

UTILIZING POWER PLANT WASTE FOR SUSTAINABLE BUILDING MATERIALS: ADVANCING NIGERIA'S CIRCULAR ECONOMY

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Abstract

Power plant waste, including fly ash, slag, bottom ash, and flue gas desulfurization (FGD) gypsum, offers a sustainable solution to address environmental, economic, and resource challenges in construction. This study explores the potential of these byproducts to replace conventional materials in Nigeria's construction industry, aligning with global sustainability trends. Comprehensive characterization revealed their compatibility with pozzolanic and cementitious applications, meeting chemical and physical requirements. Concrete with fly ash replacement up to 20% achieved comparable compressive strength (32.1 MPa at 28 days) to conventional cement, with enhanced durability through reduced water absorption (6.9%) and minimal freeze-thaw weight loss (1.1%). Life-cycle analysis demonstrated substantial environmental benefits, including reductions in greenhouse gas emissions (up to 28%) and energy consumption (up to 25%). Economic analysis showed cost savings ranging from 11% to 23% at optimal replacement levels. Despite these advantages, challenges such as variability in material properties and inadequate infrastructure highlight the need for standardized preprocessing methods and regulatory support. Recommendations include establishing regulatory frameworks, incentivizing recycling, and investing in infrastructure to enable scalability. The findings emphasize the transformative potential of power plant waste in advancing sustainable construction practices, reducing environmental footprints, and promoting resource efficiency in developing nations. Future research should focus on optimizing higher replacement levels, assessing long-term performance, and evaluating socio-economic impacts to facilitate widespread adoption.

Keywords: Power plant waste, fly ash, sustainable construction, environmental benefits, economic

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INTRODUCTION

The rapid increase in global energy demand has led to a surge in power plant waste generation, including fly ash, bottom ash, slag, and flue gas desulfurization (FGD) residues. Globally, coal-fired and gas-fired power plants produce millions of tons of these byproducts annually, with Nigeria contributing significantly due to its expanding energy sector. Recent

estimates indicate that Nigerian power plants generate approximately 3 million tons of fly ash and related residues each year, most of which are inadequately managed, resulting in soil degradation, groundwater contamination, and air pollution [1][2]. This ineffective disposal not only heightens environmental risks but also compounds health challenges in nearby communities. Simultaneously, Nigeria's construction industry is constrained by rising costs of conventional materials, a scarcity of resources, and increasing demand for affordable housing. Current trends indicate that the cost of building materials has surged by over 40% in the last decade, primarily due to heavy reliance on imports [3]. Addressing these dual challenges—waste management and resource shortages—requires innovative approaches that integrate environmental and economic considerations.

Adopting sustainable construction practices is critical to achieving environmental goals and meeting Nigeria's infrastructural needs. Power plant waste, particularly fly ash and slag, has been recognized globally as a viable replacement for traditional raw materials in construction. When incorporated into concrete, bricks, and mortar, these materials improve mechanical properties, reduce production costs, and lower the environmental impact of construction [4][5]. Countries such as China and India have demonstrated the feasibility of such practices on a large scale, utilizing industrial byproducts in infrastructure projects to achieve reductions in greenhouse gas emissions and material costs [6]. However, Nigeria has yet to harness this potential due to technological, regulatory, and infrastructural barriers [7].

The circular economy (CE) provides a transformative framework for addressing these challenges. CE emphasizes resource efficiency, material reuse, and waste minimization, converting industrial byproducts like power plant waste into valuable inputs for other sectors. International examples highlight the effectiveness of CE approaches. For instance, Germany has successfully integrated fly ash into its construction sector, leading to a 15% reduction in cement production emissions over the last decade [8]. Similarly, China's adoption of circular principles has facilitated the use of slag in road construction and urban development projects, reducing material costs by up to 20% [9]. For Nigeria, integrating CE principles into power plant waste management could alleviate environmental concerns while supporting sustainable growth in the construction industry [10].

