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Optimization of Fly Ash and Granulated Blast Furnace Slag (FA-GBFS) Mixes for Flexible Pavements

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Abstract

This study investigates the compaction, strength, and permeability characteristics of fly ash (FA) stabilized with granulated blast furnace slag (GBFS) to determine the optimal mix proportions for geotechnical applications. Standard Proctor compaction, unconfined compressive strength (UCS), California Bearing Ratio (CBR), and permeability tests were conducted on FA-GBFS mixtures, with GBFS content varying from 10 to 50% by dry weight. The results indicate that increasing GBFS content enhances the maximum dry unit weight (MDU) and UCS up to 40%, after which further addition leads to a decline. The highest UCS value of 164.51 kN/m² and a peak soaked CBR of 44.72% were observed at a 60% FA and 40% GBFS mix. Permeability values increased with GBFS content but remained below the required threshold for drainage layers. The findings suggest that FA-GBFS mixtures are best suited for use as separation or filtration layers in the lower sub-base of pavement structures, as per IRC 37-2018 and MoRTH specifications. Future research should focus on field validation and long-term durability assessments.

Keywords: Fly ash, granulated blast furnace slag, compaction characteristics, unconfined compressive strength, California bearing ratio, permeability, pavement sub-base

INTRODUCTION

The growing need for sustainable construction materials has led to increased interest in utilizing industrial byproducts such as fly ash (FA) and granulated blast furnace slag (GBFS). FA, a byproduct of coal combustion, is widely available but has low strength and poor compaction properties. GBFS, a byproduct of the steel industry, possesses pozzolanic properties that enhance the mechanical and durability characteristics of FA-based mixes. Incorporating FA and GBFS in pavement construction not only provides an eco-friendly solution but also improves engineering properties. This study aims to evaluate the optimal FA-GBFS mix proportions by examining compaction, strength, and permeability characteristics, ensuring their suitability for sub-base applications in road construction [1–4].

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OBJECTIVES

The primary objective of this study is to optimize the mix proportions of FA and GBFS to enhance their engineering properties for geotechnical applications. Specifically, the study aims to determine the optimum moisture content (OMC) and maximum dry unit weight (MDU) of FA-GBFS mixtures through Standard Proctor compaction tests. It also seeks to evaluate the unconfined compressive strength (UCS) of various FA-GBFS mix proportions to identify the most effective combination for strength enhancement. Additionally, the research focuses on assessing the California Bearing Ratio (CBR) of different FA-GBFS mixtures under both soaked and unsoaked conditions to determine their suitability for use in pavement sub-base layers. The permeability characteristics of FA-GBFS mixes are analyzed to establish their feasibility for application in drainage and filtration layers. Based on the findings, the study provides recommendations for the practical implementation of FA-GBFS mixtures in road construction, aligning with IRC and MoRTH specifications [5–8].

MATERIAL

This study utilized various materials, including marine clay, granular sub-base materials, lime, fly ash, granulated blast furnace slag (GBFS), and bagasse ash (BA) [9–12].

- *Marine Clay:* Collected from riverbanks, characterized as CH soil with low strength, classified as A-7-5 as per AASHTO.
- *Granular Sub-Base Materials:* Aggregates conforming to MoRTH Gradation I standards were used.
- *Lime:* Locally sourced quick lime (74% CaO and 7.9% silica) used for soil stabilization.
- *Fly Ash (FA):* Procured from Bhopal's industrial region, meeting IS standards for construction applications.
- *GBFS:* Industrial byproduct from Bhopal, visually glassy and granular, tested for physical properties.
- *Bagasse Ash (BA):* Collected from Bhopal's local market, exhibiting pozzolanic properties beneficial for soil stabilization.

These materials were tested for their suitability in highway pavement applications.

RESULTS

Standard Proctor compaction tests and unconfined compressive strength (UCS) tests were conducted to determine the optimal FA-GBFS mix proportions. The GBFS content varied from 10 to 50% by the dry weight of FA in increments of 10%. Each UCS test involved the preparation of at least three specimens using static loading at their respective Optimum Moisture Content (OMC) and Maximum Dry Density (MDD). Additionally, permeability tests using the falling head method were performed, with average values considered for analysis. The results from the Standard Proctor, UCS, California Bearing Ratio (CBR), and permeability tests are detailed in Table 1 [13–17].

