International Journal of Scientific Research & Engineering Trends
Volume 12, Issue 6, Nov-Dec-2026, ISSN (Online): 2395-566X

Experimental and Cost Analysis of Sustainable Concrete Using Glass Powder and Fly Ash

Vaibhav Singh[1], Tasar Aftab[2], Sachin Gautam[3], Ashish Juneja[4], Kavita Verma[5]
[1,2,3] students, [4,5] Associate Professor, Department Of Civil Engineering, B.Tech
Dr.Akhilesh Das Gupta Institute Of Professional Studies, New Delhi-110053

Abstract – Concrete is the second most widely consumed material globally after water, serving as the structural backbone of modern infrastructure. However, the manufacture of Ordinary Portland Cement (OPC) accounts for substantial greenhouse gas emissions, releasing approximately 0.8 to 1.0 ton of carbon dioxide (CO2) per ton of cement produced. Simultaneously, the accumulation of thermal power plant fly ash and municipal waste glass creates severe landfill and environmental disposal challenges. To address both environmental sustainability and construction affordability, this study investigates the dual utilization of Class F Fly Ash (FA) and Waste Glass Powder (GP) as partial cement replacements in M25 grade concrete. Following physical characterization tests on constituent materials in accordance with Bureau of Indian Standards (IS) guidelines, four concrete batches were formulated using a nominal 1:1:2 mix design: a conventional control mix (0% replacement) and three equal-proportion ternary blended mixes designated as FAGP-10 (5% FA + 5% GP), FAGP-20 (10% FA + 10% GP), and FAGP-30 (15% FA + 15% GP). Twenty-four standard concrete cubes (150 mm × 150 mm × 150 mm) were cast and evaluated for 7-day and 28-day compressive strengths, alongside an integrated Cost-Benefit Analysis (CBA) and embodied carbon footprint assessment per cubic meter. Experimental results indicate that FAGP-10 achieved a 28-day compressive strength of 25.17 N/mm2, closely matching the control mix (25.32 N/mm2) and satisfying M25 structural requirements, while reducing material cost by 2.80% (to ₹5,836.44/m3) and embodied CO2 emissions by 9.06% (to 465.58 kg CO2/m3). Higher replacement levels (FAGP-20 and FAGP-30) yielded greater cost savings up to 8.33% and carbon reductions up to 27.18%, with modest reductions in 28-day compressive strength (24.00 and 23.25 N/mm2, respectively). The findings confirm that a 10% ternary blend (FAGP-10) provides the most balanced, cost-effective, and eco-friendly alternative to conventional OPC concrete.

Keywords – Sustainable Concrete, Class F Fly Ash, Waste Glass Powder, Ternary Blended Concrete, Compressive Strength, Cost-Benefit Analysis, Embodied Carbon Footprint.

I. INTRODUCTION

Concrete is the second most widely consumed material globally after water, serving as the fundamental structural backbone for modern residential, transportation, and industrial infrastructure [1]. Its versatility, durability, and high compressive strength make it indispensable to rapid urbanization and economic development. However, the conventional production of concrete relies heavily on Ordinary Portland Cement (OPC) as its primary binding agent. The manufacturing of OPC is both energy-intensive and environmentally taxing, accounting for substantial global greenhouse gas emissions. Specifically, the calcination of limestone and the combustion of fossil fuels during clinker production release approximately 0.8 to 1.0 ton of carbon dioxide (CO2) into the atmosphere for every ton of cement manufactured [2]. As global infrastructure demand continues to escalate, particularly in developing economies like India, mitigating the embodied carbon footprint of concrete has become an urgent priority within the civil engineering and construction sectors.

In response to these environmental challenges, international building standards and construction practices are increasingly transitioning toward sustainable green concrete technologies. One of the most effective strategies for decarbonizing concrete production is the partial substitution of OPC with Supplementary Cementitious Materials (SCMs). SCMs are typically industrial by-products or processed post-consumer wastes rich in amorphous silica (SiO2) and alumina (Al2O3) [3]. When incorporated into a cementitious system alongside water, these materials undergo secondary pozzolanic reactions by consuming the free calcium hydroxide (Ca(OH)2) liberated during primary cement hydration. This chemical interaction generates additional Calcium-Silicate-Hydrate (C-S-H) gel—the primary strength-giving phase in hardened concrete—thereby refining the pore structure, densifying the interfacial transition zone, and enhancing long-term mechanical and durability properties [4].

