Soil Stabilization in Flexible Pavements by Using Industrial Waste Materials

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Abstract - This research explores the use of industrial by-products—ground granulated blast furnace slag (GGBS), fly ash, and lime—for improving the engineering properties of fine-grained soils in flexible pavement applications. The study was designed to evaluate how these stabilizers influence soil strength, density, and moisture resistance, which are critical for developing durable and sustainable pavement subgrades. Five soil samples were prepared, comprising one natural soil and four stabilized mixes. Each stabilized mix contained a constant 10% fly ash, while GGBS was varied at 5%, 10%, 15% and 20%. Additionally, 1.0% lime was incorporated to enhance chemical reactivity. Laboratory investigations included Modified Proctor Compaction, California Bearing Ratio (CBR), and Direct shear tests. Results indicated that untreated soil achieved a maximum dry density (MDD) of ~1.83 g/cc at an optimum moisture content (OMC) of ~16%. The fly ash-only mix reduced density due to its low specific gravity. However, the inclusion of GGBS significantly improved compaction characteristics, with higher GGBS contents producing denser soil matrices. The CBR values increased consistently with GGBS, peaking in the 15% GGBS + 10% fly ash + 1.0% lime mix. Plastic limit results showed reduced moisture sensitivity across all stabilized samples. The findings confirm that GGBS-fly ash-lime stabilization provides a cost-effective, sustainable method to enhance subgrade performance while promoting eco-friendly reuse of industrial waste materials.

Keywords: Ground Granulated Blast Furnace Slag (GGBS); Fly Ash; Lime Stabilization; Subgrade Soil; Flexible Pavement; Modified Proctor Test; California Bearing Ratio (CBR); Plastic Limit; Soil Compaction; Sustainable Construction; Industrial By-products; Soil Stabilization; Pavement Engineering.

1. INTRODUCTION

Soil stabilization is an essential technique in flexible pavement construction to enhance the engineering properties of clay subgrade soils. Due to rapid industrialization, large quantities of industrial waste materials are generated, posing disposal and environmental challenges. Utilizing these wastes—such as fly ash, blast furnace slag, quarry dust, and rice husk ash—offers a sustainable solution for improving soil strength and workability. These materials help increase load-bearing capacity, reduce plasticity, and improve durability of pavement layers. Incorporating industrial waste in stabilization not only minimizes construction costs but also promotes eco-friendly infrastructure development. Thus, waste-based stabilization is emerging as a viable approach for sustainable pavement engineering.

Flexible pavements are the most widely used type of road pavement in developing countries due to their cost-effectiveness, ease of construction, and maintenance flexibility. They are designed to distribute the traffic loads gradually from the surface layers to the underlying subgrade soil. The performance of a flexible pavement largely depends on the strength and stability of its individual layers — namely the surface course, base course, sub-base, and especially the subgrade. One of the main advantages of flexible pavements is their ability to absorb and distribute stresses caused by moving loads through multiple layers, which minimizes surface cracking and structural failures. The subgrade soil plays a vital role in the structural performance of flexible pavements, as it provides the foundation for all the overlying layers. If the subgrade is clay, it cannot adequately support traffic loads, resulting in excessive deformation, cracking, or even complete pavement failure. In many regions, especially in India, locally available soils such as clay soils exhibit low bearing capacity, high plasticity, and poor drainage characteristics, making them unsuitable for direct use in pavement construction. Soil stabilization is therefore essential to improve the strength, stiffness, and durability of such problematic soils. Stabilization involves modifying the physical and chemical properties of the soil to enhance its load-carrying capacity and reduce its susceptibility to moisture and volume changes.

1.1 SCOPE OF THE WORK

The scope of this study is to evaluate the effectiveness of Ground Granulated Blast Furnace Slag (GGBS) as a sustainable stabilizing material for improving the engineering behaviour of clay soils used in flexible pavement subgrades. The work focuses on examining how different proportions of GGBS influence soil strength, density, plasticity, and moisture susceptibility. It also aims to identify the optimum GGBS content that provides the highest improvement in load-bearing capacity and durability. In addition, the study evaluates the potential environmental and economic benefits of utilizing GGBS as an alternative to conventional stabilizers such as cement and lime. Through the systematic use of laboratory tests, this research seeks to promote a cost-effective, eco-friendly, and durable approach to pavement subgrade stabilization using industrial waste materials.

