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Performance Optimization Green Concrete Incorporating Fly Ash and Crushed Glass: Strength, Durability and Lifecycle Cost Analysis

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Abstract: This research investigates the combined use of fly ash and finely crushed waste glass in green concrete as partial replacements for cement and fine aggregate, respectively. Seven concrete mixes were designed with varying replacement levels (0-30% fly ash and 0-20% glass). The study evaluated mechanical properties (compressive, split tensile, and flexural strength), durability (water absorption), and economic viability (material and life-cycle cost) at 7, 14, and 28 days of curing. The results show that Mix M3 (20% fly ash and 10% glass) yielded the best mechanical performance with a 28-day compressive strength of 42.3 MPa, superior tensile and flexural strength, the lowest water absorption (4.2%), and optimal cost-efficiency. The synergistic interaction between fly ash and glass enhanced particle packing, reduced porosity, and supported sustainability by minimizing cement usage. The findings affirm that appropriately proportioned industrial by-products can produce durable, eco-efficient, and structurally sound green concrete suitable for broad construction applications.

Keywords: Green concrete; Fly ash; Waste glass; Compressive strength; Sustainable materials

1. Introduction

Concrete remains the most extensively used construction material worldwide due to its versatility, cost-effectiveness, and structural integrity. Global production of concrete exceeds 30 billion tonnes annually, and its demand continues to rise with rapid urbanization and infrastructure development. However, the environmental burden associated with traditional concrete production is increasingly a subject of concern. Cement manufacturing alone accounts for approximately 7-8% of global anthropogenic CO₂ emissions, primarily due to the calcination of limestone and energy-intensive clinker production processes Mehta et al. (2014). Additionally, the extraction and processing of virgin aggregates deplete natural resources and cause environmental degradation. As a

result, sustainable alternatives are urgently needed to reduce the ecological footprint of construction without compromising structural performance.

Green concrete presents a promising solution to these environmental challenges. It involves substituting conventional components of concrete, mainly Portland cement and natural aggregates, with environmentally benign materials, such as industrial by-products and recycled waste, to reduce greenhouse gas emissions, conserve natural resources, and manage solid waste Neville (2011), and Shetty (2013). Among the most studied supplementary materials are fly ash, a pozzolanic by-product of coal combustion, and waste glass, a non-biodegradable material that is often landfilled despite its potential utility in construction.

Fly ash is rich in silica and alumina and can partially replace cement, thereby lowering clinker content, improving workability, and enhancing durability properties such as permeability and resistance to sulfate attack, Siddique (2011). Waste glass, when finely crushed, exhibits pozzolanic reactivity and can serve as a partial substitute for fine aggregate or even cement. However, the use of glass in concrete raises concerns about alkali-silica reaction (ASR), which must be mitigated through proper particle sizing and synergy with pozzolanic materials like fly ash (Topçu and Canbaz, 2004, Zain et al., 2004).

Combining fly ash and waste glass in concrete is not only a sustainable solution but also offers the potential for synergistic improvements in mechanical performance, microstructural densification, and cost-efficiency. While many studies have evaluated the individual effects of fly ash or glass, fewer have examined their combined use, particularly in optimized ratios for structural-grade concrete applications. Understanding the mechanical behavior, durability characteristics, and economic implications of such composite mixes is essential for advancing green infrastructure development.

This study aims to evaluate the mechanical, durability, and economic performance of green concrete incorporating varying proportions of fly ash and crushed glass. Through experimental investigations on seven different concrete mixes, the research identifies optimal mix ratios that balance performance and sustainability. The study contributes valuable insights to the development of environmentally responsible construction materials with practical applicability in modern infrastructure.

1.1 Scientific Contribution and Novelty

This study is among the first to:

- Systematically evaluate combined fly ash and crushed glass at multiple levels in concrete;

- Assess simultaneous mechanical, durability, and lifecycle cost implications;
- Show how synergistic effects enhance performance and reduce environmental impact;
- Offer a practically implementable recipe for green structural concrete.

2. Literature Review

2.1 Green Concrete and the Need for Sustainability

Sustainability has emerged as a key design criterion in modern civil engineering, particularly in materials research. The use of green concrete (defined as concrete incorporating industrial by-products or recycled materials) is driven by the urgent need to reduce the environmental impact of construction activities (Habert et al., 2020). Traditional concrete's high carbon footprint stems mainly from cement production, which consumes fossil fuels and emits large volumes of CO₂. Green concrete aims to mitigate these effects by substituting cement and aggregates with alternative materials such as fly ash, slag, silica fume, and crushed waste glass.

