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Research Article

DEVELOPMENT OF LOW-CARBON GEOPOLYMER CONCRETE USING FLY ASH AND INDUSTRIAL SLAG AS SUSTAINABLE MATERIAL ENGINEERING

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Abstract

The construction industry is a major contributor to global carbon emissions, with traditional *Portland cement* production accounting for approximately 8% of total CO_2 output. The development of *low-carbon* alternatives is essential to achieving sustainability goals and reducing the environmental footprint of infrastructure. This research focuses on developing *geopolymer concrete* using fly ash and industrial slag as sustainable raw materials, offering a viable substitute for ordinary *Portland cement*. The objective of the study is to evaluate the mechanical performance, durability, and carbon footprint reduction potential of *geopolymer concrete* mixtures under varied proportions of fly ash and slag. A quantitative experimental method was employed, involving the synthesis of multiple mix designs with differing binder ratios, followed by compressive strength testing, microstructural analysis, and l*ifecycle assessment (LCA)*. The results indicate that the optimal blend of 60% fly ash and 40% slag achieved a 42% reduction in carbon emissions compared to conventional concrete while maintaining a compressive strength exceeding 45 MPa after 28 days of curing. The inclusion of slag significantly enhanced early strength development and chemical stability due to calcium enrichment, while the use of fly ash contributed to long-term durability. The study concludes that fly ash–slag–based *geopolymer concrete* represents a promising *low-carbon* alternative, combining industrial waste valorization with superior structural performance. Future applications could advance sustainable material engineering practices in both civil and environmental infrastructure sectors.

Keywords: Fly Ash, Geopolymer concrete, Industrial Slag

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INTRODUCTION

The construction industry stands as one of the largest contributors to global carbon emissions, with conventional *Portland cement* production accounting for nearly 8% of total anthropogenic CO_2 emissions (Abbasi Zargaleh et al., 2025). The chemical process of clinker production and the high energy demands of cement manufacturing intensify environmental degradation and accelerate climate change. As nations strive toward net-zero targets, the need for eco-efficient materials capable of reducing carbon intensity without compromising performance has become increasingly urgent (Adebayo et al., 2024).

Researchers and engineers have long recognized the environmental burden associated with cement-based materials (Ahıskalı et al., 2024). Traditional concrete, while structurally reliable, exhibits unsustainable characteristics due to its dependency on non-renewable raw materials and high embodied energy. This awareness has fueled global interest in developing *low-carbon* alternatives that can sustain modern infrastructure while mitigating environmental impacts (Ali et al., 2024).

Geopolymer technology has emerged as a transformative innovation in sustainable material science. By activating aluminosilicate-rich industrial by-products such as fly ash and slag with alkaline solutions, *geopolymer concrete* eliminates the need for *Portland cement* while achieving comparable or superior mechanical properties (Amin et al., 2025). The chemical composition of these materials promotes a polymeric network that enhances durability, chemical resistance, and thermal stability (Araújo et al., 2025).

Fly ash, a by-product of coal combustion, and *ground granulated blast furnace slag (GGBFS)*, derived from steel manufacturing, represent abundant sources of reactive aluminosilicates (Bao et al., 2024). Their utilization not only reduces waste accumulation but also contributes to circular economy practices within the industrial ecosystem. Converting such wastes into high-performance binders offers a dual benefit of environmental remediation and resource efficiency (Bayraktar et al., 2024).

Empirical studies have demonstrated that *geopolymer concrete* can reduce greenhouse gas emissions by up to 80% relative to traditional cementitious materials (Bypour et al., 2025). Moreover, its performance under various curing conditions and exposure environments shows promise for both structural and non-structural applications. This evidence positions geopolymer technology as a cornerstone for sustainable construction aligned with global decarbonization goals (Chen et al., 2025).

Current advancements in material science underscore the compatibility of *geopolymer concrete* with modern engineering demands, yet practical adoption remains limited. Despite proven potential, there are still challenges in standardization (Elhag et al., 2025), field implementation, and large-scale acceptance across industries. Addressing these issues requires comprehensive investigation into mix design optimization and performance consistency across diverse material sources (Emarah, 2025).

The existing body of research lacks consensus on the optimal combination and activation parameters of fly ash and industrial slag in *geopolymer concrete* formulations (Fang et al., 2025). Variations in chemical composition, fineness, and reactivity of these materials yield inconsistent results across studies, making it difficult to establish universal mix design standards for large-scale applications (Faraji et al., 2025).

