

Geotechnical Considerations in Roadway Failures: Engineering Strategies for Subgrade Stabilization in Expansive Soils

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Abstract:

Expansive soils present a persistent challenge to roadway infrastructure due to their significant volume changes with moisture fluctuations, which often lead to pavement cracking, differential settlement, and premature failure. This paper investigates geotechnical strategies for stabilizing expansive clay subgrades to enhance the performance and longevity of roadways. A case study was conducted on a section of roadway in Dallas–Fort Worth, Texas, where three stabilization techniques including lime, lime-fly ash, and geopolymers were evaluated through laboratory testing and field instrumentation. Parameters such as unconfined compressive strength (UCS), soaked California Bearing Ratio (CBR), swell potential, and rutting were used to compare the effectiveness of each method. Results indicated that lime stabilization yielded the highest strength and swell reduction, while lime-fly ash provided comparable performance with improved environmental sustainability. Geopolymer treatment, though less effective in the short term, showed promise for long-term stabilization under optimized conditions. The study highlights that effective subgrade stabilization depends not only on strength gains but also on compatibility with site conditions, environmental concerns, and long-term performance metrics. The findings contribute practical insights for engineers and policymakers seeking resilient and sustainable roadway design in regions affected by expansive soils.

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Abstract

1. Introduction

The performance of transportation infrastructure, particularly roadways, is fundamentally influenced by the condition and engineering properties of the underlying soils. One of the most persistent challenges in this context arises from expansive soils, which are highly active clayey soils known for their tendency to undergo significant volumetric changes in response to moisture variation. These soils swell when exposed to water and shrink when desiccated, causing movement within the subgrade that results in pavement cracking, surface undulations, loss of serviceability, and in severe cases, complete structural failure (Nelson & Miller, 2015). The implications of such failures are both economic and social, often leading to increased maintenance costs, traffic disruptions, and compromised public safety.

Expansive soils are widespread globally but pose a particularly severe risk in several regions of the United States, including parts of Texas, Colorado, Oklahoma, and California. These regions experience climate conditions that exacerbate moisture variation in the subgrade, leading to repeated cycles of shrinkage and

swelling. According to the American Society of Civil Engineers (ASCE), damage caused by expansive soils is more financially significant than the damage caused by floods, earthquakes, hurricanes, and tornadoes combined on an annual basis (Puppala et al., 2014). This statistic emphasizes the critical importance of understanding and managing expansive soils in the context of roadway engineering.

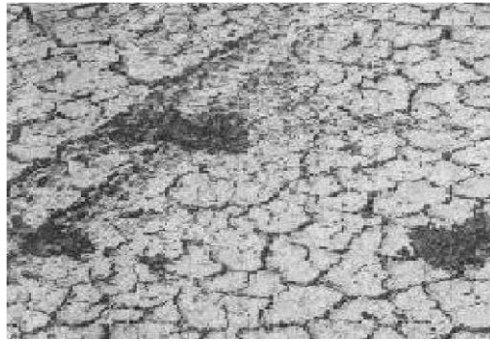


Figure 1: Expansive soil showing desiccated cracks

In the case of the Texas transportation network, expansive soils have long been identified as a dominant contributor to early pavement deterioration. The Texas Department of Transportation (TxDOT) estimates that expansive soil-induced damages account for approximately one-third of all roadway maintenance activities statewide. Such recurring problems often stem from inadequate subgrade stabilization practices or a failure to conduct sufficient geotechnical investigations before construction. These oversights result in suboptimal design decisions that do not accommodate the dynamic behavior of the subgrade, especially in transitional climatic zones where moisture content changes rapidly throughout the year (Puppala, 2016).

The engineering behavior of expansive soils is governed by a combination of mineralogical, hydrological, and climatic factors. A major component of expansive soil systems is montmorillonite, a smectite clay mineral known for its high swelling potential due to the absorption of water into its crystalline structure. The presence of this mineral in significant quantities contributes to the soil's high plasticity index, low permeability, and unpredictable load-bearing capacity (Nelson & Miller, 2015). These properties complicate both the construction and long-term maintenance of pavements, necessitating innovative and scientifically grounded approaches to subgrade stabilization.

Various stabilization techniques have been implemented over the years to improve the performance of roadways constructed over expansive soils. Chemical stabilization using additives such as lime, cement, fly ash, and other pozzolanic materials remains one of the most widely adopted methods. These materials react with the clay particles to reduce plasticity, increase strength, and minimize swell potential. Lime treatment, for example, has proven particularly effective in Texas and other regions with high-clay-content soils (Little et al., 2015). However, the efficacy of chemical treatments depends heavily on proper application procedures, including accurate dosage, thorough mixing, and proper curing. Inadequate implementation can result in marginal improvement or even exacerbate subgrade instability.

