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Evaluation of Freeze-Thaw Behavior of Ground Granulated Blast Furnace Slag Stabilized Bentonite Subgrade Soils

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Abstract

This study investigated the freeze–thaw resistance of road subgrade soils stabilized with ground granulated blast-furnace slag (GGBFS). Within the experimental program, unconfined compressive strength (UCS) tests were conducted on pure bentonite and GGBFS-blended samples following standard Proctor tests and a seven-day curing period. To ensure data reliability, triplicate testing was executed for each configuration. The results indicated that GGBFS addition significantly increased UCS values, with optimum performance achieved at a 15% additive ratio. To evaluate freeze–thaw durability, pure and 15% GGBFS-stabilized samples were subjected to 3, 6, and 12 cycles (-23 °C freezing and +23 °C thawing). It was found that the addition of 15% GGBFS increased the UCS by 166% compared to the unstabilized soil. Strength and weight losses increased with the number of cycles, reaching 66.51% and 2.03% after 12 cycles. Narrow standard deviation ranges verified the high consistency of the mechanical parameters

Keywords

Bentonite, Freeze–thaw, Ground granulated blast-furnace slag, Soil Stabilization, Transportation Geotechnics

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Öğütülmüş Yüksek Fırın Cürufu ile Stabilize Edilmiş Bentonit Yol Taban Zeminlerinin Donma-Çözülme Davranışının Değerlendirilmesi

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Özet

Bu çalışma, granüle yüksek fırın cürufu (GGBFS) ile stabilize edilmiş karayolu taban zemini zeminlerinin donma-çözünme direncini incelemiştir. Deneysel program kapsamında, standart Proctor testleri ve yedi günlük kür süresinin ardından saf bentonit ve GGBFS karışımlı numuneler üzerinde serbest basınç dayanımı (UCS) testleri yapılmıştır. Veri güvenilirliğini sağlamak için her konfigürasyon için üç tekrarlı test yürütülmüştür. Sonuçlar, GGBFS ilavesinin UCS değerlerini önemli ölçüde artırdığını ve optimum performansın %15 katkı oranında elde edildiğini göstermiştir. Donma-çözünme dayanıklılığını değerlendirmek için saf ve %15 GGBFS ile stabilize edilmiş numuneler 3, 6 ve 12 çevrime (-23 °C dondurma ve +23 °C çözündürme) tabi tutulmuştur. %15 GGBFS ilavesinin, stabilize edilmemiş zemine kıyasla UCS'yi %166 oranında artırdığı bulunmuştur. Dayanım ve ağırlık kayıpları çevrim sayısıyla artarak 12 çevrim sonunda sırasıyla %66,51 ve %2,03'e ulaşmıştır. Dar standart sapma aralıkları, mekanik parametrelerin yüksek tutarlılığını ortaya koymuştur.

Anahtar kelimeler

Bentonit,
Donma-çözülme,
Öğütülmüş yüksek fırın cürufu,
Zemin stabilizasyonu,
Ulaştırma geotekniği

1. INTRODUCTION

Soil properties, along with topography, hydraulic conditions, and climatic data, play a vital role in the design of transportation structures. Data obtained from soil investigations conducted on highway routes are of critical importance in terms of meeting economic and engineering requirements while ensuring the safety of life and property. Specifically, stabilization activities applied to soils with insufficient bearing capacity are fundamental engineering interventions that directly affect the service life of the superstructure [1, 2]. When climate data monitored by 320 meteorological stations across Türkiye are examined, it is observed that road subgrade soils are under significant risk, particularly in regions where frost events are frequent, as is the case for all engineering structures. When the air temperature drops below the freezing point, ice lenses forming between soil particles lead to volumetric expansion and, consequently, frost heave. During the thawing phase, the structure loses its form, leading to sudden losses in bearing capacity and the deterioration of the superstructure's integrity [3]. To prevent such frost damage, common practices include controlling the groundwater level with drainage systems, replacing poor-quality soil with suitable materials, and soil improvement using additives. However, today, the use of industrial by-products as alternatives to conventional methods has gained importance within the context of sustainability and cost-effectiveness [4, 5]. In this regard, it is anticipated that stabilization studies conducted with alternative materials, such as ground granulated blast-furnace slag (GGBFS), will enable safer, more economical, and environmentally friendly transportation infrastructures by increasing both the bearing capacity and the freeze–thaw resistance of soils.

The contributions of stabilization processes using additives to the freeze–thaw resistance of soils have been demonstrated by various studies in the literature. Keskin et al. [6] investigated the effects of marble, pumice, and lime powders on fine–grained soils under freeze–thaw conditions; they determined that a 5% lime addition increased strength and a 5% pumice additive provided limited improvement, but 10% pumice and marble powder did not show a positive effect. Saygılı and Dayan [7] examined the effects of silica fume, lime, and polypropylene fiber additives on the strength and freeze–thaw behavior of clayey soils, finding that the highest resistance after 28 days of curing was obtained from the mixture containing 0.25% polypropylene fiber, 5% lime, and 10% silica fume. Similarly, Liang et al. [8] found that metakaolin–based geopolymers with rice husk ash (RHA) and silica fume (SF) additives exhibited increased mechanical properties and freeze–thaw resistance due to the reduced pore structure caused by the filler effect. In a study conducted by Mohammadzadeh et al. [9], it was revealed that clayey soils modified with glass powder exhibited superior performance under freeze–thaw conditions compared to Portland cement. Aqra et al. [10] emphasized that a combination of pumice, marble, and lime successfully stabilized expansive soils and enhanced performance in freeze–thaw cycles. It has been established in the literature [11-17] that GGBFS is used in stabilization studies, increasing both strength and freeze–thaw resistance. In this context, Soğancı et al. [11] stated that soil containing Blast Furnace Slag (BFS) provides low maintenance costs and environmental sustainability in flexible pavement design. Tomaz et al. [12] showed that this additive improves compaction parameters, increasing cohesion and the internal friction angle. Hu et al. [13] and Uzer et al. [14] expressed that results modeled with machine learning and artificial neural networks for slag and fly ash-based systems confirmed the optimum strength increase. Furthermore, Wu et al. [15] found that the addition of steel slag and NaOH maintains strength by limiting frost-induced deformation, while Zhu et al. [16] reported that a 30% GGBFS and 20% activator ratio offered the highest performance in permafrost soils, and Liu et al. [17] determined that an 80:20 slag/ash ratio minimized frost-induced structural loosening.

