Sustainable Concrete Solutions: Advancing Low-Carbon Infrastructure with Fly Ash in Nigeria's Construction Industry

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Abstract
The urgent environmental challenges posed by the high carbon footprint of ordinary Portland cement (OPC) demand sustainable alternatives in the construction industry. This study aims to evaluate the mechanical performance, durability, environmental impact, and economic feasibility of fly ash-based concrete as a partial replacement for OPC in Nigeria's construction sector. Concrete mixtures with 20%, 40%, and 60% fly ash replacement were prepared and tested for compressive strength, workability, chloride penetration resistance, sulfate resistance, and water absorption. Advanced life cycle assessment (LCA) and economic analyses were conducted to quantify environmental benefits and cost savings. Results indicate that early-stage compressive strength decreases with increasing fly ash content due to slower pozzolanic reactions; however, significant strength gains occur at later curing stages, with 90-day compressive strengths reaching up to 42 MPa for 40% fly ash mixtures. Durability improvements were demonstrated by a 50% reduction in chloride permeability and a decrease in sulfate-induced mass loss from 0.7% to 0.2% at 60% fly ash replacement. The LCA revealed a reduction in CO_2 emissions by up to 51%, while economic analysis showed cost savings of up to 20% compared to conventional OPC concrete. These findings confirm that fly ash-based concrete provide enhanced durability and substantial environmental and financial advantages, making it a viable, sustainable alternative for construction in Nigeria. However, challenges such as supply chain constraints, quality control, and limited industry awareness must be addressed to enable widespread adoption. Future research should focus on improving fly ash reactivity, exploring hybrid supplementary cementitious materials, and conducting long-term field performance studies to further optimize and validate fly ash concrete applications under local climatic conditions.

Keywords: Fly ash concrete, durability enhancement, carbon footprint reduction, cost-effective infrastructure, sustainable construction, mechanical properties, machine learning optimization, Nigerian construction industry.

Introduction

Nigeria's construction industry serves as a significant driver of economic growth, contributing approximately 9% to the country's Gross Domestic Product (GDP) and providing direct employment to millions of people. However, the industry's heavy reliance on ordinary Portland cement (OPC) presents considerable environmental challenges, as cement production accounts for about 8% of global carbon dioxide (CO_2) emissions [1]. The rising demand for infrastructure has intensified cement consumption, thereby exacerbating greenhouse gas (GHG) emissions and environmental degradation. This underscores a pressing general problem: the environmental unsustainability of current construction practices, particularly due to high-carbon cement use. Consequently, identifying sustainable alternatives to reduce the carbon footprint of construction materials is essential for Nigeria to meet its climate commitments and achieve its sustainable development goals.

Fly ash, a by-product of coal combustion in thermal power plants, has gained recognition as a supplementary cementitious material (SCM) due to its potential to reduce cement consumption and enhance concrete performance. Studies have demonstrated that fly ash incorporation improves durability, workability, and resistance to chemical attacks, making it a viable substitute for OPC [2]. Countries like the United States, India, and China have successfully promoted fly ash utilization in construction through supportive policies, leading to notable CO_2 emission reductions [3]. However, in Nigeria, fly ash adoption remains limited, primarily due to supply chain challenges, inadequate regulatory frameworks, and a lack of awareness among stakeholders [4].

Concrete incorporating fly ash, offers a dual advantage of reducing environmental impact and improving material performance. Research indicates that replacing 20-40% of OPC with fly ash can reduce CO_2 emissions by up to 40%, while enhancing concrete's compressive strength and resistance to sulphate and chloride attacks over time [5]. The pozzolanic reaction of fly ash contributes to microstructure densification, reducing permeability and increasing the long-term durability of concrete structures [6]. From an economic perspective, fly ash integration in concrete also reduces production costs by lowering the reliance on energy-intensive OPC. In Nigeria, where cement prices continue to rise due to increasing energy costs and limited production capacity, fly ash presents a cost-effective alternative that supports sustainable construction goals [7]. Additionally, fly ash-modified concrete exhibits better workability and a lower heat of hydration, making it particularly suitable for large-scale concrete applications in Nigeria's hot climate [8].

Despite these well-documented advantages, several specific challenges hinder the adoption of fly ash in Nigeria. The inconsistent quality of locally available fly ash, due to variations in coal combustion processes, lead to irregularities in particle size distribution and chemical composition. Additionally, the absence of a robust policy framework for the collection, processing, and utilization of fly ash in construction further limits its large-scale application [9, 10]. These obstacles are compounded by a critical knowledge gap: most existing studies on fly ash concrete in Nigeria lack rigorous experimental validation, especially under Nigeria's unique climatic and material conditions. Moreover, there is limited empirical research that integrates economic, environmental, and durability performance assessments tailored to Nigerian scenarios. There is also a notable scarcity of studies applying advanced optimization techniques to tailor fly ash concrete mix designs based on local conditions.

This study addresses these gaps by presenting a comprehensive evaluation of fly ash-based low-carbon concrete tailored for Nigeria's construction industry. The primary focus is to evaluate the mechanical properties of fly ash-modified concrete, particularly its compressive strength, tensile strength, and workability across various mix proportions. Additionally, this research investigates the durability performance of fly ash concrete by analysing its resistance to sulphate attack, chloride ingress, and water absorption, providing insight into its long-term viability under Nigeria's diverse climatic conditions.

To quantify the environmental benefits, a life cycle assessment (LCA) methodology will be employed to measure the reduction in carbon emissions achieved through fly ash substitution. An economic feasibility analysis will also be conducted to compare the cost-effectiveness of fly ash-based concrete with conventional OPC concrete, considering both initial costs and long-term performance benefits. Furthermore, the study will identify major barriers hindering the large-scale adoption of fly ash in Nigeria, proposing actionable policy recommendations to facilitate its integration into the construction sector. Importantly, this study introduces a novel dimension by incorporating machine learning-based optimization techniques, including response surface methodology (RSM) and artificial neural networks (ANNs), to determine optimal fly ash replacement levels and water-to-binder (w/b) ratios. This data-driven approach is especially significant in the Nigerian context, where material properties, construction practices, and climatic demands differ markedly from those in existing global studies.

The findings will be highly relevant to civil engineers, construction companies, policymakers, and environmental agencies, offering practical solutions for improving the sustainability of Nigeria's construction sector.

