

Enhancement of Soil Characteristics Using Different Stabilization Techniques

Naimul Haque Nayem

Civil Engineering Department, Rajshahi University of Engineering and Technology, Rajshahi, Bangladesh

Email address:

nayemruetcivil13@gmail.com

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Abstract: Soil stabilization is a critical aspect of civil engineering, involving various methods to modify soil properties and enhance its engineering performance for diverse construction projects. The necessity for soil stabilization arises when natural soil conditions cannot support structural loads due to undesirable characteristics. Soil stabilization involves altering soil properties through chemical or physical means to increase bearing capacity, weathering resistance, and permeability while reducing construction costs. Waste management and waste materials play a significant role in soil stabilization techniques by providing sustainable and eco-friendly solutions to improve soil properties and enhance stability. The connection between waste management and soil stabilization lies in the utilization of various waste materials as stabilizing agents. These waste materials can serve as cost-effective alternatives to traditional stabilizers while reducing the environmental impact of construction and civil engineering projects. This research acknowledges the significance of soil stabilization for civil engineering purposes and explores the effectiveness of various materials as soil stabilizers. Different kinds of stabilization techniques like cement, lime, fly ash, chemical, bituminous, thermal, and electrical stabilization, and other recycled waste materials are investigated. This comprehensive review serves as a valuable resource for civil engineers, researchers, and practitioners seeking a holistic understanding of soil stabilization techniques. As infrastructure demands continue to grow, adopting and advancing soil stabilization techniques becomes imperative for ensuring safe, resilient, and cost-effective construction practices in the face of changing geotechnical challenges. The insights gained from this review will aid in making informed decisions for successful soil stabilization in various civil engineering projects, ensuring the safety, stability, and resilience of infrastructure developments in an ever-changing environment.

Keywords: Stabilization, Expansive Soil, Subgrade, Clayey Soil, Sustainable, Waste Materials, Environment, Stabilizers

1. Introduction

Expansive soil, in broad terms, refers to soil or rock material with the propensity to contract or expand as moisture levels fluctuate [1]. This natural tendency can lead to significant issues, such as structural damage to constructions like lightweight buildings, pavements, retaining walls, canal beds, and linings. These damages are particularly prevalent when these structures are situated upon expansive soil. Soil stabilization, on the other hand, can be described as any process aimed at enhancing the properties of soil, rendering it more robust and dependable. This enhancement manifests as improved load-bearing capacity, heightened soil strength, and enhanced resilience in the face of unfavorable moisture and stress conditions [2].

Dealing with soft subgrade or clay soil poses a significant challenge in various civil engineering projects, such as roadways, highways, and geotechnical engineering [3, 4]. Due to the reduction in available construction sites, finding effective soil improvement techniques to meet the demands has become crucial [4].

Clay soils in civil engineering consist of clay minerals and other mineral components, exhibiting plasticity and cohesion. Clays are fine-grained soils, but not all fine-grained soils are necessarily clays. Chemically, clays are composed of hydrous aluminosilicates and other metallic ions, forming flakes or tiny plates with repeating atomic structures. The bonding and metallic ions within the crystal lattice determine different clay minerals. Water significantly influences clay soils, with absorbed water surrounding each clay crystal.

Water absorption occurs due to electrostatic attraction between the water's charges and the clay crystal, as well as hydrogen bonding with the surface of the clay and the attraction of cations present in the water [5].

Traditionally, stabilizing soft subgrades involved removing the soft soil and replacing it with stronger materials, like crushed rock, but this approach proved costly. As a result, research has focused on alternative methods to address this problem [3]. Soil stabilization involves altering one or more properties of the soil through mechanical or chemical means [6]. The purpose of soil stabilization is not only to enhance the soil's load-bearing capacity but also to improve shear strength, filtration, drainage systems, permeability, weathering resistance, and resistance to traffic usage, meeting specific engineering project requirements [6-9].

Mechanical and physical techniques for soil stabilization include compacting to decrease voids, using non-biodegradable reinforcement materials, or altering the grain size composition of the soil particles [6, 10]. Chemical techniques involve using chemical additives or emulsions to modify soil behavior and form a strong network of bound soil grains, resulting in higher strength, durability, and overall quality compared to mechanical and physical techniques [6, 11].

The selection of the appropriate soil stabilization method depends on factors such as the amount of stabilizing agent needed, the type of additives, and the project conditions. Accurate soil description and classification are essential for choosing the correct materials and procedures for successful soil stabilization [10, 12].

