Black Sea Journal of Engineering and Science
doi: 10.34248/bsengineering.1980846

Open Access Journal
e-ISSN: 2619 – 8991

Research Article
Volume 9 - Issue 5: 2259-2268 / September 2026

EFFECT OF SOIL STABILIZATION USING GROUND GRANULATED BLAST FURNACE SLAG AND ALKALI ACTIVATED SOLUTIONS ON RIGID PAVEMENT COST

Bahadır KARABAŞ[1]*, Ali Ulvi UZER[2], Nurullah AKBULUT[3], Abdurrahman BÖLÜCÜ[4]

[1]*Inönü University, Faculty of Engineering, Department of Civil Engineering, 44280, Malatya, Türkiye*
[2]*Kayseri University, Vocational School of Technical Sciences, Department of Construction, 38280, Kayseri, Türkiye*
[3]*The Federal Waterways Engineering and Research Institute (BAW), 76152, Karlsruhe, Germany*
[4]*Hasan Kalyoncu University, Faculty of Engineering, Department of Civil Engineering, 27900, Gaziantep, Türkiye*

Abstract: This paper examines how stabilizing road subgrade soils with ground granulated blast furnace slag (GGBFS) and alkali-activated solution (AAS) influences both rigid pavement layer thicknesses and initial investment expenditures. For this investigation, bentonite (BT) samples representing the subgrade soil were blended with GGBFS and AAS solutions formulated with 8 molar sodium hydroxide at weight percentages of 5%, 10%, 15%, and 20%. Proctor and unconfined compressive strength (UCS) trials were carried out on the prepared formulations. Following a 28-day curing stage, the maximum compressive strength performance was observed in the 10% GGBFS+AAS blends. California Bearing Ratio (CBR) assessments conducted on the control soil versus the optimum 10% GGBFS+AAS mixture indicated an 11.80 fold enhancement in the CBR performance of the modified soil. Based on structural designs and economic evaluations performed in compliance with AASHTO 1993 guidelines, the results demonstrate that ground stabilization using 10% GGBFS+AAS optimizes concrete pavement layer configurations, yielding a 1.42% reduction in initial construction costs.

Keywords: Alkali activated solution, Bentonite, Ground granulated blast furnace slag, Rigid pavement design, Soil stabilization

***Corresponding author:** Inönü University, Faculty of Engineering, Department of Civil Engineering, 44280, Malatya, Türkiye
E mail: karabasbaha@gmail.com (B. KARABAŞ)
Bahadır KARABAŞ https://orcid.org/0000-0003-0416-9121
Ali Ulvi UZER https://orcid.org/0009-0002-7916-8078
Nurullah AKBULUT https://orcid.org/0000-0002-4280-1581
Abdurrahman BÖLÜCÜ https://orcid.org/0009-0000-9912-8327

Received: June 28, 2026
Accepted: July 29, 2026
Published: September 15, 2026

Cite as: Karabaş, B., Uzer, A. U., Akbulut, N., & Bölücü, A. (2026). Effect of soil stabilization using ground granulated blast furnace slag and alkali activated solutions on rigid pavement cost. *Black Sea Journal of Engineering and Science*, 9(5), 2259-2268.

1. Introduction

One of the most critical challenges encountered in the construction of highways, which form the cornerstone of transportation networks, is maintaining the stability and service life of pavements built on subgrade soils with inadequate engineering properties. Particularly, clayey soils with high plasticity, such as bentonite, lead to significant deformations and cracking in pavement layers due to their low bearing capacity and high swelling potential, thereby increasing maintenance and repair costs. The ability of highways to provide long-lasting, safe, and economical service depends directly on the engineering qualities of the road subgrade as much as the pavement design itself. Replacing weak soil with suitable material, a traditional solution, entails disadvantages such as high costs and the rapid depletion of natural resources. In this context, innovative stabilization techniques alongside traditional binders like lime, cement, and bitumen emerge as a strategic research area in highway engineering to enhance the bearing capacity and design characteristics of weak soils. For instance, Tunç (2002) and Kök (2019) demonstrated the effectiveness of conventional binders in improving mechanical performance and structural durability in pavement layers. Expanding on modern stabilization approaches, Geçkil et al. (2025a) investigated the impact of sandy soil stabilized with ground pumice stone on flexible pavement design parameters. Similarly, Geçkil et al. (2025b) evaluated the structural layer thickness and initial construction cost of flexible pavements constructed on soils improved using glass powder. Furthermore, Geçkil et al. (2026) highlighted the effectiveness of stabilizing subgrade soils with recycled glass powder to enhance their resistance against freeze–thaw cycles.

In today's engineering projects, the quest for sustainability and economic efficiency has led to an increasing number of studies on the use of waste and various additive materials in soil improvement. Topçuoğlu and Güroçak (2023) focused on determining the optimum basalt fiber ratio to achieve maximum strength in soil reinforcement. Investigating disaster-related waste recovery, Çınar (2024) analyzed the geotechnical properties of clayey sand soil stabilized with

This work is licensed (CC BY-NC 4.0) under Creative Commons Attribution 4.0 International License