Public infrastructure projects such as bridges, highways, dams, and commercial buildings will benefit from the durability and environmental advantages of fly ash concrete. Additionally, its cost-effectiveness and long-term performance make it a promising material for Nigeria's affordable housing initiatives. This research contributes a unique, context-specific framework for implementing fly ash in Nigerian construction by integrating machine learning optimization with localized experimental analysis**.** By promoting the adoption of fly ash concrete, Nigeria can significantly reduce its carbon emissions, minimize industrial waste disposal, and contribute to a circular economy. The successful implementation of fly ash as a sustainable construction material will enable Nigeria to achieve its net-zero carbon commitments while fostering a more resilient and eco-friendly construction industry.

Literature Review

Overview of Conventional Cement Production and Its Environmental Impact

Cement production remains one of the leading contributors to global carbon dioxide (CO_2) emissions, responsible for approximately 8% of total anthropogenic CO_2 emissions [11]. The energy-intensive clinker production process, which involves heating limestone and clay at temperatures exceeding 1400°C, results in high carbon emissions due to both fuel combustion and the calcination reaction. Studies have demonstrated that for every ton of cement produced, nearly 0.9 tons of CO_2 are released into the atmosphere [12]. The increasing demand for infrastructure in developing economies like Nigeria has exacerbated cement consumption, thereby increasing the carbon footprint of the construction industry.

The environmental concerns associated with cement production have led researchers to explore sustainable alternatives, particularly supplementary cementitious materials (SCMs) that partially replace OPC in concrete mixtures. Among these SCMs, fly ash, slag, and silica fume have gained significant attention due to their ability to enhance concrete durability and reduce CO_2 emissions. Fly ash, a by-product of coal combustion in thermal power plants, has emerged as one of the most viable and widely available SCMs, given its pozzolanic properties and economic benefits [13].

Fly Ash as a Supplementary Cementitious Material (SCM)

Fly ash is composed mainly of silica (SiO_2), alumina (Al_2O_3), and calcium oxide (CaO), making it a pozzolanic material that reacts with calcium hydroxide in concrete to form additional cementitious compounds. It is categorized into Class C and Class F fly ash, with Class C containing higher calcium content, which enables it to exhibit self-cementing properties, while Class F is purely pozzolanic and requires an activator such as lime [14].

Extensive research has shown that replacing 20–50% of OPC with fly ash in concrete mixtures results in significant improvements in strength, durability, and chemical resistance while reducing the carbon footprint of cementitious materials. A comprehensive review found that fly ash concrete exhibits superior resistance to sulphate attack, alkali-silica reaction (ASR), and chloride penetration, making it highly suitable for marine and sulphate-rich environments [15].

Performance and Benefits of Fly Ash-Based Concrete

Fly ash-modified concrete has been extensively studied for its ability to enhance mechanical properties and long-term durability. Research has confirmed that fly ash concrete exhibits higher compressive strength development over time compared to OPC concrete, as the pozzolanic reaction continues beyond the conventional 28-day curing period. A study conducted on fly ash-based concrete in China and India reported a 30% increase in compressive strength at 90 days compared to conventional OPC concrete [16].

Another key advantage of fly ash-based concrete is its reduced water demand and improved workability. Due to the spherical particle shape of fly ash, concrete incorporating fly ash requires 15–20% less water, resulting in improved rheology and reduced shrinkage cracking [17]. The incorporation of fly ash also significantly lowers the heat of hydration, making it particularly beneficial for mass concrete applications, where excessive heat generation can lead to thermal cracking in large structural elements [18]. From an environmental perspective, fly ash-based concrete offers substantial sustainability benefits. Research has indicated that replacing 40% of OPC with fly ash can reduce embodied CO_2 emissions by up to 45%, significantly contributing to global climate change mitigation efforts [19]. Additionally, the utilization of fly ash in concrete helps to reduce landfill waste, as fly ash is often considered an industrial by-product that requires proper disposal.

Global Case Studies on Fly Ash Utilization

Several countries have successfully implemented fly ash utilization policies in the construction sector. In the United States, the Environmental Protection Agency (EPA) has actively promoted the use of fly ash in road construction, precast concrete, and structural applications. Research on highway infrastructure projects in the US demonstrated that fly ash concrete outperformed OPC concrete in durability and cost-effectiveness [20].

In China, the government has introduced policies mandating minimum fly ash content in cementitious materials, leading to a significant reduction in CO_2 emissions and improved construction sustainability. Similarly, in Germany, fly ash has been widely integrated into precast concrete elements, high-rise buildings, and bridges, resulting in lower cement demand and enhanced durability performance [21]. In South Africa, where coal-based power generation is prevalent, the use of fly ash in large-scale infrastructure projects has led to a 25% increase in long-term durability and cost savings in construction projects. Research has highlighted that South African fly ash concrete exhibited superior sulphate resistance, making it ideal for marine and coastal infrastructure [22].

Challenges of Fly Ash Adoption in Nigeria

Despite its proven benefits, the large-scale adoption of fly ash in Nigeria faces significant challenges. The availability of high-quality fly ash is limited, as Nigeria relies more on gas-fired power plants than coal-fired ones, leading to supply chain constraints. Additionally, variations in fly ash particle size distribution and chemical composition across different sources impact its reactivity and performance in concrete applications [23].

Another critical challenge is the lack of regulatory frameworks and standardization for fly ash utilization in Nigeria. Unlike countries such as India, China, and the US, Nigeria does not have national guidelines that specify fly ash composition, quality requirements, or application procedures in concrete. This lack of standardization has contributed to scepticism among construction stakeholders regarding the reliability of fly ash-based concrete [24]. Furthermore, technical knowledge and awareness among engineers and contractors remain limited, preventing widespread adoption. Studies have reported that many construction professionals in Nigeria perceive fly ash as an inferior material, despite scientific evidence demonstrating its long-term strength benefits. Addressing this gap requires extensive industry training, awareness campaigns, and policy-driven initiatives to promote fly ash utilization in Nigeria's construction sector [25].

Previous Research on Sustainable Concrete Solutions in Developing Nations

Extensive research has been conducted on alternative cementitious materials to address sustainability concerns in developing nations. Geopolymer concrete, which utilizes fly ash and other industrial by-products as binders, has emerged as a viable low-carbon alternative to OPC-based concrete. Studies have demonstrated that geopolymer concrete can achieve compressive strengths exceeding 60 MPa while reducing CO_2 emissions by nearly 80% compared to OPC-based concrete [26]. Recent advances in artificial intelligence (AI) and machine learning (ML) have also been employed to optimize fly ash concrete mix designs. AI-based predictive models have been shown to accurately determine optimal mix proportions, ensuring higher strength and durability while minimizing raw material waste. A study on fly ash-metakaolin hybrid concrete in India and Nigeria found that a mix containing 30% fly ash and 10% metakaolin achieved a compressive strength of 55 MPa at 90 days, outperforming traditional OPC concrete in both strength and durability [27].