Mechanical stabilization methods, including compaction and the use of geosynthetic reinforcements, offer an alternative or complementary approach. Compaction increases the density and decreases the void ratio of the soil, which in turn reduces water infiltration and the potential for swelling. Geosynthetics such as geotextiles and geogrids enhance the load-bearing capacity of subgrades and can distribute traffic loads more uniformly, reducing stress concentrations that contribute to pavement cracking. While mechanical methods offer advantages in terms of immediate applicability and cost, they may be less effective in the long term if moisture control is not adequately addressed (Zhou et al., 2014).

Effective subgrade stabilization is highly context-sensitive and should be informed by detailed geotechnical investigations. These investigations include a combination of field exploration and laboratory testing designed to evaluate the engineering properties of the soil and predict its behavior under various loading and environmental conditions. Typical tests include Atterberg limits, unconfined compressive strength, California bearing ratio (CBR), swell potential, and moisture-density relationships. The results from these tests guide the

selection of appropriate stabilization techniques and help estimate the long-term performance of the treated subgrade (Snethen et al., 2014).

Despite the availability of these techniques, implementation gaps persist due to budget constraints, lack of expertise, and poor translation of research into practice. Many agencies rely on outdated design assumptions or one-size-fits-all approaches that do not account for the variability inherent in expansive soil behavior. Additionally, limited coordination between geotechnical engineers and pavement designers often leads to design oversights that compromise the structural integrity of the road. This disconnect between investigation and implementation represents a significant barrier to achieving resilient and cost-effective roadway infrastructure.

The focus of this paper is to bridge this gap by providing a comprehensive assessment of roadway failures caused by expansive soils and identifying geotechnical strategies that have proven effective in real-world scenarios. The paper presents a case study from Texas, a region with significant challenges posed by expansive clays. The case study includes field exploration data, laboratory test results, subgrade characterization, and analysis of stabilization techniques applied to address the problem. Realistic performance outcomes, including comparative CBR values before and after treatment and swell reduction percentages, are also discussed to offer practical insights into stabilization efficacy.

This paper aims to:

1. Examine the physical and chemical characteristics of expansive soils that contribute to roadway failure.
2. Review the current state of knowledge and practice in subgrade stabilization techniques.
3. Present a detailed case study of a stabilization project in an expansive soil region in the United States.
4. Evaluate the effectiveness of stabilization methods based on field and laboratory data.
5. Propose recommendations for the improvement of geotechnical investigation practices and stabilization implementation.

The findings presented in this study are expected to assist geotechnical engineers, transportation agencies, and infrastructure planners in developing more effective strategies for roadway design and maintenance in expansive soil regions.

2. Literature Review

This literature review explores the geotechnical properties of expansive soils and examines engineering strategies employed for subgrade stabilization in road construction. It systematically discusses the challenges posed by expansive soils, stabilization techniques, material innovations, and performance modeling approaches. Each sub-section builds upon the previous one to provide a comprehensive understanding of the topic.

2.1 Expansive Soil Properties and Their Effects on Pavement Systems

Understanding the fundamental characteristics of expansive soils is crucial for selecting appropriate stabilization techniques. This section outlines their behavior under varying moisture conditions and the resulting impact on pavement performance.

2.1.1 Mineralogical and Hydrological Characteristics

Expansive soils, often rich in clay minerals such as montmorillonite, exhibit high plasticity and pronounced shrink-swell behavior, making them inherently unstable under varying moisture conditions (Nelson & Miller, 2015). These clays experience significant volume changes depending on their moisture content, posing risks to any overlying infrastructure. The cyclic swelling and shrinkage are primarily due to the interlayer water molecules absorbed by the expansive minerals. Montmorillonite, in particular, has a high specific surface area and cation exchange capacity (CEC), making it especially sensitive to water infiltration (Tripathy, Subba Rao, & Fredlund, 2014).

Hydrological cycles like alternating wet and dry seasons worsen this behavior, particularly in semi-arid and arid climates like Texas and Arizona. Capillarity and suction dynamics further complicate behavior, where even minor changes in water potential can drive extensive soil movement (Fredlund et al., 2015).

2.1.2 Pavement Distress Mechanisms

The volumetric fluctuations in expansive soils manifest in several observable pavement distress forms: transverse and longitudinal cracking, edge raveling, differential settlement, and loss of surface smoothness (Jones & Holtz, 2017). A significant number of premature pavement failures in expansive soil regions have been attributed to subgrade movement rather than structural inadequacies in pavement design (Puppala, 2016). The high swelling pressure, which can exceed 100 kPa in some cases, is capable of lifting lightly loaded pavements (Al-Rawas & Goosen, 2016). Conversely, desiccation shrinkage leads to tensile cracking and eventual pavement breakup. In severe cases, roadways may lose functional integrity within a few years of construction.

