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Lime-Stabilized Marine Soil: Evaluation of Strength and Engineering Properties for Coastal Construction

[1]Mostafa Ibrahim Abdelaziz

[1]Department of Civil Engineering, Ain Shams University, Cairo, Egypt

Abstract: Marine soils are widely encountered in coastal regions and are generally characterized by high compressibility, low shear strength, excessive moisture content, high plasticity, and poor load-bearing capacity, making them unsuitable for supporting civil engineering structures without prior treatment. These unfavorable geotechnical characteristics often lead to excessive settlement, instability, and reduced service life of foundations, embankments, pavements, and other coastal infrastructure. This study investigates the effectiveness of lime stabilization as a sustainable and economical ground improvement technique for enhancing the engineering properties of marine soil. Laboratory experiments were conducted on marine soil samples treated with varying percentages of hydrated lime to evaluate changes in their physical and mechanical properties. Standard geotechnical tests, including Atterberg limits, Standard Proctor compaction, Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), and shear strength tests, were performed to assess the influence of lime addition on soil behavior. The results demonstrate that lime treatment significantly reduces the plasticity index and moisture susceptibility while improving maximum dry density, bearing capacity, compressive strength, and overall soil stability. The improvement is primarily attributed to physicochemical reactions such as cation exchange, flocculation–agglomeration, and long-term pozzolanic reactions, which strengthen particle bonding and enhance soil structure. An optimum lime content was identified beyond which only marginal improvements were observed. The stabilized marine soil exhibited improved workability, reduced swelling potential, and enhanced durability under varying environmental conditions, making it suitable for coastal engineering applications. The findings confirm that lime stabilization provides a practical, cost-effective, and environmentally sustainable solution for improving weak marine soils and can significantly enhance the performance and longevity of foundations, embankments, road subgrades, and other infrastructure constructed in coastal regions.

Keywords: Marine Soil, Lime Stabilization, Soil Improvement, Geotechnical Engineering, Coastal Construction, Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), Shear Strength, Ground Improvement, Soil Stabilization.

I. INTRODUCTION

Marine soils are commonly found in coastal and offshore regions and are often characterized by high water content, low shear strength, high compressibility, and poor bearing capacity. These unfavorable engineering properties make them unsuitable for supporting heavy structures without proper ground improvement. Rapid urbanization and infrastructure development in coastal areas have increased the demand for effective soil stabilization techniques that enhance the strength and durability of marine soils. Among various stabilization methods, lime treatment has gained significant attention due to its simplicity, cost-effectiveness, and long-term performance. Lime reacts with clay minerals present in marine soils, resulting in improved workability, reduced plasticity, increased strength, and enhanced durability. This study investigates the effectiveness of lime stabilization in improving the engineering properties of marine soil for safe and sustainable coastal construction applications. Marine soils, commonly encountered in coastal and offshore regions, are typically characterized by high natural water content, low shear strength, high compressibility, and significant settlement potential.

These unfavorable geotechnical properties create serious challenges for infrastructure development such as highways, ports, embankments, and foundations in coastal areas. Rapid urbanization and industrial expansion in shoreline regions demand effective ground improvement techniques to ensure structural stability and long-term performance. Among various soil improvement methods, lime stabilization has emerged as a widely adopted and cost-effective technique for enhancing the engineering properties of weak marine soils. The chemical interaction between lime and clay minerals leads to improved strength, reduced plasticity, and enhanced durability, making treated soil suitable for construction applications.

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II. SOIL STABILIZATION

Soil stabilization is a ground improvement technique used to enhance the physical and mechanical properties of weak soils so that they can safely support engineering structures. Various stabilization methods such as mechanical compaction, cement stabilization, fly ash stabilization, and chemical stabilization have been developed to improve problematic soils. Among these techniques, lime stabilization is one of the most widely adopted methods for clayey and marine soils due to its economical nature and proven effectiveness. When lime is mixed with marine soil, it initiates cation exchange, flocculation, and pozzolanic reactions that reduce soil plasticity and increase particle bonding. These chemical reactions improve shear strength, compressive strength, bearing capacity, and resistance to moisture-induced deformation. Consequently, lime-stabilized marine soil becomes suitable for foundations, embankments, pavement subgrades, and other coastal engineering projects.