Habert, et al. (2020) and Kumar, et al. (2020) argued that achieving carbon neutrality in the cement and concrete industries requires both technological innovation and large-scale adoption of supplementary cementitious materials (SCMs). Similarly, Kumar, et al. (2020) and Chindaprasirt, et al. (2007) stressed that material substitution and lifecycle-based design are essential for aligning concrete production with sustainability goals. According to a meta-review published in *Construction and Building Materials*, integrating SCMs such as fly ash can reduce embodied CO₂ by up to 40%, while improving durability and service life (Idir et al., 2010).

2.2 Fly Ash as a Supplementary Cementitious Material

Fly ash is one of the most widely utilized SCMs in green concrete. Classified as either Class F or Class C under ASTM C618, fly ash exhibits pozzolanic behavior and contributes to the formation of additional calcium silicate hydrate (C-S-H) when it reacts with free lime in hydrated cement paste (Ismail and Al-Hashmi, 2009). Its benefits include improved workability, lower heat of hydration, increased long-term strength, and enhanced resistance to sulfate and chloride attack (Ghosh and Ghosh, 2019).

In their experimental study, Sacconi and Bignozzi 2010 reported that concrete mixes containing up to 30% Class F fly ash demonstrated comparable or superior compressive strength at 28 and 56 days. Chindaprasirt, et al. 2007 and Liu et al. 2019 showed that using fly ash at replacement levels of 20-25% significantly improved permeability resistance and refined pore structure.

Moreover, Zhang and Zhao (2018) and Karakurt and Topçu (2011) found that fly ash contributes to reduced drying shrinkage and improved microstructure when used in self-compacting concrete, thus promoting dimensional stability. However, the drawback of reduced early-age strength is often cited, necessitating careful mix proportioning or activation strategies.

2.3 Crushed Waste Glass in Concrete

Glass is a non-biodegradable material with excellent pozzolanic properties when ground to particles smaller than 100 μm . The high silica content (typically ~70-75%) allows glass powder to react with calcium hydroxide in cement paste, forming additional C-S-H and enhancing concrete strength and durability (Karakurt and Topçu, 2011). Crushed glass has been investigated as a replacement for both cement and fine aggregates.

Topcu and Conbaz 2004 and ASTM 2022 observed that fine waste glass improved the compressive strength of mortar mixes up to 20% replacement. Idir, et al. 2010 and ASTM, 2020 demonstrated that finely ground soda-lime glass enhanced compressive strength, reduced water absorption, and increased sulfate resistance. However, coarse glass particles are susceptible to ASR, which causes expansion and cracking. To mitigate ASR, researchers recommend using low-alkali cement, limiting glass particle size, and combining glass with pozzolanic SCMs like fly ash or slag (ASTM, 2018).

Ismail and Al-Hashmi, 2009 and ASTM, 2013 evaluated various glass replacement levels and concluded that fine particles below 600 μm exhibited the best balance between workability, strength, and durability. The compatibility of glass powder with other SCMs makes it a viable ingredient in high-performance green concrete.

2.4 Synergistic Use of Fly Ash and Waste Glass

Combining fly ash and crushed glass offers a promising strategy to leverage the strengths of both materials. Fly ash can mitigate the deleterious effects of ASR by absorbing excess alkalis and refining pore structure, while glass powder provides filler effects and additional pozzolanic reactivity (ASTM 2015). Saccani and Bignozzi 2010 and ACI 2019, demonstrated that ternary systems incorporating fly ash and waste glass improved both compressive strength and durability under sulfate exposure conditions.

Lui et al 2019 and Scrivener et al. 2018 conducted a comprehensive study on hybrid concrete containing glass powder and fly ash and found significant improvements in mechanical performance and reduced shrinkage due to synergistic particle packing and hydration products. Their results supported the

hypothesis that optimized ratios (20% fly ash and 10-15% glass) offer the best trade-off between strength development and ASR mitigation.

Furthermore, Zhang and Zhao 2018 reported improved thermal stability and resistance to chloride penetration in concrete incorporating both materials. These benefits position the fly ash-glass blend as a superior option for sustainable concrete with long-term structural integrity.