Materials and Methods

Materials Selection and Characterization

The materials used in this study were selected based on their availability and compatibility with fly ash-based concrete systems. The primary materials included fly ash, ordinary Portland cement (OPC), fine and coarse aggregates, superplasticizers, and water. Fly ash was sourced from a coal-fired power plant in Nigeria and classified as Class F fly ash, characterized by its low calcium content and high silica-alumina composition, in accordance with ASTM C618-19 standards. The chemical composition of the fly ash was determined using X-ray fluorescence (XRF) spectroscopy, while its particle size distribution was analyzed using laser diffraction techniques. To further assess its suitability as a pozzolanic material, the Blaine fineness test was conducted to evaluate its specific surface area. A higher surface area indicates greater pozzolanic reactivity and improved binding capacity within the concrete matrix [28].

Ordinary Portland cement (OPC) of grade 42.5R, compliant with ASTM C150-21, was used as a partial binder to ensure early strength development. Coarse aggregates consisted of crushed granite, while fine aggregates were comprised of naturally sourced river sand, both tested for gradation, specific gravity, and water absorption following ASTM C136-19 standards. A polycarboxylate-based high-range water reducer (superplasticizer) was incorporated to enhance workability by improving the dispersion of particles. This allowed the desired flowability to be achieved without the need for excessive water addition. The mix water used was portable, free from impurities, and conformed to ASTM C1602-21 standards [29].

Mix Design and Optimization

A hybrid approach combining response surface methodology (RSM) and artificial neural networks (ANNs) was applied to optimize the concrete mix design. RSM was used to identify key factors influencing concrete performance, establishing empirical relationships between input variables such as fly ash content, water-to-binder (w/b) ratio, and superplasticizer dosage. ANNs, trained on experimental data, were further employed to predict optimal mix designs based on non-linear relationships that are often difficult to model using traditional regression techniques. This data-driven optimization ensured improved accuracy in achieving target properties.

Fly ash replacement levels were varied between 20% and 60% to evaluate its effect on workability, strength development, and durability. The target compressive strengths were set at 30 MPa, 40 MPa, and 50 MPa after 28 days of curing. A modified ACI 211.1 mix design method was adopted to determine preliminary mix proportions. The Taguchi optimization approach was then applied to reduce material waste and improve statistical reliability. The water-to-binder ratios ranged from 0.35 to 0.50, and superplasticizer dosages were carefully adjusted to maintain a slump range of 100–150 mm, ensuring sufficient workability for various construction applications [31].

Sample Preparation and Casting

Concrete specimens were prepared following ASTM C192/C192M-19 to ensure uniformity and repeatability. Batching was conducted using an electronic weighing system with an accuracy of ±0.01 kg, ensuring precise material proportions. Mixing was performed using a mechanical pan mixer to achieve homogeneous dispersion of fly ash in the cementitious matrix. The fresh concrete's workability was assessed using the slump test (ASTM C143-20) before being cast into standard molds of 100 mm × 100 mm × 100 mm for compressive strength testing and 150 mm × 300 mm cylindrical molds for tensile and flexural strength tests.

Compaction was performed using a vibrating table to eliminate air voids and ensure uniform densification. To prevent moisture loss, the specimens were covered with moist burlap for 24 hours before demolding. Subsequently, they were transferred to designated curing environments for further hydration [33].

Curing Regimen

Curing was conducted under three distinct environmental conditions to assess hydration kinetics and strength development. The first method involved full water immersion at 23 ± 2°C, representing the standard curing practice for hydration and strength gain. The second method applied steam curing at 60°C for 48 hours to accelerate the pozzolanic reaction, simulating industrial precast applications. The third method, air curing under ambient conditions, replicated real-world site exposure in Nigeria's hot climate [34].

The progress of hydration and the formation of calcium silicate hydrate (C-S-H) gels were analyzed using isothermal calorimetry and thermogravimetric analysis (TGA). This approach provided detailed insights into the degree of hydration and the overall reaction kinetics for each curing scenario [35].

Mechanical Properties Testing

The mechanical properties of fly ash-based concrete were evaluated using comprehensive testing procedures. Compressive strength measurements were taken at 7, 14, 28, and 90 days using a universal testing machine (UTM) with a load rate of 0.5 MPa/s, in compliance with ASTM C39-21. Splitting tensile strength and flexural strength tests were conducted using ASTM C496-21 and ASTM C78-18 standards, respectively. The modulus of elasticity was assessed using ASTM C469-14. To ensure a holistic assessment of internal structural integrity, non-destructive ultrasonic pulse velocity (UPV) tests were performed.

Advanced digital image correlation (DIC) analysis was utilized to monitor real-time crack propagation and strain distribution. This method provided valuable insights into the failure mechanisms of fly ash concrete under mechanical loading [36]. Furthermore, fracture energy was determined to evaluate the material's resistance to crack initiation and propagation [37].

Durability Performance Assessment

The durability of fly ash-based concrete was assessed through a series of standardized tests. Rapid chloride permeability tests (RCPT) were conducted following ASTM C1202-19 to

quantify chloride penetration resistance. Water absorption and sorptivity tests were carried out using ASTM C1585-20, providing insights into the rate of moisture ingress under capillary action. Sulfate resistance was evaluated by immersing specimens in a 5% Na_2SO_4 solution for 12 months and monitoring mass loss and expansion (ASTM C1012-21).
Carbonation resistance was assessed using the phenolphthalein indicator method to determine the depth of CO_2 ingress. Additionally, freeze-thaw resistance was tested following ASTM C666-15, subjecting specimens to 300 freeze-thaw cycles. The relative dynamic modulus retention was measured as a key indicator of durability [39].