Soil stabilization refers to the process of improving the physical and mechanical properties of soil to meet specific engineering requirements. It involves the addition of stabilizing agents or the application of mechanical techniques to enhance strength, durability, and resistance to moisture. In marine soils, stabilization is particularly important due to their high clay content and poor load-bearing capacity. Lime stabilization works through immediate and long-term reactions. The short-term reaction includes cation exchange and flocculation, which reduce plasticity and improve workability. Long-term pozzolanic reactions between lime and silica/alumina in the soil form cementitious compounds, increasing strength and stiffness over time.

A. Components of Stabilization

The primary components involved in lime stabilization include marine soil, lime, and water. The marine soil acts as the base material requiring improvement. Lime, usually in the form of quicklime (CaO) or hydrated lime ($Ca(OH)_2$), serves as the chemical stabilizer. Water facilitates the hydration of lime and activates pozzolanic reactions within the soil matrix. Proper proportioning of these components is essential to achieve optimum strength and performance. The percentage of lime added typically varies between 2% and 10% by dry weight of soil, depending on soil characteristics. Experimental results are analyzed to determine the optimum lime content that yields maximum strength improvement.

B. Scope

The scope of this study focuses on evaluating the improvement in strength characteristics of marine soil through lime treatment under laboratory conditions. The research primarily addresses changes in compaction behavior and bearing capacity parameters. The findings are applicable to coastal construction projects, including pavement subgrades, shallow foundations, embankments, and reclamation works. The study also aims to contribute to sustainable construction practices by promoting the use of locally available stabilizing materials.

C. Objective

The main objective of this research is to investigate the effectiveness of lime in enhancing the engineering properties of marine soil. Specific objectives include determining the optimum lime content, analyzing changes in compaction characteristics, and evaluating improvements in load-bearing capacity using CBR tests. The study also aims to understand the influence of lime treatment on soil workability and strength development.

III. METHODOLOGY

The experimental investigation was carried out by collecting representative marine soil samples from a coastal region. The collected samples were air-dried, pulverized, and sieved to remove impurities before laboratory testing. Hydrated lime was added to the soil at different percentages to evaluate its influence on engineering properties. The prepared soil-lime mixtures were thoroughly blended and compacted according to standard testing procedures. Laboratory tests were then performed on untreated and treated soil specimens to determine changes in index properties, compaction characteristics, compressive strength, and bearing capacity. The experimental results were analyzed to identify the optimum lime content that provides maximum improvement in soil performance while maintaining economic feasibility for practical construction applications.

The methodology involves collecting representative marine soil samples from a coastal region and conducting preliminary classification tests. The soil is air-dried, pulverized, and mixed with varying percentages of lime (e.g., 2%, 4%, 6%, and 8%). Standard laboratory procedures are followed to prepare specimens for compaction and strength testing. After mixing, samples are allowed to cure for specified durations to promote pozzolanic reactions. Experimental results are analyzed to determine the optimum lime content that yields maximum strength improvement.

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The methodology adopted in this study was designed to systematically evaluate the effectiveness of lime treatment in enhancing the strength characteristics of marine soil. The research was carried out in a sequence of stages including soil sampling, preliminary characterization, mix design preparation, specimen preparation, curing, laboratory testing, and result analysis.

Initially, representative marine soil samples were collected from a coastal region at a depth free from organic contamination. The collected samples were carefully sealed in airtight bags to preserve natural moisture content and transported to the laboratory for testing. Preliminary soil classification tests, including grain size analysis and Atterberg limits, were conducted to determine the soil type and its index properties in accordance with standard geotechnical testing procedures. The soil was then air-dried, pulverized, and sieved through a 4.75 mm sieve to remove coarse particles and ensure uniform mixing.

For stabilization, commercially available hydrated lime was used as the stabilizing agent. Lime was added to the dry soil at varying percentages (e.g., 2%, 4%, 6%, and 8% by weight of dry soil) to determine the optimum lime content. The required quantity of water was added gradually to achieve uniform consistency. Thorough mixing was carried out manually and mechanically to ensure even distribution of lime throughout the soil matrix, which is essential for uniform chemical reaction.