Embarking on a journey through the annals of research and exploration in soil stabilization, we can find a series of insightful studies that have illuminated innovative pathways for enhancing the properties of soils to meet the demands of various engineering applications. From investigations into the use of unconventional materials to the exploration of novel techniques, the literature stands as a testament to the ceaseless quest for improved soil performance.

In a study by Yadu (2013), an investigation was conducted to assess the potential of utilizing a combination of granulated blast furnace slag (GBS) and fly ash for stabilizing clayey soil [13]. The research revealed that the addition of a fly ash-GBS mixture effectively led to the stabilization of the clay, demonstrating its viability as a stabilizing agent. Another study conducted by Ransinchung et al. (2013) focused on the efficacy of fines derived from demolished concrete slabs as a soil stabilizer [14]. The concrete slabs used in the study were sourced from Shabzi Mandi of Roorkee. To establish a comparative framework, ordinary Portland cement of grade 43 was chosen as the base stabilizer. The clayey soil employed in this investigation belonged to the CI soil group as per the classification outlined in IS: 1498. During experimentation, both cement and fine demolition concrete slabs (FDCS) were individually admixed with the clayey soil, incrementally increasing the percentage from 3 to 15 percent. The addition of both cement and FDCS resulted in reductions in dry densities and plasticity indices of the soil. Notably, the inclusion of FDCS

led to enhancements in several key soil properties. These included improved soaked CBR (California Bearing Ratio) values, heightened unconfined compressive strength, and increased split-tensile strength. This suggests that the incorporation of FDCS contributes positively to the mechanical properties of the stabilized soil.

In 2015, Ghosh et al. conducted a study focusing on the utilization of construction and demolition waste [15]. The study's findings suggest that materials such as bricks, concrete, and tiles from construction and demolition waste can serve for mechanical stabilization of highly deficient soils. This can be achieved by introducing additional cementitious substances or using commercially approved stabilizers endorsed by the IRC in accordance with IRC:SP:89 standards. The construction and demolition waste material should conform to the gradation requirements outlined in IRC:SP:89. Alternatively, it could be employed partially as soil, subject to evaluations involving leachability, durability, and unconfined compressive strength testing. Following successful trial outcomes, this hybrid material has the potential for application in stabilizing poor soil either on its own or when blended with more favorable soils and appropriate additives. The attained unconfined compressive strength should meet specifications of 0.8 MPa for sub-base and 1.75 MPa for base courses, as stipulated by the revised MORTH and IRC:SP:89 guidelines.

Choudhary et al. (2010) undertook an examination of the viability of integrating plastic waste to enhance subgrade performance within flexible pavement systems [16]. Their study examined the influence of waste plastic strip content (ranging from 0.25% to 4.0%) and strip length on the California Bearing Ratio (CBR) and secant modulus of soil reinforced with these strips. The research highlights that incorporating suitably sized and proportioned waste plastic strips into the soil yields a significant enhancement in both CBR value and secant modulus of the soil.

2. Soil and Its Stabilization

Soil is a complex mixture of minerals, organic matter, gases, liquids, and a diverse array of organisms, playing a vital role in supporting life on Earth. The development of soil is an ongoing process, influenced by various physical, chemical, and biological interactions, including weathering and erosion. Soil stabilization is often necessary, particularly in soft soils like silty, clayey, peat, or organic soils, to achieve desirable engineering properties.

Sherwood suggests that stabilizing fine-grained granular materials is relatively straightforward because of their substantial surface area relative to particle size [17]. Clay soils, in particular, possess a large surface area due to their flat and elongated particle shapes [18]. However, silty materials can be sensitive to even slight changes in moisture content, making their stabilization more challenging. Peat soils and organic soils are characterized by high water content, reaching up to approximately 2000%, along with high porosity and organic content. Peat soil consistency can

vary from muddy to fibrous, and while typically shallow, in severe cases, it can extend several meters below the surface [19, 20]. The high exchange capacity of organic soils can impede the hydration process by trapping calcium ions released during the hydration of calcium silicate and calcium aluminate in cement. As a result, effectively stabilizing these soils depends on carefully choosing suitable binders and adding the right amount of binder [21]. Properly addressing these soil characteristics is crucial for successful soil stabilization in engineering projects.

