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Performance and Durability Assessment of Stabilized Marine Clay Using Lime and Sustainable Industrial By-Products

Sai Vara Prasad S[1], Prasada Raju GVR[1], Anjan Kumar M[2]

[1]*Department of Civil Engineering, Jawaharlal Nehru Technological University, Kakinada, India.*
[2]*DNR College of Engineering & Technology, Bheemavaram, India.*

Abstract

Marine clay is characterized by high plasticity, low strength, and poor durability, which limit its suitability for geotechnical engineering applications. Although previous studies have reported improvements in the strength of soft soils using lime and industrial by-products, limited attention has been given to the comparative evaluation of the durability of lime-GGBS and lime-RHA-stabilized mixes under lime leaching conditions. Therefore, the present study investigates the engineering performance and durability of marine clay stabilized using lime as the primary stabilizing agent and ground granulated blast furnace slag (GGBS) and rice husk ash (RHA) as partial replacement materials. Lime was added at 0%, 3%, 6%, 9%, and 12%, while GGBS or RHA was incorporated at replacement at 5%, 10%, 15%, and 20%. The effects of stabilization on the plasticity, compaction, strength, and durability characteristics of marine clay were evaluated through Atterberg limits, compaction, unconfined compressive strength (UCS), California bearing ratio (CBR), and lime leaching tests. The influence of curing duration and wetting-drying cycles on lime retention in the stabilized soil mixes was also investigated. The results demonstrated a notable improvement in the soil characteristics. Among the investigated mixtures, MC+6% Lime+20% GGBS and MC+9% Lime+15% RHA exhibited the best engineering performance, achieving maximum UCS values of 225 kPa and 207 kPa, respectively. The lime leaching results indicated that the incorporation of GGBS and RHA, reduced calcium loss with increasing curing duration, thereby enhancing the durability of the stabilized soil. Overall, GGBS-stabilized mixes exhibited superior engineering and durability performance compared with RHA-stabilized mixes.

Keywords*:* Marine Clay, Soil Stabilization, Industrial and Agricultural By-products, Durability Assessment, Sustainable Geotechnics, Ground Improvement.

1. Introduction

Soft and marine clay deposits are widely distributed in coastal and deltaic regions worldwide, particularly in Southeast Asia, India, China, and other estuarine environments. Recent global coastal studies indicate that approximately 21% of the world's coastline consists of muddy coastal deposits, while nearly 61% is composed of soft sediments that are potentially susceptible to erosion and instability [1]. These soils often exhibit low shear strength, high compressibility, and poor drainage characteristics, posing significant challenges for infrastructure development and ground improvement applications. They are typically characterized by high natural moisture content, a loose particle arrangement, and large void ratios, which result in low strength and stiffness [2], [3]. Hence, soft clay deposits are highly susceptible to excessive deformation and higher settlements in long-term, when subjected to structural loads [4], [5]. The behaviour of swelling and shrinkage during moisture variations can cause structural instability, cracking, and differential settlement, thereby affecting the performance and durability of foundations and

Corresponding author: Sai Vara Prasad S (siddabathunisaivaraprasad@gmail.com)
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embankments [6], [7]. Slow consolidation and prolonged settlement over time were attributed by low permeability of these type soils [8], [9]. In addition, soft clay exhibits high sensitivity, meaning that its natural structure can be easily disturbed under external loading or handling, resulting in a significant reduction in strength and an increased risk of failure [10]. The engineering behaviour of these clays is also influenced by its mineral composition and pore water chemistry. Especially presence of saline pore water affects interparticle bonding, alters strength characteristics of soil [11]. Also, the contaminants like heavy metals (if exist) in the marine clay may interact with stabilization processes and delay strength development by altering the pozzolanic hydration reactions [12]. In general, marine clay deposits may contain trace amounts of heavy metals depending on the depositional environment and surrounding anthropogenic activities. Lead, Zinc, Copper, Chromium, Nickel, Cadmium, Mercury, and Arsenic are the primary heavy metals found within marine clay deposits [13]. These contaminants may also leach into surrounding groundwater, posing environmental risks if not properly immobilized [14].

Various ground improvement and stabilization techniques have been developed to improve the performance of soft clays. Chemical stabilization using cement, lime, and other binders is the most widely adopted method. Ordinary Portland cement has been used widely due to its ability in improving the strength and reducing the compressibility through hydration reactions [15]. Similarly, lime stabilization has been widely applied for clay-structure improvement. lime increases soil pH and initiates cation exchange, flocculation and pozzolanic reactions. These reactions result in the formation of cementitious hydration products such as Calcium Silicate Hydrate (C-S-H) and Calcium Alumino-Silicate Hydrate (C-A-S-H) gels, which improve interparticle bonding, strength, and durability characteristics of stabilized soil [6], [16].

Geopolymer stabilization using industrial by-products such as fly ash and slag has also been studied as a sustainable alternative to existing binders, as these materials react in alkaline environments to form strong cementitious compounds [17], [18], Alternate stabilizing materials, including reactive magnesium oxide (MgO) and lime–gypsum mixtures, have also been investigated for improving soft clay performance. In addition, soil–binder composite systems, such as fiber reinforcement and deep soil mixing have been investigated to improve soil strength and ductility by improving the interparticle bonding [10].

Industrial and agricultural waste materials have become alternative stabilizers due to the environmental impact and high carbon emissions associated with cement production. These materials not only improve soil engineering properties but also promote sustainable waste utilization [19]. Among these, fly ash has been widely used due to its pozzolanic characteristics [20], [21]. Optimum fly ash content for inorganic soils can improve the CBR and resilient modulus significantly, it was reported that CBR improved by 10 times at 18% flay ash as replacement [22]. Similarly, coal-derived wastes and biomass fly ash have also demonstrated improvements in soil mechanical properties and microstructural modification. Industrial by-products such as gasification fly ash have been used as alkaline activators to enhance soil's performance [23].

