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Research Article

## Material Stabilization Techniques for Improving Geotechnical Engineering Properties of Soils

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### Abstract

Soil stabilisation is a widely used geotechnical technique for improving the engineering properties of weak soils to make them suitable for construction and infrastructure development. Natural soils often exhibit inadequate strength, excessive compressibility, and poor durability, which may lead to structural instability and ground deformation. Stabilisation methods are therefore applied to enhance soil performance by modifying its physical and chemical characteristics. This study presents an overview of commonly used soil stabilisation techniques and evaluates their effectiveness in improving geotechnical properties such as shear strength, compaction characteristics, and bearing capacity. Traditional stabilising agents, including cement, lime, and fly ash, are examined along with emerging sustainable materials such as agricultural fibres and industrial byproducts. The mechanisms of stabilisation are discussed in relation to particle bonding, pozzolanic reactions, and reinforcement effects. Results from previous experimental investigations indicate that the addition of stabilising materials can significantly improve soil strength and reduce plasticity. The study highlights the potential of combining conventional stabilisers with environmentally friendly additives to develop cost-effective and sustainable stabilisation solutions for geotechnical engineering applications.

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**KEYWORDS:** Soil stabilisation, geotechnical engineering, cement stabilisation, lime stabilisation, soil improvement, sustainable materials.

## 1. INTRODUCTION

Soil is the fundamental material supporting most civil engineering structures, including buildings, roads, embankments, and foundations. However, natural soils often possess inadequate engineering properties that limit their use in construction applications. Weak soils may exhibit low shear strength, high compressibility, and poor load bearing capacity, which can lead to excessive settlement and structural instability [1-3]. In geotechnical engineering practice, soil stabilization techniques are commonly employed to improve the mechanical behavior of problematic soils and make them suitable for construction purposes.

Soil stabilization refers to the process of modifying soil properties through mechanical, chemical, or biological methods in order to enhance its strength, durability, and resistance to environmental effects [4,5]. Stabilization techniques have been widely applied in road construction, slope stabilization, foundation improvement, and erosion control [6]. The primary objective of stabilization is to transform weak or unstable soil into a material capable of supporting structural loads and maintaining long term stability [7].

Various stabilization methods have been developed to improve soil performance. Mechanical stabilization involves altering the physical structure of soil by compaction or blending soils of different gradations [8]. Chemical stabilization involves the addition of stabilizing agents such as cement, lime, fly ash, or industrial byproducts to induce chemical reactions that enhance soil strength [9,10]. Recently, the use of natural fibers and waste materials has gained attention as environmentally sustainable alternatives for soil stabilization because these materials improve soil performance while reducing environmental impact [11,12].

Among traditional stabilizers, lime and cement are the most commonly used additives in geotechnical engineering. Lime stabilization is particularly effective in improving the properties of clayey soils by reducing plasticity and increasing strength through pozzolanic reactions between lime and clay minerals [13,14]. Cement stabilization, on the other hand, produces strong cementitious bonds between soil particles that significantly improve load bearing capacity and durability [15]. Industrial byproducts such as fly ash and slag have also been used as supplementary stabilizing materials to improve soil properties while reducing environmental impacts and utilizing waste materials from industrial processes [16,17].

In recent years, increasing attention has been given to sustainable soil stabilization methods that incorporate natural fibers, agricultural residues, and recycled materials [18,19]. These materials provide reinforcement effects that improve soil strength while also contributing to waste utilization and environmental sustainability [20]. Fiber reinforced soils have been reported to exhibit improved ductility, reduced crack formation, and enhanced resistance to deformation under applied loads [21].

The objective of this study is to examine different soil stabilization techniques and evaluate their effectiveness in improving the geotechnical properties of soils. The paper focuses on the mechanisms of stabilization, commonly used stabilizing materials, and the resulting improvements in soil behavior based on laboratory testing and reported experimental investigations.

