Strength Enhancement of Flexible Pavement Subgrades Using GGBS-Based Industrial Waste Stabilizers and Polypropylene Fibers

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Abstract - Black cotton soils are highly expansive and present major challenges in construction, especially for pavements. Stabilizing these soils using Ground Granulated Blast Furnace Slag (GGBS) and polypropylene fibers, both by-products of industrial processes, offers a sustainable solution. This research investigates the effects of GGBS and polypropylene fibers on critical soil properties, including Atterberg limits, maximum dry density (MDD), optimum moisture content (OMC), unconfined compressive strength (UCS), and free swell. By varying GGBS content from 0–30% and polypropylene fibers from 0–1%, the study identifies the optimal mix for stabilization. Results show that adding GGBS and polypropylene fibers significantly improves soil strength and reduces swell potential, enhancing its suitability for pavement applications.

Keywords: Black cotton soil, Ground Granulated Blast Furnace Slag (GGBS), polypropylene fibers, soil stabilization, Atterberg limits, maximum dry density (MDD), optimum moisture content (OMC), unconfined compressive strength (UCS), free swell, pavement.

1.NTRODUCTION

Transportation infrastructure plays an essential role in economic development by enabling connectivity, boosting trade, and facilitating cultural exchange. In India, road transport is critical, handling approximately 87% of passenger traffic and 60% of goods movement, thanks to a sprawling road network of about 54.83 lakh km. This network, consisting of Expressways, National Highways, State Highways, and other smaller roads, sustains significant traffic loads. However, India's diverse terrain and soil types pose unique challenges, particularly with expansive soils like black cotton soil, which is known for its high shrink-swell behavior and low load-bearing capacity. Common in regions like Maharashtra and Gujarat, black cotton soil's cyclic expansion and contraction lead to structural instability in pavements and other constructions.

Addressing these issues requires soil stabilization, a technique that enhances soil strength and durability. Stabilizing agents like Ground Granulated Blast Furnace Slag (GGBS), a by-product of steel production, and polypropylene fibers have shown promise. GGBS provides a cementitious matrix that strengthens soil, while polypropylene fibers enhance tensile strength and flexibility, reducing soil deformation and cracking. Using these stabilizers can help mitigate the negative effects of black cotton soil, making it more suitable for infrastructure.

Given India's rapid urbanization, cost-effective and sustainable stabilization methods are critical. This study explores the potential of GGBS and polypropylene fibers for stabilizing black cotton soil, aiming to improve soil properties and provide solutions for low and high-volume roads. This research not only addresses immediate structural challenges but also aligns with environmental goals by utilizing industrial by-products and reducing reliance on traditional construction materials.

1.1 RESEARCH GAP

Black cotton soil's high expansiveness and low strength pose major challenges for pavement and foundation construction. While stabilization techniques exist, limited research explores the combined use of industrial by-products like Ground Granulated Blast Furnace Slag (GGBS) and polypropylene fibers to improve soil properties sustainably. Past studies often examine GGBS or fibers individually, leaving gaps in understanding their joint effect on properties like Atterberg limits, maximum dry density (MDD), optimum moisture content (OMC), unconfined compressive strength (UCS), and free swell index. This study aims to determine optimal GGBS-fiber mix ratios for effective stabilization, targeting sustainable, cost-effective solutions for pavement applications.

1.2 OBJECTIVES

1. To establish baseline engineering properties of untreated black cotton soil by conducting Atterberg limits, maximum dry density (MDD), optimum moisture content (OMC), unconfined compressive strength (UCS), and free swell tests as reference values for stabilization effects.
2. To assess the impact of Ground Granulated Blast Furnace Slag (GGBS) on soil strength and stability by adding GGBS at intervals of 10%, 20%, and 30% and performing UCS, MDD, OMC, and free swell tests to measure improvements.
3. To evaluate the combined effects of GGBS and polypropylene fibers on soil properties by conducting UCS, MDD, OMC, and free swell tests with fiber additions at 0.5% and 1%, assessing enhancements in strength and swell reduction.
4. To identify the optimal combination of GGBS and polypropylene fibers for stabilization by analyzing UCS, MDD, OMC, and free swell results, aiming to maximize soil strength and suitability for pavement applications.

2.MATERIALS AND METHODS

2.1 Materials

2.1 Soil: Black Cotton (BC) Soil

Black Cotton (BC) soil is a highly plastic, expansive soil rich in minerals such as silica, lime, iron, magnesia, and alumina, with montmorillonite as its primary clay mineral, placing it in the smectite group. Known for its significant challenges in construction due to its shrink-swell behavior, BC soil requires stabilization to be effectively used in civil engineering applications. In this study, BC soil was sourced from Visakhapatnam, India.

