Ionic Soil Stabilization as an Alternative to Conventional Asphalt Pavements

Fernando Duarte Moreto

Master's in Engineering Management

Polytechnic University of Puerto Rico

Engineering Management Project

02/08/2026

Abstract

Transportation infrastructure plays a central role in economic development and regional integration; however, conventional asphalt pavement systems often exhibit premature deterioration when constructed over moisture-sensitive or clay-dominated subgrades. These limitations result in escalating maintenance costs, reduced structural performance, and increased environmental impact. This study evaluates ionic soil stabilization as a technically feasible, economically viable, and environmentally responsible alternative to traditional asphalt pavement construction. The research integrates theoretical analysis, literature review, laboratory testing, field performance data, and comparative cost assessment derived from real-world stabilization projects. Particular emphasis is placed on the physicochemical mechanisms governing ionic stabilization and their influence on soil bearing capacity and moisture susceptibility. Results indicate significant improvements in subgrade strength and measurable reductions in material consumption and projected life-cycle costs. The findings suggest that ionic soil stabilization offers a structurally sound and sustainable alternative for infrastructure projects, particularly in regions characterized by clay-rich soils and limited maintenance capacity.

Introduction

Transportation infrastructure is a fundamental pillar of economic development, territorial integration, and industrial productivity. Road networks enable the movement of goods, services, and labor, directly influencing regional competitiveness and quality of life. In many countries, particularly those with large rural territories,
roads represent the primary mode of transportation, making their reliability and durability critical from both engineering and public policy perspectives.

Despite decades of technological advancement in pavement engineering, conventional asphalt pavement systems remain the dominant solution worldwide. These systems typically rely on multilayer structures composed of a compacted subgrade, granular base layers, and asphalt surface courses. While effective under ideal geotechnical and climatic conditions, their performance deteriorates significantly when applied to clay-rich soils, high-moisture environments, or regions with limited maintenance capacity.

Asphalt pavements are inherently sensitive to temperature variation and moisture infiltration. Thermal expansion and contraction lead to cracking, while water ingress reduces base and subgrade strength, accelerating pavement distress. In clay soils, these effects are amplified by volumetric changes associated with swelling and shrinkage. The result is a cycle of premature deterioration, frequent maintenance interventions, and escalating life-cycle costs.

In response to these challenges, soil stabilization technologies have gained increasing attention as alternatives or complements to traditional pavement design. Among these technologies, ionic soil stabilization has emerged as a promising approach that focuses on improving the mechanical behavior of in-situ soils through chemical modification rather than material replacement. By altering electrochemical interactions at the particle level, ionic stabilization aims to increase bearing capacity, reduce moisture sensitivity, and enhance long-term durability.

This paper analyzes ionic soil stabilization as an alternative to conventional asphalt pavement systems. The study combines theoretical foundations, literature review, field performance data, economic comparison, and environmental considerations to evaluate the feasibility and advantages of this technology within modern infrastructure projects.

Objectives

The primary objective of this research is to evaluate ionic soil stabilization as a technically feasible, economically viable, and environmentally responsible alternative to conventional asphalt pavement systems. This objective is addressed through several specific goals.

First, the study aims to explain the physicochemical mechanisms that govern ionic soil stabilization and their impact on soil engineering properties. Second, it seeks to compare the structural performance of stabilized soils with that of traditional asphalt and granular base systems. Third, the research evaluates construction costs, maintenance requirements, and life-cycle implications associated with both approaches.

Additionally, this paper analyzes real-world performance data obtained from field applications to quantify improvements in bearing capacity, execution efficiency, and durability. Finally, the environmental implications of ionic stabilization, including material consumption and emissions reduction, are assessed to determine its alignment with sustainable infrastructure development principles.

Literature Review

Pavement engineering literature consistently emphasizes the critical role of subgrade performance in determining road longevity. Flexible pavement systems are designed to distribute traffic loads through layered structures; however, their effectiveness depends heavily on the mechanical stability of the underlying soil. Weak or moisture-sensitive subgrades often lead to structural distress regardless of surface layer quality.

Clayey soils pose particular challenges due to their mineralogical composition and electrochemical behavior. High plasticity clays exhibit strong affinity for water, resulting in swelling when wet and shrinkage upon drying. These volumetric changes induce tensile stresses in asphalt layers, leading to cracking and surface deformation. Numerous studies have documented accelerated pavement deterioration in clay-dominated regions.

Traditional soil stabilization methods include mechanical compaction, soil replacement, and chemical additives such as lime and cement. Lime stabilization is effective in reducing plasticity and improving strength but requires careful control of moisture and curing conditions. Cement stabilization provides high early strength but introduces significant carbon emissions and may be economically prohibitive for large-scale applications.

Polymer-based stabilization techniques represent an evolution in soil improvement methods. Unlike cementitious additives, polymers do not rely on hydration reactions. Instead, they modify soil structure through bonding and electrochemical interactions. Ionic soil stabilizers operate by altering the surface charge of clay particles, reducing the thickness of the diffuse double layer and limiting water adsorption.

Research indicates that ionic stabilization can significantly improve California Bearing Ratio (CBR), unconfined compressive strength, and resistance to erosion. Furthermore, because these stabilizers enable the reuse of in-situ soils, they reduce the need for aggregate extraction and transportation, resulting in lower environmental impact.

Despite documented benefits, the adoption of ionic stabilization has been slower than that of traditional methods. This gap is often attributed to limited awareness, lack of standardized design guidelines, and insufficient case-based economic validation. As a result, applied studies demonstrating real-world performance and cost advantages remain essential for broader acceptance.