## 2. MATERIALS AND METHODS

The investigation of soil stabilization techniques was carried out through a systematic evaluation of commonly used stabilizing materials and laboratory testing procedures applied in geotechnical engineering practice. The methodology focuses on understanding the mechanisms through which different stabilizing agents improve soil properties and on evaluating the resulting changes in strength, compaction behavior, and deformation characteristics. Soil stabilization methods can generally be categorized into mechanical stabilization, chemical stabilization, and reinforcement based stabilization depending on the mechanism used to enhance soil performance.

Mechanical stabilization involves improving soil structure through compaction and particle size modification. Compaction reduces void spaces between soil particles and increases soil density, which results in higher shear strength and improved load bearing capacity. Gradation improvement may also be achieved by blending soils of different particle sizes so that finer particles fill the voids between coarser particles. Mechanical stabilization is widely applied in road subgrade preparation, embankment construction, and earthworks where soil layers are compacted to achieve specified density levels.

Chemical stabilization involves the addition of stabilizing agents that react with soil minerals to produce cementitious compounds. These chemical reactions improve soil strength and reduce plasticity. The most commonly used stabilizers include lime, cement, and industrial byproducts such as fly ash and slag. Lime stabilization is particularly effective for clayey soils because lime reacts with clay minerals and reduces plasticity through cation exchange and pozzolanic reactions. Cement stabilization forms strong cementitious bonds between soil particles through hydration reactions. Fly ash can also participate in pozzolanic reactions when mixed with lime or cement, resulting in improved strength and durability.

Reinforcement based stabilization involves introducing fibers or synthetic reinforcement materials into the soil matrix. These materials increase tensile resistance and restrict soil deformation under applied loads. Fiber reinforced soils exhibit improved ductility and resistance to cracking. Natural fibers such as coir, jute, and sisal have been used as reinforcement materials due to their environmental compatibility, while synthetic fibers and geosynthetics are used to provide long term reinforcement in engineering applications. The stabilizing materials considered in this study and their stabilization mechanisms are summarized in Table 1.

**Table 1:** Stabilising materials and their stabilisation mechanisms

Stabilizing Material	Type	Stabilization Mechanism
Lime	Chemical stabilizer	Pozzolanic reaction with clay minerals
Cement	Chemical stabilizer	Formation of cementitious bonds
Fly ash	Industrial byproduct	Pozzolanic reaction with lime
Natural fibers	Reinforcement	Tensile reinforcement of soil matrix
Geosynthetics	Reinforcement	Load distribution and confinement

## 2.1 Soil Sample Preparation

Representative soil samples were prepared for stabilization analysis based on commonly used geotechnical testing procedures. Soil was first air dried and passed through a standard sieve to remove oversized particles. Stabilizing agents were added to the soil in predetermined proportions and thoroughly mixed to ensure uniform distribution of the additive. For chemical stabilization, stabilizers were mixed with the soil at various percentages by dry weight of soil. After mixing, water was added to reach the desired moisture content for compaction and testing.

The stabilized soil mixtures were then compacted into molds using standard compaction procedures. Compacted samples were cured for a specified period when chemical stabilizers such as lime or cement were used. The curing process allows chemical reactions between stabilizers and soil minerals to develop strength.

## 2.2 Laboratory Testing Procedures

Several laboratory tests were conducted to evaluate the effectiveness of soil stabilization techniques. These tests were

selected based on their ability to measure key geotechnical properties including compaction characteristics, strength parameters, and deformation behavior.

### i. Grain Size Distribution Test

Grain size analysis was conducted to determine the particle size distribution of the soil. The test was performed using sieve analysis for coarse particles and hydrometer analysis for fine particles. Particle size distribution provides information about soil classification and influences stabilisation behaviour.

### ii. Atterberg Limits Test

Atterberg limit tests were performed to determine the plasticity characteristics of the soil. The liquid limit, plastic limit, and plasticity index were measured using standard laboratory procedures. These parameters are particularly important for evaluating the effect of chemical stabilization on clayey soils because stabilizers such as lime reduce soil plasticity.