Soil stabilization in civil engineering refers to the biological, chemical, or mechanical modification of soil properties to enhance its engineering qualities. These properties encompass mechanical strength, permeability, compressibility, durability, and plasticity. The term "stabilization" is commonly used to describe chemical improvements achieved by adding chemical admixtures to the soil. Regardless of the technique used, soil stabilization is crucial for construction projects like buildings, roads, and airfields, as the base soil serves as the foundation. It has been a practice since ancient times, with civilizations like the Romans adopting it, and it became more widespread globally during the latter half of the 20th century, including in the United States and China. Proper soil stabilization ensures a strong foundation and the efficient use of soil as a construction material.

2.1. Why Do We Need Soil Stabilization

Soil stabilization is crucial in civil engineering and construction to enhance load-bearing capacity, engineering properties, and durability of natural soils. It mitigates settlement and erosion, reduces construction costs, and enables the use of marginal soils. Utilizing local materials and waste products, it promotes environmental sustainability and reduces the carbon footprint. Expedited construction and improved long-term performance of structures further underscore its importance. Soil stabilization ensures safe, stable, and cost-effective construction, making it an essential practice in modern engineering projects.

2.2. Utilization of Waste Materials Is a Must

Utilizing waste materials is essential for waste reduction, resource conservation, and improved environmental benefits. It promotes cost-effective practices, sustainability, and circular economy principles. By incorporating waste materials into various processes, it enhances soil and water quality, encourages innovation, and ensures compliance with environmental regulations. Waste utilization plays a vital role in sustainable development, responsible waste management, and the reduction of ecological impact.

2.3. Approaching Sustainable Development

Incorporating waste materials in soil stabilization is an approach that aligns with sustainable development principles. By utilizing waste materials like fly ash, slag, or recycled materials as additives in soil stabilization, several

sustainability objectives are achieved. Firstly, it reduces waste generation and promotes effective waste management practices, contributing to waste reduction and minimizing the burden on landfills. Secondly, this approach conserves natural resources, as it reduces the need for extracting and consuming virgin materials for construction projects. Thirdly, the use of waste materials in soil stabilization can lead to a decrease in carbon emissions and energy consumption, making it environmentally friendly and contributing to climate change mitigation. Furthermore, the incorporation of waste materials enhances soil properties, reduces the leaching of harmful substances into the environment, and improves soil quality. Overall, this sustainable approach fosters the circular economy, promotes responsible resource utilization, and contributes to a greener and more environmentally conscious construction industry.

3. Influencing the Strength of Stabilized Soil: Key Factors

The existence of organic substances, sulfates, sulfides, and carbon dioxide in stabilized soils can result in unfavorable strength and performance characteristics of the stabilized materials [17]. These elements and compounds may have adverse effects on the stability and durability of the stabilized soil, warranting careful consideration and appropriate mitigation strategies during soil stabilization processes.

3.1. Organic Matter

In numerous instances, the upper layers of soil contain substantial amounts of organic matter. In well-drained soils, this organic matter may extend to a depth of 1.5 meters [17]. When soil organic matters react with hydration products, such as calcium hydroxide ($\text{Ca}(\text{OH})_2$), it leads to a decrease in pH value. This low pH value can slow down the hydration process and adversely impact the hardening of stabilized soils, making the compaction process difficult or even impossible.

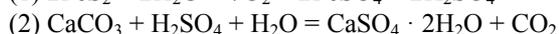
3.2. Sulfates

When calcium-based stabilizers are used in sulfate-rich soils, the stabilized soil reacts with excess moisture and forms calcium sulphoaluminate (ettringite) and/or thamausite. These reaction products occupy a greater volume than the combined volume of the reactants. However, it is worth noting that excess water, beyond what was initially present during the mixing process, may be required to dissolve the sulfate and enable the reaction to proceed effectively [17, 22]. This reaction can impact the volume and stability of the stabilized soil, and careful consideration of water content is essential to ensure proper stabilization.

3.3. Sulfides

In various waste materials and industrial by-products, sulfides in the form of iron pyrites (FeS_2) may be present. The oxidation of FeS_2 leads to the production of sulphuric acid,

which, in the presence of calcium carbonate, can undergo reactions (1) and (2) to form gypsum (hydrated calcium sulfate):



The hydrated sulfate, thus formed, in the presence of excess water, may react with the stabilized material in a manner similar to sulfates. This can potentially lead to the destabilization of the stabilized material. It is worth noting that gypsum can also occur naturally in soil [17, 20]. Hence, when using waste materials or industrial by-products in soil stabilization, careful consideration of their composition and potential reactivity is essential to avoid adverse effects on the stability and performance of the stabilized soil.