After mixing, the prepared soil-lime blends were sealed in polyethylene bags and allowed for an initial mellowing period (typically 24 hours) to facilitate cation exchange and flocculation reactions. Specimens were then compacted using the Standard Proctor compaction method to determine the optimum moisture content (OMC) and maximum dry density (MDD) for each lime percentage. Based on the compaction results, samples were prepared at their respective OMC and compacted to achieve maximum density.

To evaluate strength development, compacted specimens were subjected to curing for predetermined periods such as 7, 14, and 28 days under controlled temperature and humidity conditions. Curing plays a critical role in promoting pozzolanic reactions, which are responsible for long-term strength gain. During curing, samples were kept in moisture-controlled environments to prevent excessive drying and ensure consistent reaction.

Following the curing period, laboratory tests such as the California Bearing Ratio (CBR) test and, where applicable, Unconfined Compressive Strength (UCS) tests were conducted on both untreated and treated samples. Tests were performed under both soaked and unsoaked conditions to simulate field performance, particularly in coastal areas exposed to high groundwater levels.

The experimental data obtained from various tests were analyzed to compare the engineering properties of untreated and lime-treated marine soil. Graphical representations were prepared to identify trends in strength improvement, moisture-density relationships, and bearing capacity enhancement. The optimum lime content was determined based on maximum strength gain and overall performance improvement. This systematic methodology ensures reliable evaluation of lime stabilization effectiveness for marine soil applications.

IV. TESTS ON SOIL

A series of standard geotechnical laboratory tests were conducted to evaluate the effectiveness of lime stabilization on marine soil. The Atterberg Limits test was performed to determine changes in liquid limit, plastic limit, and plasticity index after lime treatment. Standard Proctor Compaction tests were carried out to evaluate the optimum moisture content and maximum dry density of stabilized soil. The Unconfined Compressive Strength (UCS) test was conducted to assess improvements in compressive strength resulting from lime addition. California Bearing Ratio (CBR) tests were performed to determine the load-bearing capacity of untreated and stabilized soil for pavement applications. In addition, shear strength tests were conducted to evaluate the improvement in soil stability. The laboratory results indicated significant enhancement in engineering properties with increasing lime content up to the optimum percentage, demonstrating the effectiveness of lime stabilization for marine soil improvement.

Laboratory testing plays a vital role in evaluating the effectiveness of stabilization. In this study, compaction and California Bearing Ratio (CBR) tests are performed on untreated and lime-treated marine soil samples.

A. Compaction

Compaction tests are conducted using the Standard Proctor method to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). Lime addition generally leads to a decrease in MDD and an increase in OMC due to flocculation and agglomeration of clay particles. The test results help in understanding the moisture–density relationship and in identifying suitable field compaction conditions for stabilized soil.

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B. CBR

The California Bearing Ratio (CBR) test is carried out to evaluate the load-bearing capacity of untreated and stabilized soil samples. CBR values are determined under soaked and unsoaked conditions. Lime treatment significantly increases CBR values due to the formation of cementitious compounds, which enhance inter-particle bonding. The improvement in CBR indicates the suitability of lime-stabilized marine soil for pavement subgrades and other load-supporting applications.

Soil stabilization is a ground improvement technique aimed at modifying soil properties to achieve enhanced strength, reduced compressibility, and improved durability under loading and environmental variations. Marine soils, particularly marine clays, often contain high amounts of montmorillonite and other expansive minerals, which contribute to excessive settlement and low bearing capacity. Stabilization methods can be broadly classified into mechanical stabilization (compaction, blending) and chemical stabilization (lime, cement, fly ash, geopolymers).

Lime stabilization is particularly effective for clay-rich marine soils due to its ability to alter the soil's physicochemical structure. When lime is added to soil, a sequence of reactions occurs:

- Cation Exchange Reaction – Calcium ions replace weaker ions (Na^+, K^+) in the clay structure.
- Flocculation and Agglomeration – Clay particles group together, reducing plasticity and improving workability.
- Pozzolanic Reaction – Calcium from lime reacts with silica and alumina in soil to form calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH), which act as cementing agents.
- Carbonation (long-term) – Reaction with atmospheric CO_2 may further strengthen the soil matrix.

