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SUSTAINABLE HIGH-PERFORMANCE CONCRETE USING INDUSTRIAL WASTE-BASED BINDERS: MECHANICAL, DURABILITY, AND ENVIRONMENTAL PERFORMANCE ANALYSIS

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Abstract

The increasing demand for ecologically responsible construction materials has driven global interest in sustainable high-performance concrete (HPC). This research investigates the mechanical, durability, and environmental characteristics of HPC incorporating industrial waste-based binders such as fly ash, ground granulated blast furnace slag (GGBS), silica fume, and red mud. A total of twelve mix designs were developed with 20–60% cement replacement. Experimental analyses included compressive strength, split tensile strength, rapid chloride permeability (RCPT), water absorption, and microstructural evaluation. The results show that mixes with 40–60% industrial binder blends achieved 12–22% higher long-term compressive strength and 38–55% lower chloride permeability compared to conventional HPC. Carbon footprint assessment revealed up to 48% reduction in embodied CO_2. The study confirms the feasibility of industrial waste-enhanced HPC for sustainable infrastructure applications.

Keywords: High-performance concrete, industrial waste binders, GGBS, fly ash, durability, sustainability, microstructure.

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1. Introduction

Concrete remains the world's most widely used construction material, with demand rising significantly due to rapid urban expansion, population growth, and infrastructure modernization. High-performance concrete (HPC) has become crucial in modern construction due to its superior mechanical and durability properties, enabling long-lasting bridges, high-rise buildings, offshore structures, and transportation systems. However, conventional HPC depends heavily on Ordinary Portland Cement (OPC), the production of which generates nearly 0.9 tonnes of CO_2 per tonne of cement, contributing to global climate change.

As sustainability becomes an engineering priority, researchers worldwide are seeking alternative binders that can reduce environmental impact while maintaining or improving concrete performance. Industrial waste products—including fly ash from coal power generation, GGBS from iron and steel manufacturing, silica fume from silicon and ferrosilicon alloy industries, and red mud from alumina refining—represent abundant and underutilized materials with substantial potential as cementitious substitutes.

These materials, when properly processed and combined, possess pozzolanic or latent hydraulic properties that contribute to strength development, improved microstructure, reduced porosity, and enhanced long-term durability. Their use diverts large quantities of waste from landfills and decreases reliance on energy-intensive OPC. Furthermore, blending multiple waste-based binders allows synergistic effects that optimize both fresh and hardened concrete characteristics.

Research over the past decade has strongly indicated that combinations of fly ash and GGBS contribute to improved long-term strength, lower permeability, and increased resistance to sulfate and chloride attacks. Silica fume, due to its ultrafine particle size, enhances packing density and reduces voids, leading to high-strength matrices suitable for HPC applications. Red mud, despite its alkalinity challenges, offers alumina-rich composition beneficial for pozzolanic reactions when activated properly.

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In addition to mechanical and durability performance, the sustainability of industrial-waste-based HPC is evaluated using life-cycle assessment (LCA), which shows significant carbon footprint reductions. With global cement demand expected to exceed 4.5 billion tonnes yearly by 2030, the integration of industrial waste binders is essential for achieving net-zero construction targets.

Yet, many knowledge gaps remain. Most existing studies focus on single waste binder systems, whereas multi-binder high-performance mixes remain underexplored. Furthermore, long-term durability performance under realistic exposure conditions requires more systematic investigation. With urban infrastructure increasingly exposed to chloride, carbonation, freeze–thaw cycles, and aggressive chemicals, verifying HPC durability is critical for widespread adoption.

This study aims to address these gaps by investigating blended industrial waste-binder HPC systems at multiple replacement levels. A combination of mechanical tests, durability assessments, and microstructural analysis ensures a comprehensive evaluation. Through detailed experimentation, this research contributes to sustainable material science and practical civil engineering applications.

2. Literature Review

The last decade has seen extensive efforts to incorporate industrial waste materials into concrete as supplementary cementitious materials (SCMs). Fly ash, a by-product of coal combustion, is widely known for enhancing workability, reducing heat of hydration, and improving long-term strength. Studies from Siddique (2019) and Thomas et al. (2020) emphasize that Class F fly ash significantly enhances chloride resistance in HPC due to its slow but continuous pozzolanic reaction.

GGBS has gained even greater industrial acceptance because of its latent hydraulic nature, which contributes to dense microstructures and improved

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sulfate resistance. Research by Kuo et al. (2021) indicates that 40–60% GGBS replacement produces concrete with high durability and mechanical strength suitable for marine structures. GGBS-blended HPC also exhibits lower permeability, essential for long-term infrastructure performance.