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2.2 Stabilizers

Ground Granulated Blast Furnace Slag (GGBS): A by-product of the steel manufacturing process, Ground Granulated Blast Furnace Slag (GGBS) serves as a sustainable, alternative binder for soil stabilization. GGBS is primarily composed of calcium oxide (CaO), silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and magnesium oxide (MgO). The material is produced by quenching molten blast furnace slag with water, rapidly cooling it to around 800°C. This partially cooled slag is then exposed to air, subjected to a rotating drum, and finely ground to achieve a consistent particle size suitable for construction applications. In this study, GGBS was sourced from Jindal Steel Works, Visakhapatnam. Tables 1.1 detail the physical and chemical properties of GGBS, showcasing its durability and strength-enhancing characteristics, which make it highly effective for stabilizing expansive soils.

Properties	Results
Specific gravity	2.86
Size (Micron)	<75
Water content (%)	24.5
Loss of ignition	0.05

Table1.1 Physical properties of GGBS

Polypropylene Fibers: Polypropylene fibers, derived from propylene, are synthetic polymers recognized for their durability, tensile strength, moisture resistance, and chemical stability. These fibers provide tensile reinforcement when mixed into soil, creating a matrix that enhances the shear strength and flexibility of the soil structure. Polypropylene fibers help in controlling cracking, shrinkage, and structural deformations, making them an effective solution for stabilizing expansive soils. For this study, polypropylene fibers with specified lengths and diameters were used to ensure uniform distribution and reinforcement within the soil matrix.

2.3 Methodology

The experimental methodology was structured to assess the effectiveness of GGBS and polypropylene fibers in stabilizing Black Cotton soil by examining the critical properties essential for pavement applications. Key tests included assessments of Atterberg limits, maximum dry density (MDD), optimum moisture content (OMC), unconfined compressive strength (UCS), and free swell index. The tests were conducted following IS standards for soil analysis, detailed in Table 3.3, and each test was repeated to ensure accuracy and reproducibility of results.

1. Sample Preparation: BC soil was initially air-dried and sieved to remove any large particles or impurities. The soil was then thoroughly mixed with varying proportions of GGBS and polypropylene fibers to identify the optimal blend that would achieve maximum stabilization benefits.

2. Proportioning of GGBS and Polypropylene Fibers: Different percentages of GGBS and fiber content were mixed with BC soil to examine their combined effects on soil properties. Initial proportions for GGBS started at 5%, increasing incrementally up to 30%. Polypropylene fibers were incorporated in percentages ranging from 0.25% to 1% by weight of the dry soil.

3. Atterberg Limits Testing: Atterberg limits, including liquid limit, plastic limit, and plasticity index, were tested for each mix to assess the impact of stabilizers on soil consistency. These tests were conducted as per IS: 2720 Part 5.

4. Compaction Testing (MDD and OMC): Standard Proctor tests were conducted to determine the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the stabilized soil mixtures, following IS: 2720 Part 7.

5. Unconfined Compressive Strength (UCS): UCS tests were performed to evaluate the improvement in soil strength with the addition of GGBS and fibers. The samples were molded, cured for a specified period, and tested according to IS: 2720 Part 10.

6. Free Swell Index: Free swell index tests were carried out to measure the reduction in swelling potential of BC soil, indicating the effectiveness of stabilization. The test was conducted as per IS: 2720 Part 40.

7. Data Analysis and Optimization: Results from the experimental tests were statistically analyzed to identify the optimal mix ratio of GGBS and polypropylene fibers for maximum stabilization efficiency. Key performance indicators, including UCS, MDD, OMC, and free swell index, were compared across different mix ratios to determine the most effective combination.

This methodology establishes a systematic approach to understanding the stabilization potential of GGBS and polypropylene fibers on Black Cotton soil. By quantifying the effects on various mechanical and physical properties, this research aims to offer insights into developing cost-effective, durable, and sustainable solutions for construction applications in expansive soil regions.as shown in Fig.1 flow chart methodology

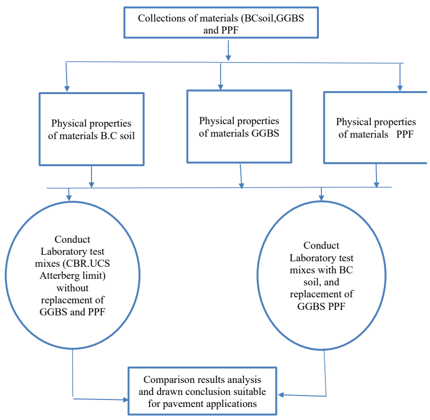

Fig. 1.1 flow chart for methodology

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3. RESULT AND ANALYSIS

Table.2 **(%) Of Replacement of GGBS with MMD**

Table.3 (%) Of Replacement of GGBS of CBR and SPT

(%) Of Replacement of GGBS AT 1 % ppf	**CBR (%)**	**SPT(g/cc)**
0	20.4	1.64
5+1%ppf	23	1.65
10+1%ppf	33	1.65
15+1%ppf	35	1.66
20+1%ppf	37	1.66
25+1%ppf	38	1.68
30+1%ppf	41	1.7