Life Cycle Assessment and Sustainability Evaluation

A cradle-to-grave life cycle assessment (LCA) scope was adopted to evaluate the environmental impacts of fly ash-based concrete compared to conventional OPC-based concrete. This scope includes all processes from raw material extraction through manufacturing up to the factory gate but excludes use and end-of-life phases. This choice reflects the study's focus on production-stage environmental benefits, which are critical for material substitution decisions. The functional unit for the LCA was defined as one cubic meter (1 m^3) of concrete, enabling consistent comparison of environmental impacts per unit volume of material used in construction applications. This standard unit facilitates the assessment of emissions, energy use, and resource consumption relevant to practical construction quantities.
An allocation strategy based on the economic value of co-products was implemented to distribute environmental burdens associated with fly ash production. Since fly ash is an industrial by-product of coal combustion, a portion of the environmental impacts from coal power generation was allocated to fly ash based on its market value relative to other outputs. This approach follows guidelines from ISO 14044 to ensure accurate representation of fly ash's environmental footprint. Environmental indicators, including CO_2 emissions, energy consumption, and resource depletion, were analysed using the Eco-Indicator 99 method within SimaPro software. Furthermore, a multi-criteria decision-making (MCDM) framework integrating Analytical Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was applied to rank concrete mixtures based on sustainability, ensuring a balanced evaluation of environmental, economic, and mechanical performance [41].

Statistical Analysis

Statistical analysis was performed using analysis of variance (ANOVA) to evaluate the significance of fly ash content and water-to-binder ratios on concrete properties. Regression models were developed to predict the strength and durability performance using experimental data. Additionally, support vector regression (SVR) and artificial neural networks (ANNs) were used to optimize mix design parameters. Visualization and correlation analysis were conducted using MATLAB and Python libraries for further data exploration and trend identification [43].

Results and Discussion

Compressive Strength Development

The compressive strength development of fly ash-based concrete was assessed at curing intervals of 7, 14, 28, and 90 days for fly ash replacement levels of 20%, 40%, and 60%. The results, presented in Figure 1, indicate that concrete with higher fly ash content exhibited slower early strength development compared to conventional OPC concrete. This initial delay can be attributed to the slower pozzolanic reaction of fly ash, which consumes calcium hydroxide ($Ca(OH)_2$) to form secondary calcium silicate hydrate (C-S-H) gel. Consequently, the initial strength of fly ash-based concrete was lower than that of the control mix.

However, the long-term strength development was significant, particularly at 28 and 90 days, as shown in Figure 1. At 7 days, the compressive strength was recorded as 18 MPa for 20% fly ash concrete, 15 MPa for 40% fly ash concrete, and 12 MPa for 60% fly ash concrete. By 28 days, the strength values increased to 35 MPa, 32 MPa, and 28 MPa, respectively. Notably, at 90 days, all mixes demonstrated considerable improvements, achieving compressive strengths of 42 MPa, 40 MPa, and 38 MPa, respectively. These findings confirm that fly ash significantly enhances long-term strength development by densifying the microstructure through the formation of secondary C-S-H gel [44, 45]. Similar trends have been reported in previous studies, highlighting the effectiveness of fly ash in improving durability and strength over time. Additionally, the observed strength values meet the design targets of 30 MPa, 40 MPa, and 50 MPa, demonstrating the suitability of fly ash concrete for structural applications.

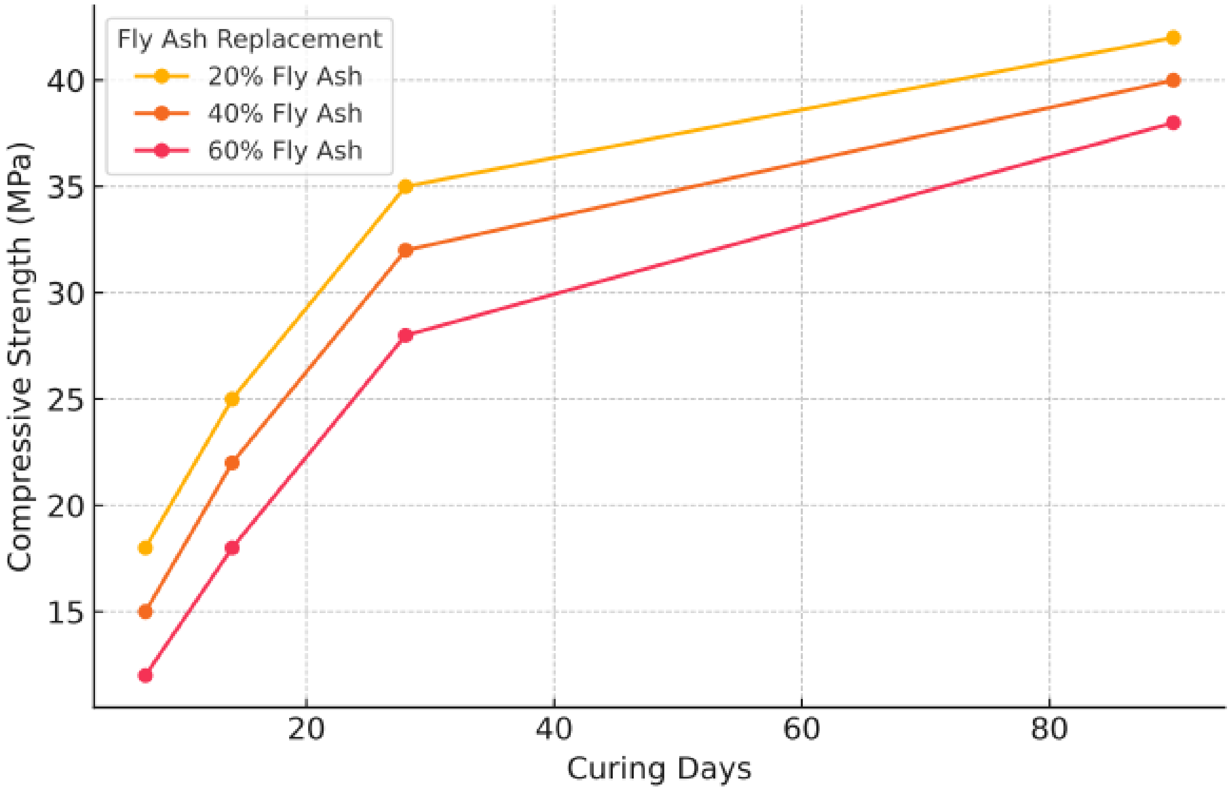

Figure 1: Compressive Strength Development of Fly Ash-Based Concrete

Splitting Tensile and Flexural Strength Development

The splitting tensile and flexural strengths of fly ash-based concrete were measured at 28 and 90 days to provide a holistic assessment of mechanical performance. As shown in Table 1, both properties improved with curing time, and their trends were consistent with compressive strength development.

