

Environmental Utilization of Gorgan Bay Sludge Ash in Stabilizing Clay Soils with Different Plasticity

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Article Info	ABSTRACT
Article type: Research Article	Objective: This study presents a technical soil stabilization solution by utilizing Gorgan Bay sludge ash (GBSA), a processed, problematic environmental by-product, for the stabilization of clayey soils with varying plasticity characteristics.” Methods: In the present study, the feasibility of using Gorgan Bay sludge ash as a pozzolanic additive for clay soil improvement while reducing the environmental impact of waste disposal was experimentally investigated. For this purpose, a wide range of clay soils, including four samples with plasticity indices of 21, 32, 40, and 68, were selected and blended with GBSA at weight fractions of 0%, 5%, 10%, 15%, 20%, and 25% based on the dry weight of the base soil. The mechanical properties of the specimens were evaluated using Atterberg limits, standard Proctor compaction, and unconfined compressive strength (UCS) tests (at curing ages of 1, 7, 28, and 56 days). Results: Experimental results show that the maximum dry unit weight increased by 5–7%, peaking consistently at 15% additive content. For strength parameters, the optimum GBSA dosage for peak UCS was 15% for lower-plasticity soils and 20% for higher-plasticity soils, indicating that additive demand scales with the initial plasticity index. At the 56-day curing mark, the relative UCS improvement ranged from 193% to 297%, with the most plastic soil (PI = 68) achieving the highest gain. While strength and density showed distinct optima, the plasticity index decreased continuously, reaching a total reduction of 58% to 75% at the 25% ash level. “These quantitative shifts, possibly associated with pozzolanic reactions and the high specific gravity of GBSA ($G_s = 2.73$), suggest that GBSA is a highly efficient stabilizer, particularly for high-plasticity (CH) clays.” Conclusions: These findings identify Gorgan Bay sludge ash as an effective additive for stabilizing problematic clay soils and offer a practical, low-cost approach for the environmentally sustainable management of this sediment waste in the region.
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1.Introduction

Gorgan Bay, as one of the most important coastal habitats in the southeastern Caspian Sea, has in recent decades faced the growing problem of sediment accumulation. This gradual deposition has obstructed the water conveyance channels at the bay entrance, leading to water recession and reduced exchange with the sea; if this process continues, it may result in the permanent drying of large portions of Gorgan Bay. Dredging and sediment relocation, which are commonly used as sediment-removal measures, do not provide long-term effectiveness because the sediments return to the bay bed under hydrodynamic forces. As a result, the process is practically ineffective and requires costly and continuous repetition. In addition to the high operational cost, this issue has created a serious environmental challenge regarding the disposal and management of the large volume of dredged sediments; therefore, identifying beneficial engineering applications for these sediments, rather than merely disposing of them, has become both a technical and economic necessity.

One of the common strategies for reducing the volume and environmental hazards of these muddy sediments is controlled incineration. The resulting mineral ash is rich in constituents such as silica, alumina, iron oxide, and calcium oxide, which suggests a potential for pozzolanic activity when mixed with clay (Pesarakloo et al., 2024). Although this ash substantially reduces the volume of waste, it still requires final disposal or a beneficial application.

From a geotechnical engineering perspective, clay soils pose major challenges in civil engineering projects due to their low shear strength and high compressibility. The addition of sludge ash to these soils is likely to promote pozzolanic reactions, in which reactive siliceous and aluminous compounds may interact with available calcium to potentially form calcium silicate hydrate (C-S-H)¹ and calcium aluminate hydrate (C-A-H)² gels. These reaction products could potentially densify the soil matrix by filling voids between clay particles and contributing to interparticle bonding. Consequently, the observed reduction in the plasticity index and the increase in unconfined compressive strength suggest a significant improvement in the engineering behavior of the soil, consistent with findings in similar studies (Consoli et al., 2011).

From an environmental perspective, using Gorgan Bay sludge ash in soil stabilization projects simultaneously fulfills two complementary environmental objectives. On the one hand, this approach prevents further accumulation of sludge in the bay bed and the resulting consequences, such as dust generation under wind action, reduction in dissolved oxygen, destruction of aquatic habitats, and increased nutrient loading. On the other hand, replacing part of conventional construction materials such as lime and cement with this recycled material significantly reduces CO₂ emissions associated with the production of these materials. This is

¹ $x\text{Ca}(\text{OH})_2 + \text{SiO}_2 + y\text{H}_2\text{O} \rightarrow \text{CaO} \cdot \text{SiO}_2 \cdot n\text{H}_2\text{O}$ (C-S-H) — calcium silicate hydrate

² $x\text{Ca}(\text{OH})_2 + \text{Al}_2\text{O}_3 + y\text{H}_2\text{O} \rightarrow \text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot n\text{H}_2\text{O}$ (C-A-H) — calcium aluminate hydrate

“These equations are presented as the expected pozzolanic pathways based on the chemical composition of GBSA and reported behavior of similar stabilizers.”

consistent with Iran's environmental commitments under international climate-change agreements and constitutes an effective step toward reducing the carbon footprint of the construction industry (Negahdar & Tohidi, 2025).

Integrating Gorgan Bay sludge ash into infrastructure projects supports circular-economy principles by transforming dredged waste into a viable stabilization resource. Unlike traditional stabilizers such as lime or cement, this ash offers significant economic advantages because of its lower material costs and regional availability in the southern Caspian Sea, which further minimizes logistical expenditures. Consequently, this approach presents a sustainable and cost-effective alternative for local engineering applications.

Numerous studies have been conducted on the stabilization of fine-grained soils using industrial waste and organic ash materials, and the most relevant findings to the present study are discussed below.

Kadhim, Al-adhamii, and Fattah (2021) examined the feasibility of using sewage sludge ash (SSA) as a stabilizer for soft clay soil. UCS, California bearing ratio (CBR), Proctor compaction, and Atterberg limits tests were conducted on samples with different percentages of SSA. The results showed that adding 10% SSA produced the best UCS performance during the 28-day curing period, and the CBR values of the samples increased significantly. The pozzolanic reaction was time-dependent, and compressive strength improved continuously with increasing curing time (Kadhim et al., 2021).

In another study, Karim and Akinkunmi (2021) used incinerated sewage sludge ash (SSA) as a soil stabilizing agent. X-ray fluorescence (XRF) analysis showed that SSA contained 61.42% silica and 23.51% alumina, indicating considerable pozzolanic capacity. Medium-plasticity clay soil was mixed with 3%, 5%, 7%, and 10% SSA, and California bearing ratio, unconfined compressive strength, compaction, and Atterberg limits tests were performed. The results indicated that 7% SSA gave the best outcome, reducing the plasticity index from 21% to 7% and improving the soil classification from A-7 to A-2 (Karim and akinkunmi, 2021).