Compaction Characteristics

The standard Proctor test results, illustrated in Figure 1, reveal that the maximum dry unit weight (MDU) of fly ash (FA) increases from 14.85 kN/m³ at 19.76% optimum moisture content (OMC) to 17.61 kN/m³ at 12.50% OMC for a blend containing 60% FA and 40% granulated blast furnace slag (GBFS). The spherical texture and greater specific gravity of GBFS compared to FA contribute to the increased density achieved at equivalent moisture content and compaction energy. Consequently, as the GBFS content rises, the MDU increases, while the OMC decreases. However, beyond 40% GBFS content, further additions result in a reduction in MDU. This is likely because the coarser GBFS particles reduce voids up to a certain level, but excess GBFS introduces more voids, thereby decreasing density [18, 19].

Table 1. Standard proctor, CBR, UCS, and permeability test results.

% Proportion of (FA+GBFS)	(100+0)%	(90+10)%	(80+20)%	(70+30)%	(60+40)%	(50+50)%
OMC (%)	19.76	17.66	16.08	14.56	12.50	13.00
MDU (kN/m^3)	14.85	15.36	15.81	16.48	17.61	17.52
UCS (kN/m^2)	41.60	100.33	114.40	147.17	164.51	102.70
CBR (Un-soaked) (%)	9.04	12.01	16.28	30.35	32.39	26.77
CBR (soaked) (%)	4.37	13.27	19.28	37.39	44.72	43.16
Coefficient of Permeability (kv.m/day)	0.047	0.054	0.059	0.066	0.089	0.425

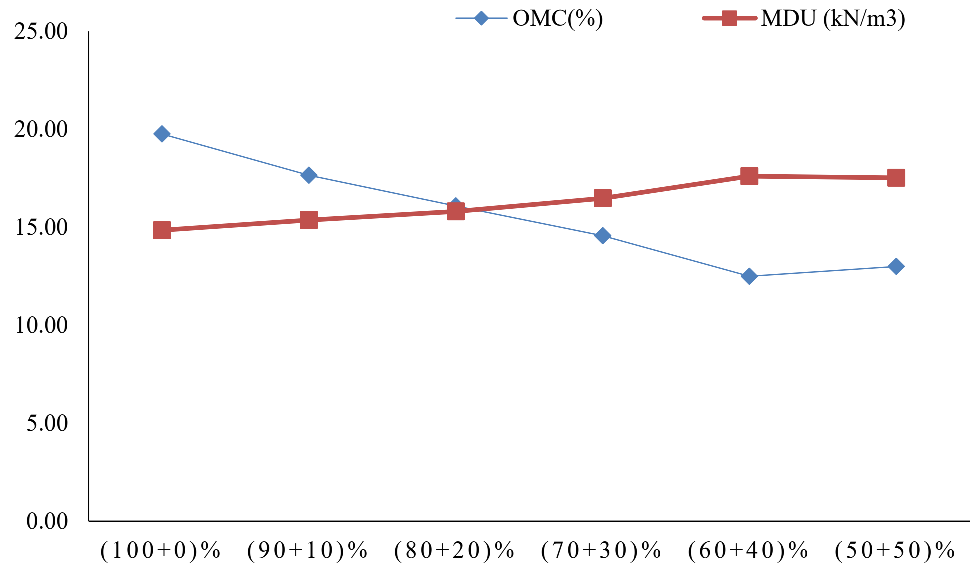

Figure 1. Variation of MDD and OMC for different FA-GBFS mixes.