aerated concrete waste. Focusing on sustainable binder systems, Karabaş (2025) evaluated the effects and sustainability of road subgrade soils stabilized with various additives on highway pavement structures. Furthermore, Karabaş and Uzer (2026) demonstrated the effect of ground granulated blast furnace slag–stabilized bentonite subgrades on flexible pavement structural thickness and cost analysis. Additionally, Tanyıldızı and Karabaş (2026) evaluated the initial construction costs and CO_2 emissions of pavements constructed over weak subgrades, highlighting that industrial additive applications effectively optimize pavement performance while reducing environmental impacts. Shabana et al. (2014), in a study on improving silty sandy soil with coconut shells, determined that the addition of 16% crushed coconut shells, with a maximum surface area of 1 cm^2, increased the bearing capacity. Babatunde et al. (2019) conducted experimental studies to evaluate the effect of glass powder on the engineering properties of soil. Glass powder was used in various percentages such as 0%, 2%, 4%, 6%, and 8% by weight, and an increase in strength was observed in mixtures containing 4% glass powder. Geçkil et al. (2021) and Geçkil and Karabaş (2026) investigated the stabilization of clayey sandy soils using carbon black obtained from waste vehicle tires, which poses a significant environmental disposal problem. They determined that CBR values increased in soils with 10% carbon black added. Bharti et al. (2023), in their study on the stabilization of black cotton soil with copper slag, prepared samples by mixing copper slag at four different ratios (5.0%, 10.0%, 15.0%, and 20.0%) and applied modified Proctor, CBR, unconfined compression, liquid limit, and plastic limit tests. They concluded that the optimum mixture was at a 20% copper slag ratio. Şengül et al. (2023) examined the mechanical performance of high-plasticity soils reinforced with fly ash and polypropylene fiber. The results showed that a 10% fly ash ratio increased the compressive strength by 85.8%, while the fiber additive strengthened the shear strength. Geçkil et al. (2025c) conducted studies on improving clayey soil with glass powder (GP) by adding 3%, 6%, 9%, and 12% GP by weight; the best strength values were obtained in mixtures containing 9% GP. In addition to various additives used in soil stabilization, sodium hydroxide stands out as a critical component that increases bearing capacity by triggering the formation of sodium alumino-silicate hydrate gels, which establish strong bonds between soil particles (Karabaş, 2025). This chemical process occurring within the mixture creates a geopolymerization structure that improves the mechanical properties of the soil, revealing the decisive role of alkali activators in stabilization performance. Abdulkarim and Sa'eed, (2020) investigated the effects of both curing time and NaOH molar concentration on soil strength. The best CBR results were obtained after a 28-day curing period with a 7M NaOH solution. Hussain (2019) examined the stabilization of clayey soil strength performance with NaOH. The study found that in mixtures with 5%, 10%, 15%, and 20% NaOH, the UCS value increased up to a 15% NaOH ratio and decreased thereafter, with a maximum increase of approximately 280%. Konai et al. (2026) attempted to improve high-plasticity expansive clay soil with rice husk ash and sodium hydroxide, achieving the best performance with 15% rice husk ash and 2M NaOH. Ground granulated blast furnace slag (GGBFS), a by-product of the iron and steel production process, is a significant industrial waste that exhibits strong pozzolanic properties by interacting with soil due to its dense silica, alumina, and calcium oxide content (Abdila et al., 2022; Bilici et al., 2020; Hu et al., 2025; Sarıca, 2019; Uzer et al., 2025). Research in the literature focusing on the performance and potential use of this material in soil stabilization by activating it with NaOH solutions is noteworthy for sustainable engineering solutions. Sarıca (2019) investigated the usability of construction and demolition waste as granular fill by improving it with pozzolanic materials. The study reported that the addition of 20% GGBFS and 8M NaOH solution provided a significant increase in strength and bearing capacity compared to the raw soil. Bilici et al. (2020), examining the strength parameters of clay soils, tested the effects of GGBFS and fly ash on samples taken from the Eskişehir region. In the experimental process where the lime ratio was kept constant at 3%, the highest strength performance was achieved in mixtures containing 3% lime and 9% GGBFS. Abdila et al. (2022) revealed that GGBFS additive increased the California Bearing Ratio (CBR) values of soils. The researchers also defined compressibility characteristics, such as maximum dry unit weight and optimum moisture content, through standard Proctor compaction tests. Addressing innovative approaches, Hu et al. (2025) analyzed the role of alkali-activated GGBFS and fly ash combinations in flexible pavement design using machine learning-based optimization methods, proving that these mixtures offer ideal strength and deformation properties. Similarly, Uzer et al. (2025) stated that slag and fly ash-based geopolymers activated with NaOH provide sustainable stabilization in clay soils, and modeling results supported by artificial neural networks confirmed this increase in strength.

Consequently, in this research, the effects of stabilizing a bentonite-characterized road subgrade with GGBFS and 8M sodium hydroxide (AAS) activation on rigid pavement design were investigated within the axis of layer thickness and cost analyses. In the experimental stage, samples prepared by adding 5%, 10%, 15%, and 20% GGBFS+AAS by weight to the base soil were subjected to standard Proctor, unconfined compression, and CBR tests. In light of the obtained data, rigid pavement slab thicknesses were calculated using AASHTO 1993 design criteria, and economic evaluations were performed. While existing literature predominantly focuses on the basic strength gain, index properties, or compaction parameters of stabilized soils without linking them to

structural highway design, this study differs by establishing a direct connection between laboratory geotechnical performance and structural pavement engineering outcomes. Specifically, the novelty of this paper lies in its integrated framework that converts laboratory-measured strength and bearing capacity enhancements directly into concrete slab thickness reductions and quantifies the net initial construction cost savings. Thus, this study presents a complementary approach that bridges geotechnical soil stabilization with practical pavement design optimization and economic feasibility.

2. Materials and Methods

2.1. Soil Sample (Sodium Bentonite)

The sodium bentonite (BT) selected for modeling the road subgrade in this research is a critical clay mineral in terms of geotechnical engineering due to its characteristics such as high plasticity limits, significant swelling potential, and low shear strength. Owing to their high montmorillonite content, these soils carry substantial risks of structural damage associated with inadequate bearing capacity, uncontrolled settlements, and volumetric changes. The samples, classified as high-plasticity clay (CH) according to the Unified Soil Classification System (USCS), were obtained from Çanbensan Çankırı Bentonit San. Tic. A.Ş. The physical and chemical properties, along with visual data of the bentonite prepared for testing in accordance with relevant standards (ASTM International, 2006; ASTM International, 2014; ASTM International, 2017a; ASTM International, 2017b) are presented in detail in Table 1, Table 2, and Figure 1, respectively.

