Research on Engineering Structures & Materials
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Research Article

Improvement of bearing capacity and settlement behavior of expansive soil using ground granulated blast furnace slag (GGBFS)

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Article Info

Article History:

Received 20 Jul 2026

Accepted 21 Sep 2026

Keywords:

Expansive soil;
Ground granulated blast furnace slag;
Soil stabilization;
Bearing capacity;
Ground improvement

Abstract

Expansive soils present major geotechnical challenges because moisture-induced volume changes are commonly accompanied by low strength and excessive deformation. This study evaluates the short-term engineering response of a high-plasticity clay from Thi-Qar Governorate, Iraq, treated with ground granulated blast furnace slag (GGBFS). Untreated soil and mixtures containing 5%, 10%, 15%, 20%, and 25% GGBFS by dry soil mass were examined using Standard Proctor compaction, Atterberg limits, unconfined compressive strength (UCS), California Bearing Ratio (CBR), and model footing tests after 7 days of curing. The maximum dry density increased from 1.62 to 1.73 g/cm^3 at 20% GGBFS, whereas the optimum moisture content decreased from 21.5% to 17.6% at 25% GGBFS. UCS, CBR, and model ultimate bearing pressure increased markedly up to 20% GGBFS, while settlement at ultimate pressure decreased from 18 mm for untreated soil to 5 mm for SC20. A slight decline at 25% indicated diminishing benefit beyond SC20 under the investigated conditions. Meyerhof-based values followed the same general trend but are treated as approximate analytical benchmarks because shear-strength parameters were not obtained from dedicated direct-shear or triaxial tests. Overall, GGBFS improved the short-term strength and model-scale load–settlement response of the investigated clay; however, direct swelling tests, longer curing periods, durability assessment, replicate-based statistics, and field-scale validation are required before generalized design recommendations are made.

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1. Introduction

Expansive soils are among the most problematic geomaterials encountered in geotechnical engineering because their volume changes with moisture variation can induce heave, shrinkage, differential movement, cracking, and loss of serviceability in foundations and pavement systems [1,2]. Such soils are widespread in arid and semi-arid regions, including Iraq [3]. Conventional chemical stabilizers such as lime and ordinary Portland cement have been widely used to improve strength and reduce plasticity; however, their production is associated with environmental burdens, and sulfate-rich environments may present durability concerns for calcium-bearing stabilized systems [4-6]. These considerations have encouraged greater use of industrial by-products in ground improvement. Ground granulated blast furnace slag (GGBFS) is one such material and has attracted attention because of its latent hydraulic and pozzolanic characteristics [7–9]. Previous studies have shown that GGBFS-containing binders can modify the plasticity, compaction, and strength of problematic fine-grained soils [7-10]. Recent investigations have further demonstrated the value of GGBFS and related industrial by-products for expansive- and soft-soil stabilization, including mechanical, durability, and microstructural assessments [11-13].

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DOI: http://dx.doi.org/10.17515/resm2026-1944ic0720rs

Alternative treatments have also been reported for Iraqi/problematic soils. Thajeel et al. [14] investigated emulsified asphalt for expansive soil, Almurshedi et al. [15] examined cement dust for swelling control, and Almurshedi et al. [16] evaluated nano-silica fume for collapsible marsh soil. Recent studies have also investigated the use of nanomaterials for improving gypseous soils. Emad and Salman [17] examined the effects of nanomaterials on shear strength and collapsibility, while Karkush et al. [18] investigated their effects on the micromechanical properties of gypseous soils. These studies demonstrate the broader use of different soil-improvement materials for problematic soils, although their soil types and treatment methods differ from the GGBFS-treated expansive clay investigated in the present study.

In shallow foundation applications, stabilization should be evaluated not only through index and strength tests but also through load–settlement response. Younes et al. [19] reported improved footing performance on chemically stabilized soil. Nevertheless, many GGBFS studies emphasize Atterberg limits, compaction, UCS, CBR, swelling, or microstructural response, whereas fewer studies link these material-scale indicators with model-footing pressure–settlement behavior for the same high-plasticity clay and mixture series. Accordingly, the present study does not claim novelty in the use of GGBFS itself. Its contribution is the integrated short-term evaluation of compaction, consistency, UCS, CBR, and model-footing response for a locally sourced CH soil treated with 0–25% GGBFS after 7 days of curing. The model footing component provides a direct comparative bridge between conventional laboratory improvement indicators and foundation-related deformation behavior. The study is intentionally limited to the investigated laboratory conditions; direct swelling tests, long-term curing, durability, detailed mineralogical/microstructural characterization, and field-scale validation were outside the original experimental program.

Table 1. Comparison of selected GGBFS/industrial-by-product stabilization studies and the research gap addressed in the present study

Study	Soil / binder	Curing / main tests	Foundation-related test	Relevance/remaining gap
Keramatikerman et al. [9]	Expansive soil / slag	Index and engineering behavior	No	Demonstrated slag-related improvement; no model-footing response in the present integrated form.
Mahedi et al. [10]	High-plasticity soils / slag and Portland cements	7, 28, and 90 d; Atterberg limits, pH, UCS, volumetric swell	No	Evaluated slag/cement stabilization of sulfate-bearing high-plasticity soils; no model-footing response.
Al-Khafaji et al. [11]	Soft soil / GGBS + CKD	7 and 28 d; Atterberg, compaction, UCS, SEM	No	Includes curing and microstructure; soft soil and binary binder rather than GGBFS-treated CH soil.
Nadeem et al. [12]	Expansive soil / fly ash and GGBFS	Compaction, UCS, Atterberg, direct shear, CBR, SEM/EDX	No	Comprehensive material-scale characterization; no model-footing load–settlement test.
Shakil et al. [13]	Expansive soil / GGBS and bagasse ash	Atterberg, compaction, swelling, direct shear	No	Includes direct swelling/shear response; different binder system and no model-footing test.
Present study	CH clay / 0–25% GGBFS	7 d; compaction, Atterberg, UCS, CBR	Yes: 100 × 100 mm model footing	Integrates conventional geotechnical indicators with comparative pressure–settlement response; limited to short-term laboratory conditions.

