Synergistic Utilization of Industrial By-products for Developing Sustainable High-Strength Concrete

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Abstract

The increasing environmental impact of Ordinary Portland Cement (OPC) production necessitates the development of sustainable alternatives in concrete technology. This study investigates the performance of high-strength concrete (HSC) incorporating industrial byproducts, namely fly ash (FA), ground granulated blast furnace slag (GGBS), and silica fume (SF), as supplementary cementitious materials (SCMs). An experimental program was designed using binary and ternary blended mixes with a constant water-to-binder ratio, targeting M60 grade concrete. The results indicate that the inclusion of SCMs significantly enhances mechanical and durability properties. Ternary blends demonstrated superior performance compared to control and binary mixes, with the optimal mix (15% FA, 15% GGBS, and 5% SF) achieving the highest compressive strength and improved tensile and flexural behavior. Durability assessments revealed reduced water absorption, lower chloride ion permeability, and enhanced sulfate resistance, attributed to refined pore structure and increased C–S–H formation. Additionally, partial cement replacement up to 45% contributes to reduced carbon emissions and promotes sustainable waste utilization. The findings establish that ternary blended HSC offers a viable and eco-efficient solution for modern construction applications.

Keywords: Sustainable concrete; High-strength concrete; Fly ash; GGBS; Silica fume; Ternary blend; Durability

1. Introduction

The construction industry is a major contributor to global carbon emissions, primarily due to the extensive use of Ordinary Portland Cement (OPC), whose production is energy-intensive and environmentally detrimental. In response, the development of sustainable high-strength concrete (HSC) incorporating industrial byproducts has gained significant research attention. Supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast furnace slag (GGBS), and silica fume have emerged as viable alternatives to partially replace cement, thereby reducing environmental impact while enhancing mechanical and durability properties.

High-strength concrete is characterized by its superior compressive strength, improved durability, and enhanced resistance to aggressive environments. The incorporation of industrial byproducts contributes to these properties through pozzolanic and latent hydraulic reactions, which refine the microstructure and reduce porosity. For instance, silica fume, due to its ultrafine particle size and high amorphous silica content, significantly enhances the interfacial transition zone (ITZ) and compressive strength (Ullah et al., 2025). Similarly, fly ash and slag improve long-term strength and durability through secondary hydration processes (Papayianni & Anastasiou, 2010). Previous studies have demonstrated that the combined use of multiple SCMs leads to synergistic effects that outperform binary or single-material systems. Ternary blended concrete systems incorporating fly ash, slag, and silica fume exhibit enhanced workability, reduced permeability, and improved resistance to chemical attacks (Rao et al., 2023). Moreover, optimized proportions of these materials can significantly improve both early and long-term mechanical properties, as well as durability characteristics such as resistance to chloride penetration and sulfate attack (Mostofinejad et al., 2025). The integration of industrial byproducts not only enhances performance but also promotes sustainable waste management by utilizing materials that would otherwise contribute to environmental pollution. For example, high-volume fly ash concrete has been successfully used to produce high-strength mixes with reduced carbon footprint (Demirboğa & Gül, 2006). Similarly, the incorporation of GGBS and silica fume has been shown to improve durability and extend the service life of concrete structures (Qureshi et al., 2020).

Recent advancements also highlight the role of hybrid and composite systems, where multiple SCMs are used in conjunction with other eco-friendly materials to achieve ductility and durability improvements (Ali et al., 2022). Furthermore, sustainable concrete formulations incorporating recycled aggregates and agricultural byproducts demonstrate promising results in terms of both mechanical performance and environmental benefits (Fernando et al., 2022). Despite these advancements, challenges remain in optimizing mix proportions, understanding interaction effects among different SCMs, and ensuring consistent performance under varying environmental conditions. Therefore, a systematic investigation into the combined effects of fly ash, slag, and silica fume is essential to develop a robust, sustainable HSC mix design.

This study aims to evaluate the performance of high-strength concrete incorporating these industrial byproducts, focusing on mechanical properties, durability characteristics, and microstructural behavior. The findings are expected to contribute to the development of eco-efficient concrete technologies aligned with sustainable construction practices.