Table 1. Properties of bentonite

Soil Property	Test	Symbo	Value	Unit
Optimum Moisture Content	ASTM D698	ω_{opt}	35.25	%
Maximum Dry Density	ASTM D698	ρ_{dmax}	1.310	g/cm³
Liquid Limit	ASTM D4318	ω_L	350-450	%
Bulk Density	ASTM D854	ρ_s	0.9	g/cm³
Sieve Residue on 150 µm Sieve	ASTM D6913	-	2.50	%
Sieve Residue on 75 µm Sieve	ASTM D6913	-	12.5	%
Unified Soil Classification System	ASTM D6913	USCS	CH	-

Table 2. Chemical composition of bentonite

Component	Value (%)	Component	Value (%)
Na_2O	2.41	K_2O	1.10
MgO	2.68	$CaCO_3$	6.91
Al_2O_3	16.54	TiO_2	0.76
SiO_2	63.40	V_2O_5	0.02
P_2O_5	0.13	Cr_2O_3	0.02
SO_3	0.41	MnO	0.08
Cl	0.03	Fe_2O_3	5.51



Figure 1. Physical appearance of the bentonite sample.

2.2. Ground Granulated Blast Furnace Slag and Sodium Hydroxide Solution

Ground granulated blast furnace slag (GGBFS), a waste product of the iron and steel industry, is a material with high hydraulic activity obtained by subjecting molten iron-steel slag to rapid cooling and grinding processes. GGBFS, which exhibits a strong pozzolanic reaction capability thanks to its calcium oxide, silicon dioxide, and aluminum oxide components, constitutes a sustainable alternative to traditional binders in soil stabilization and geopolymer synthesis. It is emphasized in the literature that the use of GGBFS significantly reduces the carbon footprint while increasing mechanical performance (Soğancı et al., 2023; Uzer et al., 2025). The chemical composition of the GGBFS used in this research, which was obtained from the İskenderun Iron and Steel Factory, is presented in Table 3.

Table 3. Chemical composition of GGBFS

Component	Value (%)
CaO	33.6
SiO_2	41.2
Al_2O_3	14.3
MgO	7.3
S	0.8
MnO	0.8
K_2O	0.9
TiO_2	1.1

Sodium hydroxide (NaOH) was preferred as the alkali activator solution to increase the reactivity of GGBFS and

to trigger the geopolymerization process. In the preparation stage, crystalline NaOH particles were dissolved in pure water to obtain a solution with a concentration of 8 molar (320 g/L) in accordance with theoretical approaches in the literature (Arulrajah et al., 2016; Sarıca, 2019; Yıldıran, 2019; Venkatesh et al., 2021; Karabaş, 2025). The characteristic properties of sodium hydroxide are detailed in Table 4, and visual representations of the GGBFS and AAS samples are shown in Figure 2.

Table 4. Properties of sodium hydroxide

Component	Value (%)
Molecular formula	NaOH
Molecular mass	40 (g/mol)
Color	White
pH	13–14
Relative density	2.13 (g/cm^3)



Figure 2. Samples of BT, GGBFS, and AAS.

2.3. Standard Proctor Test

The Standard Proctor Test, applied to determine the compaction characteristics of soils, aims to identify the maximum dry unit weight (ρ_{dmax}) and the corresponding optimum moisture content (ω_{opt}) of the samples. In the studies conducted according to the ASTM D698 (ASTM International, 2014) protocol, cylindrical molds with an inner diameter of 105 mm and a height of 115.5 mm were used. Prior to the test, the soils dried at 105°C for 24 hours were mixed with different moisture contents, placed in the mold in three layers, and subjected to 25 blows per layer using a 2.5 kg rammer. As a result of this process, repeated for five different water contents, the critical ρ_{dmax} and ω_{opt} parameters of the soil were determined via the compaction curve (Yılmaz et al., 2017).

2.4. Unconfined Compressive Strength Test

The Unconfined Compressive Strength Test, performed to measure the strength performance of the samples, was conducted in accordance with ASTM D2166 (ASTM International, 2006) guidelines. The oven-dried soil material, mixed with the calculated amounts of water, was placed in four stages into molds with dimensions of 38 mm in diameter and 76 mm in height. After each layer was compacted with 10 rammer blows, the samples were removed from the mold and preserved at room temperature for the targeted curing periods. During the test, the axial strain rate was fixed between 0.5% and 2% per minute, and the ultimate strength and deformation values were recorded (Orhan, 2013). This procedure was applied to all samples in the study following 28-day curing periods.

2.5. California Bearing Ratio Test

The CBR test, which determines the bearing capacity of soils, was conducted within the framework of ASTM D1883-13 standards by preparing the samples ρ_{dmax} and ω_{opt} conditions. The basic principle of the test is the penetration of a piston with a cross-sectional area of 1935 mm^2 into the soil at a constant rate of 1.27 mm/min. Calculations were made by proportioning the resistance shown by the sample at penetration depths of 2.5 mm and 5 mm to the reference resistance values of standard crushed stone. During the preparation process, the soil was placed in the CBR mold in three stages and compacted with 56 blows per layer. The steps for testing the samples that completed the curing process are detailed in Figure 3 (ASTM International, 2021).



Figure 3. Implementation stages of the CBR test.

2.6. Rigid Pavement Design

Rigid pavement design is based on the structural integrity of a cement-based concrete slab constructed over the road subgrade soil. The design process involves the simultaneous evaluation of multidimensional variables, such as the target service life, layer thicknesses, traffic projections, regional environmental factors, economic parameters, and soil characteristics. Selecting the appropriate concrete grade and determining the optimum layer thicknesses to resist plastic deformations caused by heavy traffic loads over the analysis period are of critical importance for the structural performance of the design (AASHTO, 1993; KGM, 2019; Geçkil et al., 2024). The typical arrangement and structural hierarchy of the layers forming the rigid pavement are detailed in Figure 4.

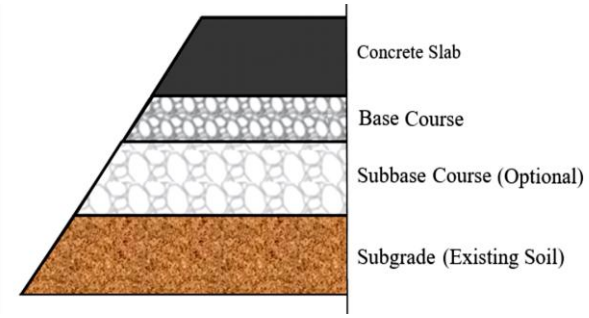


Figure 4. Cross-section of the rigid pavement (Kök, 2019; Geçkil et al., 2024).