To clearly distinguish this research from the existing literature, it is essential to highlight the specific combination of experimental boundaries that defines the novelty of this study. While previous investigations [11-17] have broadly evaluated slag-based soil stabilization, they typically focus on common high-plasticity industrial clays (CH) or lean clays (CL), often requiring chemical activators (such as NaOH or lime) to initiate slag hydration. In contrast, this study specifically addresses a pure sodium bentonite road subgrade without utilizing any chemical activators, thereby directly assessing the standalone hydraulic and pozzolanic binding efficiency of GGBFS within an highly expansive clay matrix. Furthermore, while standard literature protocols often analyze long-term curing periods (e.g., 28 days) and simple post-cyclic strength variations, this study targets short-term curing (7 days) in strict accordance with the ASTM D560/D560M-16 [18] standard specification to systematically evaluate the early-stage infrastructure vulnerability under immediate environmental thermal stress. The performance indicators introduced herein are also more comprehensive; rather than relying solely on residual unconfined compressive strength, this research simultaneously quantifies cyclic weight losses and delineates the mechanical degradation pathway through rigorous standard deviation bounds. Consequently, this multi-parametric evaluation of non-activated GGBFS on pure bentonite under cyclic thermal shocks establishes a highly specific and contemporary baseline for sustainable subgrade design.

Based on the literature review conducted in this study, it is evaluated that research focusing on the stabilization of soil classified as bentonite road subgrade with GGBFS and comparing the freeze–thaw resistance of these stabilizations fills a significant gap in the literature. In this scope, standard Proctor tests were applied to pure bentonite soil and samples supplemented with different GGBFS ratios. Subsequently, pure and GGBFS-added samples were tested with unconfined compressive strength tests after 7 days of curing. Then, soil samples to be used in freeze–thaw tests were prepared based on

the determined optimum GGBFS ratios. After 7 days of curing, 3, 6, and 12 cycles were applied to the samples, with each cycle consisting of freezing at -23 °C for 24 hours followed by thawing at 23±2 °C for 23 hours. To fulfill statistical rigor and evaluate the reproducibility of the mechanical data, three identical replicate specimens (triplicate testing) were tested for each configuration. In the comparison of freeze–thaw resistance, the unconfined compressive strength values obtained after 7 days of curing (0 cycles) were taken as a reference, and subsequently, strength and weight losses along with their corresponding standard deviation ranges were evaluated.

2. MATERIALS AND METHODS

2.1. Soil Samples

The sodium bentonite (BT) considered as the road subgrade material in this research is a clay mineral characterized by high plasticity, a significant swelling tendency, low shear strength, and high compressibility. These geotechnical properties can lead to critical engineering challenges, such as foundation settlement, bearing capacity failure problems, and structural deformations due to volumetric changes (swelling-shrinkage). The sodium bentonite samples, which consist primarily of montmorillonite with a characteristic Methylene Blue adsorption value of 75 mg/g according to the manufacturer's official technical specification sheets, were classified as high plasticity clay (CH) according to the Unified Soil Classification System. The mineralogical dominance of montmorillonite is further supported by its extreme plasticity parameters, featuring a liquid limit ranging between 350% and 450%. The material was procured from Canbensan Cankiri Bentonit San. Tic. A.S. The engineering parameters of the samples prepared in accordance with the relevant standards [19-22] are presented in Table 1. The chemical oxide proportions of the bentonite were determined via X-ray fluorescence (XRF) analysis provided by the manufacturer as follows: 2.41% Na_2O, 2.68% MgO, 16.54% Al_2O_3, 62.40% SiO_2, 0.13% P_2O_5, 0.41% SO_3, 0.03% Cl, 1.10% K_2O, 6.91% $CaCO_3$, 0.76% TiO_2, 0.02% V_2O_5 and Cr_2O_3, 0.08% MnO, and 5.52% Fe_2O_3. Figure 1 illustrates the frost susceptibility classification of the subgrade soil based on the grain size criteria. Although this methodology is rooted in classic design frameworks such as AASHTO (1993) [23], it remains highly contemporary and legally binding within local engineering practices. Specifically, this exact frost heave criteria and chart have been fully adopted by the General Directorate of Highways in Turkey (KGM) and are actively utilized in the official Highways Flexible Pavement Project Design Guide [3] to evaluate the climate-induced vulnerability of subgrade clays. Therefore, utilizing this classification alignment not only ensures compliance with international literature but also directly satisfies the contemporary regional specification requirements dictated by Turkish highway design standards [3].