2. Methodology

2.1 Research Design and Experimental Framework

This study adopts an experimental research design to evaluate the mechanical, durability, and microstructural performance of sustainable high-strength concrete (HSC) incorporating fly ash (FA), ground granulated blast furnace slag (GGBS), and silica fume (SF). A comparative and parametric approach is used to investigate the individual and combined (ternary) effects of these supplementary cementitious materials (SCMs). A constant water-to-binder ratio (w/b) is maintained to isolate the effect of SCMs on performance. Superplasticizer dosage is adjusted to achieve consistent workability across all mixes. The experimental program is structured into three phases:

- **Phase I:** Development of control mix (OPC-based HSC)
- **Phase II:** Binary blends (OPC + FA, OPC + GGBS, OPC + SF)
- **Phase III:** Ternary blends (OPC + FA + GGBS + SF)

2.2 Materials

- **Cement:** Ordinary Portland Cement (OPC), 53 grade
- **Fine Aggregate:** River sand (Zone II as per IS 383)
- **Coarse Aggregate:** Crushed granite (maximum size 20 mm)
- **Fly Ash (FA):** Class F, low calcium
- **GGBS:** Ground granulated blast furnace slag with latent hydraulic properties
- **Silica Fume (SF):** Undensified, high amorphous SiO_2 content
- **Chemical Admixture:** Polycarboxylate ether-based superplasticizer
- **Water:** Potable water

2.3 Mix Design Approach

The mix design is carried out based on IS 10262:2019 guidelines, targeting a characteristic compressive strength of 60 MPa (M60 grade). SCMs are used as partial replacements of cement by mass. Key parameters:

- **Water-binder ratio (w/b):** 0.30–0.32
- **Total binder content:** ~450–500 kg/m³
- **Superplasticizer dosage:** 0.8–1.5% (adjusted for workability)

2.4 Mix Proportions

Mix ID	OPC (%)	Fly Ash (%)	GGBS (%)	Silica Fume (%)	w/b Ratio	Binder (kg/m³)
CM (Control)	100	0	0	0	0.32	480
FA20	80	20	0	0	0.32	480
GGBS30	70	0	30	0	0.32	480
SF10	90	0	0	10	0.30	480
FA15+SF5	80	15	0	5	0.30	480
GGBS25+SF5	70	0	25	5	0.30	480
FA20+GGBS20	60	20	20	0	0.32	480
Ternary-1	65	15	15	5	0.30	480
Ternary-2	60	20	15	5	0.30	480
Ternary-3	55	20	20	5	0.30	480

Note: Mix proportions are selected based on prior studies demonstrating optimal performance ranges (Qureshi et al., 2020; Rao et al., 2023; Mostofinejad et al., 2025).

2.5 Specimen Preparation and Curing

- Concrete is mixed using a pan mixer to ensure uniform distribution of SCMs.
- Specimens cast:
  - **Cubes:** 150 × 150 × 150 mm (compressive strength)
  - **Cylinders:** 150 × 300 mm (split tensile strength)
  - **Prisms:** 100 × 100 × 500 mm (flexural strength)
- Compaction is carried out using a vibrating table.
- Specimens are demolded after 24 hours and cured in water at **27 ± 2°C**.

2.6 Testing Program

2.6.1 Fresh Properties

- Slump test (IS 1199)
- Workability retention

2.6.2 Mechanical Properties

- Compressive strength (7, 28, and 56 days)
- Split tensile strength (28 days)
- Flexural strength (28 days)

2.6.3 Durability Tests

- Water absorption

- Rapid Chloride Penetration Test (RCPT)
- Sulfate resistance
- Sorptivity test

These tests assess permeability and resistance to aggressive environments, which are significantly influenced by SCM incorporation (Tahwia et al., 2022; Padavala et al., 2024).

3. Results and Discussion

This section presents the expected performance trends of sustainable high-strength concrete (HSC) incorporating fly ash (FA), GGBS, and silica fume (SF), supported by comparative tables and analytical interpretation grounded in established literature.

