

Experimental Investigation on Strength Performance of Sustainable Ternary Blended Concrete Incorporating Ground Granulated Blast Furnace Slag, Rice Husk Ash and Silica Fume

Mahesh Mathangi¹, Anurag Angoth² and P S Harsha

¹M.Tech Student, Department of Civil Engg, Nalla Malla Reddy Engineering College, Hyderabad, Telangana, India

^{2&3}Assistant Professor, Department of Civil Engg, Nalla Malla Reddy Engineering College, Hyderabad, Telangana, India

Corresponding author: anu.kanna104@gmail.com

ABSTRACT

The increasing demand for sustainable construction materials has encouraged the use of supplementary cementitious materials (SCMs) as partial replacements for ordinary Portland cement (OPC). This study investigates the mechanical and microstructural performance of sustainable ternary blended concrete incorporating Ground Granulated Blast Furnace Slag (GGBS), Rice Husk Ash (RHA), and Silica Fume (SF) with a superplasticizer. Six concrete mixtures were developed, including one control mix with 100% OPC and five ternary blended mixes with different replacement levels. Compressive strength was evaluated at 7, 14, 28, 56, and 90 days, while Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) analyses were conducted to assess microstructural characteristics and hydration products. The results showed that all ternary blended mixes achieved higher compressive strength than the control concrete. The optimum mix containing 70% OPC, 10% GGBS, 10% RHA, and 10% SF achieved strengths of 27.0, 32.5, 40.5, 44.0, and 46.0 MPa at 7, 14, 28, 56, and 90 days, respectively. The improvements are attributed to enhanced pozzolanic activity, filler effects, improved particle packing, and additional C–S–H gel formation. SEM revealed a denser and more homogeneous microstructure, while XRD indicated increased hydration products and reduced calcium hydroxide. Overall, 30% cement replacement provided an effective balance between strength and sustainability.

1. INTRODUCTION

Concrete remains one of the most extensively used construction materials worldwide, prized for its superior mechanical strength, durability, versatility, and cost-efficiency. However, producing Ordinary Portland Cement (OPC) demands significant energy and accounts for approximately 7–8% of global carbon dioxide emissions [1]. Moreover, the surge in construction activities has escalated the depletion of natural resources and increased the generation of industrial and agricultural waste.

Integrating Supplementary Cementitious Materials (SCMs) as partial OPC replacements offers a promising path toward sustainable concrete development. Among these, Ground Granulated Blast Furnace Slag (GGBS), Rice Husk Ash (RHA), and Silica Fume (SF) stand out due to their hydraulic, pozzolanic, and micro-filling properties [2–4]. GGBS, a by-product from the iron and steel industry, enhances long-term strength and durability. RHA, derived from agricultural waste and rich in amorphous silica, possesses high pozzolanic reactivity, while SF, an ultrafine industrial by-product, improves particle packing and densifies the concrete matrix [5–7]. The synergistic use of GGBS, RHA, and SF in a ternary blend can significantly enhance particle packing, stimulate secondary hydration reactions, refine the pore structure, and boost calcium silicate hydrate (C–S–H) gel formation [8–10]. Previous research highlights that SCMs, whether used individually or in combination, improve compressive strength, reduce permeability, enhance durability, and create a denser microstructure [11–15].

1.1 Literature Review

Extensive investigations have examined the roles of GGBS, RHA, and SF in concrete. GGBS has been shown to improve long-term strength, boost durability, and increase resistance to sulfate and chloride attacks while reducing cement

demand [2,3]. Studies on RHA demonstrate its ability to increase compressive strength and lower porosity, attributed to its highly reactive amorphous silica [5,6]. Likewise, SF strengthens concrete by filling micro-pores and engaging in pozzolanic reactions, resulting in a denser matrix and an enhanced interfacial transition zone [7]. Research into binary and ternary SCM blends reveals that combining these materials produces synergistic effects that enhance both mechanical and durability properties [8–10]. Recent studies confirm that ternary blended concretes achieve superior strength, reduced permeability, and improved microstructural features through combined pozzolanic and filler effects [11–15].

1.2 Research Gap

Despite extensive research on individual SCMs and binary blends, the combined use of GGBS, RHA, and SF as a ternary replacement system remains underexplored. The optimal proportions to strike an ideal balance between mechanical performance and sustainability are yet to be fully determined. Additionally, few studies have simultaneously evaluated mechanical properties and microstructural characteristics using Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD). The interplay between these SCMs and superplasticizer admixtures also warrants further study.