Simultaneously, rapid industrialization and urban consumption have created severe solid waste management bottlenecks globally. Thermal power generation produces millions of tons of coal fly ash annually, much of which

© 2026 IJSRET

accumulates in ash ponds, posing risks of soil contamination, groundwater leaching, and airborne particulate pollution [5]. Similarly, municipal waste streams generate vast quantities of non-biodegradable post-consumer waste glass. Because mixed-color and contaminated glass is often uneconomical to recycle back into new glass containers, large volumes are discarded directly into landfills, exhausting scarce urban land resources [6]. Diverting both Class F Fly Ash (FA) and finely pulverized Waste Glass Powder (GP) from landfills into concrete production offers a synergistic dual-waste valorization pathway aligned with circular economy principles.

Extensive research has explored the individual utilization of fly ash and waste glass powder as partial cement replacements [7]–[10]. Class F fly ash, characterized by low calcium content and high aluminosilicate composition, is well established for improving the workability of fresh concrete, reducing heat of hydration, and imparting superior late-age strength and chemical resistance [5]. However, concrete mixes containing high volumes of fly ash frequently exhibit delayed early-age strength development due to the slower rate of pozzolanic reaction at ambient temperatures. Conversely, finely ground waste glass powder (milled below 90 microns) possesses a high amorphous silica content that exhibits accelerated pozzolanic reactivity and a physical micro-filler effect, contributing to early pore refinement and strength gain [8], [11]. Combining fly ash and waste glass powder in a ternary blended binder system (OPC–FA–GP) leverages their complementary physical and chemical properties: the reactive silica from the glass powder helps offset the slow early hydration of fly ash, while the fly ash mitigates potential Alkali-Silica Reaction (ASR) expansion associated with glass particles and enhances long-term matrix durability [9], [12].

Beyond technical and environmental performance, economic viability remains a decisive factor governing the practical adoption of sustainable concrete in the construction industry. Portland cement is the single costliest constituent in standard concrete mix designs. Substituting a portion of expensive OPC with locally available industrial by-products and processed waste materials has the potential to lower the overall material production cost per cubic meter of concrete, making sustainable construction financially attractive for commercial and public infrastructure projects. Despite growing global interest in ternary blended concretes [12]–[14], standardized empirical data evaluating equal-proportion blends of Class F fly ash and waste glass powder in structural-grade concrete—integrated with regional Indian cost-benefit and embodied carbon assessments—remains limited. To bridge this gap, the present study investigates the mechanical, economic, and environmental performance of sustainable M25 grade concrete incorporating equal binary-ternary replacements of Class F fly ash and waste glass powder (5% + 5%, 10% + 10%, and 15% + 15%) against conventional OPC concrete.

II. LITERATURE REVIEW

Numerous experimental investigations have evaluated the influence of waste glass powder and fly ash on the fresh, mechanical, and durability properties of cementitious composites. Shao et al. [3] and Shi et al. [4] demonstrated that finely ground waste glass passing a 90-micron sieve exhibits pronounced pozzolanic behavior due to its high amorphous silica content, contributing to secondary C-S-H gel formation and late-age strength enhancement. Schwarz et al. [9] compared fine glass powder with fly ash at 10% cement replacement and reported comparable later-age compressive strengths within a 5% margin, alongside improved pore refinement and reduced chloride ion permeability. Crucially, Schwarz et al. [9] observed that while glass powder alone partially suppresses ASR expansion, ternary blends combining glass powder and fly ash limit ASR expansion as effectively as 20% fly ash alone.