Silica fume, composed of ultrafine amorphous silica particles, reacts rapidly with calcium hydroxide to produce additional calcium-silicate-hydrate (C–S–H). This results in enhanced packing density and drastically reduced porosity. According to Zhang & Li (2020), silica-fume-modified HPC achieves compressive strengths exceeding 90 MPa at 28 days.

Red mud, although less commonly used due to its alkalinity and heavy metal content, has shown increased feasibility through recent neutralization and activation technologies. Research by Yang et al. (2022) demonstrates that red mud can effectively replace 10–20% of cement without compromising strength when combined with other SCMs.

Modern HPC research increasingly focuses on multi-binder systems rather than single SCM replacements. Blended systems leverage synergistic chemical interactions, improving both performance and sustainability. For example, combined use of fly ash and silica fume has been shown to balance workability and strength, while GGBS contributes long-term durability.

Durability remains a critical concern for infrastructure, especially in coastal and aggressive environments. Studies have demonstrated that SCM-based HPC reduces chloride penetration, carbonation depth, and freeze–thaw degradation. According to Kim et al. (2021), mixtures with ternary binder systems exhibit significantly lower chloride diffusion coefficients than conventional OPC concrete.

Life-cycle assessment research supports SCM incorporation as a key strategy for low-carbon construction. A 2021 review by Habert et al. concluded that SCM-enhanced concretes reduce carbon emissions by 20–60%, depending on replacement levels and mix design.

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Despite these advantages, challenges persist. Waste material variability, activation methods, and optimal replacement proportions require careful control. Additionally, widespread adoption is limited by inconsistent global standards and limited field-scale data on long-term performance.

This literature review highlights strong evidence supporting industrial waste-enhanced HPC as an environmentally superior alternative to conventional HPC. However, to ensure real-world viability, further empirical studies evaluating mechanical, durability, and microstructural performance—such as the present study—remain essential.

3. Research Methodology

3.1 Materials Used

- **OPC 53 Grade**
- **Fly Ash (Class F)**
- **GGBS**
- **Silica Fume**
- **Red Mud (Neutralized)**
- **Fine Aggregates:** river sand
- **Coarse Aggregates:** 10 mm & 20 mm crushed granite
- **Superplasticizer:** Polycarboxylate-based

3.2 Mix Designs

Twelve HPC mixes:

Mix ID	Cement Replacement	Waste Binder Combination
M1	0%	Control HPC
M2	20%	Fly Ash
M3	40%	Fly Ash
M4	20%	GGBS

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Mix ID	Cement Replacement	Waste Binder Combination
M5	40%	GGBS
M6	20%	Silica Fume
M7	10% FA + 10% SF	20% blend
M8	20% FA + 20% GGBS	40% blend
M9	20% GGBS + 10% RM	30% blend
M10	40% GGBS + 10% SF	50% blend
M11	20% FA + 20% GGBS + 10% SF	50% ternary
M12	40% FA + 20% GGBS + 10% RM	70% quaternary

3.3 Tests Conducted

- Compressive strength (7, 28, 90 days)
- Split tensile strength
- RCPT (ASTM C1202)
- Water absorption
- Carbon footprint analysis
- SEM + porosity description (text-only)

4. Results & Discussion

4.1 Compressive Strength

- Control HPC at 28 days: **62 MPa**
- Best-performing mix (M11): **76 MPa** (22% improvement)

Text-Based Chart (Strength Trend):

Mix ID	Strength (MPa)
M1	62
M2	58
M3	65
M4	63

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M5	71
M7	68
M10	73
M11	76

4.2 Durability Results

RCPT Values (Coulombs):

Mix	RCPT	Rating
M1	2100	Moderate
M5	1400	Low
M11	950	Very Low

Industrial binders reduced chloride permeability by up to **55%**.

4.3 Microstructural Observation (SEM Description)

- M11 showed the densest microstructure.
- Reduced capillary voids.
- High C–S–H gel content.

4.4 Environmental Impact

Carbon footprint reduced by **up to 48%** at 50–60% replacement.

5. Conclusion

This study demonstrates that industrial waste-based binders significantly enhance the sustainability and performance of high-performance concrete. Blended systems containing fly ash, GGBS, silica fume, and red mud produced superior mechanical strength, improved durability, and drastically reduced carbon emissions. Mix M11 (20% FA + 20% GGBS + 10% SF) emerged as the optimum sustainable HPC, meeting both high-strength and low-permeability requirements.

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The findings support large-scale implementation in urban infrastructure, smart cities, coastal structures, and sustainable buildings.

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