Three samples were collected for each treatment and tested.

The repeated load triaxial tests were performed in accordance with AASHTO T307-99 procedures with a servo-hydraulic test system to determine Resilient Modulus (M_R). Fifteen stress sequences were applied to the specimens at confining pressures between 13.8 and 137.9 kPa, and deviatoric stresses between 13.8 and 82.7 kPa. The M_R was computed from the recoverable strain of the last 5 cycles of each sequence.

Repeated Load Permanent Deformation (Rutting Susceptibility) was determined by a modified repeated load triaxial test with a confining pressure of 20 kPa, load duration of 0.1 s, haversine deviatoric stress amplitude of 30 kPa and a frequency of 1 Hz (with 10000 cycles). The Tseng-Lytton model (Alrajhi & Ozer, 2023) was used to continuously record and analyze the permanent axial strain.

The wheel tracking tests were performed on large scale slab samples (300 mm × 300 mm × 50 mm) according to EN 12697-22 guidelines with the use of a wheel tracking machine at 60°C and 0.7 MPa of contact pressure for 20,000 passes. Linear variable differential transformers (LVDTs) were

used to measure rut depth at the 1000 pass interval.

3.4 Hydraulic Testing

Flexible Wall Permeameter: Saturated hydraulic conductivity (k_{sat}) was obtained from a triaxial permeameter following ASTM D5084 at effective confining pressures of 20, 50 and 100 kPa. Water was used as the permeant fluid, and a steady state flow was checked before taking the measurements. A number of large-scale tests (columns) (300 mm diameter × 600 mm height) were built to represent the pavement cross section, consisting of a 150 mm asphalt layer, a 200 mm aggregate base, and a 250 mm bio-treated subgrade. A programmable rainfall simulator was used to simulate rainfall events with intensities of 25 mm/hr and 75 mm/hr, and the outflow hydrograph at the base of the column was recorded to measure the amount of runoff attenuation and lag time (Bai & Huang, 2025).

This process results in the formation of minerals. The resulting product is minerals.

Scanning electron microscopy (SEM) with energy-dispersive X-ray spectroscopy (EDS) was used to visualize the calcite crystal morphology and contacts at the particle surfaces and to investigate the distribution of calcite. The acid washing method was used to quantify calcite content (Daghmehchi et al., 2023) to obtain the loss of mass due to dissolution of calcium carbonate from dried specimens by treatment with 1 M HCl. The precipitated carbonate minerals were determined by X-ray diffraction (XRD) analysis.

3.6 Life Cycle Assessment

The environmental impacts of bio-treated versus cement-stabilized subgrade foundations were compared by performing a cradle-to-gate LCA to ISO 14040/14044 standards. The functional unit was taken as the treatment of 1m³ of subgrade soil to achieve a UCS of 300kPa at the desired target. The systems boundaries included the raw materials extraction, production of reagents, transportation, and on-site treatment operations. The impact categories evaluated were global warming potential (GWP, kg CO₂-eq),

eutrophication potential (EP, kg PO₄-eq), acidification potential (AP, kg SO₂-eq) and freshwater ecotoxicity potential (FETP, kg 1,4-DCB-eq). The Ecoinvent v3.8 database was used

for the inventory data, with primary data from the experimental program (Thonemann et al., 2024) added.