2. Materials and Methods

2.1 Soil Sampling

The expansive clay soil used in this study was collected from Thi-Qar Governorate, southern Iraq, at a depth of approximately 1.0 m below the ground surface. The sampling location was situated at coordinates 31°01′56.5″N and 46°11′08.0″E, as shown in Figure 1. The disturbed soil samples were carefully sealed and transported to the laboratory to preserve their natural condition. Prior to testing, the soil was air-dried, manually pulverized, and passed through a 4.75 mm sieve to remove gravel particles and ensure sample uniformity.

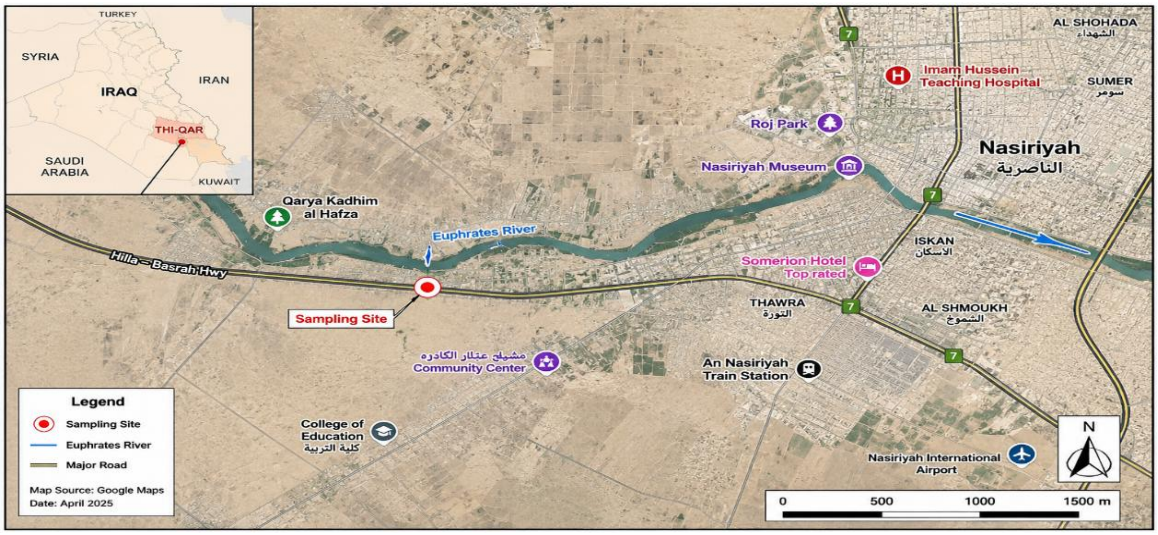


Fig. 1. Location of the soil sampling site in Thi-Qar Governorate, Iraq

2.2 Natural Soil Properties

A laboratory testing program was conducted to determine the physical and engineering properties of the natural soil using the standards applicable to the original testing program. The tests included Standard Proctor compaction, specific gravity, grain-size distribution, Atterberg limits, and unconfined compressive strength (UCS). The soil was classified as high-plasticity clay (CH) according to the Unified Soil Classification System. The measured index properties are summarized in Table 2 and the grain-size distribution is shown in Figure 2. Because free-swell, swell-percentage, swelling-pressure, XRD, and SEM tests were not included in the original program, the present study does not directly quantify swelling potential or identify the clay mineralogy.

Table 2. Physical and index properties of the natural soil

Properties	Value	Test Standard
Color	light grayish brown	Visual observation
Optimum moisture content OMC %	21.5	ASTM D698
Maximum dry density, MDD (g/cm^3)	1.62	ASTM D698
Field unit weight (kN/m^3)	19	ASTM D1556
Specific gravity (Gs)	2.72	ASTM D854
Liquid limit (LL%)	58	ASTM D4318
Plastic limit (PL %)	28	ASTM D4318
Plasticity index (PI %)	30	ASTM D4318
Clay content %	55	ASTM D422
Silt content %	40	ASTM D422
Sand content %	5	ASTM D422
Unconfined compressive strength, UCS (kPa)	120	ASTM D2166/D2166M
USCS classification	CH	ASTM D2487