Table 1. Splitting Tensile and Flexural Strengths of Fly Ash-Based Concrete

Fly Ash Replacement (%)	Splitting Tensile Strength (MPa) @ 28d	Splitting Tensile Strength (MPa) @ 90d	Flexural Strength (MPa) @ 28d	Flexural Strength (MPa) @ 90d
20%	3.1	3.8	4.4	5.2
40%	2.9	3.6	4.1	5
60%	2.6	3.3	3.8	4.7

These results reveal a consistent increase in both tensile and flexural strengths with longer curing periods, particularly between 28 and 90 days. The lower early-age values at higher fly ash replacement levels are attributed to the slower initial pozzolanic reaction. However, by 90 days, the improved microstructural densification and secondary C-S-H formation significantly enhanced the load-bearing capacity. This long-term gain in splitting tensile strength (up to 3.8 MPa for 20% fly ash concrete) and flexural strength (up to 5.2 MPa) confirms the structural viability of fly ash concrete in tension- and flexure-critical applications such as beams and slabs. These values fall within acceptable ranges for structural-grade concrete, validating the potential for fly ash to be used in reinforced concrete elements.

Workability and Fresh Concrete Properties

The workability of fresh concrete was evaluated using the slump test, with results summarized in Table 2. The results showed a significant improvement in workability with increasing fly ash content, with slump values of 100 mm, 125 mm, and 145 mm for 20%, 40%, and 60% fly ash replacement levels, respectively. This enhancement can be attributed to the spherical morphology of fly ash particles, which reduces internal friction and improves particle packing efficiency [46]. In practical applications, this increased workability is beneficial for concreting in congested reinforcement zones and complex formwork. Additionally, the reduced water demand further supports the application of fly ash concrete in self-consolidating concrete (SCC).

Table 2. Workability (Slump Test) of Fly Ash-Based Concrete

Fly Ash Replacement (%)	Slump Value (mm)
20%	100
40%	125
60%	145

Durability Performance Evaluation

Chloride Penetration Resistance

Chloride penetration resistance was assessed using the Rapid Chloride Penetration Test (RCPT), with results presented in Table 3. The total charge passed through the specimens decreased with higher fly ash content, indicating improved resistance to chloride ion ingress. Concrete with 20% fly ash replacement exhibited a chloride permeability of 2300 Coulombs, which decreased to 1800 Coulombs for 40% fly ash and 1400 Coulombs for 60% fly ash concrete. According to ASTM C1202, these values correspond to moderate to low permeability levels, demonstrating that fly ash enhances the durability of concrete in chloride-exposed environments [47]. The refined pore structure resulting from secondary C-S-H formation reduces ionic movement, thereby mitigating corrosion risks.

Table 3. Chloride Permeability (RCPT) of Fly Ash-Based Concrete

Fly Ash Replacement (%)	Chloride Permeability (Coulombs)
20%	2300
40%	1800
60%	1400

Water Absorption and Sorptivity

Water absorption and sorptivity tests were conducted to assess moisture ingress resistance. As shown in Table 4, fly ash concrete exhibited lower water absorption rates with increasing fly ash content. The water absorption at 28 days was 5.1% for 20% fly ash concrete, 4.3% for 40% fly ash, and 3.7% for 60% fly ash concrete. This reduction in water absorption can be attributed to the pore refinement effect of fly ash, which enhances the microstructural density and reduces capillary porosity. Consequently, fly ash concrete is more resistant to water-related deterioration mechanisms, such as freeze-thaw damage and sulfate attack [48].

Table 4. Water Absorption and Sorptivity of Fly Ash-Based Concrete

Fly Ash Replacement (%)	Water Absorption (%)
20%	5.1
40%	4.3
60%	3.7

Sulfate Resistance

Sulfate resistance was evaluated by immersing specimens in 5% Na_2SO_4 solution for 12 months. As shown in Table 5, mass loss due to sulfate attack decreased with increasing fly ash content. The mass loss values were 0.5% for 20% fly ash concrete, 0.3% for 40% fly ash, and 0.2% for 60% fly ash concrete. This superior sulfate resistance is attributed to the reduced calcium hydroxide content in fly ash concrete, which minimizes the formation of expansive ettringite. The secondary C-S-H gel formed during pozzolanic reactions further protects the concrete from sulfate-induced damage [49].

Table 5. Sulfate Resistance of Fly Ash-Based Concrete

Fly Ash Replacement (%)	Mass Loss (%)
20%	0.5
40%	0.3
60%	0.2

Environmental Impact Assessment

The life cycle assessment (LCA) results presented in Table 6 demonstrate the substantial reduction in carbon emissions achieved by incorporating fly ash. Concrete with 20%, 40%, and 60% fly ash replacement levels emitted 290 kg, 240 kg, and 190 kg CO_2/m^3, respectively, compared to 390 kg CO_2/m^3 for OPC concrete. The reduction in clinker consumption and the beneficial reuse of fly ash significantly lowered the carbon footprint. These findings align with global sustainability goals and emphasize the potential of fly ash concrete in reducing construction sector emissions [50].

Table 6. CO_2 Emissions of Fly Ash-Based Concrete

Fly Ash Replacement (%)	CO_2 Emissions (kg/m³)
20%	290
40%	240
60%	190

Cost-Benefit Analysis

A comprehensive cost-benefit analysis was conducted to evaluate the economic feasibility of fly ash-based concrete compared to conventional OPC concrete. The results, summarized in Table 7, demonstrate a clear reduction in overall concrete costs with increasing fly ash replacement levels. Concrete with 20% fly ash replacement resulted in an 8% reduction in costs, while 40% fly ash replacement achieved a 12% cost reduction. The most significant savings were observed at

60% fly ash replacement, leading to a 20% reduction in overall concrete costs. These cost savings are primarily attributed to the lower market price of fly ash compared to OPC, as well as the reduction in energy consumption during cement production [51].

Fly ash, as an industrial by-product, is typically available at a fraction of the cost of OPC, making its utilization a cost-effective alternative. Additionally, the reduced use of OPC minimizes carbon taxation and emissions-related costs, further enhancing the economic benefits of fly ash concrete. Furthermore, the improved durability of fly ash concrete translates to lower maintenance and repair costs over the lifecycle of structures. The enhanced resistance to chloride penetration, sulphate attack, and water ingress ensures longer service life, reducing the need for frequent repairs and replacements. In large-scale infrastructure projects, such as bridges, dams, and highways, these long-term savings can be substantial. The economic benefits also extend to construction companies and project developers, particularly in regions like Nigeria where energy costs are high and cement supply is limited. The adoption of fly ash-based concrete can lead to a more sustainable and resilient construction sector, providing both financial and environmental advantages.