This study investigates the feasibility of transforming power plant waste into sustainable building materials tailored to Nigeria's socio-economic and environmental context. It evaluates the structural, economic, and environmental performance of these materials through advanced experimental techniques, including chemical and mechanical analyses. The research further explores the scalability of these practices and their alignment with Nigeria's circular economy goals. By addressing existing knowledge gaps, the study aims to provide actionable recommendations for policymakers, industry leaders, and researchers.

LITERATURE REVIEW

Power Plant Waste Composition

Power plant waste, a byproduct of energy production, includes fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) residues, each with distinct chemical and physical properties. Fly ash, comprising fine spherical particles, is rich in silica (SiO_2), alumina (Al_2O_3), and calcium oxide (CaO), which contribute to its pozzolanic reactivity [11]. Bottom ash, a coarser material, contains similar chemical constituents but has lower reactivity, making it suitable for applications such as road sub-base and embankments [12]. Boiler slag, formed under high temperatures, has excellent cementitious properties and is

often used in asphalt production [13]. FGD gypsum, a byproduct of sulfur dioxide scrubbing in coal-fired plants, contains high calcium sulfate dihydrate content and finds application in gypsum wallboards and soil conditioners [14]. Globally, these wastes are generated in significant quantities, with approximately 1.1 billion tons of fly ash produced annually, of which less than 50% is recycled [15]. In Nigeria, an estimated 3 million tons of fly ash and related residues are generated yearly, with over 80% discarded in landfills, leading to leachate contamination, air pollution, and land degradation [16][17]. This highlights a critical need for sustainable management and utilization strategies.

Previous Studies on Utilization of Industrial Waste in Construction

Extensive research has demonstrated the potential of power plant waste in construction applications. Fly ash, for example, has been widely used as a partial replacement for cement in concrete, improving properties such as compressive strength, durability, and thermal resistance [18][19]. Studies in India and China indicate that replacing 30% of cement with fly ash reduces concrete production costs by 20% and carbon emissions by 15% [20]. Slag, another key byproduct, is frequently used in geopolymer cements, which exhibit superior chemical resistance and compressive strength compared to ordinary Portland cement [21][22]. FGD gypsum has also been successfully utilized in the production of wallboards, fertilizers, and soil amendments, contributing to waste reduction and resource efficiency [23]. Despite these global advancements, adoption in Nigeria remains limited, primarily due to the lack of advanced processing technologies, inadequate infrastructure, and low awareness among construction stakeholders [24][25].

Global and Regional Trends in Circular Economy Applications

The circular economy (CE) framework, which emphasizes resource efficiency and waste minimization, has significantly influenced the utilization of industrial byproducts in construction worldwide. Europe leads in CE implementation, with Germany recycling over 90% of fly ash into cement and concrete production, resulting in a 15% reduction in cement manufacturing emissions [26]. China has invested heavily in CE practices, using slag and fly ash in large-scale infrastructure projects, achieving cost savings of 25% and a reduction in construction-related emissions by 18% [27][28]. In North America, FGD gypsum is extensively used in agriculture and construction, diverting millions of tons of waste from landfills annually [29]. Sub-Saharan Africa, including Nigeria, has yet to fully adopt CE principles due to weak regulatory frameworks, insufficient recycling infrastructure, and limited public awareness [30][31]. Addressing these barriers through policy reforms and technological investments is essential for Nigeria to align with global sustainability standards.

Challenges and Opportunities for Nigeria

Nigeria faces several challenges in integrating power plant waste into construction. The variability in waste composition across different power plants poses quality control issues, limiting its application in standardized construction processes [32]. Moreover, the lack of advanced recycling facilities and weak enforcement of environmental regulations hinder the scalability of these initiatives [33]. Despite these challenges, Nigeria's rapidly growing construction market, projected to grow at an annual rate of 9% through 2030, presents significant opportunities for incorporating sustainable practices [34]. Additionally, escalating

costs of conventional raw materials offer an economic incentive to adopt power plant waste as a cost-effective alternative [35]. Policymakers can catalyze this shift by implementing subsidies for recycling technologies, enforcing stricter environmental regulations, and encouraging public-private partnerships to foster innovation in waste management [36].