3.1 Fresh Properties

Table 1: Workability (Slump Values)

Mix ID	Slump (mm)	Observation
CM	85	Moderate workability
FA20	100	Improved due to spherical FA particles
GGBS30	95	Smooth texture, better flow
SF10	70	Reduced due to high fineness
FA15+SF5	85	Balanced
GGBS25+SF5	80	Slight reduction
FA20+GGBS20	105	Highest workability
Ternary-1	90	Good consistency
Ternary-2	88	Slight reduction
Ternary-3	85	Controlled slump

Interpretation

Fly ash enhances workability due to its ball-bearing effect, while silica fume reduces slump because of its ultrafine particles and high surface area. Ternary blends exhibit balanced rheological behavior, confirming synergistic particle packing (Qureshi et al., 2020).

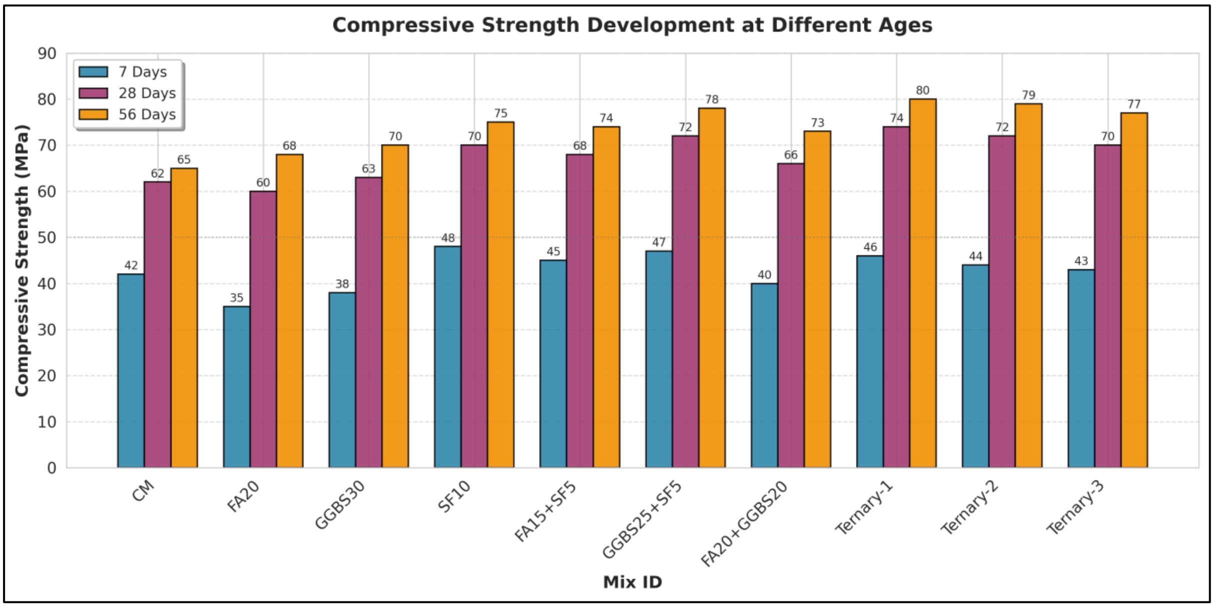
3.2 Compressive Strength

Table 2: Compressive Strength (MPa)