1.3 Objectives and Significance

This study aims to thoroughly investigate the mechanical and microstructural performance of sustainable ternary blended concrete comprising GGBS, RHA, and SF. The specific objectives are to: (1) assess the impact of GGBS, RHA, and SF on compressive strength; (2) determine the optimum cement replacement level; (3) compare ternary blended concrete against conventional OPC concrete; (4) examine microstructural features through SEM analysis; (5) identify hydration products and mineralogical transformations via XRD; and (6) evaluate the potential of industrial and agricultural wastes for sustainable concrete production. Incorporating GGBS, RHA, and SF can significantly reduce OPC consumption, lower carbon emissions, and mitigate waste disposal challenges while enhancing concrete performance, fostering resource conservation and supporting sustainable construction initiatives.

2. MATERIALS AND METHODOLOGY

2.1 Materials

Ordinary Portland Cement (OPC) of 53 grade, compliant with IS 12269:2013, served as the primary binder, fresh, free of lumps, and stored dry. Fine aggregate comprised river sand meeting Zone-II criteria as per IS 383:2016, while crushed angular coarse aggregate, with a maximum size of 20 mm conforming to IS 383:2016, was used. Ground Granulated Blast Furnace Slag (GGBS), a by-product from the iron and steel industry, was incorporated for its latent hydraulic capabilities. Rice Husk Ash (RHA), produced via controlled combustion of rice husks and rich in amorphous silica, was selected for its pozzolanic reactivity. Ultrafine Silica Fume (SF), a by-product of silicon metal production, enhanced particle packing and matrix densification. A high-range water-reducing superplasticizer conforming to IS 9103:1999 maintained workability without increasing water content, and potable water meeting IS 456:2000 was used for mixing and curing.



Figure 1: Collection of concrete materials

2.2 Chemical Composition of Cementitious Materials

Table 1 presents the typical oxide compositions of OPC, GGBS, RHA, and SF, reflecting standard ranges influenced by source and processing methods.

Oxide	OPC (%)	GGBS (%)	RHA (%)	SF (%)
SiO ₂	20–25	30–40	85–95	90–98
CaO	60–65	35–45	0.5–3	0.1–1
Al ₂ O ₃	4–8	8–18	0.5–3	0.2–1.5
Fe ₂ O ₃	2–6	0.5–2	0.5–3	0.1–1
MgO	1–4	5–15	0.2–1	0.1–1
SO ₃	1–3	0–2	Trace	Trace
K ₂ O + Na ₂ O	0.5–2	0.5–1	1–5	<0.5

Table 1: Chemical composition of cementitious materials

2.3 Mix Design

Concrete mixtures were designed for M30 grade following IS 10262:2019. The control mix utilized 100% OPC, while partial replacements with GGBS, RHA, and SF were made at varying proportions (Table 2). The control mix maintained a Cement:Fine Aggregate:Coarse Aggregate ratio of 1:0.75:1.50. The water-to-binder ratio was kept consistent across all mixes, with a fixed superplasticizer dosage to ensure desired workability.

Mix ID	Cement (%)	GGBS (%)	RHA (%)	SF (%)
CM	100	0	0	0
TB-1	85	5	5	5
TB-2	70	10	10	10
TB-3	55	15	15	15
TB-4	50	20	15	15
TB-5	45	25	15	15

Table 2: Cement replacement levels of concrete mixtures

2.4 Specimen Preparation and Curing

OPC, GGBS, RHA, SF, and aggregates were accurately weighed per the mix design and dry-blended to achieve homogeneity. Water mixed with the predetermined superplasticizer amount was then gradually incorporated with continued mixing until uniform concrete was obtained. Fresh concrete was cast in 150 × 150 × 150 mm cube moulds in three layers, each compacted using a table vibrator to minimize entrapped air. Specimens were covered and left undisturbed for 24 hours prior to demoulding, then submerged in a water-curing tank under controlled laboratory conditions and retrieved at curing intervals of 7, 14, 28, 56, and 90 days for testing.



Figure 2: Concrete specimen preparation, casting, demoulding, and curing

2.5 Compressive Strength Test

Compressive strength testing followed IS 516:2018. At each age, specimens were surface dried and placed centrally in a Compression Testing Machine (CTM). Load was applied gradually until failure, and the maximum load recorded was used to calculate compressive strength ($f_c = P/A$) based on specimen dimensions, where f_c is compressive strength in

MPa, P is the maximum load at failure in N, and A is the loaded area in mm^2 ($150 \times 150 = 22,500 \text{ mm}^2$). The average strength of three specimens was reported for each mix and curing age.