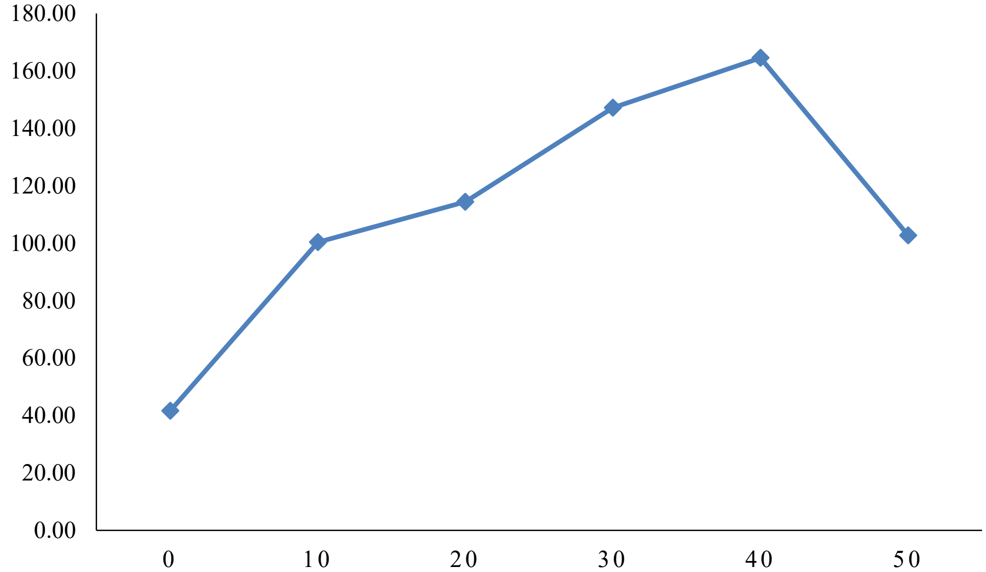

Figure 2. UCS Variations for Different FA-GBFS Mixes.

Unconfined Compressive Strength (UCS)

The unconfined compressive strength (UCS) test is a straightforward method to assess the strength of compacted samples and serves as a quality control measure. Figure 2 presents the UCS variations for different mix proportions. The results indicate an increase in UCS values with up to 40% GBFS content, followed by a decline. The strength enhancement is attributed to the improved bonding properties of the mix due to the interaction between FA and GBFS [20–23].

California Bearing Ratio (CBR)

Figure 3 shows the variations in soaked and unsoaked CBR values for different mix combinations. The CBR values increase with the addition of GBFS up to 42%, after which a decline is observed in both conditions. The soaked CBR values are higher than the unsoaked ones due to the pozzolanic reaction between the SiO_2 in FA and the $CaCO_3$ in GBFS, resulting in the formation of calcium silicate gel. The rise in CBR values indicates improved strength and durability of the mix.

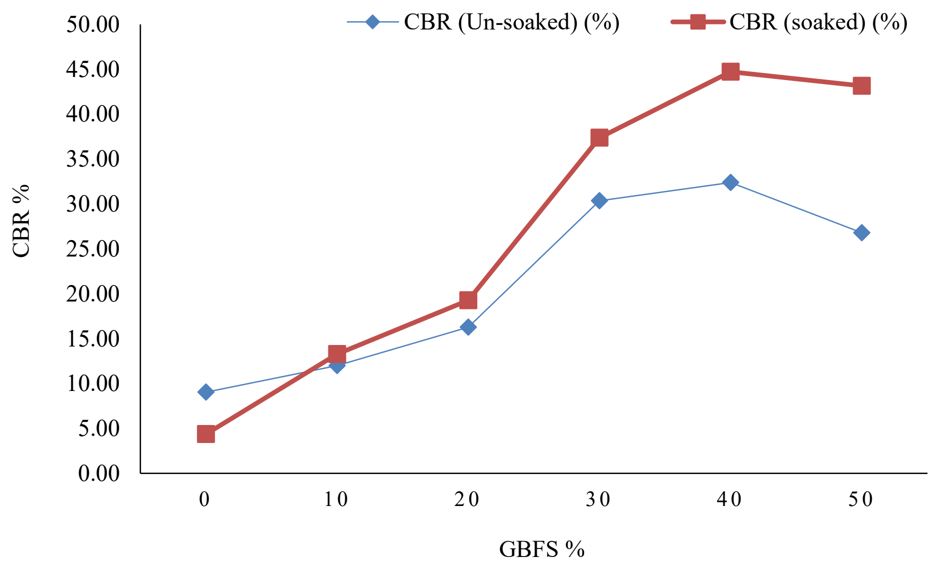

Figure 3. CBR Variations for Different FA-GBFS Mixes.