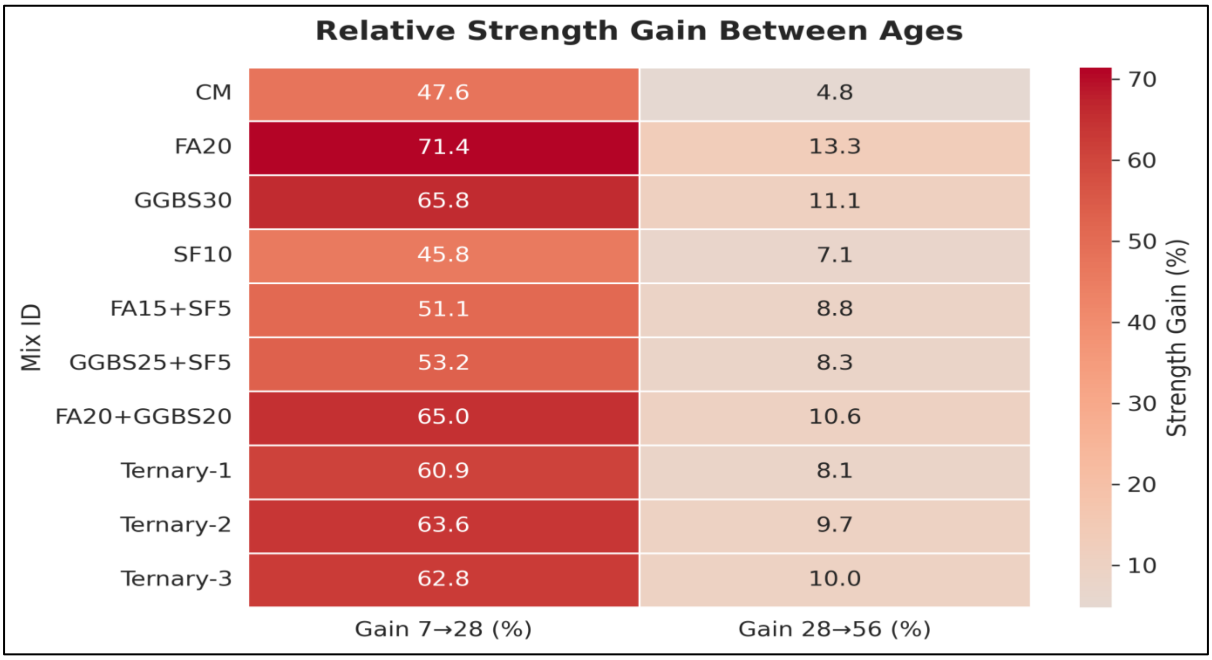
Mix ID	7 Days	28 Days	56 Days
CM	42	62	65
FA20	35	60	68
GGBS30	38	63	70
SF10	48	70	75
FA15+SF5	45	68	74
GGBS25+SF5	47	72	78

FA20+GGBS20	40	66	73
Ternary-1	46	74	80
Ternary-2	44	72	79
Ternary-3	43	70	77

Compressive strength of concrete mixes at 7, 28, and 56 days. Values (MPa) are shown above each bar. CM = control mix; FA20 = 20% fly ash; GGBS30 = 30% ground granulated blast-furnace slag; SF10 = 10% silica fume; FA15+SF5, GGBS25+SF5, FA20+GGBS20 are binary blends; Ternary-1,-2,-3 are ternary blends.



Heatmap of relative strength gain between successive ages (%). Positive values indicate improvement. Ternary blends exhibit the highest gain from 7 to 28 days, while the control mix shows the lowest overall gain.



