Community and Ecology (2024) Volume 2 Issue 2
ISSN: 3029-2239 (O)
doi: 10.59429/ce.v2i2.8888

RESEARCH ARTICLE

Climate change impact on infrastructure resilience: A chemical and geotechnical perspective on soft clay soils

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ABSTRACT

Climate change poses significant challenges to infrastructure systems, particularly those constructed on soft clay soils, which are inherently sensitive to environmental conditions. From a chemical and geotechnical engineering perspective, climate-induced factors such as rising temperatures, fluctuating groundwater levels, and extreme weather events can alter the chemical properties of soft clay soils, leading to changes in their structural behavior and stability. This review explores the critical role of chemical processes in soil stabilization, mineralogical transformations, and chemical erosion under changing climatic conditions. It synthesizes findings on chemical additives, including lime and cement treatments, for enhancing soil strength and mitigating deformation risks. The paper also highlights recent advancements in understanding ion exchange processes, pH variations, and salinity effects on soft clay properties. By bridging chemical insights with geotechnical solutions, the study provides practical recommendations for the development of climate-resilient infrastructure. This chemical-centric review contributes to advancing sustainable engineering practices in vulnerable regions.

Keywords: Climate change; Soft clay soil; Chemical stabilization; Soil chemistry; Infrastructure resilience; Mineralogical transformations; Sustainable development

1. Introduction

The rapid and unprecedented consequences of climate change have profound implications for infrastructure systems, particularly those developed on soft clay soils. These soils, characterized by high plasticity, compressibility, and water retention capacity, are vulnerable to deformation and instability under varying environmental conditions. Climate-induced factors such as rising temperatures, erratic rainfall patterns, and fluctuating groundwater levels further exacerbate the challenges posed to infrastructure stability.

From a chemical and geotechnical standpoint, environmental stressors influence key soil properties, including chemical composition, pH levels, ion exchange capacity, and mineralogical stability. Variations in these properties can significantly alter the mechanical behavior of soft clay soils, affecting their ability to

ARTICLE INFO
Received: 6 October 2025|Accepted: 6 November 2025|Available online: 24 November 2024

CITATION
M. Al Alim, S. Hore. Climate Change Impact on Infrastructure Resilience: A Chemical and Geotechnical Perspective on Soft Clay Soils. *Community and Ecology*. 2024; 2(2): 8888.doi: 10.59429/ce.v2i2.8888

support infrastructure. Understanding these interactions is critical for developing climate-resilient infrastructure solutions. This review explores the intricate chemical and geotechnical dynamics governing the behavior of soft clay soils under climate change conditions. It aims to provide a comprehensive synthesis of recent research, focusing on soil chemical processes, stabilization techniques, and the integration of chemical engineering approaches into geotechnical practices. The impact of climate change on soft clay soils has garnered significant attention in both geotechnical and chemical research due to the soils' susceptibility to environmental changes. Various studies have explored how temperature fluctuations, altered precipitation patterns, and changes in groundwater dynamics influence the behavior of soft clay soils, with far-reaching implications for infrastructure performance. Hossain’s research [1] presented a comprehensive numerical modeling approach to assess seismic soil-pile-structure interactions. Their study provided valuable insights into the dynamic behavior of soft soils under seismic loading, highlighting how climate-induced changes, such as temperature increases and fluctuating groundwater levels, can exacerbate soil instability during seismic events. Similarly, Hore[2] underscored the importance of analyzing dynamic soil properties for a better understanding of soil-structure interactions, emphasizing that the physical and chemical alterations of soils due to climate change can significantly affect the performance of infrastructure subjected to seismic forces.

