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Research Article

Sustainable stabilization of lean clay using fly ash, silica fume and GGBS: Effects on unconfined compressive strength and California bearing ratio

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Abstract

Lean clay soils are considered among the most problematic soil types in civil engineering due to their low shear strength and high compressibility, which necessitate remediation to limit post-construction settlement and ensure adequate bearing capacity. Chemical stabilization is widely adopted for improving such weak ground conditions, with cement and lime traditionally used as stabilizing agents. However, the high economic and environmental costs associated with these materials have encouraged researchers to explore more sustainable alternatives. The effect of supplementary stabilizing materials such as Fly ash (FA), Ground Granulated Blast Furnace Slag (GGBS) and Silica Fume (SF) on the unconfined compressive strength of soft soil are studied in this research work. The research aims to determine the strength characteristics (UCS) of varied eight mix proportions of (Fly Ash-GGBS-Silica Fume) are experimentally studied in the research. The unconfined compressive strength (UCS) test was conducted at curing periods of 3, 7, and 28 days to evaluate the performance of the treated soil. The results showed an increase in soil strength with the addition of these materials compared to natural soil. Among all mixtures, the R3 sample (20% fly ash, 9% GGBS, and 5% silica fume) exhibited the highest compressive strength, reaching 955 kPa at 28 days, indicating that this mix represents the best-performing tested mixture within the investigated dosage range for soil stabilization. The California Bearing Ratio (CBR) results showed significant improvement in the bearing capacity of the treated soil compared with untreated soil. This enhancement was mainly attributed to pozzolanic and cementitious reactions that produced C–S–H gel as reported in previous studies, improving particle bonding and reducing voids. Within the investigated dosage ranges, the mixture containing 20% Fly Ash, 9% GGBS, and 5% Silica Fume showed the best overall engineering performance in terms of UCS and CBR. Fly Ash improved soil structure, while GGBS increased soil stiffness and strength. Silica Fume enhanced soil densification and penetration resistance due to its ultrafine particles. However, excessive additive contents caused a slight reduction in CBR values because of increased fines content and water demand.

1. Introduction

Lean clay soils are considered among the weakest and most problematic soil types in geotechnical engineering due to their high compressibility, low shear strength, poor drainage characteristics, and excessive settlement behavior. These unfavorable engineering properties create major difficulties in the construction of foundations, highways, embankments, and other civil engineering structures. Furthermore, soft clay soils are highly sensitive to moisture changes, leading to

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instability and reduction in bearing capacity under loading conditions. Therefore, improving the engineering behavior of such soils has become an essential requirement in modern construction projects (Yang et al., [1]). Traditionally, cement and lime have been widely used as stabilizing agents to improve the strength and durability of weak soils. Although these conventional additives are effective in enhancing soil properties, their production processes consume large amounts of energy and generate significant carbon dioxide emissions, causing serious environmental concerns. Recent studies indicated that the cement industry contributes considerably to global greenhouse gas emissions, which has encouraged researchers to develop sustainable and eco-friendly alternatives for soil stabilization applications (Gong et al., [2]).

In recent years, industrial by-products such as Fly Ash (FA), Silica Fume (SF), and Ground Granulated Blast Furnace Slag (GGBS) have attracted significant attention as sustainable stabilizing materials due to their pozzolanic and cementitious properties. These materials contain high amounts of silica, alumina, and calcium compounds that chemically react with water and soil minerals to form cementitious products such as calcium silicate hydrate (C-S-H) gels. These reaction products improve the bonding between soil particles, reduce pore spaces, and significantly enhance the mechanical properties of soft soils. (Alam and Alselami, [3]). Devarangadi et al. [4] reported that the combined incorporation of Fly Ash, GGBS, and Silica Fume enhanced the engineering properties of expansive clay through pozzolanic reactions and microstructural densification, resulting in improved strength and reduced swelling potential. Sharif et al. [5] investigated the mechanical and economic performance of clayey soils stabilized with fly ash and lime. Their study revealed that incorporating 20% fly ash by dry weight of soil produced the highest improvements in shear strength, cohesion, and resilient modulus. Beyond this percentage, additional fly ash did not result in proportional strength gains. The authors attributed the enhanced performance to pozzolanic reactions between fly ash and lime, which generated cementitious compounds that densified the soil matrix. Moreover, the treated soils exhibited increased bearing capacity and reduced subgrade thickness requirements, confirming 20 % fly ash as the optimal content for balancing strength improvement and material efficiency.

Al-Gharbawi et al. [6] conducted experimental research on expansive clay soils treated with lime, cement, and silica fume. Multiple replacement levels of Silica Fume were tested, including 5%, 7%, and 9%. Results showed that 5 % silica fume provided substantial reductions in swelling potential and significant improvements in unconfined compressive strength, while higher SF percentages offered marginal additional gains. Microstructural analysis confirmed the formation of calcium silicate hydrate (C–S–H) gels that enhance soil particle bonding. These findings suggest that 5 % silica fume is the most effective dosage for improving both strength and durability of expansive clays. Behnood, A., & Gharehveran, M. M. [7] studied the stabilization of clayey soil using varying percentages of Ground Granulated Blast Furnace Slag (3%, 6%, 9%, and 12%) combined with a small percentage of quicklime as an activator. The research focused on evaluating unconfined compressive strength (UCS), shear strength parameters (cohesion and friction angle), and plasticity characteristics at different curing periods.