Pourakbar et al. (2025) investigated the feasibility of using alkali-activated sludge (AASS) as a binder for stabilizing clay soil. They used sludge in amounts of 1.5%, 2%, 2.5%, 3.5%, and 4.5% with sodium and potassium activators to prepare a geopolymer binder. Unconfined compressive strength (UCS) and direct shear tests were performed. The results showed that the unconfined compressive strength increased to above 345 kPa after stabilization. The addition of sodium hydroxide and sodium silicate to the sludge mixed with soil, after 56 days of curing, resulted in a uniaxial compressive strength of 1.46 MPa (Pourakbar et al., 2025).

Sah et al. (2025) conducted a comprehensive review of the physical and geotechnical properties of sewage sludge ash in road subgrade soils, including Atterberg limits, compaction characteristics, California bearing ratio, unconfined compressive strength, swelling, and permeability. Based on the studies, sewage sludge ash can improve soil mechanical strength and reduce the swelling behavior of expansive soils due to its pozzolanic activity. The

combination of sewage sludge ash with cement, lime, and fly ash showed better performance than the use of sewage sludge ash alone (Sah, Sah and Kumar, 2025).

Cabalar et al. (2026) investigated the effect of sewage sludge ash as a sustainable stabilizing agent for clay soil. Sewage sludge ash was mixed with soil at 0, 5, 10, 15, 20, and 30%, and Atterberg limits, compaction, falling cone, and unconfined compressive strength tests were conducted. The results showed that with increasing sewage sludge ash content up to 30%, the maximum dry unit weight decreased by about 6% and the optimum moisture content increased by 14%. The sludge ash significantly improved shear strength, such that the UCS of specimens cured for 32 days reached 1351 kPa (Cabalar et al., 2026).

While studies on sewage sludge ash exist, the literature lacks a systematic assessment of Gorgan Bay sludge ash (GBSA) across clay soils of varying plasticity. This study addresses this gap by evaluating GBSA as a sustainable stabilizer and correlating initial soil plasticity with optimum dosage. Given GBSA's distinction from municipal sludge ash, conventional environmental concerns are not directly transferable; however, further leaching assessment is recommended prior to field-scale implementation.

The main objective of the present research is to experimentally investigate the effect of different percentages of Gorgan Bay sludge ash (GBSA) on the physical and mechanical properties of four clay soil samples with different plasticity indices. For this purpose, Atterberg limits, standard compaction, and unconfined compressive strength tests were performed on both untreated samples and samples stabilized with 0 to 25% additive relative to the dry mass of untreated soil. The results of this research may, in addition to providing a technical soil-improvement solution, facilitate the practical use of an environmentally problematic waste material in geotechnical engineering.

2.Laboratory Materials and Methods

The materials used in this research consisted of kaolinite and montmorillonite, which were mixed in four different proportions. GBSA was used as the stabilizing agent. The particle-size distribution curves of materials are shown in Figure1, and the chemical composition ratios of the materials are presented in Figure 2. The materials are introduced below.

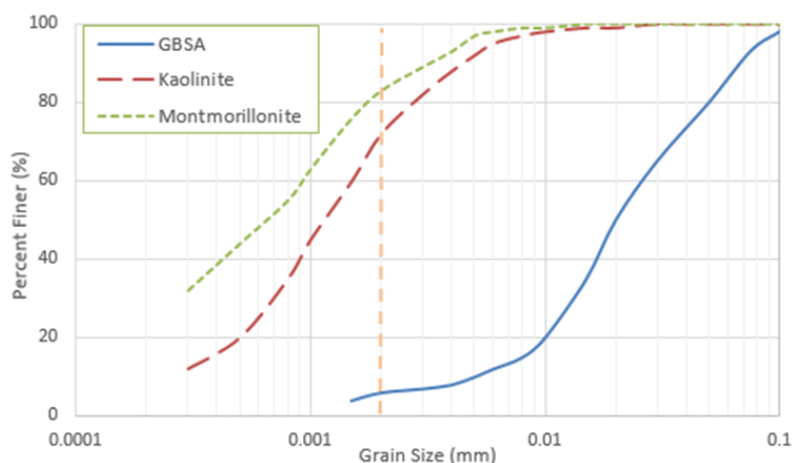


Figure 1- Particle-size distribution curves of kaolinite, montmorillonite, and GBSA

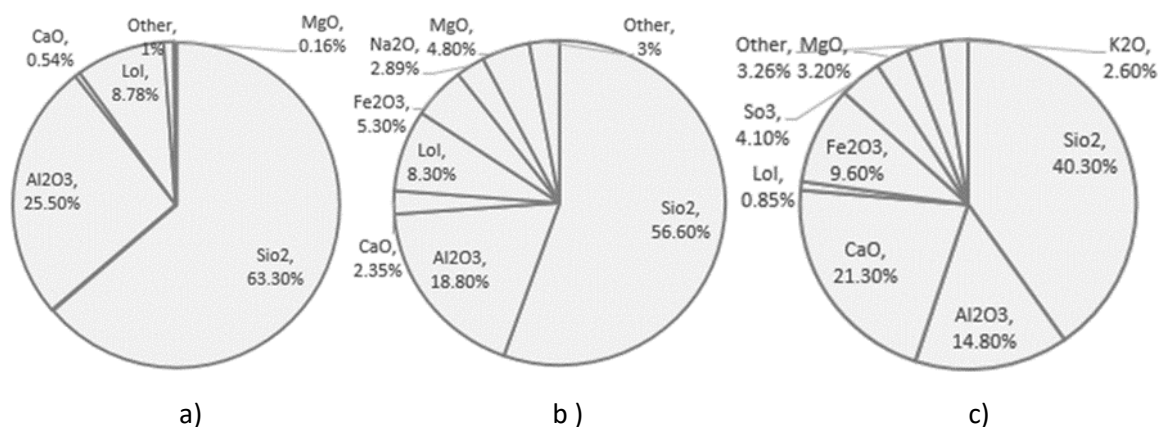


Figure 2: Chemical composition ratios (XRF analysis): (a) kaolinite, (b) montmorillonite, (c) GBSA

2.1. Kaolinite

Kaolinite has a specific surface area of 10 to 20 m²/g and a negligible cation exchange capacity. In general, it is formed by repetition and stacking of silica-gibbsite layers through hydrogen bonding (Rowe et al., 2005). In this study, the kaolinite clay mineral was used in the base soil at varying percentages. To prepare all specimens, the soil was first dried in an oven and passed through a No. 200 sieve. The composition ratios of the kaolinite clay are presented in Figure 2(a). The kaolinite used in this research was obtained from Iran chini soil Industries Company in Marand.

2.2. Montmorillonite

Montmorillonite, better known by the trade name bentonite, is one of the most well-known clays. The bonding between its layers is very weak, and water can easily penetrate between them; as a result of water absorption, it exhibits a high swelling capacity. In other words, this mineral has strong interlayer expansibility and high water absorption, and among clay minerals

it has the lowest chemical stability; therefore, its tendency to react and its reactivity are the highest among clay minerals (Zhang et al., 2025). The montmorillonite used in the study was obtained from the Semnan mine. The composition ratios of montmorillonite clay are presented in Figure 2(b).