1.2 OBJECTIVES OF THE PRESENT STUDY

The primary objective of this study is to evaluate the combined effectiveness of fly ash, Ground Granulated Blast Furnace Slag (GGBS), and lime in stabilizing weak clay soils for flexible pavement subgrades. The specific objectives are:

1. To investigate the influence of a constant 10% fly ash, varying GGBS proportions (5%, 10%, and

15%), and 1% lime on the physical, mechanical, and index properties of fine-grained soils.

2. To evaluate improvements in California Bearing Ratio (CBR) values and assess the potential for reducing pavement thickness and enhancing load-bearing capacity.
3. To analyze changes in key engineering properties after stabilization, including MDD, OMC, plasticity index, liquidity index, swelling potential, UCS, and shear strength.
4. To determine the optimum stabilizer combination that yields maximum strength, stability, and durability for subgrade use in flexible pavement construction.
5. To improve the soil strength by using additives in order to use as a base or sub base courses and carry the expected traffic and pavement loads.

2. METHODOLOGY

The present study evaluates the effectiveness of fly ash, Ground Granulated Blast Furnace Slag (GGBS), and lime in stabilizing weak clay soil for flexible pavement subgrades. The methodology involves collecting soil samples, preparing stabilized mixes with 10% fly ash, varying GGBS (5%–20%), and 1% lime, followed by laboratory testing. Modified Proctor Test is conducted to determine MDD and OMC, while Atterberg limits assess changes in soil plasticity. California Bearing Ratio (CBR) evaluates load-bearing capacity, These tests collectively determine the optimum stabilizer combination for improved subgrade performance. The methodology as shown in figure1.

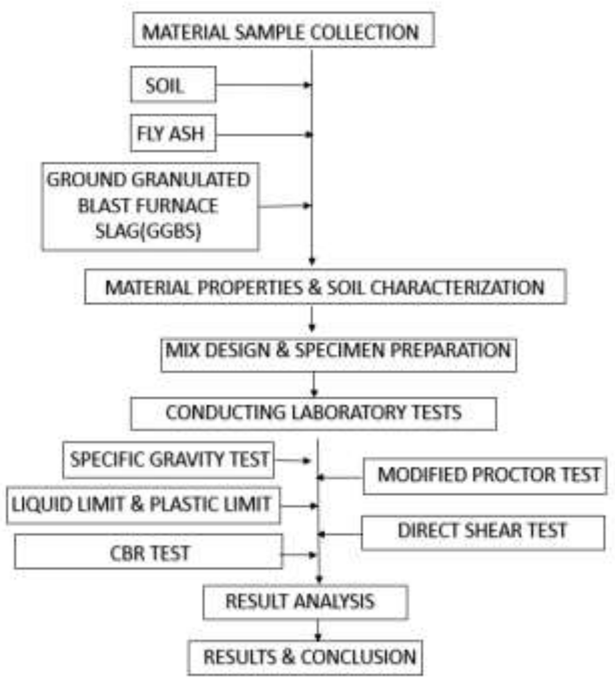

Figure 1 Flowchart of Methodology

3. MATERIALS

Fly ash, GGBS, and lime were used as stabilizers to improve the engineering properties of weak clay soil. Fly ash enhances workability and reduces plasticity through pozzolanic action. GGBS contributes latent hydraulic properties that improve long-term strength when activated with lime. Lime reduces plasticity, promotes flocculation, and initiates immediate and long-term reactions in clay soils. Their combined use enhances strength, reduces swelling, and supports sustainable pavement construction.

3.1 SOIL

The soil used in this study is Clay Soil, classified to be CI. It was air-dried, sieved through standard IS sieves, and tested for natural moisture content and basic index properties. Its expansive behaviour and low strength necessitated stabilization for subgrade applications.

3.2 FLY ASH

Fly ash, obtained from a local source, is a fine pozzolanic material widely used in soil stabilization. It reduces plasticity, improves compaction, and contributes to strength development through pozzolanic reactions. Its physical and chemical properties were within standard limits.