3.4. Compaction

The introduction of a binder to the soil has a significant impact on its density in practice. Stabilized mixtures typically exhibit a lower maximum dry density compared to unstabilized soil, even with the same degree of compaction. With increasing binder proportions, the optimum moisture content tends to rise [17]. In the case of cement-stabilized soils, the hydration process commences immediately upon contact with water. This process involves the hardening of the soil mix, necessitating prompt compaction. Any delay in compaction may lead to the hardening of the stabilized soil mass, requiring additional compaction effort to achieve the desired results. This delay-induced hardening can lead to bond breakage and subsequent loss of strength in the stabilized soil.

On the other hand, delaying compaction for lime-stabilized soils can offer certain advantages. Lime-stabilized soils benefit from a mellowing period, allowing the lime to diffuse through the soil and maximize its effects on the soil's plasticity. After this mellowing period, the lime-stabilized soil can be remixed and then subjected to final compaction, resulting in remarkable strength compared to immediate compaction [17]. The timing of compaction is a critical factor in soil stabilization techniques, and it varies depending on the type of binder used. Careful consideration of binder properties and specific stabilization requirements is essential to achieve optimal results in terms of soil density and strength.

3.5. Moisture Content

In stabilized soils, maintaining an adequate moisture content is crucial for both the hydration process and efficient compaction. When using cement as a binder, it takes up about 20% of its weight in water from the surrounding environment [17]. In contrast, quicklime (CaO) absorbs approximately 32% of its own weight in water [17, 21]. Insufficient moisture content in the soil will lead to competition between the binders and the soil particles to gain the required moisture. This can be problematic, especially for soils with a high affinity for water, such as clay, peat, and organic soils. In such cases, the hydration process may be hindered due to the lack of sufficient moisture, ultimately affecting the final strength of the stabilized soil [22].

Properly controlling the moisture content during soil stabilization is essential to ensure the success of the process. It allows for optimal interaction between the binder and the soil particles, promoting effective hydration and compactibility, which results in stabilized soils with improved strength and durability.

3.6. Temperature

The pozzolanic reaction is affected by temperature changes, which occur continuously in the field throughout the day. Lower temperatures can slow down the pozzolanic reactions between binders and soil particles, leading to reduced strength in the stabilized mass. In cold regions, it is advisable to carry out soil stabilization projects during the warm season to optimize the effectiveness of the pozzolanic reactions and achieve higher strength in the stabilized soil [7].

3.7. Freeze-Thaw and Dry-Wet Effect

Stabilized soils are not resistant to freeze-thaw cycles, making it essential to protect them against frost damage in the field. The shrinkage forces in stabilized soil are influenced by the chemical reactions of the binder used. Cement-stabilized soils are particularly susceptible to frequent dry-wet cycles caused by diurnal temperature changes. These cycles can generate stresses within the stabilized soil and, as a result, it is important to safeguard the soil against such effects [17, 21]. Proper protection measures are necessary to ensure the long-term stability and performance of the stabilized soil in regions where freeze-thaw and dry-wet cycles are prevalent.

3.8. Quality Control

Proper quality control measures during the stabilization process are essential to ensure uniformity in the mixture and avoid variations in strength.

3.9. Site-Specific Conditions

The specific engineering requirements and usage of the stabilized soil at the site should be considered when determining the required strength. Different applications may demand different levels of strength.

3.10. Testing and Monitoring

Regular testing and monitoring of the stabilized soil's strength during and after the stabilization process are crucial. This helps ensure that the desired strength is achieved and that the stabilized soil meets the engineering requirements.

4. Methods of Soil Stabilization

There are several methods of soil stabilization, each designed to improve specific soil characteristics. Some common methods include:

4.1. Lime Stabilization

Lime stabilization is a soil stabilization technique that

involves the addition of lime (calcium hydroxide or quicklime) to the soil to improve its engineering properties. Lime stabilization is commonly used in construction and civil engineering projects to enhance the performance of soft, clayey, or silty soils.

The process of lime stabilization works through a chemical reaction between the lime and the soil particles. When lime is added to the soil, it reacts with the clay minerals and other components, causing the soil to undergo several beneficial changes. The increase in soil strength is directly related to the extent of the pozzolanic reaction between lime and the soil, as observed in studies by Dallas and Syam (2009) [23].

