

Research Article

Investigating the Relationship Between Soil Stabilization Techniques and Sustainable Foundation Engineering Practices

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Abstract

This study investigates the relationship between soil stabilization techniques and sustainable foundation engineering practices, focusing on the environmental, economic, and technical aspects of various stabilization methods. The research employs a qualitative approach, specifically a literature review, to explore the effectiveness of conventional soil stabilization techniques, such as cement and lime, as well as emerging sustainable alternatives, including the use of industrial byproducts like fly ash and innovative microbial stabilization. The findings reveal that while traditional methods are effective in enhancing soil properties, they are associated with significant environmental and economic drawbacks, particularly due to high CO₂ emissions from cement production. On the other hand, alternative techniques such as fly ash stabilization and microbial-based solutions offer significant environmental benefits by reducing carbon footprints and providing cost-effective, sustainable alternatives. Additionally, the integration of environmental, economic, and technical factors into decision-making frameworks is essential for promoting sustainable foundation engineering practices. The study highlights the importance of adopting green technologies to achieve sustainability in foundation engineering and recommends further research into the long-term performance and scalability of alternative stabilization methods. Moreover, future studies should focus on developing standardized guidelines and exploring the role of policy and regulations in supporting sustainable practices in construction.



Keywords: Soil stabilization, sustainable foundation engineering, fly ash, microbial stabilization, environmental impact

INTRODUCTION

Soil stabilization techniques have long been an essential component of foundation engineering, particularly in areas where the soil conditions are inadequate for supporting heavy structures. As global urbanization accelerates, the demand for sustainable and resilient construction practices has intensified, highlighting the need for advanced soil stabilization methods (Panchal et al., 2017). These techniques aim to improve the mechanical properties of soil, such as its strength, compaction, and permeability, thus ensuring the stability and durability of foundation systems (Das & Sivakugan, 2018). However, despite the numerous advances in stabilization technology, the environmental impact and long-term sustainability of these methods remain significant concerns in modern engineering practices (Armistead et al., 2023).

As the construction industry strives toward sustainability, there is growing interest in identifying stabilization techniques that minimize ecological damage, reduce the consumption of natural resources, and enhance the durability of foundations (Gravina da Rocha et al., 2021). Traditional stabilization methods, such as the use of cement or lime, are often associated with high carbon emissions and energy consumption, posing a challenge to the goal of sustainable development (Sharma et al., 2018). Consequently, alternative methods involving bio-based materials, waste products, and minimal chemical additives have gained attention as more eco-friendly options (Mikofsky et al., 2023).

While there is an extensive body of literature on soil stabilization techniques, there remains a significant gap in understanding how these methods contribute to the broader goals of sustainable foundation engineering. Most studies have primarily focused on the technical performance of individual stabilization methods without considering their environmental implications or their alignment with sustainable construction principles (Arabani & Shalchian, 2024). Furthermore, limited research has integrated the economic feasibility of these techniques with their environmental impact and long-term structural performance, making it difficult to assess their overall contribution to sustainable foundation practices (Naik et al., 2024).

The need for sustainable foundation engineering practices has never been more pressing. As climate change intensifies, construction materials and techniques that contribute to environmental degradation must be reevaluated and improved (Behsoodi et al., 2024). Soil stabilization plays a critical role in mitigating the environmental impact of foundation construction, yet many widely used techniques remain unsustainable. Therefore, it is crucial to identify methods that not only improve soil properties but also reduce environmental harm and foster the long-term resilience of infrastructure (Barisoglu et al., 2025). This research is urgent as it aims to provide engineers and decision-makers with a comprehensive understanding of how soil stabilization can be aligned with sustainable practices in foundation engineering.

Numerous studies have investigated the effectiveness of various soil stabilization techniques. For instance, cement and lime stabilization have been well-documented for their ability to increase soil strength and prevent settlement (Jalal et al., 2020). However, their environmental cost, primarily due to the high carbon emissions associated with cement production, has raised concerns (Liu et al., 2015). Recent work has explored the use of alternative materials, such as fly ash and natural fibers, which have shown promise in reducing the environmental footprint while maintaining or enhancing soil stability (Noaman et al., 2022). Additionally, studies have highlighted the potential of biopolymer-based stabilization, which offers significant environmental benefits without compromising performance (Kumar et al., 2022).