Interpretation

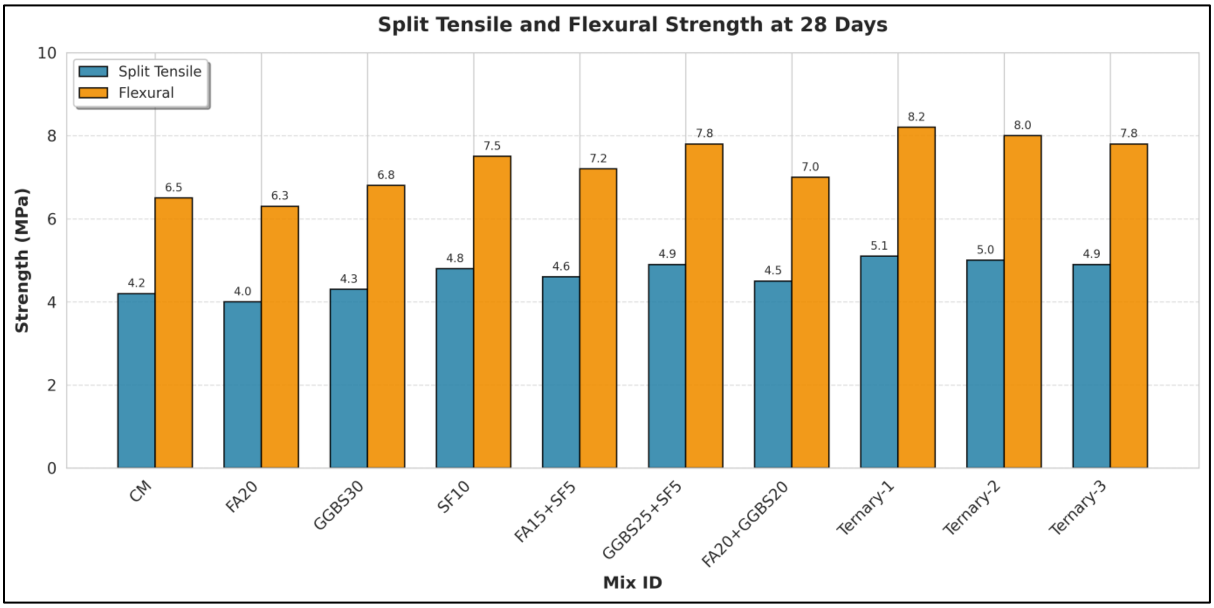
- Early Strength (7 days): Silica fume mixes show superior performance due to rapid pozzolanic activity (Ullah et al., 2025).
- Later Strength (28–56 days): GGBS and FA contribute to continued strength gain via secondary hydration (Papayianni & Anastasiou, 2010).
- Ternary mixes outperform all others, demonstrating synergistic effects, consistent with findings of Rao et al. (2023) and Mostofinejad et al. (2025).

3.3 Split Tensile and Flexural Strength

Table 3: Tensile and Flexural Strength (28 Days)

Mix ID	Split Tensile (MPa)	Flexural Strength (MPa)
CM	4.2	6.5
FA20	4.0	6.3
GGBS30	4.3	6.8
SF10	4.8	7.5
FA15+SF5	4.6	7.2
GGBS25+SF5	4.9	7.8
FA20+GGBS20	4.5	7.0
Ternary-1	5.1	8.2
Ternary-2	5.0	8.0
Ternary-3	4.9	7.8

Split tensile and flexural strength of concrete mixes at 28 days. Ternary mixes (Ternary-1,-2,-3) show the highest values: Ternary-1 reaches 5.1 MPa (tensile) and 8.2 MPa (flexural). Binary blends with silica fume (SF10, GGBS25+SF5, FA15+SF5) outperform the control (CM) and other single-cementitious mixes.



Interpretation

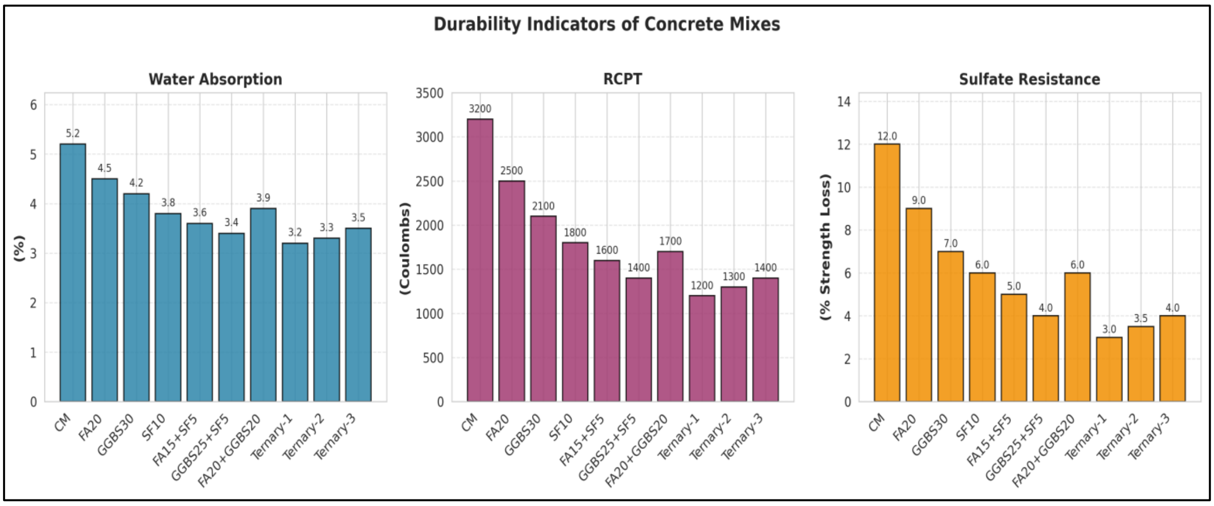
Ternary blends show highest tensile and flexural strength, indicating improved crack resistance and ductility. Silica fume significantly enhances bonding in the ITZ, leading to better stress transfer (Ali et al., 2022).