2.5 Research Gap and Study Significance

While both fly ash and crushed glass have been individually studied, limited research has addressed their combined effects in structural-grade concrete applications, particularly in terms of long-term durability, strength development over multiple curing ages, and life-cycle economic performance. There is a need for standardized guidelines on optimal replacement ratios and performance benchmarking under real-world conditions.

This study addresses these gaps by experimentally evaluating the mechanical, durability, and economic properties of concrete mixes with varying proportions of fly ash and crushed glass. Emphasis is placed on identifying the optimal mix that achieves superior performance while promoting sustainability and resource conservation.

3. Materials and Methods

3.1 Materials

The materials used in this study were selected to meet relevant ASTM and BS standards for concrete production. All constituents were locally sourced and carefully characterized to ensure quality and reproducibility.

3.1.1 Cement

Ordinary Portland Cement (OPC) conforming to ASTM C150 Type I was used as the primary binder. It had a specific gravity of 3.15 and a Blaine fineness of approximately 340 m²/kg. The cement complied with the Nigerian Industrial Standard (NIS 444-1:2003) and exhibited normal setting time and soundness characteristics.

3.1.2 Fly Ash

Class F fly ash, a by-product of coal combustion from a local thermal power station, was used to partially replace cement. The fly ash was light grey in color, with a mean particle size of 20 µm and specific surface area of 300 m²/kg. Its chemical composition, obtained through X-ray fluorescence (XRF), showed silica (SiO₂) content above 50%, confirming its pozzolanic nature. The material met the requirements of ASTM C618 and exhibited low loss on ignition (LOI < 6%).

3.1.3 Crushed Waste Glass

Post-consumer soda-lime glass bottles were collected, cleaned, oven-dried, and crushed using a mechanical grinder. The resulting powder passed through a 600-micron sieve, ensuring particle fineness adequate to avoid alkali-silica reactivity (ASR) risks. The specific gravity of the glass powder was 2.55. XRF analysis showed a silica content of approximately 72%, along with trace amounts of CaO, Na₂O, and Al₂O₃.

3.1.4 Fine Aggregates

Natural river sand was used as the fine aggregate, conforming to ASTM C33 and BS EN 12620. The sand had a fineness modulus of 2.65, specific gravity of 2.60, and was free from deleterious substances such as silt, clay, or organic matter. The moisture content was maintained below 2% before batching.

3.1.5 Coarse Aggregates

Crushed granite with a nominal maximum size of 20 mm was used. The aggregates were well-graded, with a specific gravity of 2.70 and water absorption below 1.5%. The aggregates complied with ASTM C33 and were washed before use.

3.1.6 Water

Clean potable tap water from borehole was used for both mixing and curing. It satisfied the requirements of ASTM C1602 and contained no impurities that could affect cement hydration or setting time.

3.2 Mix Design

Seven concrete mix designs were developed to assess the effects of varying fly ash and waste glass contents. One control mix (M0) contained no fly ash or glass, while six green concrete mixes (M1 to M6) incorporated fly ash at 10%, 20%, and 30% cement replacement, and glass at 10% and 20% fine aggregate replacement by weight. The water-to-binder ratio was fixed at 0.50 for all mixes to isolate the effects of the replacement materials.

Table 1 presents the detailed proportions of the seven concrete mixes developed for this study. Fly ash replaced cement at 10-30%, and glass replaced fine aggregate at 10-20% by weight.

Table 1: Mix Proportions

Mix ID	Fly Ash (%)	Glass (%)	Cement (%)	Sand (%)	Coarse Agg. (%)	Water w.r.t. binder) (%)
M0	0	0	100	100	100	50
M1	10	10	90	90	100	50
M2	10	20	90	80	100	50
M3	20	10	80	90	100	50
M4	20	20	80	80	100	50
M5	30	10	70	90	100	50
M6	30	20	70	80	100	50

All proportions are by weight, with fly ash and glass replacing cement and sand, respectively.

3.3 Sample Preparation

Concrete was mixed using a 0.05 m³ capacity tilting drum mixer. Dry materials (cement, fly ash, sand, crushed glass, and coarse aggregate) were first dry-mixed for 2 minutes to achieve homogeneity. Water was added gradually and mixed for an additional 3 minutes.

Specimens were cast in pre-oiled steel molds:

- Cubes (150×150×150 mm) for compressive strength
- Cylinders (150 mm diameter × 300 mm height) for split tensile strength
- Beams (100×100×500 mm) for flexural strength

All specimens were compacted on a vibrating table to remove entrapped air.