Figure 3: Performing the compressive strength test

2.6 SEM and XRD Analysis

SEM analysis was performed on control and optimum ternary blended concrete specimens after 90 days of curing. Small fragments were extracted from the core, dried, coated with a conductive layer, and examined at various magnifications, focusing on C–S–H gel formation, hydration products, pore structure, microcracks, particle packing, and the interfacial transition zone (ITZ). XRD was conducted on powdered samples over a diffraction angle range of approximately 10° – 80° to identify crystalline and hydration phases, including calcium hydroxide (CH), C–S–H, quartz, ettringite, calcite, and unhydrated cement compounds. A reduction in CH peak intensity alongside increased hydration-product peaks indicated enhanced pozzolanic activity. XRD findings were correlated with SEM and compressive strength data to elucidate hydration mechanisms and strength development.

2.7 Physical Properties and Fresh Concrete Tests

Property	Cement	GGBS	RHA	Silica Fume
Specific gravity	3.15	2.90	2.10	2.20
Fineness (%)	4–6	5–8	8–12	15–20
Colour	Grey	Off-white	Grey/Black	Light Grey
Main reactive compound	CaO	CaO + SiO ₂	SiO ₂	SiO ₂

Table 3: Physical properties of cementitious materials

The elevated silica content in RHA and SF, coupled with the latent hydraulic properties of GGBS, facilitates secondary hydration reactions that contribute to strength enhancement. The workability of fresh concrete was assessed using slump cone and compaction factor tests as per IS 1199:2018: the slump test involved filling the cone in three layers and measuring vertical settlement after lifting, while the compaction factor test compared the weight of partially compacted concrete to that of fully compacted concrete, evaluating the impact of GGBS, RHA, and SF on the fresh properties of the mixes.

3. RESULTS AND DISCUSSION

3.1 Compressive Strength

Compressive strength tests conducted at 7, 14, 28, 56, and 90 days revealed that the ternary blended concrete mixtures incorporating GGBS, RHA, and SF consistently outperformed the control mix. The control concrete achieved compressive strengths of 22.50, 27.00, 34.50, 38.00, and 41.00 MPa at the respective ages, exhibiting typical strength gains due to progressive cement hydration. The TB-1 mix (85% OPC, 5% each of GGBS, RHA, and SF) reached a 90-

day strength of 44.00 MPa — about 7.3% higher than the control. The optimized TB-2 mix (70% OPC, 10% GGBS, 10% RHA, 10% SF) demonstrated superior performance with strengths of 27.00, 32.50, 40.50, 44.00, and 46.00 MPa from 7 through 90 days, exceeding the control by approximately 17.4% at 28 days and 12.2% at 90 days. This enhancement stems from the synergistic hydraulic, pozzolanic, and filler effects of the supplementary materials: GGBS supports long-term hydration, while the reactive silica in RHA and SF fosters secondary C–S–H gel formation and pore refinement.

Mix ID	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)	56 Days (MPa)	90 Days (MPa)
Control Mix	22.50	27.00	34.50	38.00	41.00
TB-1	25.00	29.50	37.50	41.00	44.00
TB-2	27.00	32.50	40.50	44.00	46.00
TB-3	25.00	30.50	39.00	42.50	44.50
TB-4	24.00	29.00	38.00	41.00	43.00
TB-5	23.00	28.00	37.00	40.00	42.00

Table 4: Comparison of compressive strength at different curing ages

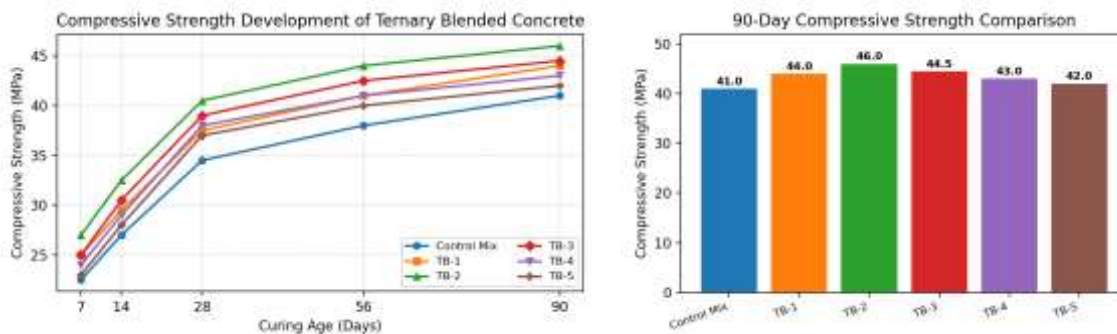


Figure 4: Compressive strength development across curing ages and 90-day comparison across mixes