Research has also demonstrated the critical role of chemical processes in soil stability. Hore et al.[3] delved into the chemical alterations occurring in soft clay soils, especially under climate change scenarios. Their findings emphasized how factors such as rising temperatures, ion exchange, and the increase in salinity can impact soil properties like plasticity and strength, which in turn affect the structural performance of infrastructure built on these soils. Ahmad et al.[4] examined the implications of heatwave patterns on soil chemical properties, focusing on the long-term effects of heat stress on clay soils. Their study revealed that prolonged exposure to elevated temperatures accelerates chemical weathering, weakening the soil’s structural integrity and compromising the stability of engineering structures. In a related study, Islam et al.[5] explored the vulnerabilities of soft clay soils to drought conditions, which can lead to water scarcity and significant changes in the soil's chemical and physical behavior. They demonstrated that reduced water content and prolonged droughts alter the soil’s mineralogical composition, leading to increased soil shrinkage, cracking, and a higher risk of erosion. These findings underline the urgent need for adaptive strategies in infrastructure development to address these vulnerabilities in regions prone to drought.

Chemical stabilization techniques, such as lime and cement treatments, have been extensively researched as solutions to mitigate the challenges posed by climate-induced soil degradation. The highlighted the effectiveness of these treatments in enhancing the soil’s strength, reducing swelling potential, and improving stability in response to fluctuating moisture content and temperature variations [6-8]. These studies also examined the interaction between chemical additives and soil mineralogy, noting that the success of stabilization measures is highly dependent on the soil's mineral composition and the specific climatic conditions in the region.

Recent advancements in bio-based and sustainable stabilization methods have also been explored. For instance, the use of bio-cementation techniques, which harness microbial processes to enhance soil strength, has shown promise in mitigating the effects of climate change on soft clay soils. These methods offer a more environmentally friendly alternative to traditional chemical stabilization and have demonstrated improved resilience to environmental stresses such as wetting-drying cycles and temperature extremes[9,10]. Additionally, the application of nanomaterials in soil stabilization is an emerging area of research. Nano-silica, nano-clays, and other nanomaterials are being studied for their ability to enhance soil properties at a molecular level, offering a potential solution to improve the durability and resilience of infrastructure in areas vulnerable to climate change.

This review synthesizes these findings to provide a comprehensive understanding of the chemical and geotechnical mechanisms that govern the behavior of soft clay soils under climate stress. By integrating chemical insights with geotechnical stabilization solutions, this work aims to advance climate-resilient infrastructure practices. The emphasis on sustainable and innovative methods in soil stabilization, coupled with a detailed understanding of the impact of climate change on soil properties, lays the foundation for developing adaptive strategies that can enhance infrastructure performance in the face of an uncertain climate future.

2. Objectives

1. To analyze the impact of climate-induced factors on the chemical properties of soft clay soils and their implications for infrastructure stability.
2. To evaluate the effectiveness of chemical stabilization techniques in mitigating climate-induced soil challenges.
3. To synthesize recent advancements in soil chemical research for developing climate-resilient infrastructure strategies.

Novelty of the Review: This review offers a novel approach by integrating chemical engineering perspectives with geotechnical practices to address the challenges posed by climate change on soft clay soils. Unlike previous studies that primarily focused on either geotechnical or climatic aspects, this paper bridges the gap by highlighting the chemical processes driving soil behavior changes. It also emphasizes the practical application of chemical treatments and their role in fostering sustainable infrastructure development. The insights provided aim to guide future research and policymaking efforts, ultimately contributing to the development of robust, climate-resilient infrastructure solutions.

