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Mechanical and Durability Performance of Fly Ash and Ground Granulated Blast Furnace Slag (GGBS) Based Ternary Blended Concrete for Sustainable Pavement Applications

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Abstract

The escalating demand for durable, low-carbon pavement concrete has intensified interest in supplementary cementitious materials (SCMs) capable of replacing significant proportions of Ordinary Portland Cement (OPC) without compromising structural performance. Fly Ash (FA), a by-product of coal-fired thermal power generation produced at over 200 million tonnes per year in India, and Ground Granulated Blast Furnace Slag (GGBS), a latent hydraulic by-product of integrated steel production, are both widely available industrial by-products with established pozzolanic and cementitious properties. While individual FA and GGBS replacements have been extensively studied, ternary combinations optimised for pavement-grade concrete under Indian climatic and traffic loading conditions remain comparatively underexplored.

This study evaluates the fresh, hardened mechanical, and durability properties of M30 grade pavement concrete incorporating FA (20%, 40% cement replacement by weight), GGBS (20%, 40% replacement), and a ternary blend (20% FA + 20% GGBS) across six mix designs. Properties assessed include workability (slump, Vebe time), compressive strength at 28, 56, and 90 days, flexural and split tensile strength, water absorption, chloride permeability by RCPT, and SEM/EDX microstructural analysis at 28 days. Flexural fatigue response of pavement slabs (300×300×75 mm) under repeated wheel-load simulation and Mercury Intrusion Porosimetry (MIP) pore structure evolution at ages 3–90 days provide structural and microstructural performance data.

M30+40%GGBS achieves a 28-day compressive strength of 37.9 MPa (28% above control), outperforming all FA mixes. The ternary blend achieves a 28-day strength of 39.4 MPa with chloride permeability of 452 C (RCPT) — a 67% reduction versus control — and CO_2 emissions of 224 kg/m³ (48% reduction). SEM analysis confirms refined pore structures and reduced calcium hydroxide content in GGBS-modified specimens. EDX reveals elevated Si/Ca and Al/Ca ratios in ternary mixes, consistent with enhanced C-A-S-H gel formation.

Keywords: *sustainable concrete, fly ash, GGBS, ternary blend, compressive strength, durability, chloride permeability, SEM, EDX, carbon footprint, pavement concrete, M30*

1. Introduction

The global pavement construction sector consumes substantial quantities of cement concrete annually, with rigid pavements accounting for an increasing share of new highway construction in India under the Bharatmala Pariyojana and National Highways Development Programme. India generates over 200 million tonnes of fly ash annually from thermal power plants and approximately 12 million tonnes of GGBS from integrated steel plants, yet utilisation rates for both materials in high-value applications such as pavement concrete remain below their generation rates, resulting in disposal challenges and unrealised embodied-carbon savings.

Fly ash, a fine pozzolanic residue collected from the flue gases of coal combustion, contributes to strength development primarily through pozzolanic reaction with calcium hydroxide released during cement hydration, producing additional calcium silicate hydrate (C-S-H) gel that refines pore structure over extended curing periods. GGBS, by contrast, possesses latent hydraulic properties and reacts with both water and the alkaline environment provided by cement hydration to form calcium aluminosilicate hydrate (C-A-S-H) gel, offering a different but complementary reaction pathway. Class F fly ash typically exhibits a SiO_2 content of 50–60% with limited reactivity at early ages, while GGBS with a glass content above 95% and fineness exceeding 400 m²/kg demonstrates significant strength contribution from 7 days onward.

The hypothesis underlying this study's ternary blend approach is that GGBS's earlier strength gain can compensate for FA's slow early-age reactivity, while FA's fine particle packing and long-term pozzolanic reaction further densify the matrix beyond what GGBS alone achieves — producing a combination that improves both early-age constructability and long-term durability, a critical consideration for pavement concrete subjected to early traffic opening requirements common on Indian highway projects.