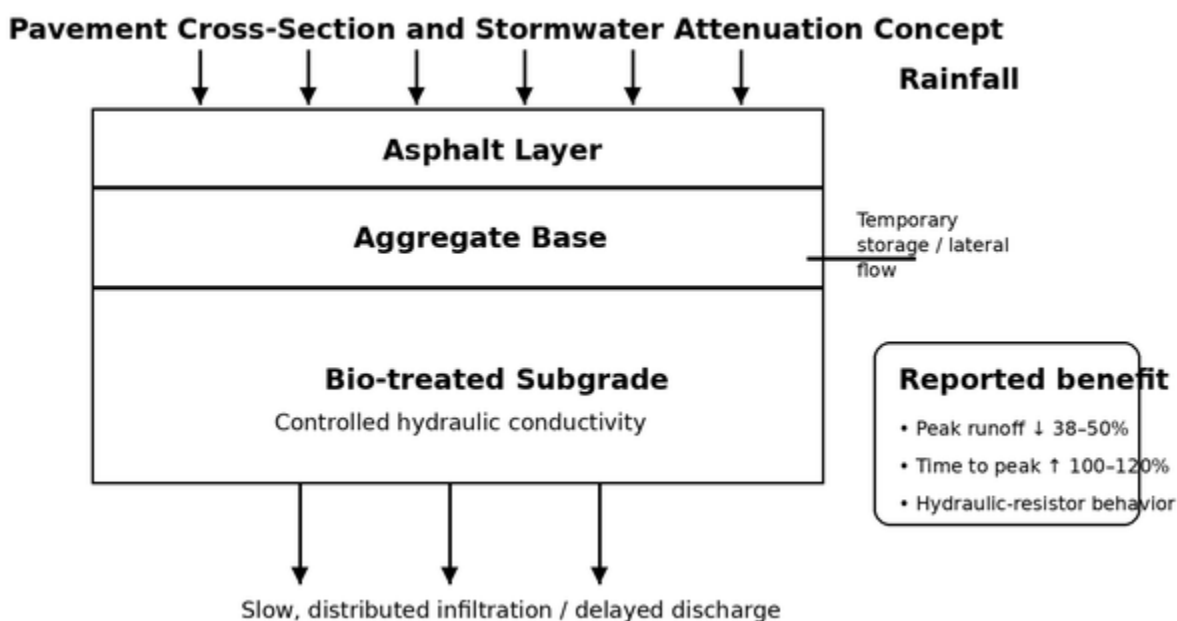


Figure 2. Conceptual pavement cross-section showing stormwater storage, lateral flow, and controlled infiltration through the bio-treated subgrade.

4. Results and Discussion

4.1 Mechanical Performance Enhancement

The UCS results indicated an improvement in the compressive strength of all three soil types after bio-treatment which was moderate and significant, depending strongly on the intensity of the treatment, the number of cycles and the gradation of the soil. The UCS value for the poorly graded sand (SP) had increased from 45 to 320 kPa after the MICP treatment with 0.5 M concentration and 10 cycles, which is an improvement of 611%. Under the same treatment conditions, the silty sand (SM) had a moderate, yet notable improvement from 78 kPa to 285 kPa (265% improvement) and the lean clay (CL) had a UCS of 195 kPa from an initial of 52 kPa (275% improvement). The findings are similar to those of Baidya et al. (2023) and (Thonemann et al., 2024), who explained the lesser treatment efficiency in fine-grained soils as the fact that the mobility of

bacteria is limited and the availability of surface area for the initiation of calcite is reduced.

The EICP treatment showed similar strength gain at similar calcite contents, with strength after 28 days curing of 290 kPa (SP), 260 kPa (SM) and 175 kPa (CL) at 1.0 M CaCl₂-urea enzyme concentration. These slightly lower strengths in the EICP-treated samples compared to the ones treated with MICP may be explained by the more uniform but less strategically ideal distribution of calcite in the enzyme-treated soils, because bacterial cell surfaces are not available to act as nucleation sites and thus the precipitation of calcite is more diffuse throughout the pore space (David et al., 2020).

The improvements were even more dramatic for the resilient modulus (M_R) results, which indicated how sensitive this parameter is to the effects of interparticle bonding and small-strain stiffness increases brought by calcite cementation. The M_R of the SP soil increased from 62 MPa to

245 MPa after 10 cycles of MICP treatment at 0.5 M; the SM soil increased from 48 MPa to 165 MPa, and the CL soil increased from 35 MPa to 110 MPa, respectively, after 10 cycles of MICP treatment at 0.5 M. The M_R values were similar to those of well-graded crushed aggregate base materials, indicating that bio-treated subgrades might be able to be used as an alternative to a thick granular base layer in pavement cross-sections, thereby making important contributions to material cost savings and construction efficiency (Bai & Huang, 2025).

4.2 Rutting Resistance

The repeated load triaxial test results were convincing proof of the rutting resistance of bio-treated subgrades. The untreated specimens of SP, SM, and CL, developed permanent strains of 1.8%, 2.9%, and 4.2%, respectively, after 10,000 loading cycles, which is greater than the failure criterion typically used in mechanistic-empirical pavement design (Yarlina et al., 2023). However, the permanent strains in the MICP treated specimens (0.5M, 10 cycles) were 0.4% (SP), 0.8% (SM) and 1.1% (CL), which are, respectively, 78%, 72% and 74% lower. The fit of the Tseng-Lytton model to the permanent strain data showed that bio-treatment had mainly reduced the rate of secondary (steady-state) creep deformation, which is consistent with the hypothesis that the calcite bridges at particle contacts were responsible for inhibiting interparticle sliding and rearrangement that governs plastic strain accumulation under cyclic loading (Zuiderveen et al., 2023).