Climate change-driven phenomena, such as extreme weather patterns, prolonged heatwaves, and unpredictable rainfall, significantly affect the chemical composition and physical behavior of soft clay soils. Rising temperatures can accelerate mineral transformations within clay particles, while increased rainfall and flooding events often lead to heightened salinity levels, altering soil pH and chemical interactions. These environmental changes affect both the strength and stability of the soil, potentially undermining the load-bearing capacity of infrastructure systems. Studies have revealed that fluctuations in soil moisture content due to seasonal climate variations can enhance ion exchange processes, leading to changes in soil compressibility and plasticity. Furthermore, prolonged exposure to increased temperatures can induce dehydration in clay minerals, resulting in shrinkage and structural instability. The impact of these changes extends to infrastructure performance, as chemically unstable soils are more susceptible to erosion, deformation, and loss of strength. Understanding these chemical processes is essential for predicting soil behavior and designing mitigation strategies that promote infrastructure resilience. One of the most widely adopted methods to mitigate the adverse effects of climate change on soft clay soils involves chemical stabilization techniques. These methods aim to enhance the strength and durability of clay soils by altering their chemical and mineralogical properties. Lime stabilization is one of the most effective methods used in engineering practice. Lime reacts with clay minerals through pozzolanic reactions, leading to the formation of cementitious compounds such as calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH). These reactions significantly improve soil strength, reduce plasticity, and increase resistance to moisture-induced changes.

Cement stabilization, another popular approach, involves the addition of Portland cement to clay soils. The hydration reactions of cement lead to the development of a rigid soil structure capable of withstanding higher loads and resisting deformation. Research by Talukder et al. [6] demonstrated that cement-stabilized clay soils exhibit enhanced shear strength and reduced compressibility under varying climatic conditions. Innovative chemical treatments, such as the use of polymer-based additives and nanomaterials, have also gained attention for their ability to modify clay soil properties effectively. These treatments offer superior bonding and durability, making them promising solutions for infrastructure development in climate-vulnerable regions. Future research should focus on optimizing the dosage and combination of chemical additives to achieve cost-effective and sustainable soil stabilization solutions. Additionally, understanding the long-term chemical interactions between additives and soil minerals under changing environmental conditions is essential for predicting infrastructure performance and resilience.

3. Chemical and geotechnical behavior of soft clay soils under climate change

3.1. Impact of temperature fluctuations on soft clay soils

Temperature fluctuations induced by climate change can have significant impacts on the geotechnical and chemical behavior of soft clay soils. Rising temperatures cause soil moisture content to fluctuate, leading to expansion and contraction of the clay particles. This phenomenon, known as "shrink-swell" behavior, is particularly detrimental to infrastructure built on soft clay soils, as it causes cyclic deformations that may weaken the foundation of structures [11].

Furthermore, temperature changes can affect the rate of mineral weathering in the soil. Clay minerals, such as montmorillonite and kaolinite, undergo structural changes when exposed to elevated temperatures, altering their cation exchange capacity (CEC) and impacting their strength and plasticity [12]. In particular, high temperatures can increase the rates of ion exchange reactions, which may further modify the soil’s structural integrity and behavior.

3.2. Groundwater level variations and their effect on soft clay soils

Fluctuations in groundwater levels due to climate change, such as those caused by altered precipitation patterns or the melting of glaciers, can significantly impact the stability and geotechnical properties of soft clay soils. The groundwater table plays a crucial role in the pore water pressure within the soil matrix, directly influencing soil strength and consolidation.

When the groundwater level rises, it can lead to the softening of the clay, decreasing its shear strength and increasing the risk of soil liquefaction during seismic events [13]. Conversely, prolonged droughts or lower groundwater levels can result in soil desiccation, causing shrinkage and cracking. These cracks can exacerbate the risk of erosion, allowing for the infiltration of harmful salts or pollutants that further degrade soil stability[14].

3.3. Extreme weather events and their consequences on soft clay properties

Climate change is predicted to increase the frequency and severity of extreme weather events, such as heavy rainfall, floods, and storms, all of which significantly affect soft clay soils. Heavy rainfall leads to an increase in pore water pressure, reducing soil strength and potentially causing soil liquefaction, especially in saturated conditions[15]. This process can result in significant damage to infrastructure, as soil behavior becomes more unpredictable and unstable under such conditions.

In addition to rainfall, flooding can induce erosion, removing surface soil layers and exposing deeper, more vulnerable soil strata. These events can lead to rapid changes in soil composition, disrupting the delicate balance of chemical properties that govern soil behavior. For instance, flooding can result in the leaching of essential minerals, thereby reducing the soil's ability to retain and exchange nutrients, thus weakening its overall structure[16].