3.3GROUND GRANULATED BLAST FURNACE SLAG (GGBS)

GGBS is a glassy industrial by-product obtained through rapid quenching of molten slag. It exhibits good reactivity when combined with lime. Its fine texture and chemical composition help improve soil strength, durability, and long-term performance the properties as shown in figure

3.4 LIME

Hydrated lime [$Ca(OH)_2$] was used to reduce plasticity and activate GGBS. It improves soil workability and induces flocculation, leading to better strength and reduced swelling. Lime used in the study had adequate purity and reactivity as required for soil stabilization. GGBS was activated using lime to initiate pozzolanic and hydraulic reactions. Activation enhances the formation of cementitious compounds such as C–A–S–H gel, improving the strength and stiffness of the stabilized soil.

3.5 MIXING PROCEDURE

The soil was air-dried, sieved, and thoroughly mixed with the required quantities of fly ash, GGBS, and lime. Lime was first blended with the soil and partially moistened to allow mellowing. The remaining stabilizers were added, and water was sprinkled gradually to achieve uniform consistency. The mixture was allowed to rest briefly before compaction and testing.

Table 1 Properties of GGBS and Fly ash

Property	Requirement	GGBS	Fly Ash
Fineness (m^2/kg)	GGBS ≥ 275 / Fly Ash ≥ 320	390.12	340.15
Specific Gravity	-	2.852	2.182
45 µm Passing (%)	Fly Ash ≥ 75	97.08	89.06
Loss on Ignition (%)	GGBS ≤ 3.0 / Fly Ash ≤ 5.0	0.263	1.54
Moisture Content (%)	≤ 1.0	0.101	0.21
SiO_2 (%)	Fly Ash ≥ 35	-	55.37
Glass Content (%)	GGBS ≥ 67	91.05	-

4..RESULTS AND DISCUSSIONS

A total of five soil samples were prepared to evaluate the effect of GGBS, a constant 10% fly ash, and lime on the engineering properties of fine-grained soils. One untreated sample was included for baseline comparison. The details are:

Sample 1: Natural soil (Clay soil).

Sample 2: Soil + 5% GGBS +10% fly ash + 1.0% lime.

Sample 3: Soil + 10% GGBS + 10% fly ash + 1.0% lime.

Sample 4: Soil + 15% GGBS + 10% fly ash + 1.0% lime.

Sample 5: Soil + 20% GGBS + 10% fly ash + 1.0% lime.

4.1 SPECIFIC GRAVITY

The specific gravity values of the soil samples (S1–S5) ranged between 2.63 and 2.66, indicating noticeable variations due to the inclusion of fly ash, GGBS, and lime. The combined addition of 15 % GGBS + 10 % fly ash + 1 % lime (S4) produced the highest specific gravity of 2.66

Table 2 Determination of Specific Gravity

Sample No	**S1**	**S2**	**S3**	**S4**	**S5**
Specific Gravity (G)	2.65	2.63	2.65	2.66	2.64

4.2 LIQUID LIMIT

The Liquid Limit Test results showed a consistent reduction in water content with the addition of fly ash, GGBS, and lime, indicating improved soil consistency and reduced plasticity. The untreated soil (S1) had a liquid limit of 48.5%. With 10% fly ash (S2) it decreased to 42.1% (13.2% reduction), and with 5% GGBS + 10% fly ash (S3) it further reduced to 41.3% (14.8% reduction). The S4 mix (15% GGBS + 10% fly ash + 1% lime) showed 40.2% (17.1% reduction), while S5 (20% GGBS + 10% fly ash + 1% lime) reached 39.2% (19.1% reduction). Lime enhanced flocculation, lowering water-holding capacity. The trend as shown in figure2

