

Investigation of the Plasticity and Bearing Capacity of Beach Sand-Stabilized Clay under Different Soaking Durations

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Abstract

Clay soils are widely recognized for their unfavorable geotechnical properties, including high plasticity and low bearing capacity, which often compromise the performance of subgrades and foundations. Conventional stabilizers such as cement and lime are effective but limited by cost and environmental concerns. Beach sand with its non-plasticity, density, and high internal friction angle, offers potential as a natural stabilizer. This study investigates the stabilization of clay soil using Kupa beach sand (KBS) under various soaking durations. The evaluation focuses on compaction and CBR tests to determine the bearing capacity, as well as Atterberg limit tests to assess the plasticity of the stabilized samples. The findings show that incorporating 30% Kupa beach sand optimally improves engineering properties, reducing the Plasticity Index (PI) from 40,94% to 6,18% and significantly increasing CBR value from 7,638% (KBS0%) to 38,227% (KBS30%) under unsoaked conditions. Although prolonged soaking reduced CBR values due to weakened particle bonding, the stabilized mixture retained higher CBR value (20,672%) than untreated clay (3,546%) after 21 days, indicating durability under saturated conditions. These results confirm that beach sand effectively decreases plasticity, enhances strength, and mitigates moisture susceptibility.

Keywords: Beach Sand, Bearing Capacity, Clay, Plasticity, Soaking Duration

1. INTRODUCTION

Clay soils are often characterized by unfavorable properties such as high plasticity, significant swelling-shrinkage potential, and low bearing capacity (Assadollahi & Nowamooz, 2020; Díaz-López et al., 2023; Harichane et al., 2018). These characteristics pose major challenges in various construction projects, particularly in roadworks, foundations, and other infrastructures. When used as subgrade or embankment material, clay soils tend to undergo significant deformation due to variations in water content, which can compromise the stability of the overlying structures (Darmawan et al., 2025; Olivia Aziza & Irika, 2023). Under saturated conditions, the expansive behavior of clay worsens, leading to pavement cracking and foundation damage (Zhang et al., 2023). Furthermore, the increase in pore water pressure caused by traffic or structural loads may induce consolidation and settlement, ultimately resulting in structural cracking and failure (Sukiman & Yakin, 2017).

To address these issues, a range of soil stabilization techniques has been developed. Chemical stabilization using cement or lime has proven effective; however, its application is often limited by high costs, environmental concerns, and scalability constraints (Abeyasinghe et al., 2025; Díaz-López et al., 2024; Luo et al., 2025). Hence, the utilization of alternative materials that are more environmentally friendly and locally available, such as industrial by-products or natural resources, has gained increasing attention as soil stabilizers (Humairah et al., 2024; Humairah et al., 2024). One promising natural material

is beach sand. Beach sand is a granular material formed through coastal geomorphological processes, with a particle size of 0.55–2.5 mm, predominantly composed of quartz, calcite, and feldspar (Herman & Fiska, 2020). Its mechanical properties are characterized by non-plasticity, high permeability, relatively high density, and a large internal friction angle, which suggest its potential to enhance the stability and strength of clay soils. An additional distinctive factor is its salinity, which can influence the physico-chemical interactions among soil particles (Saputra & Ridha, 2019).

Recent studies reinforce that the inclusion of granular materials (including sand) into clay soils generally improves geotechnical properties by reducing plasticity index and unconfined compressive strength, while increasing shear strength and CBR values (Dewi et al., 2022; Ferdian et al., 2015; Leonard & Mabui, 2025; Rambe et al., 2016; Rasinan et al., 2021). Meta-analyses and experimental studies have consistently demonstrated that the addition of sand fractions (both aeolian and fine sand) reduces liquid limit and plasticity index while improving gradation, which subsequently enhances CBR under unsaturated conditions. Recent findings on aeolian sand (2025) further indicate that even small sand fractions (2.5–30%) can optimize the strength parameters of problematic clay soils, highlighting the practical potential of natural sand as a cost-effective stabilizer (Boukhatem et al., 2025; Li et al., 2024).

Specifically for beach sand, several regional experimental studies have shown that it can decrease plasticity index and improve CBR when mixed with clay soils. Fathonah et al. (2022) reported that adding 36% beach sand reduced the plasticity index of clay from 22.86% to 9.49%. Other research confirmed an increase in CBR values in clay–beach sand mixtures (Kusuma et al., 2017; Simanjuntak et al., 2017), while Wiqoyah et al. (2024) observed an increase in internal friction angle despite a reduction in cohesion. Laboratory reports further revealed significant CBR improvements at beach sand proportions of 20–40% by mass, alongside reductions in swell/free swelling. However, variations in mineralogy and particle size distribution resulted in differences across locations. These findings underscore the role of sand as a granular skeleton that reduces the proportion of fine particles and alters particle interaction mechanics (Ndruru et al., 2025; Wibowo, 2020).