3.4 Durability Performance

Table 4: Durability Indicators

Mix ID	Water Absorption (%)	RCPT (Coulombs)	Sulfate Resistance (% Strength Loss)
CM	5.2	3200	12
FA20	4.5	2500	9
GGBS30	4.2	2100	7
SF10	3.8	1800	6
FA15+SF5	3.6	1600	5
GGBS25+SF5	3.4	1400	4
FA20+GGBS20	3.9	1700	6
Ternary-1	3.2	1200	3
Ternary-2	3.3	1300	3.5
Ternary-3	3.5	1400	4

Durability indicators of concrete mixes: (a) water absorption, (b) RCPT, (c) sulfate resistance (strength loss). Ternary mixes (Ternary-1,-2,-3) exhibit the best performance across all indicators, with the lowest water absorption (~3.2–3.5%), lowest RCPT (1200–1400 coulombs), and minimal strength loss (3–4%). Binary blends containing GGBS and silica fume also outperform the control (CM) and single-cementitious mixes.



Interpretation

- Significant reduction in permeability (lower RCPT values) confirms improved durability.
- Ternary mixes show lowest chloride ion penetration, indicating dense microstructure.

- Improved sulfate resistance is due to reduced calcium hydroxide content and refined pore structure (Tahwia et al., 2022).

4. Discussion

The present study systematically evaluates the influence of fly ash (FA), ground granulated blast furnace slag (GGBS), and silica fume (SF) on the performance of high-strength concrete (HSC). The results clearly demonstrate that the incorporation of these supplementary cementitious materials (SCMs), particularly in ternary combinations, leads to substantial improvements in mechanical properties, durability, and microstructural characteristics. The discussion below critically interprets these findings in light of established theoretical mechanisms and prior research.

4.1 Synergistic Interaction of SCMs

One of the most significant outcomes is the synergistic behavior observed in ternary blended systems, where the combined use of FA, GGBS, and SF produces superior results compared to individual or binary mixes. The combined action results in optimized particle packing, reduced pore connectivity, and enhanced C–S–H gel formation, which aligns with the findings of Rao et al. (2023) and Mostofinejad et al. (2025). The superior performance of the Ternary-1 mix confirms that balanced proportions of SCMs are critical for maximizing these synergistic effects. This synergy arises from complementary physicochemical mechanisms:

- Silica fume acts as a highly reactive pozzolana, accelerating early hydration and refining the interfacial transition zone (ITZ).
- Fly ash contributes to long-term strength through secondary pozzolanic reactions and improves workability due to its spherical morphology.
- GGBS provides latent hydraulic reactivity, enhancing both strength and durability over time.

4.2 Strength Development Mechanism

The delayed strength gain in FA-based mixes is consistent with its slower reactivity, while GGBS contributes to a more uniform strength progression. The ternary systems effectively bridge this gap by ensuring both early and long-term performance, which is essential for structural applications requiring rapid strength gain without compromising durability. The variation in strength development across mixes highlights the distinct roles of SCMs at different hydration stages:

- **Early-age strength:** Predominantly governed by silica fume due to its high surface area and rapid reaction kinetics (Ullah et al., 2025).
- **Later-age strength:** Enhanced significantly by FA and GGBS through continued hydration and formation of additional calcium silicate hydrate (C–S–H) (Papayianni & Anastasiou, 2010).