The layer thicknesses of the rigid pavement are calculated using equation 1 according to the AASHTO (1993) Design Guide (KGM, 2019).

$$\log_{10}(T_{8,2})=Z_R.\,S_0+7.35.\log_{10}(d+1)-0.06+\frac{\log_{10}[\frac{\Delta PSI}{4,2-1,5}]}{1+\frac{1,624.10^7}{(d+1)^{8,46}}}$$
$$+(4.22-0.32.Pt).\log_{10}[\frac{S'c.Cd(d^{0,75}-1,132)}{215,63.J[d^{0,75}-\frac{18,42}{(Ec/k)^{0,25}}]}] \quad (1)$$

Here;

- $T_{8.2}$: Number of repetitions of the 8.2-ton equivalent single axle load,
- Z_R: Standard normal deviate,
- So: Composite standard error of the traffic forecast and performance prediction,
- d: Thickness of the rigid pavement concrete layer (inches),
- Δ_{PSI}: P0 – Pt (amount of serviceability loss),
- P_0: Initial serviceability index,
- Pt: Terminal serviceability index,
- S'c: Modulus of rupture of concrete (flexural tensile strength) (psi),
- J: Load transfer coefficient,
- Cd: Drainage coefficient,
- Ec: Modulus of elasticity of concrete (psi),
- k: Subgrade reaction modulus (pci).

3. Results and Discussion

In this study, where the effect of road subgrade stabilization with GGBFS+AAS on rigid pavement was investigated, the experimental results and design outputs are presented below.

3.1. Standard Proctor Test Results

BT samples representing the road subgrade were prepared with GGBFS+AAS additives at ratios of 5%, 10%, 15%, and 20% by weight and subjected to standard Proctor tests. The values for maximum dry unit weight, optimum moisture content, and optimum moisture content with alkali activator for the pure BT and the mixtures containing GGBFS+AAS obtained from these tests are presented in Figures 5 and 6.

Upon analyzing the Proctor test results, it was determined that as the GGBFS ratio in the AAS-added mixtures increased, the ω_{optAAS} values also increased, whereas the ρ_{dmax} values decreased compared to both pure BT and other GGBFS+AAS mixtures. These trends observed in relation to the GGBFS ratio are found to be in agreement with similar studies in the literature (Hamed and Demiroz, 2024; Sarıca et al., 2025; Shakil et al., 2025; Tanyıldızı, 2020). The primary reason for this behavior, as noted in the literature (Sas et al., 2021; Shakil et al., 2025), is evaluated to be the low specific gravity and porous particle structure of GGBFS, which increases the void ratio and subsequently reduces the compressibility of the mixture. This structure leads to a higher demand for liquid, which in this case explains the increased AAS requirement in the prepared mixtures.

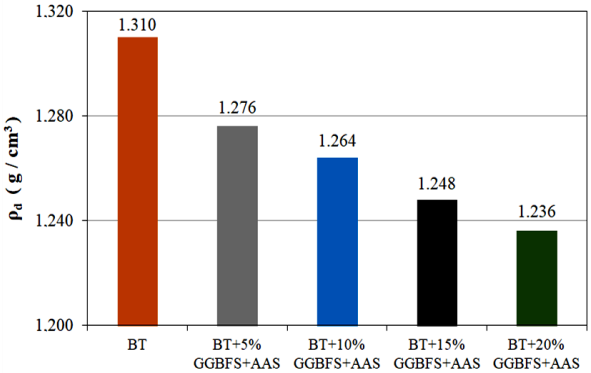


Figure 5. Maximum dry unit weight results of the Standard Proctor test.

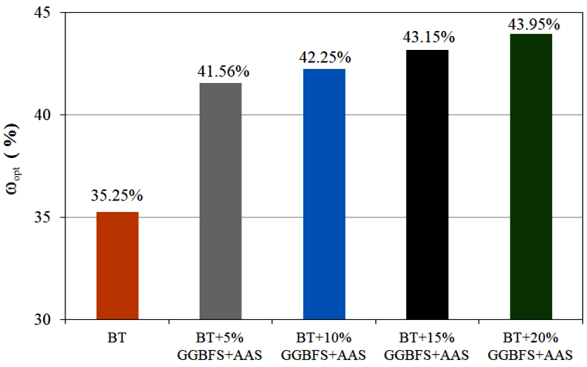


Figure 6. Optimum moisture content results of the Standard Proctor test.

3.2. Unconfined Compressive Strength Test Results

Unconfined compressive strength test specimens, prepared with additive ratios of 5%, 10%, 15%, and 20% GGBFS+AAS by weight, were fabricated based on the determined ρ_{dmax} and ω_{opt} data. The specimens were stored at room temperature. Following a 28-day curing period, the unconfined compressive strength test was performed. The axial stress (q) versus axial strain (ε) results for the additive-free BT soil and GGBFS+AAS added specimens are presented in Figure 7.

Furthermore, the unconfined compressive strength (q_u) and axial strain at failure (ε_u) values are provided in Table 5.

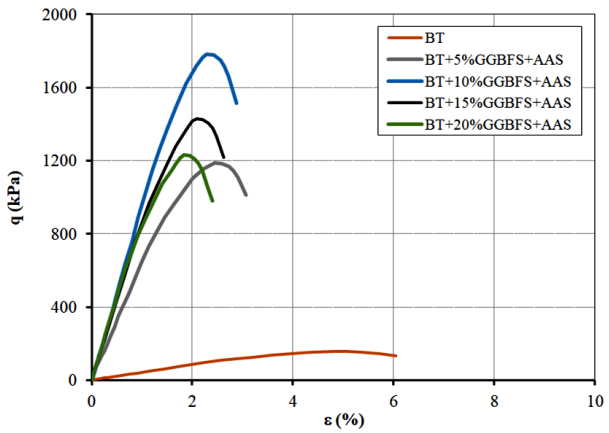


Figure 7. Stress-strain behavior of BT and GGBFS+AAS modified mixtures subjected to 28-day curing.