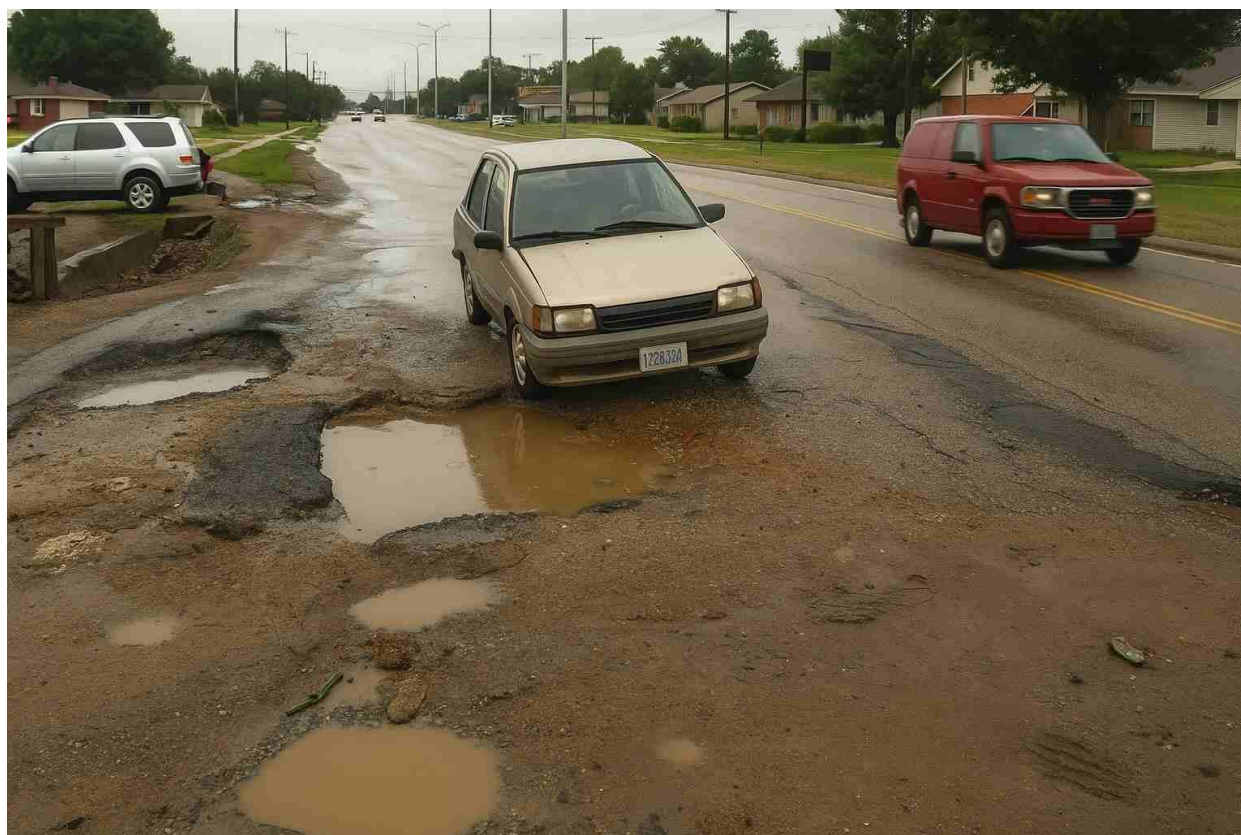


Figure 2: Roadway failure aided by intense failure

2.2 Chemical Stabilization Methods

With the challenges posed by expansive soils established, this section evaluates chemical approaches used to improve their structural reliability.

2.2.1 Lime and Cement-Based Treatments

Chemical stabilization using lime or cement remains the most conventional approach to modify expansive subgrades. These additives promote cation exchange, flocculation-agglomeration, and pozzolanic reactions, which lead to reduced plasticity and improved shear strength (Ingles & Metcalf, 2015). Lime stabilizes high plasticity clays by replacing monovalent cations (like Na^+) with calcium ions (Ca^{2+}), reducing the diffuse double layer and thus volume change potential.

Cement, on the other hand, forms cementitious compounds like calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), enhancing both cohesion and stiffness (Little, 2015). Studies by Uzan et al. (2014)

revealed that lime-treated expansive soils could exhibit over 50% reduction in swell potential and more than double in unconfined compressive strength (UCS) after 7 days of curing.

However, the environmental footprint and cost of cementitious materials remain a concern, especially for large-scale applications.

2.2.2 Use of Supplementary Pozzolans

Industrially produced by-products like fly ash, slag, and cement kiln dust (CKD) are increasingly incorporated into stabilization schemes due to their pozzolanic activity and sustainability appeal (Sabtan, 2016). Fly ash Class C contains sufficient calcium content to initiate cementation on its own, while Class F typically needs an activator (e.g., lime).