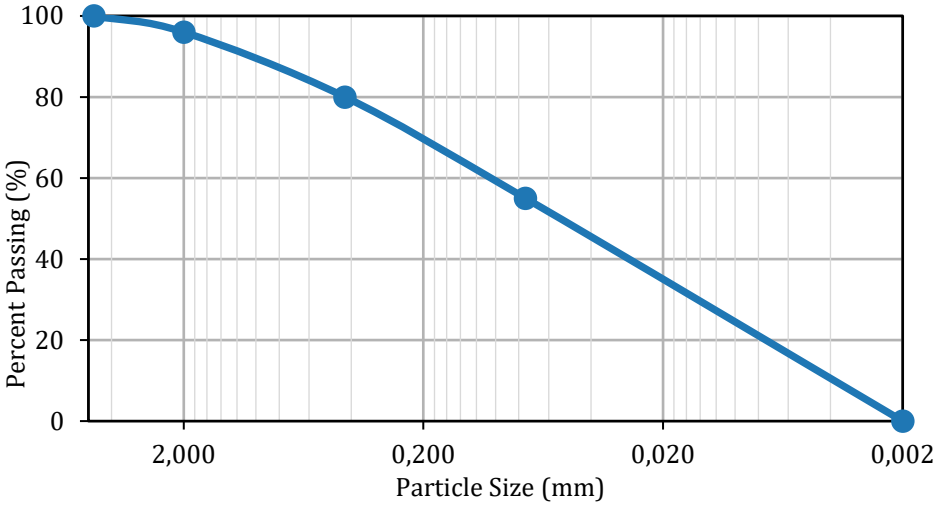


Fig. 2. Grain-size distribution curve of the expansive soil

2.3 Slag Cement Stabilizer

Ground granulated blast furnace slag (GGBFS) was used as the stabilizing material. GGBFS is an industrial by-product produced by rapid quenching of molten blast-furnace slag followed by grinding. It is widely reported to have latent hydraulic and pozzolanic properties that make it suitable for soil stabilization [7,11,20]. The GGBFS used in this study was a fine powder with a light-gray to off-white color. Complete characterization data for the GGBFS used in this study, including verified manufacturer/source information, XRF/XRD composition, particle-size distribution, and Blaine fineness, were not available in the original experimental records. Therefore, no unverified chemical or mineralogical values are presented as measured properties of the material used. Typical physical and chemical properties of GGBFS reported in the literature are summarized in Table 3. These values are provided for general reference and do not represent measured properties of the GGBFS used in this study.

Table 3. Typical physical and chemical properties of GGBFS reported in the literature

Property	Value
Physical state	Fine powder
Color	Light gray to off-white
Specific gravity	2.85 – 2.95
Fineness (specific surface area)	400 – 600 m^2/kg
Calcium oxide (CaO)	35 – 45 %
Silicon dioxide (SiO_2)	30 – 40 %
Aluminum oxide (Al_2O_3)	8 – 15 %
Magnesium oxide (MgO)	5 – 10 %

When GGBFS is added to fine-grained soils, previous studies have reported that calcium-related reactions, particle flocculation, and the formation of cementitious products can improve bonding between soil particles and increase soil stiffness [7,9,11,12,20]. These mechanisms may explain the improvements observed in the present experimental results. However, specific reaction products, such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), were not directly confirmed in this study because XRD and SEM analyses were not performed.

2.4 Preparation of Stabilized Soil Mixtures

The expansive soil was treated with GGBFS contents of 0%, 5%, 10%, 15%, 20%, and 25% by dry mass of soil. The mixtures were designated SC0, SC5, SC10, SC15, SC20, and SC25, respectively. Air-dried soil and GGBFS were first dry-mixed to promote uniform distribution. Water corresponding to the optimum moisture content (OMC) determined for each mixture from Standard Proctor testing was then added gradually and mixed to a homogeneous condition. Specimens were

compacted according to the requirements of each laboratory test, sealed in airtight plastic bags, and cured for 7 days under ambient laboratory conditions. Continuous numerical records of laboratory temperature and relative humidity were not available; therefore, specific environmental ranges are not reported retrospectively. The 7-day curing period defines the short-term scope of this investigation and should not be interpreted as evidence of long-term GGBFS performance.

2.5 Experimental Testing Program

The experimental program evaluated the short-term influence of GGBFS treatment on compaction, consistency, strength, CBR response, and model-footing load-settlement behavior. Tests were conducted on untreated and treated mixtures using the standards applicable to the original testing program. The program included Standard Proctor compaction, Atterberg limits, UCS, CBR, and model footing tests.

2.5.1 Compaction Characteristics

Standard Proctor compaction tests were conducted in accordance with ASTM D698 to determine the maximum dry density (MDD) and optimum moisture content (OMC) for each soil-stabilizer mixture. The obtained compaction parameters were subsequently used in preparing UCS, CBR, and model footing test specimens.

2.5.2 Atterberg Limits

Liquid limit (LL), plastic limit (PL), and plasticity index (PI) tests were performed according to ASTM D4318 to evaluate the influence of GGBFS on the consistency and plasticity characteristics of the expansive soil.

2.5.3 Unconfined Compressive Strength (UCS)

Unconfined compressive strength tests were conducted in accordance with ASTM D2166/D2166M to evaluate the improvement in soil strength after stabilization. Cylindrical specimens were prepared at their corresponding OMC and MDD values and tested after a curing period of 7 days.

2.5.4 California Bearing Ratio (CBR)

CBR tests were performed following ASTM D1883 to assess the improvement in the subgrade performance of stabilized expansive soil. All specimens were compacted at their corresponding optimum conditions and tested after 7 days of curing.

2.5.5 Model Plate Load Test

Model footing tests were conducted to compare the bearing-pressure and settlement response of untreated and GGBFS-treated soil. The setup is shown in Figure 3.