The findings indicated that mechanical properties improved significantly as GGBS content increased up to 9%. The 9% mixture demonstrated the most balanced and effective strength enhancement under the tested conditions. The improvement was attributed to lime-activated pozzolanic reactions leading to the formation of calcium silicate hydrate (C–S–H) gel. The authors emphasized that 9% was optimal for their soil type. However, the performance of multi-component stabilization systems depends on the interactions among the constituent materials rather than the individual effect of each stabilizer. Therefore, investigating ternary mixtures provides a more realistic evaluation of soil stabilization performance. This concept was highlighted by Khan et al. , [8] who emphasized the importance of multi-component interactions in determining the overall performance of composite systems. Although previous studies have reported the combined use of fly ash, GGBS, and silica fume for soil stabilization, most investigations have focused on different soil types, mixture proportions, or individual engineering properties. The present study evaluates selected ternary mixtures prepared within practical dosage ranges for stabilizing soft clay collected from Al-Mahaweel, Iraq. The engineering performance was assessed using both Unconfined Compressive Strength (UCS) and soaked California Bearing Ratio (CBR) tests under identical curing conditions. Therefore, this study contributes by providing a comparative evaluation of selected ternary formulations under unified testing conditions and identifies the best-performing tested mixture within the investigated dosage range. The specific objectives of the research are as follows:

- To determine the optimum blended proportion of Fly Ash, Silica Fume, and GGBS for improving the engineering properties of soft soil.
- To evaluate the effect of Fly Ash, Silica Fume, and GGBS on the Unconfined Compressive Strength (UCS) of soft soil.
- To investigate the influence of various additive contents and curing periods on the California Bearing Ratio (CBR) and strength characteristics of stabilized soft soil.
- To evaluate the influence of Fly Ash, GGBS, and Silica Fume on the strength development of soft soil at different curing periods.
- To promote the utilization of Fly Ash, GGBS, and Silica Fume as sustainable stabilizing materials for soft soil improvement.

The research methodology comprises the following features:

- Soil samples were collected from the selected site, air-dried, and prepared under controlled laboratory conditions to ensure uniformity and removal of impurities.
- Fly Ash, GGBS, and Silica Fume were prepared in different percentages and thoroughly mixed with the natural soil to obtain homogeneous stabilized soil mixtures.
- Unconfined Compressive Strength (UCS) test was performed on both untreated and treated soil samples to determine the improvement in shear strength and overall strength characteristics after stabilization.
- California Bearing Ratio (CBR) test was conducted to evaluate the improvement in bearing capacity and load-bearing behavior of the stabilized soil compared to natural soil.
- The methodology adopts the use of industrial by-products (fly ash, GGBS, and silica fume) as sustainable stabilizing agents in soil treatment, aiming to reduce environmental impact while improving soil engineering properties.

2. Materials and Methods

2.1. Materials

2.1.1. Soil

According to the Unified Soil Classification System (USCS), the natural soil used in this study is classified as lean clay (CL). The soil samples were collected from Al-Mahaweel city in Babylon, Iraq after removing the top surface layer within a depth ranging from 0.5 to 1.0 m to avoid organic matter and contaminants. The collected soil was transported to the laboratory and oven-dried at 110°C for 24 hours to remove moisture. After drying, the particle size distribution was determined as shown in Fig. 1, and the soil was pulverized and passed through sieve No. 4 to eliminate impurities and oversized particles before conducting laboratory tests. Table 1 below summarizes the engineering properties of the natural soil according to ASTM standards. The results indicate that the soil contains a high percentage of fine particles (clay and silt) with a plasticity index of 19%, suggesting moderate plasticity behavior. The obtained properties confirm the need for stabilization to enhance the soil performance for geotechnical applications.

Table 1. Engineering properties of the natural soil

Soil properties	Value	Specification
Color	Light brown	Visual Observation
LL (%)	44	ASTM D4318
PL (%)	25	ASTM D4318
PI(%)	19	ASTM D4318
Gravel (%)	0.4	ASTM D422
Sand (%)	11.6	ASTM D422
Silt (%)	41	ASTM D422
Clay (%)	47	ASTM D422

Soil properties	Value	Specification
Specific gravity (Gs)	2.7	ASTM D854
Optimum moisture content (ω%)	15.6	ASTM D698
Maximum Dry Density (ρ(g/cm^3))	1.72	ASTM D698
Unconfined Compressive Strength (UCS (kPa))	102	ASTM D2166
Soil Classification (USCS)	Lean Clay (CL)	ASTM D2487