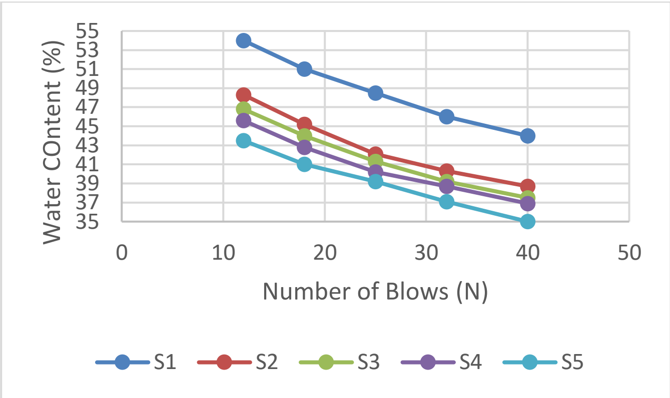

Figure 2 Liquid Limit

4.3 PLASTIC LIMIT

The plastic limit test results for samples (S1–S5) show a clear reduction in water content with the inclusion of stabilizing materials. This significant decrease can be attributed to lime's cation exchange and pozzolanic reactions, which reduce the plasticity and enhance the soil's stiffness.

Table 3 Determination of Plastic Limit

Sample No	**S1**	**S2**	**S3**	**S4**	**S5**
Plastic limit(%)	47.65%	43.95%	36.05%	30.85%	28.35%

4.4 MODIFIED PROCTOR COMPACTION TEST

The results of the Proctor Compaction Test clearly indicate that the addition of stabilizing materials such as GGBS, fly ash, and lime influenced both the dry unit weight and the optimum moisture content of the fine-grained soil. For the untreated sample (S1), the maximum dry unit weight (MDD) was 1.83 g/cc at an optimum moisture content (OMC) of 16 %, representing the natural compaction behavior of the soil. With the inclusion of 10 % fly ash (S2), the MDD remained nearly the same at 1.83 g/cc, but the OMC slightly decreased to around 15.8 %, reflecting the lighter nature and lower specific gravity of fly ash that replaced part of the soil solids. When 5 % GGBS and 10 % fly ash were added (S3), the MDD increased marginally to 1.84 g/cc, showing about a 0.5 % improvement over S1, while the OMC slightly reduced to 15.5 %, indicating better particle packing and reduced void spaces due to GGBS's fine particle filling effect. The mix containing 15 % GGBS, 10 % fly ash, and 1 % lime (S4) achieved the highest MDD of 1.85 g/cc, representing approximately a 1.1 % increase compared with the untreated soil. The mix containing 20 % GGBS, 10 % fly ash, and 1 % lime (S5) achieved MDD of 1.83 g/cc. This improvement is attributed to lime-induced flocculation and the formation of cementitious compounds, which enhanced the inter-particle bonding and compatibility of the mix

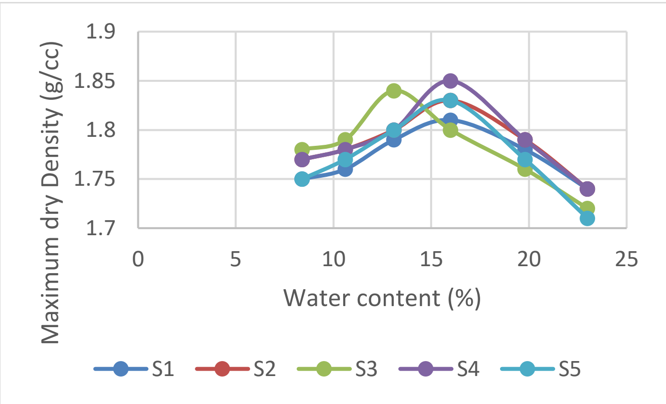

Figure 3 Compaction Test for different Samples

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4.5 CALIFORNIA BEARING RATIO (CBR)

The CBR results showed a significant improvement in load-bearing capacity for stabilized soils compared with the untreated sample. At 2.5 mm penetration, the natural soil (S1) carried 80.68 kg, while S2, S3, and S4 recorded 94.5 kg, 89.62 kg, and 104.34 kg, indicating increases of 17.1%, 11.1%, and 29.3%, respectively. At 5 mm penetration, S1 showed 114.59 kg, whereas S2, S3, and S4 achieved 139.3 kg, 131.24 kg, and 149 kg—improvements of 21.6%, 14.5%, and 30.1%. These gains result from pozzolanic and cementitious reactions of fly ash, GGBS, and lime, which enhance bonding, densify the soil matrix, and improve strength. The S4 mix, containing 1% lime, provided the highest CBR due to accelerated reactions and improved particle cohesion. The trend as shown in figure