Wu Li (2010) conducted a study to stabilize Tanzania soil using lime as the stabilization material. In the study, the author employed three different soil types: moderately plastic silty clay (N-11), moderately plastic tan clay (N-12), and heavy clay (N-13). To stabilize each of these soil types, a 5% dosage of hydrated lime was utilized. The plasticity index decreased from 25% to 4% for N-11, 29% to 6% for N-12, and 36% to 9% for N-13. Unconfined compressive strength changed from 145 to 2770 kPa for N-11, 280 to 3000 kPa for N-12, and 163 to 2200 kPa for N-13. The resilient modulus exhibited significant changes during the testing phase. For N-11 soil, it increased from 79 MPa to 275 MPa, while for N-12 soil, it ranged from 53 MPa to 63 MPa. In the case of N-13 soil, the resilient modulus varied from 35.8 MPa to an impressive 209 MPa [24].

Olugbenga et al. (2010) studied the stabilization of lateritic soil using lime. Lateritic soil comprises various yellow, brown, and red fine-grained residual soils of light texture, characterized by the presence of iron and aluminum oxide or hydroxide that gives color to the soil. The study assessed the suitability and lime stabilization requirement of lateritic soil samples (A, B, C) collected from a dam site and stabilized with 0%, 2%, 4%, 6%, 8%, and 10% of lime. The optimum lime content for samples A, B, C was found to be 8%, 6%, and 6%, respectively. As lime content increased, the plasticity index decreased. The California Bearing Ratio (C.B.R) of sample A showed a noticeable improvement, rising from 10.6% at 0% lime to 29.0% with an 8% lime content. Similarly, sample C demonstrated enhancement, increasing from 2.5% to 8.6% with a 6% lime content. The compressive and shear strength also improved, with the uncured compressive strength of sample B improving from 119.13 KN/m² at 0% to 462.81 KN/m² at 6% lime. The author concluded that samples A and B would be suitable as base material, while sample C would be suitable as subgrade material [25].

Malhotra and John described the use of mechanical equipment in constructing four stretches of lime-stabilized roads, each extending over a length of twenty kilometers in Amraoti circle, Maharashtra. These roads were composed of B.C soil of the CH group, and the stabilization involved 2% lime. The stabilized sections behaved satisfactorily for four years, but afterward, the lime-treated stretches started to deteriorate [26].

Ankur et al. (2014) conducted a study to stabilize black cotton soil using lime and stone dust. The black cotton soil

sample was obtained from the Gwalior-Jhansi road in Madhya Pradesh, while the stone dust was collected from the Aman Vihar Industrial area in New Delhi. The specific gravity of the black cotton soil was 2.61, with a liquid limit of 57%, plastic limit of 31.4%, plasticity index of 26.5%, and unconfined compressive strength of 166.2 KN/m². The authors classified the soil as CH according to the unified soil classification system. They determined the optimum percentage of lime as 9% and mixed stone dust at different percentages (5%, 10%, 15%, 20%, and 25%) by weight of lime-black cotton soil. The MDD of lime-stabilized B.C. soil increased up to the addition of 20% stone dust, and further increase of the stone dust decreased the value. Likewise, the strength of the lime-stabilized soil exhibited an increase in both CBR (California Bearing Ratio) and UCS (Unconfined Compressive Strength) with the addition of up to 20% stone dust [27].

4.2. Fly Ash Stabilization

Fly ash stabilization refers to the process of using fly ash, a byproduct of coal combustion, to improve the engineering properties and stability of soils. This technique involves mixing fly ash with the soil to enhance its strength, reduce compressibility, increase durability, and mitigate environmental concerns related to the disposal of fly ash. Fly ash stabilization is commonly employed in road construction, building foundations, and other civil engineering projects to optimize soil characteristics and ensure long-term stability.