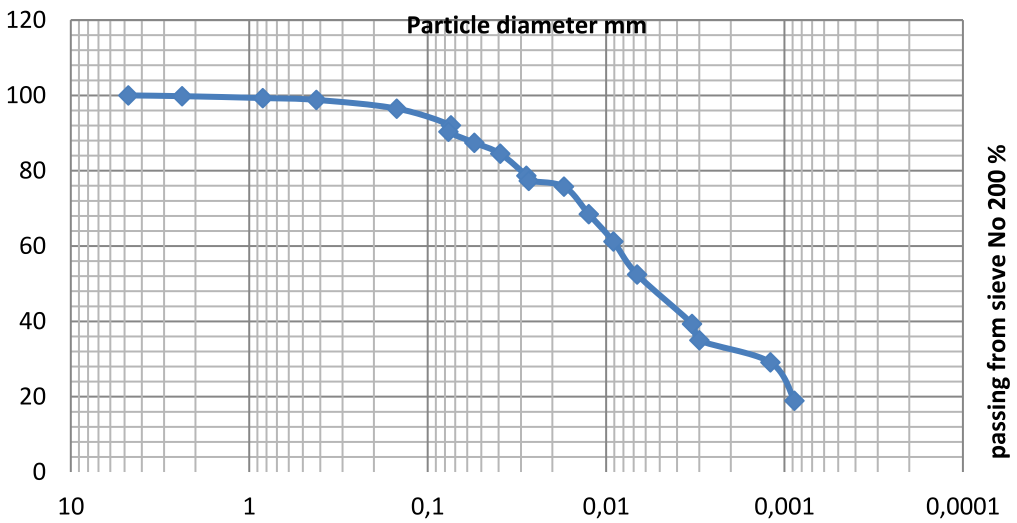

Fig. 1. Particle size distribution curve of the natural soil

2.1.2. Fly Ash

Fly ash (Type C) is a fine, powdery material that is widely used in civil engineering applications, particularly in soil stabilization. It was supplied by EUROBUILD Construction Chemicals, United Arab Emirates (UAE) and complied with ASTM C618 requirements. The physical and chemical properties of the fly ash are presented in Table 2. It is classified as a pozzolanic material because it contains reactive silica and alumina, which chemically react with calcium hydroxide in the presence of water to form cementitious compounds. These reactions improve strength, reduce permeability, and enhance the long-term durability of treated materials.

Table2. Physical and chemical properties of fly ash

Items test	SiO_2 + AL_2O3 + Fe_2O_3 SO_3	SO_3	Moisture Content %	LOI %	Fineness (+325)	Density	Autoclave Expansion	Water req.	Type of fly ash	Colors
Results	min 50%	max 5%	max 3%	max 6%	max 34%	max 5%	max 0.58%	max 105%	C	Light Grey

2.1.3. Silica Fume

Silica fume, also known as microsilica, is an ultrafine and highly reactive pozzolanic material primarily composed of amorphous silicon dioxide (SiO_2). The silica fume used in this study was obtained from Hebei Weiran Building Materials Technology Co., Ltd., China. The properties of Silica Fume as shown in table (3). It is widely used as a stabilizing additive for improving the engineering properties of clayey soils. When mixed with clay soil, silica fume enhances strength, reduces compressibility and swelling potential, and improves shear strength and bearing capacity. Due to its extremely fine particle size, silica fume fills the micro-voids between soil particles and reacts chemically with available calcium compounds to form cementitious products such as calcium silicate hydrate (C–S–H) gel as reported in previous studies. This reaction increases soil cohesion and overall stability.

Table 3. properties of silica fume

Test items	SiO_2 (%)	pH	C (%)	Water Content (%)	CaO (%)	Fe_2O_3 (%)	K_2O (%)	Al_2O_3 (%)	Density (kg/m^3)	Activity Index (%)
Results	85-92	7–8	≤ 3	≤ 1	≤ 1	≤ 2	≤ 2	≤ 1	550–680	≥ 105

2.1.4. GGBS

Ground Granulated Blast Furnace Slag (GGBS) is a finely ground cementitious material widely used in civil engineering applications, particularly in soil stabilization. It was supplied from China. The properties of GGBS as shown in table (4). It possesses latent hydraulic and pozzolanic properties, which contribute to improved strength, reduced permeability, and enhanced long-term durability of treated materials.