2.3. Gorgan Bay sludge ash (GBSA)

In this research, Gorgan Bay sludge ash (GBSA) was used to improve soil strength. The Gorgan Bay sludge was collected from the dredged waterway between the Caspian Sea and Gorgan Bay (Figure 3, Region 2).

As noted previously, burning the sludge produces significant amounts of CaO , SiO_2 , and Al_2O_3 . One objective of this study was to determine the optimum temperature that produces most of these compounds. For this purpose, the results of thermogravimetric analysis (TGA) were used.



Figure 3-Geographic extent of accumulation and disposal sites of Gorgan Bay sediments

The presented diagram (Figure 4) shows the thermogravimetric analysis of the sludge over the temperature range of 25 to 1,000 °C. The weight curve (dashed line) shows a continuous decrease from 100% to about 84%, indicating the gradual loss of volatile materials, structural water, and organic matter. The DTG curve (blue line) reveals a clear and prominent peak at 715°C. This peak represents the maximum rate of weight loss at this temperature and is attributed to the decomposition of calcium carbonate (CaCO_3) into calcium oxide (CaO) and carbon dioxide (CO_2). This reaction, known as calcination, is one of the most important phase transformations in the sludge-burning process.

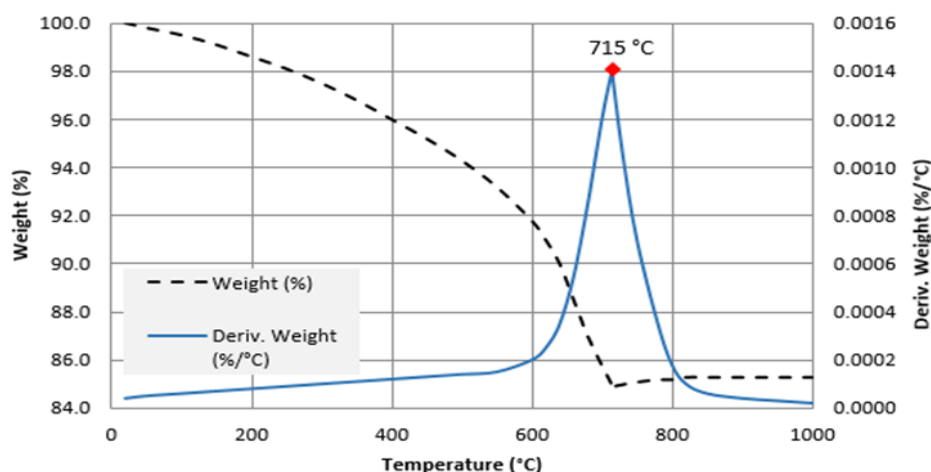


Figure 4- Thermogravimetric analysis (TGA) and derivative thermogravimetric (DTG) results of sludge ash.

At temperatures below 600°C, the weight loss rate is low and gradual, which is attributed to the evaporation of free and adsorbed moisture (below 200 °C) and the combustion of organic matter (300–600 °C). After the DTG peak at 715°C, the weight curve reaches a relatively stable plateau (approximately 84% to 85%), indicating that no major thermal transformations occur beyond this temperature.

Based on the TGA results and the literature, 715 °C was selected as the optimum range for GBSA production. In this range, organic matter is removed, which may contribute to improved engineering properties of the sludge ash (Mojtahed et al., 2023); carbonate decomposition is initiated or maximized; and crystalline phases have not yet become dominant. These conditions promote the formation of amorphous SiO_2 and Al_2O_3 , which are essential for pozzolanic reactivity in clay soils (Zhou et al., 2024).

The sludge ash produced at the optimum temperature, when mixed with clay soil and lime or cement, initiates pozzolanic reactions (C–S–H and C–A–H) that lead to a reduction in the plasticity index, an increase in unconfined compressive strength (UCS), a reduction in swelling behavior, and an improvement in the California Bearing Ratio (CBR) of the clay soil. These developments are dependent on the curing time, and optimum results are typically obtained after 28 to 90 days (Almuaythir et al., 2024).

Accordingly, the sludge was air-dried and calcined in a temperature-controlled electric furnace at 715 °C for 2 h to produce ash with a stable mineral composition, then sieved through No. 200 to obtain a particle size comparable to the clay fraction of the soil. As shown by the XRF results in Figure 2-c, the combined content of $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ is approximately 64.7%, placing the material within the Class C natural pozzolan range, while its relatively high CaO content (21.3%), attributed to carbonate-bearing coastal sediments and minerals, enhances its self-cementing potential compared with typical Class F fly ash (ASTM C618, 2019). Although no direct leaching or environmental characterization tests were performed, the thermal treatment, also supported by the TGA/DTG results in Figure 4, likely reduced unstable organic

constituents; however, further environmental assessment is still required before large-scale application (Liu and Wu, 2012; Shi et al., 2022).

2.4. Experimental Program and Additive Percentages

To cover a wide range of clay soil behavior and to take into account the effect of the plasticity index as an important parameter, different proportions of the clay minerals kaolinite and montmorillonite were mixed with one another in accordance with Table 1.

Table 1-Physical properties of the base clay soil samples investigated

Sample ID	Kaolinite (%)	Montmorillonite (%)	Liquid Limit, LL (%)	Plastic Limit, PL (%)	Plasticity Index, PI (%)	Maximum Dry Unit Weight, γ_{dmax} (kN/m ³)	Optimum Moisture Content (%)	Specific Gravity, Gs	USCS Classification
90K10M	90	10	45	24	21	17.8	15.2	2.65	CL
70K30M	70	30	60	28	32	16.1	20.7	2.67	CH
50K50M	50	50	73	33	40	15.5	25.3	2.69	CH
0K100M	0	100	112	44	68	14.2	30	2.70	CH

2.5. Sample Preparation

The materials for each mix design were blended until a homogeneous mixture was obtained. The GBSA dosage was calculated relative to the dry mass of the untreated soil, as expressed in Eq (1):

$$\text{GBSA content (\%)} = \times 100 \text{ (Eq. 1)} \left(\frac{M_{GBSA}}{M_{dry \text{ untreated soil}}} \right) \quad (1)$$

where M_{GBSA} is the mass of GBSA and $M_{dry \text{ untreated soil}}$ is the dry mass of the base soil. For example, a 15 wt.% GBSA dosage corresponds to adding 15 g of GBSA to 100 g of dry untreated soil. Next, the required amount of water was added based on the target moisture content, and mixing continued for approximately 6 to 8 min until the soil and GBSA were uniformly distributed. After sample preparation, the Atterberg limits and standard compaction tests were performed. For the UCS test, cylindrical specimens were prepared in a mold 38 mm in diameter and 76 mm in height. Before filling, the mold was lubricated, then the mixture was placed inside and compacted using a jack. The prepared specimens were weighed and their dimensions were checked before curing. To minimize moisture loss and ensure controlled strength development, the specimens were wrapped in thin plastic stretch film, sealed in airtight plastic bags, and stored in a curing chamber at 22 ± 1 °C and relative humidity above 95% for 1, 7, 28, and 56 days prior to testing (Figure 5).



