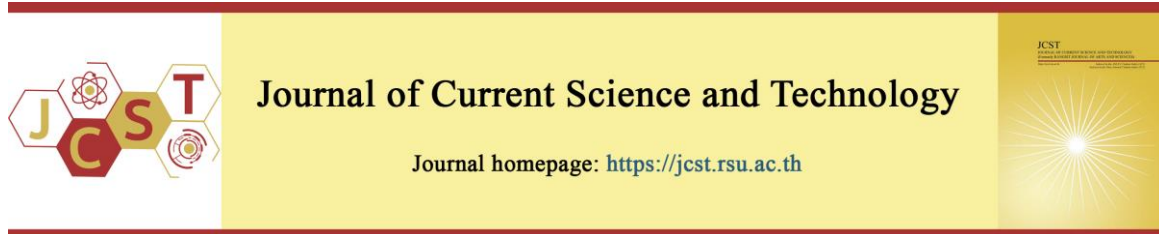


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Expanding Polyurethane Foam Injection for Ground Improvement: Mechanisms of Soil–Resin Interaction, Field Verification Methods, and Practical Design Considerations

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Abstract

Expanding polyurethane (PU) foam injection has emerged as a technically versatile alternative to cementitious grouting for geotechnical rehabilitation, offering rapid cure, low unit weight, and suitability for both dry and actively seeping ground conditions. Despite growing field adoption, systematic guidance on material selection, injection design, and performance verification remains absent, with knowledge distributed across disparate testing protocols and performance metrics. This review synthesizes laboratory experiments, field case studies, and monitoring data to address three deficiencies: an incomplete mechanistic understanding of soil–resin interactions across injection regimes; the absence of an integrated verification protocol; and the lack of standardized design codes. PU systems span hydrophobic and hydrophilic types across a density range of 35–1,000 kg/m³, achieving cured compressive strengths of 0.3–10 MPa and hydraulic conductivities of 10^{−5} to 10^{−8} m/s. Three injection configurations, which are slab jacking, tunnel void grouting, and deep foundation underpinning, are distinguished by borehole geometry, pressure limits, and staging sequence. Field evidence confirms pavement faulting reductions of 2 to 5 mm, a 160% foundation stiffness increase at Noi Bai International Airport, and a 98% seepage reduction in tunnel waterproofing applications. Comparative analysis demonstrates that PU foam outperforms cementitious grouting in cure speed, fine-void penetrability, and faulting correction, while cement retains advantages in bulk compressive strength and unit material cost. Key limitations include buoyancy risk in saturated ground, chemical sensitivity above pH 9, exothermic damage risk in confined spaces, and insufficient long-term durability data to support design codification. The review consolidates the evidence into a structured framework linking PU material class, injection parameters, and verification method to specific geotechnical objectives, providing a unified resource for researchers and practitioners.

Keywords: cone penetration test, ground improvement, lifting, underpinning, polyurethane foam, polyurethane grouting, resin injection, soil stabilization

1. Introduction

The rehabilitation of aging civil infrastructure represents one of the most pressing engineering challenges of the current century, with a growing proportion of bridges, pavements, and underground structures approaching or exceeding their intended service life (American Society of Civil Engineers, ASCE, 2021). Ground settlement and subgrade instability are

further intensified by environmental and land-use factors, including rainfall-induced changes in soil moisture, erosion, sediment transport, and land-use alteration (Hapsari et al., 2026; Ray et al., 2023). Ground improvement solutions that can be applied rapidly, with minimal disruption to traffic and adjacent structures, and with predictable long-term performance are therefore urgently needed.

Conventional cementitious grouting has long served as the primary method for stabilizing weak subgrades and filling structural voids; however, its application is constrained by slow strength development (12 – 72 hours to serviceable strength), high material unit weight (1,800 – 2,200 kg/m³) that increases dead load on already weak subgrades, high water demand, and limited penetrability into irregular void networks or fine fissures (Bodi et al., 2012; Thompson-Colon et al., 2006). These deficiencies have driven increasing adoption of polymer-based alternatives, with expanding polyurethane (PU) foam emerging as the most widely applied option across a broad spectrum of geotechnical rehabilitation contexts.

PU foam is a two-component reactive system comprising a polyol and an isocyanate that, upon mixing, undergoes rapid exothermic polymerization to produce a lightweight, self-expanding composite (Buzzi et al., 2010; Sukkaneewat et al., 2019; Wang et al., 2022). The cured product spans a density range of 35 to 1,000 kg/m³, allowing the use of low-density void fillers or high-density polyurethane (HDP) foam for structural resin applications, and achieves near-full mechanical strength within 15 to 30 minutes of injection, which is a curing speed unmatched by cementitious alternatives (Al-Atroush & Sebaey, 2021; Chun & Ryu, 2000). The system can further be formulated as hydrophobic or hydrophilic, extending applicability from dry cavities to actively seeping saturated ground. Owing to these attributes, PU foam has been documented in pavement rehabilitation, foundation underpinning, tunnel waterproofing, and collapsible soil treatment across multiple countries and infrastructure sectors (Escolano Sánchez et al., 2017; Fortunatus, 2018; Trong, 2023; Qin, 2025). However, the rapid growth of field practice has outpaced the systematic accumulation of engineering knowledge, creating identifiable gaps that constrain reliable design and performance prediction.

Three specific knowledge gaps motivate this review. First, while individual studies have characterized foam expansion and strength gain in specific soil types (Buzzi et al., 2010; Wang et al., 2020), no unified framework exists that links soil gradation, saturation state, and in-situ confinement to injection regime selection, whether permeation, fracture-filling, or compaction grouting, and expected treatment outcome. Practitioners therefore lack mechanistic guidance for translating site characterization data directly into injection design parameters. Second, performance verification methods, including cone penetration testing (CPT), falling weight deflectometer (FWD)

testing, and electrical resistivity tomography (ERT), have each been validated independently for PU-treated ground (Apuani et al., 2015; Vennapusa et al., 2016), but no integrated verification protocol exists that specifies method selection, acceptance criteria, or monitoring frequency as a function of treatment type and depth. Third, the absence of standardized design codes compels practitioners to rely on empirical judgment or proprietary vendor guidance; this situation is compounded by insufficient long-term durability and cyclic loading data that would otherwise provide the evidential foundation for codification (Fortunatus, 2018; Mistry et al., 2024; Qin et al., 2025). These three deficiencies, in mechanistic understanding, verification practice, and design standardization, define the scope and structure of this review.

This review addresses the identified gaps by synthesizing published laboratory studies, field case evidence, and monitoring data to establish a coherent and practice-relevant knowledge base for PU foam in geotechnical applications. Three objectives structure the review: (1) to characterize the material chemistry, density classes, and soil–resin interaction mechanisms that govern PU foam performance across different injection regimes and ground conditions; (2) to critically evaluate the capabilities, limitations, and appropriate application contexts of current in-situ and laboratory performance verification methods for PU-treated ground; and (3) to consolidate the reviewed evidence into a structured design framework that links material selection, injection parameters, and verification methods to specific geotechnical objectives, providing a unified resource for researchers and practitioners.

2. Objectives

This review aims to synthesize current knowledge on expanding polyurethane foam injection as a ground improvement technique by examining its material behavior, soil–resin interaction mechanisms, field application methods, and performance verification approaches. Additionally, the review compares polyurethane foam injection with conventional cementitious grouting, identifies key technical limitations and research gaps, and proposes practical design considerations linking material selection, injection parameters, verification methods, and geotechnical application requirements.

3. Review Methodology

A total of 66 articles were examined during the preparation of this review. Forty-five of these appear in the final reference list, as illustrated by the start of

the references section; a further 21 papers were excluded because they were duplicates, non-English publications or lacked relevant experimental data on polyurethane foam for geotechnical applications. The majority of the referenced literature came from journals and conference proceedings indexed in Scopus, reflecting the dominance of applied geotechnical research within that database; examples include papers on PU-based soil stabilization and pavement rehabilitation. A smaller set was sourced from Web of Science, such as works on dynamic probing and cone-penetration testing that met the inclusion criteria. Two references were drawn directly from the American Society of Civil Engineers (ASCE)-the infrastructure report card and an article from the Journal of Performance of Constructed Facilities-highlighting the contribution of professional society publications to the evidence base.

3.1 Scope and Eligibility

The focus was placed on laboratory experiments, field case studies, and previous reviews that investigated expanding polyurethane (PU) or similar polymeric grouts for ground improvement. Studies were included if they reported quantitative performance data (e.g., density, compressive strength, permeability) or field outcomes (e.g., slab lifting results, underpinning effectiveness). Publications that addressed other polyurethane applications (such as insulation or adhesives) or numerical modelling without experimental validation were excluded. Only English-language articles were considered to maintain consistent interpretation.

3.2 Search Strategy

A comprehensive search was performed in March 2026 across Scopus, Web of Science, and Google Scholar. Search strings combined terms such as “polyurethane foam injection,” “ground improvement,” “resin injection,” “polymer grouting,” and application descriptors like “slab jacking” or “underpinning.” Searches were restricted to studies published between 1990 and 2026 to capture both early and contemporary research. Citation lists of key papers were hand-searched to identify additional sources. The search strategy and database choice follow recommendations that methods should be rigorous and replicable.

3.3 Selection and Data Extraction

All retrieved records were imported into reference-management software, and duplicates were removed. Full texts of potentially relevant articles

were then assessed. For each included study, data were extracted into a structured spreadsheet capturing:

- PU formulation (hydrophobic vs. hydrophilic)
- Injection regime (e.g., permeation, fracture filling)
- Soil type and conditions
- Performance metrics (e.g., compressive strength, stiffness increase, permeability reduction)
- Verification methods (e.g., cone penetration testing, falling-weight deflectometer, electrical resistivity tomography)

Disagreements were resolved by consensus.

3.4 Quality Assessment and Synthesis

Given the heterogeneity of included studies, basic quality indicators were recorded, such as clarity of material composition, adequacy of experimental controls, and completeness of performance reporting. Studies lacking essential methodological details were noted but retained to avoid biasing the review. Findings were synthesized narratively, grouping evidence by PU material class, injection method, and application context. Quantitative ranges (density, strength, hydraulic conductivity) were summarized, and comparisons to conventional cementitious grouting were made where data were available.