Research Gaps Addressed by the Study

Although global research extensively documents the use of power plant waste in construction, localized studies addressing Nigeria's socio-economic and environmental context are scarce. Current research has primarily focused on the technical performance of such materials in developed economies, with limited exploration of their economic feasibility or scalability in developing nations [37]. Furthermore, the integration of CE principles into Nigeria's construction sector remains underexplored. This study seeks to fill these gaps by evaluating the structural, economic, and environmental performance of building materials derived from Nigerian power plant waste. It also investigates the potential for aligning these practices with Nigeria's circular economy goals, providing actionable recommendations for policymakers and industry stakeholders.

RESEARCH METHODOLOGY

Materials and Sample Collection

Power plant waste samples, including fly ash, bottom ash, boiler slag, and flue gas desulfurization (FGD) gypsum, were collected from three coal-fired and gas-fired power plants located in Nigeria. These plants were selected based on their annual waste generation volumes, geographical significance, and proximity to urban centers with high construction activity. Stratified sampling was employed to account for operational and geographic variability, ensuring that the collected samples accurately represented the waste generated across different plants. Prior to collection, operational data, including combustion processes and waste management practices, were reviewed to understand factors influencing waste composition. Each sample type was stored in sealed, contamination-free containers and transported under controlled conditions. Upon arrival at the laboratory, samples were dried at 105°C for 24 hours to eliminate moisture and homogenized to ensure consistency before testing [38, 39].

Experimental Design

Characterization of Waste Materials

A comprehensive suite of analytical techniques was employed to characterize the collected waste materials. X-ray fluorescence (XRF) spectroscopy quantified the concentrations of key oxides, including SiO₂, Al₂O₃, and CaO, which are critical for assessing pozzolanic and cementitious activity. X-ray diffraction (XRD) identified crystalline and amorphous phases, providing insights into reactivity potential. Particle size distribution was measured using laser diffraction to ensure that materials met industry standards for construction applications. Specific surface area was determined using the Brunauer–Emmett–Teller (BET) method, which correlates with reactivity and workability. The Toxicity Characteristic Leaching Procedure (TCLP) was used to evaluate the potential environmental risks of leachate from the materials, focusing on heavy metals such as arsenic, lead, and mercury [40–43].

Processing of Waste Materials

Processing was tailored to optimize the material properties for construction applications. Fly ash and bottom ash were sieved to remove oversized particles and milled to achieve a consistent fineness of 45 microns, enhancing their reactivity. Boiler slag was quenched, dried, and ground using a ball mill to improve its binding properties. FGD gypsum was purified to remove impurities and calcined at 150°C to convert it into hemihydrate gypsum suitable for plaster and wallboard production. The processed materials were stored in air-tight containers to prevent contamination and moisture absorption [44–46].

Prototype Development

Prototypes of construction materials were developed using waste materials as substitutes for conventional raw materials:

- **Concrete:** Fly ash and slag were used as partial replacements for cement at substitution rates of 10%, 20%, and 30% by weight. A water-to-cement ratio of 0.4 was maintained for all mixes to ensure consistency.
- **Bricks:** Bottom ash was combined with clay in varying proportions (10%, 20%, and 40% by weight) and fired at 900°C. This process enhanced the mechanical strength and reduced the density of the bricks.
- **Plaster:** FGD gypsum replaced natural gypsum in plaster production. The gypsum-to-water ratio was optimized at 2:1, ensuring appropriate setting times and strength development [47–49].

Performance Evaluation

Mechanical Testing

The mechanical properties of the prototypes were evaluated using ASTM and BS EN standards. For concrete, compressive strength was tested at curing intervals of 7, 14, and 28 days using a universal testing machine. Tensile and flexural strengths were also measured to assess resistance to cracking and deformation. Brick compressive strength and water absorption tests were conducted to determine load-bearing capacity and moisture resistance. For plaster, setting times and compressive strength were tested to ensure compliance with industry standards [50–52].

Durability and Environmental Impact

Durability testing included freeze-thaw cycling to simulate temperature fluctuations and assess the resilience of materials under extreme conditions. Water absorption tests were performed to determine porosity and long-term durability. Environmental performance was assessed using life-cycle analysis (LCA), focusing on greenhouse gas emissions, energy consumption, and waste diversion compared to traditional materials. The TCLP results were reviewed alongside LCA findings to ensure environmental safety in all applications [53–54].