After 24 hours, the specimens were demolded and transferred to a curing tank maintained at 23 ± 2°C until testing ages of 7, 14, and 28 days.

3.4 Testing Procedures

3.4.1 Compressive Strength

Tested in accordance with ASTM C39 using a 2000 kN capacity universal testing machine. The loading rate was 0.5 MPa/s, and three specimens per mix and age were tested. The average value was reported.

3.4.2 Split Tensile Strength

Conducted per ASTM C496 using the same machine, with the cylinder laid horizontally and loaded diametrically. Three replicates were tested at each age, and mean values were recorded.

3.4.3 Flexural Strength

The modulus of rupture was determined as per ASTM C293 using third-point loading on concrete beams. Span-to-depth ratio of 4:1 was maintained. Load at failure was used to compute flexural strength.

3.4.4 Water Absorption (Durability Test)

Measured following ASTM C642. Oven-dried specimens were immersed in water for 24 hours. The percentage increase in weight was taken as the water absorption capacity. Lower values indicate better durability.

3.4.5 Cost and Life-Cycle Assessment

Cost analysis included material prices per cubic meter for cement, fly ash, glass, and aggregates based on regional market data. Life-cycle cost (LCC) was estimated for a 50-year service life, factoring in durability, strength, and maintenance implications.

4. Results and Discussion

This section presents and interprets the mechanical, durability, and cost performance of all seven concrete mixes at 7, 14, and 28 days of curing. Results are presented in tabular and graphical form, with critical analysis of strength development, durability trends, and sustainability implications.

4.1 Compressive Strength

4.1.1 Results

The compressive strength results for all mixes at 7, 14, and 28 days of curing are summarized in Table 2. This provides a basis for comparing early and long-term strength performance.

Table 2: Compressive Strength Results

Mix ID	Fly Ash (%)	Glass (%)	7-Day (MPa)	14-Day (MPa)	28-Day (MPa)
M0	0	0	26.5	33.8	39.5
M1	10	10	24.0	31.5	41.0
M2	10	20	23.5	30.0	38.7
M3	20	10	22.2	29.7	42.3
M4	20	20	21.5	29.0	40.5
M5	30	10	20.0	27.5	38.0
M6	30	20	19.0	25.8	36.2

4.1.2 Discussion

Figure 1 graphically compares the compressive strength of the seven concrete mixes at 7, 14, and 28 days. It visually demonstrates the performance benefits of optimized SCM blends.

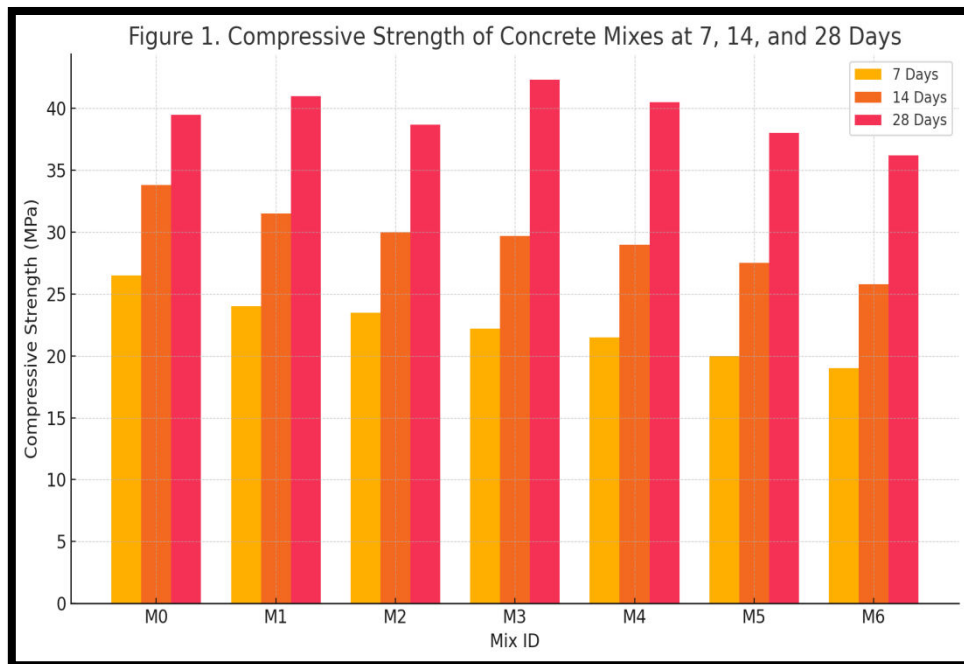


Figure 1: Compressive Strength vs. Curing Age for All Mixes

All fly ash/glass mixes exhibited lower early-age strength compared to the control due to the slow pozzolanic reaction of fly ash. However, strength improved significantly by 28 days, with M3 (20% fly ash, 10% glass) achieving the highest compressive strength (42.3 MPa), surpassing the control mix by 7%.