4. Main Findings

4.1 Characteristic of Polyurethane

Polyurethane foam systems used in geotechnical applications are two-component reactive materials comprising a polyol (Component A) and an isocyanate (Component B), most commonly methylene diphenyl diisocyanate (MDI) (Wang et al., 2022). Upon mixing, an exothermic polymerization reaction forms a crosslinked polymer network dominated by urethane linkages ($-\text{NH}-\text{C}(=\text{O})-\text{O}-$). In water-reactive or moisture-exposed systems, isocyanate groups may also react with water to generate carbon dioxide and urea linkages, contributing to foaming and network development (Bodi et al., 2012). The reaction kinetics, expansion ratio, and final mechanical properties are sensitive to the formulation chemistry, mixing ratio, ambient temperature, and in-situ moisture content (Thompson-Colon et al., 2006). For geotechnical injection, PU systems are commonly classified by water affinity, formulation chemistry, density, expansion ratio, and intended engineering function. Water interaction is particularly important because it influences reaction pathway, foaming behavior, cell morphology, swelling potential, and the engineering behavior of the cured material (Figure 1).

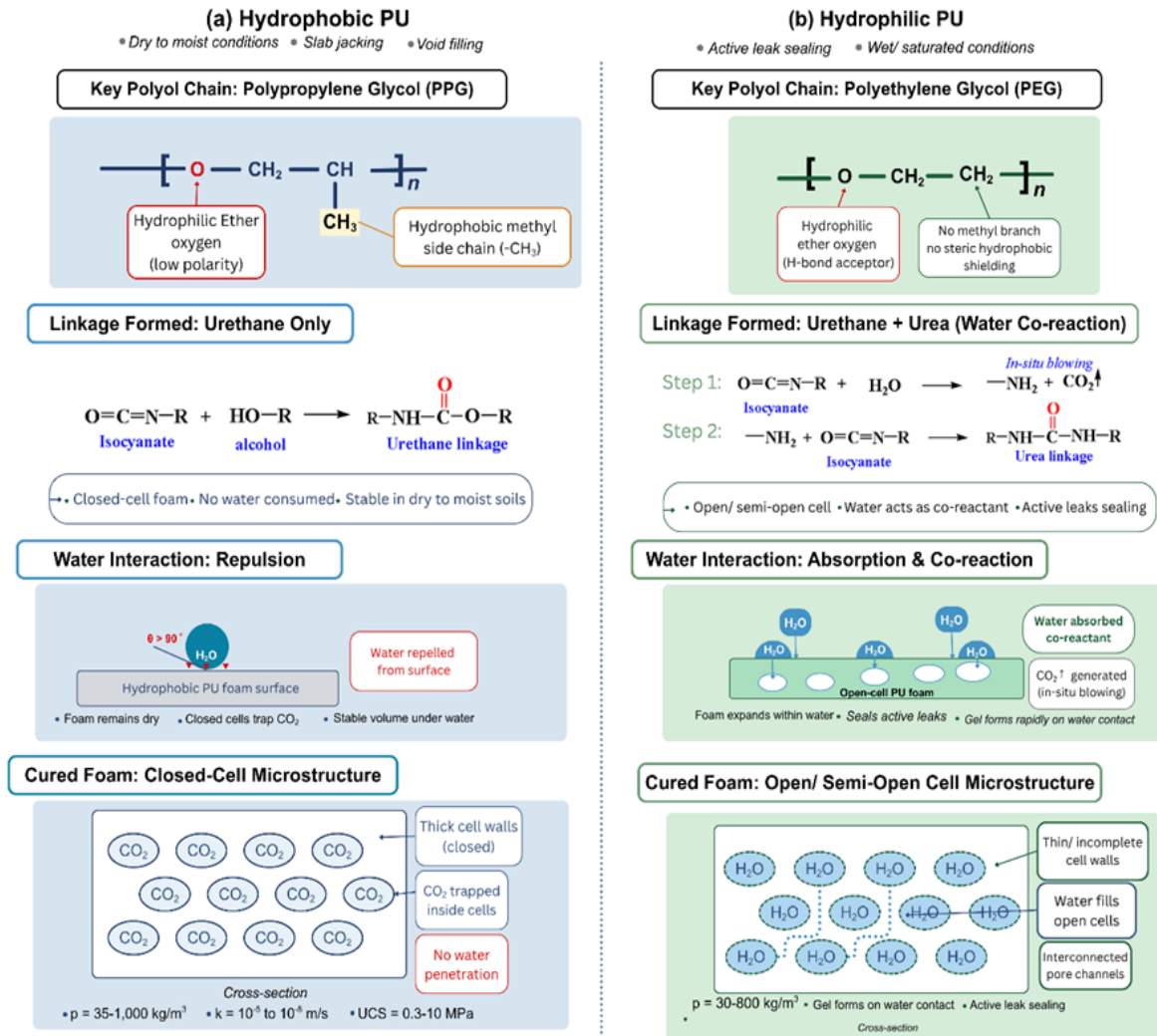


Figure 1 Molecular characteristics and engineering behavior of hydrophobic and hydrophilic polyurethane systems: (a) Hydrophobic PU showing a PPG polyol chain with a methyl side group, a standard urethane linkage, a water contact angle greater than 90 degrees, and a closed-cell microstructure containing trapped carbon dioxide; (b) Hydrophilic PU showing a PEG polyol chain with an ether oxygen hydrogen-bond acceptor, concurrent urethane and urea linkages derived from the water reaction, and an open or semi-open cell microstructure

4.1.1 Hydrophobic Polyurethane

Hydrophobic PU systems are commonly based on propylene-oxide-rich polyether polyols, such as polypropylene glycol (PPG), whose repeat unit ($[-\text{CH}_2-\text{CH}(\text{CH}_3)-\text{O}]_n-$) contains methyl side groups that reduce affinity for water and contribute to the water-repellent behavior of the cured polymer (Figure 1a, polyol chain). In two-component ground-improvement foams, the dominant network-forming reaction occurs between polyol hydroxyl groups and isocyanate groups, producing urethane linkages ($-\text{NH}-\text{C}(=\text{O})-\text{O}-$). However, in some commercial hydrophobic injection grouts, residual isocyanate groups may also

react with moisture to generate CO₂ and urea linkages. Expansion is achieved through the released CO₂, which becomes trapped and forms discrete cells bounded by thick polymer walls (Figure 1a, cell structure). Foaming may be controlled by incorporated blowing agents or by limited moisture-driven reactions, depending on the formulation.

Hydrophobic PU surfaces commonly exhibit water-repellent behavior, often indicated by a water contact angle greater than 90°, although the measured value depends on surface roughness, formulation, additives, and curing conditions (Figure 1a, water interaction).

After curing, hydrophobic PU generally resists water uptake and tends to occupy void spaces, yielding densities of 35–1,000 kg/m³, hydraulic conductivities of 10⁻⁵–10⁻⁸ m/s, and unconfined compressive strengths of 0.3–10 MPa. These properties may vary depending on the formulation, particularly the type and proportion of additives, blowing agents, catalysts, surfactants, and fillers incorporated into the PU system. These characteristics make hydrophobic PU the preferred choice for void filling, slab jacking, and ground stabilization under dry to moderate moist conditions (Al-Atroush & Sebaey, 2021; Chun & Ryu, 2000).

4.1.2 Hydrophilic Polyurethane

Hydrophilic PU systems generally contain ethylene-oxide-rich polyether polyols or polyethylene glycol (PEG) segments, whose repeat unit (–[CH₂–CH₂–O]_n–) lacks methyl side groups and contains ether oxygens capable of hydrogen bonding with water molecules (Figure 1b, polyol chain). This structural distinction increases water affinity and, in water-reactive PU systems, allows moisture to participate in the isocyanate reaction pathway. In the first step, the isocyanate reacts with water to generate a primary amine and carbon dioxide ($R-NCO + H_2O \rightarrow R-NH_2 + CO_2\uparrow$), providing in-situ blowing without an external agent. In the second step, the amine product reacts with a further isocyanate group to form a urea linkage ($R-NH_2 + OCN-R \rightarrow R-NH-C(=O)-NH-R$), which supplements the conventional urethane linkage (Figure 1b, linkage) (Qin, 2025; Wang et al., 2022). The resulting urethane–urea network can promote rapid foaming, gel formation, or swelling on contact with water, enabling the material to enter wet pathways and seal actively flowing leaks (Figure 1b, water interaction). Depending on formulation, the

cured product may exhibit gel-like, open-cell, semi-open-cell, or closed-cell morphology; however, hydrophilic PU generally maintains stronger water interaction than hydrophobic PU and is therefore effective in wet or actively leaking environments (Figure 1b, cell structure). Hydrophilic PU is therefore commonly selected for tunnel waterproofing, active leak control in basements and underground structures, and injection grouting in saturated or water-bearing soils where water-triggered foaming or swelling is required (Qin, 2025; Wang et al., 2022).

The contrasting molecular architectures summarized in Figure 1 translate directly into distinct engineering applications: hydrophobic PU delivers stable, load-bearing void filling and ground improvement under dry to moderately moist conditions, whereas hydrophilic PU provides rapid, water-activated sealing in environments where conventional dry-mix systems cannot function. In practice, dual-component injection systems can combine both chemistries to address site conditions that transition between saturated and unsaturated zones within a single treatment operation (Bodi et al., 2012; Qin et al., 2025).

4.2 Engineering Properties

PU foam systems are engineered across a wide range of cured densities to suit different geotechnical objectives. Density strongly influences mechanical strength, stiffness, permeability, expansion ratio, and load-bearing capacity, but these properties also depend on formulation chemistry, confinement, soil type, moisture content, and curing conditions (Choi & Kim, 2021). Based on field practice and laboratory characterization, PU systems can be classified into three primary density classes (see Table 1).