Table 5. Summary of of q_u and ε_u parameters for GGBFS+AAS reinforced samples

Test Samples	q_u (kPa)	ε_u (%)
BT	156.41	4.80
BT+5% GGBFS+AAS	1189.43	2.44
BT+10% GGBFS+AAS	1783.04	2.28
BT+15% GGBFS+AAS	1431.01	2.08
BT+20% GGBFS+AAS	1230.76	1.84

Upon examination of the unconfined compressive strength data, it was determined that the additive free BT specimens exhibited lower strength at the end of the 28-day curing period compared to the mixtures containing GGBFS and AAS. It was observed that the addition of GGBFS to the mixture significantly enhanced the strength performance, with the highest strength value being achieved in the specimens containing 10% GGBFS+AAS. At this optimal additive ratio, an 11.40-fold increase in strength was recorded at the end of the 28-day curing period compared to the untreated specimens. This positive effect of GGBFS and AAS usage on strength is consistent with studies in the literature (Sas et al., 2021; Tanyıldızı, 2020; Hamed and Demiroz, 2024; Sarıca et al., 2025; Shakil et al., 2025). Furthermore, the decrease observed in axial strain values depending on the increase in GGBFS content and curing time is evaluated to result from the increase in the material's stiffness; this finding is also in alignment with the relevant literature (Uzuner, 2016).

3.3. California Bearing Ratio Test Results

The specimens prepared within the scope of the CBR test were fabricated based on the untreated BT and the optimum mixture ratio of 10% GGBFS+AAS determined from the unconfined compressive strength test results. The ρ_{dmax}, ω_{opt} and ω_{optAAS} values were utilized in the preparation of the test specimens. The samples were kept at room temperature in a protected environment, shielded from external factors, during the 28-day curing period. Following the completion of the curing process, the dry CBR test was performed. The load-displacement graphs obtained from the CBR test are shown in Figure 8, while the CBR values are provided in Table 6.

Upon analysis of the CBR test results, it was determined that the GGBFS+AAS mixtures significantly increased the CBR values. At the end of the 28-day curing period, the CBR values for the GGBFS+AAS mixtures were identified as 64.27% and 74.07% for 2.5 mm and 5 mm penetrations, respectively. These values represent a 10.48-fold and 11.80-fold increase compared to the initial state for 2.5 mm and 5 mm penetrations, with the maximum increase observed at the 5 mm penetration level.

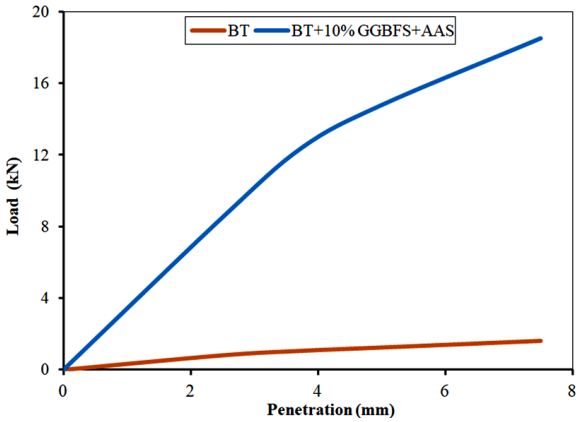


Figure 8. Load-displacement curves of untreated and 10% GGBFS+AAS stabilized specimens.

Table 6. CBR values of the specimens after 28 days of curing

Test Specimen	CBR value for 2.5 mm penetration, (%)	CBR value for 5 mm penetration, (%)
BT	6.13	6.28
BT+10% GGBFS+AAS	64.27	74.07

The experimental results prove that GGBFS+AAS-added mixtures exhibit a substantially higher bearing capacity compared to the control sample (pure BT). These findings are in full agreement with literature studies (Tanyıldızı, 2020; Hamed and Demiroz, 2024; Sarıca et al., 2025; Uzer et al., 2025) emphasizing the remedial effect of GGBFS addition on soil bearing strength. The reactive nature of calcium, silica, and alumina components within the GGBFS content triggers the formation of cementitious hydration products between soil particles. This chemical process enhances mechanical strength and controls volumetric changes by densifying the soil microstructure. It is well-documented that GGBFS, acting as an effective binder due to its pozzolanic and hydraulic properties, plays a critical role in the stabilization of low-strength and high-plasticity clays (Tanyıldızı, 2020; Hamed and Demiroz, 2024; Sarıca et al., 2025; Uzer et al., 2025). Additionally, it is assessed

that the AAS system strengthens the composite matrix by constituting a more compact geopolymer structure, which is decisive in the strength gain. Conversely, once the optimum additive threshold is exceeded, no further improvement in strength was observed due to the increase in unreacted waste material.

3.4. Rigid Pavement Design

The rigid pavement design was performed within the framework of AASHTO 1993 standards, based on the 28-day CBR data of both the untreated BT sample and the 10% GGBFS+AAS added mixture. Within the scope of this study, Jointed Plain Concrete Pavement (JPCP) thickness was analyzed. In determining the design parameters: A project life of 30 years was projected, assuming the route is a 2x2 lane state highway. Based on the first-year daily traffic volume of 1,395 trucks, 598 trailers, 1,809 buses, 12,520 cars, and 1,203 minibuses, the total traffic load was calculated as 160,000,000 equivalent 8.2-ton standard single axle loads (ESALs).With a reliability level selected as R = 99.9%, layer thicknesses were determined assuming the presence of a base or sub-base layer. The maximum CBR values 6.28% for the untreated sample and 74.07% for the 10% GGBFS+AAS mixture were utilized as critical design inputs. All variables were processed according to the parameters presented in Table 7.

Table 7. Rigid pavement design parameters

Parameters	Selected Values
Number of repetitions of the 8.2-ton equivalent single axle load, $T_{8.2}$	160,000,000
Load transfer coefficient, J	2.7
Drainage coefficient, Cd	1
Modulus of rupture of concrete	660
Composite standard error of the traffic forecast and performance prediction, S_0	0.35
Initial serviceability index, P_0	4.5
Terminal serviceability index, Pt	2.5
Po − Pt (amount of serviceability loss), Δ_{PSI}	2
Modulus of elasticity of concrete, Ec (C 35/45)	4786244
Standard normal deviate, Z_R	-3.09

In the calculations, the modulus of subgrade reaction (k) and the resilient modulus (M_R) of the road subgrade were first determined. For the calculation of M_R, the correlation MR (psi) = 2555 $(CBR)^{0.64}$ (AASHTO, 2024), as provided in the 3rd edition of the Pavement Design Guide containing mechanical-empirical technical revisions published by AASHTO in January 2024 (MEPDG-3), was utilized along with the correlation k = MR / 19.4 (AASHTO, 1993).