In this study, pure sodium bentonite was intentionally selected and utilized not as a typical desirable subgrade material, but as a model expansive clay and a standard laboratory reference material representing an extreme problematic soil condition. In geotechnical engineering research, pure bentonite serves as an ideal baseline for a 'worst-case scenario' due to its exceptionally high plasticity, dominant montmorillonite mineralogy, and extreme swelling-shrinkage potential. The practical relevance of choosing this extreme material relies on a conservative engineering approach: if a non-activated industrial by-product like GGBFS can successfully stabilize and enhance the freeze–thaw durability of pure sodium bentonite, it can be inferred that such a stabilization framework will perform even more effectively on natural, less-severe problematic high-plasticity clays (CH) encountered in actual highway routes. Under field conditions, while uniform pure bentonite strata are rare along road alignments, localized expansive clay pockets, montmorillonite-rich deposits, or highly unstable subgrade layers frequently demand immediate stabilization. In such scenarios, GGBFS stabilization can be practically applied through in-situ shallow soil mixing or deep mixing methods, providing a sustainable and cost-effective alternative to complete soil replacement.

Table 1. Properties of bentonite

Soil Property	Symbol	Value	Unit	Test Standards
Unified Soil Classification System	USCS	CH	-	ASTM D6913 [19]
Bulk Density	ρ_s	0.9	g/cm^3	ASTM D854 [20]
Optimum Moisture Content	ω_{opt}	35.25	%	ASTM D698 [21]
Maximum Dry Density	ρ_{dmax}	1.310	g/cm^3	ASTM D698 [21]
Liquid Limit	LL	350-450	%	ASTM D4318[22]
Sieve Residue on 150 µm Sieve	-	2.50	%	ASTM D6913 [19]
Sieve Residue on 75 µm Sieve	-	12.5	%	ASTM D6913 [19]

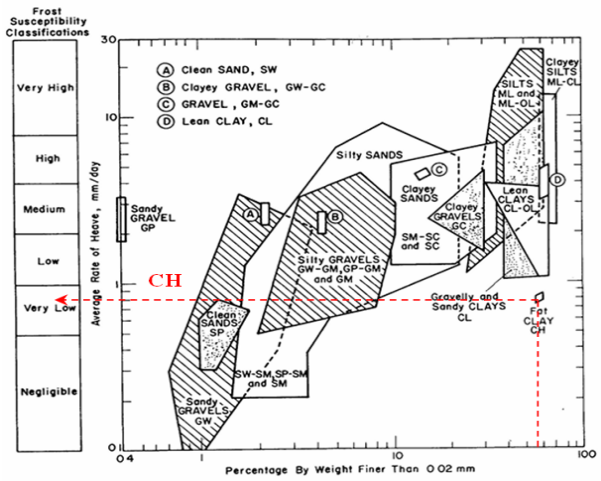


Figure 1. Frost susceptibility chart for soils [3, 31].

Based on the grain size distribution parameters of the pure sodium bentonite (100% passing the No. 200 sieve and approximately 98% of particles finer than 0.02mm), the soil is located on the far right boundary of Figure 1, aligning with the 'Fat Clay (CH)' and 'Lean Clays (CL)' zones. According to the AASHTO criteria depicted in Figure 1, this positioning classifies the material as having a 'Very Low' frost susceptibility. This classification may appear counterintuitive given the high plasticity of bentonite; however, it is heavily governed by hydraulic conductivity limitations. In ultra-fine clay matrices like pure bentonite, the permeability is exceptionally low, which physically restricts the rapid capillary water migration required to feed and grow large localized ice lenses. Consequently, the macro-structural volumetric frost heave remains minimized.

Nevertheless, a clear distinction must be established between the frost susceptibility classification (which strictly measures volumetric heave rate) and the post-cyclic strength degradation. Even though the volumetric heave rate is classified as 'Very Low' due to the restricted water movement during freezing, the insitu pore water undergoes localized phase changes. The expansion of this trapped pore water into ice exerts substantial microstructural crystallization pressures, permanently disrupting the inter-particle cohesive bonds and destroying the soil skeleton. Upon thawing, this microstructural damage manifests as a severe reduction in the unconfined compressive strength (UCS), explaining why a soil with low volumetric heave classification can still exhibit significant mechanical degradation after freeze–thaw cycles.

2.2. Ground Granulated Blast Furnace Slag

Ground Granulated Blast Furnace Slag (GGBFS) is an industrial by-product with hydraulic binding properties, obtained by the rapid quenching (granulation) of molten slag from blast furnaces during the iron and steel production process, followed by fine grinding. Due to its high content of calcium oxide (CaO), silicon dioxide (SiO_2), and aluminum oxide (Al_2O_3), it has the ability to form a binding matrix by developing pozzolanic reactions. In line with these characteristic attributes, GGBFS is widely used not only as a cement replacement but also as a sustainable binder alternative in geopolymer synthesis and soil improvement projects. Studies in the literature confirm that the use of GGBFS significantly minimizes the carbon footprint while optimizing structural engineering performance [11 and 14]. The GGBFS used in the current experimental study was procured as a by-product from the İskenderun Iron and Steel Factory. When evaluating the chemical composition of the material, the proportions were identified as 32.7% CaO, 41.2% SiO_2, 14.3% Al_2O_3, 7.3% MgO, 0.8% S, 0.8% MnO, 0.9% K_2O, and 1.1% TiO_2. The physical appearance of the sample is shown in Figure 2.



Figure 2. GGBFS sample.

2.3. Standard Proctor Test

The Standard Proctor test, based on the principle of removing air voids in soil samples through mechanical energy, was conducted in accordance with ASTM D698 (2014) standards. In this context, soil samples dried at 105 °C for 24 hours were mixed with the target moisture content and compacted into the mold in three stages, applying 25 blows per layer using a 2.5 kg rammer, and their weights were recorded. To precisely construct the moisture-density relationship and establish a reliable compaction curve, this experimental process was executed at five distinct, incrementally increasing water content levels for each soil-binder mixture configuration. The peak point of the resulting five-point compaction curve uniquely determined the maximum dry density and optimum moisture content parameters for the respective combinations [21, 24].