TABLE.3 (%) Of Replacement of GGBS AT 1 % ppf of CBR and SPT

	OMC	MMD
0	19.9	16.3
5	19.8	1.64
10	19.6	1.64
15	19.5	1.65
20	18.1	1.65
25	18.2	1.66
30	16.9	1.67

3.2

RESULT ANALYSIS

Table.4 vertical deformations and compressive stress for 30% GGBS

Vertical Deformation (DL)	Vertical Strain (ε)	1-E	Corrected Area	Compressive Load	Compressive Stress (N/mm^2)
0.5	0.006622517	0.993377483	1082.67	155.547	0.143669816
1	0.013245033	0.986754967	1089.936242	313.563	0.287689305
1.5	0.01986755	0.98013245	1097.300676	503.676	0.459013661
2	0.026490066	0.973509934	1104.765306	678.975	0.614587547
2.5	0.033112583	0.966887417	1112.332192	876.495	0.787979532
3	0.039735099	0.960264901	1120.003448	1046.856	0.934689979
5	0.066225166	0.933774834	1151.776596	1283.88	1.114695337
7	0.092715232	0.907284768	1185.405109	1185.12	0.999759483
9	0.119205298	0.880794702	1221.056391		
11	0.145695364	0.854304636	1258.918605		
11	0.145695364	0.854305	1258.918605		

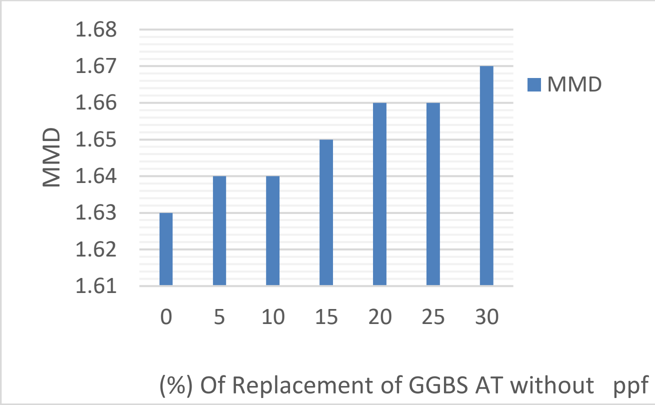

Fig 2. (%) Of Replacement of GGBS with MMD

With increasing GGBS replacement, the Maximum Dry Density (MMD) slightly increases from 1.64 g/cm³ at 5% replacement to 1.67 g/cm³ at 30% replacement, indicating a gradual rise in material density as GGBS content increases.as shown in fig.2

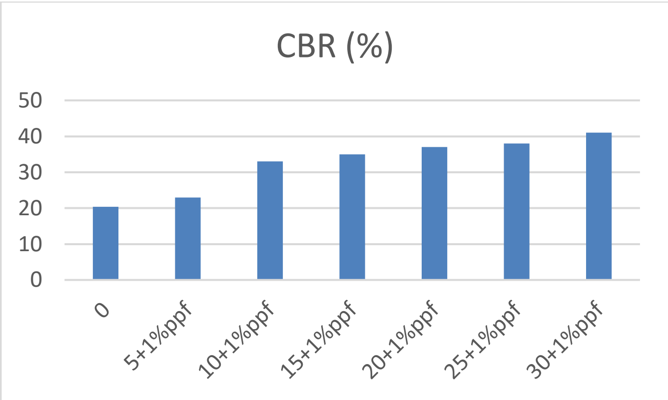

Fig. 3.%of GGBS of replacement vs CBR at 1% PPF

The impact of GGBS replacement on the CBR and SPT values at 1% ppf is evident in the data. With 0% GGBS, the CBR is 20.4%, and the SPT value is 1.64 g/cc. As the GGBS replacement increases, both the CBR and SPT values improve. At 5% GGBS, the CBR reaches 23%, and at 25% GGBS, it achieves 38%. The maximum CBR of 41% is observed at 30% GGBS replacement, with a corresponding SPT value of 1.7 g/cc. These results highlight the positive influence of GGBS and 1% fiber on the material's strength and compaction properties.as shown in Fig.3