Ground granulated blast furnace slag (GGBS) is a by-product of the steel industry also an alternative stabilizing material. In the presence of calcium and water, GGBS forms cementitious compounds that significantly improve soil strength, stiffness, and durability. Similarly, steel slag has also been reported to enhance soil strength. Other industrial by-products such as red mud and calcium carbide residue have also been utilized as alternative binders [24]. Rice husk ash (RHA), which is rich in amorphous silica, reacts with calcium hydroxide to form cementitious compounds that improve strength and reduce permeability [25]. Presence of RHA offered resistance under acidic conditions but minimized the leachability under neutral and alkaline conditions [26]. In addition, other agricultural wastes such as sugarcane bagasse ash have been used to improve soil.

Eggshell powder has been used by various authors in improving the strength and reduce plasticity in fine-grained soils. The combined use of marble powder or eggshell powder with fly ash or other pozzolanic materials has also shown enhanced stabilization performance due to accelerated cementitious reactions [27].

Previous studies reported that lime and GGBS stabilization significantly improve strength through pozzolanic reactions and C-A-S-H gel formation [4], [8]. Similarly, RHA-based stabilization has shown improvement in plasticity reduction and strength enhancement due to its high amorphous silica content [25].

Although several studies have investigated the stabilization of soft and marine clays using lime, GGBS, fly ash, and rice husk ash individually, most have primarily focused on short-term strength improvement and compaction behaviour. In particular, very few studies have comparatively evaluated the engineering performance of lime-GGBS, and lime-RHA stabilized marine clay. Furthermore, the influence of curing duration on calcium immobilization and resistance to lime leaching has not been adequately investigated in previous stabilization studies.

Therefore, the present study investigates the stabilization of marine clay using lime as the primary stabilizing agent and GGBS and/or RHA as sustainable replacement materials. The study evaluates the effects of stabilization on the plasticity, compaction, strength, and durability characteristics of marine clay, with particular emphasis on lime leaching behaviour under different curing periods and wetting-drying cycles. The specific objectives of the study are as follows:

i. To evaluate the effectiveness of lime, GGBS, and RHA in improving the plasticity, compaction, and strength characteristics of marine clay.
ii. To determine the optimum mix proportions based on engineering performance.
iii. To investigate the durability of stabilized marine clay through lime leaching studies under repeated wetting–drying cycles.
iv. To examine the influence of curing duration on calcium leaching and the durability performance of stabilized marine clay.

2. Methodology

2.1. Materials used and proportions

The marine clay investigated in the present study was collected from a depth of 2.5 m below ground level near the Vakalapudi Lighthouse area in Kakinada, Andhra Pradesh, India. Locally available lime was procured for use as the stabilizing additive. GGBS was obtained from the ash silos of the Visakhapatnam Steel Plant, Andhra Pradesh, India. RHA was sourced from the captive power plant of Lalitha Rice Industries, located in Peddapuram, East Godavari District, Andhra Pradesh, India. The overall methodology adopted in the present investigation is illustrated in Figure 1.

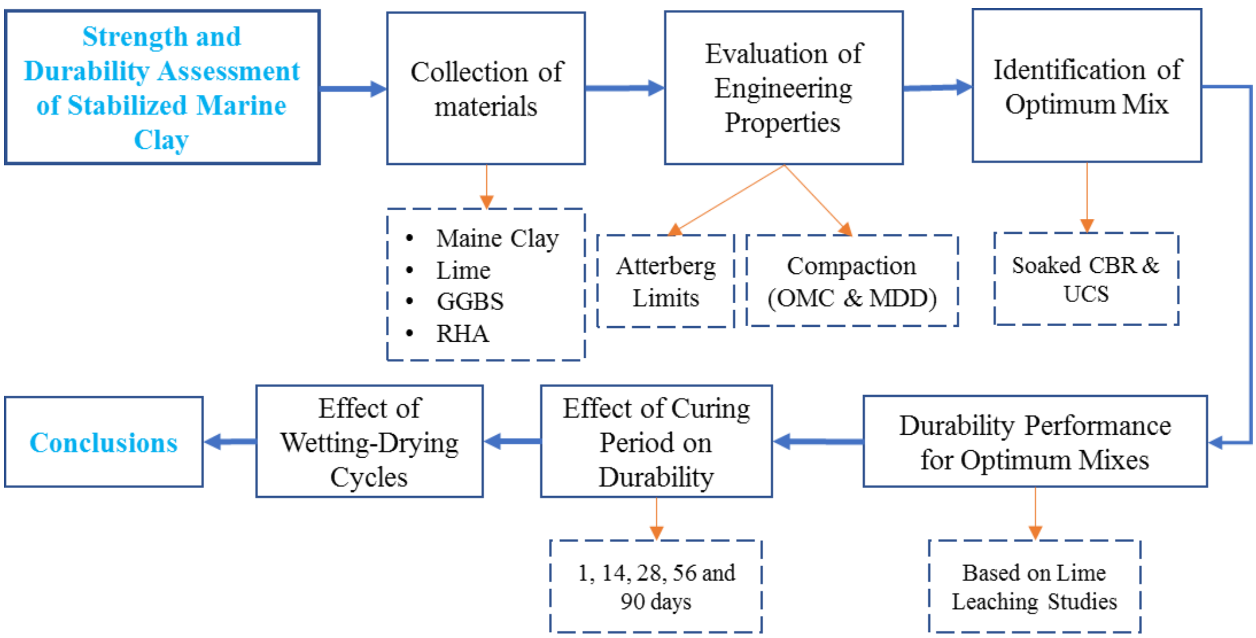

Figure 1. Methodology adopted for evaluation of strength and durability characteristics of stabilized marine clay.