Nevertheless, several studies emphasize that environmental conditions, particularly soaking duration and wet–dry cycling, exert substantial influence on engineering parameters such as soaked CBR. Experimental results suggest that CBR values decline exponentially with increasing soaking duration, reaching residual levels once full saturation is achieved. Thus, conducting CBR tests at multiple soaking durations is critical for predicting the long-term performance of subgrade soils (Chengula, 2023; Nova et al., 2024). Despite this, most prior studies have primarily focused on the effects of sand content variation on plasticity and bearing capacity, without adequately considering environmental conditions characteristic of tropical coastal regions, namely prolonged submersion due to groundwater fluctuations or inundation. While a few studies highlight that soaking duration can reduce CBR (Assadollahi & Nowamooz, 2020; Balqis & Widiyanti, 2023), systematic investigations on how soaking duration affects the plasticity and bearing capacity of clay stabilized with beach sand remain limited. Moreover, the effects of salinity and microstructural interactions under extended soaking conditions have not been extensively explored.

Based on these considerations, this study aims to evaluate the plasticity and bearing capacity (CBR value) of clay soils stabilized with beach sand under varying soaking durations. The findings are expected to provide theoretical contributions to understanding clay, beach sand, and water interactions, as well as practical insights for recommending beach sand as a stabilization material for subgrades in flood-prone coastal areas.

2. METHODS

A. Materials

This research focuses on the stabilization of clay soil, with the sample collected from the subgrade of an embankment and road project in Tello, Makassar. Whereas, the stabilizing material (beach sand) was obtained from Kupa Beach in Barru Regency, South Sulawesi. Its chemical composition has been previously analyzed by Heriansyah et al. (2024) and presented in **Table 1**.

Table 1 Chemical Composition of Kupa Beach Sand (Heriansyah et al., 2024)

Composition	Percentage (%)
SiO ₂	7,349
Al ₂ O ₃	2,882
Fe ₂ O ₃	84,359
CaO	2,002
K ₂ O	1,168
SO ₃	1,055
TiO ₂	0,813
P ₂ O ₅	0,189
MnO	0,032
V ₂ O ₅	0,031
SrO	0,013
ZnO	0,012
Y ₂ O ₃	0,008

Two major chemical components of Kupa beach sand are SiO₂ and Fe₂O₃. The exceptionally high Fe₂O₃ content indicates that this sand can essentially be classified as iron sand, in which iron oxides act as micro-cementing agents. These oxides promote flocculation and aggregation of clay particles, thereby reducing plasticity and enhancing soil bearing capacity, even under saturated conditions (Yan et al., 2025).

B. Sample Preparation

The samples were prepared according to the needs of each test. Preparation began by testing the clay soil and Kupa beach sand (KBS) separately to determine their respective physical characteristics. The clay samples were tested for specific gravity, unit weight, sieve analysis, and Atterberg limits, while the Kupa beach sand (KBS) samples were tested for specific gravity and unit weight. Following characterization, mixed samples were prepared by substituting Kupa beach sand into the clay soil at proportions ranging from 0% to 50%, with 10% intervals. This range of substitution was determined with reference to several previous studies, such as Kusuma et al. (2017), who used 10%, 20%, and 30% variations of marine sand; Sitinjak et al. (2021), who used 0%, 5%, 10%, and 15%; and Fathonah et al. (2022), who applied 12%, 24%, and 36% variations of beach sand combined with curing times of 0, 7, 14, and 21 days. Most of these studies, however, did not consider the effect of soaking duration on the behavior of stabilized soils. Therefore, this study incorporated soaking duration as an additional factor, with variations of 0, 7, 14, and 21 days, to evaluate the response of clay soil stabilized with Kupa beach sand under wet environmental conditions over different time periods. This approach is expected to provide a more comprehensive understanding of the long-term stability of clay soil stabilized with beach sand.

C. Experiment Procedure

The experiment procedure was designed to evaluate the effect of beach sand stabilization on the plasticity and bearing capacity of clay soil under different soaking durations with 34 total specimens. The testing sequence included sample collection, physical characterization, compaction tests, Atterberg limits, and California Bearing Ratio (CBR) tests, each performed in accordance with ASTM and SNI standards.

Clay samples were air-dried, sieved through a No. 4 sieve (4.75 mm), and blended with beach sand prepared in the same way. Physical tests such as specific gravity, unit weight, and grain-size distribution were conducted, while Atterberg limits were determined using ASTM D4318. Following the characterization, test specimens were prepared by blending clay soil with Kupa beach sand (KBS) at proportions of 0%, 10%, 20%, 30%, 40%, and 50% by dry weight. Each mixture was thoroughly homogenized before compaction. The Standard Proctor Compaction Test was conducted to determine the maximum dry density (MDD) and optimum moisture content (OMC) for each mix. For this test, a cylindrical Proctor mold (101,6 mm diameter, 116,4 mm height), a 2,5 kg rammer with 305 mm drop height, and a balance were employed. Samples were compacted in three layers with 25 blows per layer. Moisture content was determined using oven drying at 105–110°C. Compaction curves were plotted to identify the OMC and MDD of each mix.