Table 4. Physical and chemical properties of ground granulated blast furnace slag (GGBS)

Test items	Fineness m^2/kg	Specific Surface Area m^2/kg	Density g/cm^3	Moisture Cont. %	Sulfur Trioxide (SO_3) Cont. %	Chloride Ion Cont. %	Loss on Ignition (LOI) %	Vitreous Cont. %	Activity Index at 7 Days %	Activity Index at 28 Days %	Relative Water Req. %
Results	490-510	418	2.9	0.1	0.3	0.02	0.2	93	77	107	106

2.2. Methods of Testing

To obtain a uniform particle size distribution, the collected soil samples were first oven-dried at 110°C in the laboratory. After drying, the soil was passed through a sieve No. 4 to remove oversized particles. To prevent moisture reabsorption, the dried soil was stored in airtight, moisture-resistant containers. According to ASTM standards, the prepared soil was then used for various geotechnical tests, including the unconfined compressive strength (UCS) test and CBR test. These initial tests were conducted to evaluate the natural engineering properties of the soil and to serve as a reference for assessing the effectiveness of the improvement process

Fly Ash, GGBS, and Silica Fume were incorporated as stabilizing materials to enhance the engineering properties of the soil. These additives were blended with the dry soil manually until a uniform mixture was obtained. Water was added and manually mixed until a homogeneous state was achieved. The prepared mixture was compacted immediately after mixing. The additive percentages were calculated based on the dry mass of the soil (All additive percentages were calculated based on the original dry mass of the soil). These proportions were selected according to findings from previous studies as mentioned above in (Sharif et al., [5] ; Al-Gharbawi et al., [6] and Behnood and Gharehveran, [7]) are presented in Table 2, Table 3 and Table 4. that reported significant improvement in soil strength and durability with in these ranges.

After preparation, the stabilized soil samples were subjected to laboratory tests, and their results were compared with those of untreated soil to evaluate performance improvement. After compaction, all UCS and soaked CBR specimens were carefully sealed with plastic film to minimize moisture loss and were stored under identical laboratory conditions at room temperature throughout the curing periods (3, 7, and 28 days). This curing procedure was applied consistently to all mixtures to ensure comparable testing conditions.

2.2.1. Unconfined Compression Strength Test

The Unconfined Compression Strength (UCS) test aims to evaluate the strength of cohesive soil-based structures. This test is performed by releasing a soil sample from its lateral restraint, a special type of triaxial compression test. This test is also known as a "rapid" test because pore water is not allowed to drain from the sample despite the application of an axial force. the test is conducted according to ASTM D2166.

Specimens are prepared according to mixing ratios based on optimum moisture content (OMC) and maximum dry density (MDD) determined using a standard Proctor test, with the addition of waste material (Fly ash, GGBS, Silica fume). The test is performed on cylindrical specimens measuring 76 mm in height and 38 mm in diameter. After being removed from the mold, the untreated specimens are subjected to direct examination. The treated specimens are wrapped in plastic film and placed in sealed plastic bags before being stored in a designated container for (3, 7, 28) days at laboratory temperature.

After the curing period, the specimen is placed in the Unconfined compressive strength test device as shown in Figure 2(a), where increasing axial load is applied until failure is reached. During the test, the apparatus' vertical displacement rate is set at 1 mm/min according to ASTM D 2166, and 15 to 20 data points are recorded to study the stress-strain relationship. The test is terminated after the failure condition is achieved, such that the time to failure does not exceed 15 minutes or 20% of the specimen height. For each mixture and curing period, three identical specimens were prepared and tested. The reported UCS values represent the average of the three test results to improve the reliability and repeatability of the experimental data. These tests are conducted to analyze the stress-strain response of soils under all the conditions. The maximum unconfined compressive strength (qu) was obtained from the curve, and the undrained shear strength (Cu)was calculated as half of the value of qu ($c_u = q_u/2$).

(a) (b)

Fig. 2. (a) Unconfined compressive strength test device; (b) sample failure after the test

2.2.2. The California Bearing Ratio Test (CBR)

The California Bearing Ratio (CBR) test is one of the most important geotechnical tests used to evaluate the bearing capacity and strength of subgrade soils for pavement applications. The test measures the resistance of soil against penetration under controlled moisture and density conditions, and the result is expressed as a percentage relative to standard crushed stone. In this study, the test was conducted according to ASTM D1883 using cylindrical molds with dimensions of 150 mm diameter and 120 mm height as shown in Figure 3. The soil was mixed with Fly Ash, GGBS, and Silica Fume at different proportions as shown in Table 2, 3 and 4 and compacted in five layers using various compaction energies. The required water content was added according to the optimum moisture content obtained from the modified compaction test (the modified compaction parameters obtained by converting the Standard Proctor (ASTM D698) results through the appropriate conversion equations). Compaction was carried out using 10, 25, and 56 blows, and the equivalent modified compaction energy was determined using the conversion equations. Load correction was also performed using the adopted equations, and the final CBR values were determined at a penetration depth of 5.0 mm. All specimens were submerged in water for four days before performing the CBR test. For each mixture and curing period, three identical specimens were prepared and tested. The reported soaked CBR values represent the average of the three test results to improve the reliability and repeatability of the experimental data.