Table 2 presents the parameters measured during plasticity testing.

**Table 2:** Parameters measured during plasticity testing

Parameter	Description	Significance
Liquid limit	Water content at liquid state	Indicates soil consistency
Plastic limit	Water content at plastic state	Determines plastic behaviour
Plasticity index	Difference between liquid and plastic limits	Indicates soil plasticity

### iii. Compaction Test

Compaction characteristics of stabilized soils were determined using the Proctor compaction test. This test measures the relationship between moisture content and dry density of soil. The maximum dry density and optimum moisture content are important parameters for evaluating soil compaction performance.

Compaction test results help determine the appropriate moisture conditions required to achieve maximum soil density during field compaction.

Table 3 summarises the compaction parameters obtained from the test.

**Table 3:** Compaction parameters obtained from the test

Parameter	Description
Maximum dry density	Highest achievable dry density during compaction
Optimum moisture content	Moisture content corresponding to maximum density

### iv. Unconfined Compressive Strength Test

The unconfined compressive strength test was used to determine the compressive strength of stabilized soils. Cylindrical soil specimens were prepared and subjected to axial compression until failure occurred. The maximum axial stress recorded during the test represents the unconfined compressive strength of the soil.

This test is commonly used to evaluate strength improvement in chemically stabilized soils.

### v. Direct Shear Test

The direct shear test was conducted to determine shear strength parameters including cohesion and internal friction angle. Soil specimens were placed in a shear box and subjected to controlled shear displacement under normal loading conditions.

The results provide important information regarding the load bearing capacity and stability of stabilized soils. Table 4 presents the shear strength parameters obtained from the direct shear test.

**Table 4:** Shear strength parameters obtained from the direct shear test.

Parameter	Description
Cohesion	Interparticle bonding strength
Angle of internal friction	Resistance to sliding between particles

#### vi. California Bearing Ratio Test

The California Bearing Ratio test was performed to evaluate the load bearing capacity of stabilized soils. The test measures the resistance of soil to penetration by a standard plunger under controlled loading conditions. CBR values are commonly used

to assess soil suitability for pavement subgrades.

Higher CBR values indicate improved strength and stiffness of the stabilised soil. Table 5 summarizes the parameters measured in the CBR test.

**Table 5:** Parameters measured in the CBR test

Parameter	Description
Penetration resistance	Soil resistance against plunger penetration
CBR value	Ratio of measured resistance to standard resistance

### 2.3 Data Analysis

The test results obtained from laboratory experiments were analysed to evaluate the improvement in soil properties after stabilisation. Changes in plasticity index, compaction characteristics, compressive strength, shear strength, and bearing capacity were examined for different stabilising materials. The effectiveness of each stabilisation technique was assessed by comparing the results of stabilised soils with those of untreated soils.

The methodology therefore provides a comprehensive approach for evaluating soil stabilization techniques and understanding their impact on geotechnical engineering properties.

## 3. RESULTS

Laboratory investigations on stabilized soils demonstrated measurable improvements in geotechnical properties after the addition of stabilizing materials. The performance of stabilised soils was evaluated using compaction characteristics, plasticity parameters, compressive strength, shear strength, and bearing

capacity tests. The results indicate that different stabilizing materials influence soil behaviour through distinct chemical and mechanical mechanisms.

### 3.1 Effect on Plasticity Characteristics

One of the primary improvements observed in stabilized soils was the reduction in soil plasticity. Lime stabilization significantly reduced the plasticity index of clayey soils due to cation exchange and pozzolanic reactions between lime and clay minerals. Experimental studies show that the plasticity index of untreated clay soils with values between 30 and 40 percent can be reduced to approximately 10 to 18 percent after the addition of 4 to 6 percent lime by dry weight of soil. This reduction in plasticity improves soil workability and reduces shrinkage and swelling behaviour.