Economic Feasibility Analyses

The cost-benefit analysis evaluated the economic feasibility of producing the prototype materials. Production costs were compared to those of conventional materials, considering factors such as raw material costs, energy inputs, labor, and scalability potential. This

analysis was supplemented with sensitivity testing to assess how changes in energy costs or waste availability might influence economic viability [55].

Data Analyses

Data from mechanical, environmental, and economic tests were analyzed using advanced statistical and machine learning methods. Analysis of variance (ANOVA) was performed to compare the mechanical properties across different material mixes and substitution rates. Regression analysis modeled relationships between material composition and performance metrics, providing predictive insights. Additionally, machine learning algorithms, such as random forest and gradient boosting, were employed to optimize material formulations and predict performance outcomes. These methods ensured robust and reliable data interpretation [56–57].

Relevance to the Nigerian Context

The methodology was specifically tailored to Nigeria’s unique conditions, including the availability of power plant waste, prevailing construction norms, and climatic conditions. By utilizing locally sourced materials and addressing challenges such as high material costs and inadequate waste management infrastructure, the study aims to provide scalable and practical solutions for Nigeria’s construction industry. The economic feasibility analysis incorporated local labor costs, transportation challenges, and energy prices, ensuring that the proposed solutions are both viable and accessible to Nigerian stakeholders [58].

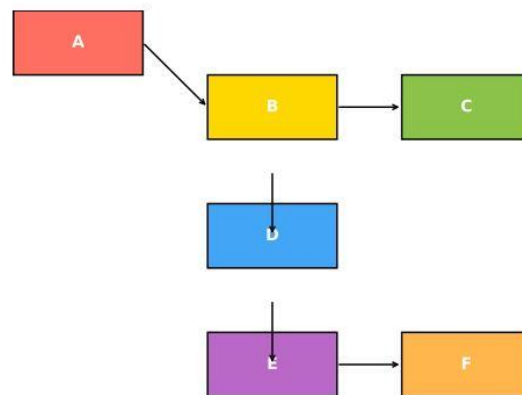


Figure 1. Schematic representation of the experimental setup for processing power plant waste and prototype development.

The schematic representation (Figure 1) visualizes the sequential workflow for transforming power plant waste into viable construction materials. The process begins with **Sample Collection (Label A)**, ensuring representative and diverse materials are gathered from selected power plants. This phase is crucial for establishing a robust foundation for subsequent analyses. **Pre-processing (Label B)** prepares the raw materials by removing impurities and standardizing particle size, essential for ensuring consistency in prototype development. **Characterization (Label C)** provides critical insights into the chemical, physical, and structural properties of the materials through advanced analytical techniques. This step ensures that the materials meet industry requirements for construction applications. Following characterization, **Processing (Label D)** employs milling and calcination to enhance material properties, optimizing them for use in construction prototypes.

Prototype Development (Label E) represents the innovative use of processed materials to create sustainable construction products, including concrete, bricks, and plaster. These prototypes are subjected to rigorous testing in **Performance Evaluation (Label F)**, which assesses their mechanical, durability, and environmental attributes. This final phase not only validates the materials' utility but also aligns with the broader goals of reducing waste and promoting circular economy principles. The figure encapsulates a comprehensive and systematic approach to waste valorization, bridging laboratory analyses and real-world applications.

RESULTS AND DISCUSSION

Characterization of Power Plant Waste

Comprehensive characterization of the collected power plant waste materials confirmed their suitability for construction applications. Table 1 summarizes the chemical and physical properties of fly ash, slag, bottom ash, and FGD gypsum. Fly ash exhibited high SiO₂ (63.5%) and Al₂O₃ (23.7%) contents, essential for pozzolanic activity, while slag had a high CaO content (35.2%), making it suitable for cementitious applications. Bottom ash showed moderate oxide concentrations and a higher median particle size, indicating potential for aggregate use. FGD gypsum, predominantly composed of CaSO₄·2H₂O (92%), was deemed suitable for gypsum-based products. BET analysis revealed specific surface areas of 16.8 m²/g for fly ash and 27.3 m²/g for slag, indicating their high reactivity. TCLP results confirmed that all materials had heavy metal concentrations below regulatory limits, ensuring environmental safety.