The chemical compositions of lime, GGBS, and RHA are presented in Table 1. The major oxide constituents indicate the presence of reactive silica, alumina, and calcium compounds, which are responsible for the pozzolanic and cementitious reactions that occur during the stabilization process.

Table 1. Chemical composition of various stabilizing materials [28], [29], [30].

S.No.	Component	Percentage		
		Lime	GGBS	RHA
1	SiO_2	-	33.6	89.9
2	Al_2O_3	-	12.5	0.46
3	Fe_2O_3	0.77	0.52	0.47
4	CaO	92.2	42.5	1.01
5	MgO	1.1	7.52	0.79
6	SO_3	5.93	1.68	-
7	K_2O	-	-	4.5
8	P_2O_5	-	-	2.45
9	CO_2	-	-	0.1
10	MnO	-	-	0.14

2.2. Mix proportions

The present study was conducted in two phases to investigate the stabilization of the selected marine clay (MC) using the chosen stabilizing materials. In Phase 1, GGBS was used as a partial replacement for MC at replacement levels of 5%, 10%, 15%, and 20%. In Phase 2, MC was partially replaced with RHA at the same replacement levels of 5%, 10%, 15%, and 20%. In both phases, lime was incorporated as the primary stabilizing agent at dosages of 3%, 6%, 9%, and 12% by dry weight of soil. In addition, the effect of lime alone, without GGBS or RHA, was also investigated. The mix proportions and experimental variables considered in this study are presented in Table 2. The maximum lime content was limited to 12% based on preliminary observations and findings reported in previous stabilization studies, which indicated that higher lime contents may result in the presence of unreacted free lime, increased brittleness, and reduced economic feasibility. Prior to sample preparation, the collected marine clay was air-dried, pulverized, and passed through a 4.75 mm IS sieve to remove oversized particles. The particle size distribution curve of the untreated marine clay is presented in Figure 2. The soil predominantly consists of fine-grained particles, comprising approximately 73% clay, 19% silt, and 8% sand, indicating the characteristics of a highly plastic clay.

Table 2. Details of stabilizing agents used in the current study.

S.No	Description of mix proportion	Variables	No. of Mixes
1	Lime as additive	0, 3, 6, 9 and 12	5
2	GGBS as Replacement to each Lime-MC mix	5, 10, 15 and 20	20
3	RHA as Replacement to each Lime-MC mix	5, 10, 15 and 20	20
Total mix proportions studied			45

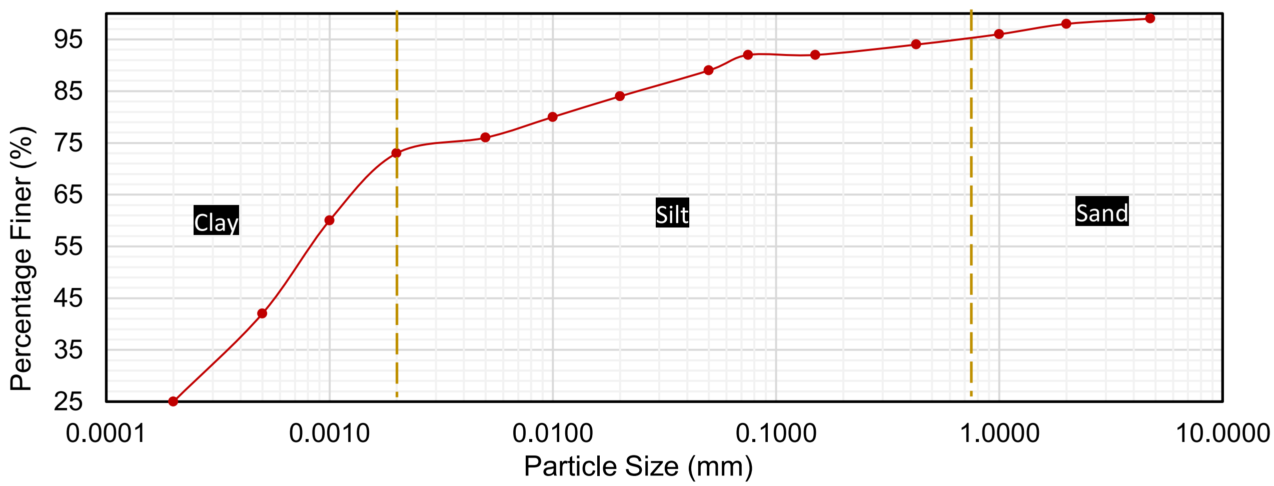

Figure 2. Particle size distribution curve of untreated marine clay.

2.3. Experimental studies

Different laboratory tests were conducted on untreated and treated marine clay in accordance with Indian Standard (IS) 2720, as summarized in Table 3.

Table 3. Various tests conducted

S.No.	Test Conducted	IS Code
1	Specific Gravity	IS 2720 (Part 3/Sec 1): 1980
2	Grain Size Distribution	IS 2720 (Part 4): 1985
3	Liquid Limit and Plastic Limit	IS 2720 (Part 5): 1985
4	Compaction	IS 2720 (Part 7): 1980
5	CBR	IS 2720 (Part 16): 1987
6	UCS	IS 2720 (Part 10): 1991

The tests included specific gravity, grain size distribution, liquid limit, plastic limit, Standard Proctor compaction, soaked California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS) tests. For the Standard Proctor compaction test, which conducted in accordance with IS 2720 (Part 7) using standard compaction energy to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of untreated and stabilized mixes. Further, the specimens for strength tests (CBR and UCS) were prepared at their respective OMC and MDD conditions. All the engineering and strength parameters were determined for each of the 45 mix proportions listed in Table 2. For each UCS and soaked CBR test, a minimum of three specimens were tested for every mix proportion, and the reported values represent the average of these measurements.