(a) (b)

Fig. 3. (a) device used for the CBR test; (b) Mold used for CBR samples

3. Results and Discussion

3.1. Results of Unconfined Compression Strength of Soft Soil

3.1.1. The Effect of Fly Ash on Unconfined Compression Strength

The results of the Unconfined Compressive Strength (UCS) test showed that the addition of Fly Ash with constant percentages of GGBS (9%) and Silica Fume (5%) improved the strength of the soft soil compared with the natural soil (N.S) as shown in Table 5 and Figure 4. The UCS value increased from 102 kPa for untreated soil to 955 kPa for sample P2 after 28 days of curing. The strength values also increased with curing time from 3 to 7 and then to 28 days due to continuous pozzolanic reactions and the formation of cementitious compounds such as C-S-H gel as reported in previous studies, which enhanced the bonding between soil particles. Sample P2 containing 20% Fly Ash achieved the highest UCS values, indicating that this percentage represents the best-performing fly ash content for soil stabilization; this improvement is also related to the fine particle size and uniform dispersion of the stabilizing materials, which enhance particle packing and improve the interaction within the soil matrix. Similar observations were reported by Sharif et al. [5]

Table 5. The effect of Fly Ash on UCS and CBR of the soft soil

No. of Mix	Symbol	Fly Ash %	GGBS %	Silica Fume %	OMC %	MD D g/cm^3	UCS 3 day	UCS 7 day	UCS 28 day	CBR % (25 blows)
—	N.S	0	0	0	15.6	1.72	102	102	102	2.95
1	P1	15	9	5	17.8	1.642	470	486	790	12.36
2	P2	20	9	5	19.2	1.621	557	632	955	18.66
3	P3	25	9	5	20.7	1.609	324	410	726	13.13

However, the strength decreased in sample P3 with 25% Fly Ash because excessive Fly Ash caused unreacted particles and increased voids within the soil matrix. The reduction in strength at higher additive contents may be attributed to particle agglomeration and poor dispersion, which reduce the effectiveness of the soil matrix. These findings agree with recent studies Sharif et al. [5] which reported that moderate Fly Ash content combined with GGBS and Silica Fume provides the best mechanical performance for soft soil stabilization, while excessive Fly Ash reduces density and internal bonding. The increase in strength is attributed to pozzolanic reactions and improved particle bonding, despite the decrease in maximum dry density.

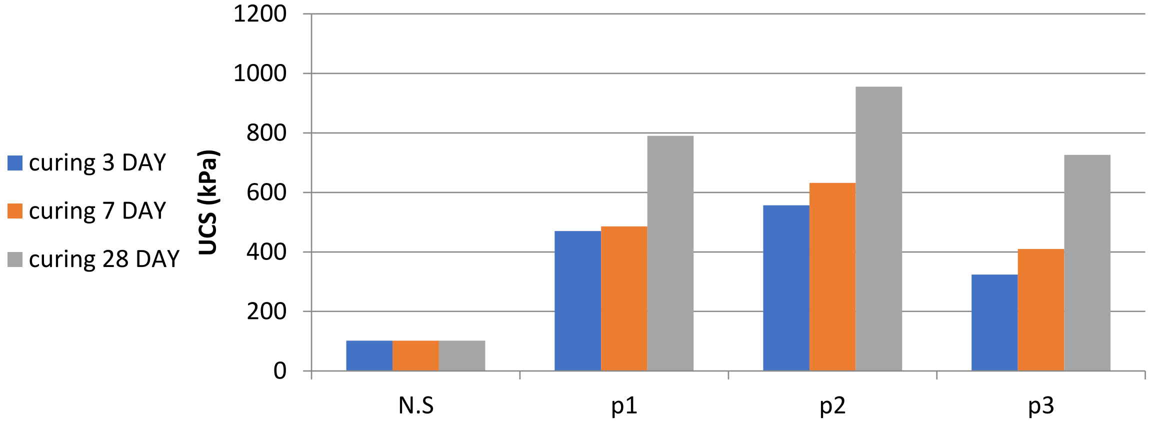

Fig. 4. The effect of Fly Ash on UCS of soft soil

3.1.2. The Effect of GGBS on Unconfined Compression Strength

The results indicate that increasing the GGBS content from 3% to 9%, while keeping Fly Ash (20%) and Silica Fume (5%) constant as shown in Table 6 and Figure 5, significantly improved the unconfined compressive strength (UCS) at all curing periods. The UCS values increased from 321, 452, and 701 kPa for mix R1 to 557, 632, and 955 kPa for mix R3 at 3, 7, and 28 days, respectively.