2.4. Unconfined Compressive Strength (UCS) Test

The Unconfined Compressive Strength (UCS) test, applied to determine the strength characteristics of the samples after specific curing periods, was carried out according to the ASTM D2166-06 (2006) [24] standard. In the specimen preparation stage, the raw materials were first dried at 105 °C to ensure accurate dry weight calculations, and then all mixtures were compacted at their specific optimum moisture content values to target their corresponding maximum dry density values determined from the Standard Proctor tests. To replicate the Standard Proctor Compaction Energy level (approximately 592.5 kJ/m3) within the smaller cylindrical molds (38 mm in diameter and 76 mm in height) used for the UCS and freeze–thaw tests, a systematic compaction procedure was adopted in

accordance with established geotechnical laboratory practices. The mixtures were compacted in 4 equal layers, and each layer received 10 blows from a 2.5 kg mold-specific custom hammer with a free-fall height of 50–60 mm. This strict protocol ensured that the applied compaction energy per unit volume was completely equivalent to the ASTM D698 standard effort. Furthermore, to ensure statistical reliability and reproducibility of the experimental data, a minimum of three replicate specimens (triplicate) were manufactured and tested for each specific mixture combination under every environmental condition, and the average values were reported.To prevent any moisture loss during the hydration and pozzolanic reaction phases, the prepared specimens were immediately extracted from the molds and placed inside airtight sealed plastic containers. This procedure effectively created a self-contained, moisture-locked micro-environment for each specimen, entirely isolating them from external ambient effects. Subsequently, these sealed containers were kept in a temperature-controlled laboratory environment maintained at a stable temperature of 23±2 °C throughout the 7-day curing period. They were placed in the testing apparatus. To satisfy statistical rigor and ensure the reproducibility of the mechanical data, three identical replicate specimens (triplicate testing) were fabricated and tested for each specific mixture design and curing history. The final representative unconfined compressive strength and axial strain values were determined by taking the arithmetic average of these three independent replicate tests. During the test, the axial strain rate was maintained between 0.5% and 2% per minute, ensuring the total duration did not exceed 10 minutes, and ultimate strength values were determined based on the resulting strain and deformations [24, 25]. The application stages of the unconfined compressive strength test and specimen preparation are presented in Figure 3.



Figure 3. Application stages of the unconfined compressive strength test

2.5. Freeze-Thaw Test

The Freeze–thaw test, conducted to examine the behavior of water in soil pores under freeze and thaw cycles due to temperature changes, was performed according to ASTM D560/D560M-16 (2016) principles. Samples prepared using the UCS methodology and having completed the 7-day curing period were frozen at –23 °C for 24 hours and then allowed to thaw at 23 ± 2 °C for 23 hours. Following this procedure, which represents one full cycle, the study was concluded by measuring the strength performance of the samples that completed the predetermined number of cycles [18, 26]. The choice of a 7-day curing period was determined strictly in accordance with the standard specification outlined in ASTM D560/D560M-16, which requires prepared soil-binder specimens to be stored in a moisture-controlled environment for a period of seven days before being subjected to repeated freezing and thawing cycles. From an engineering and design perspective in transportation geotechnics, evaluating stabilized road layers at this early curing stage also provides a conservative baseline and a realistic representation of short-term durability. While it is well known that hydraulic and pozzolanic reactions of GGBFS are strongly time-dependent and strength gains become significantly more pronounced at extended curing durations (such as 28 or 56 days), The 7-day curing approach originates from the ASTM D560/D560M-16 standard.

2.6. Preparation of Test Samples and Applications

Within the scope of this study, the Standard Proctor test was applied to determine the maximum dry unit weights and optimum moisture contents of pure and modified soil samples. Modified samples were created by adding GGBFS to sodium bentonite soil at ratios of 5%, 10%, 15%, and 20% by dry weight of soil. Based on the obtained compaction parameters (maximum dry density and optimum water content), UCS test samples were prepared for both pure and GGBFS-containing soils. The prepared samples were isolated from environmental effects and subjected to a 7-day curing period; at the end of this period, the stabilization effectiveness of GGBFS on BT soils was analyzed through UCS tests. The 15% GGBFS ratio, where the highest strength increase was observed, was identified as the optimum additive amount, and freeze–thaw tests were conducted using this ratio.

Freeze–thaw samples were prepared following the UCS procedures and, after completing the 7-day curing period, were subjected to 3, 6, and 12 cycles. In the selection of the number of cycles, the 12-cycle criterion prescribed in the ASTM D560/D560M-16 [18] standard and the minimum 5-cycle condition in the General Directorate of Highways (KGM) specifications [26] were taken as references. Performance evaluations were based on the UCS values obtained after 7 days of curing (0 cycles); following the completion of the cycles, the final UCS values and changes in weight loss of the samples were examined in detail. The application stages of the freeze–thaw test are presented in Figure 4.



Figure 4. Application stages of the freeze–thaw test

3. RESEARCH FINDINGS AND DISCUSSION

The objective of this study was to improve BT soil, accepted as a road subgrade, using GGBFS and to investigate the freeze–thaw resistance of the resulting stabilizations. The experimental applications and the findings obtained are presented in the following sections.

3.1. Standard Proctor Test Findings

Standard Proctor tests were conducted on BT soil and samples containing 5%, 10%, 15%, and 20% GGBFS by weight. The resulting maximum dry density and optimum moisture content graphs are provided in Figures 5, 6, and the values are summarized in Table 2.