Table 1 Typical Physical and Mechanical Properties of Polyurethane Systems for Geotechnical Applications

Property	Low-Density PU Foam	Medium-Density PU Foam	High-Density PU Resin	Permeable PU Grout	Key References
Density (g/cm ³)	0.03–0.10	0.10–0.40	0.40–1.20	0.80–1.10	Lat et al. (2022) Jaber et al. (2025) Zvierieva et al. (2025) Pang et al. (2026)
Expansion Ratio	15:1 to 40:1	5:1 to 15:1	1:1 to 5:1	1:1 to 3:1	Lat et al. (2020) Jaber et al. (2025) Somarathna et al. (2018) Hong et al. (2021)
Reaction Time (sec)	10–60	30–120	60–300	30–180	Somarathna et al. (2018) Zvierieva et al. (2025)
Compressive Strength (MPa)	0.1–0.5	0.5–2.0	2.0–8.0	3.0–10.0	Jaber et al. (2025) Somarathna et al. (2018) Kinay & Bakis (2025) Haruna et al. (2025)
Tensile Strength (MPa)	0.2–0.8	0.8–2.5	2.5–8.0	5.0–15.0	Jaber et al. (2025) Pang et al. (2026) Somarathna et al. (2018)
Elastic Modulus (MPa)	2–20	20–100	100–500	200–800	Jaber et al. (2025) Zvierieva et al. (2025) Somarathna et al. (2018)
Shear Strength (MPa)	0.05–0.3	0.3–1.5	1.5–5.0	2.0–6.0	Jaber et al. (2025) Somarathna et al. (2018) Haruna et al. (2025)
Internal Friction Angle (°)	25–35	35–45	45–55	40–50	Jaber et al. (2025) Zvierieva et al. (2025)
Cohesion (kPa)	50–200	200–500	500–1500	400–1200	Jaber et al. (2025) Zvierieva et al. (2025)
Permeability (m/s)	1×10 ⁻⁴ to 1×10 ⁻³	1×10 ⁻⁵ to 1×10 ⁻⁴	1×10 ⁻⁷ to 1×10 ⁻⁵	1×10 ⁻⁶ to 1×10 ⁻⁴	Somarathna et al. (2018) Zvierieva et al. (2025) Hong et al. (2021)
Exotherm Temperature (°C)	80–150	100–180	120–200	90–160	Somarathna et al. (2018) Zvierieva et al. (2025)
Lifting Capacity (kPa)	50–150	150–400	400–1000	300–800	Lat et al. (2019) Jaber et al. (2025)
Injection Pressure (MPa)	0.1–0.3	0.2–0.5	0.3–0.8	0.2–0.6	Somarathna et al. (2018) Zvierieva et al. (2025)
Curing Time (hours)	0.5–2	1–4	2–8	1–6	Zvierieva et al. (2025) Kinay & Bakis (2025) Xu et al. (2024)

Note: Values represent reported ranges compiled from the literature and should not be interpreted as universal design constants. Actual performance depends on PU formulation chemistry, catalyst dosage, expansion ratio, ambient temperature, moisture condition, degree of confinement, soil type, and injection procedure

4.2.1 Low-Density Foams (35–150 kg/m³)

These highly expansive foams (expansion ratios of 15:1 to 40:1) are generally suitable for void-filling applications where low unit weight and volumetric expansion are more important than structural load-bearing capacity (Lat et al., 2019). Their low unit weight minimizes additional stress on

weak subgrades, making them suitable for filling loose or eroded zones. However, in saturated soils, low density may also introduce buoyancy or upward migration risks that must be controlled through confinement and staged injection (Lat et al., 2022). However, their compressive strength is limited

(typically 0.1 – 0.5 MPa), restricting their use to non-structural applications (Choi & Kim, 2021).

4.2.2 Medium-Density Foams (150–400 kg/m³)

This class represents a balance between expansion capability (5:1 to 15:1) and mechanical performance (Chun & Ryu, 2000). Medium-density foams are commonly used for slab jacking and pavement re-leveling, where controlled lifting and moderate load transfer are required (Vennapusa et al., 2016). Compressive strengths typically range from 0.5 to 2.0 MPa, with elastic moduli between 20 and 100 MPa (Choi & Kim, 2021).

4.2.3 High-Density Resins (400–1000 kg/m³)

These low-expansion systems (1:1 to 5:1) are formulated for structural applications requiring high compressive strength (2.0 – 8.0 MPa) and stiffness (elastic moduli of 100 – 500 MPa) (Choi & Kim, 2021; Wang et al., 2024). High-density PU resins are used for foundation underpinning, load-bearing soil stabilization, and situations where significant confinement limits expansion (Escolano Sánchez et al., 2017). Laboratory studies have demonstrated that high-density PU can increase the unconfined compressive strength of silty soils by more than an order of magnitude, with treated specimens achieving strengths up to 5 MPa (Wang et al., 2020; Wang et al., 2024).

4.2.4 Permeability and Hydraulic Characteristics

The permeability of cured PU foam varies significantly with density and formulation (Choi & Kim, 2021). Low-density foams exhibit relatively high permeability (10^{-4} to 10^{-3} m/s), making them unsuitable for applications requiring hydraulic cut-off (Lat et al., 2019). In contrast, high-density resins can achieve permeabilities on the order of 10^{-7} to 10^{-5} m/s, providing effective sealing in water-bearing formations (Jumadilova, 2024; Qin, 2025). Hydrophilic PU systems, which form gel-like structures upon reacting with water, have been shown to reduce water seepage in tunnels from flow rates exceeding 1800 liters per minute to less than 30 liters per minute, demonstrating their effectiveness in high-flow conditions (Qin, 2025).

4.3 Application Techniques and Methods

The application of polyurethane foam in geotechnical engineering relies on specialized injection techniques designed to achieve controlled ground improvement while minimizing disturbance to

existing structures. Success depends not only on material properties but also on the specific delivery method, pressure control, and monitoring strategies employed during execution. Geotechnical applications of polyurethane and their characteristics are summarized in Table 2.

4.3.1 Injection Application Methods

PU foam injection is delivered through small-diameter boreholes (16 – 25 mm) using a dual-component lance that mixes polyol (Component A) and isocyanate (Component B) at the point of injection, initiating the exothermic polymerization reaction in situ. The two components are usually conveyed through separate hoses from independent pumping units, with the mix ratio controlled according to the manufacturer's formulation requirements. Although many commercial systems use an approximately 1:1 volumetric ratio, the required ratio is formulation-specific and should not be generalized. Equipment selection, borehole configuration, and injection sequence are governed by treatment depth, target void geometry, and the engineering objective of each application scenario, as illustrated by the three configurations in Figure 2.

(a) Slab Jacking and Pavement Void Filling

For shallow pavement rehabilitation (Figure 2a), injection ports are drilled at regular grid intervals of 1.0 – 2.5 m through the concrete slab using rotary or percussive equipment fitted with diamond-tipped or carbide bits to produce clean-edged holes that accept the lance packer without blow-by leakage. Port locations are concentrated preferentially near slab edges, corners, and transverse joints, where subgrade voids most commonly initiate water erosion and traffic-induced pumping. Injection follows a perimeter-to-center sequence: peripheral ports are treated first to establish a foam containment boundary that prevents lateral resin migration beyond the treatment zone, after which interior ports are injected to fill the enclosed void volume. Within each port, injection proceeds from the slab–subgrade interface upward so that expanding foam displaces entrapped water and air ahead of the advancing foam front rather than trapping them beneath the slab. Injection pressure is maintained below 0.5 MPa throughout to preclude hydraulic fracturing of the subbase.

Real-time monitoring of injection pressure, flow rate, and surface elevation is conducted during injection to detect slab response and prevent overlifting (Chun & Ryu, 2000).

Table 2 Recommended Polyurethane System Selection Guide for Geotechnical and Structural Repair Applications

Application	Recommended PU Type	Key Properties Required	Typical Performance Targets	Key References
Structural Crack Repair (<1 mm width)	Low-viscosity injectable PU resin	Viscosity 50–150 cP; high penetrability; strong adhesion to concrete substrate; rapid gel time	Bond strength >2 MPa (per ASTM ACI 546-06); complete crack filling with no voids	Haruna et al. (2025) Somarathna et al. (2018)
Wide Crack Repair (1–10 mm width)	Medium-viscosity flexible PU or PU sealant	Viscosity 150–300 cP; good adhesion; flexibility and elongation; compatible with damp substrates	Bond strength >1.5 MPa; elongation at break >200%; watertight over 10-year service	Haruna et al. (2025) Li et al. (2021); Somarathna et al. (2018)
Pavement Joint Sealing	Flexible PU sealant (self-levelling or gun-grade)	High elongation 300–600%; low elastic modulus; UV and weathering resistance; good adhesion to concrete/asphalt	Joint movement capability $\pm 25\%$; watertight seal; service life ≥ 10 years without resealing	Li et al. (2021) Somarathna et al. (2018)
Leak Sealing (active water flow)	Hydrophilic expanding PU (water-reactive foam)	Reaction time <60 s on contact with water; expansion ratio 5–15 $\times$; capable of sealing under positive water pressure	Seepage reduction >95%; sustained water tightness under hydraulic head ≥ 0.5 bar	Somarathna et al. (2018) Zvierieva et al. (2025)
Tunnel / Underground Waterproofing	Hydrophobic or hydrophilic PU injection grout	Excellent water resistance; rapid set (gel time <5 min); strong adhesion to rock and concrete; chemical durability	Post-treatment permeability <1 $\times 10^{-7}$ m/s; interface bond strength >2 MPa; no shrinkage cracking	Li et al. (2021) Somarathna et al. (2018)
Slab Jacking / Lifting and Leveling	Medium- to high-density expanding PU foam	Controlled expansion ratio 3–8 $\times$; high compressive strength; precise and progressive lifting; low injection pressure	Lifting capacity >300 kPa; leveling accuracy ± 5 mm; minimal surface disruption; traffic reopened within 2–4 h	Jaber et al. (2025) Lat et al. (2020)
Void Filling (beneath slabs and pavements)	Low- to medium-density expanding PU foam	High expansion ratio 10–30 $\times$; low injection pressure; self-filling geometry; lightweight end product	Complete void filling confirmed by GPR survey; in-situ foam density 80–200 kg/m ³ ; minimal surcharge on subbase	Lat et al. (2020) Zvierieva et al. (2025)
Soil Stabilization (clay/sandy soils)	High-density PU resin or permeable PU grout	High final compressive strength; good soil penetration and bonding; controlled exothermic reaction; minimal shrinkage	Bearing capacity increase up to 43 $\times$ (4,314%); cohesion improvement >10 $\times$; permeability reduction >2 orders of magnitude	Huang et al. (2021) Jaber et al. (2025) Zvierieva et al. (2025)
Foundation Underpinning and Settlement Control	High-density expanding PU resin	Compressive strength >5 MPa; low exotherm (<80 °C); controlled gel time; compatibility with in-situ moisture	Bearing capacity restoration >500 kPa; post-treatment differential settlement <10 mm; minimal excavation required	Lat et al. (2020) Zvierieva et al. (2025)
Pavement Subbase and Base Stabilization	Medium- to high-density PU foam or PU-bonded aggregate	Controlled expansion; high stiffness; resistance to dynamic loading and moisture; good adhesion to aggregate	Stiffness increase >150%; uniform load distribution; CBR improvement >3 $\times$; traffic reopened within 4–6 h	Huang et al. (2021) Lat et al. (2020) Li et al. (2021)
Emergency Leak Control (large water inflow)	Fast-reacting hydrophilic expanding PU foam	Very fast reaction time <30 s on water contact; high expansion >15 $\times$; strong initial gel for immediate sealing; water-activated	Immediate stoppage of seepage flow; sustained closure under hydraulic head; expandable volume >15 $\times$ original	Somarathna et al. (2018) Zvierieva et al. (2025)
Deep Injection (depth >5 m)	Low-viscosity, high-strength PU resin (two-component)	Very low viscosity (30–80 cP) for pumpability at depth; controlled gel time; high final compressive strength; thermally stable	Effective penetration depth >5 m; final strength >3 MPa; volume increase after injection 2–5 $\times$ for gap filling	Huang et al. (2021) Jaber et al. (2025) Zvierieva et al. (2025)