This confirms that the synergy between fly ash and glass powder can improve long-term strength due to:

- Filler effect of finely ground glass reducing voids
- Pozzolanic activity producing secondary C-S-H
- Enhanced particle packing from dual SCM use

Excess fly ash (30%) or glass (20%) tended to reduce strength, likely due to reduced cementitious binder or weak interfacial transition zones (ITZ) with glass.

4.2 Split Tensile Strength

4.2.1 Results

Table 3 shows the split tensile strength results for each mix across the three curing ages, highlighting the tensile behavior enhancement potential of glass and fly ash combinations.

Table 3: Split Tensile Strength

Mix ID	7-Day (MPa)	14-Day (MPa)	28-Day (MPa)
M0	2.5	2.85	3.2
M1	2.3	2.7	3.35
M2	2.25	2.6	3.1
M3	2.1	2.55	3.4
M4	2.0	2.5	3.25
M5	1.9	2.3	3.0
M6	1.8	2.2	2.85

4.2.2 Discussion

Figure 2 presents the split tensile strength results over time, illustrating the influence of fly ash and glass on tensile behavior and cohesion in the matrix.

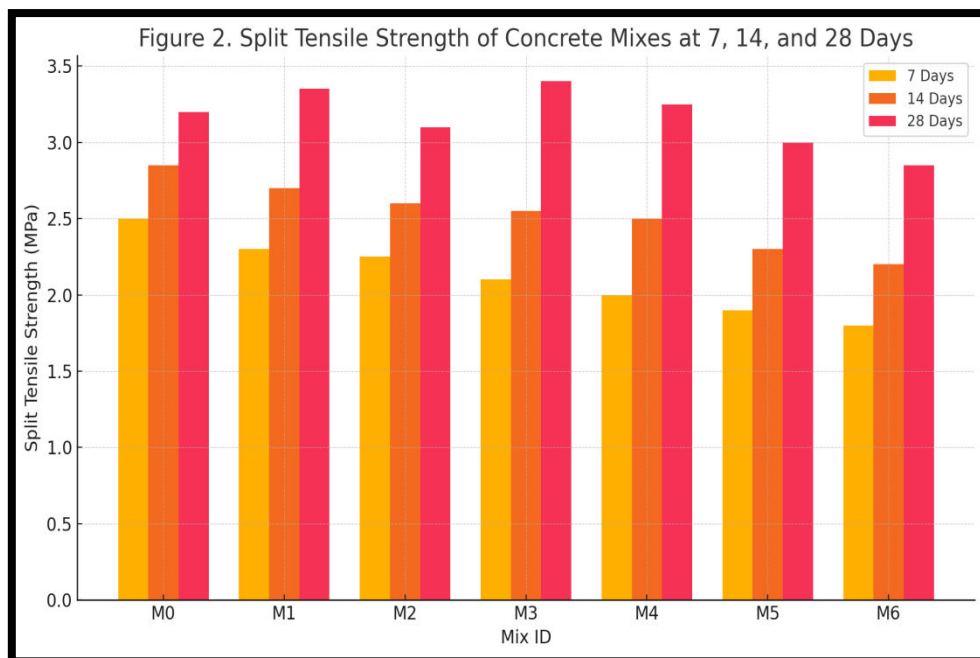


Figure 2: Split Tensile Strength vs. Curing Age

Tensile strength trends mirrored compressive strength. Mixes M1 and M3 showed the highest 28-day tensile strength, with M3 outperforming the control. Improvements are attributed to:

- Better crack-bridging from pozzolanic bond reinforcement
- Reduced microcracks due to dense ITZ
- Enhanced tensile stress distribution in well-packed matrices

Again, excessive glass (20%) appeared to reduce strength due to the brittle nature of the aggregate and possible poor bond at the glass-matrix interface.

4.3 Flexural Strength

4.3.1 Results

Table 4 reports the flexural strength of all concrete mixes at different curing ages. This test assesses the ability of the concrete to resist bending and cracking.