Subsequently, specimens were prepared at MDD and OMC for CBR testing. Cylindrical molds of 150 mm diameter and 175 mm height were used, compacted in 3 layers, and soaked in water tanks for 0, 7, 14, and 21 days to simulate field wetting conditions. California Bearing Ratio was determined using a CBR testing machine equipped with a loading frame, proving ring, dial gauge, and a 50 mm diameter penetration piston. The piston was penetrated at a constant rate of 1,27 mm/min, and penetration loads at 2,5 mm and 5 mm were recorded to compute the CBR values.

Finally, data were compiled and analyzed to evaluate the influence of sand content and soaking duration on soil plasticity and strength. Particular emphasis was placed on identifying the optimum percentage of beach sand substitution (KBS) that yields the highest CBR while accounting for the reduction in strength due to soaking. The systematic sequence of testing ensured that both physical and mechanical behaviors of the stabilized clay were rigorously assessed.

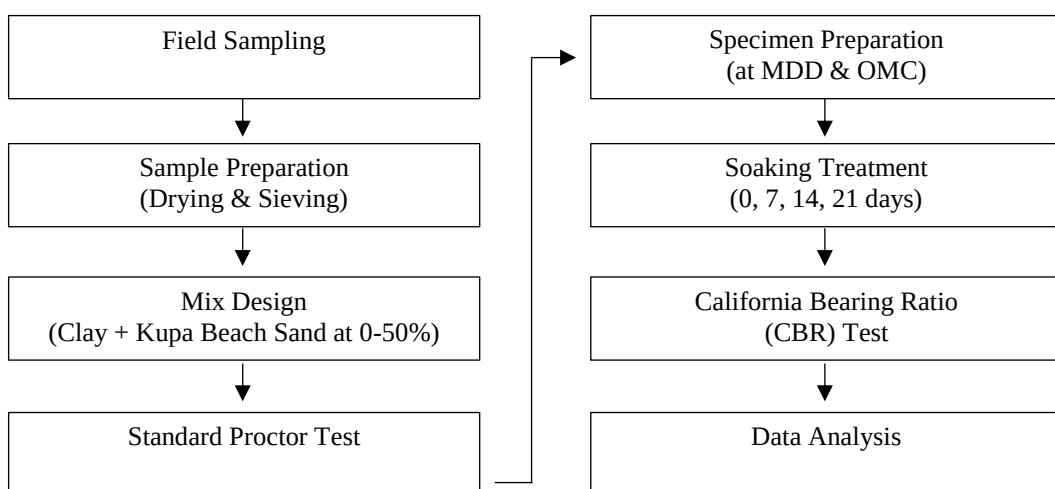


Figure 1 Research Flowchart for Evaluating Clay Stabilized with Kupa Beach Sand under Soaking Treatment

3. RESULT AND DISCUSSION

A. Physical Properties

To understand the fundamental characteristics of the materials used in this study, laboratory tests were conducted on the physical properties of the clay and Kupa beach sand (KBS). These tests included specific gravity, unit weight, sieve analysis, and Atterberg limits. The results are presented **Table 2**.

Table 2 Characteristics of Clay and Kupa Beach Sand (KBS)

Experimental Properties	Result		Unit
	Clay	Beach Sand	
Specific Gravity	2,624	2,472	-
Wet Unit Weight	1,544	1,694	gr/cm ³
Dry Unit Weight	1,398	1,582	gr/cm ³
Atterberg Limit	LL	59,64	-
	PL	18,70	-
	PI	40,94	-

According to the laboratory testing results presented in Table 2, the physical properties indicate that the clay has a specific gravity of 2,624 g/cm³, while Kupa beach sand (KBS) shows a value of 2,472 g/cm³. In general, the typical specific gravity values for natural clays range between 2,60–2,80, and for sand around 2,60–2,70 (Bowles, 1992). Therefore, the specific gravity of the clay fits within the normal range. On the other hand, the specific gravity of the beach sand is slightly below the typical range, suggesting that it may contain lighter components such as organic matter. This finding is consistent with Pratiwi et al. (2021), who reported that beach sand can have a specific gravity as low as 2,09, which is below the standard range for sands in general.

The wet unit weight values for both clay and KBS are 1,544 g/cm³ and 1,694 g/cm³, respectively, while the dry unit weights are 1,398 g/cm³ and 1,582 g/cm³. Typical dry unit weight for clay soils ranges from 1,3–1,6 g/cm³, and for KBS from 1,5–1,8 g/cm³. In general, the typical dry unit weight for clay soils ranges from 1,30–1,60 g/cm³, and for beach sands from 1,50–1,80 g/cm³ (Pratiwi et al., 2021; Yuliani et al., 2022). These results show that both materials fit within the normal range. The higher unit weight of the beach sand indicates that it has a coarser grain texture and lower porosity than clay soil.

The Atterberg limits were tested only for the clay sample. The results show a liquid limit (LL) of 59,64%, plastic limit (PL) of 18,70%, and plasticity index (PI) of 40,94%, which classify the material as high-plasticity clay (CH) according to the Unified Soil Classification System (USCS). A Plasticity Index (PI) value greater than 35% generally indicates a strong potential for swelling and shrinkage due to the presence of expansive clay minerals such as montmorillonite (Annisa, et al., 2024; Hardiyatmo, 2018).