For the untreated BT, the MR and k values were calculated as 8,281 psi (57,110,646 Pa) and 426.86, respectively. For the 10% GGBFS+AAS mixture, the MR and k values were determined to be 40,176 psi (277,072,870 Pa) and 2,070.91. Using these data and the values in Table 7 in conjunction with Equation (1), the slab thickness (d) for C 35/45 grade concrete was selected as 17.55 inches (applied as 45 cm) for the untreated BT soil, and 14.85 inches (applied as 38 cm) for the 10% GGBFS+AAS stabilized soil. According to these results, it was determined that the layer thickness for the 10% GGBFS+AAS mixtures decreased by 7 cm compared to the untreated BT soil, representing a reduction of approximately 15.56%.

3.5. Economic Analysis of Rigid Pavement

The impact of stabilizing the BT road subgrade with GGBFS+AAS on the cost of rigid highway pavement was evaluated according to the General Directorate of Highways (KGM) specifications. Based on the 2026 unit price schedules of the Ministry of Environment, Urbanization and Climate Change (ÇSB,2026), the unit area (m^2) cost of concrete with a C 35/45 compressive strength class was calculated. According to the analysis and cost estimations, the unit cost of rigid pavement for the untreated BT was determined to be 1,726.65 TL/m^2, while for the 10% GGBFS+AAS stabilized soil, it was 1,458.06 TL/m^2. This data is detailed in Table 8.

Table 8. Unit costs of pavement layers for untreated BT and 10% GGBFS+AAS stabilized soils

Item No.	Description	Unit	Unit Price (TL)	m^2 /cm Cost (TL)	Calculated Thick. (cm)	m^2 Cost (TL)
15.150. 1007	Placement of C 35/45 Concrete Produced On-Site or Ready-Mix and Pumped Including Transportation	m^3	3638.85	38.37	45	1726.65
					38	1458.06

Furthermore, in the analysis for stabilizing the road subgrade to a thickness of 15 cm (Karabaş, 2025) with 10% GGBFS+AAS, the following operations were taken as the basis: transportation of materials, loosening of the soil with a tractor ripper, distribution of the stabilizer material with a tractor bulldozer, spreading and mixing with a grader, watering with a water tanker, and compaction using both vibratory and pneumatic-tired rollers. Since GGBFS is a waste material, the transportation of GGBFS to the construction site at a maximum distance of 500 km was calculated considering the 2026 Ministry of Environment, Urbanization and Climate Change calculation methodology. The unit costs per square meter (m^2) for the stabilization are provided in Table 9. Additionally, the concrete layer and soil stabilization costs, calculated by considering both the untreated soil and the soil improved with the addition of 10% GGBFS+AAS, are shown in Figure 9. When the calculated layer costs are evaluated, a reduction of 1.42% in construction costs is observed. According to these calculations, for a road 20 meters wide and 1,000 meters long, a saving of 489,200.00 TL will be achieved by using a road subgrade improved with 10% GGBFS+AAS. In this context, considering the total length of the highway network, it is anticipated that significant gains can be realized in the construction of rigid pavements through soil stabilization.

Table 9. Unit stabilization costs for soil stabilized with 10% GGBFS+AAS

Item No.	Description	Unit	Unit Price (TL)	Cost (TL/ m^2)
KGM 03.507	Hourly Cost of Tractor Ripper	h	3389.77	0.51
KGM 03.511	Hourly Cost of Bulldozer	h	3141.42	2.12
KGM/15.140	Mechanical Spreading and Mixing	m^3	22.88	3.43
KGM/15.047	Watering by Water Truck	ton	168.98	2.53
KGM/15.052/3	Compaction Using Vibratory Roller	h	2722.76	4.08
KGM/15.058/1	Compaction Using Pneumatic-Tired Roller	h	2116.99	3.18
Market Price	Supply and Transportation of 10% GGBFS+AAS	kg	6.23	228.27
			Total:	244.13

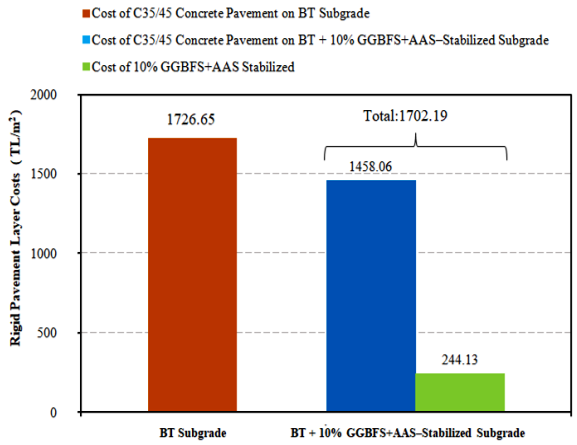


Figure 9. Concrete pavement and subgrade stabilization costs for untreated and 10% GGBFS+AAS-stabilized BT.

4. Conclusions and Recommendations

In this research, the effects of improving a Bentonite (BT) road subgrade with GGBFS+AAS on rigid pavement thickness and initial construction costs were examined across various additive contents (5%, 10%, 15%, and 20% by weight). Based on the comparative experimental evaluations, increasing the stabilizer content up to 10% significantly enhanced the mechanical properties and bearing capacity of the soil; however, further additions (15% and 20%) led to a slight decline in performance, establishing 10% GGBFS+AAS as the optimum stabilization ratio. The key findings obtained for both the overall mixture trends and the optimum 10% GGBFS+AAS ratio are summarized below.

Standard Proctor Test: It was determined that as the GGBFS ratio in the AAS mixture increased, the ω_{optAAS} value increased, while ρ_{dmax} decreased for both pure BT and GGBFS+AAS mixtures. This behavior is attributed to the low specific gravity and porous structure of GGBFS, which increases inter-granular voids, thereby reducing compressibility and increasing the liquid demand (AAS requirement) of the mixture.