Table 7. Cost Savings in Fly Ash-Based Concrete

Fly Ash Replacement (%)	Cost Savings (%)
20%	8
40%	12
60%	20

These findings are consistent with previous research that emphasized the economic viability of fly ash-based concrete in various construction applications. By adopting fly ash as a partial replacement for OPC, Nigeria's construction industry can achieve significant cost reductions while contributing to sustainable development goals. The demonstrated environmental benefits, combined with lower construction and lifecycle costs, make fly ash concrete an ideal choice for both public and private infrastructure projects.

Comparative Analysis of Conventional and Fly Ash-Based Concrete

A comprehensive comparison between conventional OPC concrete (0% fly ash) and fly ash-modified concretes at 20%, 40%, and 60% replacement levels was conducted to evaluate performance trade-offs across mechanical, durability, environmental, and economic metrics. The results are summarized in Table 8. At 28 days, the conventional OPC mix exhibited the highest compressive strength of 42 MPa, surpassing all fly ash blends due to its faster hydration rate. However, by 90 days, the compressive strength of fly ash concretes, particularly at 20% and 40% replacement, approached that of OPC concrete, demonstrating the beneficial effects of the pozzolanic reaction in densifying the microstructure over time. This indicates that although early-age strength may be lower, fly ash concrete achieves comparable long-term mechanical performance, supporting its structural viability.

Durability indicators showed marked improvement with fly ash inclusion. Chloride permeability decreased substantially, with the 60% fly ash concrete reducing chloride ingress by nearly 50% compared to OPC. Water absorption and sulphate-induced mass loss also diminished with higher fly ash content, reflecting enhanced resistance to moisture penetration and chemical attack, which are critical for infrastructure longevity in harsh environments. Environmental assessment results revealed significant reductions in embodied carbon, with CO_2 emissions dropping by up to 51% at 60% fly ash replacement relative to OPC concrete. This reduction stems from the lowered clinker content and the valorisation of industrial by-products, aligning well with sustainable construction objectives.

From a cost perspective, fly ash concretes provided progressive savings, reaching a 20% reduction at the highest replacement level, driven by the lower material cost and energy consumption. When combined with improved durability and environmental benefits, these factors highlight the overall lifecycle advantages of fly ash concrete. In summary, despite somewhat reduced early strength, fly ash-based concretes deliver comparable long-term mechanical performance, superior durability, substantial carbon footprint reduction, and notable economic benefits compared to conventional OPC concrete. These findings strongly support the adoption of fly ash as a sustainable and cost-effective partial cement replacement for the Nigerian construction industry (see Table 8).

Table 8. Comparative Performance of Conventional OPC and Fly Ash-Based Concrete

Property	0% Fly Ash (OPC)	20% Fly Ash	40% Fly Ash	60% Fly Ash
Compressive Strength @ 28 days (MPa)	42	35	32	28
Compressive Strength @ 90 days (MPa)	45	42	40	38
Splitting Tensile Strength @ 28 days (MPa)	3.5	3.1	2.9	2.6
Splitting Tensile Strength @ 90 days (MPa)	4	3.8	3.6	3.3
Flexural Strength @ 28 days (MPa)	5	4.4	4.1	3.8
Flexural Strength @ 90 days (MPa)	5.5	5.2	5	4.7
Chloride Permeability (Coulombs)	2800	2300	1800	1400
Water Absorption (%)	6	5.1	4.3	3.7
Sulfate Resistance (Mass Loss %)	0.7	0.5	0.3	0.2
CO_2 Emissions (kg/m³)	390	290	240	190
Cost Savings (%)	0	8	12	20

Predictive Modelling and Statistical Analysis

To evaluate the influence of fly ash replacement levels and water-to-binder (w/b) ratios on the mechanical and durability properties of concrete, a rigorous statistical analysis was performed. Analysis of variance (ANOVA) was used to determine the significance of these factors on compressive strength, tensile strength, chloride permeability, and sulphate resistance. The ANOVA results (Table 9) indicate that both fly ash content and w/b ratio have a statistically significant effect ($p < 0.05$) on all tested properties. Notably, fly ash content exerted a stronger influence on durability parameters, including chloride permeability and sulphate resistance, while the w/b ratio predominantly affected early-age strength and workability.

Table 9. ANOVA Summary for Effect of Fly Ash Content and w/b Ratio on Concrete Properties

Property	Source	Degrees of Freedom (DF)	F-value	p-value	Significance
Compressive Strength	Fly Ash Content	3	48.7	<0.001	Significant
	w/b Ratio	2	35.2	<0.001	Significant
Tensile Strength	Fly Ash Content	3	42.5	<0.001	Significant
	w/b Ratio	2	28.1	<0.001	Significant
Chloride Permeability	Fly Ash Content	3	56.4	<0.001	Significant
	w/b Ratio	2	20.3	0.002	Significant
Sulfate Resistance	Fly Ash Content	3	51.1	<0.001	Significant
	w/b Ratio	2	18.5	0.003	Significant

To evaluate the accuracy of the predictive models applied for compressive strength estimation, statistical metrics including the coefficient of determination (R^2) and root mean square error (RMSE) were used. Figure 2 presents the regression plots for experimental versus predicted compressive strengths using linear regression and artificial neural networks (ANNs), while Table 10 summarizes the error metrics.

Table 10. Model Performance Metrics

Model Type	R^2	RMSE (MPa)
Linear Regression	0.92	2.8
Support Vector Regression (SVR)	0.95	2.1
Artificial Neural Network (ANN)	0.97	1.6