Pavement system level results from the wheel tracking tests confirmed the results of the triaxial test. Rut depths of the composite slab specimens with untreated CL subgrade after 20,000 passes at 60°C exceeded the 10 mm limit for acceptable performance set by EN 12697-22. Further, the treated slabs with MICP-treated CL subgrade (0.5 M, 10 cycles) had a rut depth of just 4.2 mm (66% reduction) and most of the rutting in those treated slabs was due to the deformation in the asphalt concrete layer, suggesting that bio-treatment was effective in removing the rutting problem from the subgrade and placing it into the surfacing layer

where it can be addressed more easily by optimizing mix design (Subramaniam et al., 2021).

4.3 Hydraulic Conductivity and Stormwater Runoff Attenuation

The hydraulic conductivity results showed a systematic trend in decreasing with the increasing bio-treatment intensity, indicating a controllable reduction in k_{sat} . For the SP soil, k_{sat} decreased from 2.8×10^{-4} m/s (untreated) to 4.5×10^{-6} m/s after 10 cycles of MICP treatment at 0.5 M, and further to 8.2×10^{-7} m/s at 1.0 M with 15 cycles. The same trends were observed for the SM and CL soils, where k_{sat} decreased by 1.5 to 2.0 orders of magnitude at moderate treatment levels. Importantly, the moderately treated soils (0.5 M, 5 – 10 cycles) produced hydraulic conductivities ranging between 10^{-5} and 10^{-6} m/s with an optimum range for bioretention and infiltration-based stormwater management systems of 10^{-6} to 10^{-8} m/s (Wicaksono et al., 2025).

The infiltration column tests directly confirmed stormwater attenuation capacity of bio-treated subgrades in a realistic context of the pavement cross section. The 25 mm/hr rainfall simulation produced a peak outflow of 18.5 L/hr for the untreated CL subgrade, compared to 48 minutes for the time to peak, and a peak outflow of 9.2 L/hr (50% reduction) for the column with MICP-treated CL subgrade (0.5 M, 10 cycles). The higher 75 mm/hr event saw the peak reduction to 38% (down from 42.0 L/hr to 26.0 L/hr) with the time to peak increased from 15 minutes to 35 minutes. The results provided herein show that bio-treated subgrades are capable of performing the functions of detention and retention as the SUDS infrastructure, with capability of reducing peak discharge and increasing the time of runoff released, akin to the functions of a hydraulic resistor.

This stormwater attenuation is a result of the gradual degradation of vertical permeability in the bio-treated layer, resulting in a perched water table above the subgrade during rainfall events that allow the stormwater to flow laterally and temporarily be stored in the aggregate base layer, before slowly infiltrating the bio-treated layer. This

is different than traditional cement-stabilized subgrades which usually have k_{sat} values less than 10^{-8} m/s and act as a near impervious barrier forcing all infiltrated water to the pavement edges, resulting in concentrated runoff and erosion (Baidya et al., 2023).

4.4 Microstructural Analysis

The SEM-EDS imaging of the bio-treated samples showed the differences in calcite morphology and distribution between two bio-treatment methods (MICP and EICP) (Jamaldar et al., 2025). For MICP treated SP specimens, the calcite crystals were mainly rhombohedral and between 5 and 25 μm in diameter and appeared at particle-particle contact points as effective cementation bridges that directly led to the increase in strength. The CaCO_3 peaks in the EDS analysis confirmed the presence of this compound, with a small amount of Mg substitution, suggesting magnesian calcite formation. On the contrary, EICP-treated specimens had smaller (2-10 μm) and more spherical calcite crystals and were more evenly distributed in the pore space, even at particle surfaces away from contacts, as reported by Zomorodian et al., 2023. The more diffused distribution is the reason why EICP results in slightly lower mechanical efficiency than MICP for the same calcite content, as described in Section 4.1.

The X-ray diffraction (XRD) analysis confirmed the presence of calcite as the dominant polymorph in all the treated samples, and minor vaterite was found in the low temperature (20°C) cured EICP-treated samples. Acid washing showed a calcite content between 1.2 and 5.8% by dry weight depending on the treatment conditions, with the highest value being observed for the treatment of the SP soil under 1.0 M and 15 cycles of MICP. For calcite content < 4%, the relationship between the content and UCS was approximately linear, and a threshold effect was found with a decrease in returns for calcite content > 4%, which is similar to the pore filling saturation mechanism proposed by (Zhang et al., 2025).