Unconfined Compressive Strength, the highest strength value at the end of the 28-day curing period was determined in the specimens with 10% GGBFS+AAS. Compared to the untreated BT soil, a 11.40-fold increase in strength was observed. Furthermore, the increase in GGBFS+AAS content enhanced the stiffness of the specimens, leading to a decrease in axial strain.

CBR Test, for the 10% GGBFS+AAS stabilized soils, CBR values at the end of 28 days showed an increase of 10.48 and 11.80 times for 2.5 mm and 5 mm penetrations, respectively. These results prove that GGBFS+AAS significantly improve the bearing capacity of the soil.

Pavement Design: A reduction of 15.56% was achieved in the rigid pavement thickness designed for 10% GGBFS+AAS stabilized subgrades. This demonstrates the positive impact of GGBFS and AAS on the structural bearing capacity.

Economic Analysis: The pavement costs for 10% GGBFS+AAS stabilized soils decreased by 1.42% compared to the untreated soil. Based on these calculations, a saving of 489,200.00 TL can be achieved in the rigid pavement cost of a 1,000-meter-long, 20-meter-wide divided highway.

In conclusion, the stabilization of road subgrades uses waste materials like GGBFS and AAS increases bearing capacity while reducing both rigid pavement thickness and costs. Although the soil strength increases significantly, the cost of stabilizer materials remains a primary factor in the applicability of this model. Furthermore, the utilization of GGBFS as a waste product and the reduction in materials used for rigid pavement construction will decrease environmental damage particularly CO_2 emissions arising from cement and aggregate production, transport, and application. Increasing the use of GGBFS+AAS in road construction activities is evaluated as a viable path to further reducing the initial construction costs of highway projects.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	B.K.	A.U.U.	N.A.B	A.B.
C	25	25	25	25
D	25	25	25	25
S	25	25	25	25
DCP	25	25	25	25
DAI	25	25	25	25
L	25	25	25	25
W	25	25	25	25
CR	25	25	25	25
SR	25	25	25	25
PM	25	25	25	25
FA	25	25	25	25

C= concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

References

Abdulkarim, I. I., & Sa'eed, Y. U. (2020). Performance evaluation of the effect of sodium hydroxide on geotechnical properties of lateritic soil for rural road construction. *FUOYE Journal of Engineering and Technology*, *5*(2), 213–216.

Abdila, S. R., Abdullah, M. M. A. B., Ahmad, M., Azmi, N. J., & Jaya, R. P. (2022). Potential of soil stabilization using ground granulated blast furnace slag (GGBFS) and fly ash via geopolymerization method: A review. *Materials*, *15*(1), 375.

American Association of State Highway and Transportation Officials (AASHTO). (1993). *Guide for design of pavement structures (Interim)*. AASHTO.

American Association of State Highway and Transportation Officials (AASHTO). (2024). *Mechanistic–empirical pavement design guide (3rd ed., MEPDG-3)*. AASHTO.

Arulrajah, A., Mohammadinia, A., Horpibulsuk, S., & Samingthong, W. (2016). Influence of class F fly ash and curing temperature on strength development of fly ash-recycled concrete aggregate blends. *Construction and Building Materials*, 127, 743.

ASTM International. (2006). Standard test method for specific gravity of soils (ASTM D854).

ASTM International. (2006). Standard test method for unconfined compressive strength of cohesive soil (ASTM D2166-06).

ASTM International. (2014). Standard test methods for laboratory compaction characteristics of soil using standard effort (ASTM D698).

ASTM International. (2017a). Standard test methods for liquid limit, plastic limit, and plasticity index of soils (ASTM D4318).

ASTM International. (2017b). Standard test methods for particle-size distribution (gradation) of soils using sieve analysis (ASTM D6913).

ASTM International. (2021). Standard test method for California Bearing Ratio (CBR) of laboratory-compacted soils (ASTM D1883-21).

Babatunde, O. A., Sani, E. J., & Sambo, A. H. (2019). Black cotton soil stabilization using glass powder. *International Journal of Innovative Research in Science, Engineering and Technology*, 8(5).

Bharti, G., Hurukadli, P., & Shukla, B. K. (2023). Environmental impact analysis and utilization of copper slag for stabilising black cotton soil. *Materials Today: Proceedings*, 2023(3).

Bilici, H., Okur, D. V., Türköz, M., & Savaş, H. (2020). Effect of fly ash and blast furnace slag additives on the strength of clay soil and comparative analysis (in Turkish). *Bitlis Eren University Journal of Science and Technology*, 9(2), 910–919.

Çınar, M. (2024). Investigation of geotechnical properties of clayey sand soil stabilized with aerated concrete waste after Kahramanmaraş earthquake (in Turkish). *Dicle University Journal of Engineering*, 15(1), 269–275. https://doi.org/10.24012/dumf.1404478

Geçkil, T., & Karabaş, B. (2026). Evaluating the effects of carbon black from recycled tires on subgrade stabilization, pavement design, and construction-phase CO_2 emissions. *Indian Journal of Engineering and Materials Sciences (IJEMS),* 33(01), 111–125.

Geçkil, T., Sarıca, T., & Karabaş, B. (2021). Effects of black carbon stabilized soil on rigid pavement thickness and cost (in Turkish). *ECJSE*, 8(3), 1372–1384. https://doi.org/10.31202/ecjse.894046

Geçkil, T., Sarıca, T., & Karabaş, B. (2024). Investigation of the effects of soil improvement with metakaolin on rigid pavement thickness and cost. *Black Sea Journal of Engineering and Science*, 7(5), 11–12.

Geçkil, T., Sarıca, T., & Karabaş, B. (2025a). Investigation of the effect of sandy soil stabilized with ground pumice stone on flexible pavement design (in Turkish). *International Journal of Pure and Applied Sciences,* 11(1), 176–192.