B. Gradation

The sieve analysis results of clay stabilized with the addition of beach sand, as shown in **Figure 2**, indicate significant changes in the gradation characteristics of the clay. In the initial condition, where the clay was not stabilized with sand (KBS0%), the particle size distribution curve was predominantly positioned on the right side of the graph. This indicates that most of the particles were very fine, consistent with the fact that 63,2% of soil fraction passed through sieve No. 200.

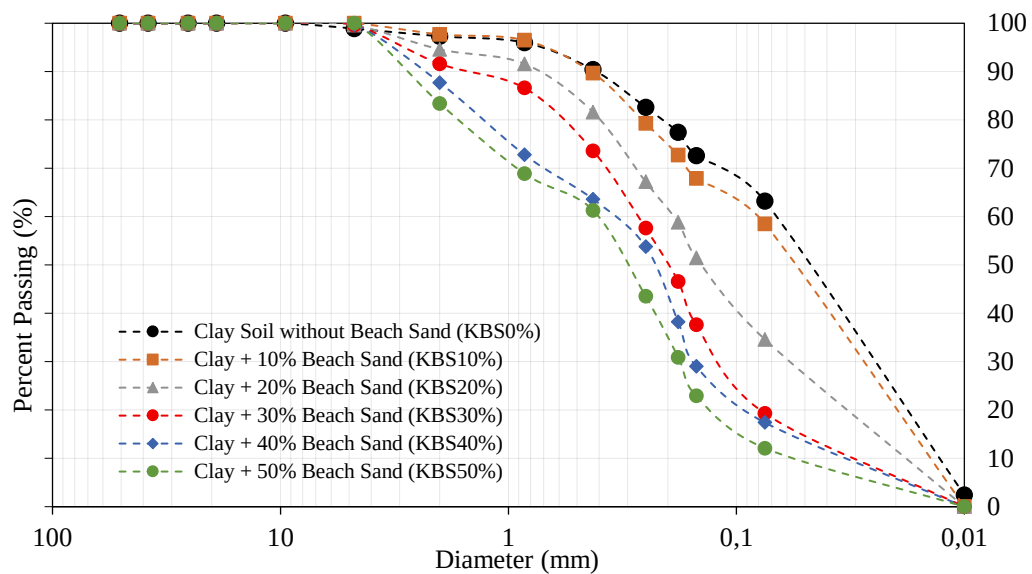


Figure 2 Grain Size Distribution Curves of Clay Stabilized with Varying Percentages of Kupa Beach Sand (0% - 50%, with 10% Intervals)

C. Compaction Characteristics

The initial specimen tested was the untreated clay soil sample (KBS0%). This test aimed to evaluate the initial compaction characteristics of the clay soil prior to stabilization with Kupa beach sand. The results are presented in **Figure 3**.

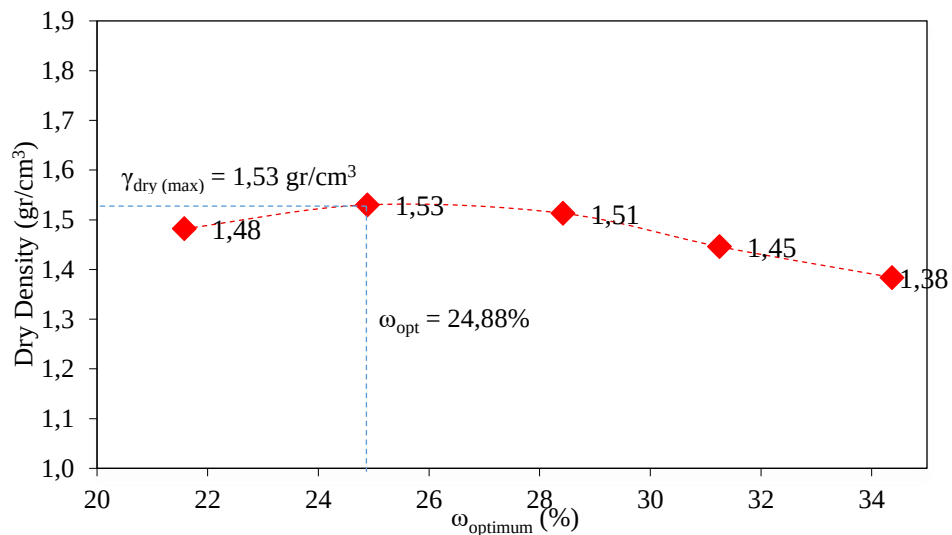


Figure 3 Compaction Test Result of Untreated Clay Soil (KBS0%)

The compaction test result on untreated clay soil (KBS0%) is presented in **Figure 3**. The dry density increased to 1.53 gr/cm³ at an optimum water content of 24.88%, but decreased significantly when the water content exceeded this value. Therefore, the maximum dry density (γ_{dmax}) of the clay soil is 1.53 gr/cm³.