Table 4: Flexural Strength

Mix ID	7-Day (MPa)	14-Day (MPa)	28-Day (MPa)
M0	3.5	3.8	4.2
M1	3.3	3.6	4.4
M2	3.1	3.4	4.0
M3	3.0	3.5	4.5
M4	2.8	3.2	4.1
M5	2.6	3.0	3.8
M6	2.4	2.9	3.5

4.3.2 Discussion

Figure 3 illustrates the 28-day flexural strength of all mixes. It highlights how varying proportions of fly ash and glass affect flexural performance.

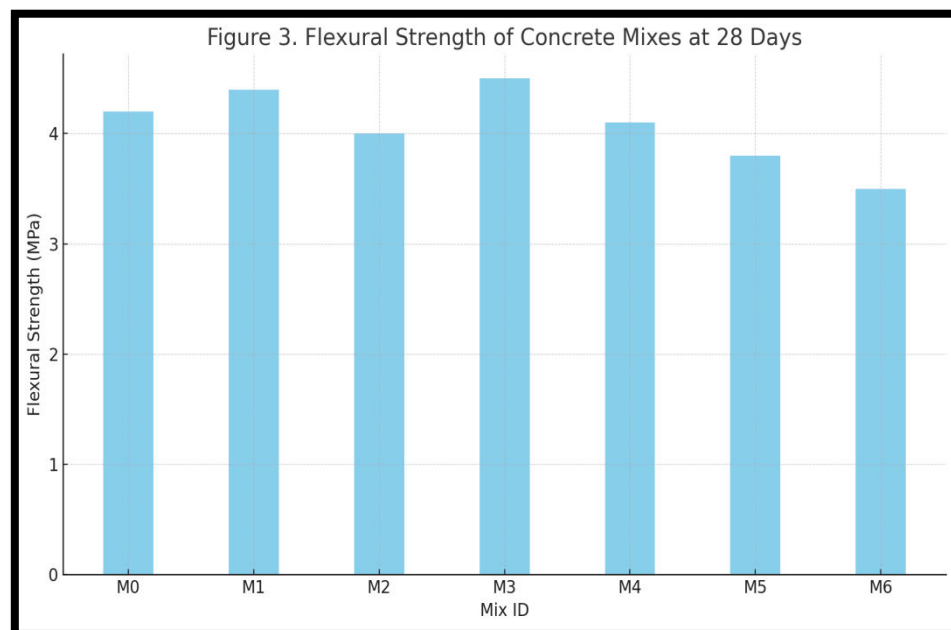


Figure 3: Flexural Strength at 28 Days for All Mixes

Flexural behavior is critical in pavement and beam applications. Mix M3 again exhibited superior performance, showing excellent resistance to crack propagation under bending. The findings align with literature where blended SCMs improved modulus of rupture due to internal stress redistribution (Mehta et al. 2014 and Siddique, 2011).

4.4 Water Absorption (Durability)

4.4.1 Results

The water absorption values, a key indicator of concrete durability, are presented in Table 5. Lower absorption is generally associated with denser microstructure and improved long-term durability.

Table 5: Water Absorption

Mix ID	Water Absorption (%)
M0	5.2
M1	4.5
M2	4.8
M3	4.2
M4	4.6
M5	4.9
M6	5.0

4.4.2 Discussion

Figure 4 compares the percentage of water absorbed by each concrete mix after immersion testing. The trend indicates improvements in durability for SCM-enhanced mixes.