Geçkil, T., Sarıca, T., & Karabaş, B. (2025b). Investigation of layer thickness and cost of flexible pavement designed on soil improved using glass powder (in Turkish). *Journal of Innovative Engineering and Natural Sciences*, 5(1), 80–98. https://doi.org/10.61112/jiens.1509488

Geçkil, T., Sarıca, T. & Karabaş, B., (2025c). Investigation of freeze-thaw resistance of road substrates stabilized with metakaolin. *Osmaniye Korkut Ata University Journal of the Institute of Science and Technology.* https://doi.org/10.47495/okufbed.1548511

Geçkil, T., Sarıca, T., & Karabaş, B. (2026). Investigation of the effect of stabilizing subgrade soils with recycled glass powder on freeze–thaw resistance. *Gümüşhane University Journal of Science and Technology*, 1(1), 179–196. https://doi.org/10.17714/gumusfenbil.1802171

Hamed, E., & Demiroz, A. (2024). Optimization of geotechnical characteristics of clayey soils using fly ash and granulated blast furnace slag-based geopolymer. *Construction and Building Materials*, 441, Article 137488.

Hu, J., Zhang, X., Wang, Y., & Liu, L. (2025). Machine learning-based optimization of geopolymer-stabilized soil formulation using blast furnace slag and fly ash. *Materials Today Communications*, Article 113500.

Hussain, S. (2019). Stabilization of expansive soil using sodium hydroxide [Master's thesis, Near East University]. Near East University Repository.

Karabaş, B. (2025). Effects and sustainability of road subgrade soils stabilized with various additives on highway pavement (Publication No. 960734) [Doctoral dissertation, İnönü University]. National Thesis Center.

Karabaş, B., & Uzer, A. U. (2026). Effect of ground granulated blast furnace slag–stabilized bentonite soils on flexible pavement design and cost analysis. *Al-Qadisiyah Journal for Engineering Sciences,* 19(2), 001–008. https://doi.org/10.30772/qjes.2026.169263.1896

Kök, B. V. (2019). *Highway engineering and design* (in Turkish). Nobel Academic Publishing.

Konai, S., Mayur, M., Dutta, S., & Hinge, G. (2026). Sustainable soil stabilization using alkali-activated rice husk ash. *Journal of Hazardous, Toxic, and Radioactive Waste,* 30(1), Article 04025041.

Orhan, M. (2013). *Soil mechanics laboratory tests* (in Turkish). Gazi Publishing.

Republic of Türkiye Ministry of Environment, Urbanization and Climate Change. (2026, January 28). Unit prices. https://yfk.csb.gov.tr/birim-fiyatlar-i-100468

Sarıca, T. (2019). Evaluation of the usability of construction and demolition wastes reinforced with pozzolan as granular fill (in Turkish) [Master's thesis, Inonu University]. Graduate School of Natural and Applied Sciences.

Sarıca, T., Geçkil, T., Ok, B., & Aksoy, H. S. (2025). An investigation of the usability of alkali-activated blast furnace slag-additive construction demolition waste as filling material. *Materials,* 18(2), Article 398. https://doi.org/10.3390/ma18020398

Sas, W., Dzięcioł, J., Radzevičius, A., Radziemska, M., Dapkienė, M., Šadzevičius, R., & Głuchowski, A. (2021). Geotechnical and environmental assessment of blast furnace slag for engineering applications. *Materials,* 14(20), Article 6029.

Shabana, S., Anshi, C., Shamseera, P., Shyamili, T. M., Sruthi, V., & Suhaira, P. (2014). Study on CBR values of soil with crushed coconut shells. *International Journal of Advanced Engineering and Technology*, 5(3), 55–58.

Shakil, M., Nazar, S., Ameen, H. F. M., Shahzad, A., & Ahmad, F. (2025). A comparative study of ground granulated blast furnace slag and bagasse ash incorporation on enhancing mechanical properties of expansive soil. *Results in Engineering*, 25, Article 103569.

Soğancı, A. S., Yenginar, Y., & Orman, A. (2023). Geotechnical properties of clayey soils stabilized with marble dust and granulated blast furnace slag. *KSCE* Journal of Civil Engineering, 27(11), 4622–4634.

Şengül, T., Akray, N., & Vitoşoğlu, Y. (2023). Investigating the effects of stabilization carried out using fly ash and polypropylene fiber on the properties of highway clay soils. *Construction and Building Materials*, 400, Article 132590. https://doi.org/10.1016/j.conbuildmat.2023.132590

T.C. Ministry of Transport KGM Technical Research Department. (2019). Highway concrete pavement design guide (in Turkish). KGM Technical Research Department.

Tanyıldızı, M. M. (2020). Effects of clayey soil stabilized with blast furnace slag on highway flexible pavement layer thicknesses and cost (in Turkish). *Firat University Journal of Engineering Sciences*, 32(2), 509–520. https://doi.org/10.35234/fumbd.738512

Tanyıldızı, M. M., & Karabaş, B. (2026). Zayıf zeminlerde YFC ve çelik lifli beton yolların ilk yapım maliyeti ve CO_2 emisyonuna etkisi. *Black Sea Journal of Engineering and Science,* 9(2), 516–548.

Topçuoğlu, Y. A., & Güroçak, Z. (2023). Determination of optimum basalt fiber ratio for maximum strength in soil reinforcement (in Turkish). *Dicle University Journal of Engineering,* 14(3), 479–487.

Tunç, A. (2002). *Geotechnics and applications in road engineering* (in Turkish). Nobel Publishing.

Uzer, A. U., Tunç, U., Acar, M. C., & Çelik, A. I. (2025). Sustainable stabilization of clay soils using fly ash and blast furnace slag-based geopolymers: Comprehensive experimental evaluation and artificial neural network modelling. *Structural Engineering and Mechanics*, 96(1), 13–33.

Uzuner, B. A. (2016). *Introduction to foundation engineering* (in Turkish). Derya Publishing.

Venkatesh, N., Mallikarjuna, R. G., Reddy, S. K., & Chavali, R. V. P. (2021). Strength and durability characteristics of GGBS geopolymer stabilized black cotton soil. *Materials Today: Proceedings*, 43, 2373–2376.

Yıldıran, E. S. (2019). Investigation of the effects of various additives on road subgrade soil (in Turkish) [Master's thesis, Inonu University]. Graduate School of Natural and Applied Sciences.

Yılmaz, I., Yıldıran, M., & Keskin, I. (2017). *Soil mechanics laboratory tests and solved problems* (in Turkish). Seçkin Publishing.