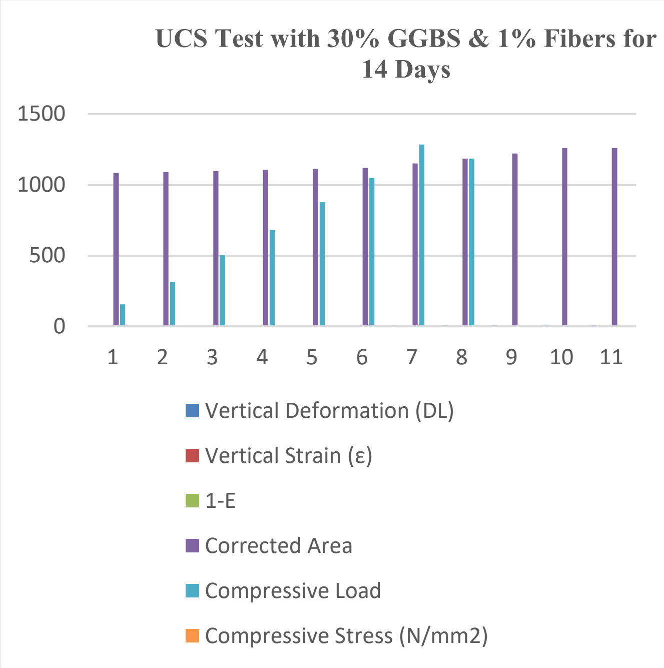

Fig. 4. **UCS Test with 30% GGBS & 1% Fibers for 14 Days**

The UCS test for a mix containing 30% GGBS and 1% fibers was conducted over 14 days. At 14 days, the sample exhibited a vertical deformation of 0.1457 mm and a strain of 0.8543. The applied compressive load was 1258.92 N, resulting in a compressive stress of 0.9998 N/mm². These results indicate substantial compressive strength development over the 14-day period, demonstrating the effectiveness of 30% GGBS and 1% fibers in enhancing the material's performance. The sample shows consistent strength increase, signifying a durable and robust material for construction applications.as shown in fig.4

4.CONCLUSION

The experimental findings emphasize the positive impact of Ground Granulated Blast Furnace Slag (GGBS) and polypropylene fibers (PPF) on enhancing soil properties, with notable improvements in strength, stability, and compaction. With varying GGBS replacement percentages, the Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), Standard Penetration Test (SPT), Optimum Moisture Content (OMC), Maximum Dry Density (MDD), and Free Swell Index (FSI) results collectively reveal that GGBS and PPF synergistically enhance soil performance, making it more suitable for construction applications.

In UCS tests, soils with 30% GGBS and 1% PPF exhibited a marked increase in compressive strength, with significant gains over both 7 and 14-day curing periods. This indicates a material that can withstand high compression stresses, with PPF contributing to better load distribution and reduced risk of cracking. Lower percentages of GGBS also improved UCS but with less impact compared to the 30% GGBS replacement level, suggesting a clear benefit from higher GGBS content.

The CBR and SPT results further illustrate that higher GGBS levels enhance the soil's stability and load-bearing capacity, critical for road and foundation applications. With a reduction in OMC and an increase in MDD as GGBS content rises, the soil becomes more compact and less water-dependent, benefiting construction projects by reducing water usage while achieving optimal compaction.

Moreover, the Free Swell Index (FSI) decreased significantly as GGBS content increased, indicating reduced expansiveness and enhanced stability. PPF's role in reducing FSI and further stabilizing the soil highlights the effectiveness of this additive combination for minimizing soil swelling, a common issue in construction.

Overall, a blend of 30% GGBS and 1% PPF offers optimal improvements in soil performance, providing a robust and durable solution for civil engineering applications requiring stability, strength, and durability in construction, especially where flexural strength is critical.

4.1 FURTHER STUDY

Further studies are essential to expand the understanding of GGBS and PPF in soil stabilization. Long-term performance testing under various environmental conditions, such as freeze-thaw cycles and moisture exposure, is needed to assess the durability of GGBS and PPF-enhanced soil. Additionally, exploring different types of fibers (e.g., glass, steel) could help identify the most effective fiber for improving soil properties. The effect of GGBS on various soil types should also be examined, as results may vary with different soil compositions. Moreover, a life cycle assessment (LCA) would provide insight into the environmental benefits of using GGBS in soil stabilization, contributing to more sustainable construction practices. Field implementation is crucial for verifying the laboratory results, particularly in real-world applications like road construction and foundation stabilization. Optimization of GGBS and PPF proportions should also be explored to determine the most efficient mix for achieving superior strength and compaction. Additionally, evaluating the material's performance in seismic zones could determine its suitability for earthquake-resistant infrastructure. Expanding research into these areas will help refine soil stabilization techniques, improve their performance, and promote sustainable, cost-effective materials for construction.

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