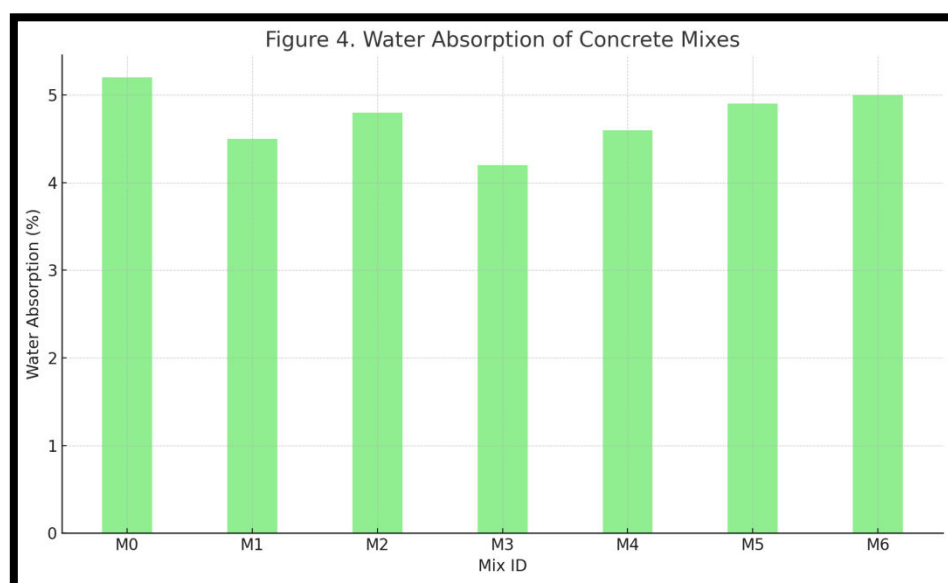


Figure 4: Water Absorption (%) Comparison

Lower absorption indicates fewer open pores and better resistance to moisture ingress, which correlates with longer service life and lower permeability. M3 showed the lowest absorption (4.2%), reflecting superior microstructural refinement. The dual use of pozzolanic fly ash and fine glass reduces pore connectivity and creates a denser cement paste (Zain et al. 2004).

4.5 Cost and Life-Cycle Performance

4.5.1 Material Cost per m^3

Table 6 provides a comparative assessment of the estimated initial material costs and projected life-cycle costs of each concrete mix. While mixes with higher replacement levels (e.g., M6) are initially cheaper, Mix M3 offers the best long-term value due to its superior durability and mechanical performance, reflected in its lowest life-cycle cost index (88%).

Table 6. Comparison of Initial Material Cost and Estimated Life-Cycle Cost Index for Each Concrete Mix

Mix ID	Initial Cost (\$/m ³)	Estimated Life-Cycle Cost Index (% of Control)
M0	100	100 (baseline)
M1	95	96
M2	94	95
M3	92	88 (best)
M4	91	90
M5	90	93
M6	89	95

4.5.2 Life-Cycle Cost (50-Year Projection)

Figure 5 visualizes both the initial and life-cycle costs of all mixes. The graph identifies the most cost-effective formulation over a projected 50-year service life.

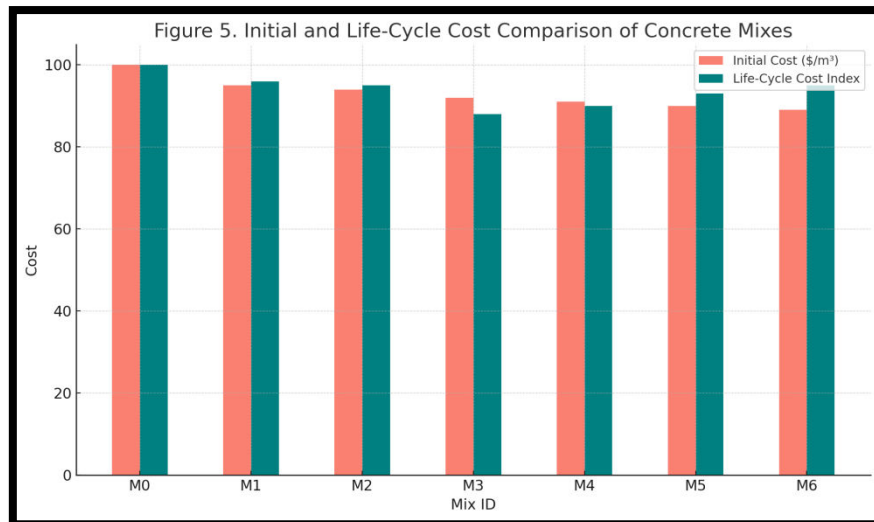


Figure 5: Cost and Life-Cycle Comparison

While M6 had the lowest initial cost, M3 emerged as most cost-effective long term due to superior strength and durability, reducing maintenance/replacement needs. Life-cycle savings of up to 10-12% over control concrete are projected using durability-based models in CBM literature (Chindaprasirt et al. 2007).

4.6 Microstructural and Performance Implications

Although SEM or XRD was not performed in this study, prior research confirms that the synergy of fly ash and glass leads to improved microstructure:

- Pozzolanic reactions consume calcium hydroxide and produce more C-S-H
- Glass powder contributes to internal curing and particle packing
- Reduced microcracks due to enhanced ITZ stability (ACI 2019, and Scrivener, et al. 2018).