Table 6. The effect of GGBS on UCS and CBR of the soft soil

No. of Mix	Symbol	Fly Ash %	GGBS %	Silica Fume %	OMC %	MDD g/cm^3	UCS 3 day	UCS 7 day	UCS 28 day	CBR % (25 blows)
—	N.S	0	0	0	15.6	1.72	102	102	102	2.95
1	R1	20	3	5	18.5	1.632	321	452	701	11.11
2	R2	20	6	5	18.8	1.628	390	489	760	12.89
3	R3	20	9	5	19.2	1.621	557	632	955	18.66

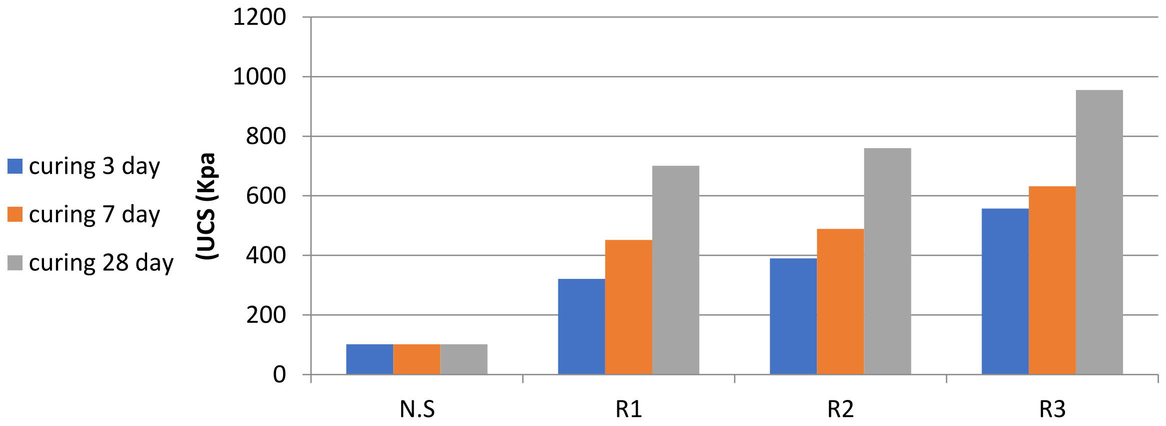

Fig. 5. The effect of GGBS on UCS of soft soil

This improvement is mainly attributed to the high calcium content of GGBS, which accelerates the pozzolanic and cementitious reactions within the soil matrix, producing additional C–S–H gel that enhances particle bonding and soil densification as reported in previous studies. Moreover, the continuous increase in strength with curing time confirms the progressive hydration reaction and formation of stable cementitious compounds. Similar findings were reported by Sharma and Sivapullaiah [9] in Soils and Foundations, where the inclusion of GGBS with fly ash significantly enhanced UCS due to increased pozzolanic activity. Recent studies by Li et al. [10] in Frontiers in Materials also confirmed that higher GGBS contents improve strength and stiffness because of rapid hydration and improved microstructural bonding in stabilized soils.

3.1.3. The Effect of Silica Fume on Unconfined Compression Strength

The results indicate that increasing silica fume from 5% to 10%, while keeping Fly Ash (15%) and GGBS (9%) constant, reduced the unconfined compressive strength (UCS) at all curing periods. The UCS values decreased from 470, 486, and 790 kPa for Q1 to 306, 375, and 687 kPa for Q2 at 3, 7, and 28 days, respectively as shown in Figure 6 and Table 7. This reduction may be due to the excessive silica fume content, which increased water demand and caused particle agglomeration, leading to weak bonding and higher void ratios. In addition, excess silica fume reduced the efficiency of pozzolanic reactions because of insufficient available calcium compounds. Similar findings were reported by Zhang et al. [11] , who confirmed that UCS decreases when silica fume exceeds the optimum percentage due to increased pore spaces and incomplete bonding in stabilized soil.

Table 7. The effect of silica fume on UCS and CBR of the soft soil

No. of Mix	Symbol	Fly Ash %	GGBS %	Silica Fume %	OMC %	MDD g/cm^3	UCS 3 day	UCS 7 day	UCS 28 day	CBR % (25 blows)
—	N.S	0	0	0	15.6	1.72	102	102	102	2.95
1	Q1	15	9	5	17.8	1.642	470	486	790	12.36
2	Q2	15	9	10	19	1.621	306	375	687	9.84