Note: PU = Polyurethane. Performance targets represent published values from field and laboratory studies; actual values depend on site conditions, PU formulation, mixing ratio, and injection parameters. Values in parentheses indicate typical ranges reported in literature

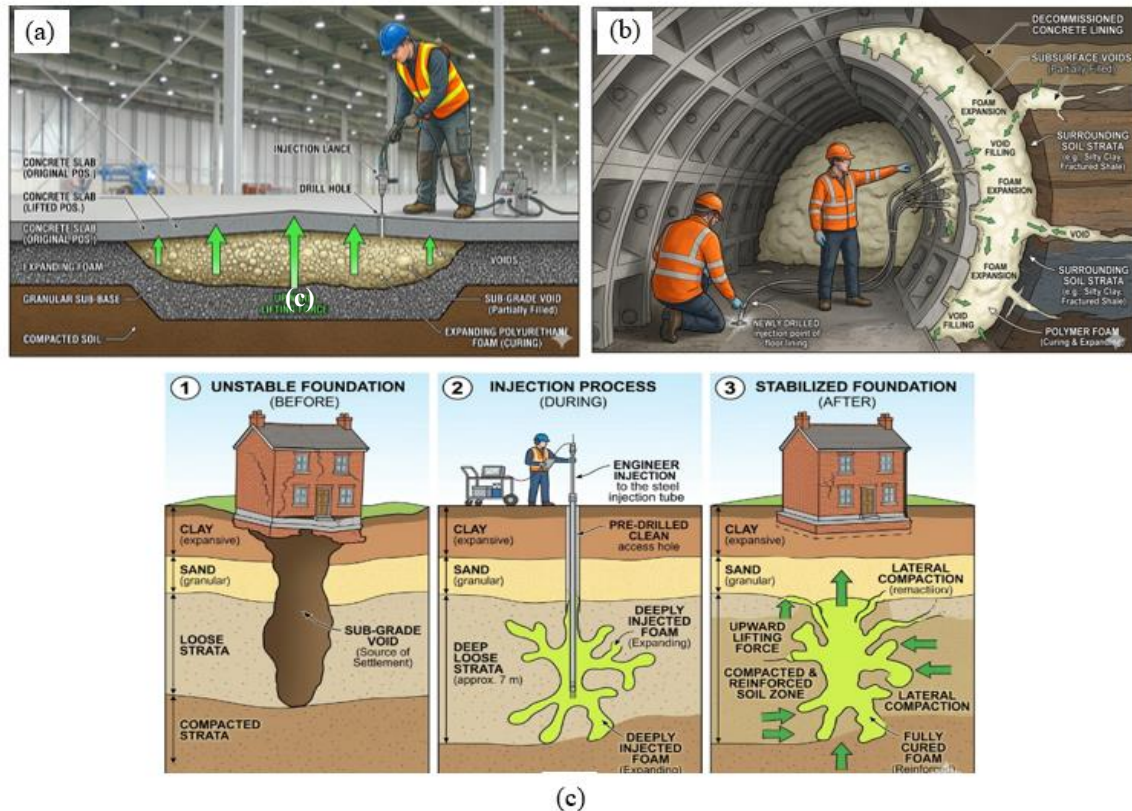


Figure 2 Common polyurethane foam injection techniques in geotechnical applications: (a) slab jacking for pavement re-leveling, where expanding foam is injected beneath concrete slabs to restore grade and fill voids; (b) sequential void injection for shallow soil stabilization using grid pattern placement; (c) deep injection method for foundation underpinning and bearing capacity improvement at depths of 0.25-10 m

(b) Tunnel Lining and Underground Void Grouting

For tunnel lining rehabilitation and underground void-filling applications (Figure 2b), injection ports are cored through the structural lining at predetermined spacings determined by the estimated void geometry from pre-injection ground-penetrating radar or impact-echo surveys. Inflatable packers are seated within the cored holes to create a pressure-tight seal against the lining surface before injection commences. The expanding foam progresses outward from each port to fill irregular void spaces, including inter-strata gaps, annular voids behind the lining, and fracture networks in cohesive soil or shale, that are inaccessible to cementitious grouts because of their higher pre-gel viscosity and absence of self-expansion (Bodi et al., 2012). Formulation selection, hydrophilic or hydrophobic, is made on the basis of prevailing groundwater conditions: hydrophilic systems are selected where active seepage is present and the co-reaction with water is required to drive foam expansion and form a watertight gel, while hydrophobic systems

are used in predominantly dry voids where dimensional stability and compressive strength are the primary requirements (Somarathna et al., 2018). Injection is staged from the outermost void layer progressively inward, confirmed by pressure response at neighbouring ports, to achieve systematic encapsulation without applying net expansive pressure against the structural lining that could induce cracking or joint displacement.

(c) Deep Foundation Underpinning

For foundation underpinning and subgrade strengthening at depths of up to 7 – 10 m (Figure 2c), injection tubes are advanced to target strata through pre-drilled access holes positioned adjacent to or beneath the existing foundation element, eliminating the need for open excavation. Sleeve-pipe (tube-à-manchette) or withdrawal-and-inject lance configurations are used to deliver resin incrementally at prescribed depth intervals, typically 0.5 – 1.0 m per stage, working upward from the deepest target stratum to the

foundation bearing level (Karol, 2003). At each stage, the expanding resin compacts the surrounding loose or weak soil laterally through controlled displacement, forming a densified soil-polymer composite zone around the injection point (Wang et al., 2020). The lance is retracted to the next stage only after the pressure response at that depth has stabilized, indicating that the foam has fully expanded and the immediate zone of influence has been treated. Surface and structural response, monitored via settlement gauges, tilt meters, and crack monitors fixed to the overlying structure, must be evaluated between stages, as premature advancement of the injection depth before the previous stage has cured can generate uncontrolled uplift forces against the foundation slab

4.3.2 Injection Regimes

The interaction between expanding PU foam and the surrounding soil is governed by the injection regime, which is primarily determined by the injection pressure, soil permeability, and foam expansion characteristics (Chun & Ryu, 2000; Karol, 2003; Wang et al., 2020). Three distinct injection regimes have been identified in the literature.

(a) Permeation Regime (Low Pressure, Permeable Soils)

In this regime, the liquid resin penetrates the pore spaces of coarse-grained or highly permeable soils (sands, gravels, or fractured rock) before expanding and curing in situ (Wang et al., 2020). Permeation is most effective when injection pressures are kept below 0.2 – 0.3 MPa and the soil permeability exceeds 10^{-4} m/s (Chun & Ryu, 2000). Laboratory studies have shown that permeable PU grouts can increase the unconfined compressive strength of sandy silts by factors of 5 to 15, with treated specimens exhibiting improved cohesion and internal friction angles (Wang et al., 2020).

(b) Fracture-Filling Regime (Moderate Pressure, Low-Permeability Soils)

In fine-grained soils (silts and clays) or soils with low initial permeability, injected PU foam does not permeate the pore network uniformly; instead, it tends to propagate by hydraulic fracturing, forming discrete veins or lenses along paths of least resistance (Chun & Ryu, 2000). This regime typically develops at injection pressures of roughly 0.3 – 0.5 MPa. As the foam expands, it generates localized stress concentrations and follows preferential pathways, producing an interconnected lattice or honeycomb of

cured resin that densifies the surrounding soil and increases the stiffness of the treated mass (Sabri et al., 2021). Field applications have shown that this fracture-filling behavior can stabilize weak subgrades beneath pavements and reduce differential settlement (Rabbi et al., 2020).

(c) Jetting and Hydraulic Fracturing (High Pressure, Overpressure Conditions)

At injection pressures exceeding 0.5–0.8 MPa, the expanding foam can induce hydraulic fracturing or “jetting,” where the resin forcefully displaces soil particles and creates irregular, uncontrolled pathways (Chun & Ryu, 2000; Wang et al., 2020). This regime is generally undesirable, as it leads to uneven treatment, excessive material consumption, and potential damage to overlying structures (Fortunatus, 2018). Proper injection control, including staged dosing and real-time monitoring of uplift or pressure, is essential to avoid this regime.

4.4 Execution and Quality Control

Effective implementation requires precise control over dosing and real-time monitoring:

- **Staged Dosing:** To manage the high expansion forces and exothermic heat, injection is performed in stages, with each stage limited to a controlled volume delivered at a regulated flow rate (typical field flow rates are on the order of 6–12 L/min, with per-stage volumes restricted to a few litres rather than a single large charge). Allowing the foam to cure between stages prevents over-expansion and ensures better confinement of the treatment zone.

- **Real-Time Monitoring:** Continuous monitoring of surface displacement using laser levels or automated sensors is essential to detect slab lift or ground heave immediately. Pressure sensors at injection points help identify blockages or the formation of preferential flow paths.

- **Safety Considerations:** The exothermic reaction of PU can generate temperatures approaching or exceeding $\sim 100^{\circ}\text{C}$, requiring strict management of injection rates to prevent thermal damage to adjacent utilities or structures. Additionally, workers must be protected from chemical exposure and the high expansion forces inherent to the process.

4.5 Performance Verification and Testing Methods

Reliable assessment of PU foam injection outcomes requires a two-tier evaluation strategy that combines in-situ field verification with controlled laboratory characterization. Field methods provide

spatially continuous evidence of treatment extent and post-injection load response under realistic confining conditions, whereas laboratory testing on extracted or prepared specimens isolates material-level behavior, which includes strength, permeability, and durability, independent of site variability. Neither tier is sufficient alone: field data without laboratory benchmarks cannot confirm whether observed improvements reflect durable material performance or transient stress redistribution, while laboratory results without field correlation cannot verify adequate spatial coverage or injection uniformity. Together, the two approaches constitute a coherent quality-assurance framework consistent with the standards expected for applied geotechnical research.

4.5.1 In-Situ Field Verification

In-situ verification exploits measurable changes in subsurface physical properties, which include mechanical resistance, structural stiffness, and electrical resistivity, to map the spatial extent and magnitude of improvement following PU injection. Three methods have been systematically applied in the literature and are evaluated below in terms of operating principle, reported performance benchmarks, and practical limitations.