3.2 Effect of Replacement Level and Curing Age

The data indicate that a total cement replacement of 30% (as in TB-2) achieves the best strength outcomes, optimizing particle packing, promoting secondary hydration, and densifying the cementitious matrix. Replacement levels exceeding 30% led to a gradual decline in strength, though all mixes remained stronger than the control; this reduction is mainly attributed to the dilution effect, where excessive substitution lowers the OPC content available for primary hydration, limiting hydration product formation. All mixtures exhibited continuous strength gain from 7 to 90 days: the control mix achieved 54.9% of its 90-day strength at 7 days, whereas TB-2 reached approximately 58.7%, reflecting superior early-age strength development. The enhanced late-age strength in ternary blends results from ongoing pozzolanic and hydraulic reactions, as reactive silica from RHA and SF reacts with calcium hydroxide released during hydration to produce additional C–S–H gel, while GGBS further contributes to hydration and long-term strength.

3.3 SEM Analysis

SEM images of control specimens revealed relatively larger capillary pores, discontinuous hydration products, and visible calcium hydroxide crystals, indicative of higher porosity. Conversely, the optimized TB-2 mix displayed a denser, more homogeneous microstructure characterized by abundant C–S–H gel, reduced pore volume, enhanced particle packing, fewer microcracks, and a stronger interfacial transition zone (ITZ). Ultrafine SF particles facilitated micro-filling, while GGBS and RHA induced secondary pozzolanic reactions, further enriching C–S–H formation — explaining the improved compressive strength observed in the ternary blend.