Storm surges and coastal flooding also pose a significant threat to soft clay soils, especially in coastal regions. Salinity intrusion from seawater can alter the ionic composition of the soil, leading to changes in its electrochemical properties. Higher salinity can reduce the soil's cohesion and shear strength, exacerbating the risk of failure in the event of an earthquake or other stress-inducing events[17]. **Figure 1** shows the Climate change impact on soil profile.

3.4. Chemical processes and soil degradation under climate change

Chemical processes such as ion exchange, oxidation-reduction reactions, and dissolution play a pivotal role in shaping the properties of soft clay soils under climate change. Increased temperatures and fluctuations in groundwater can promote the leaching of essential minerals, altering the soil's mineralogy and chemical composition. This can weaken the soil's ability to resist deformation and increase its susceptibility to erosion [18].

For instance, the dissolution of calcium carbonate in the presence of acidic groundwater, which may be caused by increased CO2 levels due to climate change, can lead to a decrease in soil stiffness and strength. Additionally, the precipitation of salts from evaporating groundwater during dry periods can increase soil salinity, resulting in a decrease in soil plasticity and an increase in cracking behavior[19].

Figure 1. Climate change impact on soil profile.

4. Soil stabilization techniques for climate-resilient infrastructure

4.1. Chemical additives for soil stabilization

Soil stabilization plays a crucial role in mitigating the adverse effects of climate change on soft clay soils. Various chemical additives are widely used to enhance the strength and stability of soft clay, particularly in regions vulnerable to climate-induced changes such as fluctuating groundwater levels, extreme temperatures, and heavy rainfall.

1. **Lime Stabilization**: Lime stabilization is one of the most commonly used techniques for improving the engineering properties of soft clay soils. The process involves mixing lime (usually quicklime or hydrated lime) with the soil to facilitate chemical reactions that improve its workability and strength. Lime reacts with the clay minerals to promote flocculation, which reduces plasticity, increases compaction, and improves the overall shear strength of the soil [20]. Lime is particularly effective in reducing the susceptibility of soft clay to shrink-swell behavior, making it an ideal solution for mitigating the impact of temperature fluctuations and wetting-drying cycles caused by climate change.
2. **Cement Stabilization**: Cement treatment is another widely adopted method for stabilizing soft clay soils. The use of Portland cement, which reacts with water to form calcium silicate hydrate (C-S-H) gel, enhances soil strength and reduces plasticity. Cement stabilization can be particularly beneficial in addressing the impacts of extreme weather events, such as heavy rainfall or flooding, by increasing the soil's resistance to erosion and improving its load-bearing capacity [21]. Moreover, cement stabilization can help reduce the risk of soil liquefaction in saturated conditions, which is essential in areas prone to both earthquakes and climate-induced extreme weather events.
3. **Polymer and Synthetic Additives**: Recent advancements in polymer chemistry have introduced the use of synthetic additives to stabilize soft clay soils. Polymers, such as polyethylene oxide (PEO) and polyacrylamide (PAM), are utilized to enhance soil cohesion and reduce permeability. These polymer-based stabilizers improve soil resistance to erosion, increase compaction, and provide long-term durability under varying climatic conditions [21]. The benefit of these synthetic additives is their ability to function effectively even in saline or chemically aggressive environments, where traditional methods like lime or cement may not be as effective.

4.2. Geotechnical methods for soil stabilization

In addition to chemical stabilization, various geotechnical techniques are used to improve the engineering properties of soft clay soils, particularly when addressing the challenges posed by climate change. **Figure 2** shows the Impact on Soil Stabilization before and after improvement.