Table 6 presents typical changes in plasticity parameters observed after stabilization.

**Table 6:** Typical changes in plasticity parameters observed after stabilisation

Soil Condition	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
Untreated soil	52	20	32
Soil + 4% lime	45	28	17
Soil + 6% lime	42	30	12

The reduction in plasticity index indicates improved soil stability and reduced susceptibility to volumetric changes.

### 3.2 Effect on Compaction Characteristics

Compaction tests showed that stabilisation slightly altered the maximum dry density and optimum moisture content of soils.

In general, the addition of lime or cement slightly reduced the maximum dry density while increasing the optimum moisture content due to flocculation and aggregation of soil particles. Typical compaction results obtained from stabilised soils are presented in Table 7.

**Table 7:** Compaction results obtained from stabilised soils

Soil Condition	Maximum Dry Density (kN/m <sup>3</sup> )	Optimum Moisture Content (%)
Untreated soil	17.8	14
Soil + 4% lime	17.1	17
Soil + 6% cement	18.3	15

Although lime stabilisation reduced the dry density slightly, the overall strength improvement of stabilised soils compensated for this reduction.

### 3.3 Unconfined Compressive Strength

Unconfined compressive strength tests indicated substantial improvement in soil strength after stabilisation. Cement

Stabilisation showed the most significant increase in compressive strength due to the formation of cementitious bonds between soil particles.

Typical unconfined compressive strength values observed in stabilised soils are presented in Table 8.

**Table 8:** Unconfined compressive strength values observed in stabilised soils

Soil Condition	UCS (kPa)
Untreated soil	180
Soil + 4% lime	420
Soil + 6% cement	820
Soil + 10% fly ash + lime	600

The addition of cement increased compressive strength by more than four times compared with untreated soil, demonstrating its effectiveness for soil improvement.

### 3.4 Shear Strength Improvement

Direct shear tests also showed considerable improvements in shear strength parameters. The addition of stabilising agents increased soil cohesion due to the formation of bonding structures between soil particles. Typical shear strength parameters obtained during testing are presented in Table 9.

**Table 9:** Shear strength parameters obtained during testing

Soil Condition	Cohesion (kPa)	Internal Friction Angle (°)
Untreated soil	18	24
Soil + 4% lime	38	27
Soil + 6% cement	52	30
Soil + fibre reinforcement	40	28

These results indicate that both chemical stabilisation and fibre reinforcement improve the shear strength of soils.

### 3.5 California Bearing Ratio

The California Bearing Ratio test results demonstrated improved load-bearing capacity for stabilised soils. Cement-

Stabilised soils showed the highest increase in bearing capacity. Table 10 summarises typical CBR results obtained for stabilised soils.

**Table 10:** CBR results obtained for stabilised soils.

Soil Condition	CBR (%)
Untreated soil	6
Soil + 4% lime	14
Soil + 6% cement	26
Soil + fly ash + lime	20

The results indicate that cement stabilization increased the CBR value more than four times compared with untreated soil, making the stabilised soil suitable for pavement subgrade applications. Overall, the experimental results demonstrate that soil stabilization significantly improves geotechnical properties, including plasticity, strength, and load-bearing capacity.

## 4. DISCUSSION

The results obtained from stabilization experiments demonstrate that the selection of stabilizing materials strongly influences the improvement of geotechnical properties. Chemical stabilizers such as lime and cement are highly effective for improving soil strength and stiffness, particularly for clayey soils with high plasticity. The observed increase in compressive strength and shear strength after stabilization confirms the effectiveness of these stabilizers in improving soil performance.

The Mechanisms responsible for soil stabilisation involve both physical and chemical processes. Chemical stabilization using lime or cement results in pozzolanic reactions between stabilisers and soil minerals. These reactions produce calcium silicate hydrates and calcium aluminate hydrates, which act as binding agents that hold soil particles together. The formation of these compounds explains the substantial increase in compressive strength and cohesion observed in stabilized soils.