The optimum mix proportions for the MC–Lime, MC–GGBS–Lime, and MC–RHA–Lime mixtures were determined based on the UCS results. Lime leaching studies were subsequently conducted on the optimum mixes to evaluate their durability and long-term performance under simulated field exposure conditions, such as rainfall infiltration. Leaching of calcium (lime) from the stabilized soil layer reduces the availability of the binder required for continued cementation and may lead to a gradual deterioration in strength and engineering performance over time. Therefore, quantifying the calcium concentration in the leachate provides a direct measure of lime retention within the stabilized soil matrix. The lime leaching tests were conducted using a galvanized iron (GI) cylindrical tank with a diameter of 190 mm and a height of 335 mm, as shown in Figure 3. A 150 mm thick stabilized soil layer was compacted at its respective Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). A constant water head of 100 mm was maintained throughout the leaching process to simulate continuous moisture infiltration conditions that may occur in field subgrade and coastal environments. This water head was selected to ensure downward percolation through the stabilized soil layer without causing excessive hydraulic disturbance to the compacted specimen.

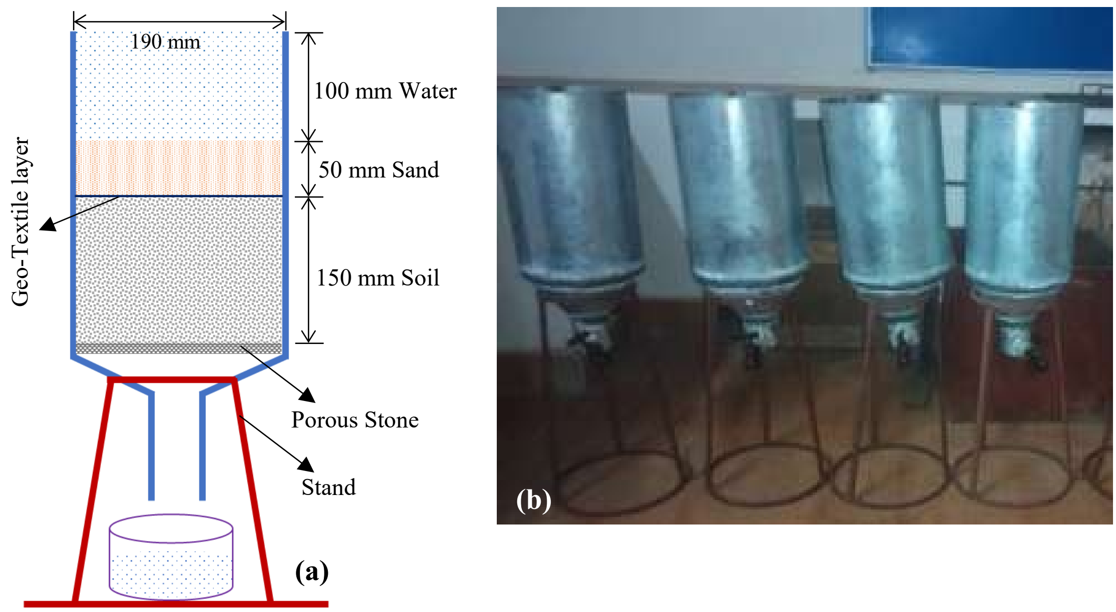

Figure 3. (a) Schematic view of the lime leaching test setup; (b) Experimental tanks used for lime leaching studies in the laboratory.

During the leaching process, the leachate was collected at 24-hour intervals. After five days of leachate collection, the specimen was allowed to air-dry for five days, thereby completing one wetting–drying cycle. A total of five wetting–drying cycles were performed to comparatively evaluate the durability and lime retention of the stabilized soil matrix under repeated moisture exposure conditions. These wetting-drying cycles were selected to simulate the alternating moisture conditions commonly experienced by stabilized subgrade soils under Indian climatic conditions, particularly during successive monsoon and dry seasons. The collected leachate was analyzed for Ca^{2+} concentration using EDTA (*ethylenediaminetetraacetic acid*) complexometric titration at a pH of 12.5 [31], [32].

The effect of curing duration on lime leaching was also investigated by allowing the prepared soil specimens to undergo curing before initiating the leaching experiments. The curing durations considered in the present study were 1, 14, 28, 56, and 90 days. After sample preparation, the specimens were sealed in polythene covers and cured under laboratory ambient conditions. Moist curing was maintained by wrapping the specimens in wet jute bags to minimize moisture loss throughout the curing period.

3. Results and Discussions

Initially, the engineering and strength characteristics of the untreated marine clay (MC), GGBS, and RHA were determined separately and are presented in Table 4 (MC) and Table 5 (GGBS and RHA). The untreated marine clay exhibited highly plastic behaviour, characterized by a high liquid limit and plasticity index. The low soaked CBR value (0.89%) and UCS (71 kPa) indicate poor strength characteristics, making the untreated soil unsuitable for subgrade or foundation applications without stabilization. As presented in Table 5, both GGBS and RHA exhibited non-plastic behaviour.

3.1. Effect of lime on Plasticity Index (PI) of MC-GGBS and MC-RHA mixes

The plasticity index (PI) of the marine clay decreased consistently with the addition of lime and the partial replacement of soil with GGBS or RHA, indicating a significant improvement in the consistency characteristics of the soil, as shown in Figure 4. The untreated marine clay exhibited a high PI of 50.8%, confirming its highly plastic nature. With the addition of lime alone, the PI decreased progressively to 33.2% at a lime content of 12%. A further reduction was observed when GGBS and RHA were incorporated as replacement materials. At 12% lime with 20% replacement, the PI decreased substantially to 8.7% and 6.8% for the GGBS- and RHA-stabilized mixes, respectively. This reduction in PI can be attributed primarily to cation exchange and flocculation, which reduce the thickness of the diffuse double layer and promote the aggregation of clay particles. Comparatively, RHA exhibited a slightly greater reduction in PI than GGBS at higher replacement levels.

Table 4. Properties of untreated Marine Clay (MC).