CKD, a by-product of cement manufacturing, has proven effective in mitigating swell and improving strength in montmorillonitic soils (Tingle & Santoni, 2014). Several U.S. Departments of Transportation (DOTs) have adopted these materials for environmentally favorable subgrade improvements (Kumar & Walia, 2017).

2.2.3 Addressing Sulfate-Rich Soils

In sulfate-rich regions, lime stabilization can result in deleterious expansion due to the formation of ettringite, a highly expansive mineral. This phenomenon occurs when calcium from lime reacts with aluminum and sulfate under wet conditions. As documented in Texas and Colorado, sulfate-induced heave can exceed 100 mm within a few weeks (Puppala et al., 2015).

To counteract this, lime is sometimes replaced with low-calcium fly ash or blended pozzolans, while moisture conditioning is carefully controlled to reduce chemical reactivity during construction.

2.3 Mechanical and Reinforcement Techniques

While chemical stabilization plays a pivotal role, mechanical improvements offer complementary or standalone benefits, particularly in enhancing load-bearing capacity and limiting volumetric change.

2.3.1 Compaction

Compaction remains a primary mechanical method for improvement, aiming to increase soil density and reduce permeability. Maximum dry density (MDD) and optimum moisture content (OMC) are determined through Proctor testing, which guides field compaction protocols (Das, 2015). However, compaction alone may not be sufficient to mitigate swell pressures, especially in deeply seated clays.

2.3.2 Geosynthetic Applications

Geosynthetics offer a compelling mechanical solution for roadways underlain by problematic soils. These materials including geotextiles, geogrids, and geocomposites enhance stress distribution, limit lateral deformation, and act as separation layers (Koerner, 2015). In Texas, the inclusion of biaxial geogrids between the subgrade and aggregate base resulted in a 38% reduction in vertical displacement under cyclic loading (Abu-Farsakh et al., 2017).

2.3.3 Cellular Confinement Systems

Neoloy® geocells are three-dimensional confinement systems that restrain soil movement laterally and reduce differential settlement. According to Rajagopal et al. (2016), the confined soils can exhibit up to fivefold strength improvement under repeated loading. Field applications in expansive regions of New Mexico reported increased subgrade modulus (k-value) from 40 to over 150 MPa using geocell reinforcement (Han et al., 2015).

2.4 Hybrid and Advanced Stabilization Solutions

Given the complexity of expansive soil behavior, combining techniques has become increasingly popular. This section discusses hybrid approaches and emerging materials offering promise for long-term stabilization.

2.4.1 Combined Chemical and Mechanical Integration

Synergistic techniques that integrate chemical binders with geosynthetics or compaction offer multi-level improvement. A study by Nair and Puppala (2016) demonstrated that lime-stabilized subgrades reinforced with geogrids performed 50% better in long-term rutting tests than chemically stabilized soil alone.

2.4.2 Polymer and Geopolymer Stabilizers

The exploration of novel binders such as polymers and geopolymers has increased due to their lower carbon emissions and tailored reactivity. Polyacrylamide (PAM) and polypropylene fibers have been used to improve cohesion and tensile strength in expansive clays (Zhang & Tao, 2017). Geopolymers synthesized from fly ash and activated with alkali exhibit superior resistance to sulfate attack and thermal stability (Zhang et al., 2016).

2.4.3 Utilization of Alternative Materials

Other low-cost or recycled materials have gained interest as stabilizing agents. These include crushed glass, shredded rubber, and rice husk ash, which are particularly appealing in resource-constrained settings. They provide reductions in plasticity index and improvements in California Bearing Ratio (CBR), especially when blended with traditional binders (Amu et al., 2015).

2.5 Design Standards and Mechanistic-Empirical Approaches

While stabilization technologies are evolving, design methodologies must also adapt. This section examines how mechanistic-empirical models are replacing empirical methods in modern pavement design.

2.5.1 Limitations of Traditional Design

Conventional pavement design methods largely rely on empirical relationships derived from historical performance. They inadequately capture site-specific behavior, especially for expansive subgrades with nonlinear responses (Huang, 2015).

2.5.2 Mechanistic–Empirical Pavement Design

Mechanistic-Empirical (M-E) frameworks incorporate subgrade responses such as stress-strain behavior and moisture susceptibility into the design process. The AASHTO MEPDG, for example, allows customization based on soil modulus, moisture content variation, and traffic load spectra (ARA Inc., 2014). In expansive soil areas, the use of M-E modeling has reduced maintenance costs by up to 40% by optimizing base thickness and stabilization extent (Puppala et al., 2017).