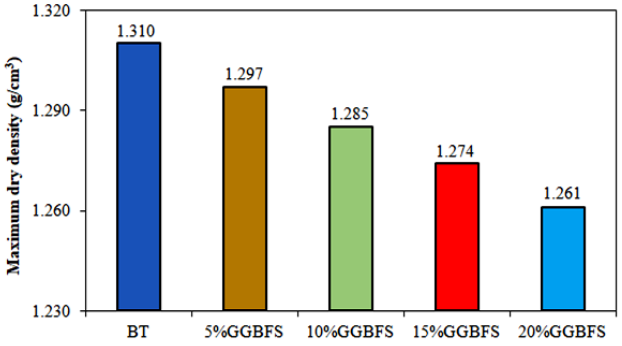


Figure 5. Maximum dry density results of BT soil with different GGBFS contents

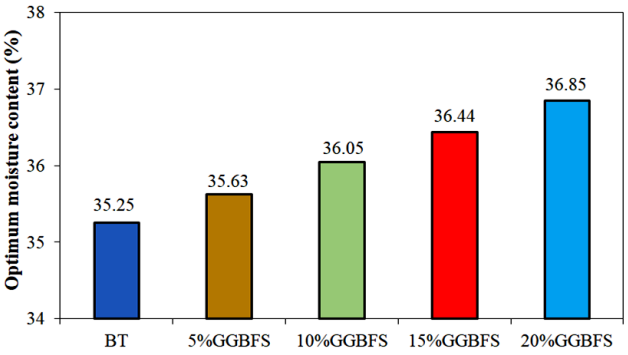


Figure 6. Optimum moisture content results of BT soil with different GGBFS contents

Table 2. Standard Proctor test results of BT and GGBFS mixtures

Samples	ρ_{dmax} (g/cm^3)	ω_{opt} (%)
BT	1.310	35.25
BT+5% GGBFS	1.297	35.63
BT+10% GGBFS	1.285	36.05
BT+15% GGBFS	1.274	36.44
BT+20% GGBFS	1.261	36.85

When the Proctor test data are evaluated, it appears that the optimum moisture content slightly increases and the maximum dry density decreases as the amount of GGBFS in the mixture increases. These findings are consistent with the existing literature [27-30]. The primary reason for this trend can be attributed to the low specific gravity of GGBFS. The conclusions in the literature suggesting that the fine-grained structure of GGBFS increases water demand [29, 31] are found to be in parallel with the results of this study.

3.2. Unconfined Compressive Strength Test Findings

Unconfined compressive strength (UCS) samples containing 5%, 10%, 15%, and 20% GGBFS by weight for BT soil were prepared based on the maximum dry density and optimum moisture content values obtained from the standard Proctor test. After being cured at room temperature for 7 days, the samples were subjected to the UCS test. It was ensured that the duration of the tests did not exceed 10 minutes. The results of the unconfined compressive strength (q_u) and axial strain (ε_u) for the pure and GGBFS-added soils are presented in Figures 7 and 8, and summarized in Table 3.

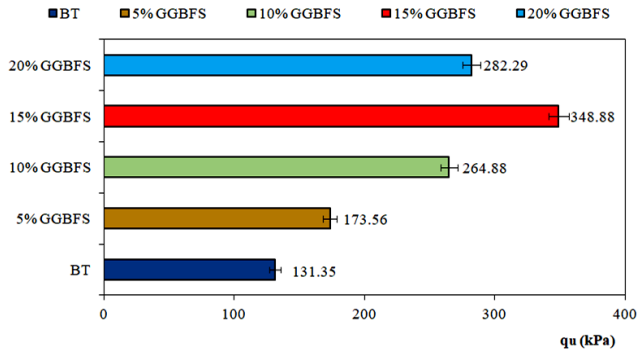


Figure 7. Unconfined compressive strength results of BT soil and samples containing various GGBFS ratios with corresponding standard deviation error bars

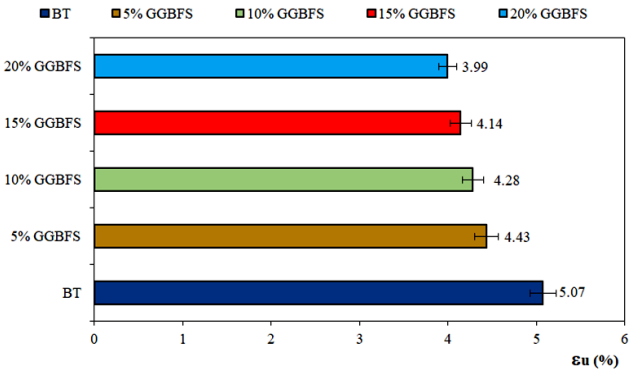


Figure 8. Axial strain results of BT soil and samples containing various GGBFS ratios with corresponding standard deviation error bars

Table 3. Unconfined compressive strength - axial strain data of BT and GGBFS-added mixtures obtained after 7 days of curing

Samples	q_u (kPa)	ε_u (%)
BT	131.35	5.07
BT+5% GGBFS	173.56	4.43
BT+10% GGBFS	264.88	4.28
BT+15% GGBFS	348.88	4.14
BT+20% GGBFS	282.29	3.99