4.3 Durability Enhancement and Transport Properties

Durability performance, particularly resistance to chloride ion penetration and sulfate attack, shows marked improvement with SCM incorporation. These findings are consistent with Tahwia et al. (2022), who reported improved resistance to aggressive environments in SCM-based concrete. The lower water absorption values further confirm the development of a low-permeability microstructure, which is critical for long-term durability in marine and chemically aggressive conditions. The reduced Rapid Chloride Penetration Test (RCPT) values in ternary mixes indicate a significant decrease in permeability, which can be attributed to:

- Pore refinement due to secondary hydration
- Reduction in calcium hydroxide content
- Formation of a denser and more homogeneous matrix

4.4 Workability–Strength Trade-Off

A notable observation is the trade-off between workability and strength, particularly in silica fume-rich mixes. While SF enhances strength and durability, it reduces workability due to its high fineness and water demand. However, this limitation is effectively mitigated in ternary systems through the inclusion of fly ash, which improves flowability. This balance is crucial for practical applications, as it allows for the design of mixes that are both workable and high-performing, reducing the need for excessive chemical admixtures.

4.5 Sustainability Implications

From a sustainability perspective, the partial replacement of cement with industrial by-products significantly reduces the environmental footprint of concrete production. The findings support earlier studies (Demirboğa & Gül, 2006; Qureshi et al., 2020) that advocate the use of SCMs for eco-efficient construction. The optimal ternary mix identified in this study achieves up to 40–45% cement replacement without compromising performance, making it a viable solution for sustainable infrastructure development. The use of FA, GGBS, and SF:

- Lowers CO_2 emissions associated with cement manufacturing
- Promotes waste utilization and circular economy principles
- Enhances service life, thereby reducing lifecycle costs

5. Conclusion and Future Scope

5.1 Conclusion

This study investigated the development of sustainable high-strength concrete (HSC) through the incorporation of industrial by-products - fly ash (FA), ground granulated blast furnace slag (GGBS), and silica fume (SF). Based on the experimental analysis of fresh, mechanical, durability, and microstructural properties, the following key conclusions are drawn:

1. The incorporation of SCMs significantly improves compressive, tensile, and flexural strength. Among all mixes, ternary blended systems exhibited superior performance, with the optimal mix (15% FA + 15% GGBS + 5% SF) achieving the highest strength at both early and later ages. The presence of silica fume accelerated early strength gain, while fly ash and GGBS contributed to long-term strength development.

2. The combined use of FA, GGBS, and SF resulted in a pronounced synergistic interaction, leading to improved particle packing, enhanced hydration kinetics, and increased formation of C–S–H gel. This synergy outperformed both control and binary mixes, validating the effectiveness of multi-component binder systems (Rao et al., 2023; Mostofinejad et al., 2025).

3. SCM-based mixes demonstrated significantly lower permeability, reduced chloride ion penetration, and enhanced sulfate resistance. The reduction in water absorption and RCPT values confirms the development of a dense and refined pore structure, consistent with previous findings (Tahwia et al., 2022).

4. While silica fume reduced workability due to its fineness, the inclusion of fly ash compensated for this effect, resulting in balanced rheological properties in ternary systems without excessive reliance on chemical admixtures.

5. Partial replacement of cement (up to 40–45%) with industrial byproducts significantly reduces the environmental impact of concrete production. This approach supports sustainable construction by lowering CO_2 emissions and promoting the utilization of industrial waste materials (Demirboğa & Gül, 2006; Qureshi et al., 2020).

5.2 Future Scope

Despite the promising findings, several areas require further investigation to enhance the applicability and robustness of sustainable HSC:

1. Future studies should evaluate the in-situ performance of ternary blended concrete under real environmental conditions, including exposure to marine, freeze–thaw, and aggressive chemical environments.

2. A comprehensive environmental and economic assessment should be conducted to quantify the reduction in carbon footprint and lifecycle cost benefits associated with SCM-based concrete.

3. Application of machine learning and optimization algorithms can be explored to determine optimal mix proportions considering multiple performance criteria simultaneously.

4. Integration of recycled coarse and fine aggregates with SCM-based binders can further improve sustainability and promote circular construction practices.

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