1. **Compaction Techniques**: Compaction is a widely applied method to enhance the density and stability of soft clay soils. Proper compaction increases soil strength, reduces permeability, and minimizes settlement. This method is particularly effective in mitigating the impact of extreme weather events, as it ensures better resistance to water infiltration and erosion. In regions with fluctuating groundwater levels, compaction can help prevent excessive swelling or shrinkage of the clay by reducing moisture movement through the soil matrix [22].
2. **Deep Mixing and Grouting**: Deep mixing techniques involve the introduction of stabilizing agents, such as cement or lime, into the soil using a series of vertical augers or rotary drilling. This process results in a column of stabilized soil that can significantly improve soil bearing capacity and reduce the potential for ground settlement. In combination with geotechnical grouting, which involves injecting a stabilizing fluid (usually cement or polyurethane) into the soil, this technique can be used to enhance the strength of soft clay soils, especially in areas subject to liquefaction or heavy rainfall. Grouting can also help reduce soil permeability and mitigate the effects of erosion during flooding or storm events.
3. **Geosynthetics**: The use of geosynthetic materials, such as geotextiles, geogrids, and geomembranes, has gained popularity in soft clay soil stabilization, particularly for infrastructure projects vulnerable to climate-induced degradation. Geosynthetics serve to reinforce the soil,

improve drainage, and prevent erosion. For example, geogrids can provide tensile strength, reducing the risk of soil displacement, while geomembranes can act as barriers to moisture movement. In areas prone to flooding or high salinity, geosynthetics can help protect the soil from further degradation by reducing the infiltration of water or chemicals.

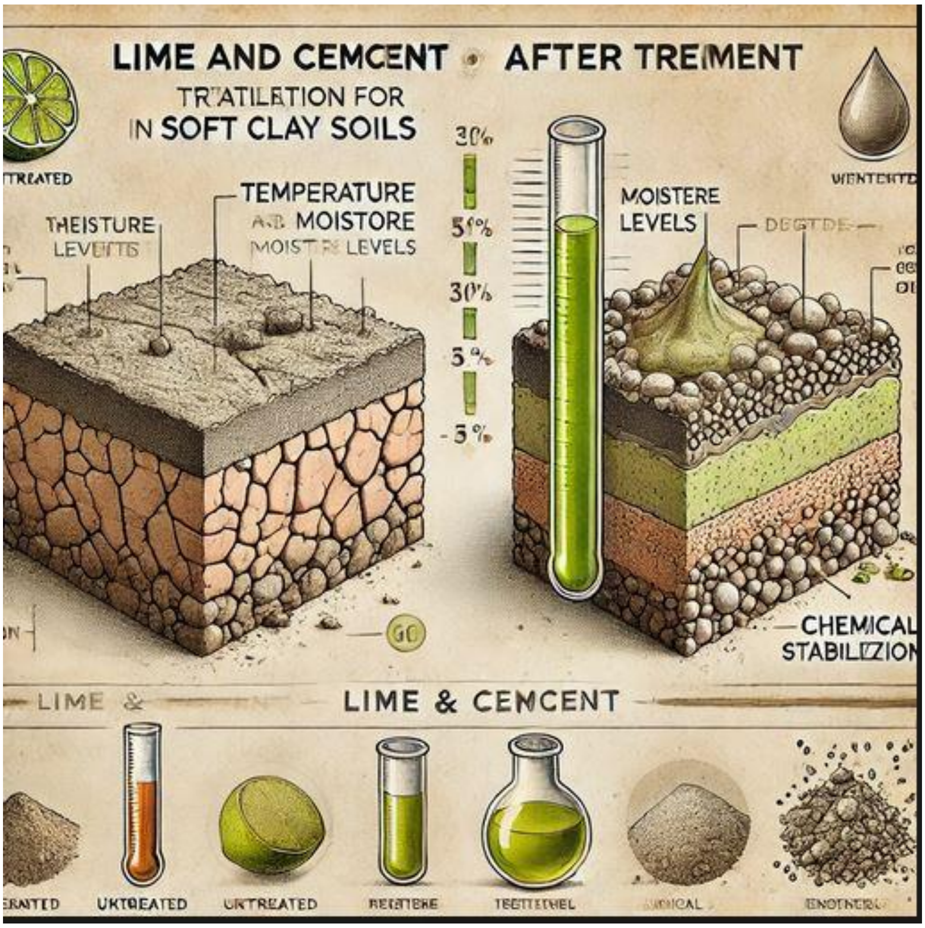

Figure 2. Impact on Soil Stabilization before and after improvement.