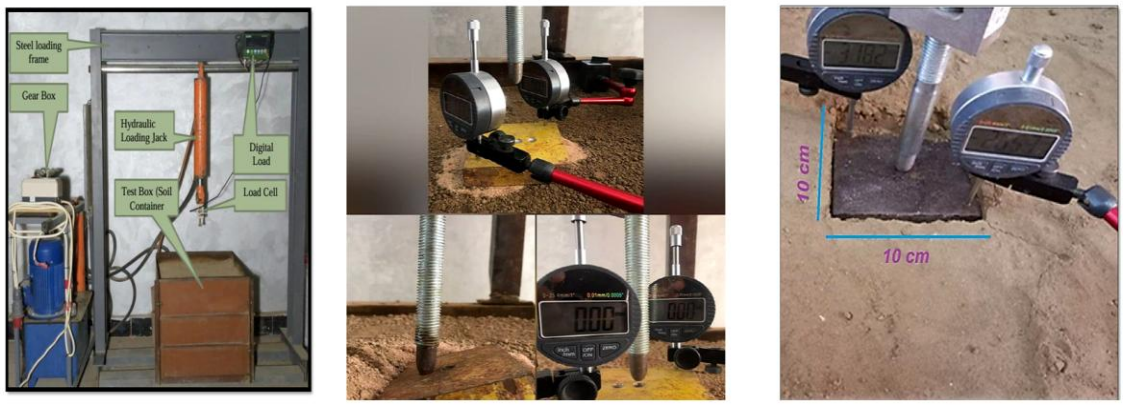


Fig. 3. Experimental setup of the model plate load test: (a) general view of the loading apparatus and soil container, (b) placement of the model footing and dial gauges during testing, and (c) square footing dimensions and loading configuration

Tests were performed in a rigid steel container measuring 600 × 600 × 200 mm using a centrally positioned square steel footing, 100 × 100 × 25 mm. The soil mixtures were prepared at their adopted compaction moisture condition based on the corresponding OMC and compacted for comparative testing; the specimens were not tested in a fully saturated condition. Vertical load was applied incrementally through a hydraulic loading system. Settlement was measured using digital dial gauges with 0.01 mm resolution, and load was monitored using a calibrated load cell connected to a digital indicator. Pressure-settlement curves were obtained for the investigated mixtures, and model ultimate bearing pressure was interpreted from the observed load-settlement response and failure/deformation characteristics. The rigid container, finite soil depth, and small footing size can affect confinement, stress distribution, and settlement; consequently, the model results are used for controlled comparison among mixtures and should not be extrapolated directly to full-scale foundations without validation. The available records do not preserve a complete replicate level dataset for the model tests, so unsupported repeatability statistics are not reported.

2.6 Theoretical Evaluation of Bearing Capacity

The theoretical ultimate bearing pressure was estimated using Meyerhof's general bearing-capacity framework. For a shallow footing, the calculation may be written in the general form

$q_u = cN_cs_cd_c + qN_qs_qd_q + 0.5\gamma BN_\gamma s_\gamma d_\gamma$, where c is cohesion, q is the surcharge at footing level, γ is soil unit weight, B is footing width, Nc, Nq, and Nγ are bearing-capacity factors, and s and d denote the applicable shape and depth factors. The analytical calculations used the available unit-weight and strength information for the investigated mixtures. Dedicated direct-shear or triaxial tests were not performed for each GGBFS content; therefore, the shear-strength parameters required for the Meyerhof calculations were derived from the available laboratory strength characteristics and empirical correlations used in the original analysis. Because the original records do not preserve a complete correlation-specific set of c and φ inputs for every mixture, a defensible specimen-by-specimen reconstruction or sample calculation cannot be reported retrospectively. This introduces uncertainty into the theoretical values. Accordingly, the Meyerhof results are used only as approximate analytical benchmarks for comparison with the model-footing trend and are not treated as independently validated design predictions. A flowchart summarizing the overall experimental and theoretical methodology adopted in the present study is presented in Figure 4.

2.7 Experimental Scope and Data Limitations

The original experimental records provide representative results for the investigated mixtures but do not preserve a systematic replicate-testing dataset for every test type. Consequently, standard deviations, coefficients of variation, confidence intervals, ANOVA results, and error bars cannot be reconstructed reliably and are not introduced retrospectively. Where replicate counts are not verifiable from the original records, the reported values should be interpreted as representative experimental results rather than statistically derived means. In addition, direct swelling tests, XRD/SEM characterization, long-term curing, wetting–drying durability, sulfate-resistance testing, and quantitative soil sulfate/salt analyses were outside the original program. No life-cycle assessment, carbon-footprint calculation, or comparative cost analysis was performed. These limitations are explicitly considered when interpreting the results and defining the engineering significance of the study.

3. Results and Discussion

3.1 Compaction Characteristics

The Standard Proctor results (Table 4 and Figure 5) show a systematic change in compaction response with GGBFS content. MDD increased from 1.62 g/cm^3 for SC0 to 1.73 g/cm^3 for SC20 and then decreased slightly to 1.72 g/cm^3 for SC25, whereas OMC decreased from 21.5% to 17.6% across the investigated range. The increase in MDD up to SC20 is consistent with improved particle packing and filler effects, while literature on GGBFS-treated soils also attributes strength and densification changes to flocculation and time-dependent cementitious reactions [7,11,12,20]. The lower OMC may reflect changes in particle arrangement and water demand as the proportion of clay is reduced by GGBFS addition. Because microstructural tests were not performed, these

mechanisms are literature-supported interpretations rather than direct observations. The small MDD decrease at SC25 indicates diminishing densification benefit beyond SC20 under the adopted compaction condition.