Next, clay soil samples mixed with Kupa beach sand (KBS) in proportions ranging from 10% to 50% (at 10% intervals) were tested to determine their maximum dry density (MDD) and optimum moisture content (OMC), respectively. The results are presented in **Figure 4**.

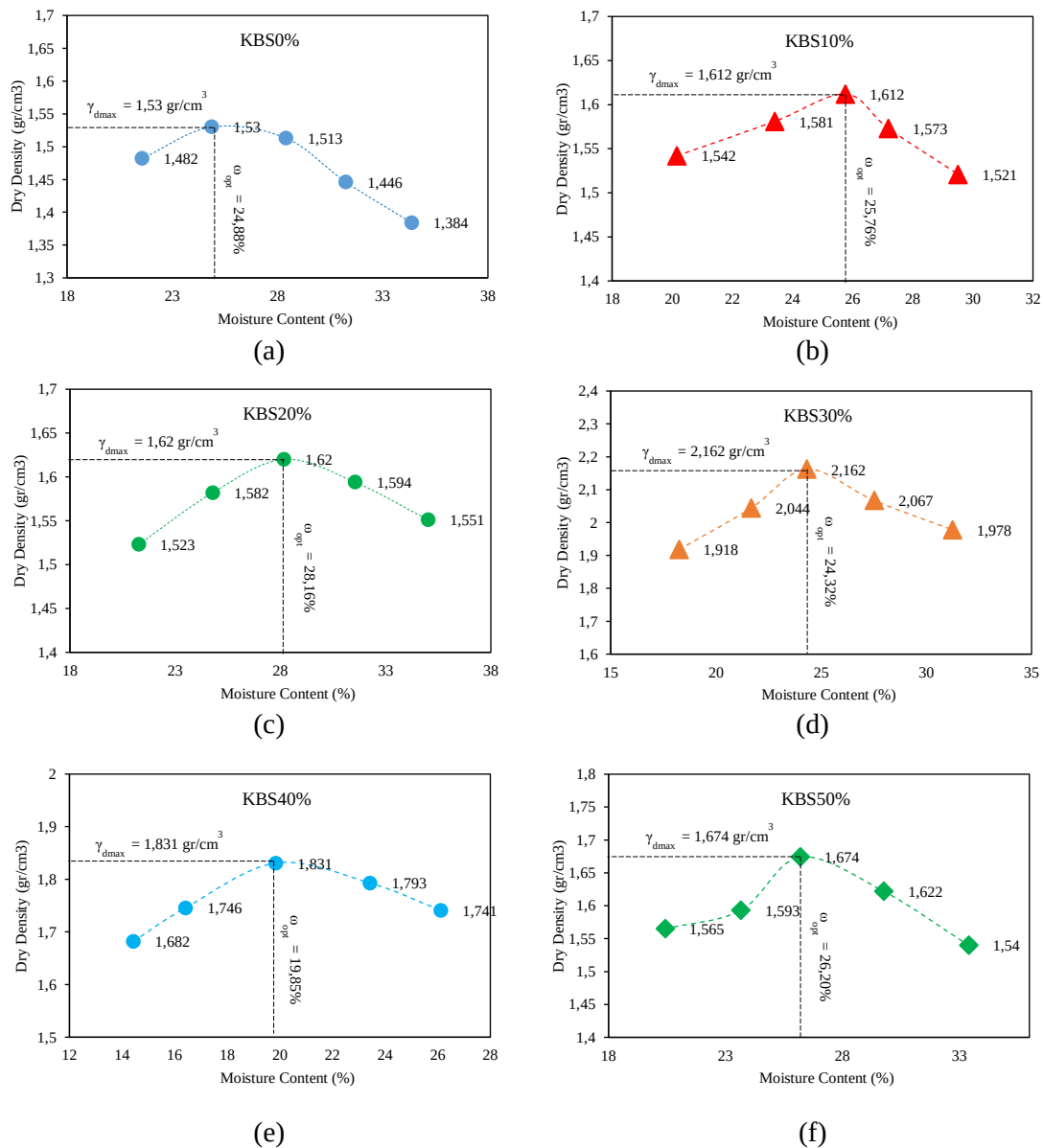


Figure 4 Compaction Test Result, (a) Untreated Clay Soil (KBS0%), (b) Clay Soil with 10% KBS, (c) Clay Soil with 20% KBS, (d) Clay Soil with 30% KBS, (e) Clay Soil with 40% KBS, (f) Clay Soil with 50% KBS

Based on **Figure 4**, each variation of Kupa Beach Sand (KBS0%–KBS50%) shows distinct trends in dry density and moisture content. The corresponding maximum dry densities (MDD) for KBS0% to KBS50% were 1,530 g/cm³, 1,612 g/cm³, 1,620 g/cm³, 2,162 g/cm³, 1,831 g/cm³, and 1,674 g/cm³, respectively. The corresponding optimum moisture contents (OMC) were 24,88%, 25,76%, 28,16%, 24,32%, 19,85%, and 26,20%. Overall, the incorporation of Kupa Beach Sand (KBS) significantly influenced the compaction characteristics of the clay. Dry density increased progressively up to 30% KBS, indicating that sand addition enhanced particle interlocking and reduced void spaces. The peak MDD of 2,162 g/cm³ was obtained at 30% KBS, representing the optimum mixture ratio. At this level, sand particles effectively filled the voids between clay particles while maintaining sufficient clay content to ensure cohesion and particle bonding. Beyond 30% KBS, the

MDD decreased, likely due to excessive sand disrupting the cohesive matrix and reducing compaction efficiency.