S.No.	Property	Value
1	Specific Gravity	2.60
2	**Grain size Distribution**	
	Sand (%)	8.00
	Silt (%)	19.00
	Clay (%)	73.00
3	**Compaction parameters**	
	Maximum Dry Density (g/cm^3)	1.36
	Optimum Moisture Content (%)	30.70
4	**Atterberg's limits**	
	Liquid Limit (%)	75.0
	Plastic Limit (%)	24.2
	Plasticity Index (%)	50.8
	Shrinkage Limit (%)	13.20
5	Free Swell Index (%)	33.00
6	Soaked CBR (%)	0.89
7	Unconfined Compressive Strength (kPa)	71.00
8	IS Classification	CH

Table 5. Engineering Properties GGBS and RHA.

S.No.	Property	Value	
		GGBS	RHA
1	Specific gravity	2.85	2.04
2	Plasticity Index	NP	NP
3	**Grain Size Distribution**		
	Sand size (%)	15.00	89.00
	Silt & clay size (%)	85.00	11.00
4	**Compaction Parameters**		
	MDD (g/cm^3)	1.80	0.89
	OMC (%)	15.00	38.30
5	**Shear Parameters**		
	Cohesion (kPa)	27.00	
	Angle of Internal Friction (Degrees)	8.00	-

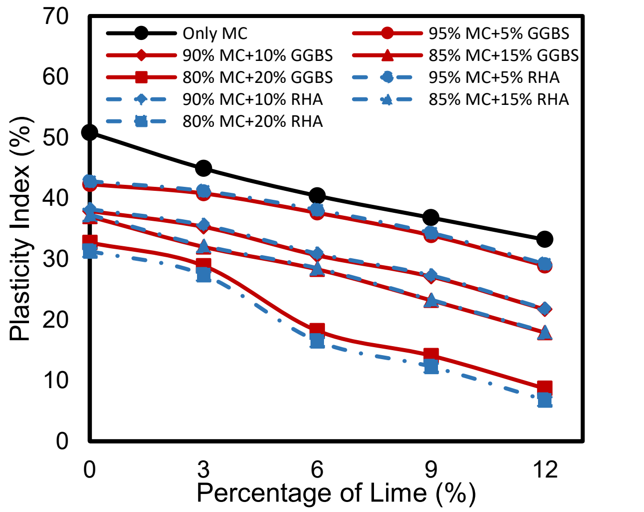

Figure 4. Effect of lime content on plasticity index of MC-GGBS and MC-RHA mixes.

3.2. Effect of lime on compaction parameters of MC-GGBS and MC-RHA Mixes

The compaction characteristics of marine clay changed significantly with the addition of lime and the partial replacement of soil with GGBS or RHA. Figure 5 illustrates the variation in OMC of marine clay with lime addition and replacement using GGBS or RHA. The untreated marine clay exhibited an OMC of 30.7%, which gradually decreased to 25.9% with increasing lime content. When GGBS and RHA were introduced, the OMC further decreased. The minimum OMC values of 20.5% and 20.8% were observed at 12% lime with 20% GGBS and RHA replacement, respectively. This decrease may be due to the replacement of highly plastic clay with less water-absorbing non-plastic materials [33].

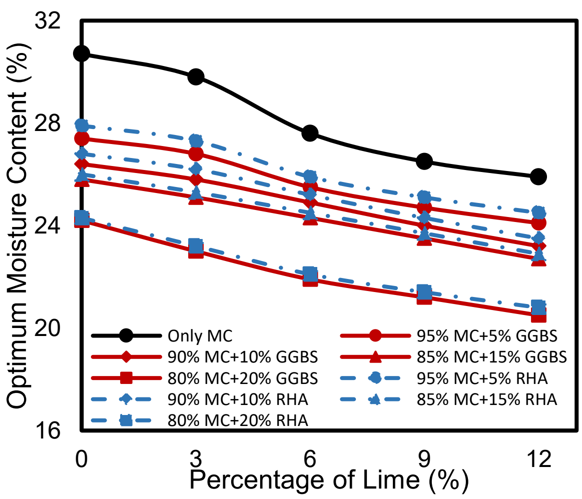

Figure 5. Effect of lime content on optimum moisture content of MC-GGBS and MC-RHA mixes.

As shown in Figure 6, the Maximum Dry Density (MDD) of the untreated marine clay was 1.36 g/cm³, which increased consistently with the addition of lime, reaching 1.51 g/cm³ at a lime content of 12%. This increase indicates improved particle packing resulting from the flocculated arrangement of clay particles. The MDD increased further with the incorporation of GGBS, reaching a maximum value of 1.68 g/cm³ for the mix containing 6% lime and 20% GGBS. Similarly, RHA replacement also improved the MDD, with a maximum value of 1.63 g/cm³ obtained for the mix containing 9% lime and 15% RHA. However, at higher replacement levels, the MDD exhibited a decreasing trend, particularly in the RHA-stabilized mixes. This behaviour can be attributed to the lower specific gravity and porous nature of RHA particles. In addition, excessive replacement may reduce effective particle-to-particle contact and increase the void ratio within the stabilized soil matrix, thereby limiting further densification of the compacted mixes.

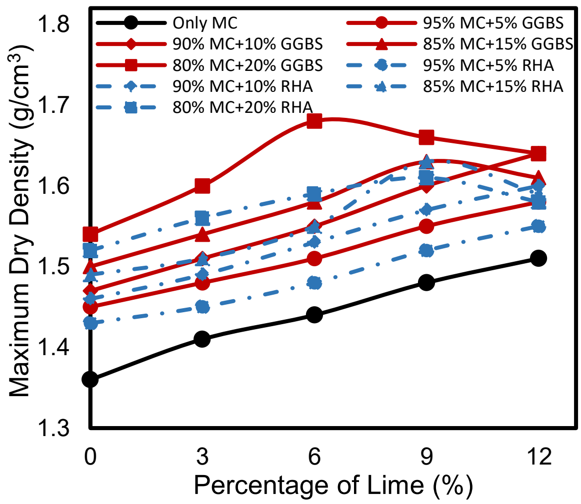

Figure 6. Effect of lime content on maximum dry density of MC-GGBS and MC-RHA mixes.