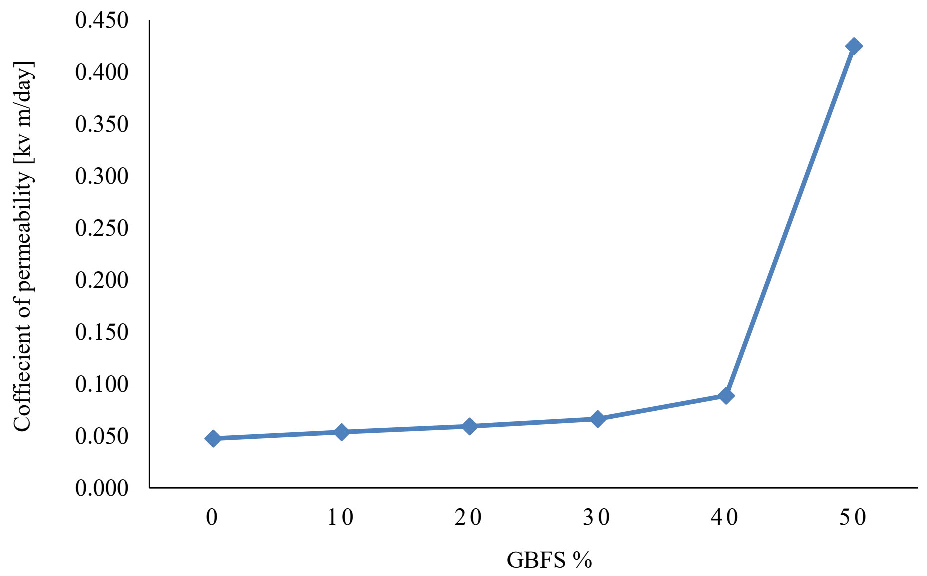

Figure 4. Permeability coefficients for various GBFS mixes.

Permeability Characteristics

FA-GBFS mixes are proposed for use as separation layers in the lower sub-base, serving as cement-treated sub-base materials (CTSB). Falling head permeability tests were conducted to evaluate the permeability characteristics, and the results are depicted in Figure 4. The permeability coefficient increases with the GBFS content, likely due to the higher sand content in GBFS, which creates additional voids. According to MoRTH and IRC 37-2018 specifications, the acceptable permeability for drainage layers is 300 m/day. Based on the results, FA-GBFS mixes may not be suitable as drainage layers. However, as recommended by IRC and MoRTH, these materials can function as separation or filtration layers in the lower sub-base. Geo-composite materials can be incorporated into the upper layer for drainage purposes

CONCLUSION

This study demonstrates that FA-GBFS mixtures exhibit promising geotechnical properties suitable for pavement sub-base applications. The results indicate that the addition of GBFS enhances compaction characteristics, with maximum dry unit weight (MDU) increasing and optimum moisture content (OMC) decreasing as GBFS content rises up to 40%. Unconfined compressive strength (UCS) and California Bearing Ratio (CBR) values also improve significantly up to 40% GBFS content, indicating enhanced strength and durability. However, further additions of GBFS beyond this threshold lead to a reduction in strength properties. While permeability values increase with GBFS content, they remain below the recommended limits for drainage layers, suggesting that FA-GBFS mixes are more suitable as separation or filtration layers in pavement sub-bases. The findings align with IRC and MoRTH guidelines, reinforcing the potential for FA-GBFS blends in sustainable road construction. Future research should focus on long-term performance assessments and field trials to validate laboratory results and enhance the practical applicability of FA-GBFS mixtures in geotechnical engineering.

Overall Recommendation

The optimal FA-GBFS mix proportion is identified as 60% FA and 40% GBFS, as this combination achieves the highest strength and stability without excessive permeability. These results support the potential use of FA-GBFS mixtures in road construction, particularly in the lower sub-base, aligning with the guidelines set by IRC 37-2018 and MoRTH specifications. Future research should focus on the long-term durability and field performance of these materials under varying environmental conditions.

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