Figure 5- Prepared samples

2.6.Laboratory Program

Table 2 provides an overview of the experimental program considered in this study. It summarizes the scope of the laboratory testing campaign and presents the overall distribution of the tests performed for evaluating the behavior of the soil-GBSA mixtures. The table also indicates the number of primary tests and the targeted repeated tests carried out to ensure the consistency and reliability of the experimental results.

Table 2- Summary of the laboratory testing program

Test Type	Reference Standard	Additive Content (%)	Curing Time	Baseline Tests	Targeted Retests	Total Tests
Atterberg limits	ASTM D4318	0, 5, 10, 15, 20, 25	after mixing	48	10	58
Standard compaction	ASTM D698	0, 5, 10, 15, 20, 25	after mixing	24	6	30
Unconfined compressive strength	ASTM D2166	0, 5, 10, 15, 20, 25	1, 7, 28, and 56 days	84	16	100

2.7.Atterberg Limits Test

The liquid limit test was performed using the Casagrande cup method, and the plastic limit test was carried out using the hand-rolling method, in accordance with ASTM D4318, on all soil–ash mixtures. The liquid limit is the moisture content at which the shear strength of the soil decreases to a very small value (about 2.5 kPa according to the Casagrande relationship), and the soil changes from the plastic state to the liquid state. This parameter is a suitable criterion for evaluating the effect of the additive on the hydrophilic behavior of clay minerals.

2.8.Standard Compaction Test

The standard Proctor compaction test was conducted in accordance with ASTM D698 to determine the moisture content–dry unit weight relationship for each soil–GBSA mixture, including additive contents up to 25%. For each combination, 4 to 5 target moisture contents were tested to define the compaction curve, and the maximum dry unit weight (γ_{dmax}) and

optimum moisture content (OMC) were determined directly from the highest measured dry unit weight point and its corresponding moisture content, without applying any curve fitting or interpolation. These parameters are essential for defining practical compaction conditions in geotechnical applications such as embankments and subbase layers.

2.9. Unconfined Compressive Strength Test

The unconfined compressive strength (UCS) test was carried out in accordance with ASTM D2166 on cylindrical specimens with a height-to-diameter ratio of 2 (38 mm in diameter and 76 mm in height) under a constant loading rate of 1 mm/min. This test is a rapid and commonly used index for evaluating the strength of stabilized cohesive soils. It was conducted at four curing ages (1, 7, 28, and 56 days) to investigate strength development from the early stages of reaction through the long term. Because temperature significantly affects uniaxial compressive strength (Sametzadeh et al., 2025), all specimens were cured under identical temperature conditions.

3. Results

3.1. Atterberg Limits Test

The results of the Atterberg limits tests for the four types of clay soil at different sludge ash contents (0 to 25%) show that, with increasing sludge ash content, the liquid limit decreases and the plastic limit increases in all samples, the direct consequence of which is a continuous reduction in the plasticity index up to the highest additive content tested (25%). Figure 6 shows a comparison of the variations in the plasticity index (PI) of the four soil samples as a function of sludge ash content

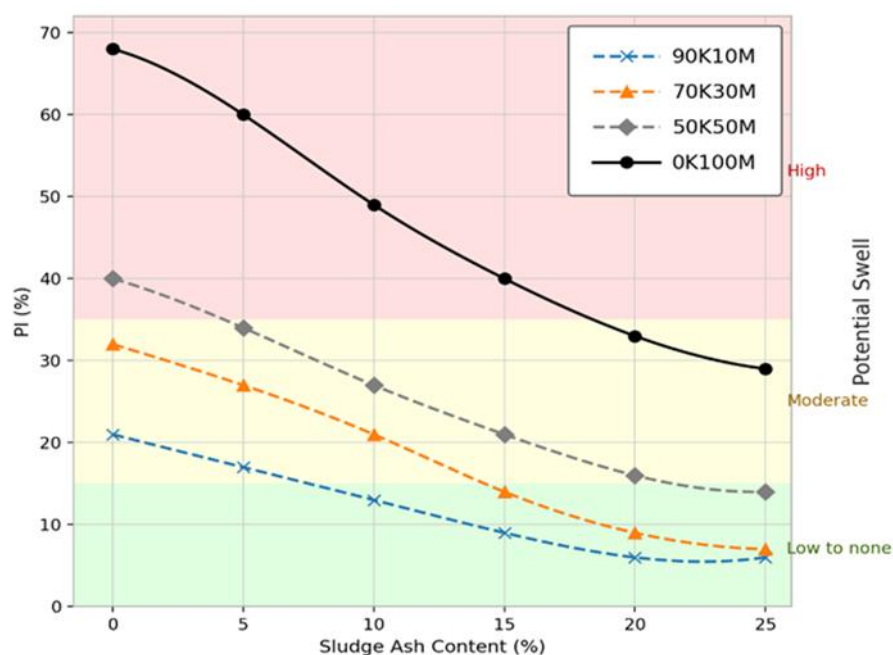


Figure 6- Comparison of plasticity index (PI) variations for the four soil samples versus the sludge ash additive percentage.

The decreasing trend of the plasticity index can be attributed to two main mechanisms: First, the instantaneous cation exchange reaction between free calcium ions present in the sludge ash (due to the CaO content of about 21%) and the sodium and potassium cations adsorbed on the surface of the clay particles, which leads to a reduction in the thickness of the electrical double layer and the flocculation of clay particles; this phenomenon occurs immediately after mixing and causes an increase in the plastic limit (reduction in sensitivity to deformation at low moisture contents). Second, the reduction of the effective specific surface area of clay particles due to flocculation, which decreases the water requirement to reach the liquid state and lowers the liquid limit (Jalal, F.E., et al., 2020).

The 0K100M soil has the highest initial PI (~68%), and despite a relatively good reduction due to the addition of sludge ash, even at 25% sludge ash, it still remains at a PI of about 29% and does not leave the high swelling zone. This behavior demonstrates the high resistance of montmorillonite to stabilization with this type of additive. The 70K30M and 50K50M soils exhibit intermediate behavior. The 70K30M soil, with an initial PI of ~32%, enters the low swelling zone at 15% to 20% sludge ash, while the 50K50M soil, with an initial PI of ~40%, requires about 25% sludge ash to reach the same zone. The 90K10M soil, which is predominantly composed of kaolinite and has an initial PI of ~21%, moves to the low swelling zone with the addition of only 10% to 15% sludge ash, demonstrating the best response to stabilization with sludge ash.