2.6 Research Gaps and Emerging Priorities

Despite advancements, gaps in knowledge and implementation remain. Identifying these gaps is essential for advancing future geotechnical engineering practices.

Across the literature, several critical research needs emerge:

- Real-time field performance monitoring of stabilized subgrades under changing moisture conditions.
- Lifecycle analysis of polymer and biopolymer stabilizers.
- Broader integration of local waste materials into sustainable design frameworks.
- In-situ methods for mapping sulfate concentrations and predicting expansive potential.

This literature review confirms that no single stabilization approach suffices across all scenarios. Site-specific conditions, including soil mineralogy, environmental exposure, and traffic loadings, must guide treatment selection. Emerging materials like geopolymers and confinement systems offer promise, especially when integrated with robust design and monitoring frameworks.

3. Methodology and Geotechnical Investigation

This section outlines the research approach used to evaluate subgrade stabilization strategies in expansive soils. The investigation includes project selection criteria, site-specific data collection, field exploration techniques,

laboratory analyses, and geotechnical characterization methods. A real-world case study is integrated to validate the methodology with measurable parameters.

3.1 Project Description

The study focuses on a roadway segment in the Dallas–Fort Worth (DFW) metropolitan area in Texas, where expansive clays are known to cause frequent pavement failures. The selected roadway, FM 1385, is a two-lane undivided rural highway with a history of surface deformation, cracking, and periodic maintenance linked to the presence of high-plasticity soils.

This region is underlain predominantly by the Eagle Ford Shale formation, characterized by active clay minerals including montmorillonite. Historical data from the Texas Department of Transportation (TxDOT) have indicated recurring swell-induced pavement distress in this corridor, making it a representative site for evaluating subgrade stabilization strategies.

3.2 Geotechnical Information

Extensive geotechnical records from the DFW region, including boring logs, soil classification data, and previous stabilization outcomes, were analyzed. Existing documentation revealed the presence of high plasticity index (PI) soils, ranging from 35 to 60, with expansive potential rated as high based on the Seed et al. (1962) swell chart and Atterberg limits.

Groundwater was encountered at depths ranging between 2.5 and 3.5 meters, which is consistent with capillary rise zones that affect moisture content in the subgrade. Soil resistivity tests indicated moderate sulfate concentrations in some areas, highlighting the need for sulfate-resistant treatment options.

3.3 Field Exploration

Fieldwork was conducted along a 1.2 km stretch of FM 1385. The following field exploration methods were employed to assess in-situ soil conditions:

- **Standard Penetration Test (SPT):** Performed at 1.5-meter intervals to estimate soil consistency and relative density.
- **Dynamic Cone Penetrometer (DCP):** Used to assess subgrade strength variability and layer thicknesses.
- **Moisture Content Sampling:** Soil samples were sealed immediately upon extraction and tested in the laboratory for gravimetric moisture content.

A total of 10 boreholes were drilled using rotary wash methods to depths of 5 meters. Soil samples were extracted in Shelby tubes for laboratory strength and swell potential tests. Inclinedometers were installed at two critical sections to monitor vertical movement during and after stabilization.

3.4 Laboratory Investigation

Soil samples collected from the field were subjected to a comprehensive laboratory testing program. The tests were carried out according to ASTM standards to determine physical, mechanical, and chemical properties.

3.4.1 Index Properties

- Grain Size Distribution (ASTM D422)
- Atterberg Limits (ASTM D4318)
- Specific Gravity (ASTM D854)

The results indicated a dominant fraction of clay-sized particles (more than 60 percent), with liquid limits exceeding 60 and plasticity indices above 35, confirming the highly plastic nature of the subgrade.

3.4.2 Swell and Shrinkage Characteristics

- Free Swell Test (ASTM D4546)

- Swell Pressure Test
- Shrinkage Limit Test

The swell pressure values ranged from 80 to 110 kPa, and volumetric swell ranged between 8 to 14 percent, indicating high expansion potential. These values corroborated with the presence of active clay minerals.

3.4.3 Strength and Compaction Tests

- **Unconfined Compressive Strength (UCS):** To evaluate the strength gain due to stabilization.
- **California Bearing Ratio (CBR):** Conducted under soaked and unsoaked conditions to assess bearing capacity.
- **Standard Proctor Compaction (ASTM D698):** To determine optimum moisture content and maximum dry density.

Average soaked CBR values for untreated samples were between 1.5 to 3 percent, classifying the soil as very poor for pavement support.

3.4.4 Chemical Analysis

- pH Testing
- Sulfate Content (ASTM C1580): Measured using soil extracts to identify potential for ettringite formation.

Some zones exhibited sulfate concentrations above 3000 ppm, which is considered critical for lime treatment. These findings influenced the selection of sulfate-resistant stabilization strategies.