(a) Cone Penetration Testing (CPT) and Dynamic Probing (DPT)

CPT advances a standardized conical probe at a constant rate and continuously records tip resistance (q_c), sleeve friction (f_s), and the pore-pressure ratio (B_q), producing a high-resolution stratigraphic profile that permits direct before-and-after comparison at the same location. In PU-treated ground, the expanding foam bonds soil particles and stiffens the inter-granular matrix, so post-injection tip resistance serves as a direct index of cementation effectiveness. Published evaluations report q_c increases of 50% to 200% following injection, with the magnitude governed by initial relative density, foam density class, and the degree of pore-network saturation by foam (Dominijanni et al., 2022). Greater gains are consistently observed in loose, coarse-grained soils where foam can permeate the pore network uniformly; stiff or fine-grained deposits show more modest improvement because advancing foam preferentially exploits existing fissures rather than displacing pore fluid throughout the matrix (Apuani et al., 2015). Dynamic probing (DPT), recording hammer blows per unit penetration, provides a portable and cost-effective complement to CPT for shallow verification (depths

up to 5 – 6 m) where full CPT rigs are impractical. A key limitation shared by both methods is their point-measurement nature: because PU injection is inherently discontinuous, a single sounding may miss treated zones or traverse a foam lens without capturing the surrounding untreated matrix. A verification grid spacing of 1 – 2 m, with additional soundings adjacent to each injection point, is therefore recommended to achieve representative spatial coverage.

(b) Falling Weight Deflectometer (FWD) Testing

The FWD applies a controlled impulse load to the pavement surface and measures the resulting deflection basin through geophones at increasing radial offsets from the load plate. Back-calculation of the deflection bowl yields layer moduli and identifies loss of subgrade support, making FWD the principal quantitative tool for evaluating PU injections in pavement rehabilitation contexts. The two parameters most sensitive to PU treatment are (i) peak deflection under the load plate, which reflects overall subgrade stiffness, and (ii) load transfer efficiency (LTE) at joints and cracks, which quantifies the proportion of applied load carried by the adjacent slab. Field evaluations confirm that PU injection reduces peak pavement deflections by 20% to over 60%, with the magnitude depending on initial void severity, injection depth, and foam density (Boonsung et al., 2024). The greatest structural gains are recorded at joints and cracks rather than at mid-panel locations, because the primary mechanism of improvement is the restoration of subgrade contact and aggregate interlock disrupted by void formation (Vennapusa et al., 2016). This spatial pattern is diagnostically useful: a post-injection FWD survey showing large LTE improvements at joints alongside limited mid-panel gain is characteristic of successful void filling rather than inadequate treatment. FWD testing is non-destructive and rapid, enabling comprehensive surveys across entire project sections and supporting long-term performance monitoring through periodic re-testing.

(c) Three-Dimensional Electrical Resistivity Tomography (ERT)

ERT injects electrical current between electrode pairs and records the resulting potential distribution across a surface array; inversion of the voltage data yields a 3D resistivity model that maps spatial heterogeneity in soil fabric, moisture content, and cementation state. Cured PU foam has substantially higher electrical resistivity than the surrounding moist or saturated soil, so zones of successful injection appear

as distinct high-resistivity anomalies in the post-treatment tomogram. Comparison of pre- and post-injection models therefore provides a non-invasive, spatially continuous map of treatment extent and uniformity that no point-measurement method can replicate (Apuani et al., 2015). Published studies report a strong spatial correspondence between elevated resistivity anomalies and regions of increased stiffness confirmed by concurrent CPT soundings, validating ERT as an independent cross-check for injection coverage (Apuani et al., 2015). The technique is particularly valuable on large-scale treatments where coring or excavation is impractical and where spatially uniform coverage must be demonstrated. Practical limitations include sensitivity to pre-existing resistivity contrasts - such as buried utilities, natural clay lenses, or groundwater level changes - that may be misread as PU anomalies if baseline surveys are not conducted before injection. Depth resolution also degrades progressively, restricting confident delineation of injected zones to approximately the upper 10 – 15 m under typical electrode spacings.

4.5.2 Laboratory Characterization of PU-Treated Soils

Laboratory testing on PU-treated specimens quantifies material-level improvements in strength, permeability, and durability that underpin field performance predictions. Specimens are prepared by injecting foam into mold-contained natural soil under controlled density and moisture conditions, or by extracting intact cores from field-treated sections for index and mechanical testing. Four test categories are most widely reported in the geotechnical PU literature and are discussed below in terms of testing principle, applicable standards, reported results, and conditions necessary for valid cross-study comparison.

(a) Unconfined Compressive Strength (UCS)

UCS testing compresses a cylindrical specimen at a constant strain rate under zero lateral confinement, recording axial stress and deformation to failure. For PU-treated soils, the test captures the combined resistance of the cemented soil matrix and the foam skeleton, making it the most direct material-scale indicator of treatment effectiveness. Published results consistently demonstrate strength increases of 5 to 15 times relative to untreated control specimens, with silty soils treated using high-density PU achieving unconfined compressive strengths of up to 5 MPa (Wang et al., 2020; Wang et al., 2024). Improvement magnitude increases with foam density and injection volume but approaches a plateau once

the accessible pore network is saturated, beyond which additional injection yields diminishing strength returns. Testing should be conducted in accordance with ASTM D2166 or equivalent standards, with specimens conditioned for a minimum of 24 hours at controlled temperature following injection to ensure complete cure. Reporting the foam expansion ratio and the pre-treatment void ratio alongside UCS values is essential for cross-study comparability, as these parameters govern the foam volume fraction and therefore the achievable strength ceiling.

(b) Shear Strength Parameters

Direct shear and triaxial compression tests determine the Mohr–Coulomb failure envelope parameters, effective cohesion (c') and internal friction angle (ϕ'), of PU-treated soil. These parameters are essential inputs for slope stability analysis, bearing capacity estimation, and retaining structure design in treated ground. PU injection predominantly increases apparent cohesion by cementing inter-particle contacts and bridging macro-pores, while the friction angle is less systematically affected, being governed primarily by particle shape and surface texture rather than cementation state (Wang et al., 2020). Published direct shear studies report cohesion increases of 200% to 400% following high-density PU injection in silty and sandy soils, with c' values rising from near zero in untreated specimens to 100 – 300 kPa in treated counterparts (Wang et al., 2020). Triaxial testing under multiple confining pressures is preferred over direct shear for establishing the full failure envelope, particularly in treated soils where the foam–soil composite may exhibit brittle failure at low confining pressures and more ductile behaviour at higher confinements. A minimum specimen diameter of 50 mm is recommended for laboratory-prepared specimens, with larger diameters (100 mm) preferred for field-extracted cores to ensure adequate representation of the foam network geometry.

(c) Hydraulic Conductivity

Falling-head and constant-head permeability tests quantify the hydraulic conductivity (k) of PU-treated soil, governing groundwater flow, seepage pressures, and the effectiveness of PU injection as a waterproofing or cutoff measure. The test principle follows ASTM D5084, but specimen preparation requires particular care: the foam must be fully cured and any injection-induced macro-cracks or interface gaps sealed before testing, as preferential flow paths along the specimen periphery will bias k values

upward relative to the bulk treated mass. Published data show that PU injections can reduce hydraulic conductivity by two to four orders of magnitude compared with untreated specimens, depending on foam density and injection method (Jumadilova, 2024). High-density resins consistently achieve k values on the order of 10^{-8} m/s or lower, satisfying the hydraulic cutoff criterion for most seepage control applications. Low-density foams retain k values in the range of 10^{-4} to 10^{-3} m/s, rendering them unsuitable for waterproofing but acceptable for void filling where permeability control is not a primary design objective. Pre-injection void ratio, injection pressure, and cured foam density should be reported alongside hydraulic conductivity data to enable meaningful cross-study comparison.

(d) Durability and Environmental Resistance

The long-term field performance of PU-treated ground depends on the chemical and physical stability of the foam under service conditions including freeze–thaw cycling, wet – dry fluctuation, sustained mechanical load, and potential chemical attack from pore fluids. Laboratory durability protocols expose treated specimens to accelerated versions of these conditions and track changes in UCS, stiffness, and mass relative to baseline values (Mistry et al., 2024). Freeze–thaw cycling tests (typically 5 to 25 cycles, -20°C to $+20^{\circ}\text{C}$) are particularly relevant for pavement and shallow foundation applications in temperate and cold climates, where pore-water phase changes degrade the foam–soil interface over repeated thermal cycles. Wet–dry cycling simulates seasonal groundwater fluctuation and is critical for hydrophilic PU systems where repeated water uptake and drying may induce volumetric fatigue in the open-cell foam

network. Chemical exposure tests assess resistance to acidic or alkaline pore fluids ($\text{pH} < 4$ or $\text{pH} > 9$) and to organic contaminants such as petroleum hydrocarbons, which can cause swelling or partial dissolution of specific PU formulations. Despite the recognized importance of long-term durability, published geotechnical PU studies remain heavily weighted toward short-term strength characterization; systematic multi-cycle durability data sets are sparse and rarely collected under standardized protocols, constraining the establishment of design service lives and performance guarantees (Mistry et al., 2024). Future research should prioritize standardized durability test frameworks that permit direct cross-study comparison and provide the empirical foundation for lifetime performance models.

4.6. Field Applications and Case Studies

Quantitative performance evidence from selected field case studies and laboratory investigations is summarized in Table 3.

A critical analysis of these cases reveals consistent patterns: successful PU treatment is most strongly associated with thorough pre-injection characterization, appropriate resin selection, controlled staged dosing, pressure management, and real-time monitoring of surface or structural response. The variability reported by Fortunatus (2018) in Tennessee demonstrates that inadequate site investigation, rather than material inadequacy, is the primary driver of suboptimal outcomes. This finding implies that PU foam ground improvement should be understood as an execution and design problem as much as a materials selection problem. The cases below are analyzed through this lens, drawing out transferable design lessons.