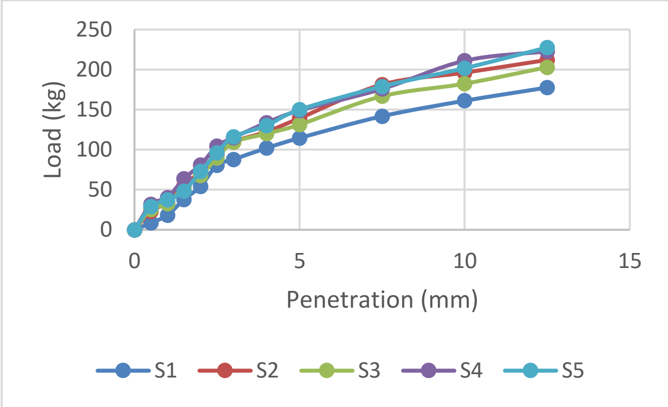

Figure4 CBR values samples

4.6 DIRECT SHEAR TEST

The variation of cohesion (c) and angle of internal friction (φ) for samples S1–S5 shows a clear improvement in shear strength with the addition of fly ash, GGBS, and lime. The untreated soil (S1) had the lowest values (c = 20 kPa, φ = 20°), reflecting weak bonding. In S2 (5% GGBS + 10% FA + 1% Lime), cohesion increased to 28 kPa (40% rise) and φ to 21° (5% increase) due to pozzolanic bonding. S3 (10% GGBS) further improved c to 35 kPa (75% rise) and φ to 22° (10% increase). Maximum strength occurred in S4 (15% GGBS), where c reached 45 kPa (125% increase) and φ 23.5° (17.5% rise). In S5 (20% GGBS), cohesion dropped to 40 kPa and φ to 22°, indicating that excessive GGBS reduces shear strength. Improvements from S1 to S4 result from lime–GGBS reactions that promote cation exchange, flocculation, and cementitious bonding. Overall, cohesion and friction angle increase with stabilizers up to the optimum mix, demonstrating significant enhancement in shear-strength behaviour.

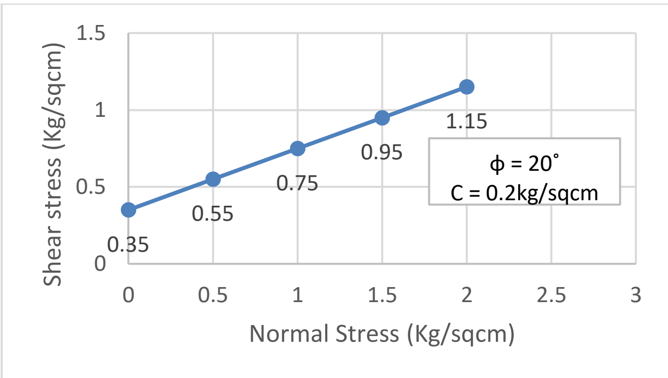

Figure 5 Failure envelop of Direct Shear Test conducted on S1

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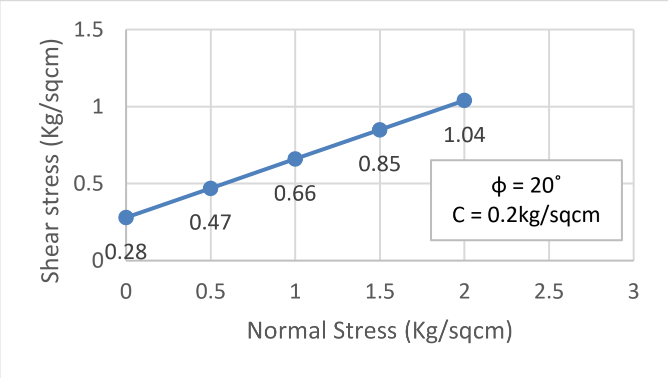