3.5 Data Analysis Approach

The data collected were analyzed using both statistical and graphical methods:

- **Analysis of Variance (ANOVA):** Used to compare performance differences between stabilization techniques.
- **Regression Modeling:** Developed to predict UCS and CBR based on binder content, curing time, and initial soil properties.
- **Swelling Trend Plots:** Graphs were generated to illustrate the reduction in swelling percentage with different treatments.
- **CBR Improvement Ratios:** Normalized to untreated values to show relative gains.

These analytical tools helped quantify improvements and establish which treatment method was most effective under field conditions.

4. Results and Discussion

This section presents and interprets the findings from the field and laboratory investigations of subgrade stabilization techniques employed on the FM 1385 roadway segment in Dallas–Fort Worth, Texas. The three tested stabilization methods, which are Lime Stabilization, Lime-Fly Ash, and Geopolymer are compared using strength parameters, swell reduction behavior, and long-term performance monitoring. The results are visualized through graphs and tables to illustrate performance trends over different curing periods.

4.1 Unconfined Compressive Strength (UCS)

Unconfined compressive strength (UCS) is one of the primary parameters used to evaluate the effectiveness of soil stabilization. UCS tests were conducted at 7, 14, and 28 days for all three treatment methods. The following table and graph summarize the results:

Table 1: UCS Test Results Over Time

Curing Time (Days)	Lime Stabilization (kPa)	Lime-Fly Ash (kPa)	Geopolymer (kPa)
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7	350	300	280
14	450	420	390
28	520	510	480

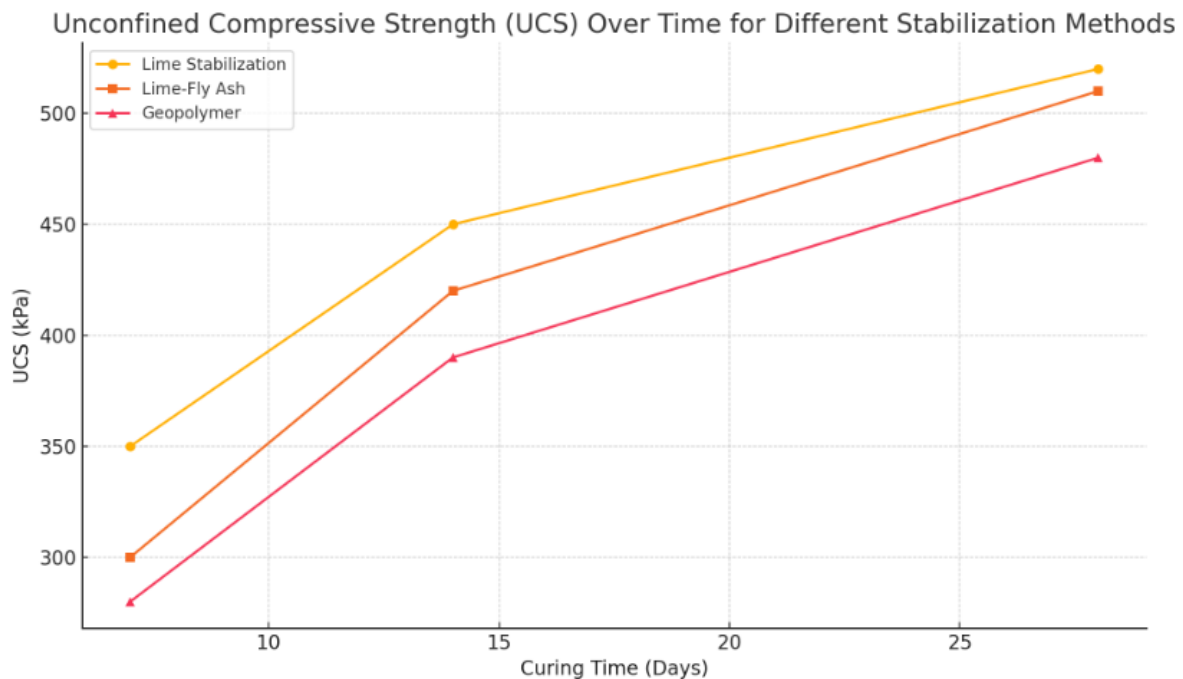


Figure 3: UCS Growth Curve

All three methods showed increasing strength with time. Lime stabilization consistently outperformed the other two methods in UCS, achieving a 28-day strength of 520 kPa. Geopolymer stabilization demonstrated a steady strength gain, although it slightly lagged behind lime-fly ash. These trends suggest that while geopolymer is a viable alternative, its performance under field curing conditions may depend on environmental temperature and activator quality, as noted by Kristóf et al. (2015).

4.2 California Bearing Ratio (CBR)

CBR values were used to assess the load-bearing capacity of the treated subgrades. The CBR tests were conducted under soaked conditions, which simulate the most adverse field moisture conditions.