Methodology

This study adopts a comparative analytical methodology combining qualitative assessment and quantitative performance evaluation. The research framework is based on two real-world soil stabilization projects supplemented by technical documentation and cost benchmarks derived from conventional pavement construction practices.

The methodology consists of four primary stages. First, baseline soil conditions were characterized through laboratory testing, including moisture content, plasticity index, and California Bearing Ratio (CBR) measurements. Second, ionic stabilization was applied following standardized procedures involving surface preparation, controlled emulsion application, mechanical mixing, compaction, and curing.

Third, post-treatment testing was conducted using identical methods to ensure comparability of results. Finally, construction costs, execution timelines, and maintenance considerations were analyzed relative to conventional asphalt pavement systems used as reference models.

This structured approach allows for a comprehensive evaluation of both engineering performance and practical feasibility under real infrastructure constraints.

Data Collection

Data were collected from two soil stabilization projects executed under distinct geotechnical and operational conditions. The first project involved a roadway segment characterized by low initial bearing capacity and moisture-sensitive soils. Soil samples were collected prior to treatment to establish baseline CBR values and moisture conditions.

Following stabilization, additional samples were extracted from treated sections for post treatment testing. The second project focused on a worksite dominated by high-plasticity clay soils, where stabilization activities were constrained by underground utilities and variable site geometry.

In addition to laboratory data, field observations were recorded, including construction duration, equipment deployment, treated area dimensions, and curing periods. Economic data were derived from standardized cost models comparing traditional asphalt and gravel construction with ionic stabilization-based solutions.

Data Analysis

Analysis of laboratory and field data revealed consistent performance improvements attributable to ionic soil stabilization. In both projects, post-treatment CBR values increased substantially compared to untreated conditions, demonstrating enhanced load-bearing capacity and improved resistance to deformation.

Table 1

Cost Comparison Between Conventional Asphalt and Ionic Soil Stabilization (per kilometer)

Method	Estimated Cost (USD)	Maintenance Demand
Asphalt + Gravel (Traditional)	$300,000	High
Asphalt + Ionic Stabilization	$250,000	Low

As summarized in Table 1, ionic soil stabilization yields a direct construction cost reduction of approximately $50,000 per kilometer. These savings are primarily associated with reduced aggregate importation and lower asphalt layer thickness requirements.

Table 2

CBR Performance Before and After Ionic Soil Stabilization

Soil Condition	Average CBR (%)	Engineering Interpretation
Untreated Clay Soil	6–8	Low bearing capacity

Ionic Stabilized Soil	14–18	Improved structural support

The improvement in CBR values shown in Table 2 confirms the effectiveness of ionic stabilization in reducing soil plasticity and increasing interparticle bonding. These gains translate directly into improved pavement performance and reduced maintenance requirements.

Figure 1. CBR Comparison Before and After Ionic Soil Stabilization

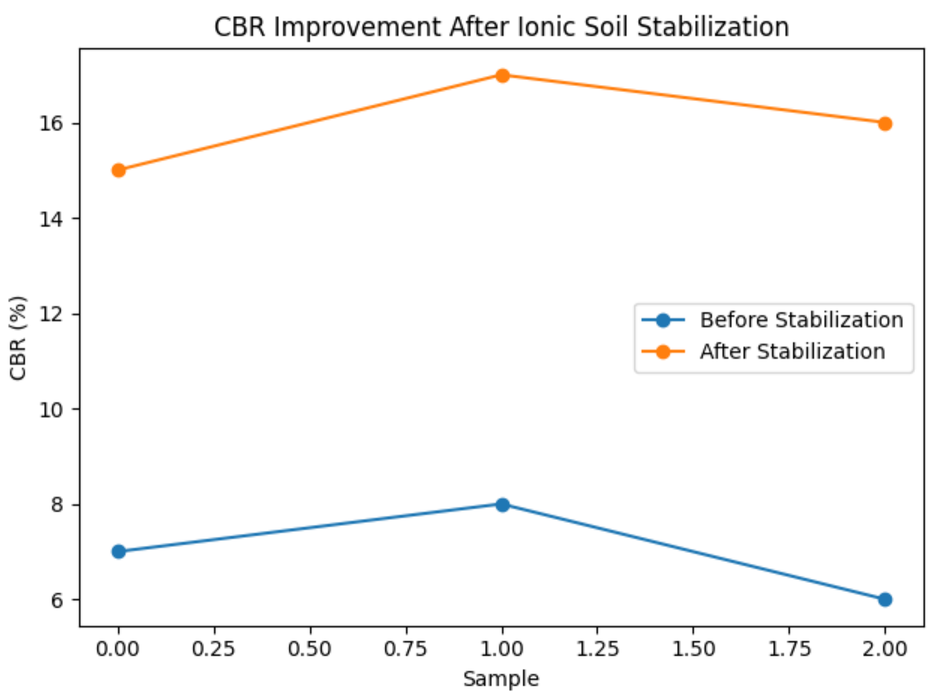

Figure 1 illustrates consistent performance gains across all test samples, reinforcing the reliability of ionic stabilization under varying soil conditions.

Limitations and Future Research

While the findings support the effectiveness of ionic soil stabilization, the analysis is limited by the number of case studies evaluated. Future research should incorporate long-term monitoring and comparative analysis with alternative stabilizers such as lime and cement.

Conclusion

This study demonstrates that ionic soil stabilization represents a technically robust, economically viable, and environmentally responsible alternative to conventional asphalt pavement systems. By enhancing in-situ soils, this approach reduces material consumption, lowers costs, and improves long-term infrastructure performance.

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