Table 3 Summary of Quantitative Performance Evidence from Field Case Studies and Laboratory Investigations

Application Type	Location/Project	PU System Used	Key Performance Metrics	Duration Monitored	Reference
Pavement Slab Repair	Iowa DOT, USA	HDP foam injection	Faulting: 2-5 mm reduction, LTE: +15-30%	2-3 years	Vennapusa et al. (2016)
Airport Pavement	Noi Bai, Vietnam	High-density PU foam	PCN increase: 20%, stiffness: +160%	5 years	Trong (2023)
Tunnel Leak Sealing	Various tunnels	Expanding hydrophilic PU	Seepage: 1,800 to 30 L/min (98% reduction)	1-2 years	Bodi et al. (2012)
Building Underpinning	Segovia, Spain	Expanding PU resin	Settlement arrested, foundation stabilized	3+ years	Escolano Sánchez et al. (2017)
Soil Stabilization	Laboratory studies	Permeable PU grout	Strength increase: >10× in silty soils	N/A	Wang et al. (2020)
Slab Jacking	Tennessee DOT, USA	HDP foam	Variable outcomes, leveling accuracy issues	1-2 years	Fortunatus (2018)
Foundation Repair	Malaysia	PU foam/resin grout	Rapid remediation, settlement control	6 months to 2 years	Jais et al. (2016)
Collapsible Soil Treatment	Iraq	PU foam injection	Collapse potential reduced significantly	Laboratory	Abdulrasool & Al-Wakel (2021)

4.6.1 Pavement Slab Stabilization and Re-Leveling

PU foam injection has been widely adopted for stabilizing and re-leveling concrete pavement slabs affected by subgrade erosion, settlement, or void formation (Fortunatus, 2018; Vennapusa et al., 2016). A comparative field study conducted by the Iowa Department of Transportation evaluated the performance of PU foam injection versus conventional cementitious grouting for pavement slab stabilization (Vennapusa et al., 2016). The study found that both methods significantly improved load transfer efficiency and reduced faulting at joints and cracks. However, PU foam injection achieved faulting reductions of 2 – 5 mm, compared to 1 – 2 mm for cementitious grout, and allowed for traffic reopening within 2 – 4 hours, compared to 24 – 72 hours for cementitious systems (Vennapusa et al., 2016).

A separate study of high-density polyurethane (HDP) foam injection for pavement preservation in Tennessee found more variable results (Fortunatus, 2018). While some sections showed improved pavement condition and reduced roughness, others exhibited minimal improvement or even slight deterioration. The study concluded that the effectiveness of PU injection is highly dependent on proper site investigation, accurate void detection, and precise injection control (Fortunatus, 2018). Inadequate pre-investigation and over-injection were identified as primary causes of poor performance.

4.6.2 Airport Pavement Foundation Repair

A notable application of PU foam for ground improvement was implemented at Noi Bai International Airport in Vietnam, where pavement distress was attributed to weak foundation soils and inadequate drainage (Trong, 2023). High-density PU foam was injected beneath distressed pavement sections to stabilize the foundation and increase bearing capacity. Post-treatment monitoring over a 5-year period showed a 20% increase in pavement classification number (PCN) and a 160% increase in foundation stiffness, as measured by FWD testing (Trong, 2023). The treatment also improved drainage conditions and reduced the rate of pavement deterioration, demonstrating the long-term effectiveness of PU foam for airport pavement rehabilitation.

4.6.3 Foundation Underpinning

PU foam injection has been successfully used for underpinning historic buildings and structures affected by differential settlement (Escolano Sánchez et al., 2017). A case study from Segovia, Spain, documented the use of expanding PU resin to underpin the shallow foundations of the Cardinal Diego de Espinosa Palace, a 16th-century structure that had experienced significant settlement and cracking (Escolano Sánchez et al., 2017). The treatment involved injecting high-density PU resin through boreholes drilled adjacent to the existing foundations.

Post-treatment monitoring showed that settlement was arrested, and the building's structural stability was restored. The project demonstrated the feasibility of using PU foam for sensitive underpinning applications where minimal vibration and rapid curing are essential (Escolano Sánchez et al., 2017).

4.6.4 Tunnel Leak Sealing and Water Control

Hydrophilic PU grouts have been widely used to control water seepage in tunnels, basements, and underground structures (Qin, 2025). A field application in a tunnel experiencing heavy seepage (1800 – 2000 liters per minute) demonstrated the effectiveness of PU grouting for emergency water control (Qin, 2025). Hydrophilic PU was injected through boreholes drilled into the water-bearing zones, where it reacted with the inflowing water to form an impermeable gel. Within hours of injection, the seepage rate was reduced to 25 – 30 liters per minute (a 98% reduction), and the tunnel was stabilized (Zhang et al., 2024). This case study highlights the unique capability of hydrophilic PU systems to function effectively in high-flow, saturated conditions where conventional cementitious grouts would be washed out.

4.6.5 Stabilization of Expansive and Collapsible Soils

PU foam has also been investigated as a remedial measure for problematic soils, including expansive clays and collapsible loess (Abdulrasool & Al-Wakel, 2021; Rabbi et al., 2020). In a study of pavement sections constructed over expansive soils in Louisiana, PU grout injection was used to reduce differential heave caused by seasonal moisture variations (Rabbi et al., 2020). The treatment involved injecting PU foam into the subgrade to fill voids, reduce permeability, and provide a barrier against moisture infiltration. Post-treatment monitoring showed significant reductions in pavement roughness and distress, indicating that PU injection can be an effective remedial measure for expansive soil-related problems (Dong et al., 2024).

Laboratory studies on collapsible soils have shown that PU foam injection can significantly reduce collapse potential by filling pore spaces and binding soil particles (Abdulrasool & Al-Wakel, 2021). However, field applications for collapsible soils remain limited, and further research is needed to establish design guidelines for this application.

4.7 Comparative Performance: PU Foam vs. Cementitious Grouting

The selection of appropriate grouting material for geotechnical repair and stabilisation involves multi-criteria trade-offs that extend beyond individual mechanical properties. Although expanding polyurethane (PU) foam and conventional cementitious grout are both widely deployed, they occupy distinct performance niches that make direct substitution inadvisable without rigorous site assessment. Table 4 provides a structured, criterion-by-criterion comparison; the following discussion synthesises those data into an analytical framework that integrates geomechanical performance, durability, economics, and environmental considerations to guide material selection in practice.

The most immediate practical distinction between the two systems lies in their time-dependent behaviour. PU foam achieves approximately 90% of its design strength within 15 to 30 minutes of injection and typically permits traffic reinstatement within 2 to 12 hours (Chun & Ryu, 2000; Mohamed Jais, 2017). Cementitious grouts, by contrast, require 12 to 72 hours to develop adequate bearing capacity, and full cure may be delayed further by ambient temperature, water content, and mix design (Vennapusa et al., 2016). For high-traffic infrastructure, including motorways, airport runways, and urban arterial roads, this difference often determines method selection independently of other factors, since extended closures impose disproportionate economic and logistical costs. The speed advantage of PU foam is, however, accompanied by a higher operational complexity: dual-component pumping, real-time thermal monitoring, and precise pressure control are mandatory to prevent uncontrolled heaves or void under-filling (Lat et al., 2022).

With respect to geomechanical performance, the two systems exhibit complementary rather than competing strength profiles. PU foam's low pre-expansion viscosity (150 – 300 mPa·s) enables it to penetrate micro-fissures and pore-scale voids that are inaccessible to cement-based slurries, and its post-cure expansion ratio of 5 – 30× allows it to fill geometrically complex void networks under controlled pressure (Bodi et al., 2012; Jaber et al., 2025). However, PU foam's moderate compressive strength (0.3 – 10 MPa) and relatively low elastic modulus mean it is less suited to applications demanding high rigid bearing capacity than it is to applications requiring flexibility, void-filling efficiency, or dynamic load absorption (Somarathna et al., 2018). Cementitious grouts exhibit higher bulk stiffness and unconfined

compressive strength (typically 5 – 30 MPa) and are preferred where sustained point loading or load transfer across joints is the primary objective (Vennapusa et al., 2016). Notably, in saturated conditions, the buoyancy risk associated with low-density PU foam warrants site-specific confinement design, a limitation absent from the heavier cement matrix (Lat et al., 2022). The reduction in pavement faulting further illustrates this contrast: field measurements report 2 – 5 mm faulting reduction with PU foam compared to 1 – 2 mm for cementitious systems under equivalent loading, attributable to PU foam's crack-bridging and differential settlement accommodation capacity (Vennapusa et al., 2016).

Long-term durability data remains more extensively documented for cementitious systems than for PU foam. Cement-based grouts have a multi-decade performance record, though their susceptibility to sulfate attack, carbonation, and acid environments constitutes a known vulnerability in chemically aggressive soils (Vennapusa et al., 2016). Cured PU foam demonstrates good resistance to some petroleum hydrocarbons and organic solvents, but its durability may decrease under strongly alkaline conditions and prolonged ultraviolet exposure (Somarathna et al., 2018). More critically, the long-term mechanical behaviors of PU foam within the in-situ soil matrix, particularly under sustained cyclic loading, wet-dry cycles and freeze-thaw action, is insufficiently characterized compared with that of cement-based counterparts, and this knowledge gap represents a significant barrier to its adoption in high-consequence infrastructure settings (Mistry et al., 2024).

Economic and environmental considerations reinforce the case for context-dependent selection rather than a universal preference for either material. On a per-kilogram basis, PU foam carries a higher unit material cost, but project-level analyses consistently indicate that its rapid installation reduces total expenditure by 33 – 50% when indirect costs, including traffic management, labor, equipment mobilization, and lost road-user time, are properly accounted for (Mohamed Jais, 2017; Mistry et al.,

2024). From a life cycle assessment perspective, PU foam's production phase generates approximately 2–3 times more greenhouse gas emissions per kilogram than Portland cement owing to its petrochemical feedstock (Silva et al., 2023). Nevertheless, these embodied-carbon penalties are partially offset during the operational phase by reductions in transport mass, smaller equipment fleets, and shorter traffic disruption windows that lower vehicle idling emissions (Al-Atroush & Sebaey, 2021; Silva et al., 2023). End-of-life recyclability remains the weakest dimension of PU foam's environmental profile: the thermoset polymer network is not readily recoverable, and disposal typically involves landfilling or incineration (Mistry et al., 2024). The development of bio-based polyols derived from vegetable oils offers a potential pathway to reducing production-phase impacts by 30 – 40%, though field-scale durability under geotechnical loading conditions requires validation before widespread adoption can be recommended (Qin et al., 2025).

Taken together, the evidence synthesized in Table 4 suggests that PU foam and cementitious grouting should be regarded as complementary rather than interchangeable technologies.

PU foam is most advantageous in time-sensitive, access-constrained, or geometrically complex applications where lightweight void-filling, high penetration, or waterproofing is the primary requirement. Cementitious grouts remain the preferred choice for large-volume stabilization, high-strength underpinning, and projects with extended construction windows where lower material cost and a well-established durability record are decisive. An integrated decision process should incorporate site geotechnical conditions, required performance timeline, subsurface void geometry, service environment, and life cycle cost, criteria that no single material can simultaneously optimize. Future research should prioritize long-term cyclic loading performance of PU foam in diverse soil environments, standardized life cycle assessment boundaries, and the validation of bio-based PU formulations under geotechnical field conditions.