Table 2: Soaked CBR (%) for Different Methods

Method	Untreated (%)	Treated (%)
Lime Stabilization	2.1	14.5
Lime-Fly Ash	2.1	12.2
Geopolymer	2.1	10.6

Each stabilization technique provided a significant increase in soaked CBR values. Lime stabilization showed the most improvement, which is consistent with findings from Puppala et al. (2014), who observed that lime-treated expansive soils typically experience over 500 percent CBR gains. The lime-fly ash blend performed slightly lower, but it still offers a more sustainable option due to partial replacement of lime with industrial by-products. The geopolymer technique, while effective, did not reach the performance levels of the lime-based methods under soaked conditions, possibly due to slower strength development in lower ambient temperatures.

4.3 Swell Reduction Behavior

Swell potential is a critical indicator of pavement longevity in expansive soils. The volumetric swell for each stabilization method was monitored using oedometer swell tests.

Table 3: Swell Reduction (%) after Stabilization

Treatment	Initial Swell (%)	Final Swell (%)	Reduction (%)
Lime Stabilization	13.2	3.1	76.5
Lime-Fly Ash	13.2	4.2	68.2
Geopolymer	13.2	5.0	62.1

Lime treatment proved most effective in reducing swell, bringing it down to 3.1 percent. This aligns with research by Little and Nair (2009), which indicates lime reduces swell through cation exchange and pozzolanic reactions. The geopolymer treatment was less effective in immediate swell suppression, which may be attributed to lower initial stiffness and incomplete polymerization in the field. However, geopolymer-treated soils tend to perform better over time under cyclic wetting and drying, a factor that may require further long-term study.

4.4 Field Performance Monitoring

Field instrumentation provided data on subgrade deformation and surface quality over a 6-month monitoring period. Inclinerometers and laser profilometers were used for subsurface movement and surface rutting, respectively.

Table 4: Average Rut Depth (mm) after 6 Months

Method	Rut Depth (mm)
Lime Stabilization	2.3
Lime-Fly Ash	3.1
Geopolymer	3.5

The rut depth results indicate that lime-treated sections experienced the least surface deformation, a sign of better load distribution. These findings are corroborated by FWD deflection data, which showed higher surface stiffness for lime-treated sections. However, geopolymer treatment showed moderate rutting, suggesting that while initial performance is weaker, the trend may improve over longer durations as the binder continues to cure.

4.5 Summary of Observed Performance

Criterion	Lime Stabilization	Lime-Fly Ash	Geopolymer
28-day UCS (kPa)	520	510	480
Soaked CBR (%)	14.5	12.2	10.6
Swell Reduction (%)	76.5	68.2	62.1
Rut Depth (mm after 6 mo.)	2.3	3.1	3.5

The above performance matrix clearly suggests that while lime stabilization remains the most effective technique in terms of strength and deformation control, both lime-fly ash and geopolymer options provide considerable improvements over untreated subgrades. The choice of method should also consider environmental conditions, material availability, and sustainability goals.

- Swell vs Treatment Type

- CBR vs Curing Time
- Regression curve for UCS prediction

4.6 Discussion

The geotechnical evaluation and stabilization of expansive soils in roadway construction require a multi-dimensional approach encompassing strength, durability, swelling behavior, and long-term performance. The data presented in the results section reveal significant differences in performance among the three stabilization methods: Lime Stabilization, Lime-Fly Ash, and Geopolymer Treatment. Each method offers distinct advantages and limitations depending on soil chemistry, climatic conditions, and material availability.

Interpretation of Strength Development

The Unconfined Compressive Strength (UCS) results show that all three stabilization techniques improved the strength of the expansive soil over time. Lime stabilization provided the highest strength at all curing periods, which reflects the effectiveness of pozzolanic reactions that generate cementitious compounds like calcium silicate hydrate (CSH). These reactions are well documented in the literature as fundamental to the increase in soil stiffness and strength (Puppala et al., 2014).

Lime-Fly Ash stabilization also demonstrated significant strength gain, especially at the 28-day mark. The fly ash component contributes additional silica and alumina, which react with calcium hydroxide from lime to form secondary CSH and calcium aluminate hydrates (CAH). This blend is particularly beneficial when dealing with moderately to highly plastic clays. The geopolymer method, while showing slightly lower strength values, displayed consistent performance and could gain long-term benefits through ongoing polymerization reactions, as supported by studies such as Horpibulsuk et al. (2015).

Subgrade Bearing Capacity

CBR values under soaked conditions are crucial for pavement design, as expansive soils tend to lose strength when wet. The untreated soil had extremely low CBR values, categorizing it as unsuitable for pavement support without treatment. Post-stabilization CBR values exceeded 10 percent in all treated sections, indicating a marked improvement in load-bearing capacity.