In summary, the optimum mixture was achieved at 30% Kupa Beach Sand (KBS30%) and optimum moisture content (24,32%), resulting in the most efficient compaction behavior. This composition was selected for California Bearing Ratio (CBR) laboratory test to evaluate the bearing capacity under different soaking durations.

D. Bearing Capacity (CBR) Performance

The clay soil mixed with 30% Kupa Beach Sand (KBS30%) was tested using the CBR method, and the results are presented in **Table 3**. The table compares the CBR values of untreated clay (KBS0%) and the stabilized sample (KBS30%) under soaking durations of 0, 7, 14, and 21 days.

Table 3 California Bearing Ratio (CBR) Test Results of Untreated Clay (KBS0%) and Clay Stabilized with 30% Kupa Beach Sand (KBS30%) under Different Soaking Durations (0, 7, 14, and 21 Days)

Kupa Beach Sand (%)	Blow (N)	Penetration (inch)	CBR (%)			
			0 day	7 days	14 days	21 days
KBS0%	10	0,1	3,675	2,427	2,054	1,701
		0,2	3,880	2,531	2,220	1,740
	25	0,1	6,210	4,122	3,237	2,179
		0,2	5,895	4,540	3,528	2,353
	56	0,1	7,350	6,265	4,260	3,220
		0,2	7,638	6,520	4,641	3,546
KBS30%	10	0,1	23,320	20,248	15,817	9,853
		0,2	28,250	23,430	16,302	10,094
	25	0,1	31,412	24,204	18,092	13,608
		0,2	34,470	29,152	22,340	15,063
	56	0,1	31,721	28,771	25,569	19,504
		0,2	38,227	33,986	26,120	20,672

Table 3 summarizes the CBR values obtained from laboratory testing, whereas **Figure 5** provides a graphical representation of these results. The plotted trend further visualizes the decline in CBR values with increasing soaking duration and the performance of the 30% KBS-stabilized soil compared to the untreated sample.

Clear difference in bearing capacity is observed between untreated clay (KBS0%) and clay stabilized with 30% Kupa Beach Sand (KBS30%) across all soaking durations, based on **Figure 5**. In the unsoaked condition (0 day), KBS0% exhibits 7,638% CBR value, while KBS30% achieves 38,227%, showing an improvement about 30,589%. This significant increase indicates that the addition of Kupa beach sand enhances particle interlocking, reduces clay plasticity, and improves compaction, leading to higher density and strength.

During the soaking process, both samples experience a gradual reduction in CBR values. Between 0 and 7 days, KBS30% decreases from 38,227% to 33,986%, while KBS0% drops from 7,638% to 6,520%. The most pronounced decline occurs between 7 and 14 days, where KBS30% decreases to 26,120%, and KBS0% drops to 4,641%, suggesting that prolonged water infiltration weakens the interparticle bonding and frictional resistance.

After 21 days of soaking, the stabilized sample (KBS30%) still maintains a relatively high CBR value of 20,672%, compared to 3,546% for untreated clay. Although this represents a reduction of 45,92% from its initial value, the mixture retains a significantly higher residual strength. This demonstrates that the incorporating of Kupa Beach Sand effectively

enhances the soil's bearing capacity and improves its durability under prolonged soaking conditions, making it a promising stabilizing agent for subgrade improvement.

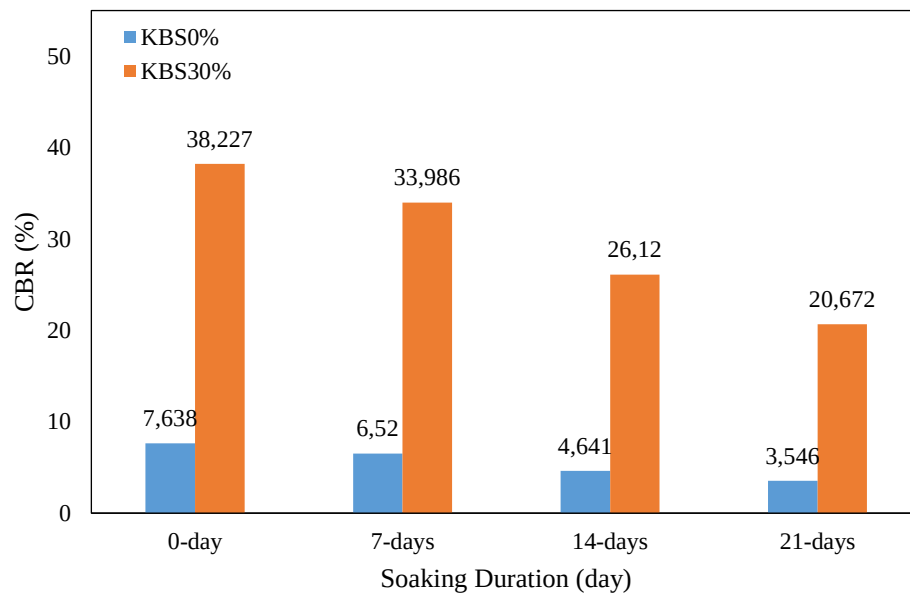


Figure 5 Comparison of CBR Value on Untreated Clay Soil (KBS0%) and Clay Soil with 30% Kupa Beach Sand (KBS30%)