3.3. Effect of lime on strength parameters of MC-GGBS and MC-RHA Mixes

The strength behaviour of marine clay stabilized with lime, GGBS, and RHA was evaluated using soaked CBR (Figure 7) and UCS (Figure 8) tests, and the results indicated substantial improvement compared to untreated marine clay. The soaked CBR of untreated marine clay was very low at 0.89%, confirming its poor load-bearing capacity. With lime addition alone, the CBR improved gradually to 3.15% at 12% lime. However, significantly higher improvement was observed when GGBS and RHA were used along with lime. The maximum CBR value of 7.7% was achieved at 6% lime with 20% GGBS, which is about 8.65 times higher than untreated soil. Similarly, RHA mixes also showed considerable improvement, reaching a maximum CBR of 7.25% at 9% lime with 15% RHA.

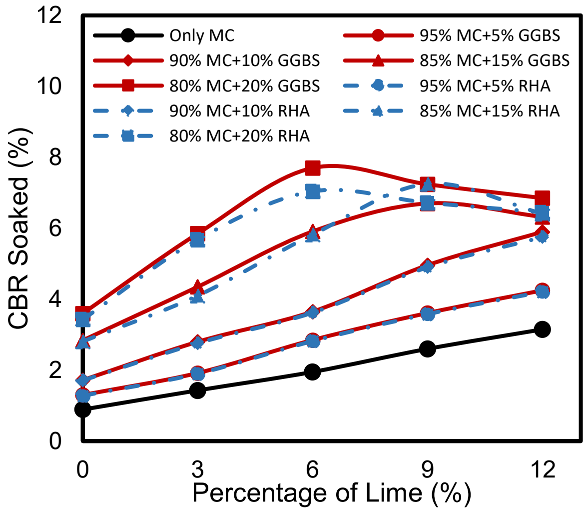

Figure 7. Effect of lime content on soaked CBR of MC-GGBS and MC-RHA mixes.

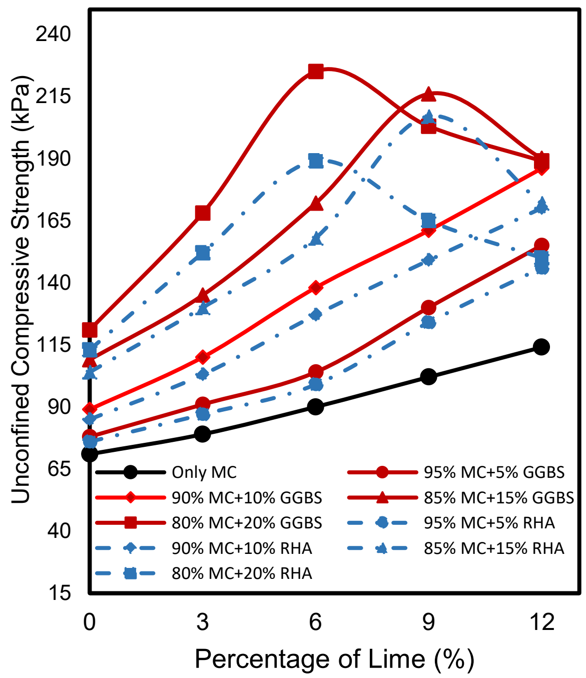

Figure 8. Effect of lime content on unconfined compressive strength of MC-GGBS and MC-RHA mixes.

Similarly, the UCS of the untreated marine clay increased from 71 kPa to 114 kPa with the addition of 12% lime. The incorporation of GGBS resulted in a substantial increase in strength, with a maximum UCS value of 225 kPa obtained for the mix containing 6% lime and 20% GGBS, representing more than three times the strength of the untreated marine clay. Likewise, the incorporation of RHA increased the UCS to a maximum value of 207 kPa for the mix containing 9% lime and 15% RHA. However, at higher replacement levels, the UCS exhibited a slight decline, which may be attributed to the excessive replacement material reducing effective soil–binder contact. Overall, the GGBS-stabilized mixes exhibited higher UCS values than the RHA-stabilized mixes.

The comparatively higher strength obtained for GGBS-stabilized mixes may be due to the higher latent hydraulic reactivity of GGBS in the presence of lime [34]. GGBS contains reactive calcium, silica, and alumina, which promote the formation of cementitious hydration products such as calcium silicate hydrate (C-S-H) and calcium alumino-silicate hydrate (C-A-S-H) gels. These compounds improve interparticle bonding and produce a denser stabilized soil matrix. In case of RHA, it primarily promotes C-S-H formation because of its silica-rich composition and comparatively slower cementitious reaction and lower strength development compared to GGBS-stabilized mixes [35], [36].

3.4. Effect of Curing period on lime leaching behavior of stabilized marine clay

The optimum mix proportions were identified as 12% lime for MC-Lime stabilization, 6% lime with 20% GGBS for MC-GGBS-Lime stabilization, and 9% lime with 15% RHA for MC-RHA-Lime stabilization based on maximum UCS and CBR values. Accordingly, lime leaching studies were conducted on these optimum mixes, as described in the methodology.

Figure 9 (a)-(d) presents the percentage of lime leached during various wetting-drying cycles. The results indicate that the percentage of lime leached decreased significantly with increasing curing period and number of wetting-drying cycles for all mixes.