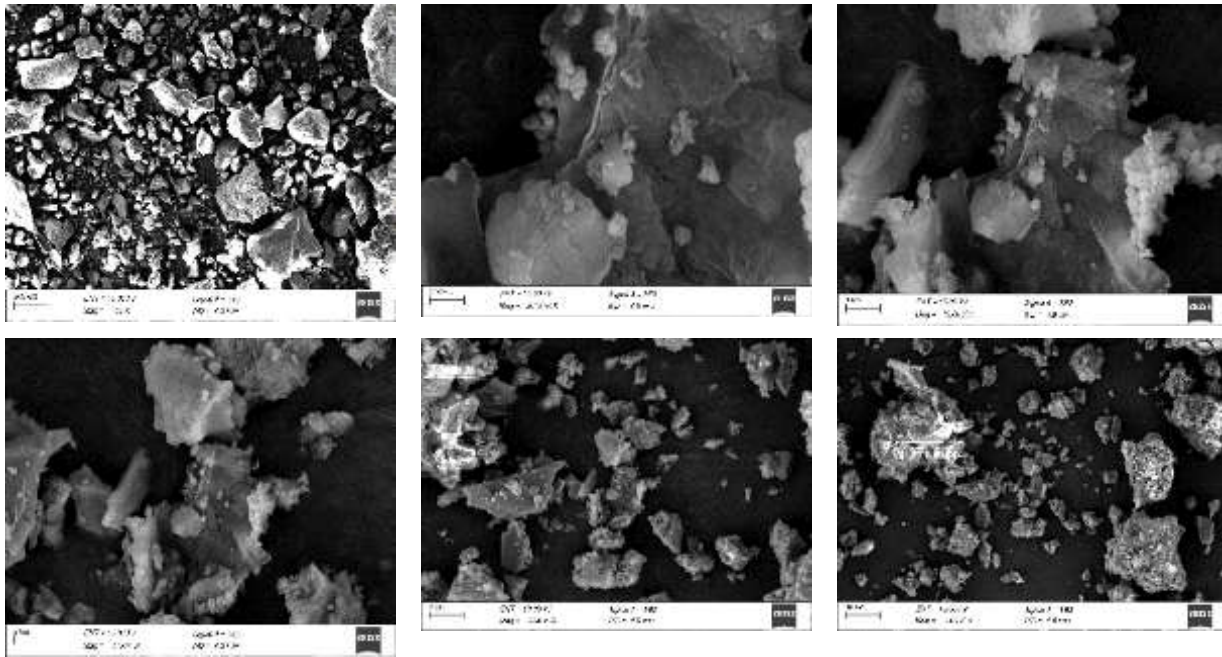


Figure 5: SEM micrographs of control and optimized (TB-2) concrete specimens

3.4 XRD Analysis

XRD results identified key mineralogical and hydration phases in both control and TB-2 mixtures. The control exhibited typical peaks corresponding to calcium hydroxide, quartz, and partially hydrated cement compounds. In contrast, TB-2 showed diminished calcium hydroxide peak intensity and elevated hydration-product peaks, signaling enhanced pozzolanic activity consuming calcium hydroxide. The resultant increase in stable hydration products like C–S–H contributed to a denser matrix and strength gains.

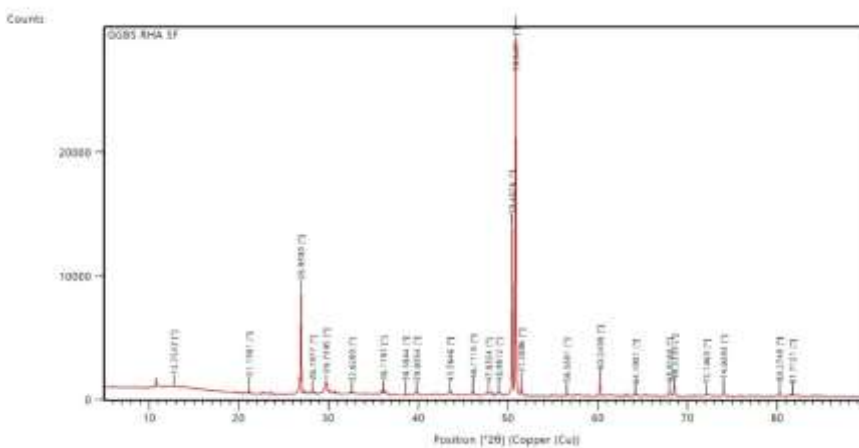


Figure 6: XRD graph analysis of the optimized (TB-2) mix

3.5 Correlation of Mechanical and Microstructural Properties

The mechanical strength results align closely with SEM and XRD observations. TB-2 achieved the highest compressive strength (46.0 MPa at 90 days) and exhibited a refined microstructure with amplified C–S–H gel presence, reduced calcium hydroxide, and improved particle packing. The synergistic effects of GGBS, RHA, and SF drive enhanced hydration, pore refinement, and matrix densification. The consistent correlation among compressive strength, SEM micrographs, and XRD patterns confirms that the superior performance of ternary blended concrete primarily arises from intensified secondary hydration reactions, pozzolanic activity, and microstructural enhancement.

4. CONCLUSION

1. The integration of GGBS, RHA, and SF significantly enhanced the compressive strength of ternary blended concrete compared to the control across all curing periods.
2. The optimized mixture — comprising 70% OPC, 10% GGBS, 10% RHA, and 10% SF (TB-2) — achieved compressive strengths of 27.0, 32.5, 40.5, 44.0, and 46.0 MPa at 7, 14, 28, 56, and 90 days, respectively.
3. TB-2 exhibited approximately 17.4% higher strength at 28 days and 12.2% higher strength at 90 days compared to the control, demonstrating that 30% total cement replacement strikes an effective balance between mechanical performance and cement reduction.
4. Replacement levels exceeding 30% led to a gradual decline in strength, primarily due to the dilution effect and diminished availability of OPC for primary hydration.
5. The superior performance of TB-2 is attributed to the synergistic interplay of GGBS, RHA, and SF: GGBS supports long-term hydration, RHA drives secondary pozzolanic reactions, and SF refines particle packing and pore structure.
6. SEM analysis revealed a denser, more homogeneous microstructure characterized by increased C–S–H gel formation, reduced pore volume, fewer microcracks, and stronger aggregate–paste bonding.
7. XRD results confirmed a reduction in calcium hydroxide (CH) and an increase in hydration products, validating enhanced pozzolanic activity and corroborating the SEM and strength findings.
8. Overall, the findings demonstrate that a ternary blend of 10% GGBS + 10% RHA + 10% SF can produce sustainable concrete with improved mechanical and microstructural attributes, while significantly lowering OPC consumption and environmental impact, showing promising potential for sustainable structural applications.

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