Table 4 Comparative performance of expanding polyurethane foam and conventional cementitious grouting across key geotechnical selection criteria

Performance Criterion	Expanding PU Foam	Conventional Cementitious Grouting
Reaction & Cure Time	Reaches ~90% strength within 15 – 30 min; traffic reopening in 2 – 12 h (Chun & Ryu, 2000; Mohamed Jais, 2017).	Full cure requires 12 – 72 h; interim closure may extend to several days under cold or wet conditions (Vennapusa et al., 2016).
Density & Unit Weight	Low unit weight: 30 – 1,000 kg/m ³ . Minimizes surcharge on weak subgrades; buoyancy or upward migration risk exists in fully saturated ground (Lat et al., 2022).	High unit weight: 1,800 – 2,200 kg/m ³ . Adds dead load to the subgrade; low uplift risk (Vennapusa et al., 2016).
Initial Viscosity & Penetration	Low pre-expansion viscosity (150 – 300 mPa·s) enables penetration into fine fissures and pore-scale voids before reaction onset (Bodi et al., 2012; Chun & Ryu, 2000).	High viscosity limits penetration to macro-voids (> 0.3 mm); pre-fracturing or sleeve grouting may be required in fine-grained soils (Vennapusa et al., 2016).
Volume Expansion	Expands 5 – 30× original liquid volume; actively fills irregular voids and exerts controlled lifting pressure (< 0.4 MPa) (Jaber et al., 2025; Lat et al., 2020).	Negligible expansion: volume-stable but relies on bulk displacement; cannot compensate for complex void geometry (Vennapusa et al., 2016).
Permeability After Curing	Effectively impermeable: cured foam achieves $k = 10^{-5} - 10^{-8}$ m/s, forming a durable hydraulic barrier (Zvierieva et al., 2025).	Variable: typical $k = 10^{-6} - 10^{-4}$ m/s; residual porosity allows moisture transmission under sustained hydraulic gradients (Vennapusa et al., 2016).
Mechanical Stiffness & Strength	Moderate compressive strength (0.3–10 MPa depending on density); high flexibility and crack-bridging capacity; friction angle ~2× that of dense clay (Jaber et al., 2025; Somarathna et al., 2018).	High bulk stiffness (UCS typically 5 – 30 MPa); superior for load transfer near joints but prone to brittle fracture under differential settlement (Bodi et al., 2012).
Pavement Faulting Reduction	Superior: field trials report faulting reduction of 2 – 5 mm with sustained improvement over 2–3 years (Vennapusa et al., 2016).	Moderate: faulting reduction typically 1 – 2 mm; performance may degrade faster due to rigid–flexible interface issues (Vennapusa et al., 2016).
Durability & Chemical Resistance	Resistant to petroleum products and solvents; degrades progressively above pH 9; long-term soil interaction and UV creep are less well characterized (Somarathna et al., 2018; Mistry et al., 2024).	Stable at high pH; vulnerable to sulfate attack, carbonation, and acid environments; established durability data spanning decades (Vennapusa et al., 2016).
Life Cycle & Environmental Impact	Higher embodied carbon in production (~2 – 3× per kg vs. cement); partially offset in use phase by lower transport mass, rapid placement, and reduced traffic idling; end-of-life recyclability is limited (Silva et al., 2023; Mistry et al., 2024).	Lower production carbon per kg; heavier mass increases transport and placement footprint; alkaline by-products can affect local groundwater; material is inert at end of life (Silva et al., 2023).
Total Project Economics	Higher unit material cost; overall project cost reduced by 33–50% through faster cure, smaller crew, and reduced traffic control duration (Mohamed Jais, 2017; Mistry et al., 2024).	Lower raw material cost; higher indirect costs from extended road closures, larger equipment, and labor; cost-effective for large-volume, non-urgent applications (Vennapusa et al., 2016).
Operational Complexity	Requires trained operators, dual-component pumping systems, and thermal monitoring; injection pressure must be controlled to avoid slab heave (Lat et al., 2022).	Standard grout pumps; simpler quality control; but larger volumes require batching plants on site (Vennapusa et al., 2016).

Note: PU = polyurethane; UCS = unconfined compressive strength; k = hydraulic conductivity; LCA = life cycle assessment. Values shown represent published ranges from field and laboratory studies; actual performance is site- and formulation-dependent

5. Limitations, Challenges, and Research Gaps

Despite its growing adoption, PU foam injection is subject to several limitations that affect design reliability, field execution, and long-term acceptance. First, its low unit weight creates a buoyancy and uplift risk in saturated ground, particularly in soft

marine clays and loose sands, where existing predictive models remain insufficiently validated for routine design (Lat et al., 2019, 2022). Second, long-term performance data under sustained cyclic loading are sparse; fatigue, creep, and stress relaxation over 10+ years of service have yet to be resolved through systematic field

monitoring or standardized laboratory protocols (Fortunatus, 2018; Mistry et al., 2024; Qin et al., 2025). Third, chemical sensitivity constrains the application scope: some PU formulations may degrade under strong alkaline pore-water conditions; exothermic reactions can generate high temperatures in confined or high-volume injections; and isocyanate handling, volatile emissions, and potential groundwater interactions require careful environmental and occupational safety management. In addition, isocyanate handling, VOC emissions during curing, and potential interactions with groundwater require careful environmental and occupational safety management (Mistry et al., 2024; Qin et al., 2025). Fourth, the absence of standardized design codes and quality-assurance protocols forces practitioners to rely on proprietary guidance and empirical judgement, yielding inconsistent field outcomes and limiting regulatory acceptance (Fortunatus, 2018; Mistry et al., 2024). Addressing these gaps through long-term monitoring programs, bio-based low-exotherm formulations, comprehensive life cycle assessments, and the development of unified design standards, is essential for PU foam to transition from a niche to a mainstream geotechnical intervention (Mistry et al., 2024; Qin et al., 2025).

6. Conclusion

Polyurethane foam injection has proven to be a technically mature and operationally superior alternative to conventional cementitious grouting for a broad spectrum of geotechnical applications. Its rapid cure kinetics, reaching approximately 90% design strength within 15 minutes, combined with an engineerable property range spanning densities of 35 – 1,000 kg/m³ and post-cure hydraulic conductivities of 10⁻⁵ to 10⁻⁸ m/s, enable a single material platform to address diverse challenges from void filling and slab leveling to deep soil stabilization and hydraulic sealing. Field performance data consistently confirm pavement stiffness gains of up to 70% and faulting reductions of 2–5 mm, alongside bearing capacity improvements exceeding 40 times that of untreated soils.

Successful outcomes, however, depend fundamentally on execution rigor: precise injection pressure control, systematic site characterization, and continuous real-time monitoring are prerequisites, particularly in saturated ground where buoyancy-induced uplift introduces design constraints absent from cementitious systems. Looking forward, the principal barriers to wider adoption, namely the

absence of standardized design codes, limited long-term cyclic loading data, and unresolved life cycle sustainability questions, must be addressed through coordinated research and regulatory effort. As these gaps are closed, expanding polyurethane foam is well positioned to become a mainstream geotechnical solution supporting the sustainable rehabilitation of ageing civil infrastructure.

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8. CRediT Statement

Nares Pataratorn: Conceptualization, Data Curation Methodology, Critical review, Validation, Writing – Original Draft, revision

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9. Abbreviations

Abbreviation	Full Term
PU	Polyurethane
CPT	Cone penetration testing
DPT	Dynamic probing test
ERT	Electrical resistivity tomography
FWD	Falling weight deflectometer
LTE	Load transfer efficiency
UCS	Unconfined compressive strength
MDI	Methylene diphenyl diisocyanate
PPG	Polypropylene glycol
PEG	Polyethylene glycol
GPR	Ground-penetrating radar
PCN	Pavement classification number
LCA	Life cycle assessment
VOC	Volatile organic compound

10. References

- Abdulrasool, A. S., & Al-Wakel, S. F. (2021). Effects of polyurethane foam on the behaviour of collapsible soils. *Geotechnical Research*, 8(4), 108-116.
<https://doi.org/10.1680/jgere.21.00005a>
- Al-Atroush, M. E., & Sebaey, T. A. (2021). Stabilization of expansive soil using hydrophobic polyurethane foam: A review. *Transportation Geotechnics*, 27, Article

100494.
<https://doi.org/10.1016/j.trgeo.2020.100494>
- American Society of Civil Engineers (ASCE). (2021). *A comprehensive assessment of America's infrastructure*. Retrieved from <https://infrastructurereportcard.org/>
- Apuani, T., Giani, G. P., d'Attoli, M., Fischanger, F., Morelli, G., Ranieri, G., & Santarato, G. (2015). Assessment of the efficiency of consolidation treatment through injections of expanding resins by geotechnical tests and 3D electrical resistivity tomography. *The Scientific World Journal*, 2015(1), Article 237930. <https://doi.org/10.1155/2015/237930>
- Bodi, J., Bodi, Z., Scucka, J., & Martinec, P. (2012). Polyurethane grouting technologies. *Polyurethane*, 1, 307-336. <https://doi.org/10.5772/35791>
- Boonsung, A., Phunpeng, V., Horpibulsuk, S., Pathompongpaioj, A., Sawatwutichaikul, A., Choenklang, P., ... & Arulrajah, A. (2024). Performance of the polyurethane foam injection technique for road maintenance applications. *Transportation Geotechnics*, 49, Article 101411. <https://doi.org/10.1016/j.trgeo.2024.101411>
- Buzzi, O., Fityus, S., & Sloan, S. W. (2010). Use of expanding polyurethane resin to remediate expansive soil foundations. *Canadian Geotechnical Journal*, 47(6), 623-634. <https://doi.org/10.1139/T09-132>
- Choi, J., & Kim, D. (2021). Analysis of the physical and mechanical properties of injected high-density polyurethane from laboratory experiments and field tests. *Economic and Environmental Geology*, 54(1), 83-92. <https://doi.org/10.9720/KSEG.2021.1.083>
- Chun, B. S., & Ryu, D. S. (2000). A study on applications of polyurethane injection material for ground improvement. *KSCE Journal of Civil Engineering*, 4(4), 245-250. <https://doi.org/10.1007/BF02830823>
- Dominijanni, A., Gabassi, M., Minardi, A., & Pavan, S. (2022). The use of dynamic probing tests and cone penetration tests to verify the effectiveness of expanding polyurethane resin injections for ground improvement. In G. Gottardi & L. Tonni (Eds.), *Cone Penetration Testing 2022: Proceedings of the 5th International Symposium on Cone Penetration Testing (CPT'22)*, 8-10 June 2022, Bologna, Italy (pp. 907-912). CRC Press. <https://doi.org/10.1201/9781003308829-135>
- Dong, H., Li, S., Jia, Z., Luo, Y., Chen, Y., Jiang, J., & Ji, S. (2024). A review of polyurethane foams for multi-functional and high-performance applications. *Polymers*, 16(22), Article 3182. <https://doi.org/10.3390/polym16223182>
- Escolano Sánchez, F., Mazariegos de la Serna, A., Sánchez Lavín, J. R., & Bueno Aguado, M. (2017). Underpinning of shallow foundations by expansive polyurethane resin injections: Case study Cardinal Diego de Espinosa Palace in Segovia (Spain). *Revista de la Construcción*, 16(3), 420-433. <https://doi.org/10.7764/RDLC.16.3.420>
- Fortunatus, M. (2018). *Evaluation of the performance of polyurethane foams in rigid pavement preservation* [Doctoral dissertation]. Iowa State University Digital Repository, Ames, US.
- Hapsari, R. I., Putri, F. S., Harsanti, W., Nugroho, G. A., Nurlatifah, A., Awaludin, A., & Halim, H. B. A. (2026). Effects of land use change and climate projections on erosion and sediment transport in the Kricik River Basin, Indonesia: A modeling study. *Journal of Current Science and Technology*, 16(2), Article 177. <https://doi.org/10.59796/jcst.V16N2.2026.177>
- Haruna, S. I., Ibrahim, Y. E., Gora, A. M., & Ibrahim, M. N. (2025). Polyurethane grout as repair material for concrete structures: Performance evaluation. *Materials Research Proceedings*, 48, 569-576. <https://doi.org/10.21741/9781644903414-62>
- Hong, B., Lu, G., Li, T., Lin, J., Wang, D., Liang, D., & Oeser, M. (2021). Gene-editable materials for future transportation infrastructure: A review for polyurethane-based pavement. *Journal of Infrastructure Preservation and Resilience*, 2, Article 27. <https://doi.org/10.1186/s43065-021-00039-w>
- Huang, J., Kogbara, R. B., Hariharan, N., Masad, E. A., & Little, D. N. (2021). A state-of-the-art review of polymers used in soil stabilization. *Construction and Building Materials*, 305, Article 124685. <https://doi.org/10.1016/j.conbuildmat.2021.124685>
- Jaber, L., Balhas, R., El Ahmad, M., & Alhakim, G. (2025). Soil stabilization utilizing an optimized combination of polyurethane foam