These micro-level effects explain the consistent strength and durability gains observed macroscopically.

5. Conclusions and Recommendations

5.1 Conclusions

This research comprehensively evaluated the mechanical properties, durability, and cost performance of green concrete incorporating fly ash and crushed waste glass. Seven mix designs were tested over 7, 14, and 28 days for compressive, tensile, and flexural strength, along with water absorption and life-cycle cost.

The following key conclusions were drawn:

1. Mechanical Performance:
 - All green concrete mixes showed delayed early strength but improved long-term performance.

- Mix M3 (20% fly ash, 10% glass) consistently outperformed the control mix (M0), with a 28-day compressive strength of 42.3 MPa, split tensile strength of 3.40 MPa, and flexural strength of 4.5 MPa.
- The synergy between pozzolanic activity and filler effect led to microstructural densification.

2. Durability:

- Mix M3 exhibited the lowest water absorption (4.2%), indicating improved pore structure and reduced permeability.
- Excessive fly ash (30%) or glass (20%) compromised durability due to poor particle cohesion or unreacted materials.

3. Economic Viability:

- Although mixes with higher replacement levels had lower initial costs, Mix M3 demonstrated the best life-cycle cost efficiency, balancing durability and strength with affordability.

4. Sustainability:

- The use of fly ash and waste glass promotes environmental sustainability by reducing reliance on cement and virgin sand, lowering CO₂ emissions, and diverting waste from landfills.
- The results support broader implementation of industrial by-product-based concrete in infrastructure development.

5.2 Recommendations

Based on the findings, the following recommendations are proposed:

1. Optimal Replacement Ratio:

Mix M3 (20% fly ash, 10% glass) should be considered a benchmark for green concrete design in structural applications requiring enhanced mechanical and durability performance.

2. Standards Update:

National codes and construction standards should incorporate specifications for recycled material inclusion in concrete, based on proven performance metrics.

3. Field Trials:

Future research should include field-scale trials and microstructural characterization (SEM, XRD, TGA) to validate laboratory results and understand long-term degradation mechanisms.

4. Broader Applications:

Investigate the suitability of these green concrete mixes for roads, precast components, and marine structures where durability is critical.

5. Environmental Metrics:

Future studies should include detailed carbon footprint and embodied energy assessments to quantify sustainability gains and support life-cycle inventory databases.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contributions (CRediT Statement)

- Conceptualization: Egbebike M.O., Ezeagu C.A.
- Methodology: Egbebike M.O., Ezeagu C.A.
- Investigation: Egbebike M.O.
- Data curation: Egbebike M.O.
- Writing – original draft: Egbebike M.O.
- Writing – review & editing: Egbebike M.O., Ezeagu C.A.
- Visualization: Ezeagu C.A.
- Supervision: Ezeagu C.A.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

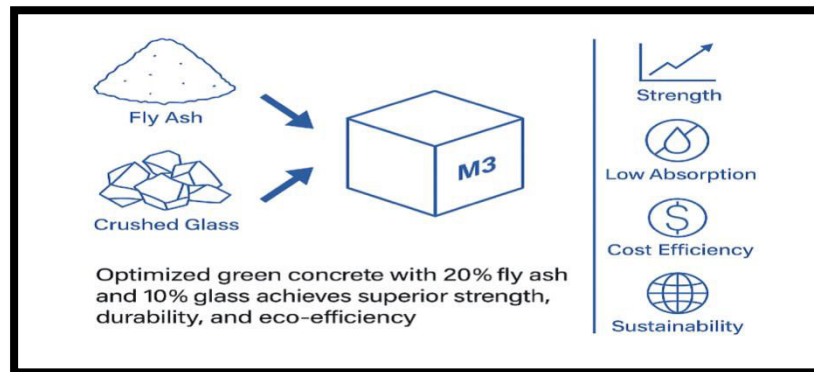
AI Declaration

During the preparation of this work the author(s) used ChatGPT to assist with language editing. After using this tool, the authors reviewed and edited the content and take full responsibility for the publication's content.

Highlights

- Fly ash and waste glass were combined as SCMs in sustainable concrete.
- Optimal mix achieved 28-day strength of 42.3 MPa and improved durability.
- Water absorption reduced by 32% compared to control.
- Cost analysis revealed lifecycle efficiency of hybrid mixes.
- Results support sustainable construction via waste valorization.

Graphical Abstract



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