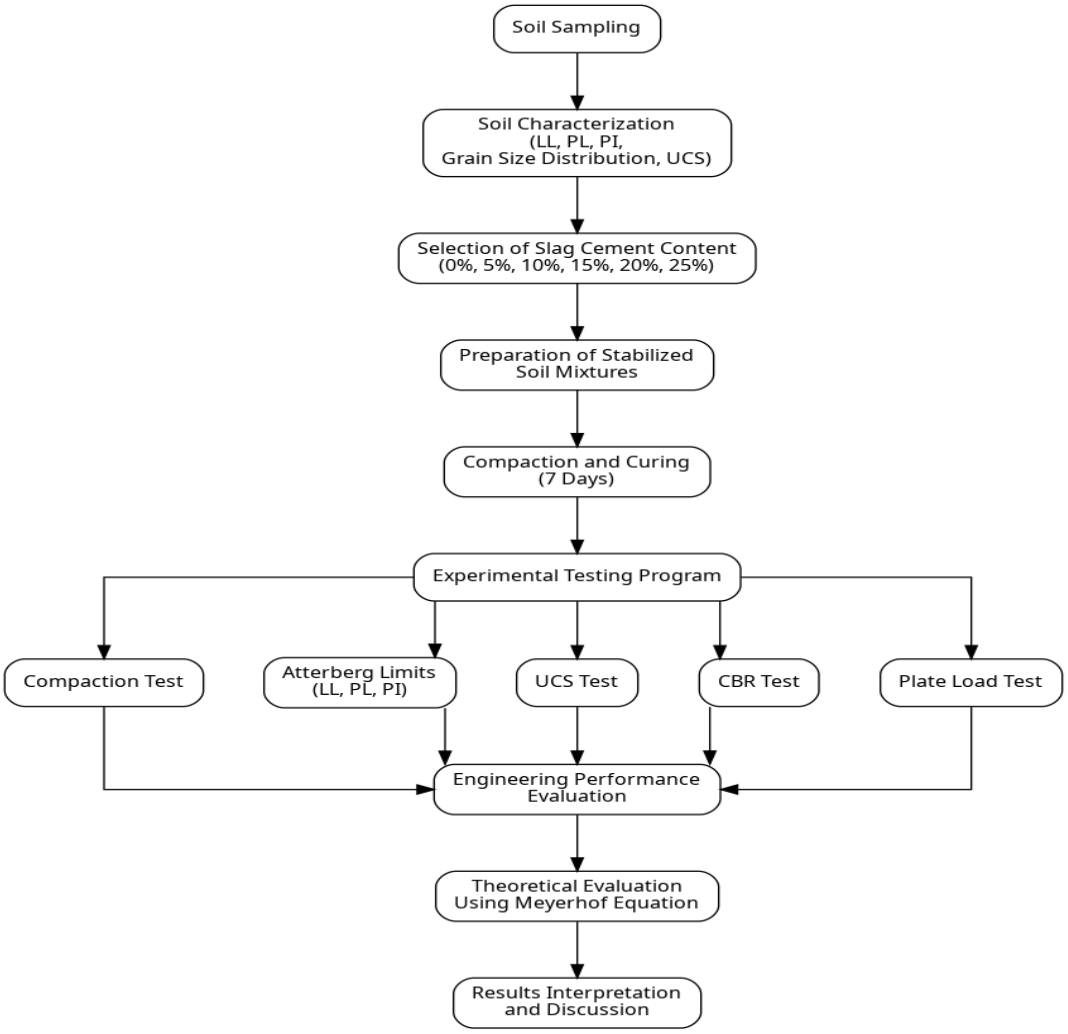


Fig. 4. Flowchart of the experimental and theoretical methodology adopted in the present study

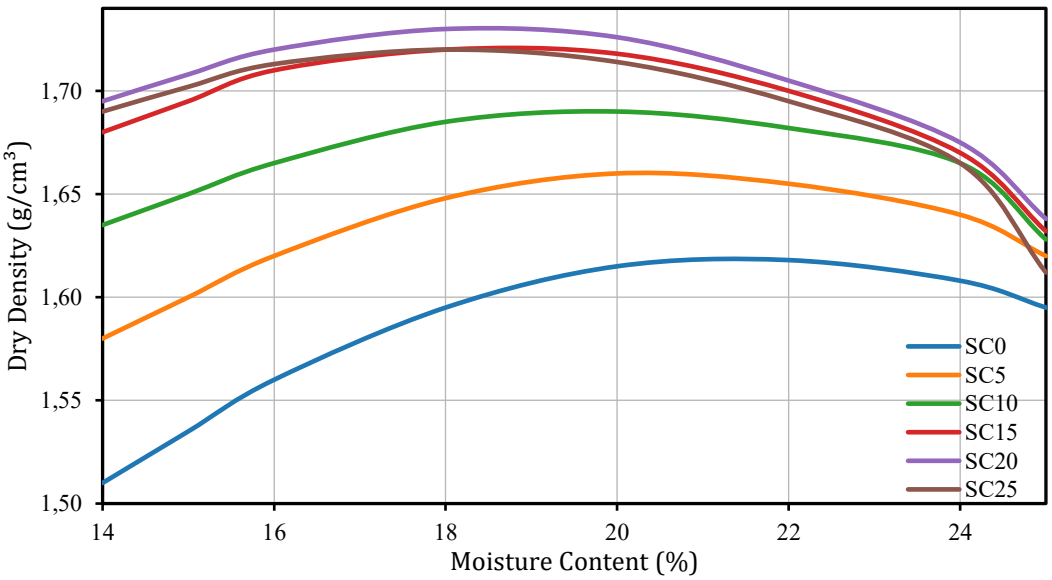


Fig. 5. Compaction curves of expansive soil stabilized with varying GGBFS contents