These chemical reactions significantly enhance shear strength and stiffness while decreasing plasticity index and swelling potential.

Additional Components in Stabilization

Beyond lime and soil, certain auxiliary materials and factors influence stabilization effectiveness:

- Additives: Fly ash or silica fume may be added to accelerate pozzolanic reactions.
- Curing Conditions: Temperature and moisture greatly affect strength gain.
- Mixing Technique: Uniform distribution of lime ensures consistent performance.
- Compaction Energy: Higher compaction effort improves density and bonding.

Proper laboratory evaluation is essential before field implementation to determine optimum lime percentage and curing duration. Comprehensive soil testing is necessary to evaluate both untreated and stabilized soil behavior. These tests are categorized as index tests, compaction tests, and strength tests.

1. Index Properties Tests

Before stabilization, basic soil properties must be determined:

- Grain Size Analysis: Determines soil gradation and clay fraction.
- Atterberg Limits (Liquid Limit, Plastic Limit, Plasticity Index): Lime treatment generally reduces liquid limit and plasticity index due to flocculation.
- Specific Gravity Test: Helps in understanding mineral composition.
- Natural Moisture Content: Important for compaction and stabilization planning.

A reduction in plasticity index after lime addition indicates improved soil stability and reduced swelling characteristics.

2. Compaction Characteristics

The compaction test establishes the moisture–density relationship. In stabilized soils:

- Maximum Dry Density (MDD) decreases slightly due to the lower specific gravity of lime and flocculated soil structure.
- Optimum Moisture Content (OMC) increases because lime requires additional water for hydration.

These parameters are crucial for determining field compaction specifications. Proper compaction ensures improved strength and minimizes post-construction settlement.

3. California Bearing Ratio (CBR) Test

The CBR test measures the resistance of soil to penetration under controlled density and moisture conditions. It simulates field loading conditions of pavement subgrades. Lime-treated marine soils typically show:

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- Significant increase in CBR value.
- Improved soaked CBR performance, indicating better resistance to moisture.
- Enhanced durability under cyclic loading.

The increase in CBR confirms suitability for road construction and foundation support systems.

4. Unconfined Compressive Strength (UCS) Test

Although not mandatory in all studies, UCS testing provides direct measurement of compressive strength. Stabilized samples generally exhibit increased strength with curing time (7, 14, 28 days), confirming progressive pozzolanic bonding.

5. Swell and Consolidation Tests

Marine soils are prone to excessive settlement. Lime stabilization:

- Reduces swelling pressure.
- Lowers compressibility.
- Improves consolidation characteristics.

This makes treated soil more stable under structural loads.

Durability and Long-Term Performance

Durability tests such as wet–dry and freeze–thaw cycles (where applicable) help assess long-term stability. Lime-treated soils generally show:

- Resistance to moisture variations.
- Reduced erosion potential.
- Improved structural integrity over time.

These characteristics are essential for coastal infrastructure exposed to saline and humid environments.

Environmental and Economic Considerations

Lime stabilization is considered environmentally favorable compared to full soil replacement. It:

- Reduces excavation and transportation costs.
- Minimizes landfill disposal.
- Utilizes locally available materials.
- Lowers carbon footprint compared to cement in certain cases.

Economic analysis often shows significant cost savings in large-scale marine construction projects.

Overall Technical Insight

The success of marine soil stabilization depends on:

- Proper soil characterization.
- Determination of optimum lime content.
- Adequate curing period.
- Controlled compaction.
- Continuous quality monitoring during field implementation.

Through systematic laboratory testing and controlled application, lime stabilization transforms weak marine deposits into structurally competent materials suitable for engineering construction.