E. Plasticity Characteristics

The sample with the highest bearing capacity (CBR), namely 30% Kupa beach sand (KBS30%), then tested for Atterberg limits to determine its plasticity characteristics. The Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI) are presented as the outcomes of the Atterberg limit test, particularly for conditions before and after soaking under different durations. **Table 4** presents the results of the Atterberg Limit test.

Table 4 Plasticity Characteristics of Clay Soil Specimens Stabilized with 30% Beach Sand (KBS30%) under Different Soaked Durations

Kupa Beach Sand (%)		Atterberg Limit (%)			
		0 Hari	7 Hari	14 Hari	21 Hari
KBS0%	LL	59,64	65,58	66,51	67,05
	PL	18,70	23,06	21,91	21,64
	PI	40,94	42,52	44,60	45,41
KBS30%	LL	15,70	25,04	31,05	34,30
	PL	9,52	13,46	15,07	17,21
	PI	6,18	11,58	15,98	17,09

The test results presented in **Table 4** and **Figure 6** indicate that the plasticity characteristics of clay soil specimen soil (KBS0%) tends to increase with longer soaking durations. The Liquid Limit (LL) increase from 59,64% on day 0 to 67,05% on day 21, while the Plastic Limit (PL) showed fluctuating increase, rising from 18,70%, 23,06%, 21,91%, and 21,64%. Consequently, the Plasticity Index (PI) consistently remained within a high range, approximately 40,94% – 45,41%. This condition suggests that clay soil specimen soil can be classified as highly plastic clay, making it highly susceptible to volumetric changes

under water-saturated conditions and potentially compromising the stability of the subgrade layer.

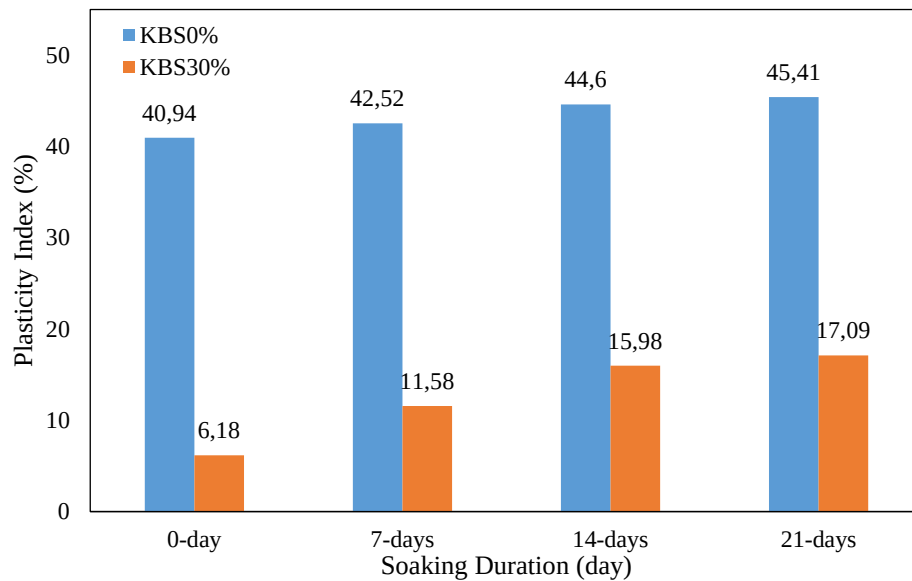


Figure 6 Comparison of Plasticity Between Untreated Clay Soil (KBS0%) Specimens and Clay Stabilized with 30% Beach Sand (KBS30%) Under Different Soaked Durations

In contrast, clay soil stabilized with 30% Kupa beach sand (KBS30%) exhibited a different trend. The initial LL was considerably lower, only 15,70%, although it increased to 34,30% after 21 days of soaking. Similarly, the PL values were lower compared to KBS0%, ranging from 9,52% to 17,21%. The PI showed a substantial reduction from 40,94% in clay soil specimen to only 6,18% at the initial condition of KBS30%. Although it increased to 17,09% after 21 days of soaking, the PI remained significantly lower than clay soil specimen. These results demonstrate that the incorporation of beach sand effectively decreases the soil's plasticity and enhances its stability, even under saturated conditions.