Furthermore, the results indicate that the effectiveness of sludge ash is directly dependent on the mineralogical composition of the soil. The higher the montmorillonite ratio in the soil, the higher the percentage of sludge ash required to achieve an acceptable engineering plasticity index ($PI < 15\%$).

3.2. Standard Compaction Test

Figure 7 presents the compaction curves for different soil samples at various additive ratios. In contrast to many conventional soil stabilization studies using ordinary fly ash, in which the addition of ash consistently reduces the maximum dry unit weight, the results of the present study show a non-uniform trend with a distinct peak for γ_{dmax} . In all four soil samples, the maximum dry unit weight gradually increased as the additive content rose from 0 to 15%, after which a mild decreasing trend began from 15 to 20%, followed by a more noticeable drop at 25%. For the 90K10M sample, γ_{dmax} increased from 17.8 kN/m³ in the control condition to a peak of 18.7 kN/m³ at 15% additive content (an increase of approximately 5%), and then decreased to 17.6 kN/m³ at 25%, which is even slightly lower than the control value. A similar pattern, with varying magnitudes, was also observed in the other samples.

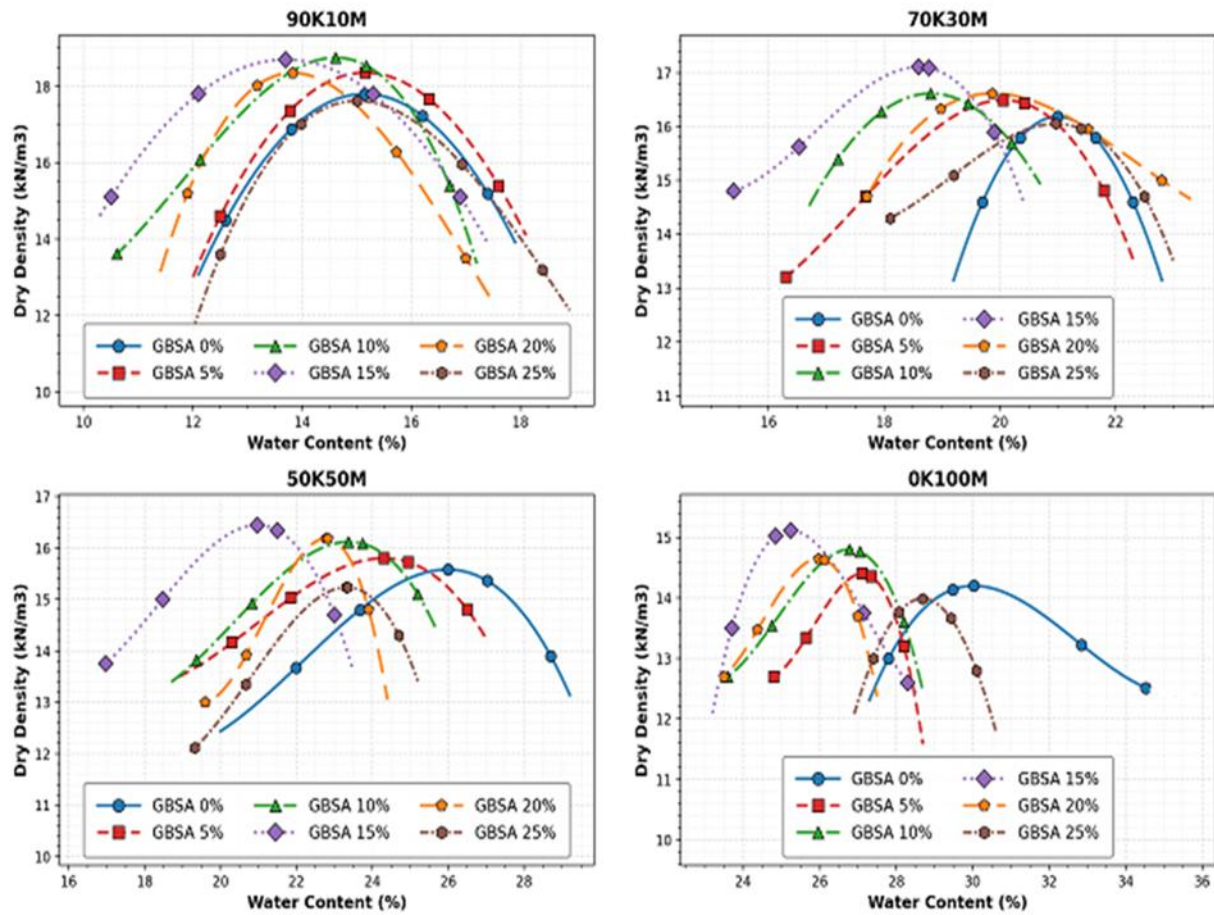


Figure 7- Standard compaction curves for the four soil samples.

The values of the maximum dry unit weight and optimum moisture content of soil-GBSA mixtures are listed in Table 3. Figure 8 shows the variations in maximum dry unit weight (γ_{dmax}), and Figure 9 shows the variations in optimum moisture content (OMC) versus the additive percentage.

Table 3- Maximum dry unit weight and optimum moisture content of soil-GBSA mixtures

Soil ID	0%	0%	5%	5%	10%	10%	15%	15%	20%	20%	25%	25%
	γ_{dmax}	w%	γ_{dmax}	w%	γ_{dmax}	w%	γ_{dmax}	w%	γ_{dmax}	w%	γ_{dmax}	w%
	kN/m³		kN/m³		kN/m³		kN/m³		kN/m³		kN/m³	
90K10M	17.8	15.2	18.2	14.6	18.6	14.1	18.7	13.6	18.3	14.1	17.6	14.8
70K30M	16.1	20.7	16.4	20.5	16.5	19.3	17.1	18.7	16.6	20.1	16.0	21.3
50K50M	15.5	25.3	15.7	23.5	16.1	23.1	16.3	21.6	16.0	22.3	15.2	23.6
0K100M	14.2	30.0	14.4	27.4	14.7	26.3	14.9	25.9	14.6	25.7	13.9	28.5