Despite these advances, there is a lack of comprehensive studies that combine the technical, economic, and environmental aspects of soil stabilization in the context of foundation engineering. This research aims to fill this gap by investigating the relationship between soil stabilization techniques and sustainable foundation practices, providing a holistic perspective on their contributions to long-term infrastructure sustainability.

The novelty of this study lies in its integrated approach to evaluating soil stabilization techniques in the context of sustainable foundation engineering. Previous studies have often treated these elements in isolation, focusing either on the technical performance or environmental impact without considering their combined effect on sustainability in construction. This research introduces a framework that evaluates soil stabilization methods not only for their technical efficacy but also for their environmental impact and economic feasibility. By doing so, it aims to identify the most suitable techniques for promoting sustainable foundation practices, making a significant contribution to both the scientific literature and practical engineering applications (Fatehi et al., 2021).

The main objective of this research is to investigate the relationship between various soil stabilization techniques and sustainable foundation engineering practices. The specific aims include:

1. To assess the technical performance of different soil stabilization methods in terms of strength, durability, and long-term stability.
2. To evaluate the environmental impact of these methods, particularly in terms of carbon emissions, resource use, and waste generation.
3. To compare the economic feasibility of these techniques, considering factors such as material cost, labor, and long-term maintenance.
4. To identify the most sustainable and cost-effective soil stabilization techniques for foundation engineering.

This study will provide valuable insights for engineers, architects, and policymakers, helping them make informed decisions about selecting soil stabilization methods that contribute to the sustainability of foundation systems. Furthermore, it will contribute to the development of new standards and guidelines for sustainable construction practices, promoting the integration of environmentally friendly techniques in foundation engineering (Ahmed et al., 2023).

Soil Stabilization Techniques

Soil stabilization techniques are critical in geotechnical engineering, particularly when the soil on a construction site is unsuitable for the intended structural loads. These methods aim to improve the soil's properties, such as strength, compaction, and stability, to make it more suitable for supporting foundations. Traditionally, soil stabilization has involved the addition of chemicals, such as lime, cement, or bitumen, to alter the soil's physical properties. Lime and cement stabilization, for instance, are commonly used to increase soil strength and reduce plasticity (MolaAbasi et al., 2022). Lime, by reacting with the clay particles in soil, forms calcium silicate hydrates that bond the particles together, increasing the soil's shear strength and reducing its susceptibility to erosion (Manzoor & Yousuf, 2020).

While traditional chemical stabilization methods have proven effective, they come with significant environmental costs, especially in terms of carbon emissions from cement production (Dunuweera & Rajapakse, 2018). As a result, there has been a growing interest in alternative soil stabilization techniques that use more sustainable materials. For example, the use of fly ash, a waste byproduct of coal combustion, has been explored as a stabilizing agent because it is abundant, cost-effective, and environmentally friendly (Kelechi et al., 2022). Another promising approach is the use of biopolymers and natural fibers, which offer a more eco-friendly alternative to conventional stabilizers by enhancing the soil's structure without the use of harmful chemicals (Kumar et al., 2022).

Furthermore, the stabilization of soil using microbial methods, known as biogeochemical soil stabilization, has recently gained attention. This technique leverages microorganisms to improve soil properties, offering a more sustainable, low-carbon alternative (Wei et al., 2025). These innovative techniques not only improve the physical properties of the soil but also contribute to reducing the ecological footprint of soil stabilization processes. However, despite their potential, these techniques require further research and practical validation to establish their long-term performance and economic viability (Jordão & Almeida, 2017).

Sustainable Foundation Engineering Practices

Sustainable foundation engineering practices are central to modern civil engineering, as they ensure that construction methods meet the needs of the present without compromising the ability of future generations to meet their own needs (Das & Sivakugan, 2018). The foundation of any structure is its most critical component, and its design must account for both immediate structural stability and long-term environmental and economic sustainability. Sustainable foundation engineering involves the integration of environmentally friendly materials and construction techniques that minimize environmental impact while ensuring the durability and stability of the structure (Abera, 2024).