4.5 Environmental Sustainability Assessment

The LCA outcomes are very clear and showed that bio-treated foundations have a clear environmental advantage compared to conventional cement stabilization, in each of the impact categories that were assessed (Generowicz-Caba & Kulczycka, 2025). The GWP of the functional unit of treating 1 m^3 of subgrade soil to a target UCS of 300 kPa (MICP treatment) was found to be 18.5 kg $\text{CO}_2\text{-eq}$, which is a 55% reduction from the GWP of the cement stabilization treatment at 6% Portland cement by dry weight (41.2 kg $\text{CO}_2\text{-eq}$). The EICP treatment had a GWP of 26.8 kg $\text{CO}_2\text{-eq}$, which was 35% lower than cement – the higher impact being a result of the high energy-consuming enzyme extraction process.

The potential for eutrophication was more complicated. When the production phase is considered alone, MICP had the lower EP (0.032 kg $\text{PO}_4\text{-eq}$), but the EP of MICP increased to 0.055 kg $\text{PO}_4\text{-eq}$ when the ammonium byproduct release from urea hydrolysis was added in. The EP for MICP had a slightly lower EP (0.032 kg $\text{PO}_4\text{-eq}$) than cement stabilization (0.048 kg $\text{PO}_4\text{-eq}$) if only production phase is considered, but when the production of ammonium byproduct from urea hydrolysis is added to the EP of MICP it becomes 0.055 kg $\text{PO}_4\text{-eq}$, which is slightly higher than the EP of cement. The discovery of this trade-off is an important one that has been previously unexplored in the vast majority of previous LCA-based bio-cementation studies (Bishop et al., 2021). Urea decomposition produces about 2 moles NH_4^+ for every mole of urea, which can be leached out and cause nitrogenous pollution of surface water and groundwater systems, leading to eutrophication. To tackle this concern, ammonium removal technologies such as using nitrifying bacterial consortia to transform ammonium to nitrate or incorporating ammonium-adsorbing zeolite amendments into the treatment solution should be investigated (Sadeghi et al., 2025).

The acidification potential and freshwater ecotoxicity effects of bio-treated foundations were 40-50% lower than cement stabilization as there

was no clinker production and release of SO_2 , NO_x and heavy metals. Overall, the LCA results indicate that bio-treatment is beneficial for the environmental performance for pavement

foundation applications if the management of ammonium is put in place to reduce eutrophication risk.

Integrated Bio-Treated Pavement Foundation Framework

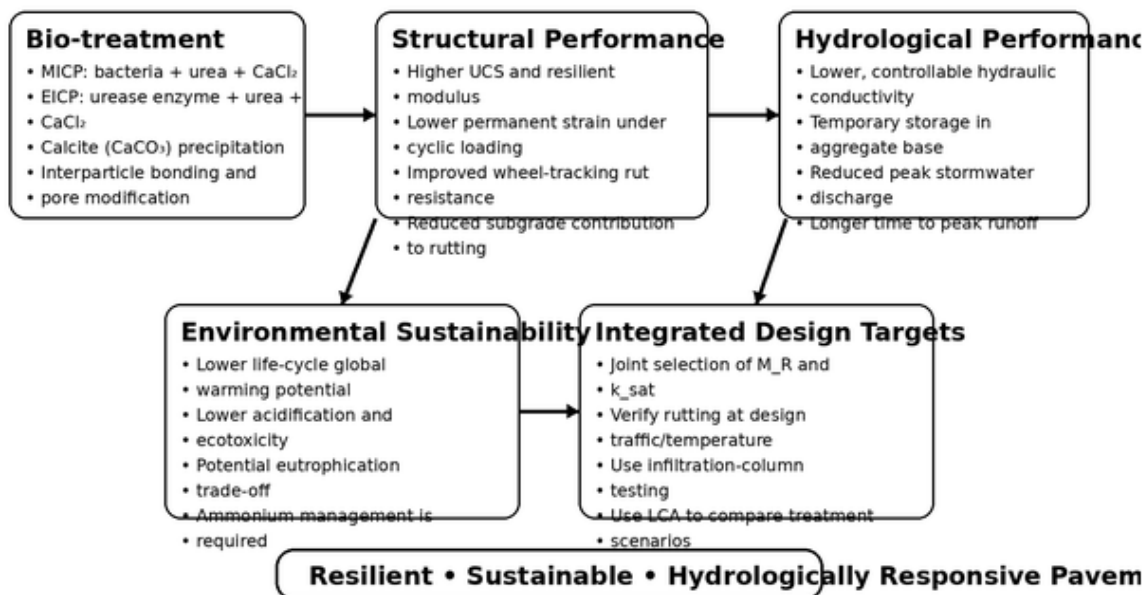


Figure 2. Integrated conceptual framework linking bio-treatment, structural performance, stormwater attenuation, and environmental sustainability.