Table 4. Compaction characteristics of untreated and GGBFS-stabilized expansive soil mixtures

Mix ID	GGBFS Content (%)	OMC (%)	MDD (g/cm^3)
SC0	0	21.5	1.62
SC5	5	20.3	1.66
SC10	10	19.2	1.69
SC15	15	18.4	1.72
SC20	20	17.9	1.73
SC25	25	17.6	1.72

3.2 Atterberg Limits

The Atterberg-limit results (Table 5 and Figure 6) show that increasing GGBFS content reduced LL from 58% to 40% and PI from 30% to 16%, while PL changed from 28% to 24%. These measured changes demonstrate a substantial reduction in plasticity and are consistent with particle flocculation, cation-related interactions, and cementitious processes reported for GGBFS-containing fine-grained soils [9,11-13,21,22]. However, the present study did not include free-swell or swelling-pressure tests; therefore, the reductions in LL and PI should be interpreted as evidence of improved consistency and potentially lower moisture sensitivity rather than direct proof of swelling suppression. Likewise, specific hydration products were not verified by XRD or SEM in this investigation.

Table 5. Atterberg limits of untreated and GGBFS-stabilized expansive soil mixtures

Mix ID	Liquid Limit LL (%)	Plastic Limit PL (%)	Plasticity Index PI (%)
SC0	58	28	30
SC5	54	27	27
SC10	49	26	23
SC15	45	25	20
SC20	42	24	18
SC25	40	24	16

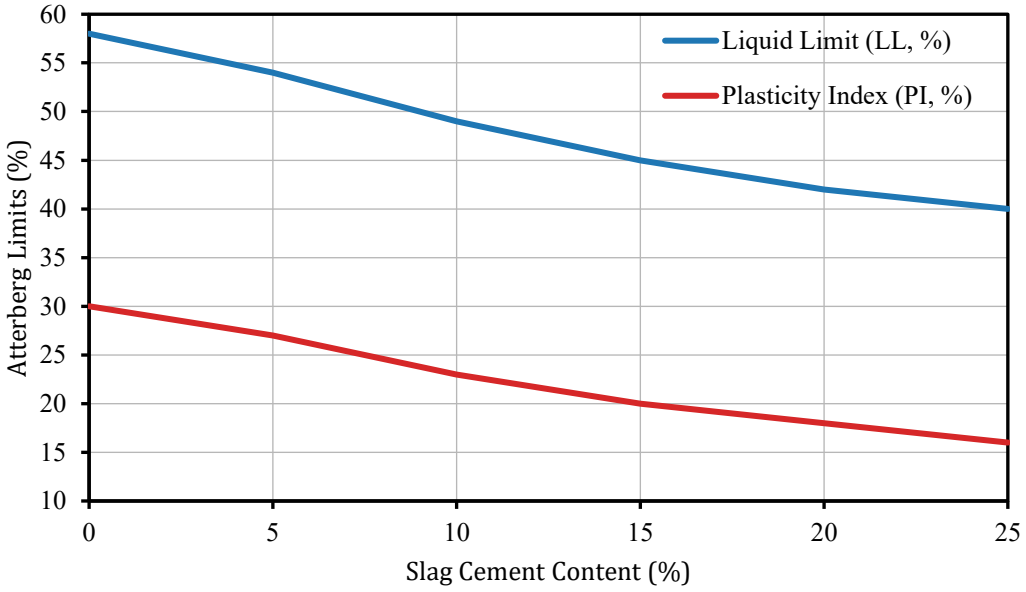


Fig. 6. Variation of Atterberg limits with GGBFS content

3.3 Unconfined Compressive Strength (UCS)

After 7 days of curing, UCS increased from 120 kPa for SC0 to 680 kPa for SC20 and then decreased slightly to 660 kPa for SC25 (Table 6). Thus, SC20 produced the highest measured short-term UCS

within the investigated range. The increase is consistent with improved interparticle bonding and stiffness associated in the literature with GGBFS-related hydraulic/pozzolanic reactions and particle restructuring [9,11,12,20]. Because XRD/SEM analyses were not performed, the formation of particular C-S-H or C-A-H phases is not directly demonstrated by the present data. The slight reduction at SC25 suggests diminishing benefit at the highest dosage under the 7-day condition. SC20 is therefore described as the best-performing content in this experimental range, not as a statistically optimized or universally applicable dosage. Longer curing periods are required to determine whether the ranking changes as latent GGBFS reactions continue.

Table 6. Seven-day unconfined compressive strength of untreated and GGBFS-stabilized expansive soil mixtures

Mix ID	UCS (kPa)
SC0	120
SC5	210
SC10	340
SC15	520
SC20	680
SC25	660

3.4 California Bearing Ratio (CBR)

CBR increased from 3% for SC0 to 38% for SC20 and then decreased slightly to 36% for SC25 (Table 7). The measured increase indicates substantially greater penetration resistance under the adopted laboratory condition and supports improved short-term subgrade response. The trend is consistent with the concurrent reductions in plasticity and increases in UCS, as well as with literature reporting improved stiffness and bonding in GGBFS-containing stabilized soils [9,11–13,20]. Nevertheless, the results represent the investigated 7-day laboratory condition; soaked/long-term durability behavior and field performance were not established. SC20 again provided the highest measured CBR within the tested range, whereas the small decline at SC25 indicates diminishing benefit rather than a formally optimized threshold.