When the unconfined compressive strength test findings are evaluated, it is observed that the strength values of BT samples are lower than those containing GGBFS at the end of the 7-day curing period. It was found that the addition of GGBFS positively affected the strength performance of the mixtures, with net strength improvements realized at 31%, 102%, 166%, and 115%, respectively. The highest strength increase was recorded in samples with 15% GGBFS content. To verify the

reproducibility and statistical reliability of these findings, standard deviation (SD) values were calculated for each mixture series. The average unconfined compressive strength (q_u) and corresponding SD values for BT, BT+5% GGBFS, BT+10% GGBFS, BT+15% GGBFS, and BT+20% GGBFS were obtained as 131.35 kPa (SD = 4.23 kPa), 173.56 kPa (SD = 5.18 kPa), 264.88 kPa (SD = 6.47 kPa), 348.88 kPa (SD = 7.76 kPa), and 282.29 kPa (SD = 6.84 kPa), respectively. Furthermore, the average axial failure strain (ε_u) and its corresponding SD values for the same sequences were recorded as 5.07% (SD = 0.15%), 4.43% (SD = 0.13%), 4.28% (SD = 0.12%), 4.14% (SD = 0.12%), and 3.99% (SD = 0.10%), respectively. The low standard deviation bounds obtained for both strength and strain parameters clearly demonstrate the high consistency of the experimental data and the uniformity of the specimen fabrication process. This situation shows parallelism with the existing literature [27-30] regarding the enhancing effect of GGBFS on strength. Furthermore, a decrease in the axial strain capacity of the samples was observed depending on the increase in GGBFS dosage and curing time; this trend is anticipated to stem from the increase in sample rigidity, and the results are consistent with related studies [32].

It was determined that the strengths of BT-based mixtures were higher than those of the pure samples, thus confirming literature data [27-30] indicating that the use of GGBFS improves the bearing capacity of soils. As stated in the literature [27-30], the reactive nature of the calcium, silica, and alumina components within GGBFS allows for the synthesis of hydration products that exhibit binding properties between soil particles. While this process ensures the densification of the soil microstructure, an increase in mechanical resistance, and the minimization of volumetric changes, it is known that the material plays the role of an effective binder due to its hydraulic and pozzolanic character. In this context, It is observed that GGBFS holds critical importance in the stabilization of soils that exhibit weak engineering properties, such as high-plasticity clays. The experimental results revealed that GGBFS significantly improved the mechanical parameters of the mixtures. However, it was considered that when the optimum GGBFS level is exceeded, the unreacted excess additive does not provide additional contribution to the strength increase.

It was determined that the strengths of BT-based mixtures were higher than those of the pure samples. The reactive calcium, silica, and alumina components within GGBFS allow for the synthesis of hydration products that exhibit binding properties between soil particles, ensuring the densification of the soil microstructure and an increase in mechanical resistance. More specifically, the interaction between high-plasticity bentonite and GGBFS involves short-term physical-chemical mechanisms. When GGBFS is mixed with the soil in the presence of water, the released divalent calcium (Ca^{2+}) cations rapidly replace the monovalent sodium (Na^{+}) cations on the exchange complex of the clay. This immediate cation exchange compresses the diffuse double layer surrounding the clay particles, diminishing electrostatic repulsive forces and promoting a structural shift from a dispersed state to a flocculated and agglomerated state. This flocculation-agglomeration process transforms the fine clay matrix into larger aggregates, decreasing plasticity and enhancing early-stage stability. Subsequently, long-term hydraulic and pozzolanic reactions take place, synthesizing secondary cementitious gels such as calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) that permanently lock these structures. In this context, It is observed that GGBFS holds critical importance in the stabilization of soils that exhibit weak engineering properties, such as high-plasticity clays, thus confirming related literature data [27-30]. The experimental results revealed that GGBFS significantly improved the mechanical parameters of the mixtures. However, when the GGBFS content was increased to 20%, a noticeable decrease in the unconfined compressive strength was observed, identifying 15% as the optimum stabilization threshold. This strength reduction beyond the optimum binder dosage is primarily attributed to a combination of the dilution effect and the physical disruption of the soil skeleton by unreacted excess material. At higher replacement levels, the relative proportion of the clay fraction within the solid matrix decreases, causing a dilution effect that limits the available silica and alumina sources required to sustain continuous pozzolanic activity. Furthermore, since the hydration and activation reactions consume a finite amount of water and ions, the excess GGBFS remains unreacted in the pore spaces. This unreacted granular additive acts as inert, non-cohesive particulate matter within the stabilized matrix, physically separating the clay particles and undermining the localized cohesion. This excess material ultimately disrupts the structural integrity of the consolidated soil skeleton, thereby creating weak microstructural zones that lead to premature failure under mechanical loading [27-31].

3.3. Freeze-Thaw Test Findings

To evaluate freeze–thaw performance, BT soil samples were prepared using the optimum GGBFS additive ratios determined from the unconfined compressive strength tests. The samples were prepared based on MDD and OMC content and then subjected to 3, 6, and 12 cycles after a 7-day curing period. As a result of the experiments, losses in unconfined compressive strength, weight loss, and axial strain values (taking the 7-day strength, referred to as 0 cycles, as a reference) were analyzed. Comparative strength/axial strain data are presented in Figures 9, 10 and Table 4, while strength/weight loss data are provided in Figures 11, 12, and Table 5.