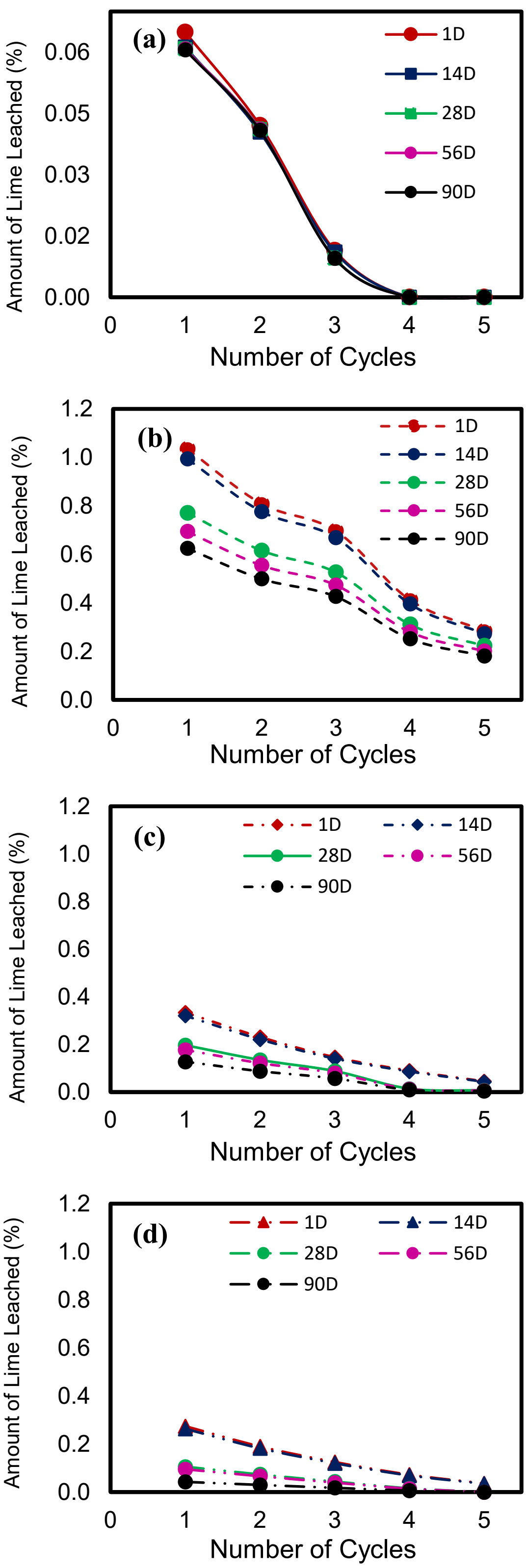

Figure 9. Effect of curing period on percentage of lime leaching for different stabilized marine clay mixes; (a) Only MC; (b) MC+12% Lime; (c) 85% MC+9% Lime+15% RHA; (d) 80% MC+6% Lime+20% GGBS

The MC + Lime mix exhibited the highest lime leaching at all curing periods, with an initial leaching of 1.03% at 1-day curing, which reduced to 0.624% at 90 days of curing. The higher leaching observed at lower curing periods may be attributed to the presence of free calcium ions that were not fully consumed in pozzolanic reactions at the early stages of curing. In addition, curing showed a significant influence after multiple wetting-drying cycles. After five wetting-drying cycles, the percentage of lime leached reduced from 0.28% for 1-day curing to 0.18% for 90 days of curing.

The inclusion of GGBS and RHA significantly reduced lime leaching compared to the lime-only mix. Among all the mixes, the MC + 6% Lime + 20% GGBS mix exhibited the lowest lime leaching, decreasing from 0.27% after 1 day of curing to nearly 0% after five wetting–drying cycles at 28, 56, and 90 days of curing. Similarly, the MC + 9% Lime + 15% RHA mix also exhibited very low lime leaching, decreasing to 0.005% after 90 days of curing.

As shown in Figure 10 (a)–(d), the cumulative percentage of lime leached demonstrates that the lime-only stabilized marine clay experienced the highest total lime loss across all curing periods and wetting–drying cycles. In contrast, the incorporation of GGBS and RHA substantially reduced the cumulative lime loss. This reduction with increasing curing duration indicates the progressive consumption of free lime through pozzolanic reactions, leading to the formation of stable cementitious compounds such as C–S–H and C–A–S–H, which immobilize calcium within the soil matrix [37]. Overall, the cumulative lime loss decreased with increasing curing duration, with the GGBS-stabilized mixes exhibiting the lowest lime loss, followed by the RHA-stabilized mixes and the lime-only mix.

The enhanced calcium immobilization resulting from the formation of stable hydration products is the primary reason for the superior performance of GGBS-stabilized mixes compared to RHA-stabilized mixes. The pozzolanic and latent hydraulic reactions of GGBS consume free calcium hydroxide more effectively, thereby reducing the availability of leachable calcium within the soil matrix. Although RHA also contributed to reducing lime leaching through secondary pozzolanic reactions, its lower reactivity and porous nature may have resulted in slightly higher calcium loss than that observed in the GGBS-stabilized mixes.