In the context of foundation engineering, sustainability can be achieved through several strategies. First, the use of renewable or waste materials, such as recycled concrete aggregates, industrial byproducts, and bio-based soil stabilizers, can significantly reduce the reliance on natural resources and reduce the carbon footprint of the construction process (Rylko-Polak et al., 2022). Second, optimizing the design of foundations to reduce material consumption and energy usage, such as

using lighter and more durable foundation systems, is a key component of sustainable engineering practices (Hassan, 2025).

Moreover, sustainable foundation engineering requires consideration of the soil's interaction with the built environment. Understanding how soil stabilization techniques influence the long-term behavior of foundations is crucial for enhancing the resilience of infrastructure against climate change and other environmental challenges (Naskar et al., 2025). The use of soil stabilization techniques that improve soil properties, such as load-bearing capacity and resistance to erosion, can prolong the lifespan of foundations, reduce maintenance needs, and minimize environmental degradation over time (Afrin, 2017). By integrating these sustainable practices, engineers can design foundation systems that not only support the structural integrity of buildings but also contribute to the broader goal of sustainable development.

In addition to technical and environmental considerations, sustainable foundation engineering practices also include economic feasibility. The adoption of cost-effective and environmentally sound techniques for soil stabilization and foundation construction can make these practices more accessible and practical for a wide range of projects. This includes evaluating the lifecycle costs of stabilization methods, factoring in not only initial construction costs but also long-term maintenance and repair costs (Frangopol & Liu, 2019).

Thus, sustainable foundation engineering practices are not limited to minimizing the environmental impact; they also encompass improving the overall efficiency and longevity of construction projects, ensuring that they are both economically and environmentally viable in the long run (Nwaogbe et al., 2025).

METHODS

This study employs a qualitative research approach, specifically a literature review methodology, to explore the relationship between soil stabilization techniques and sustainable foundation engineering practices. Qualitative research is particularly effective for understanding complex phenomena and synthesizing existing knowledge on a particular subject (Creswell & Poth, 2016). Given the multidimensional nature of soil stabilization and sustainability in foundation engineering, a comprehensive review of the literature allows for a deeper understanding of the various techniques employed in practice, their environmental implications, and their alignment with sustainability goals.

The data for this study is derived primarily from peer-reviewed academic articles, books, technical reports, and conference proceedings. Sources include prominent journals in the fields of geotechnical engineering, civil engineering, and environmental sustainability. Key databases such as Google Scholar, ScienceDirect, SpringerLink, and Wiley Online Library are used to gather relevant publications published over the past two decades. These sources provide a robust base of evidence, as they cover a wide range of perspectives and provide insights from global studies (Darian-Smith & McCarty, 2017). Furthermore, relevant reports from engineering institutions and environmental agencies have been incorporated to broaden the

scope of data and ensure a comprehensive understanding of sustainable practices in soil stabilization.

Data collection in this study is carried out through an extensive systematic literature review, which involves selecting, analyzing, and synthesizing previous research related to soil stabilization techniques and their application in foundation engineering. The literature review process follows a structured approach, starting with identifying key themes, terms, and concepts related to soil stabilization methods, sustainability in foundation engineering, and their interconnections (Tranfield et al., 2003). Relevant publications are selected based on criteria such as relevance, impact factor, and publication year to ensure that the review encompasses both foundational studies and the latest advancements in the field.

The research criteria for inclusion of studies are based on a combination of the following: empirical studies, review articles, case studies, and experimental research that assess the technical, environmental, and economic aspects of soil stabilization methods (Baldovino et al., 2024). Only peer-reviewed literature published in reputable journals or conference proceedings is considered, which ensures the validity and reliability of the data.

The data analysis is conducted using thematic analysis, which involves categorizing and organizing the data into key themes and sub-themes that emerge from the literature. This method is particularly suited for qualitative data as it allows for the identification of patterns, similarities, and discrepancies across different studies (Braun & Clarke, 2006). Through thematic analysis, the study investigates the different soil stabilization techniques, their effectiveness in enhancing foundation performance, and their compatibility with sustainable construction practices.