F. Discussion

a) Bearing Capacity (CBR) of Clay Soil Stabilized with Beach Sand after Soaking with Different Durations

The addition of beach sand significantly increased the CBR values of clay soil, even after being subjected to soaking in different soaking durations. In the unsoaked condition, untreated clay soil (KBS0%) had only 7,638% CBR value, whereas the mixture containing 30% beach sand (KBS30%) reached 38,227%. The difference in CBR value between before and after stabilized 30% beach sand (KBS30%) is 38,227%, which indicate that the sand fraction plays a crucial role to improve gradation and reduces soil porosity. Mechanically, coarse sand grains fill the voids between clay particles, forming a denser structure and enhances the soil's bearing capacity.

This finding is consistent with the research results of Fathonah et al. (2022), who reported that adding beach sand to clay soil can significantly increase CBR values more than 30% at the optimum content, as sand functions as a granular skeleton that enhances soil gradation and reduces the influence of moisture variations. Similar conclusions were drawn by Simanjuntak et al. (2017) and Sitinjak et al. (2021), who found that

incorporating beach sand into clay subgrade increased CBR, with the optimum values achieved at 30–40% beach sand content. In addition, Banyhussan et al. (2025) observed that using granular sand-based material increased the CBR of clay soil by up to 63% at 15% sand content compared to untreated soil.

Despite this initial improvement, the soaking test results revealed a decreasing trend in CBR with longer soaking durations, with the sharpest reduction occurring between 7 and 14 days. Under saturated conditions, the bonding between clay particles become lower, causing the sand no longer function effectively as a void filler. Banyhussan et al. (2025) explained this phenomenon as the migration of fine clay particles into the voids between sand grains, which decreases contact between granular particles and weakens the soil skeleton.

Nevertheless, the stabilization effect of beach sand remained significant even after 21-day soaking duration. After 21 days, the CBR value of the stabilized mixture (KBS30%) remained at 20,672%, which is still higher than KBS0% (3,546%). In summary, this study demonstrates that Kupa beach sand can effectively serve as a natural stabilizing material for clay soils. The higher optimum content was identified at 30% (KBS30%), which offers the best balance between increased density, enhanced bearing capacity, and acceptable resistance to soaking effects.

b) Plasticity of Clay Soil which Stabilized with Beach Sand after Soaking with Different Durations

The Atterberg limit test results show differences in plasticity behavior between untreated clay (KBS0%) and clay stabilized with 30% Kupa Beach Sand (KBS30%). For the untreated clay (KBS0%), both the Liquid Limit (LL) and Plastic Limit (PL) increased with soaking duration, from 59,64% to 67,05% and from 18,70% to 21,64%, respectively. Consequently, the Plasticity Index (PI) ranged from 40,94% to 45,41%, classifying the soil as *high-plasticity clay*. This high PI value indicates that the clay possesses a strong affinity for water and a significant potential for volume change, which can reduce its long-term stability under saturated conditions.

In contrast, the KBS30% mixture exhibited a substantial reduction in plasticity. The LL increased moderately from 15,70% (unsoaked) to 34,30% (21 days soaked), and the PL rose from 9,52% to 17,21%. Most importantly, PI dropped from over 40% in clay soil specimen to only 6,18% in KBS30% at the initial condition, and after 21 days of soaking, PI remained considerably lower than clay soil specimen. This reduction in PI signifies a major improvement in soil behavior.

These findings align with previous studies. Alnmr & Ray (2024) reported that sand addition to expansive clay systematically decreases LL and PI, thereby mitigating volume change susceptibility. Meddah et al. (2022) further observed that the incorporation of sand and lime into highly plastic clay effectively reduces PI, with optimum stabilization occurring at specific sand contents. Moreover, Kim et al. (2018) highlighted that the presence of sand particles in clay–sand mixtures not only reduce plasticity but also enhances the internal friction angle (ϕ), leading to improved shear strength and mechanical stability.

Overall, the reduction in LL and PI observed in the KBS30% mixture emphasizes the beneficial role of Kupa beach sand (KBS) in modifying soil structure by disrupting the dominance of clay particles. This transformation diminishes the soil's affinity for water, reduces deformation under wet conditions, and enhances its engineering suitability as a subgrade material, particularly in areas prone to flooding or high groundwater levels.

4. CONCLUSION

The findings indicate that the stabilization of clay soil with Kupa beach sand, particularly at optimum content (30% Kupa beach sand) significantly improves its engineering properties. The addition of sand increased the California Bearing Ratio (CBR) from 7,638% at KBS0% to 38,227% at KBS30% under unsoaked conditions. While prolonged soaking reduced CBR values due to weakened bonding among the particles in saturated conditions, the stabilized mixture still maintained a much higher CBR (20,672%) compared to KBS0% (3,546%) after 21 days, confirming the durability of sand stabilization.

In terms of plasticity, the incorporation of 30% beach sand drastically reduced the Plasticity Index (PI) from over 40% in clay soil specimen only 6,18% in the stabilized clay soil (KBS30%), with values remaining significantly lower even after extended soaking. This reduction reflects improved soil stability, reduced susceptibility to volumetric changes, and enhanced suitability as subgrade material under fluctuating moisture conditions. Overall, the results validate the potential of Kupa beach sand as an effective stabilizing material for clay soil, capable of increasing bearing capacity while reducing plasticity.

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