- and cement. *Geo-Engineering*, 16, Article 20. <https://doi.org/10.1186/s40703-025-00246-4>
- Jais, I. M., Ali, M. M., & Muhamad, H. (2016). *Alternative ground improvement solution with polyurethane foam/resin* [Conference presentation]. In CIEC 2015: Proceedings of the International Civil and Infrastructure Engineering Conference. Springer Singapore. https://doi.org/10.1007/978-981-10-0155-0_38
- Jumadilova, S. Z. (2024). Injection of two-component Geopur resin for strengthening sandy soils. *Bulletin of Kazakh Leading Academy of Architecture and Civil Engineering*, 3(93), 62–70. <https://doi.org/10.51488/1680-080X/2024.3-07>
- Karol, R. H. (2003). *Chemical grouting and soil stabilization* (3rd ed., rev. & expanded). Marcel Dekker. <https://doi.org/10.1201/9780203911815>
- Kinay, F., & Bakis, A. (2025). Usability of polyurethane resin binder in road pavement construction. *Applied Sciences*, 15(19), Article 10592. <https://doi.org/10.3390/app151910592>
- Lat, D. C., Ali, N., Jais, I. B. M., Yunus, N. Z. M., Razali, R., & Talip, A. R. A. (2020). A review of polyurethane as a ground improvement method. *Malaysian Journal of Fundamental and Applied Sciences*, 16(1), 70–74. <https://doi.org/10.11113/mjfas.v16n1.1235>
- Lat, D. C., Jais, I. B. M., Ali, N., Baharom, B., Mohd Yunus, N. Z., & Mat Yusof, D. A. (2019). Uplift and settlement prediction model of marine clay soil integrated with polyurethane foam. *Open Engineering*, 9(1), 521–530. <https://doi.org/10.1515/ENG-2019-0054>
- Lat, D. C., Jais, I. B. M., Ali, N., Yunus, N. Z. M., Zarin, N. H. W. N., & Zainuddin, A. N. (2022). Consolidation integrated buoyancy equation for soft ground improved with lightweight polyurethane foam. *IJUM Engineering Journal*, 23(1), 90–105. <https://doi.org/10.31436/ijumej.v23i1.1781>
- Li, X., Li, J., Wang, J., Yuan, J., Jiang, F., Yu, X., & Xiao, F. (2021). Recent applications and developments of Polyurethane materials in pavement engineering. *Construction and Building Materials*, 304, Article 124639. <https://doi.org/10.1016/j.conbuildmat.2021.124639>
- Mistry, M., Prajapati, V., & Dholakiya, B. Z. (2024). Redefining construction: An in-depth review of sustainable polyurethane applications. *Journal of Polymers and the Environment*, 32(7), 3047–3073. <https://doi.org/10.1007/s10924-023-03161-w>
- Mohamed Jais, I. B. (2017). Rapid remediation using polyurethane foam/resin grout in Malaysia. *Geotechnical Research*, 4(2), 107–117. <https://doi.org/10.1680/jgere.17.00003>
- Pang, C., Huang, Z., Song, J., Geng, L., Sun, M., & Li, H. (2026). Road performance of polyurethane mixtures and load response behaviors of typical polyurethane pavement structures. *Coatings*, 16(2), Article 185. <https://doi.org/10.3390/coatings16020185>
- Qin, L., Kou, D., Jiang, X., Yang, S., Hou, N., & Huang, F. (2025). Research progress on polyurethane-based grouting materials: modification technologies, performance characterization, and engineering Applications. *Polymers*, 17(17), Article 2313. <https://doi.org/10.3390/polym17172313>
- Qin, P. (2025). Analysis of seepage failure mechanism in silty-fine sand and its prevention and control research. *Scientific Reports*, 15, Article 15847. <https://doi.org/10.1038/s41598-025-00749-1>
- Rabbi, M. F., Boudreau, R. L., Chittoori, B. C., Sotirin, M., & Mishra, D. (2020). Polyurethane grout injection as remedial measure to reduce differential heave in pavement sections constructed over expansive soils. *Journal of Transportation Engineering, Part B: Pavements*, 146(4), Article 04020068. <https://doi.org/10.1061/JPEODX.0000221>
- Ray, R., Samui, P., & Roy, L. B. (2023). Reliability analysis of a shallow foundation on clayey soil based on settlement criteria. *Journal of Current Science and Technology*, 13(1), 91–106. <https://doi.org/10.14456/jcst.2023.9>
- Sabri, M. M. S., Vatin, N. I., & Alsaffar, K. A. M. (2021). Soil injection technology using an expandable polyurethane resin: A review. *Polymers*, 13(21), Article 3666. <https://doi.org/10.3390/polym13213666>
- Silva, R., Barros-Timmons, A., & Quinteiro, P. (2023). Life cycle assessment of fossil- and bio-based polyurethane foams: A review. *Journal of Cleaner Production*, 430, Article 139697. <https://doi.org/10.1016/j.jclepro.2023.139697>
- Somarathna, H. M. C. C., Raman, S. N., Mohotti, D., Mutalib, A. A., & Badri, K. H. (2018). The use of polyurethane for structural and infrastructural engineering applications: A

- state-of-the-art review. *Construction and Building Materials*, 190, 995-1014.
<https://doi.org/10.1016/j.conbuildmat.2018.09.166>
- Sukkaneewat, B., Sridaeng, D., & Chantarasiri, N. (2019). Fully water-blown polyisocyanurate-polyurethane foams with improved mechanical properties prepared from aqueous solution of gelling/blowing and trimerization catalysts. *e-Polymers*, 19(1), 277-289.
<https://doi.org/10.1515/epoly-2019-0028>
- Thompson-Colon, J., Jack, W. J., Sumner, K. H., & Stoneburner, S. (2006). *Solid polyurethane compositions, infrastructure repair and geo-stabilization processes* [Patent]. U.S. Patent Application Publication.
- Trong, H. N. (2023). Study on distress of airport pavement foundation and solution applied to Noi Bai international airport. *The Transport and Communications Science Journal*, 74(4), 484-496. <https://doi.org/10.47869/tcsj.74.4.8>
- Vennapusa, P. K. R., Zhang, Y., & White, D. J. (2016). Comparison of pavement slab stabilization using cementitious grout and injected polyurethane foam. *Journal of Performance of Constructed Facilities*, 30(6), Article 04016091.
[https://doi.org/10.1061/\(ASCE\)CF.1943-5509.0000916](https://doi.org/10.1061/(ASCE)CF.1943-5509.0000916)
- Wang, C., Liu, Q., Guo, C., Zhu, J., Xia, K., Sun, T., & Ding, Y. (2020). An experimental study on the reinforcement of silt with permeable polyurethane by penetration grouting. *Advances in Civil Engineering*, 2020, Article 8834331.
<https://doi.org/10.1155/2020/8834331>
- Wang, F., Li, K., & Liu, Y. (2024). Experimental study on the mechanical behaviour of silty soil stabilized with polyurethane. *Construction and Building Materials*, 411, Article 135251.
<https://doi.org/10.1016/j.conbuildmat.2024.135251>
- Wang, J., Gao, S., Zhang, C., Wang, Y., & Xu, D. (2022). Preparation and performance of water-active polyurethane grouting material in engineering: A review. *Polymers*, 14(23), Article 5099.
<https://doi.org/10.3390/polym14235099>
- Xu, L., Lu, T., Chen, Z., Ni, H., Sun, D., & Tian, Y. (2024). A review of polyurethane as an alternative to asphalt binder for more sustainable roads: Performance, environment, and economy. *Journal of Traffic and Transportation Engineering (English Edition)*, 11(6), 1268-1290.
<https://doi.org/10.1016/j.jtte.2024.10.001>
- Zhang, C., Zhou, J., Zheng, X., Yang, J., Zhan, S., & Yang, L. (2024). A novel water-swelling grouting material formulation and its performance for water rushing in karst strata. *Construction and Building Materials*, 416, Article 135245.
<https://doi.org/10.1016/j.conbuildmat.2024.135245>
- Zvierieva, A., Borziak, O., Dudin, O., Panchenko, S., & Rucińska, T. (2025). Research on polyurethane-stabilized soils and development of quantitative indicators for integration into BIM-based project planning. *Sustainability*, 17(17), 7781.
<https://doi.org/10.3390/su17177781>