Table 7. California Bearing Ratio of untreated and GGBFS-stabilized expansive soil mixtures after 7 days of curing

Mix ID	CBR (%) at 2.5 mm penetration
SC0	3
SC5	7
SC10	15
SC15	25
SC20	38
SC25	36

Table 8. Model ultimate bearing pressure and corresponding settlement of untreated and GGBFS-stabilized expansive soil mixtures

Mix ID	model ultimate bearing pressure q_u (kPa)	Settlement at q_u, S (mm)
SC0	85	18
SC5	140	14
SC10	210	10
SC15	310	7
SC20	420	5
SC25	400	6

3.5 Bearing Capacity and Settlement Behavior

Model-footing results (Figure 7 and Table 8) show a clear improvement in load-settlement response up to SC20. Model ultimate bearing pressure increased from 85 kPa for SC0 to 420 kPa for SC20, while settlement at the interpreted ultimate pressure decreased from 18 to 5 mm. SC25 produced a slightly lower ultimate pressure of 400 kPa and a settlement of 6 mm. These trends are consistent with the higher density/strength and lower plasticity measured for the treated mixtures and with improved footing response reported for stabilized foundation soils [19,23-25]. Literature supported mechanisms include improved particle packing and cementitious bonding, but the specific reaction products were not directly verified in this study. Because the footing was tested in a rigid box at model scale and the soil was prepared at the adopted OMC-based condition rather than full saturation, the measured pressures and settlements should be interpreted comparatively. Boundary confinement, finite soil depth, scale effects, and the absence of saturated testing limit direct extrapolation to field foundations. Under these conditions, SC20 gave the most favorable combined bearing-pressure and settlement response within the investigated range.

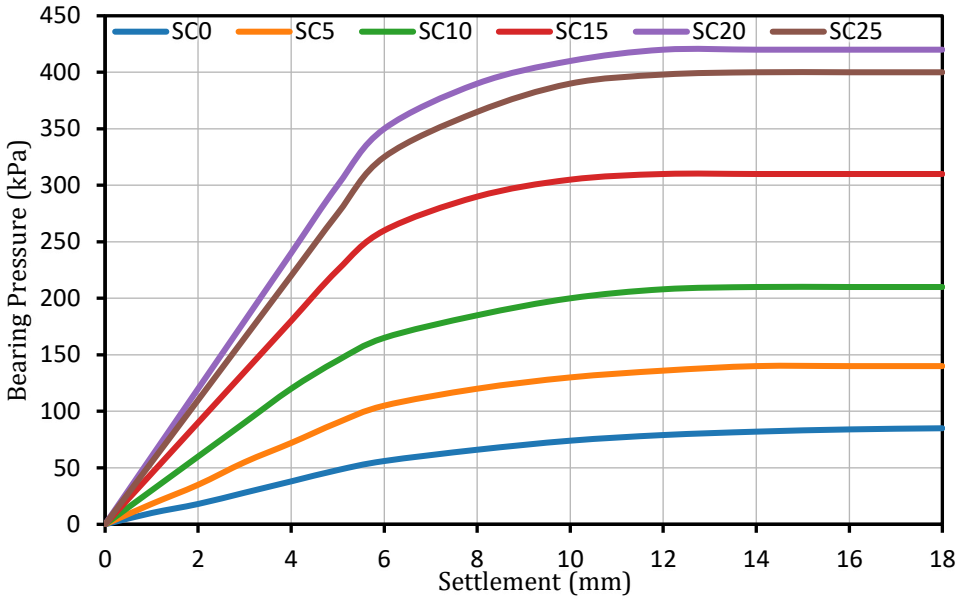


Fig. 7. Pressure-settlement curves of expansive soil stabilized with varying GGBFS contents

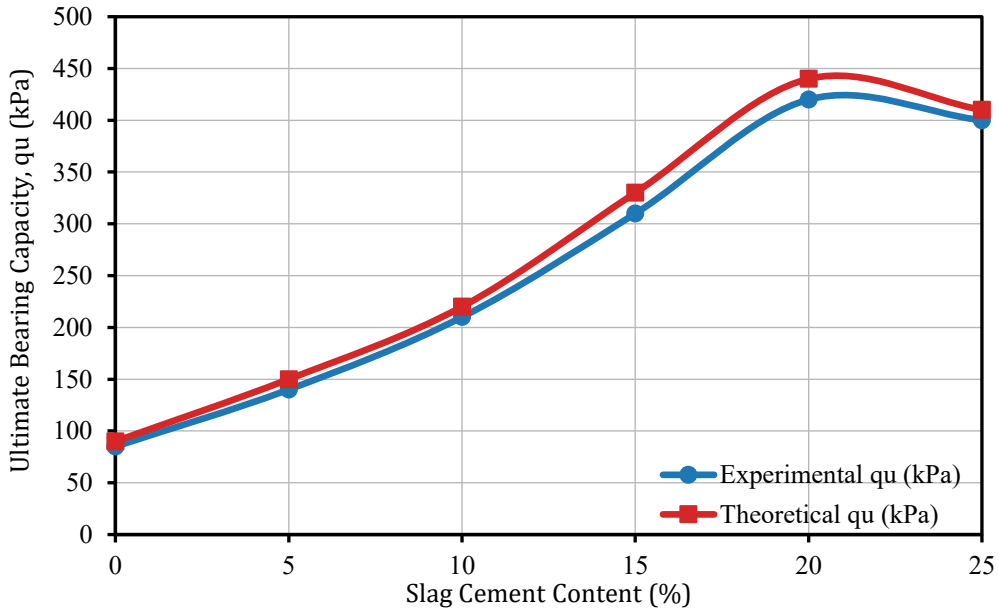


Fig. 8. Comparison between experimental and theoretical ultimate bearing capacity values