5. Integrated Design Framework

The above experimental and analytical results provide justification for the development of a framework for an integrated design of bio-treated soil foundations that balance structural performance, stormwater management and environmental sustainability. The framework consists of four interrelated components:

Part 1: Treatment Specification Based on Treatment Performance. Treatment intensity (reactant concentration, number of cycles, treatment method) should be chosen to meet joint target values of M_R and k_{sat} to optimally treat the specific traffic loading and hydrological conditions at the project site. The recommended values for M_R and k_{sat} are 150–200 MPa and 10^{-5} to 10^{-6} m/s, respectively, for the high-traffic arterial roads in moderate rainfall areas, and can

be obtained by treating sandy soils with 0.5 M MICP, with a treatment cycle of 10.

Component 2: Hydrological Integration. The bio-treated subgrade layer should be designed as a part of the overall stormwater management system, and the hydraulic conductivity should be adjusted for desired peak flow attenuation and volume retention requirements based on local SUDS requirements. The infiltration column test methodology outlined in Section 3.4 is a practical approach to testing the hydrological performance of the proposed treatment design (Petchgate et al., 2025).

Component 3: Verification of Rutting Performance. Bio-treated subgrade material should be subjected to repeated load triaxial tests at design traffic loading and temperature conditions to confirm its permanent deformation

properties, and the acceptance criteria used should be based on the MEPDG rutting model. The permanent strains for the subgrade layer are not allowed to be more than 1.0% after 10,000 cycles (Deng & Shi, 2023).

Component 4: Minimising the impact of the service. The LCA framework outlined in section 3.6 should be used in the design stage to compare different treatment scenarios and determine the scenario that has the lowest life cycle environmental impact in all pertinent categories. It is important to include ammonium management in the treatment protocol, so that the eutrophication potential is not higher than the conventional one (Cardoso et al., 2023).

6. Limitations and Future Research Directions

Although this study provides evidence for the high potential of bio-treated soil foundations for integrated structural and environmental performances, there are certain caveats. Second, the scalability of MICP and EICP treatments to full scale pavement construction projects is a challenge with respect to delivery of a uniform treatment solution over the large scale of the pavement and quality control of in-situ bio-cementation (Mi et al., 2023). Third, the economic feasibility of bio-treatment compared to traditional stabilization techniques needs to be explored, especially in view of the high cost of the biological reagents and the absence of an established supply chain for large-scale applications (Zhang et al., 2025). Further research should focus on long-term field testing of treated pavement foundations under representative traffic and climate conditions, in-situ treatment delivery systems that are cost-effective, treatment management strategies for ammonia and the incorporation of bio-treatment with other sustainable pavement technologies, including recycled aggregate, warm-mix asphalt, and permeable pavement systems. Moreover, the addition of precipitated calcite as a carbon sink, by sequestering atmospheric CO₂, is another consideration that needs to be investigated as part of the infrastructure for net-zero (Zandieh et al., 2024).

7. Conclusions

This thorough study of bio-treated soil foundations for stormwater runoff mitigation and pavement rutting resistance has led to the following important findings:

Structural Performance: MICP and EICP treatments give significant improvement in the mechanical properties of subgrade soils, with UCS treated soils showing a 250 to 600% increase and a 200 to 400% increase in Resilient Modulus at moderate treatment intensities. The improvements will provide enough material and cost savings to significantly minimize the thickness of overlying pavement layers.

3. Rutting Resistance: Permanent strain reductions of 70-78% compared to untreated subgrades under cyclic loading are dramatically improved in bio-treated subgrades. Wheel tracking tests have been successfully used to validate that bio-treatment influences the critical rutting mechanism to occur within the asphalt layer, rather than the subgrade, where it is more amenable to management.

Stormwater Attenuation: Bio-treating a subgrade that has been reduced in hydraulic conductivity provides hydrological services within the pavement structure including the ability to control peak stormwater runoff by 38-50% and time to peak discharge by 100-120%.

4. Environmental Sustainability: Life cycle assessment shows a reduction of 35–55% in GWP for bio-treated foundations when compared to foundations that are cement stabilized. This result is followed by a reduction in the acidification and ecotoxicity categories. The eutrophication potential of by-products of ammonium, however, needs to be managed carefully.

6. Integrated Framework: The proposed design framework offers a systematic design approach to optimize bio-treatment parameters for simultaneously maintaining structural, hydrological and environmental performance, which is a great step towards truly sustainable pavement infrastructure.

The combination of bio-geotechnical engineering and pavement and stormwater design is a new paradigm in infrastructure design and

development, and is not a traditional approach. With the rising importance of climate adaptation and decarbonization, bio-treated soil foundations provide a promising avenue for infrastructure that is less harmful, but also more environmentally regenerative.

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