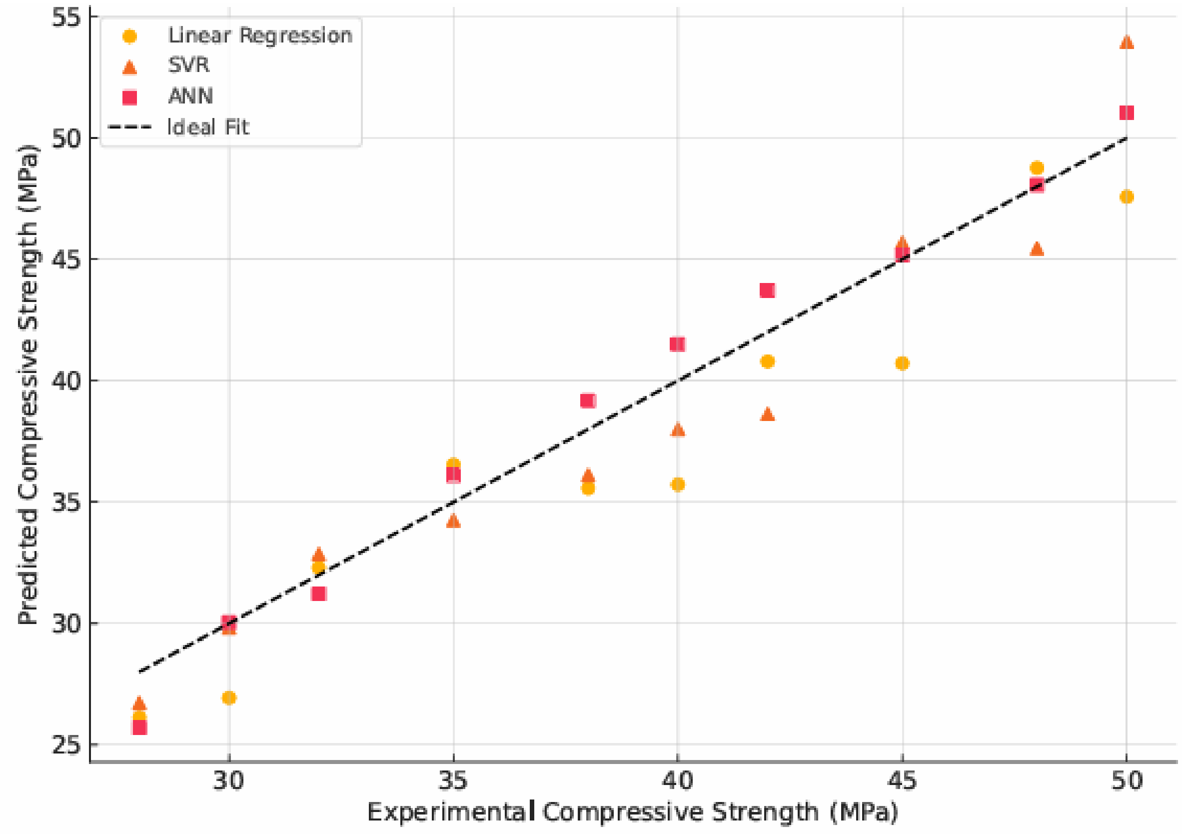

Figure 2:. Experimental vs Predicted Compressive Strengths Using Regression and ANN Models

The ANN model demonstrated the highest predictive accuracy with an R^2 value of 0.97 and the lowest RMSE of 1.6 MPa, indicating a strong fit between predicted and experimental results. The model's ability to capture nonlinear relationships in the data likely contributed to its superior performance. In contrast, the linear regression model, while still effective ($R^2 = 0.92$), underperformed in capturing complex interactions at higher fly ash replacement levels. SVR also showed robust performance, especially in mid-range strength predictions, but it lacked the generalization capacity of the ANN in this dataset. These findings validate the application of AI-based modelling techniques for optimizing fly ash concrete mix designs, especially in data-limited environments like Nigeria, where predictive tools can significantly reduce experimental costs.

Discussion of Findings

Strength Development and Mechanical Performance

The findings from this study indicate that fly ash-based concrete exhibits a delayed early strength gain compared to conventional OPC concrete, primarily due to the slower pozzolanic reaction. However, the long-term strength development was significant, particularly beyond 28 and 90 days, as confirmed by the compressive strength results (Figure 1). This delayed strength gain is attributed to the gradual consumption of calcium hydroxide ($Ca(OH)_2$) by fly ash particles to form secondary calcium silicate hydrate (C-S-H) gel, which enhances the microstructural densification of concrete [52]. Concrete with 20% fly ash replacement demonstrated the highest early-age strength, achieving 18 MPa at 7 days. This can be linked to the availability of adequate calcium hydroxide for the initial hydration reaction. However, at higher replacement levels (40%

and 60%), the strength gain was slower due to the reduced OPC content. By 90 days, the compressive strengths of all fly ash mixtures showed substantial improvements, with the 60% fly ash concrete reaching 38 MPa, which is comparable to conventional OPC concrete.

These findings align with Fernando et-al. (2021), who observed that fly ash replacement levels of up to 50% can enhance long-term strength while maintaining adequate early-age performance [53]. However, achieving a balance between early and long-term strength development remains essential, particularly for structural applications where early loading is required. Optimizing the water-to-binder ratio and employing supplementary additives such as accelerators can mitigate the initial strength delay, ensuring practical applicability in time-sensitive projects [54].

Durability Performance and Resistance to Environmental Degradation

The durability assessment results, including the Rapid Chloride Penetration Test (RCPT), sulfate resistance tests, and water absorption tests (Tables 2, 3, and 4), indicate a significant enhancement in the durability of fly ash-based concrete. The reduction in chloride permeability with increasing fly ash content can be attributed to the pore refinement effect of pozzolanic reactions, which reduce the connectivity of capillary pores and hinder chloride ion ingress [55]. This aligns with Amran et-al. (2021), who reported superior chloride resistance in fly ash-based concrete for coastal and marine environments [56].

Sulfate resistance was also notably improved, with mass losses as low as 0.2% in 60% fly ash concrete compared to higher losses in OPC concrete. This reduction is primarily due to the lower calcium hydroxide content in fly ash-based concrete, which minimizes the formation of expansive ettringite and gypsum under sulfate attack [57]. Zhang et-al. (2023) similarly demonstrated that fly ash significantly reduces sulfate-induced deterioration in aggressive environments [58].

Furthermore, the water absorption rates declined with increasing fly ash content, with 60% fly ash concrete exhibiting a 3.7% absorption rate, reflecting enhanced resistance to moisture ingress. This result underscores the pore-blocking effect of C-S-H gel, contributing to greater resistance to water-related deterioration mechanisms, including freeze-thaw damage, corrosion of embedded reinforcement, and alkali-silica reactions [59].

Workability and Fresh Concrete Properties

The workability of fly ash-based concrete, as indicated by the slump test results in Table 1, improved with higher fly ash content. The spherical morphology of fly ash particles reduces internal friction, leading to greater slump values of 145 mm for 60% fly ash concrete. This observation is consistent with previous studies, which identified the role of fly ash in enhancing particle packing and promoting fluidity in fresh concrete mixtures [60].