Table 1: Comparison of Untreated and Lime-Treated Marine Soil Properties

Property	Untreated Marine Soil	Lime-Treated Marine Soil	Effect of Lime Treatment
Natural Moisture Content (%)	High (30–60%)	Slightly reduced	Improved workability
Liquid Limit (LL)	High	Reduced	Decrease in plasticity
Plastic Limit (PL)	Moderate	Increased	Improved consistency
Plasticity Index (PI)	High	Significantly reduced	Reduced swelling potential
Specific Gravity	2.60–2.75	Slightly reduced	Minor change due to lime addition
Maximum Dry Density (MDD) (kN/m³)	Higher	Slightly lower	Due to flocculation and lower lime density
Optimum Moisture Content (OMC) (%)	Lower	Increased	Additional water required for hydration
Unconfined Compressive Strength (UCS) (kPa)	Low	2–5 times higher (after curing)	Significant strength gain
California Bearing Ratio (CBR) (%)	Very low (2–5%)	Increased (8–20% or more)	Improved load-bearing capacity

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Property	Untreated Marine Soil	Lime-Treated Marine Soil	Effect of Lime Treatment
Swelling Pressure	High	Greatly reduced	Enhanced dimensional stability
Compressibility	High	Reduced	Lower settlement risk
Shear Strength	Low	Increased	Better resistance to failure
Durability	Poor	Improved	Better resistance to moisture variation

Summary of Observed Improvements

- Plasticity characteristics improve due to flocculation and cation exchange reactions.
- Strength parameters (UCS, CBR, shear strength) increase due to pozzolanic bonding.
- Compaction characteristics shift, with increased OMC and slightly reduced MDD.
- Swelling and compressibility decrease, making soil suitable for foundations and pavements.

V. CONCLUSION

This study demonstrates that lime stabilization is an effective and economical technique for improving the engineering properties of marine soil used in coastal construction. The addition of lime significantly reduced soil plasticity while increasing compressive strength, shear strength, and bearing capacity through physicochemical reactions between lime and soil particles. The stabilized soil exhibited improved workability, reduced moisture susceptibility, and enhanced durability compared with untreated marine soil. Experimental results confirmed the existence of an optimum lime content that provides maximum strength improvement without unnecessary material consumption. The findings suggest that lime-treated marine soil can be successfully utilized for foundations, embankments, road subgrades, and other coastal infrastructure projects. Overall, lime stabilization offers a sustainable and practical solution for ground improvement, contributing to safer, more durable, and cost-effective construction in marine environments. The study demonstrates that lime stabilization is an effective technique for improving the strength and bearing capacity of marine soils. The addition of lime reduces plasticity, enhances compaction characteristics, and significantly increases CBR values. An optimum lime content exists beyond which strength gain becomes marginal. The treated soil exhibits improved workability and durability, making it suitable for various coastal infrastructure applications. Therefore, lime stabilization provides a sustainable and economical solution for ground improvement in marine environments. The present study confirms that lime stabilization is a highly effective technique for improving the engineering performance of marine soils. The experimental investigation demonstrated that the addition of lime significantly modifies the physicochemical characteristics of the soil through cation exchange, flocculation–agglomeration, and long-term pozzolanic reactions. These mechanisms collectively reduce plasticity, improve workability, and enhance strength parameters. Compaction test results indicated an increase in optimum moisture content and a slight reduction in maximum dry density, reflecting changes in soil structure due to lime addition. More importantly, substantial improvement was observed in strength-related parameters such as California Bearing Ratio (CBR) and unconfined compressive strength (UCS). The increase in CBR values under both soaked and unsoaked conditions confirms the suitability of lime-treated marine soil for pavement subgrades and foundation applications in coastal environments. The study also revealed that an optimum lime content exists beyond which strength gain becomes marginal. Therefore, proper laboratory evaluation is essential before field application to ensure cost-effectiveness and performance optimization. Additionally, lime stabilization contributes to sustainable construction practices by minimizing soil replacement, reducing material transportation, and utilizing locally available stabilizers. Overall, lime treatment transforms weak and highly compressible marine soils into structurally competent materials capable of supporting infrastructure loads. Future research may focus on microstructural analysis using advanced techniques such as SEM and XRD, durability assessment under saline exposure, and field-scale performance monitoring to validate laboratory findings.

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