4.3. Innovative soil stabilization technologies for climate change adaptation

As climate change exacerbates the challenges posed by soft clay soils, innovative stabilization technologies have emerged to enhance the resilience of infrastructure. These technologies aim to improve soil stability while also promoting environmental sustainability. **Figure 3** shows the Chemical ingredient change during climatic effect

1. **Bio-cementation**: Bio-cementation is a novel approach that leverages microbial processes to induce the precipitation of calcium carbonate, thereby strengthening soft clay soils. The process involves introducing specific bacteria (e.g., *Sporosarcina pasteurii*) into the soil, which promotes the formation of a cement-like material that binds soil particles together [21, 23]. This technique has the advantage of being environmentally friendly, cost-effective, and capable of functioning in low pH conditions, which are increasingly common due to the effects of climate change.

2. **Nanomaterial-based Stabilization**: Nanotechnology offers promising advancements in soil stabilization. Nanomaterials, such as nano-silica and nano-clays, are used to improve the mechanical properties and stability of soils at a molecular level. These materials enhance the soil's resistance to deformation, water infiltration, and erosion. Nanomaterial-based stabilizers have

shown considerable potential in addressing the challenges posed by extreme weather conditions and rising temperatures [21].

4.4. Challenges and limitations of soil stabilization techniques

While various stabilization techniques offer promising solutions for improving soil resilience to climate change, they are not without their challenges. Some of the limitations include:

- **Cost-Effectiveness**: Chemical treatments, such as cement or polymer stabilization, can be expensive, particularly when applied to large-scale infrastructure projects.
- **Environmental Impact**: Certain stabilization methods, such as cement and lime, may have negative environmental impacts, particularly in terms of carbon emissions during production and application [24].
- **Long-Term Durability**: The long-term effectiveness of certain stabilizers, particularly polymers, is still a subject of ongoing research, and their performance under extreme climatic conditions needs to be more thoroughly evaluated.