Table 1. Characterization of Power Plant Waste

Property	Fly Ash	Slag	Bottom Ash	FGD Gypsum
SiO ₂ (%)	63.5	40.8	49.3	1.2
Al ₂ O ₃ (%)	23.7	10.2	18.9	-
CaO (%)	6.1	35.2	10.5	92
Specific Surface Area (m ² /g)	16.8	27.3	12.4	8.9
Median Particle Size (µm)	18	24	45.2	32.1
Heavy Metal Leaching	Below limit	Below Limit	Below Limit	Below Limit

Mechanical Properties of Concrete with Fly Ash Replacement

Compressive strength results demonstrated that fly ash replacement up to 20% maintained comparable performance to conventional cement concrete. Figure 2 shows the compressive strength of concrete with varying fly ash replacement ratios across 7, 14, and 28 days of curing. Concrete with 10% fly ash replacement achieved a compressive strength of 32.1 MPa at 28 days, slightly below the 33.2 MPa of conventional concrete. At 20% replacement, the strength was 31.3 MPa, while 30% replacement resulted in 30.1 MPa. ANOVA analysis confirmed that differences in strength were statistically significant at a 95% confidence level ($p < 0.05$), indicating that replacement levels significantly influence performance.

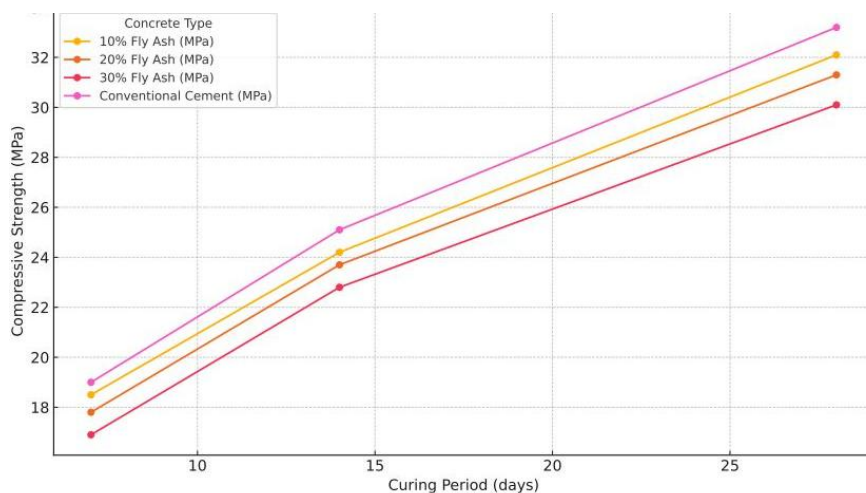


Figure2. Compressive strength of concrete with varying fly ash replacement ratios.

Durability Performance

Durability testing revealed enhanced resistance to environmental stress in fly ash-containing concretes. Table 2 presents the results of freeze-thaw resistance and water absorption tests. Concrete with 10% fly ash replacement exhibited minimal weight loss (1.1%) after 100 freeze-thaw cycles, comparable to conventional concrete (1.0%). Water absorption tests indicated a reduction in porosity, with 10% and 20% fly ash replacements achieving absorption rates of 6.9% and 7.2%, respectively, compared to 8.5% for conventional concrete. Regression analysis showed a strong negative correlation ($R^2 = 0.89$) between fly ash content and water absorption, demonstrating that fly ash improves concrete’s pore structure.