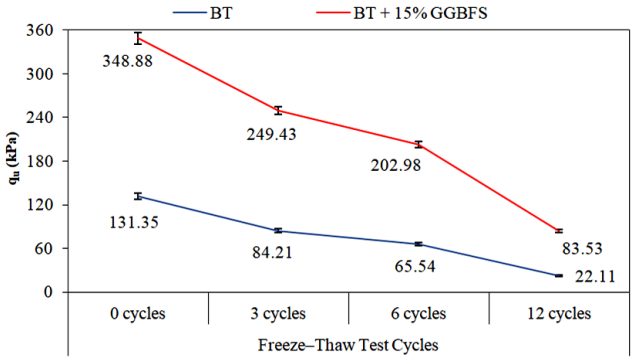


Figure 9. Variation of unconfined compressive strength for BT soil and 15% GGBFS-stabilized samples following freeze–thaw cycles with corresponding standard deviation error bars

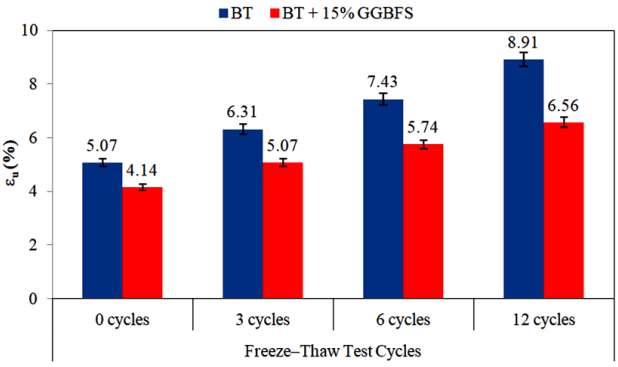


Figure 10. Variation of axial strain at failure for BT soil and 15% GGBFS-stabilized samples following freeze–thaw cycles with corresponding standard deviation error bars

Table 4. Comparison table of strength and axial strain at failure for BT soil and 15% GGBFS-added samples after the freeze–thaw test

Test samples	Freeze–thaw test results				
	Parameters	0 Cycles	3 Cycles	6 Cycles	12 Cycles
BT	q_u (kPa)	131.35	84.21	65.54	22.11
	ε_u (%)	5.07%	6.31%	7.43%	8.91%
BT+%15 GGBFS	q_u (kPa)	348.88	249.43	202.98	83.53
	ε_u (%)	4.14%	5.07%	5.74%	6.56%

When the freeze–thaw test results for 3, 6, and 12 cycles presented in Figures 9, 10, and Table 5 are examined, the strength values for the samples prepared with pure BT and 15% GGBFS were determined as 84.21 and 249.43 kPa after 3 cycles, 65.54 and 202.98 kPa after 6 cycles, and 22.11 and 83.53 kPa after 12 cycles, respectively. The calculated standard deviation (SD) values for the unconfined compressive strength (q_u) of pure BT specimens were recorded as 2.78 kPa at 3 cycles, 2.30 kPa at 6 cycles, and 1.05 kPa at 12 cycles, whereas the corresponding SD values for the 15% GGBFS-stabilized specimens were 5.60 kPa, 4.40 kPa, and 2.07 kPa for the same cycle sequences, respectively.

The axial strain values at failure for the pure BT and 15% GGBFS samples were determined as 6.31% and 5.07% after 3 cycles, 7.43% and 5.74% after 6 cycles, and 8.91% and 6.56% after 12 cycles, respectively. Regarding the axial failure strain (ε_u) parameters, the standard deviation bounds for the pure BT samples were evaluated as 0.18% (3 cycles), 0.22% (6 cycles), and 0.25% (12 cycles). For the 15% GGBFS-blended samples, the strain SD values were obtained as 0.15%, 0.17%, and 0.19% after 3, 6, and 12 cycles, respectively. These minor standard deviation ranges confirm the strong structural stability and consistent engineering behavior of the fabricated clay-binder matrices under cyclic thermal stress.

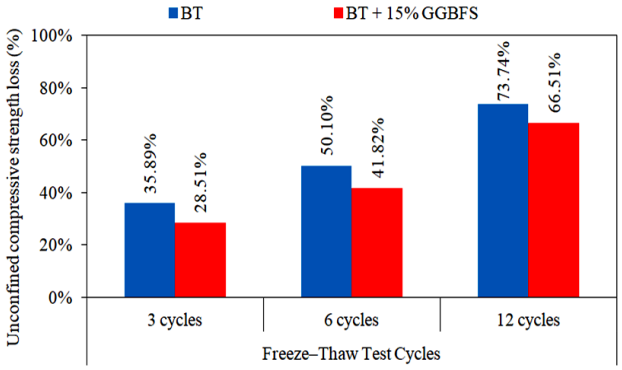


Figure 11. Graphs of unconfined compressive strength loss values for BT soil and 15% GGBFS-added samples after the freeze–thaw test

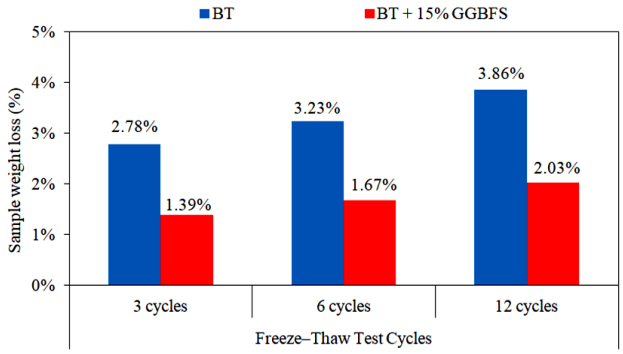


Figure 12. Graphs of weight loss values for BT soil and 15% GGBFS-added samples after the freeze–thaw test

Table 5. Comparison table of unconfined compressive strength loss and weight loss values for BT soil and 15% GGBFS-added samples after the freeze–thaw test

Test samples	Freeze–thaw Test Results					
	Unconfined compressive strength loss(%)			Sample weight loss (%)		
	3 Cycles	6 Cycles	12 Cycles	3 Cycles	6 Cycles	12 Cycles
BT	35.89%	50.10%	73.74%	2.78%	3.23%	3.86%
BT + 15% GGBFS	28.51%	41.82%	66.51%	1.39%	1.67%	2.03%

In the samples prepared with pure BT, the strength loss and specimen weight loss relative to the 0-cycle values were determined as 35.89% and 2.78% after 3 cycles; 50.10% and 3.23% after 6 cycles; and 73.74% and 3.86% after 12 cycles, respectively. For the samples prepared with GGBFS, the strength loss and weight loss relative to the 0-cycle values were determined as 28.81% and 1.39% after 3 cycles; 41.82% and 1.67% after 6 cycles; and 66.51% and 2.03% after 12 cycles, respectively.