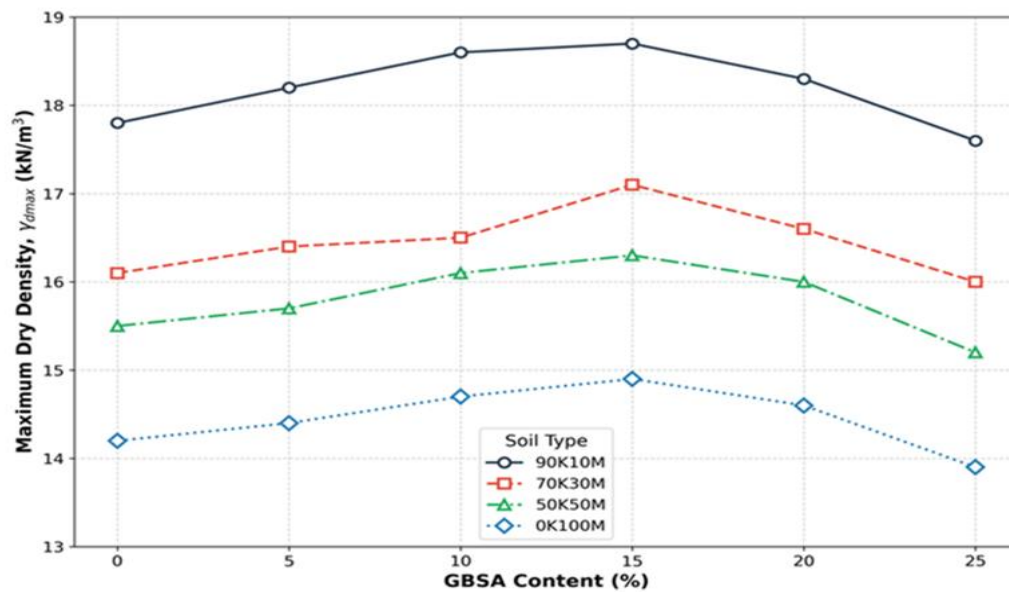


Figure 8-Variation in the maximum dry unit weight (γ_{dmax}) of the soil samples with additive content.

This non-uniform behavior is directly related to the physical characteristics of Gorgan Bay sludge ash. As described in the Materials and Methods section, the specific gravity of the ash particles ($G_s = 2.73$) is higher than that of the four soil samples. At low to moderate additive contents (up to about 15%), the fine, relatively dense ash particles occupy void spaces between the coarser clay particles, and this filling effect dominates the overall density of the mixture. Therefore, despite partial flocculation of the clay particles, the overall dry unit weight increases. However, as the additive content rises to 20–25%, the increasing number of ash particles begins to hinder optimal particle packing. A possible increase in particle aggregation or flocculation may also produce a more open, porous structure. These effects eventually outweigh the contribution of the dense ash particles, reducing the maximum dry unit weight at high additive contents (Kadhim et al., 2021).

Corresponding to this trend, the optimum moisture content (OMC) initially decreases as the additive content increases up to 15%, and then rises again up to 25%. This mirror-like pattern is fully consistent with the well-known inverse relationship between γ_{dmax} and OMC in compaction curves. The initial decrease in OMC can be attributed to the reduced amount of water required to fill the voids, since part of these voids are occupied by ash particles. In contrast, the subsequent increase at higher additive contents is associated with the increase in the overall specific surface area of the mixture, caused by the excess fine ash particles, and the resulting greater water demand for lubrication during compaction.

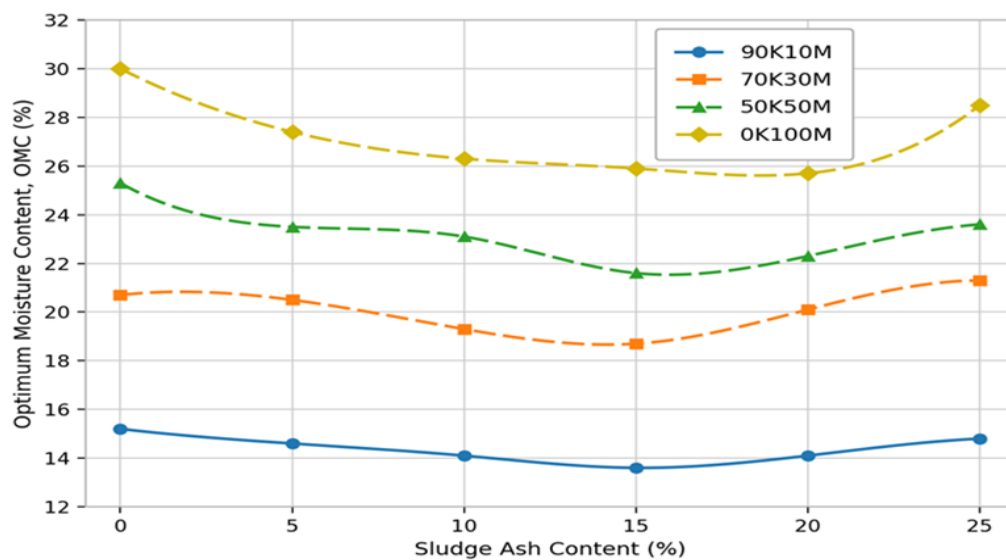


Figure 9- Variation of the optimum moisture content (OMC) of the four soil samples with additive content

From a practical perspective, this finding indicates that, unlike conventional lightweight pozzolanic additives (such as Class F fly ash with low specific gravity), the use of Gorgan Bay sludge ash up to the optimum content (approximately 15%) can simultaneously improve strength properties and contribute to a slight increase in the density of the compacted soil. In terms of reducing the required embankment volume to achieve a specified relative compaction, this may be regarded as an important constructional advantage

3.3.Unconfined Compressive Strength (UCS) Test

Figure 10 shows the results of the unconfined compressive strength (q_u) test at different additive ratios for specimens cured for 1, 7, 28, and 56 days. Figure 11 presents the improvement ratio (IR) of the unconfined compressive strength of the soil specimens at the optimum additive contents as a function of curing time.

Unconfined compression test results indicate that, across all four mix designs, the unconfined compressive strength q_u increases markedly as curing time extends from 1 to 56 days. This suggests that strengthening processes continue with time and that stronger bonds develop within the soil–ash matrix. Regarding the effect of sludge ash content, all specimens (considering plasticity index) exhibit a clear trend: strength increases with increasing ash content up to an optimum level and then decreases. This behavior implies that sludge ash acts as a reinforcing agent at low to moderate contents; however, at higher contents its effect becomes adverse due to dilution of the soil matrix and reduced effective interparticle contact.