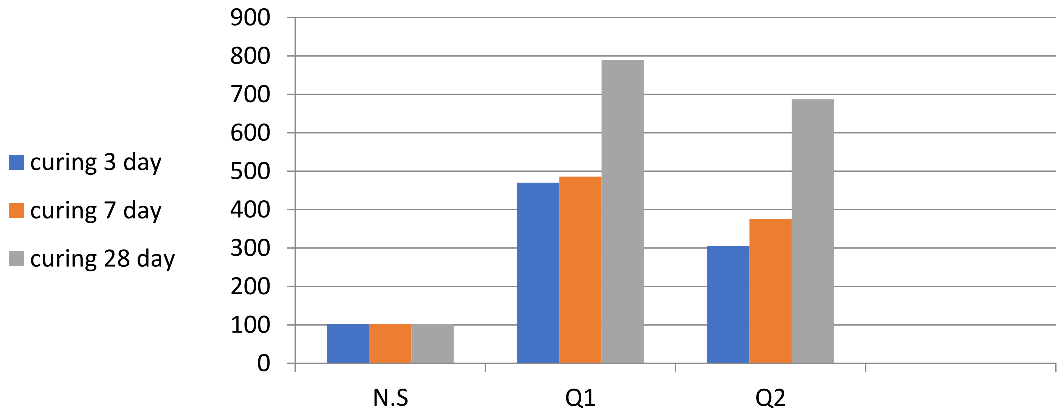

Fig. 6. The effect of silica fume on UCS of soft soil

3.2. Results of the California Bearing Ratio Test (CBR)

3.2.1. The Effect of Fly Ash on the CBR Test

The results showed that adding Fly Ash with 9% GGBS and 5% Silica Fume significantly improved CBR values compared with untreated soil due to pozzolanic reactions and formation of C-S-H gel. The mixture containing 15% Fly Ash increased soil density and stiffness, while 20% Fly Ash achieved the highest CBR value and was considered the best-performance content for stabilization. Increasing Fly Ash to 25% caused a slight reduction in CBR because excessive fines reduced compaction efficiency and weakened bonding between soil particles as shown in Figure 7 and the percentage of mix shown in Table 2. Similar findings were reported by Rahman et al. [12] The stabilized soil shows promising potential for pavement applications, but further durability studies are required.

3.2.2. The Effect of GGBS on the CBR Test

The results showed that increasing GGBS content improved the CBR values of stabilized soil compared with untreated soil due to the formation of cementitious compounds and pozzolanic reactions. The addition of 3% GGBS enhanced soil compaction and penetration resistance by reducing internal voids and improving particle interlocking. Increasing GGBS to 6% further increased CBR values because of higher production of C-S-H gel as reported in previous studies and stronger bonding between soil particles. The highest CBR value was achieved at 9% GGBS with 20% Fly Ash and 5% Silica Fume, indicating the best-performing mixture within the investigated dosage range. as show in Figure 8 and percentage of mix shown in Table 3. This improvement was attributed to enhanced soil density, reduced void ratio, and stronger internal structure. Similar findings were reported by Wang et al. [13]. The stabilized soil shows promising potential for pavement applications, but further durability studies are required.

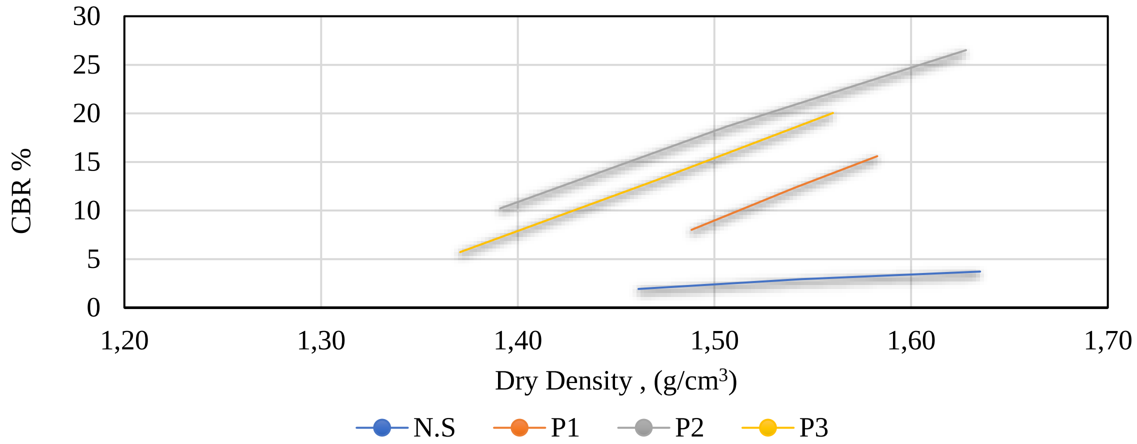

Fig. 7. The effect of Fly Ash on the CBR test under different compaction efforts(10,25 and 56 blows)

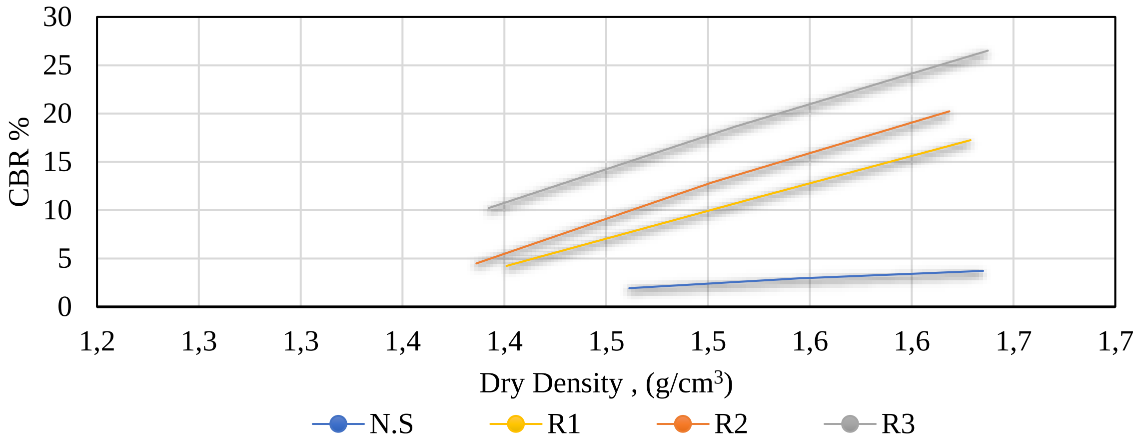

Fig. 8. The effect of GGBS on the CBR test under different compaction efforts(10,25 and 56 blows)