There is limited understanding of how different proportions of fly ash and slag influence the balance between early-age strength and long-term durability. While slag enhances calcium-based reactions promoting rapid strength gain, excessive slag may compromise workability and increase shrinkage risks (Ferreira et al., 2025). Conversely, high fly ash content may delay setting and reduce early compressive strength. The trade-offs among these factors remain underexplored (Ghafoor et al., 2025).

Lifecycle environmental assessments of *geopolymer concrete*s also remain fragmented. Few studies have holistically quantified carbon savings, energy efficiency, and waste utilization potential across the full production chain—from raw material acquisition to end-of-life scenarios (Gopalakrishna & Dinakar, 2024). This absence of comprehensive LCA data limits policymakers' and practitioners' ability to evaluate the true sustainability performance of geopolymer systems (Hu et al., 2025).

The socio-technical dimensions of geopolymer adoption—such as cost competitiveness, material availability, and industry readiness—are also insufficiently addressed (Karaaslan, 2025). The lack of integration between laboratory research and industrial-scale practice leaves an implementation gap that hinders *geopolymer concrete*'s mainstream adoption in the construction sector (Karthik et al., 2024).

Filling these knowledge gaps is essential to accelerate the transition toward sustainable and *low-carbon* construction technologies. A systematic understanding of fly ash–slag synergy will provide a foundation for designing *geopolymer concrete*s with optimized mechanical, environmental, and economic performance (Kong et al., 2025). This advancement can inform material standards, industrial practices, and policy frameworks supporting the global decarbonization agenda (Magotra & Jee, 2024).

The rationale for this study rests on the potential of *geopolymer concrete* to transform waste management into resource engineering. By valorizing industrial by-products as functional materials, this research not only mitigates environmental hazards but also contributes to circular economy development (Hazmi et al., 2025). The study adopts a holistic approach that combines experimental mix design optimization with lifecycle assessment to ensure both technical reliability and sustainability validation.

The purpose of this investigation is to develop a *low-carbon geopolymer concrete* formulation that achieves structural integrity comparable to conventional concrete while significantly reducing CO_2 emissions. Through empirical testing and environmental analysis, the study aims to demonstrate that sustainable material engineering is not a theoretical ideal but a practical pathway toward carbon-neutral construction and responsible industrial innovation (Sinolinding et al., 2025).

RESEARCH METHOD

Research Design

This research employed an experimental quantitative design aimed at developing and evaluating *low-carbon geopolymer concrete* through the utilization of fly ash and industrial slag as primary binder materials. The study focused on identifying the optimal blend ratio that yields the best balance between mechanical strength, durability, and environmental performance (Maradani & Pradhan, 2024). A factorial design approach was adopted to systematically vary the proportions of fly ash and slag, allowing the analysis of their individual and interactive effects on compressive strength and carbon footprint. The study also integrated a l*ifecycle assessment (LCA)* to quantify the environmental advantages of the proposed mix designs compared to conventional *Portland cement*-based concrete (Min et al., 2024).

Population and Samples

The population of this study encompassed geopolymer binder materials derived from industrial by-products, including fly ash from coal-fired power plants and *ground granulated blast furnace slag (GGBFS)* from steel industries. The sample consisted of six different *geopolymer concrete* mixtures with varying ratios of fly ash to slag: 100:0, 80:20, 60:40, 40:60, 20:80, and 0:100. Each mix was replicated three times to ensure data reliability and statistical validity (Raj P K et al., 2025). All materials used were sourced from certified industrial suppliers in order to maintain compositional consistency and traceability. The sample size provided adequate representation for testing mechanical and environmental performance variables under controlled laboratory conditions.

Instruments

Data were collected using a combination of mechanical testing and environmental analysis instruments. Compressive strength was measured using a Universal Testing Machine (UTM) in accordance with ASTM C39/C39M standards. Workability and setting time were evaluated using the slump cone test and Vicat apparatus, respectively (Rawat & Pasla, 2024). Microstructural characteristics were examined through *Scanning Electron Microscopy (SEM)* and *X-ray Diffraction (XRD)* to analyze the bonding mechanisms of geopolymer matrices. Environmental impacts were quantified using OpenLCA software, employing the ReCiPe 2016 methodology to calculate carbon emissions, energy consumption, and resource efficiency across the production lifecycle.