In a series of studies conducted by various researchers, the use of fly ash for soil stabilization has been investigated, yielding significant findings. Karthik et al. (2014) found that adding 6% fly ash to soft fine-grained red soil increased the bearing capacity from 10kg/mm² to 35kg/mm², and the CBR value from 3.1% to 4.82%, leading to a pavement thickness reduction from 12 inches to 8.5 inches [28]. Ahmed (2014) determined that a 15% fly ash ratio for stabilizing clayey soil in urban road construction resulted in optimal properties, with the CBR value increasing from 3% to 56% [29]. Gyanen et al. (2013) observed that up to 15% fly ash improved the dry density and reduced the liquid limit and plasticity index of stabilized black cotton soil [30]. Ashish et al. (2013) achieved the best results using 20% fly ash for black cotton soil stabilization [31]. Bhuvaneshwari et al. (2005) reported that increasing fly ash content decreased dry density and unconfined compressive strength [32]. Brooks (2009) found that a mixture of 25% fly ash and 12% rice husk ash effectively strengthened CH type expansive soil [33]. Anil Kumar and Sudhanshu (2014) observed improvements in various soil properties by stabilizing expansive soil with fly ash and rice husk ash [34]. Dilip Shrivastava et al. (2014) noted increased CBR value and unconfined compressive strength with higher rice husk ash content [35]. Yadu and Tripathi (2013) determined that a mix of 3% fly ash and 6% granulated blast furnace slag was the optimal combination for stabilizing soft soil [36]. Raut et al. (2014) found that adding fly ash and murrum increased UCS and M.D.D up to certain proportions. In their study conducted in 2014 [37], Singh and Pani employed lime and fly ash for highway stabilization,

resulting in enhanced dry unit weight and maximum dry density (M.D.D), as well as improved CBR values for both soaked and un-soaked conditions [38]. These studies collectively highlight the promising potential of fly ash as a stabilizing agent for various soil types, contributing to improved engineering properties for construction applications.

4.3. Cement Stabilization

Cement stabilization is a soil improvement technique that involves the addition of cement to the soil in order to enhance its engineering properties. The process typically entails mixing the soil and cement thoroughly to create a homogenous mixture. When water is added, the cement reacts and forms a bond with the soil particles, resulting in increased strength and reduced compressibility. According to Rawas et al. (2005), several reactions occur, including flocculation, ion exchange, carbonation, and pozzolanic reactions [39]. Cement stabilization is commonly used in construction projects, such as road bases, building foundations, and embankments. It helps to improve the load-bearing capacity of the soil, increase resistance to moisture infiltration, and reduce settlement. Additionally, cement stabilization can be effective in treating expansive soils, making them less susceptible to swelling and shrinking due to changes in moisture content. Cement stabilization is a widely adopted method to transform poor-quality soils into stable and durable materials suitable for various engineering applications.

In their research, Oyediran and Kalejaiye (2011) examined the influence of increasing cement content by weight on the strength and compaction characteristics of lateritic soil in the southwestern region of Nigeria [40]. They obtained three soil samples from different depths (0.5m, 1.0m, and 2.0m) and treated the soil with varying percentages of cement, namely 2%, 4%, 8%, 10%, and 20% by weight. The soil collected from the pits had the following average properties: Specific gravity of 2.60, Liquid Limit of 40.91%, plastic limit of 23.59%, plasticity Index of 17.31%, 8.33% gravel content, 52.33% sand content, 18.00% silt content, 21.33% clay content, and a fineness amounting to 39.33%. As the cement content increased, the Maximum Dry Density (M.D.D), California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS) of the soil also increased, while there was a reduction in the Optimum Moisture Content (O.M.C). However, when the cement content exceeded 10% by weight, M.D.D, UCS, and CBR decreased, and O.M.C increased. The authors concluded that simply increasing the percentage of cement did not guarantee an improvement in the geotechnical properties of the lateritic soil under consideration.

Zoubi (2008) conducted a study on the stabilization of expansive soil from Jordan using cement [41]. The natural soil had a liquid limit of 53% and a plasticity index of 26%, which classified it as inorganic clay of high plasticity (CH) according to the unified soil classification system. Different percentages of cement, ranging from 0% to 25%, were added to the soil. The research findings indicated that the liquid limit of the soil decreased up to a cement content of 6%, but then started

increasing as the cement content was further raised from 6% to 10%. Beyond this point, the liquid limit reached a constant value. Moreover, the study revealed that the swelling potential of the soil decreased with a cement content up to 4%, followed by an increase from 4% to 6%. After this, the swelling potential either decreased or remained constant, depending on the initial water content of the soil. Furthermore, the undrained shear strength of the soil exhibited an upward trend with an increase in cement content from 0% to 20%. The maximum rate of increase in undrained shear strength was observed within the range of 6% to 10% of cement content. These results highlight the effectiveness of cement stabilization in improving the geotechnical properties of the expansive soil from Jordan.

4.4. Stabilization by Expanded Polystyrene (EPS) Geofoam

Stabilization by Expanded Polystyrene (EPS) Geofoam is a technique used in geotechnical engineering to improve the performance and stability of soil and structures. EPS Geofoam is a lightweight, cellular plastic material that is made up of expanded polystyrene beads. It is commonly used as a fill material in various civil engineering applications.