Key themes explored include the environmental impact of stabilization methods (e.g., carbon emissions, resource use), the economic feasibility (e.g., material cost, labor cost), and the long-term durability of foundations. Data from various studies are compared and contrasted to draw comprehensive conclusions regarding the most sustainable soil stabilization practices in foundation engineering.

Additionally, a comparative analysis is employed to evaluate the relative effectiveness of different stabilization techniques in terms of both their technical performance and sustainability. The findings from various studies are analyzed to identify trends and to determine the overall contribution of these techniques to sustainable foundation engineering practices. This approach allows the study to provide a clear, evidence-based understanding of the relationship between soil stabilization and sustainability in foundation design.

RESULT AND DISCUSSION

The results of this study underscore the significant relationship between soil stabilization techniques and sustainable foundation engineering practices. Through a systematic literature review, several critical findings have emerged, which are discussed below.

Impact of Soil Stabilization on Soil Properties

Soil stabilization techniques are essential for improving the mechanical properties of soil, which is crucial for foundation engineering. Stabilization methods,

such as lime, cement, and fly ash, have been found to effectively enhance the strength, compaction, and resistance to erosion of soil, which improves the load-bearing capacity of the foundation soil. For instance, the addition of lime or cement significantly increases the soil's cohesion, making it more suitable for supporting heavy structures. Lime stabilization works by neutralizing the acidic properties of clay soils, forming a strong bond between the soil particles, which increases shear strength and reduces soil plasticity (Manzoor & Yousuf, 2020). Cement stabilization, on the other hand, not only improves soil strength but also enhances its resistance to moisture fluctuations, which is essential for the durability of the foundation in regions with variable climate conditions (Naskar et al., 2025).

However, while these traditional methods are effective, they come with significant environmental costs. The production of cement is one of the largest sources of CO₂ emissions globally (Andrew, 2018). This has led to the exploration of alternative stabilizers, such as fly ash, a byproduct of coal combustion, which has shown promise as an eco-friendly alternative. Studies have indicated that fly ash not only enhances the strength of soil but also reduces the carbon footprint associated with soil stabilization by substituting cement in the mixture (George & Deepa, 2020). Additionally, bio-based stabilizers such as natural fibers and biopolymers have gained attention for their ability to stabilize soils without relying on chemical additives, further advancing sustainable soil stabilization methods (Gowthaman et al., 2018).

Environmental Impact of Soil Stabilization Techniques

The environmental impact of soil stabilization techniques has been a significant concern, especially with the use of traditional stabilizers like cement and lime. Cement production, as one of the most energy-intensive industries, contributes significantly to global greenhouse gas emissions (Wu et al., 2022). As a result, there has been growing interest in exploring more sustainable alternatives. Among the various sustainable alternatives, the use of industrial byproducts such as fly ash and slag is gaining traction. Fly ash not only reduces the demand for raw materials but also helps mitigate waste by utilizing this byproduct of the coal industry. Studies have shown that fly ash can effectively improve the strength of soil while reducing the overall environmental footprint of the stabilization process (Baloochi et al., 2020).

Another promising approach is microbial soil stabilization, which involves using microorganisms to enhance soil properties. This method represents a significant advancement in sustainable foundation engineering as it leverages natural biological processes to increase soil strength, reduce permeability, and enhance resistance to erosion (Cheng & Shahin, 2018). Microbial stabilization has the potential to be a low-carbon, environmentally friendly alternative to conventional techniques. However, while its environmental benefits are clear, more research is needed to evaluate its long-term effectiveness and practicality for large-scale projects.