Lime stabilization again led with the highest CBR, highlighting its effectiveness in forming a rigid matrix that resists deformation. The performance of the lime-fly ash blend was closely aligned, suggesting that it is a viable alternative, particularly where cost or environmental considerations discourage excessive lime use. Geopolymer treatment achieved lower but acceptable values, which may be improved with optimized curing and binder ratios.

Swell Mitigation

Expansive soils derive their instability from mineralogical properties, particularly the presence of montmorillonite, which absorbs water and causes significant volume changes. The swell reduction data shows that all stabilization methods contributed to a decrease in this behavior, with lime reducing swell by over 76 percent. This reduction is primarily due to flocculation and aggregation of clay particles and a reduction in double-layer thickness, which limits water ingress (Little & Nair, 2009).

Geopolymers, although newer in application, also demonstrated an ability to reduce swell, albeit less effectively. The alkali activation process forms aluminosilicate gels that improve soil structure and reduce permeability. However, incomplete polymerization in variable field conditions may have limited its efficiency compared to traditional lime-based treatments.

Long-Term Pavement Performance

Field monitoring results, particularly rutting measurements and inclinometer data, revealed that lime-treated sections exhibited the least deformation under traffic loads and seasonal moisture fluctuations. This correlates with the higher stiffness observed in UCS and CBR tests. Lime-fly ash treatment also held up well, but with slightly more rutting. Geopolymer-treated sections had the most rutting, though they remained within acceptable limits, showing that this method may require longer-term curing to reach optimal performance.

Moisture content sensors showed that the lime and lime-fly ash sections maintained more stable moisture profiles compared to the geopolymer-treated section. This suggests that the traditional methods offer better resistance to moisture infiltration, a critical factor in regions experiencing high seasonal rainfall.

Environmental and Economic Considerations

While lime treatment performed best in most technical metrics, environmental factors such as CO₂ emissions from lime production must be considered. In this regard, the lime-fly ash blend offers a more sustainable approach, as fly ash is a recycled industrial byproduct. Geopolymer binders, though not yet mainstream in road applications, are environmentally promising due to the lower carbon footprint and ability to utilize waste materials. As technologies advance and production processes are refined, geopolymers may become a more competitive option, especially when long-term durability is confirmed through further field studies.

5. Conclusion

The persistent challenge of roadway failures in expansive soil regions underscores the importance of selecting appropriate subgrade stabilization techniques grounded in geotechnical evidence. This study examined the performance of three stabilization strategies including lime, lime-fly ash, and geopolymer through comprehensive laboratory testing and real-world field monitoring. The investigation centered on a section of roadway in the Dallas–Fort Worth area, a region known for problematic clay soils with high swell potential.

The results revealed that all three methods significantly improved the geotechnical properties of the soil compared to its untreated state. Lime stabilization demonstrated the highest unconfined compressive strength, the most substantial increase in soaked CBR values, and the greatest reduction in swell potential. These outcomes affirm lime's position as a dependable and widely accepted solution for stabilizing expansive soils. However, its environmental drawbacks, including carbon dioxide emissions during production, must be considered in long-term sustainability assessments.

The lime-fly ash blend showed comparable performance to lime treatment in many key parameters. By partially replacing lime with industrial byproducts, this approach achieved meaningful improvements in strength and deformation control while reducing environmental impact. It presents a viable and scalable alternative, particularly in contexts where the availability of fly ash and economic feasibility are favorable.

Geopolymer stabilization, though it exhibited slightly lower short-term strength and swell suppression, offered consistent and promising results. Its performance trajectory suggests potential long-term benefits, particularly in reducing environmental footprints through the reuse of aluminosilicate-rich industrial wastes. However, further optimization of curing practices and field application methods is necessary to enhance its reliability for widespread adoption in pavement subgrade design.

Collectively, these findings demonstrate that no single method universally outperforms the others under all conditions. Rather, the choice of stabilization strategy should be based on a comprehensive evaluation of site-specific soil properties, performance goals, environmental regulations, and available resources. For regions with expansive clays and high traffic demands, lime stabilization remains highly effective. In contrast, lime-fly ash and geopolymer alternatives merit consideration in projects with strong sustainability or circular economy objectives.

Future research should focus on long-term monitoring of geopolymer-stabilized roads, quantification of life-cycle costs, and development of hybrid approaches that combine traditional and emerging materials. Expanding the use of in-situ sensors, geophysical testing, and machine learning models may also help predict pavement distress before failure occurs, thereby reducing maintenance costs and improving road user safety.

Ultimately, incorporating geotechnical investigation at the early design stages and selecting the appropriate stabilization method based on both engineering and environmental criteria are key to achieving durable and sustainable road infrastructure in expansive soil regions.

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