Aliabdo et al. [8] reported that waste glass powder replacements up to 15% enhance concrete workability and mechanical performance, whereas higher dosages beyond 15% reduce 28-day compressive strength unless compensated by lowering the water-cement ratio. Similarly, Nath and Sarker [5] established that incorporating Class F fly ash significantly reduces drying shrinkage, water sorptivity, and chloride permeability over extended curing periods, although early-age strength gain is moderated. In ternary systems, Demiss et al. [12] showed that combining fly ash and waste glass powder produces dense microstructures with superior compressive strength under standard water curing. More recently, Yusuf and AlSodani [13] and Dural et al. [14] evaluated OPC–FA–GP ternary concrete mixtures across total replacement levels ranging from 10% to 30%, concluding that balanced ternary proportions maintain structural compressive strength comparable to control concrete while substantially lowering embodied carbon emissions. Vishwakarma [15] further confirmed that partial cement substitution with 10% fly ash and glass powder yields mechanical strengths suitable for structural applications without compromising engineering integrity.

III. MATERIALS AND METHODOLOGY

1. Materials Characterization

All constituent materials were procured from standard local sources and characterized in the laboratory in accordance with relevant Bureau of Indian Standards (IS) specifications:

- **Ordinary Portland Cement (OPC):** Commercially available standard-grade OPC was used as the primary

© 2026 IJSRET

binder. Laboratory characterization yielded a fineness of 5% retained on an IS 90-micron sieve (within the 10% permissible limit), a normal consistency of 32% using the Vicat apparatus, an initial setting time of 40 minutes, a final setting time of 420 minutes, and Le Chatelier soundness expansions between 1.0 mm and 1.5 mm, confirming compliance with IS standards.

- **Class F Fly Ash (FA):** Low-calcium Class F fly ash obtained as an industrial by-product from a thermal power plant was utilized as an SCM. Rich in reactive silica and alumina, it improves fresh concrete rheology and promotes long-term pozzolanic hydration.
- **Waste Glass Powder (GP):** Post-consumer waste glass was collected, cleaned of impurities, and pulverized into a fine powder passing the 90-micron sieve to ensure high specific surface area and consistent pozzolanic reactivity.
- **Fine and Coarse Aggregates:** Clean river sand conforming to standard grading zones and free from silt or organic impurities was used as fine aggregate. Locally crushed angular stone aggregates were used as coarse aggregate, exhibiting an Aggregate Impact Value (AIV) of 23.0% and an Aggregate Crushing Value (ACV) of 17.75%, confirming high toughness and resistance to crushing.
- **Water:** Clean, potable laboratory tap water free from deleterious acids, alkalis, oils, or organic matter was used for both concrete mixing and specimen curing.

2. Mix Design and Specimen Preparation

The experimental program was designed for standard M25 grade concrete using a nominal volumetric mix proportion of 1:1:2 (cement : fine aggregate : coarse aggregate) with a water requirement of 180 liters/m3. Four distinct concrete batches were formulated: a baseline Control Mix (0% replacement) and three ternary blended mixes replacing OPC with equal proportions of Class F fly ash and waste glass powder at total replacement levels of 10%, 20%, and 30%, as detailed in Table I.

TABLE I: MIX PROPORTION DETAILS FOR M25 GRADE CONCRETE

Mix ID	Total Repl. (%)	OPC (%)	Fly Ash (%)	Glass Powder (%)
Control	0	100	0	0
FAGP-10	10	90	5	5
FAGP-20	20	80	10	10
FAGP-30	30	70	15	15

For each mix proportion, six standard concrete cubes of dimensions 150 mm × 150 mm × 150 mm were cast (24 specimens in total). Dry constituents were thoroughly mixed to achieve a uniform color before adding potable water. Fresh concrete was placed into oiled steel molds in three layers and compacted properly to eliminate entrapped air voids. The cast specimens were demolded after 24 hours and submerged in a clean water curing tank at ambient laboratory temperature until the testing ages of 7 and 28 days.

3. Testing and Analytical Framework

At 7 and 28 days of water curing, three cubes from each batch were surface-dried and tested under axial compression using a calibrated Compression Testing Machine (CTM) in accordance with IS 516. The ultimate failure load was divided by the cross-sectional area (22,500 mm2) to determine the compressive strength in N/mm2.