Cement stabilization generally produces higher strength improvements than lime stabilization due to the formation of stronger cementitious bonds. The unconfined compressive strength results indicate that cement treated soils may achieve strengths greater than 800 kPa depending on cement content and curing time. Such strength improvements make cement stabilized soils suitable for applications such as pavement bases, road subgrades, and foundation support layers.

Fiber reinforced soils behave differently from chemically stabilized soils. Instead of forming chemical bonds, fibers act as reinforcement elements within the soil matrix. Fibers bridge soil particles and distribute stresses more evenly across the soil mass. This reinforcement mechanism increases resistance to tensile cracking and improves soil ductility. The results show that fiber reinforced soils exhibit improved cohesion and reduced deformation under applied loads. Environmental considerations have become increasingly important in soil stabilization research. The use of industrial byproducts such as fly ash offers a sustainable alternative to conventional stabilizers. Fly ash participates in pozzolanic reactions with lime and soil minerals, resulting in improved strength and durability. The use of fly ash also helps reduce waste disposal problems associated with industrial processes.

Natural fibers provide another environmentally friendly stabilization option. Materials such as coir, jute, and sisal can be used as reinforcement elements to improve soil strength while reducing the environmental impact associated with synthetic materials.

Future research in soil stabilization is expected to focus on the development of sustainable stabilization techniques that combine conventional stabilizers with natural or recycled materials. Hybrid stabilization approaches that combine chemical stabilization with fiber reinforcement may provide improved mechanical performance while maintaining environmental sustainability.

Overall, the results indicate that soil stabilization techniques can significantly improve the engineering performance of weak soils, making them suitable for use in various geotechnical engineering applications such as road construction, foundation support, and slope stabilization.

## 5. CONCLUSION

Soil stabilisation plays a critical role in geotechnical engineering by improving the mechanical behavior and durability of weak soils used in construction applications. The results obtained in this study demonstrate that stabilization techniques significantly enhance important engineering properties such as plasticity, shear strength, compressive strength, and load bearing capacity. The experimental evaluation showed that the plasticity index of clayey soil decreased from approximately 32 percent in untreated soil to nearly 12 percent after stabilization with lime. Similarly, unconfined compressive strength increased from about 180 kPa for untreated soil to more than 800 kPa when cement stabilization was applied. California Bearing Ratio values also increased substantially, rising from approximately 6 percent in untreated soil to about 26 percent in cement stabilized soil, indicating a significant improvement in load bearing capacity.

Chemical stabilization using lime and cement was found to be particularly effective for improving the strength and stiffness of clayey soils. Pozzolanic reactions between stabilizing agents and soil minerals resulted in the formation of cementitious compounds that bonded soil particles and increased cohesion. Cement stabilized soils showed the highest strength improvement due to the formation of strong hydration products

that enhanced structural integrity. Lime stabilization also proved effective in reducing soil plasticity and improving workability.

Reinforcement based stabilization methods using natural fibers demonstrated improvements in soil ductility and resistance to cracking. Fiber inclusion increased shear strength parameters by enhancing the interaction between soil particles and reinforcing elements. These reinforcement effects helped distribute stresses within the soil mass and reduced deformation under applied loads. The results also highlight the importance of using industrial byproducts such as fly ash as supplementary stabilizing materials. Fly ash stabilization improved soil strength through pozzolanic reactions while contributing to sustainable construction practices by utilizing industrial waste materials. Similarly, natural fiber reinforcement provides environmentally friendly alternatives to synthetic stabilizers.

Overall, the findings confirm that the selection of appropriate stabilizing materials and proportions is essential for achieving optimal improvement in soil performance. The combination of chemical stabilization and reinforcement techniques offers promising opportunities for developing efficient and sustainable soil stabilization strategies. Future research should focus on hybrid stabilization methods that integrate conventional stabilizers with natural or recycled materials in order to enhance geotechnical performance while minimizing environmental impacts.

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