Shelke and Murty (2010) conducted a study where they utilized EPS Geofoam to alleviate the swelling pressure of expansive soil [42]. The research involved black cotton soil sourced from Ahmednagar district in Maharashtra, classified as CH type according to the USCS soil classification system. The initial properties of the soil included a Liquid Limit of 61%, Plastic Limit of 31%, Plasticity Index of 30%, Optimum Moisture Content (OMC) of 20%, Maximum Dry Density (MDD) of 16.2 kN/m³, and Free Swell Index of 85.7%. During the investigation, two types of EPS Geofoam were employed, with thicknesses of 6mm and 12mm. The application of these Geofoams resulted in a significant reduction in the soil's swelling behavior. The swelling of the soil decreased from 8.64% to 82.72% when using the 6mm and 12mm EPS Geofoam, respectively. Additionally, the swelling pressure exhibited a remarkable decrease of 42.86% with the 6mm Geofoam and an impressive reduction of approximately 90% with the 12mm Geofoam. These findings highlight the efficacy of EPS Geofoam in mitigating swelling issues related to expansive soil, offering promising solutions for geotechnical challenges in soil stabilization.

4.5. Geo-Textile Stabilization

Geo-textile stabilization is a soil improvement technique that involves the use of geotextiles, which are permeable fabrics made from synthetic materials like polypropylene, polyester, or polyethylene. They come in various forms, including woven, non-woven, and grid varieties, each offering specific benefits. Geotextiles possess high strength and, when properly embedded in the soil, contribute to its stability. These materials find wide application in the construction of unpaved roads on soft soils, where they reinforce the soil for stabilization by incorporating metallic strips and providing anchor or tie-back support for facing skin elements [43].

Previous research has demonstrated that nonbiodegradable

reinforcing materials, such as fibers, geotextiles, geogrids, and geocomposites, can significantly enhance the strength and load-bearing capacity of subgrades and base course materials. Their inclusion in construction projects can improve overall performance and durability, potentially reducing construction costs for future highways. However, current research primarily involves laboratory tests, which are only partially comprehensive. To develop precise design specifications based on material properties, further laboratory testing and evaluations are required. Subsequently, large-scale field tests will be necessary to verify the effectiveness and applicability of these specifications in practical scenarios.

4.6. Chemical Stabilization

Soil chemical stabilization involves modifying the physicochemical properties of clay particles, both inside and around them. This results in reduced water absorption and improved stability. Calcium chloride is a well-known additive for soil stabilization due to its hygroscopic and deliquescent nature. It helps retain water in mechanically stabilized soil bases and surfaces. Its presence leads to lower vapor pressure, increased surface tension, and slower evaporation rate. Additionally, it lowers the freezing point of water, effectively preventing or reducing frost heave. Calcium chloride works by reducing the electric double layer, which decreases water uptake and prevents the loss of strength in fine-grained soils. It also serves as a soil flocculent, simplifying the compaction process. However, regular application may be required to counteract any chemical leaching. For best results, the relative humidity of the atmosphere should be above 30%. An alternative chemical for soil stabilization is sodium chloride, which has similar effects to calcium chloride. Furthermore, a combination of sodium silicate with other chemicals such as calcium chloride, polymers, chrome lignin, alkyl chlorosilanes, siliconites, amines, quaternary ammonium salts, sodium hexametaphosphate, and phosphoric acid with a wetting agent can also be used as a viable option for this purpose [44].

4.7. Bituminous Stabilization

Bituminous soil stabilization is a precise procedure that involves thoroughly blending a carefully measured quantity of bituminous material with the existing soil or aggregate material. This results in the formation of a stable and long-lasting foundation or surface. The key component, bitumen, plays a vital role in enhancing cohesion and load-bearing capacity while offering protection against water damage. Depending on factors like soil type, construction method, and prevailing weather conditions, different types of bitumen such as asphalt cement, asphalt cutback, or asphalt emulsions can be used. It is essential to avoid using tar as a binder in regions prone to frost due to its vulnerability to high temperatures. In pavement construction, asphalts and tars are the commonly used bituminous materials for soil stabilization. When introduced into the soil, these bituminous materials not only improve cohesion but also reduce water absorption, making the stabilized base more reliable and resistant.