3.6 Comparison Between Experimental and Theoretical Results

The Meyerhof-based values are compared with the model-footing results in Table 9 and Figure 8. Both datasets follow the same general trend: bearing pressure increases from SC0 to SC20 and decreases slightly at SC25. The analytical values are modestly higher than the measured model values, with the tabulated differences remaining below approximately 8%. This agreement is useful as a trend comparison; however, it should not be interpreted as validation of Meyerhof's equation for the treated soil. The analytical calculation relies partly on empirically derived shear-strength parameters rather than dedicated direct-shear/triaxial measurements, while the model test is affected by footing scale, rigid boundaries, finite soil depth, and laboratory stress distribution [23-25]. Accordingly, the theoretical results are considered approximate benchmarks that support the observed trend but retain uncertainty in absolute magnitude.

Table 9. Comparison of experimental model and Meyerhof-based ultimate bearing pressure values

Mix ID	Experimental q_u (kPa)	Meyerhof q_u (kPa)	Difference (%)
SC0	85	90	5.9
SC5	140	150	7.1
SC10	210	220	4.8
SC15	310	330	6.5
SC20	420	440	4.7
SC25	400	410	2.5

3.7 Engineering Implications and Limitations

The combined results indicate that GGBFS can improve the short-term engineering response of the investigated CH soil, particularly around SC20 under the adopted 7-day laboratory condition. The model-footing results extend the conventional UCS/CBR assessment by showing a corresponding reduction in deformation and increase in model bearing resistance. Nevertheless, several limitations constrain direct field application. The study did not directly measure free swell or swelling pressure, did not verify reaction products by XRD/SEM, and did not include extended curing or wetting–drying durability. The sulfate and soluble-salt contents of the soil were not quantified; therefore, sulfate-induced reactions, including possible deleterious ettringite formation in calcium- and alumina-bearing systems, cannot be assessed from the present data. The model footing was tested at small scale in a rigid box and at the adopted OMC-based condition rather than full saturation. In addition, a complete replicate dataset was not available for formal statistical inference. Finally, no life-cycle, carbon-footprint, or economic comparison with lime, cement, or soil replacement was performed. Thus, the potential sustainability relevance of GGBFS here is associated with beneficial industrial by-product reuse rather than a quantified environmental or economic advantage.

4. Conclusions

Based on the short-term laboratory investigation of the Thi-Qar high-plasticity clay treated with 0–25% GGBFS and cured for 7 days, the following conclusions are drawn. The conclusions apply to the tested materials and laboratory conditions and should not be generalized to long-term field performance without further validation.

- GGBFS treatment systematically modified the compaction response. MDD increased from 1.62 g/cm^3 for untreated soil to a maximum of 1.73 g/cm^3 at SC20, while OMC decreased from 21.5% to 17.6% at SC25. The slight MDD decline at SC25 indicates diminishing densification benefit beyond SC20 under the adopted compaction condition.
- Plasticity and short-term strength improved markedly. LL decreased from 58% to 40% and PI from 30% to 16%, while 7-day UCS increased from 120 kPa to a maximum of 680 kPa at SC20 before decreasing slightly to 660 kPa at SC25. These results demonstrate improved consistency and strength, but they do not directly prove swelling suppression or specific

hydration products because free-swell/swelling-pressure tests and XRD/SEM analyses were not performed.

- CBR increased from 3% for SC0 to 38% for SC20 and then decreased slightly to 36% for SC25. This trend, together with the UCS response, indicates improved short-term load resistance for subgrade-related applications under the investigated laboratory condition. Longer curing, soaked testing, and durability assessment are required before long-term pavement performance is inferred.
- The model-footing tests provided an important foundation-related response beyond conventional material tests. Model ultimate bearing pressure increased from 85 kPa for SC0 to 420 kPa for SC20, while settlement at ultimate pressure decreased from 18 to 5 mm. SC25 showed a small reduction to 400 kPa and 6 mm, respectively. Thus, SC20 provided the most favorable combined response within the tested range; it is not claimed as a statistically or economically optimized universal dosage.
- Meyerhof-based bearing pressures followed the same overall mixture trend and were moderately higher than the model measurements. Because the analytical calculation relied partly on empirically derived shear-strength parameters rather than dedicated direct-shear/triaxial data, the comparison should be regarded as an approximate analytical benchmark rather than independent validation of the equation for GGBFS-treated expansive soil.
- From an engineering perspective, the consistency among MDD/OMC, PI, UCS, CBR, and model-footing trends supports the use of GGBFS as a promising short-term improvement option for the investigated CH soil. However, the small model footing, rigid container boundaries, finite soil depth, OMC-based rather than saturated test condition, and lack of complete replicate-based statistics limit direct extrapolation of the measured bearing pressures and settlements to full-scale foundations.
- Before field implementation, future work should include direct swelling and swelling-pressure measurements; verified XRF/XRD/SEM and particle-size characterization of the actual GGBFS batch; direct shear or triaxial testing; systematic replicated testing with statistical analysis; curing periods of at least 14, 28, 56, and 90 days; wetting–drying and other relevant durability cycles; sulfate/salt characterization and sulfate-resistance assessment; and large-scale or field footing validation. Economic comparison and life-cycle/carbon assessment are also required before environmental or cost superiority over conventional stabilizers can be claimed.

Acknowledgement

The authors sincerely thank the Editor-in-Chief, the handling editor, and the anonymous reviewers for their constructive comments, which helped improve the clarity and scientific quality of the manuscript.

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