3.2.3. The Effect of Silica Fume on the CBR Test

The results showed that adding Silica Fume significantly improved the CBR values of stabilized soil compared with untreated soil. This improvement was mainly due to the high pozzolanic activity and ultra-fine particles of silica fume, which enhanced bonding and reduced soil voids. The mixture containing 5% Silica Fume achieved the highest CBR value because it increased soil densification and formed additional calcium silicate hydrate (C-S-H) gel as reported in previous studies. However, increasing Silica Fume to 10% caused a slight reduction in CBR due to excessive fine particles and higher water demand, which reduced compaction efficiency. Despite this decrease, the values remained higher than those of natural soil. Overall, the best performance was obtained with 5% Silica Fume combined with 15% Fly Ash and 9% GGBS as shown in figure (9) and percentage of mix shown in table (4), making it suitable for improving weak subgrade soils used in pavement applications. Similar behavior was observed by Rahman et al. [14], who reported that increasing silica fume beyond the best performing mixture may negatively affect soil compaction and reduce strength performance due to excessive fines content. Therefore, the stabilized soil shows promising potential for pavement applications, but further durability studies are required. Similar conclusions were also reported by Patel and Sharma [15].

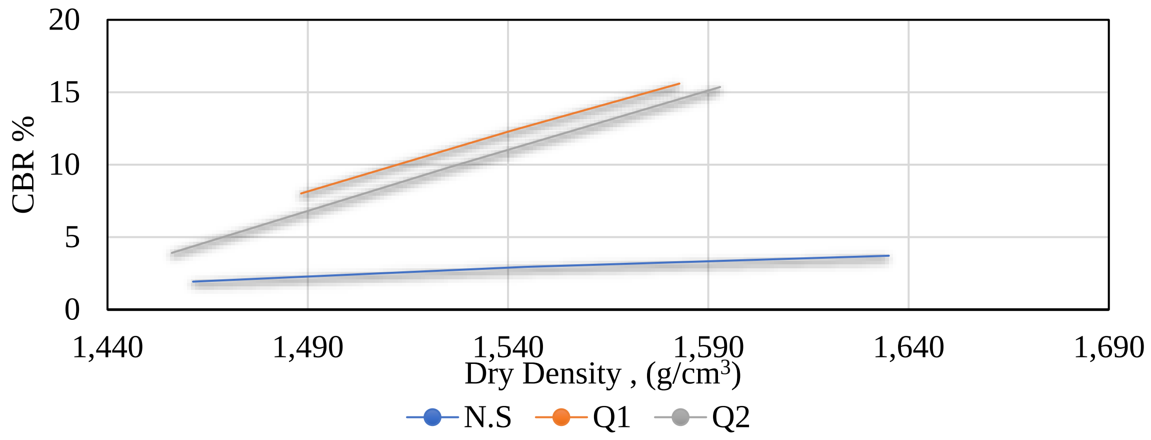

Fig. 9. The effect of silica fume on the CBR test under different compaction efforts(10,25 and 56 blows)

4. Summary and Conclusions

- Lean clay soil was stabilized using Fly Ash (FA), Ground Granulated Blast Furnace Slag (GGBS), and Silica Fume (SF) to improve its engineering properties.
- Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR) tests were conducted to evaluate the strength and bearing capacity of the treated soil.
- The UCS values increased significantly with curing time due to pozzolanic reactions and the formation of cementitious products such as C-S-H gel as reported in previous studies.
- The obtained results are consistent with previous studies reported in the literature. Sharif et al. [5] observed that the best content Fly Ash content for clay stabilization was approximately 20%, which agrees with the present findings. Similarly, Behnood and Gharehveran [7] reported that 9% GGBS provided significant strength enhancement due to the formation of cementitious compounds. Al-Gharbawi et al. [6] also concluded that 5% Silica Fume was sufficient to achieve substantial improvements in soil strength and durability. Therefore, the optimum mixture identified in this study is strongly supported by previous research findings.
- CBR results showed substantial improvement in bearing capacity, indicating the suitability of the stabilized soil for pavement subgrade applications.
- A limitation of this study is that only ternary mixtures were investigated. Therefore, the individual contribution of each stabilizer and their possible synergistic effects could not be fully evaluated. Future studies should include single- and binary-additive control mixtures.
- The proposed stabilization system promotes environmental sustainability through the beneficial reuse of industrial wastes, reducing waste disposal and supporting eco-friendly geotechnical engineering practices.

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