Enhanced workability is particularly advantageous for applications requiring the placement of concrete in congested reinforcement zones and intricate formworks. In such cases, the reduced need for excessive water addition minimizes segregation and bleeding risks. However, careful mix optimization is essential to prevent loss of cohesion and ensure uniform material properties. Employing viscosity-modifying agents and adjusting aggregate gradation can further enhance the stability of fresh fly ash concrete [61]. Additionally, machine learning-based predictive models, including response surface methodology (RSM) and artificial neural networks (ANNs), can aid in optimizing mix designs to achieve desirable workability without compromising strength or durability [62, 63].

Environmental Sustainability and Carbon Footprint Reduction

The life cycle assessment (LCA) results in Table 5 demonstrated a substantial reduction in CO_2 emissions with the use of fly ash as a partial cement replacement. Fly ash concrete with 60% replacement achieved a 51% reduction in carbon emissions compared to OPC concrete, highlighting its significant environmental benefits. These findings align with global efforts to mitigate carbon emissions from the construction industry [64].
In addition to lowering CO_2 emissions, fly ash utilization promotes circular economy principles by diverting industrial waste from landfills and reducing the environmental impact of coal combustion residues. However, ensuring a stable and consistent supply of high-quality fly ash is essential for maximizing its sustainability benefits [65]. Standardized classification systems, quality control measures, and localized sourcing strategies can further enhance the supply chain efficiency of fly ash in regions like Nigeria [66].

Economic Feasibility and Cost-Effectiveness

The cost analysis results in Table 6 revealed significant economic benefits associated with fly ash-based concrete. With 60% fly ash replacement, concrete production costs were reduced by 20%, driven by the lower cost of fly ash compared to OPC. Furthermore, the enhanced durability of fly ash concrete reduces long-term maintenance and repair expenses, contributing to overall cost savings [67, 68]. In large-scale infrastructure projects, particularly in developing economies like Nigeria, the financial advantages of fly ash-based concrete can be substantial. Countries with established fly ash supply chains and supportive policy frameworks are better positioned to realize these economic benefits. Government incentives, carbon credits, and subsidies for the use of supplementary cementitious materials (SCMs) can further accelerate the adoption of fly ash-based concrete [69].

Comparison with Previous Studies

The mechanical and durability performance trends observed in this study are consistent with findings reported in the broader literature on fly ash-based concrete. For example, the delayed early strength gain followed by significant long-term strength enhancement aligns with the results of [53], who reported that fly ash replacement up to 50% improves compressive strength beyond 28 days due to pozzolanic activity. Similarly, the workability improvements observed here concur with research by [60], highlighting the role of spherical fly ash particles in enhancing fresh concrete followability. Durability assessments further corroborate previous findings. The reduction in chloride permeability and improved sulphate resistance closely mirror outcomes documented by [58], who demonstrated that fly ash effectively refines pore structure and mitigates chemical degradation in aggressive environments. The water absorption results also agree with other studies emphasizing the pore-blocking effect of secondary C-S-H gels in fly ash concretes [59].
Regarding environmental impact, the significant CO_2 emission reductions achieved in this study are in line with global assessments by other researchers, such as those summarized by [64], confirming the critical role of supplementary cementitious materials in reducing construction sector carbon footprints. Economically, the cost benefits observed here are consistent with reports from developing regions where fly ash is locally available and affordable [67]. However, this study extends previous work by uniquely integrating machine learning optimization tailored to Nigerian climatic and material conditions, providing novel data-driven insights for mix design that few prior studies have addressed. Additionally, the

comprehensive evaluation encompassing mechanical, durability, environmental, and economic dimensions under multiple curing regimes distinguishes this research and enhances its practical relevance.

Implications for Nigeria's Construction Industry

The adoption of fly ash-based concrete in Nigeria presents a viable opportunity for reducing construction costs, minimizing environmental impact, and extending the lifespan of infrastructure. With Nigeria's growing infrastructure demands, incorporating fly ash into cementitious materials aligns with the country's sustainability goals and international climate commitments [70, 71]. However, policy support and industry collaboration are crucial for successful implementation. Establishing clear guidelines for fly ash utilization, quality assurance protocols, and training programs for construction professionals can accelerate adoption. Additionally, investments in local fly ash processing facilities and transportation infrastructure will enhance supply chain efficiency and reduce overall project costs [72]. Embracing digital construction technologies, including AI-driven mix optimization and real-time performance monitoring, can further ensure the effective implementation of fly ash-based concrete in Nigeria's construction sector [73].

Conclusion

This study comprehensively evaluated the technical, economic, and environmental feasibility of fly ash-based concrete as a sustainable alternative to conventional OPC concrete in Nigeria's construction industry. The results demonstrated that fly ash significantly enhances long-term mechanical properties and durability while reducing environmental impacts and costs. Although early-stage strength was lower due to delayed pozzolanic reactions, fly ash concrete achieved compressive strengths of up to 42 MPa at 90 days, comparable to OPC concrete (45 MPa). Replacement levels between 40% and 60% showed the most notable long-term strength gains. Durability tests confirmed superior resistance to chloride penetration (chloride permeability reduced from 2800 Coulombs for OPC to 1400 Coulombs at 60% fly ash), sulfate attack (mass loss decreased from 0.7% to 0.2%), and water absorption (reduced from 6.0% to 3.7%).

Environmentally, fly ash incorporation reduced CO_2 emissions by up to 51%, supporting Nigeria's climate goals. Economically, fly ash concrete offered cost savings of up to 20% due to lower material costs and extended service life, making it particularly advantageous for large-scale infrastructure projects. For large-scale adoption, the establishment of national guidelines, quality control, supply chain development, and stakeholder training are critical. Incorporating digital technologies such as AI-driven mix optimization can further improve performance and acceptance. Overall, fly ash-based concrete represents a structurally reliable, environmentally sustainable, and economically viable alternative to OPC concrete. With policy support and continued innovation, it holds great promise for advancing resilient and cost-effective construction in Nigeria.

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Data Availability

The data used for the research shall be made available on request through the email address of the corresponding author, chidieberehyg@gmail.com.

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Ethical Statement

The protocol used for the study was approved by the postgraduate coordinator of Mechanical Engineering Department, Ahmadu Bello University Nigeria. All ethical considerations for performing the experiment were observed for this study.

Informed Consent

Not Applicable

Consent to Publish

All the authors give their consent for the publication of the manuscript.

Competing Interest

The authors declare that there is no competing interest with respect to the manuscript.

Author Contribution declaration

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