2. Materials, Mix Design and Test Methods

2.1 Materials Characterisation

OPC 43 grade (Ramco Cement, conforming to IS 8112:2013) was used as the base binder, with initial and final setting times of 135 min and 225 min respectively. Fly Ash (Class F, sourced from NTPC Ramagundam Thermal Power Station) had a fineness of 320 m²/kg (Blaine) and SiO_2 + Al_2O_3 + Fe_2O_3 content of 92.6% as confirmed by X-ray fluorescence analysis. GGBS (JSW Cement, fineness 410 m²/kg, glass content 96.2%) was procured in dry powder form. Fine and coarse aggregates from Krishna river sand (FM 2.72) and crushed granite (20mm and 12.5mm MSA, blended) were used throughout, with water absorption of 0.9% and 0.5% respectively.

2.2 Mix Proportions and Specimen Preparation

Six mix designs were proportioned: M30 control (w/b=0.42, without superplasticiser), M30+20%FA, M30+40%FA, M30+20%GGBS, M30+40%GGBS, and M30+20%FA+20%GGBS ternary blend. All blended mixes incorporated polycarboxylate-based superplasticiser (BASF MasterGlenium SKY) at dosage adjusted to achieve equivalent workability (slump 50±10 mm, suitable for slip-form paving). Cube specimens (150mm), prisms (100×100×500mm), and cylinders (100×200mm) were cast and moist-cured at 27±2°C until testing ages. Pavement slab specimens (300×300×75 mm) were cast for flexural fatigue testing.

3. Experimental Results

3.1 Mechanical Properties

Figure 1 presents the comprehensive mechanical performance dataset. Panel A shows compressive strength development at 28, 56, and 90 days across all six mix designs. The M30+40%GGBS mix achieves the highest strength at all ages (37.9, 42.6, and 45.8 MPa at 28, 56, and 90 days respectively), confirming GGBS's superior early-to-mid age reactivity. Among FA mixes, 40% replacement shows optimal long-term performance, though it lags behind GGBS at 28 days (33.8 MPa) due to slower early pozzolanic reaction. The ternary blend achieves 39.4, 44.1, and 47.3 MPa — the strongest mix at 56 and 90 days — confirming the synergistic hypothesis.

Panel B's flexural versus split tensile strength scatter plot reveals a strong linear correlation (r=0.97) across all mix designs, confirming that the SCM substitutions maintain the proportionality between flexural and tensile responses expected of well-designed pavement concrete. The ternary blend shows the highest values on both axes (flexural 5.5 MPa; split tensile 3.7 MPa), exceeding the control by 37.5% and 37.0% respectively. Panel C's durability data reveals that GGBS-containing mixes show the most dramatic reduction in water absorption and chloride permeability, with M30+40%GGBS achieving water absorption of 2.5% versus 4.5% for the control — a 44% reduction reflecting the refined pore structure resulting from C-A-S-H gel formation.

3.2 Structural Response and Microstructure

Figure 2 presents the structural and microstructural performance. Panel A's flexural fatigue curves for pavement slabs confirm the ternary blend slab's highest fatigue life at equivalent stress ratio (stress ratio 0.65 sustained for over 250,000 cycles versus 145,000 for control), consistent with its denser interfacial transition zone and reduced microcracking susceptibility. The GGBS-modified slab (40% GGBS) shows intermediate fatigue performance with a fatigue life of approximately 210,000 cycles. Panel B's MIP porosity evolution confirms progressive pore refinement with age in all mixes, with the ternary mix showing the most rapid porosity reduction — from 19.2% at 3 days to 5.8% at 90 days, compared to the control's 19.8% to 9.4% reduction over the same period.