4.8. Thermal Stabilization

Thermal stabilization is a soil improvement technique used to enhance the engineering properties of soils by subjecting them to controlled heating or cooling processes. This method is particularly useful for treating expansive or problematic soils that may undergo significant volume changes due to temperature variations. The primary objective of thermal stabilization is to reduce soil expansion and contraction, thereby increasing its stability and load-bearing capacity. In the case of heating, the process involves applying controlled heat to the soil to increase its temperature. This causes the soil particles to expand, which in turn fills the voids and increases overall soil density. The heating process can also remove excess moisture from the soil, making it less susceptible to volume changes upon temperature fluctuations. Once the soil cools down, it contracts and solidifies, resulting in improved strength and reduced susceptibility to swelling and shrinking. Conversely, cooling stabilization involves the controlled reduction of soil temperature. Cooling causes the soil particles to contract, thereby densifying the soil and reducing its volume. This method can be particularly useful in regions with high temperatures, where expansive soils are common.

Thermal stabilization can be employed in various engineering applications, including road construction, foundation design, and slope stabilization. It is essential to determine the appropriate temperature, duration, and depth of treatment based on the specific soil characteristics and engineering requirements to achieve the desired improvements effectively.

4.9. Electrical Stabilization

Electrical stabilization, also known as electrokinetic stabilization or electro-osmotic stabilization, is a soil improvement technique that utilizes electrical current to alter the properties and behavior of soils. This method is typically applied to fine-grained soils, such as clays, silts, and peat, which often exhibit poor engineering properties, such as low shear strength and high compressibility. The process of electrical stabilization involves the insertion of electrodes into the ground at specific intervals and creating an electric field within the soil mass. When an electric current is applied through the electrodes, several electrochemical processes occur, leading to changes in the soil's behavior. The primary mechanisms involved are electroosmosis and electromigration.

Electrical stabilization is used in various geotechnical applications, such as foundation improvement, embankment construction, and slope stability enhancement. However, it is crucial to take into account factors such as the soil type, electrical conductivity, and the efficacy of the method concerning the specific soil conditions. This consideration helps determine its appropriateness and success for a particular engineering undertaking.

4.10. Recycled and Waste Products

The growing need for improved chemical and mechanical

stabilization techniques has become evident in the context of waste materials such as foundry sand, plastic waste, glass cullet, paper mill sludge, sewage sludge, and rubber tire chips. These materials, while holding promise for recycling, also present potential hazardous attributes, underscoring the critical importance of developing practical and cost-effective methods to assess pollution risks stemming from their leachates and emissions during the recycling process. The urgency of this matter is amplified by the existence of stringent environmental regulations that may impede comprehensive risk evaluations. As we address these challenges, it is essential to foster innovative solutions that balance sustainability and environmental responsibility, enabling us to unlock the full potential of recycling while safeguarding our ecosystems and communities.

5. Conclusion

This paper highlights the proven effectiveness of various materials discussed in stabilizing soft soils and improving soil strength. However, to fully harness the potential of these stabilizers, further investigation and evaluation in real-world field applications are essential, moving beyond a focus solely on experimental studies. This will enable us to better understand their practical performance and suitability for diverse engineering projects. As technology continues to advance and economic conditions evolve, the horizon of soil stabilization techniques widens. The introduction of new chemical agents into subgrades holds the promise of enhancing compactibility, durability, and strength. However, comprehensive performance-based testing is necessary to validate the efficacy of these stabilization agents fully. Additionally, exploring the untapped potential of chemicals used in the petrochemical industry for soil stabilization opens avenues for groundbreaking research. Further research and development efforts should also explore innovative processes, such as injection and spray-on techniques, to achieve more cost-effective soil treatment. Considering potential changes due to global climate shifts is crucial in the development of future soil stabilization techniques. The durability and application of stabilizers may be affected by these climate changes, necessitating adaptive strategies. As the field of soil stabilization continues to evolve, it is imperative to maintain a collaborative and interdisciplinary approach, bringing together researchers, industry experts, and policymakers. By addressing the challenges and seizing the opportunities presented in this domain, we can usher in a new era of sustainable soil stabilization, contributing to resilient infrastructure, eco-friendly practices, and a more sustainable future for our planet.

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Biography



Naimul Haque Nayem completed his Bachelor of Science degree in Civil Engineering from Rajshahi University of Engineering & Technology, Rajshahi, Bangladesh. During his undergraduate studies, he focused his research on Soil Stabilization, exploring innovative methods to enhance soil strength and stability. His academic pursuits have fostered a deep interest in Soil Stabilization Technology, Sustainable Development, Environmental Management, and Soil Engineering.