To evaluate economic viability per cubic meter of concrete, a Cost-Benefit Analysis (CBA) was formulated based on prevailing Indian industrial market rates: OPC at ₹380 per 50 kg bag (₹7.60/kg), Class F fly ash at ₹1,200/ton (₹1.20/kg), pulverized waste glass powder at ₹8,000/ton (₹8.00/kg), fine aggregate at ₹1,000/ton (₹1.00/kg), coarse aggregate at ₹1,000/ton (₹1.00/kg), and water at ₹0.12/liter. The total material cost per cubic meter (Cmix) was computed using (1):

$$Cmix = Mcem \cdot Rcem + MFA \cdot RFA + MGP \cdot RGP + Msand \cdot Rsand + Magg \cdot Ragg + Mwater \cdot Rwater \quad (1)$$

where Mi denotes the mass (kg or liters) and Ri denotes the unit rate (INR) of each constituent per cubic meter of concrete. Similarly, the environmental impact was quantified by calculating total embodied carbon emissions (Emix in kg CO2/m3) using standard Embodied Carbon Coefficients (ECC): 0.90 kg CO2/kg for OPC, 0.027 kg CO2/kg for fly ash, and 0.10 kg CO2/kg for waste glass powder [16], as expressed in (2):

$$Emix = \Sigma (Mi \times ECCi) \quad (2)$$

IV. RESULTS AND DISCUSSION

1. Compressive Strength Evaluation

The individual and mean compressive strength results for all four concrete mixes at 7 and 28 days of curing are presented in Table II and illustrated in Fig. 1, Fig. 2, and Fig. 3. At 7 days, the nominal Control mix achieved an average compressive strength of 15.10 N/mm2. The ternary mixes FAGP-10, FAGP-20, and FAGP-30 recorded 7-day average strengths of 14.66, 13.47, and 12.88 N/mm2, representing minor early-age reductions of 2.91%, 10.79%, and 14.70%, respectively, compared to the control batch. This gradual decline at 7 days is attributed to the dilution of Portland cement clinker and the relatively slower initial pozzolanic reaction of Class F fly ash during the first week of hydration.

© 2026 IJSRET

TABLE II: COMPRESSIVE STRENGTH TEST RESULTS AT 7 AND 28 DAYS

Mix ID	7-Day Cubes (N/mm2)	7-D Avg (N/mm2)	28-Day Cubes (N/mm2)	28-D Avg (N/mm2)
Control	14.66, 15.55, 15.11	15.10	25.33, 25.77, 24.88	25.32
FAGP-10	13.77, 14.66, 15.55	14.66	24.88, 25.77, 24.88	25.17
FAGP-20	13.33, 13.77, 13.33	13.47	24.00, 24.44, 23.55	24.00
FAGP-30	13.33, 12.88, 12.44	12.88	23.55, 23.11, 23.11	23.25

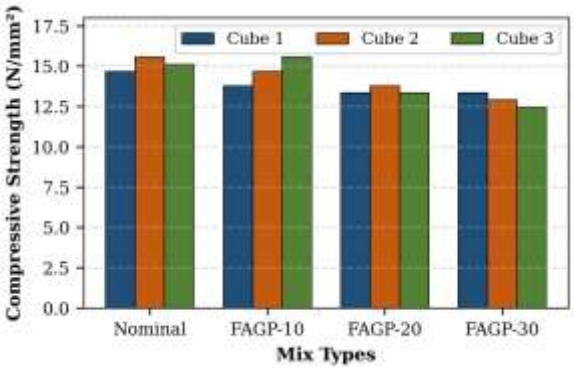


Fig. 1. Individual cube compressive strength test results at 7 days.

By 28 days, substantial strength recovery was observed across all ternary mixes due to ongoing pozzolanic reactions between the reactive silica/alumina in the glass powder and fly ash and the calcium hydroxide liberated from OPC hydration, as shown in Fig. 2 and Fig. 3. Notably, FAGP-10 (5% FA + 5% GP) attained an average 28-day compressive strength of 25.17 N/mm2, which is virtually identical (99.41% retention) to the Control mix (25.32 N/mm2) and exceeds the characteristic design strength of 25.0 N/mm2 required for M25 concrete. This parity confirms that the physical micro-filler effect and high amorphous silica reactivity of 5% glass powder effectively compensate for the 10% cement reduction. At higher replacement levels, FAGP-20 and FAGP-30 achieved 28-day mean strengths of 24.00 N/mm2 (5.21% reduction) and 23.25 N/mm2 (8.18% reduction), respectively, making them suitable for non-structural or moderate-load concrete applications where high early strength is not critical.