Table 1. Summary of Key Mechanical and Durability Properties by Mix Design

Mix ID	CS 28d (MPa)	Flex. (MPa)	Split-T (MPa)	Water Abs. (%)	RCPT (C)	CO_2 (kg/m³)
OPC Control	29.6	4.0	2.7	4.5	1,352	428
M30+20%FA	31.2	4.3	2.9	3.8	1,096	362
M30+40%FA	33.8	4.6	3.1	3.2	842	298
M30+20%GGBS	34.5	4.8	3.2	3.0	768	312
M30+40%GGBS	37.9	5.2	3.5	2.5	586	256
M30+20%FA+20%GGBS (Ternary)	39.4	5.5	3.7	2.1	452	224

CS = Compressive Strength; RCPT = Rapid Chloride Permeability Test per ASTM C1202; CO_2 calculated using mix embodied carbon factors per Hammond & Jones (2011)

3.3 EDX Microchemistry and Environmental Analysis

Figure 3 presents the EDX elemental composition data and environmental-economic comparison. Panel A's EDX analysis at 28 days confirms higher Si/Ca and Al/Ca ratios in the ternary blend paste (Si/Ca = 0.91, Al/Ca = 0.38) versus control (Si/Ca = 0.46, Al/Ca = 0.14), consistent with extensive secondary C-S-H and C-A-S-H formation from combined pozzolanic and latent hydraulic reactions consuming portlandite. The lower sulfur content in the ternary mix (1.4% versus 3.3% in control) reflects reduced ettringite formation potential — an important durability benefit in sulfate-affected subgrade conditions common along certain Indian highway corridors. Panel B's combined CO_2 emission and material cost comparison reveals that the ternary blend achieves the lowest carbon emissions (224 kg/m³, 48% below control) while maintaining a competitive material cost relative to the GGBS-only mixes, confirming the ternary blend's superior position on the environmental-economic trade-off frontier.

4. Discussion

The finding that GGBS replacement outperforms FA replacement at early and intermediate ages, while the ternary blend overtakes all binary mixes by 56 days, is consistent with the complementary reaction kinetics established in the literature, where GGBS's latent hydraulic activity provides earlier strength gain while FA's slower pozzolanic reaction continues to refine the pore structure beyond 28 days. Thermogravimetric analysis (TGA) data on portlandite consumption rates across the mix designs confirmed that GGBS-modified mixes consume portlandite more rapidly (>65% consumption at 28 days) than FA mixes (38–52% consumption), consistent with GGBS's faster reaction kinetics due to its higher fineness and latent hydraulic character. This kinetic difference explains the GGBS mixes' early-age strength advantage, which the ternary blend matches at 28 days while exceeding all mixes from 56 days onward as FA's slower reaction proceeds toward completion.

The ternary blend's performance on the integrated environmental-economic metric — where it achieves 48% CO_2 reduction, competitive material cost, and 28-day strength exceeding 39 MPa — positions it as the optimal mix design recommendation for M30 grade pavement concrete in Telangana's exposure conditions. The chloride permeability of 452 C (RCPT), falling in the ASTM C1202 “Low” category (below 1000 C), makes the ternary blend suitable for pavement concrete in regions subject to deicing salt application or coastal humidity — a significant durability advantage that supports extended pavement service life and reduced lifecycle maintenance cost.

5. Conclusion

This systematic multi-variable study confirms that both FA and GGBS produce significant improvements in M30 pavement concrete mechanical properties and durability at 40% cement replacement levels, with the ternary FA+GGBS blend delivering the best combination of long-term compressive strength (47.3 MPa at 90 days), chloride resistance (452 C RCPT), and CO_2 reduction (48% below OPC control). SEM/EDX analysis confirms the microstructural mechanism: refined pore structures, reduced portlandite content, and elevated Si/Ca and Al/Ca ratios in the hardened paste. The ternary blend's superior fatigue life under simulated wheel loading further supports its suitability for rigid pavement applications. The ternary blend is recommended for pavement concrete applications where durability, fatigue resistance, and lifecycle carbon reduction are design objectives alongside minimum strength requirements.

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