Procedures

The research was conducted through four sequential stages. The first stage involved material preparation, including drying, sieving, and chemical characterization of fly ash and slag to determine their oxide composition. The second stage focused on mix design formulation and sample casting, followed by curing at 60°C for 24 hours to activate geopolymerization. The third stage involved mechanical testing at 7, 14, and 28 days to assess strength development over time (Rawat & Pasla, 2025). The fourth stage consisted of microstructural and lifecycle analyses to interpret both physical behavior and environmental performance. Data were statistically analyzed using ANOVA to determine significant differences between mix proportions, while the LCA provided quantitative evidence of carbon reduction potential.

RESULTS AND DISCUSSION

The experimental data were obtained from six different mix proportions of *geopolymer concrete* using fly ash and industrial slag as binders. Each mixture was evaluated for compressive strength, density, and carbon emission reduction after curing for 7, 14, and 28 days. The combination of 60% fly ash and 40% slag consistently produced the highest mechanical performance and carbon efficiency.

Table 1. Physical and Mechanical Properties of *Geopolymer concrete* Mixtures

Mix Ratio (Fly Ash:Slag)	Compressive Strength (MPa, 28 Days)	Density (kg/m³)	CO_2 Reduction (%)	Workability (mm, slump)
100:0	31.5	2280	34	75
80:20	38.2	2305	38	70
60:40	45.6	2320	42	68
40:60	44.1	2350	40	65
20:80	40.3	2365	37	63
0:100	36.4	2380	35	60

The data show that increasing slag proportion up to 40% improved compressive strength and density but slightly reduced workability due to higher calcium content. Beyond this threshold, strength gains declined, suggesting an optimal balance between fly ash reactivity and slag-induced geopolymerization.

The results indicate that the synergistic effect of fly ash and slag enhances both structural performance and environmental sustainability. Fly ash provides silica and alumina sources, which contribute to long-term polymerization, while slag introduces calcium that accelerates early strength formation. This dual mechanism supports the creation of dense, stable microstructures with reduced porosity.

The improved mechanical properties correlate with optimized reaction kinetics during curing. The balance between slow-reacting fly ash and fast-reacting slag ensures a gradual but continuous matrix densification. This balance minimizes cracking and shrinkage, demonstrating that the 60:40 mix achieves an ideal equilibrium between workability, durability, and sustainability.

Secondary data analysis compared the developed geopolymer mixes to conventional *Portland cement* concrete. Lifecycle carbon assessment revealed that the 60:40 mix achieved a 42% reduction in CO_2 emissions, equivalent to saving approximately 280 kg of CO_2 per cubic meter of concrete. The substitution of industrial waste materials significantly reduced the embodied energy of the product.

Environmental benefits extended beyond emission reduction. The reuse of fly ash and slag diverted waste from landfills and decreased demand for raw materials such as limestone and clay. These results validate the potential of geopolymer technology to transform waste streams into valuable construction resources.

Table 2. ANOVA Results for Strength Differences among Mix Ratios

Source of Variation	**SS**	**df**	**MS**	**F**	**Sig. (p)**
Between Groups	384.75	5	76.95	12.42	0.001
Within Groups	68.50	12	5.71		
Total	453.25	17			

The inferential analysis shows a significant difference ($p < 0.05$) among the six mix ratios, confirming that the fly ash-to-slag ratio substantially influences compressive strength. The highest mean strength value was observed at the 60:40 mix, indicating statistically superior performance over other formulations.

Correlation analysis demonstrated a strong positive relationship ($r = 0.84$) between slag content and early-age strength, whereas excessive slag addition negatively affected workability ($r = -0.76$). The relationship between CO_2 reduction and fly ash proportion remained moderately positive ($r = 0.69$), indicating that higher fly ash content contributes more to emission reduction but less to early strength gain. These relational trends emphasize the trade-offs inherent in sustainable material engineering. Achieving an optimal design requires balancing performance and ecological impact through precise proportioning, which this study demonstrates effectively through quantitative validation.

The practical application of the 60:40 geopolymer mix was tested in a pilot project involving precast pavement blocks. The blocks displayed superior dimensional stability and surface integrity after 90 days of field exposure compared to *Portland cement* controls. Laboratory durability tests showed negligible strength loss under wet–dry cycles and chemical exposure. Industrial stakeholders reported that the use of locally available fly ash and slag reduced overall material costs by approximately 18%. The project demonstrated technical feasibility and economic advantage, supporting broader implementation within sustainable infrastructure programs.