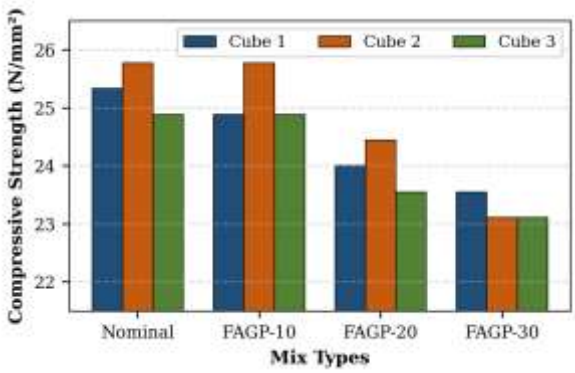


Fig. 2. Individual cube compressive strength test results at 28 days.

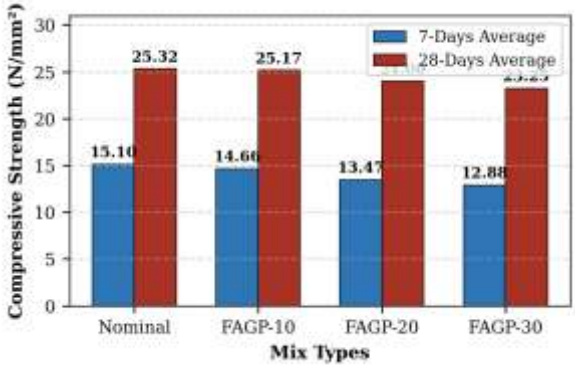


Fig. 3. Comparison of mean compressive strength at 7 and 28 days across mix types.

2. Economic Cost-Benefit Analysis

For 1 m3 of nominal M25 concrete (1:1:2), the baseline material quantities were 554.4 kg of OPC (11 bags), 616 kg (0.385 m3) of fine aggregate, 1,155 kg (0.77 m3) of coarse aggregate, and 180 liters of water, resulting in a total baseline production cost of ₹6,004.60/m3. As summarized in Table III and depicted in Fig. 4, partial substitution of OPC with fly ash and glass powder yielded progressive cost savings across all blended batches.

TABLE III: COST-BENEFIT ANALYSIS PER CUBIC METER OF CONCRETE

Mix ID	Replacement Level	Material Cost (INR/m3)	Cost Saving (%)
Control	0% (Baseline)	6,004.60	0.00%
FAGP-10	5% FA + 5% GP	5,836.44	2.80%
FAGP-20	10% FA + 10% GP	5,670.60	5.56%
FAGP-30	15% FA + 15% GP	5,504.40	8.33%

© 2026 IJSRET

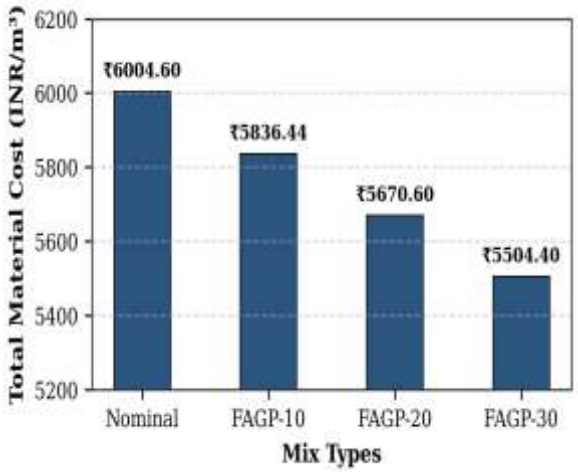


Fig. 4. Total material production cost per cubic meter for different concrete mixes.