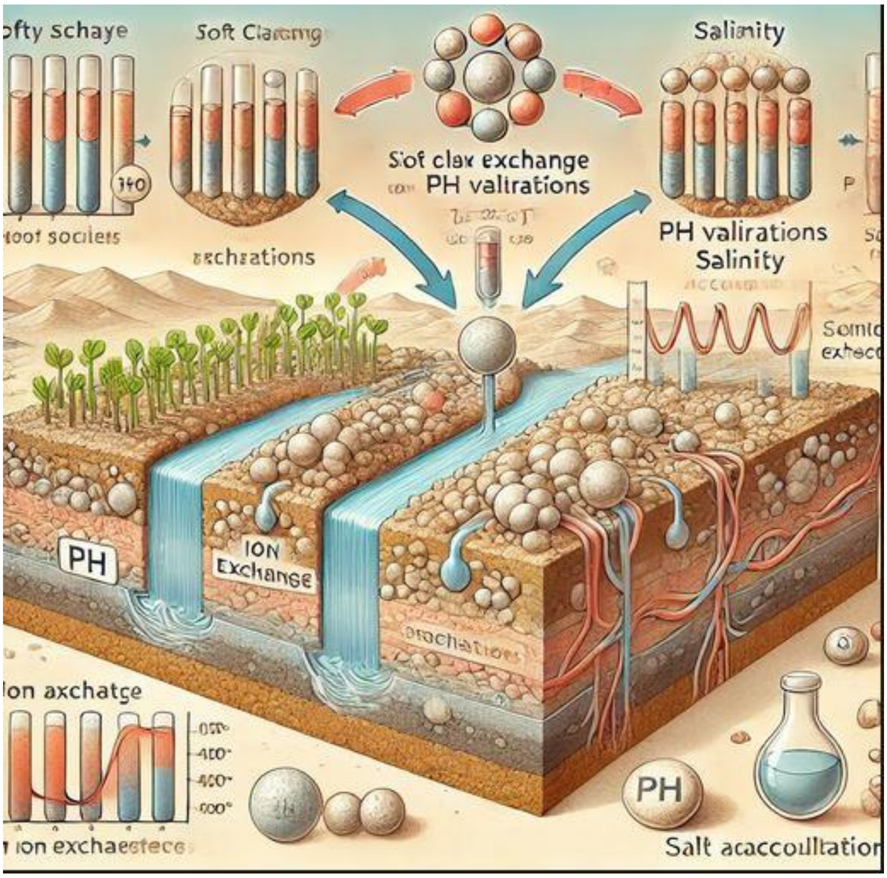

Figure 3. Chemical ingredient change during climatic effect.

5. Discussion and analysis

The impact of climate change on infrastructure resilience, particularly in regions with soft clay soils, is a multifaceted issue that requires a multidisciplinary approach to effectively address. The chemical and geotechnical behavior of soft clay soils, reveals how fluctuating environmental conditions including rising temperatures, altered groundwater levels, and extreme weather events can significantly alter the engineering properties of these soils. This chapter has outlined the challenges posed by climate change, including the shrink-swell behavior, erosion, and soil liquefaction in saturated conditions, all of which compromise the stability of infrastructure.

The findings from Chapter 4 highlight the various soil stabilization techniques that have been developed to mitigate these climate-induced challenges. The use of chemical additives such as lime, cement, and polymer-based stabilizers, as well as geotechnical methods like compaction, deep mixing, and grouting, all offer valuable solutions to enhance soil strength and prevent degradation. However, the application of these techniques is not without limitations, particularly in terms of cost, environmental impact, and long-term durability.

5.1. Chemical stabilization and environmental considerations

Chemical stabilization techniques, such as lime and cement treatments, have been widely used for enhancing soil properties in response to climate change. These methods are effective in addressing soil plasticity, improving compaction, and enhancing resistance to erosion. Lime, in particular, is effective in mitigating shrink-swell behavior, which is crucial for regions with significant temperature fluctuations. However, the use of lime and cement raises environmental concerns due to their carbon footprint during production and application. Cement production alone is responsible for approximately 8% of global CO2 emissions, making it necessary to explore more sustainable alternatives, such as bio-cementation and nanomaterial-based stabilizers.

The incorporation of bio-cementation, leveraging microbial processes for calcium carbonate precipitation, offers an environmentally friendly alternative with great potential for soil stabilization. Studies indicate that bio-cemented soils not only demonstrate improved strength but also offer resilience under climate-induced stresses, such as wetting-drying cycles and temperature variations. Similarly, the use of nanomaterials, such as nano-silica and nano-clays, is a promising frontier, enhancing the soil's mechanical properties at a molecular level. While the cost of these materials remains a concern, their potential for long-term sustainability in climate-resilient infrastructure makes them a valuable area for future research.

5.2. Geotechnical stabilization methods in response to climate change

Geotechnical stabilization techniques, such as compaction, deep mixing, and grouting, are essential for enhancing soil strength and mitigating the impacts of extreme weather events, such as heavy rainfall and flooding. Compaction reduces the permeability of soft clay soils, thus preventing water infiltration and reducing the risk of erosion. It also helps to counteract the effects of shrink-swell behavior caused by fluctuating groundwater levels. The combination of compaction with deep mixing and grouting can provide additional reinforcement, especially in flood-prone regions or areas susceptible to soil liquefaction.

The use of geosynthetics, such as geogrids and geomembranes, in soil stabilization has gained attention due to their ability to improve soil resistance to displacement, provide drainage, and prevent erosion. These materials are particularly beneficial in coastal areas, where storm surges and salinity intrusion are major concerns. Geosynthetics offer a cost-effective and sustainable solution to address soil instability under the pressure of climate change-induced stresses.