Considering the strength and weight losses at the end of all cycles, it was determined that the freeze–thaw resistance of the BT soil was lower compared to the GGBFS-added samples, and that GGBFS increased the freeze–thaw resistance of the mixtures. In this regard, it is observed that GGBFS is effective in increasing freeze–thaw resistance, just as it is effective in increasing

the strength of mixtures as reported in the literature [27-30].

When the strength change ratios of the mixtures are examined, the net strength improvement of the stabilized specimens compared to the unstabilized soil was 166% at 0 cycles, and this relative performance gap expanded to 196%, 210%, and 278% after 3, 6, and 12 freeze–thaw cycles, respectively.

The fact that the weight loss of the prepared samples was less than that of the BT soils is attributed to the compact structure of the specimens resulting from the increased strength via soil stabilization, which effectively restricts the physical detachment of soil aggregates under cyclic thermal stresses [4,5]. It is further considered that the freeze–thaw resistance was enhanced because the stabilization with GGBFS reduced the movement of water—which would otherwise feed ice lenses during freezing due to the very small particle size and high fine-grain content of BT. This reduction in hydraulic conductivity and capillary water migration, achieved through the filling of micro-pores with pozzolanic hydration products, aligns closely with established mechanisms in the literature regarding frost susceptibility mitigation in stabilized clay matrices [15,16]. Additionally, it is evaluated that the SiO_2 in the chemical structure of GGBFS may be effective in increasing freeze–thaw resistance, as observed in other mixtures containing SiO_2 [19, 33].

Furthermore, considering that BT soil is attributed with "very low" frost susceptibility according to the AASHTO (1993) guide, the variability in freeze–thaw resistance and strength losses relative to stabilization-induced strength increases highlights the necessity of investigating soil behavior under laboratory conditions, emphasizing the importance of experimental laboratory studies.

4. DISCUSSION AND CONCLUSION

This study comprehensively investigated the macro-mechanical behavioral changes and freeze–thaw durability of a high-plasticity model expansive soil stabilized with ground granulated blast furnace slag (GGBFS). The experimental program was systematically conducted by preparing mixtures with varying slag content (5%, 10%, 15%, and 20% by dry weight of soil) and evaluating their performance through standard compaction, 7-day unconfined compressive strength (UCS), and cyclic freeze–thaw exposure (3, 6, and 12 cycles) tests. The obtained empirical results were cross-evaluated alongside physical and mechanical parameters to delineate the operational limits and stabilization efficiency of the GGBFS-clay matrix under structural and environmental loads. Based on the systematically analyzed experimental data, the specific concluding remarks and primary findings of this investigation are presented below:

- Standard Proctor test results for mixtures prepared with BT soil showed that as the GGBFS ratio increased, the optimum moisture content increased slightly, while the maximum dry density decreased. This is attributed to the low specific gravity of GGBFS.
- The increase in optimum moisture content and the decrease in maximum dry density are thought to result from GGBFS increasing the fine-grain ratio, thereby increasing water demand.
- According to the unconfined compressive strength test results, the highest strength value after a 7-day curing period was observed in samples with 15% GGBFS by weight.
- The unconfined compressive strength of the mixture optimized with 15% GGBFS exhibited a 166% increase compared to the pure BT soil. It was found that axial strain decreased as the GGBFS content in the mixtures increased.
- In the freeze–thaw tests of the 15% GGBFS-added mixtures, the strength loss relative to the 0-cycle value was 28.51%, 41.82%, and 66.51% after 3, 6, and 12 cycles, respectively. The weight loss was determined as 1.39%, 1.67%, and 2.03% respectively. These losses were found to be significantly lower than those detected in the pure BT soil.
- For the mixtures modified with 15% GGBFS, the observed mechanical performance and freeze–thaw durability are linked to the pozzolanic reactions initiated by the silicate (SiO_2) components within the slag structure, which promote the formation of stabilizing hydration products. This chemical interaction fills the micro-pores of the clay matrix, thereby reducing hydraulic conductivity and capillary water migration that would otherwise feed ice lenses, resulting in minimized weight loss and restricted aggregate detachment under cyclic thermal stresses.
- Despite the "very low" frost susceptibility of BT soil according to AASHTO (1993), the increase in freeze–thaw resistance through stabilization emphasizes the importance of evaluating soil behavior under laboratory conditions.

In conclusion, stabilization of BT soils with GGBFS increases both the strength and freeze–thaw resistance of the mixtures. Furthermore, it is evaluated that this study can be expanded by considering factors such as highway pavement base, subgrade level, groundwater table, and freezing index in a road section designed based on specific traffic loads according to the KGM (General Directorate of Highways) Pavement Design Guide. Using GGBFS in road subgrade stabilization can reduce maintenance and repair costs by increasing subgrade strength. Utilizing a waste material like GGBFS is expected to contribute to the national economy and provide an effective disposal method. Such applications could reduce the amount of material used in maintenance work and minimize environmental damage, particularly CO_2 emissions occurring during the production, transportation, and application of these materials.

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AUTHORS' CONTRIBUTION

All authors contributed equally to the preparation of this article.

DECLARATION OF COMPETING INTEREST

The authors declare no conflicts of interest.

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