Specifically, FAGP-10 reduced the concrete production cost to ₹5,836.44/m3 (a net saving of ₹168.16/m3 or 2.80%), FAGP-20 lowered the cost to ₹5,670.60/m3 (5.56% saving), and FAGP-30 achieved the lowest cost at ₹5,504.40/m3 (8.33% saving). Although pulverized glass powder carries a processing cost of ₹8.00/kg, the combined replacement with low-cost thermal fly ash (₹1.20/kg) still outperforms conventional OPC (₹7.60/kg) economically while eliminating landfill disposal expenses.

3. Embodied Carbon Footprint Assessment

The embodied CO2 emissions per cubic meter of concrete for each mix proportion are presented in Table IV and illustrated in Fig. 5. Because OPC clinker production is the dominant contributor to embodied carbon, replacing OPC with low-emission industrial by-products substantially lowered the environmental footprint of the concrete.

TABLE IV: EMBODIED CARBON FOOTPRINT ANALYSIS PER CUBIC METER

Mix ID	Binder Composition (kg/m3)	Embodied CO2 (kg/m3)	CO2 Red. (%)
Control	554.40 OPC	511.95	0.00%
FAGP-10	498.96 OPC + 27.72 FA + 27.72 GP	465.58	9.06%
FAGP-20	443.52 OPC + 55.44 FA + 55.44 GP	419.20	18.12%
FAGP-30	388.08 OPC + 83.16 FA + 83.16 GP	372.83	27.18%

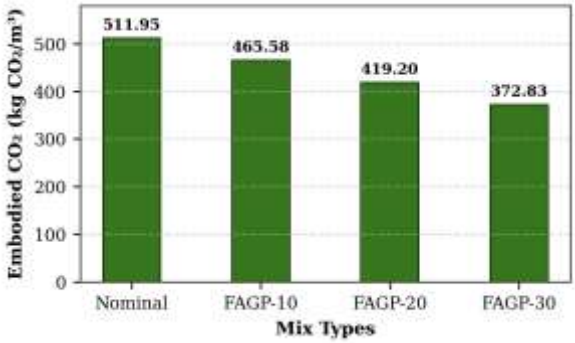


Fig. 5. Total embodied CO2 emissions per cubic meter across different concrete mixes.

Compared to the Control mix baseline of 511.95 kg CO2/m3, FAGP-10 reduced embodied carbon emissions to 465.58 kg CO2/m3 (9.06% reduction). FAGP-20 and FAGP-30 achieved even greater reductions of 18.12% (419.20 kg CO2/m3) and 27.18% (372.83 kg CO2/m3), respectively. When evaluated holistically across structural strength, material cost, and carbon intensity, FAGP-10 emerges as the optimal mix design for structural M25 applications.

V. CONCLUSION

This study evaluated the mechanical, economic, and environmental performance of sustainable M25 grade concrete incorporating equal binary-ternary proportions of Class F fly ash and waste glass powder. Based on the experimental and analytical findings, the following conclusions are drawn:

- FAGP-10 (5% fly ash + 5% waste glass powder) achieved a 28-day compressive strength of 25.17 N/mm2, maintaining 99.41% of the conventional control mix strength (25.32 N/mm2) and satisfying M25 structural design requirements due to synergistic pozzolanic reactivity and micro-pore refinement.
- Higher replacement levels in FAGP-20 (24.00 N/mm2) and FAGP-30 (23.25 N/mm2) exhibited modest reductions of 5.21% and 8.18% in 28-day compressive strength, making them viable for mass concrete, pavements, and non-structural elements.
- Material production costs decreased linearly with increasing cement replacement, yielding cost savings of 2.80% (₹5,836.44/m3), 5.56% (₹5,670.60/m3), and 8.33% (₹5,504.40/m3) for FAGP-10, FAGP-20, and FAGP-30, respectively.
- Embodied carbon emissions dropped significantly from 511.95 kg CO2/m3 in the control mix to 465.58, 419.20, and 372.83 kg CO2/m3 for FAGP-10, FAGP-20, and FAGP-30, representing net carbon reductions of 9.06%, 18.12%, and 27.18%.