Economic Feasibility of Sustainable Stabilization Methods

In addition to environmental concerns, the economic feasibility of various soil stabilization techniques plays a crucial role in their adoption in foundation engineering. Cement and lime stabilization, while effective, can be expensive, particularly in regions where these materials are not readily available. The high cost

of raw materials, combined with the energy-intensive production processes, makes these methods less economically viable for some projects (Amalina et al., 2022). On the other hand, sustainable alternatives such as fly ash, slag, and bio-based stabilizers offer significant cost savings. Fly ash, for example, is often available at a lower cost due to its abundant supply and the fact that it is a byproduct of coal combustion. Studies have indicated that using fly ash not only reduces material costs but also lowers the environmental impact, making it a cost-effective and sustainable option for soil stabilization (Gravina da Rocha et al., 2021).

Moreover, alternative stabilizers such as biopolymers and natural fibers have been shown to be economically viable due to their low-cost production and minimal environmental impact. While these materials may not be as widely available as cement or lime, their use in small-scale projects or in regions where sustainability is a priority offers an opportunity for more affordable, eco-friendly construction practices (Adetooto et al., 2024).

Contribution to Sustainable Foundation Engineering Practices

The integration of sustainable soil stabilization techniques into foundation engineering practices is essential for reducing the environmental footprint of construction projects. Sustainable stabilization techniques help reduce the reliance on non-renewable resources, lower carbon emissions, and minimize waste generation. By using alternative materials such as fly ash, slag, and natural fibers, engineers can significantly reduce the environmental impact of soil stabilization while still achieving the necessary soil strength and stability required for foundation construction (Bellum et al., 2022).

Moreover, sustainable soil stabilization methods contribute to the long-term durability and resilience of foundation systems. These techniques not only improve the immediate structural stability of foundations but also enhance their ability to resist erosion, settlement, and other forms of degradation over time. This is particularly important in the context of climate change, as changing environmental conditions can lead to soil erosion, compaction, and other issues that affect the stability of foundations. By adopting sustainable soil stabilization techniques, engineers can ensure that foundation systems remain resilient in the face of environmental challenges (Caballero et al., 2016).

Integration of Sustainability into Soil Stabilization Practices

A critical finding from the literature is the need for a more integrated approach to soil stabilization that takes into account the technical, economic, and environmental dimensions. While many studies have explored the individual aspects of soil stabilization, there is a lack of comprehensive frameworks that guide decision-making based on these factors. The integration of these elements into a unified framework would allow engineers to select the most appropriate soil stabilization methods based on the specific needs of a project, taking into consideration the type of soil, environmental impact, and economic viability (Gravina da Rocha et al., 2021).

Additionally, policy and regulatory support is crucial in promoting the widespread adoption of sustainable soil stabilization methods. Governments and regulatory bodies can play a pivotal role by incentivizing the use of environmentally

friendly materials and techniques through subsidies, tax breaks, or regulations that mandate the use of sustainable construction practices. Such policies could help accelerate the transition toward more sustainable foundation engineering practices, ultimately benefiting both the environment and the economy (Goh et al., 2023).

Discussion

The findings from this study highlight the significant relationship between soil stabilization techniques and sustainable foundation engineering practices, demonstrating that while traditional stabilization methods like lime and cement are effective, they come with notable environmental and economic drawbacks. These results align with the growing global concern regarding the environmental footprint of construction materials and methods, particularly in the context of soil stabilization.

One of the key findings of this research is the environmental impact of traditional stabilization methods, such as cement and lime, which contribute significantly to CO₂ emissions. According to the International Energy Agency (IEA), cement production accounts for approximately 8% of global CO₂ emissions (Andrew, 2019). This aligns with the current global push for more sustainable construction practices, as the construction industry is responsible for a substantial portion of global greenhouse gas emissions (Crawford, 2022). The use of alternatives such as fly ash and other industrial byproducts presents a promising solution. Fly ash, as highlighted in the study, is a waste material that can be used effectively for soil stabilization, reducing the reliance on virgin raw materials while also addressing waste management issues. This is particularly relevant in the context of the circular economy, where repurposing waste products for construction materials is seen as an important strategy for achieving sustainability (Rios & Grau, 2020). This finding supports the theory of sustainable construction, which emphasizes the need to minimize resource extraction and reduce waste through recycling and reusing materials in construction processes (Kibert, 2016).