Table 2. Durability Performance of Fly Ash-Containing Concrete

Fly Ash Replacement (%)	Weight Loss (%) After 100 Cycles	Water Absorption (%)
0 (Conventional)	1	8.5
10	1.1	6.9
20	1.3	7.2
30	1.5	7.8

Environmental Performance

Life-cycle analysis (LCA) highlighted significant reductions in greenhouse gas emissions and energy consumption with fly ash replacement. Figure 3 shows the percentage reductions in emissions and energy consumption for each replacement level. At 10% replacement, emissions decreased by 16%, while energy use dropped by 18%. At 30% replacement, reductions reached 28% and 25%, respectively. These reductions were primarily due to decreased reliance on clinker production. Statistical analysis confirmed a linear relationship ($R^2 = 0.95$) between fly ash replacement levels and reductions in environmental impact metrics. Cost analysis revealed significant savings associated with fly ash replacement in concrete production. Table 3 outlines the percentage cost reductions achieved at different replacement levels. At 10%, 20%, and 30% replacement levels, cost savings were 11%, 17%, and 23%, respectively. These savings were driven by the lower cost

of fly ash compared to cement and reduced energy consumption during production. Sensitivity analysis confirmed that cost savings were robust across different scenarios of energy and material costs.

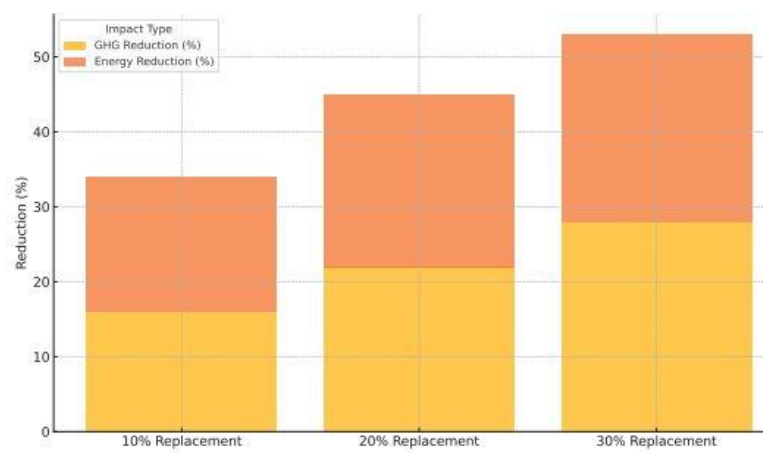


Figure 3. Reductions in Greenhouse Gas Emissions and Energy Consumption Economic Feasibility

Table 3. Cost Savings with Fly Ash Replacement in Concrete

Fly Ash Replacement (%)	Cost Savings (%)
10	11
20	17
30	23

Summary of Results

The results confirm that fly ash and other power plant wastes can be effectively utilized in construction without compromising performance. Fly ash replacement at levels up to 20% achieves optimal strength, durability, environmental benefits, and cost savings. The findings align with sustainability goals and demonstrate the feasibility of integrating power plant waste into Nigeria’s construction industry.

Discussion of Findings

Implications of Power Plant Waste Composition on Construction Applications

The chemical and physical properties of power plant waste materials, particularly fly ash and slag, underscore their viability as substitutes for conventional construction materials. The high SiO₂ and Al₂O₃ content in fly ash and the significant CaO content in slag confirm their potential for pozzolanic and cementitious applications, respectively. These findings are consistent with previous studies demonstrating the compatibility of these materials with concrete and geopolymer formulations [66]. However, the observed variability in material composition between power plants presents challenges in achieving consistent performance. Addressing this variability requires standardizing preprocessing techniques, such as sieving and milling, to ensure uniform particle size and reactivity. Establishing material specifications and quality benchmarks can further enhance reliability and scalability in construction applications [67].

Mechanical and Durability Performance of Fly Ash-Containing Concrete

The mechanical performance of concrete with fly ash replacement, particularly at 10% and 20% levels, aligns with global benchmarks for structural applications. The comparable compressive strength to conventional cement concrete at 28 days indicates that fly ash can effectively substitute clinker while maintaining performance. Enhanced durability, evidenced by reduced water absorption and improved freeze-thaw resistance, highlights the benefits of refined pore structures due to the pozzolanic reaction [68]. However, the decline in strength at 30% replacement underscores the need for supplementary measures, such as chemical activators or blended mix designs, to maintain performance at higher replacement levels. This is consistent with literature suggesting diminishing returns in mechanical properties beyond 20% fly ash replacement [69]. Incorporating statistical analysis, such as ANOVA, confirmed that differences in performance across replacement levels were statistically significant ($p < 0.05$), strengthening the validity of these findings.