© 2026 IJSRET

- Overall, FAGP-10 represents the most balanced ternary concrete formulation for practical civil engineering adoption. Future investigations should evaluate extended curing durations (56 and 90 days), tensile and flexural strength parameters, durability against chloride ingress and Alkali-Silica Reaction (ASR), and microstructural characterization via SEM and XRD.

ACKNOWLEDGMENT

The authors express their sincere gratitude to Prof. (Dr.) Niranjan Bhattacharyya, Director, and Dr. Kavita Verma, Head of the Department of Civil Engineering, Dr. Akhilesh Das Gupta Institute of Professional Studies, New Delhi, for providing the laboratory infrastructure and institutional support necessary to carry out this experimental investigation.

REFERENCES

1) V. M. Malhotra and P. K. Mehta, High-Performance, High-Volume Fly Ash Concrete: Materials, Mixture Proportioning, Properties, Construction Practice, and Case Histories. Ottawa, Canada: Supplementary Cementing Materials for Sustainable Development Inc., 2002.
2) D. J. Flower and J. G. Sanjayan, "Green house gas emissions due to concrete manufacture," The International Journal of Life Cycle Assessment, vol. 12, no. 5, pp. 282–288, 2007.
3) Y. Shao, T. Lefort, S. Moras, and D. Rodriguez, "Studies on concrete containing ground waste glass," Cement and Concrete Research, vol. 30, no. 1, pp. 91–100, 2000.
4) C. Shi, Y. Wu, C. Riefler, and H. Wang, "Characteristics and pozzolanic reactivity of glass powders," Cement and Concrete Research, vol. 35, no. 5, pp. 987–993, 2005.
5) P. Nath and P. Sarker, "Effect of fly ash on the durability properties of high strength concrete," Procedia Engineering, vol. 14, pp. 1149–1156, 2011.
6) A. Shayan and A. Xu, "Value-added utilisation of waste glass in concrete," Cement and Concrete Research, vol. 34, no. 1, pp. 81–89, 2004.
7) R. Siddique, "Performance characteristics of high-volume Class F fly ash concrete," Cement and Concrete Research, vol. 34, no. 3, pp. 487–493, 2004.
8) A. A. Aliabdo, A. E. M. Abd Elmoaty, and A. Y. Aboshama, "Utilization of waste glass powder in the production of cement and concrete," Construction and Building Materials, vol. 124, pp. 866–877, 2016.
9) N. Schwarz, H. Cam, and N. Neithalath, "Influence of a fine glass powder on the durability characteristics of concrete and its comparison to fly ash," Cement and Concrete Composites, vol. 30, no. 6, pp. 486–496, 2008.
10) G. S. Islam, M. H. Rahman, and N. Kazi, "Waste glass powder as partial replacement of cement for sustainable concrete practice," International Journal of Sustainable Built Environment, vol. 6, no. 1, pp. 37–44, 2017.
11) R. Jurczak and F. Szmatuła, "Evaluation of the possibility of replacing fly ash with glass powder in lower-strength concrete mixes," Applied Sciences, vol. 11, no. 1, p. 396, 2021.
12) B. A. Demiss, W. O. Oyawa, and S. M. Shitote, "Mechanical and microstructural properties of recycled reactive powder concrete containing waste glass powder and fly ash at standard curing," Cogent Engineering, vol. 5, no. 1, p. 1464877, 2018.
13) M. O. Yusuf and K. A. A. AlSodani, "Strength and microstructural characteristics of fly ash waste glass powder ternary blended concrete," Materials, 2025.
14) E. Dural, G. Adzhygulova, G. Karadeniz, and M. Karadeniz, "Sustainable concrete production using fly ash and recycled glass powder: Environmental and mechanical performance evaluation," Sustainability, vol. 18, no. 13, p. 6622, 2026.
15) A. Vishwakarma, "Optimum use of fly ash and glass powder as a partial replacement for cement in concrete," International Journal for Research in Applied Science & Engineering Technology (IJRASET), 2020.
16) D. Patel, R. P. Tiwari, R. Shrivastava, and R. K. Yadav, "Effective utilization of waste glass powder as the substitution of cement in making paste and mortar," Construction and Building Materials, vol. 199, pp. 406–415, 2019.

© 2026 IJSRET