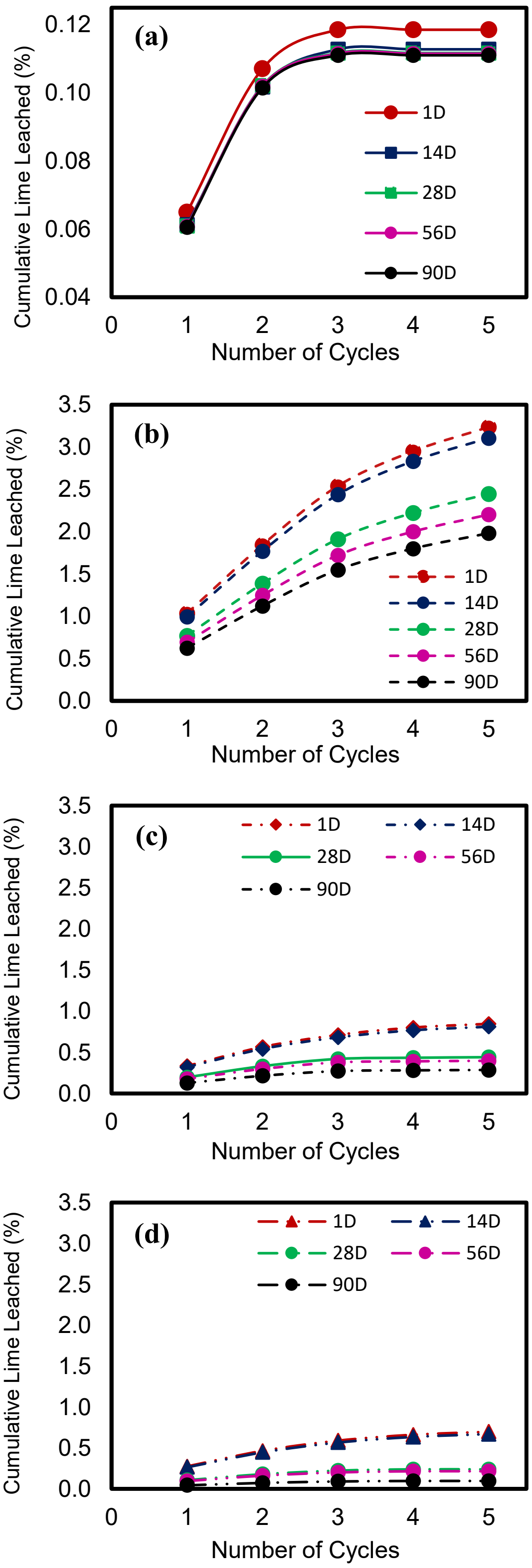

Figure 10. Effect of curing period on cumulative percentage of lime leaching for different stabilized marine clay mixes; (a) Only MC; (b) MC+12% Lime; (c) 85% MC+9% Lime+15% RHA; (d) 80% MC+6% Lime+20% GGBS.

4. Conclusions

The present study evaluated the effectiveness of lime, GGBS, and RHA in stabilizing marine clay, with emphasis on its engineering performance and durability characteristics. Based on the experimental investigation, the following conclusions are drawn:

- The addition of lime, GGBS, and RHA significantly reduced the plasticity characteristics of marine clay. The plasticity index decreased from 50.8% to 8.7% and 6.8% with MC-GGBS-Lime and MC-RHA-Lime mixes respectively. This indicating substantial improvement in soil consistency behavior.
- The compaction characteristics improved considerably with stabilization through reduction in OMC and increase in MDD. The highest MDD of 1.68 g/cm³ was obtained for the MC + 6% Lime + 20% GGBS mix, indicating improved particle packing and densification. Comparatively, GGBS-stabilized mixes exhibited better compaction behavior than RHA mixes due to the higher specific gravity and latent hydraulic reactivity of GGBS.
- Significant improvement in strength characteristics was observed for stabilized marine clay. The UCS increased from 71 kPa for untreated marine clay to 225 kPa and 207 kPa for GGBS and RHA optimum mixes, respectively. Similarly, the soaked CBR improved from 0.89% to 7.7% and 7.25%, confirming substantial improvement in load-bearing capacity. Superior performance of GGBS-stabilized mixes may be attributed to the formation of denser cementitious compounds such as C-S-H and C-A-S-H gels.
- The durability assessment through lime leaching studies indicated that calcium leaching decreased with increasing curing period and was significantly lower in GGBS and RHA-stabilized mixes compared to lime-only stabilization. The reduced lime leaching confirms improved calcium immobilization and enhanced durability performance of stabilized marine clay under wetting–drying conditions.
- The optimum mix proportions identified from the present investigation were MC + 12% Lime, MC + 6% Lime + 20% GGBS, and MC + 9% Lime + 15% RHA, among which the GGBS-stabilized mix exhibited the best overall engineering and durability performance.

The results of the present study demonstrate that lime-GGBS and lime-RHA stabilization can be effectively utilized for improving problematic marine clay in pavement subgrades, embankments, coastal foundations, and other ground improvement applications. In addition to improving engineering performance, the use of GGBS and RHA promotes sustainable utilization of industrial and agricultural waste materials.

5. Study Limitations

The present has the following limitations:

- Although at least three specimens were tested for each UCS and CBR condition, only the averaged values were retained for analysis. Consequently, statistical measures of variability such as standard deviation and error bars were not presented.
- Investigation was limited to laboratory-scale experimental conditions, and the long-term field performance of stabilized marine clay under varying environmental and loading conditions was not evaluated.
- Factors such as climate, groundwater conditions, cyclic loading, and field compaction may influence the long-term behavior of stabilized soils in practical applications.
- The discussion of C-S-H and C-A-S-H formation was presented as a literature-supported interpretation and didn't determine experimentally.
- Microstructural characterization techniques, such as Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD) and Fourier Transform Infrared Spectroscopy (FTIR) were not performed due to the unavailability of the required testing facilities. Future research should focus on investigating these treated soil mixtures using SEM and XRD to examine the microstructural changes.

Competing Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

All data generated or analyzed during this study are included in this published article. Additional information related to the study may be made available by the corresponding author upon reasonable request at siddabathunisaivaraprasad@gmail.com.

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Author Contribution Roles

Sai Vara Prasad S: Conceptualization, Methodology, Investigation, Data acquisition, Analysis, Visualization, Writing – Original Draft Preparation.

Prasada Raju GVR: Supervision, Validation, Writing – Review & Editing.

Anjan Kumar M: Technical Review, Validation, Writing – Review & Editing.

Statement on the Ethical Use of AI Tools

AI-assisted tools were used only for language refinement and grammatical improvement during the preparation of the manuscript. All technical content, analysis, interpretations, and conclusions were developed and verified by the authors.

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