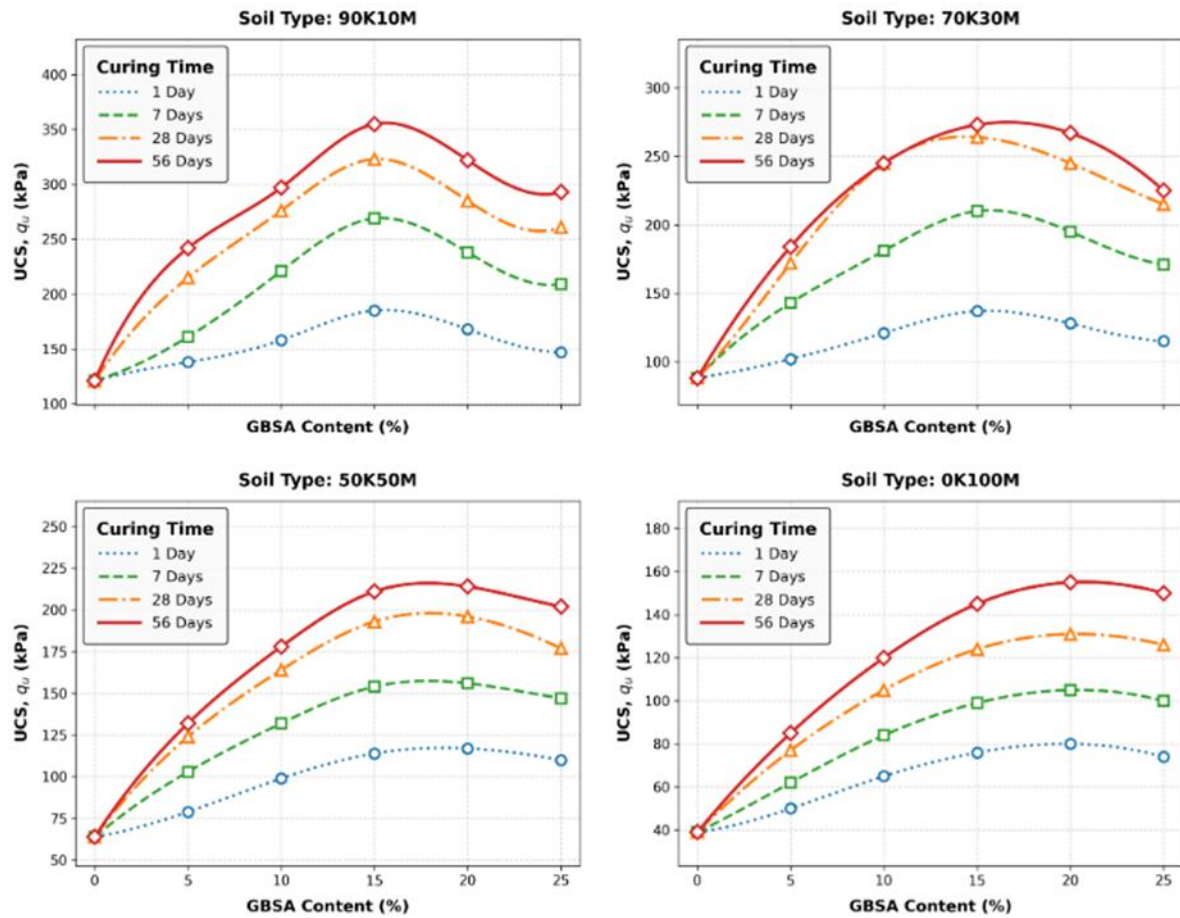


Figure 10- Trends of unconfined compressive strength (q_u) variations versus additive percentage at different curing times, presented separately for each soil samples.

For the 90K10M mixture, the maximum strength occurs at approximately 15% sludge ash, with q_u reaching about 355 kPa at 56 days. The same pattern is observed for 70K30M, with an optimum also around 15%, although the overall strength level is lower and the 56-day peak is approximately 275 kPa. These results indicate that as the proportion of sludge ash in the base mixture increases, the ability to achieve higher strengths is maintained, while the absolute strength level decreases. In 50K50M, the optimum shifts to about 20%, and the maximum 56-day strength is roughly 210 kPa. In 0K100M, the highest q_u is likewise obtained near 20% sludge ash, with a 56-day strength of about 155 kPa.

This non-linear response, which has an optimum point, is well documented in the soil-stabilization literature for pozzolanic materials and is commonly attributed to two mechanisms. First, below the optimum content, increasing the additive increases the availability of free calcium and reactive silica and alumina, thereby promoting pozzolanic reactions and the formation of cementitious products. Second, beyond the optimum, excess ash particles that do not participate in pozzolanic reactions may act as inert inclusions or structural weak points (e.g., potential slip planes or non-uniform agglomerations) within the soil fabric. This reduces overall

coherence and can lead to a relative decrease in strength (Toghraee et al., 2026). Accordingly, the optimum additive content varies with clay mineral type, and clays with a higher plasticity index generally require a higher additive dosage to achieve maximum unconfined compressive strength.

The strength improvement ratio (IR) in the optimal proportions with time (Figure 11) for the four curing ages of 1, 7, 28, and 56 days shows that at 1 day the strength difference between the control and stabilized specimens is still limited. However, this difference increases progressively with time, reaching more than twice the control strength at 56 days. The strength increase from 7 to 56 days (an increase of about 30–47%) in specimens containing the optimum additive content indicates that pozzolanic reactions are time-dependent. Unlike untreated clay—where strength gain is mainly associated with a reduction in natural moisture content during curing—strength development in sludge-ash-stabilized soils continues with a notable rate even up to 56 days, demonstrating the long-term and gradual nature of the mechanical improvement provided by this additive.

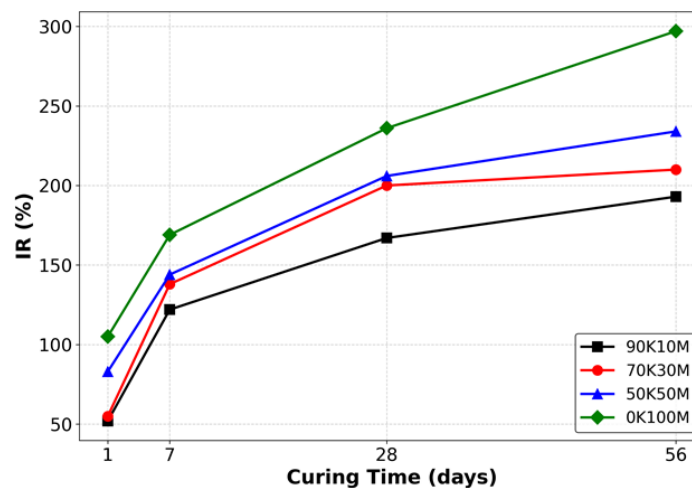


Figure 11- Strength improvement ratio (IR) at the optimum GBSA contents across different curing times

The investigation of the effect of the initial plasticity index on the degree of strength improvement indicates that the highest relative improvement in unconfined compressive strength at 20% additive content compared with the control condition at 56 days was observed for the 0K100M specimen with a plasticity index of 68 (an increase of 297%), whereas this value was about 193% for the 90K10M specimen with a plasticity index of 21. This finding suggests that soils with higher plasticity, which generally have lower inherent strength, exhibit greater potential for relative improvement when stabilized with sludge ash.

4. Discussion

The experimental findings demonstrate a clear correlation between the host soil's initial plasticity and the effectiveness of Gorgan Bay sludge ash (GBSA) as a stabilizer. Although

GBSA consistently improves the mechanical properties of all four soil mixtures, the magnitude of this improvement and the required dosage are governed by the clay's mineralogical composition, as also reported by Bakhtiari et al. (2024), and by the resulting stabilizer demand of the clay matrix.