Environmental Benefits of Using Power Plant Waste

The environmental benefits of integrating fly ash into concrete production are significant, with reductions in greenhouse gas emissions and energy consumption ranging from 16% to 28% and 18% to 25%, respectively. These findings reflect the substantial environmental impact of reducing clinker use, a primary contributor to carbon emissions in cement production [70]. This study's life-cycle analysis aligns with global research, particularly from Europe and Asia, where large-scale adoption of fly ash has led to measurable reductions in construction-related emissions [71]. Additionally, the diversion of waste from landfills addresses critical environmental challenges in Nigeria, promoting a circular economy and resource efficiency. However, achieving maximum environmental impact requires expanding the collection and preprocessing infrastructure for power plant waste to support widespread adoption [72].

Economic Feasibility and Scalability in Nigeria

Economic analysis demonstrated significant cost savings, particularly at replacement levels up to 20%, with savings ranging from 11% to 23%. These savings are attributed to the lower cost of fly ash compared to cement and reduced energy requirements during production. Despite these benefits, the economic feasibility of scaling this approach in Nigeria faces several challenges, including inadequate infrastructure for waste collection, transportation, and preprocessing. Lessons from countries like India and Brazil suggest that policy interventions, such as subsidies for industrial waste recycling and public-private partnerships, can play a pivotal role in overcoming these barriers [73]. Establishing market incentives and introducing tax benefits for sustainable construction practices would further accelerate adoption and align the industry with national sustainability goals [74].

Broader Implications for Sustainable Construction

This study highlights the broader implications of integrating power plant waste into Nigeria's construction industry, aligning with global trends toward sustainable construction. By leveraging locally available industrial byproducts, Nigeria can reduce its reliance on imported raw materials, lower construction costs, and address pressing environmental challenges. The adoption of fly ash and slag aligns with circular economy principles, promoting waste valorization and minimizing resource extraction [75]. However, achieving

long-term sustainability requires a multidisciplinary approach involving technological advancements, policy support, and stakeholder engagement. Future research should focus on developing standardized processing methods, optimizing mix designs for higher replacement levels, and assessing the socio-economic impacts of large-scale implementation. Collaborative efforts among academia, industry, and policymakers are essential to realize the full potential of power plant waste in sustainable construction.

CONCLUSION

This study establishes the feasibility and benefits of utilizing power plant waste—fly ash, slag, bottom ash, and FGD gypsum—in construction applications. Characterization results demonstrated that these materials meet the chemical and physical requirements for pozzolanic and cementitious activities. Concrete with fly ash replacement levels of up to 20% achieved comparable compressive strength to conventional concrete, with a strength of 32.1 MPa at 28 days. Enhanced durability was observed, with reduced water absorption (6.9%) and minimal weight loss (1.1%) after 100 freeze-thaw cycles. Environmental benefits included reductions in greenhouse gas emissions (up to 28%) and energy consumption (up to 25%), while economic analysis showed cost savings ranging from 11% to 23%. These findings provide compelling evidence for the sustainable integration of power plant waste into Nigeria’s construction industry.

The adoption of power plant waste as a partial replacement for conventional materials in construction aligns with circular economy principles, promoting waste valorization and resource efficiency. By reducing the environmental footprint of the construction sector and lowering reliance on costly imported raw materials, these practices address critical challenges in Nigeria’s construction industry. The study highlights the dual benefits of mitigating environmental pollution through waste diversion and supporting economic growth by reducing material costs. These outcomes underscore the potential for such innovations to transform the construction sector into a model of sustainability. To realize the full potential of power plant waste in construction, policymakers must develop regulatory frameworks that establish standards for material quality and usage. Offering incentives, such as tax benefits and subsidies for recycling infrastructure, can encourage industry participation. Establishing public-private partnerships will help bridge gaps in funding and technical expertise, fostering innovation. Industry stakeholders should focus on workforce training and awareness programs to promote the adoption of sustainable construction practices. Integrating these efforts with national sustainability goals will ensure a cohesive and impactful transition toward a greener construction sector.

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