While these geotechnical methods provide significant benefits, their effectiveness can be compromised by the environmental conditions they are intended to mitigate. For instance, the increased frequency of extreme rainfall events can overwhelm the capacity of compacted soils to resist erosion, especially in regions with poorly managed drainage systems. Similarly, deep mixing and grouting may not be sufficient in regions with high water tables or unstable soil profiles, requiring additional interventions to maintain infrastructure integrity.

5.3. The role of integrated approaches for soil stabilization

As climate change continues to challenge the stability of soft clay soils, it becomes increasingly clear that an integrated approach combining both chemical and geotechnical stabilization methods is essential for ensuring infrastructure resilience. The synergy between lime or cement stabilization and geotechnical reinforcement techniques, such as deep mixing and the use of geosynthetics, offers a more comprehensive solution to the complex issues posed by climate change. Moreover, the integration of innovative technologies, such as bio-cementation and nanomaterials, provides a sustainable pathway for addressing soil instability, particularly in regions where traditional methods may not be effective or environmentally feasible.

Additionally, it is crucial to consider site-specific factors, such as soil composition, local climate patterns, and environmental regulations, when selecting the most appropriate stabilization techniques. For example, in regions where groundwater levels are particularly volatile, lime or cement stabilization combined with deep mixing techniques may offer greater long-term benefits than other methods. In contrast, in coastal or flood-prone areas, the use of geosynthetics and bio-based stabilization methods may provide better resistance to water infiltration and soil erosion.

5.4. Challenges and future directions

Despite the availability of various soil stabilization methods, several challenges remain. The cost of implementing these techniques at scale remains a significant barrier, particularly in low-income regions or areas with limited resources for large-scale infrastructure projects. Additionally, there is a need for more research into the long-term durability and environmental impact of some stabilization techniques, especially with regard to their performance under increasingly extreme climate conditions.

Future research should focus on improving the efficiency and sustainability of soil stabilization methods, particularly by exploring the potential of alternative materials, such as waste products and low-carbon stabilizers, for enhancing soil strength. Furthermore, the development of advanced modeling techniques to predict the long-term effects of climate change on soil behavior will be essential for optimizing stabilization strategies and ensuring the resilience of infrastructure.

6. Conclusion

This study underscores the critical impact of climate change on the stability of infrastructure built on soft clay soils. The findings highlight how environmental factors such as temperature fluctuations, groundwater variations, and extreme weather events influence the geotechnical and chemical properties of these soils, leading to shrink-swell behavior, erosion, and potential liquefaction. Addressing these challenges requires targeted soil stabilization approaches that enhance resilience and adaptability.

A comprehensive review of stabilization techniques reveals that both chemical and geotechnical methods play crucial roles in strengthening soft clay soils. Chemical treatments, including lime, cement, and polymer-based stabilizers, have proven effective, yet their environmental impact calls for further exploration of sustainable alternatives such as bio-cementation and nanomaterials. Geotechnical techniques, including deep mixing, compaction, and the use of geosynthetics, offer additional reinforcement and improved drainage, particularly in regions susceptible to flooding and coastal influences. Despite advancements in stabilization strategies, challenges remain in terms of cost-effectiveness, long-term durability, and environmental sustainability. Future research should focus on optimizing existing methods, developing eco-friendly solutions, and advancing predictive models for assessing soil behavior under evolving climatic conditions. The integration of cutting-edge materials and data-driven engineering approaches will be key to enhancing the resilience of infrastructure.

Building climate-resilient infrastructure demands a collaborative effort among researchers, engineers, and policymakers. By implementing adaptive, region-specific stabilization strategies and fostering interdisciplinary cooperation, infrastructure systems can be safeguarded against climate-induced risks, ensuring long-term safety and sustainability for vulnerable communities.

Conflict of interest

The authors declare no conflict of interest.

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