The observed reduction in the plasticity index (PI) is particularly significant in high-plasticity soils such as 0K100M and 50K50M. This phenomenon is likely attributed to the cation exchange process, where divalent cations present in the GBSA promote the flocculation of clay particles. This process reduces the thickness of the diffuse double layer surrounding the montmorillonite particles, leading to a more granular-like behavior and reduced water affinity—a mechanism consistent with the findings of Aldaood et al. (2014) regarding chemical soil modification. In contrast, low-plasticity soils (90K10M) reach their stability threshold more rapidly due to the lower specific surface area and lower activity of kaolinite, which limits the extent of additional chemical interaction.

From the perspective of swelling susceptibility, the reduction in plasticity index (PI) shown in Figure 6 indicates that GBSA treatment shifted the studied soils from the high swelling potential range toward the moderate and low-to-none ranges. This trend suggests improved volumetric stability, particularly for the montmorillonite-rich mixtures. In addition, compaction can further limit swelling by reducing void ratio and restricting water ingress; however, its effect is also dependent on molding water content and soil structure (Seed et al., 1962, Aldaood et al. 2014). Although direct swell tests were beyond the scope of the present study, these findings provide preliminary evidence of reduced expansivity after GBSA treatment.

The compaction results (Table 3) provide further insight into the physical role of GBSA. The consistent trend of maximum dry unit weight (γ_{dmax}) increasing up to 15% additive content, regardless of soil type, suggests a dominant “filler effect.” Since GBSA has a specific gravity ($G_s = 2.73$) higher than or comparable to many clay minerals, its particles effectively occupy the interstitial voids within the soil fabric, leading to a denser packing. However, the subsequent decrease in γ_{dmax} beyond 15–20% additive indicates that an excess of fine ash particles may begin to interfere with the efficient rearrangement of soil grains during compaction, a trend similarly reported by Kannan et al. (2019) for industrial by-product additives.

The Unconfined Compressive Strength (UCS) results highlight a critical shift in the optimum additive content: 15% for lower-plasticity soils and 20% for higher-plasticity soils. This shift suggests that soils with higher clay activity require a greater quantity of GBSA to achieve effective particle-to-particle bridging and pozzolanic bonding. The relative strength gain is most pronounced in the 0K100M soil, which can be justified by its inherently low initial strength in the untreated state; the GBSA effectively “reinforces” this weak matrix through pore refinement and the formation of cementitious compounds over time. This dependency of the optimum dosage on the soil's clay fraction is in line with the observations of Kadhim et al. (2021).

In conclusion, while GBSA exhibits high efficiency in stabilizing highly plastic clayey soils (CH), the technical justification for using dosages beyond 20% diminishes from a structural strength perspective. However, higher percentages could still be strategically utilized for waste management purposes or for further reducing swelling potential if required. As highlighted by recent studies on sustainable soil stabilization (Mostafaei et al., 2026) and infrastructure protection (Asadoullahtabar et al., 2024), establishing GBSA as a reliable alternative to cement or lime requires careful consideration of soil-specific dosages.

Although this laboratory study demonstrates that GBSA effectively improves the index and strength properties of the tested clayey soils based on their plasticity, these findings represent short-term geotechnical improvement rather than guaranteed long-term field performance. A key limitation is the absence of direct microstructural and mineralogical characterizations (such as SEM and XRD); thus, the chemical stabilization mechanisms and pozzolanic reactions were inferred solely from macroscopic engineering behavior. Consequently, future studies incorporating microstructural analyses, durability testing, environmental leaching behavior, and field-scale trials are essential to verify the practical implementation and long-term sustainability of GBSA-stabilized subgrades.

5. Conclusions

This study experimentally investigated the effects of adding Gorgan Bay sludge ash at contents ranging from 0% to 25% on the physical and mechanical properties of four clay soil samples with plasticity indices of 21%, 32%, 40%, and 68%. The investigation included Atterberg limits, standard compaction, and unconfined compressive strength tests at curing ages of 1, 7, 28, and 56 days. The key findings are summarized as follows:

1. The addition of Gorgan Bay sludge ash led to a continuous decrease in the plasticity index across all specimens, even up to the highest tested content (25%). This reduction is attributed to cation exchange reactions and the flocculation of clay particles induced by free calcium ions present in the ash. The greatest relative reduction in the plasticity index was observed in the soil with the lower initial plasticity ($PI = 21$).
2. Standard compaction test results showed that the sludge ash additive, due to the relatively high specific gravity of the ash particles ($G_s = 2.73$) and the dominance of the void-filling effect, increases the maximum dry unit weight (γ_{dmax}) up to approximately 15% additive content. Beyond this threshold, the flocculation effect of clay particles overrides the weight effect of the ash particles, causing γ_{dmax} to decrease. The optimum moisture content exhibited a mirror-image behavior (initially decreasing, then increasing). This trend was observed across all four soil samples.
3. For soils with lower plasticity indices (90K10M and 70K30M), the unconfined compressive strength (q_u) increased continuously up to approximately 15% additive content, followed by a gradual decrease from 15% to 25%. This indicates an optimum additive content of approximately 15% for maximum strength improvement.

4. For soils with higher plasticity indices (50K50M and 0K100M), the unconfined compressive strength increased continuously up to approximately 20% additive content, followed by a gradual decrease from 20% to 25%. This indicates an optimum additive content of approximately 20% for maximum strength improvement.
5. Based on the results for clayey soils with different plasticity indices, the optimum additive percentage for unconfined compressive strength increases with an increase in the plasticity index.
6. The investigation of the strength development trend over four curing periods (1, 7, 28, and 56 days) revealed that strength development in the stabilized specimens, unlike the control specimens, continues at a significant rate even up to 56 days, reflecting the time-dependent nature of pozzolanic reactions.
7. The highest relative improvement in unconfined strength parameters was observed in the soil with the higher initial plasticity index (comparing the four specimens in the UCS test, the highest relative improvement belonged to the 0K100M0 specimen with PI = 68). This indicates that Gorgan Bay sludge ash has higher relative efficiency particularly for improving highly plastic clayey soils (CH), which are typically the most challenging engineering subgrades.
8. From an environmental perspective, utilizing sludge ash in soil stabilization is a practical approach to reduce the volume of waste sent to landfills, decrease the carbon footprint associated with cement consumption, and implement circular economy principles in waste management within the Gorgan Bay region.

Future research should include microstructural and mineralogical analyses (XRD, SEM, and EDS) to clarify the stabilization mechanisms and verify the formation of cementitious products. In addition, the swelling behavior, permeability, wetting–drying durability, and long-term field performance of GBSA-stabilized soils should be investigated. Environmental assessments, including leaching tests such as TCLP, are also recommended to confirm the suitability of GBSA for large-scale applications.

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