Figure 6 Failure envelop of Direct Shear Test conducted on S2

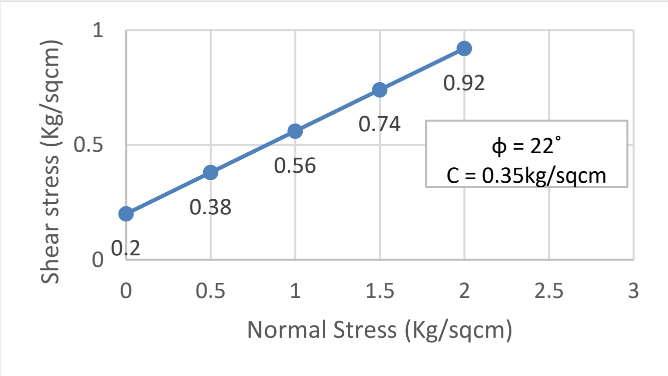

Figure 7 Failure envelop of Direct Shear Test conducted on S3

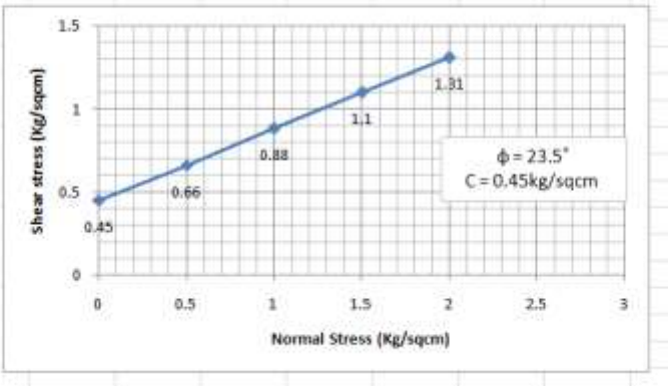

Figure 8 Failure envelop of Direct Shear Test conducted on S4

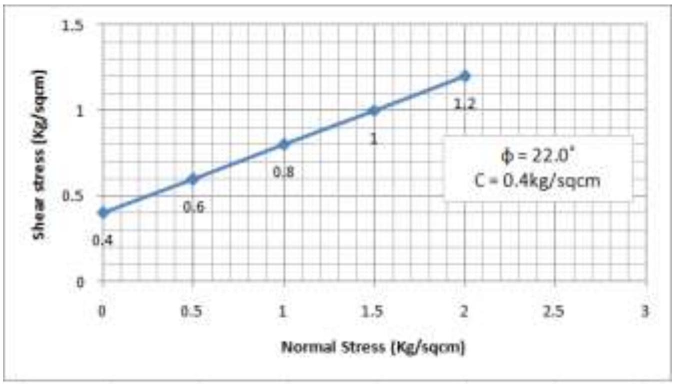

Figure 9 Failure envelop of Direct Shear Test conducted on S5

5.CONCLUSION

Stabilizing natural soil with GGBS, fly ash, and lime significantly enhances its suitability for flexible pavement applications.

- The MDD showed a moderate increase, the OMC exhibited a slight reduction, indicating denser packing and better moisture control. Among all combinations, the S4 mix (5 % GGBS + 10 % fly ash + 1 % lime) achieved the highest compaction efficiency, proving its suitability for soil stabilization and subgrade improvement.
- The CBR results confirm that the combination of GGBS, fly ash, and lime significantly increases the load-bearing strength of fine-grained soil. The strength gain from S1 to S5 demonstrates the synergistic effect of blended stabilizers, with lime acting as an activator and GGBS contributing long-term strength development. Among all mixes, S4 exhibited the highest improvement, making it the most effective for subgrade stabilization and pavement applications.
- The direct shear test results, it is concluded that the incorporation of GGBS, fly ash, and lime significantly improves the shear strength characteristics of fine-grained soils. The last sample S5 showed a decrease to 22˚ and this decrease in shear characteristics prove that the S4 sample is the optimum mix. Thus, the combined stabilization using GGBS and lime provides the most effective improvement in shear strength and stability, making the soil more suitable for subgrade and foundation applications.

Based on the results of this study,it appears that the selected clay soil can be effectively stabilized with the addition of 15%GGBS+10%Fly Ash+1%Lime.

The results confirm that industrial by-products can effectively enhance soil behaviour, offering a sustainable and cost-efficient alternative to traditional stabilizers. The use of GGBS–fly ash–lime blends contribute to improved pavement performance while promoting environmentally responsible construction practices. Future studies may extend these findings through durability assessments, microstructural analysis, field validations, and evaluation of additional waste-based stabilizers.

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