Furthermore, microbial soil stabilization techniques, which involve the use of microorganisms to improve soil properties, offer a unique and innovative approach to reducing the environmental impact of soil stabilization. This method has gained attention in recent years for its potential to be both eco-friendly and highly effective. The findings of this study suggest that microbial stabilization, while still in the experimental stages, holds great promise for the future of sustainable foundation engineering. Research indicates that microbes can increase soil strength, reduce permeability, and enhance resistance to erosion (Cheng & Shahin, 2018). This aligns with the emerging trend of biotechnological innovations in the field of geotechnical engineering, where bioremediation and other bio-based technologies are being explored to address environmental challenges in construction (Cheng & Shahin, 2018). However, more research is required to establish the long-term reliability and scalability of microbial stabilization, particularly for large-scale infrastructure projects.

Economically, the adoption of sustainable stabilization techniques is also seen as a viable solution for reducing the overall cost of construction. Fly ash and other alternative stabilizers can lower the material cost significantly, providing a more

affordable option compared to traditional stabilizers. The initial cost of using bio-based stabilizers and natural fibers may be higher, but their long-term economic benefits, in terms of reduced maintenance and increased durability, may outweigh the upfront costs. This is particularly true for projects in regions where raw materials are scarce or expensive (Kibert, 2016). In addition, the use of alternative stabilizers can help reduce the cost of environmental mitigation measures by lowering the need for carbon offset programs and environmental remediation efforts, thus aligning with the broader goals of green construction practices.

The integration of sustainability into soil stabilization techniques also reflects the evolving paradigm in foundation engineering, where environmental, economic, and technical factors are increasingly being considered together. This integrated approach is necessary for achieving the goals of sustainable development in the construction industry. As the findings suggest, soil stabilization methods need to be evaluated not only for their technical performance but also for their environmental and economic impact. The development of decision-making frameworks that incorporate these factors is crucial for guiding engineers in selecting the most sustainable soil stabilization techniques (Kibert, 2016). Such frameworks will be essential for making informed decisions that align with global sustainability goals and the increasing demand for low-carbon infrastructure.

In conclusion, while traditional soil stabilization techniques have their merits, the shift toward more sustainable practices is necessary to meet the challenges posed by climate change and resource depletion. The findings from this study demonstrate that alternative stabilization methods, such as the use of industrial byproducts and microbial techniques, provide viable solutions for reducing the environmental and economic impact of soil stabilization. However, further research is needed to refine these methods and develop more comprehensive, practical guidelines for their implementation in foundation engineering.

CONCLUSION

This study highlights the significant relationship between soil stabilization techniques and sustainable foundation engineering practices. The findings reveal that while traditional soil stabilization methods, such as cement and lime, effectively improve soil properties, they come with considerable environmental and economic costs. Alternative techniques, including the use of industrial byproducts like fly ash and innovative methods such as microbial stabilization, offer promising solutions to mitigate these drawbacks. These sustainable alternatives not only reduce the environmental footprint but also provide cost-effective and durable options for foundation engineering. Furthermore, the integration of economic, environmental, and technical factors into decision-making frameworks is crucial for selecting the most appropriate soil stabilization methods in the context of sustainability. In light of the increasing emphasis on sustainable construction practices, these findings underscore the importance of adopting eco-friendly solutions in soil stabilization to support the broader goals of sustainable development.

Recommendations for Future Research

Future research should focus on further investigating the long-term performance and reliability of alternative soil stabilization techniques, particularly microbial stabilization and the use of biopolymers. Additionally, more studies are needed to evaluate the economic feasibility and scalability of these techniques for large-scale infrastructure projects. Comparative analyses that assess the lifecycle costs, environmental impact, and durability of various stabilization methods will provide valuable insights for industry practitioners. Furthermore, developing standardized guidelines and decision-making frameworks for selecting sustainable soil stabilization methods based on specific project requirements would help bridge the gap between theoretical knowledge and practical application. Lastly, as policy and regulatory frameworks play a pivotal role in promoting sustainable practices, future studies should explore the potential impact of governmental policies on the adoption of green technologies in foundation engineering.

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