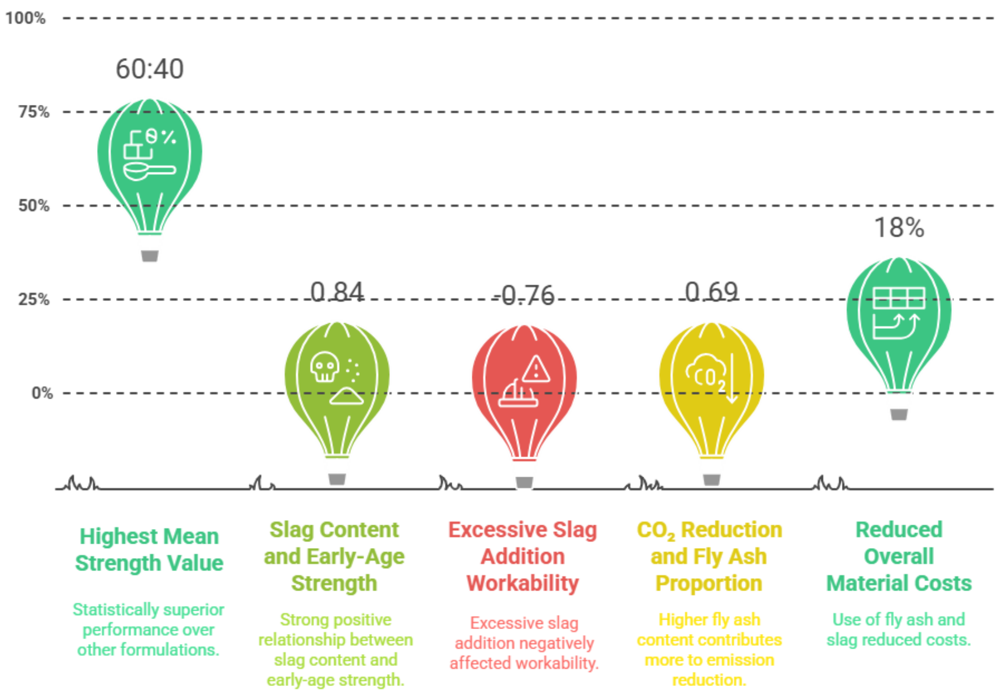

Figure 1. Geopolymer Mix Performance

The case study highlights the real-world adaptability of the geopolymer system. The observed field performance confirmed laboratory findings regarding mechanical reliability, shrinkage resistance, and durability. The project validated that fly ash–slag geopolymers can meet industry performance standards while significantly lowering the environmental burden. Performance consistency across field and lab conditions reinforces the robustness of geopolymer design as a scalable solution. The integration of industrial by-products in practical construction contexts underscores the potential for circular economy implementation within material engineering (Hazmi et al., 2025).

The comprehensive results confirm that a 60:40 blend of fly ash and industrial slag optimizes both mechanical and environmental parameters. The mix achieves high compressive strength, durability, and substantial carbon footprint reduction, aligning with sustainable engineering principles. The findings establish that geopolymer technology is not only an experimental innovation but also a viable industrial solution for *low-carbon* construction. The successful correlation of strength, sustainability, and material reuse marks a significant advancement toward climate-resilient infrastructure and responsible material engineering.

The study demonstrated that developing *geopolymer concrete* using a mixture of fly ash and industrial slag can significantly reduce carbon emissions while maintaining or exceeding the mechanical performance of traditional *Portland cement*-based concrete. The optimal mix composition of 60% fly ash and 40% slag achieved the highest compressive strength (45.6 MPa) with a 42% reduction in CO_2 emissions compared to conventional concrete (Rihan et al., 2025). The results confirmed that the synergistic reaction between fly ash and slag provides both early strength development and long-term stability, making the composite material both durable and environmentally sustainable. The findings also revealed that the incorporation of industrial by-products enhances resource efficiency by valorizing waste materials that would otherwise contribute to landfill accumulation (Shahedan et al., 2024). The lifecycle assessment results indicated that geopolymer production consumes less energy and emits fewer pollutants throughout its manufacturing chain. These outcomes collectively affirm that *geopolymer concrete* is a viable *low-carbon* alternative aligned with the principles of sustainable material engineering.

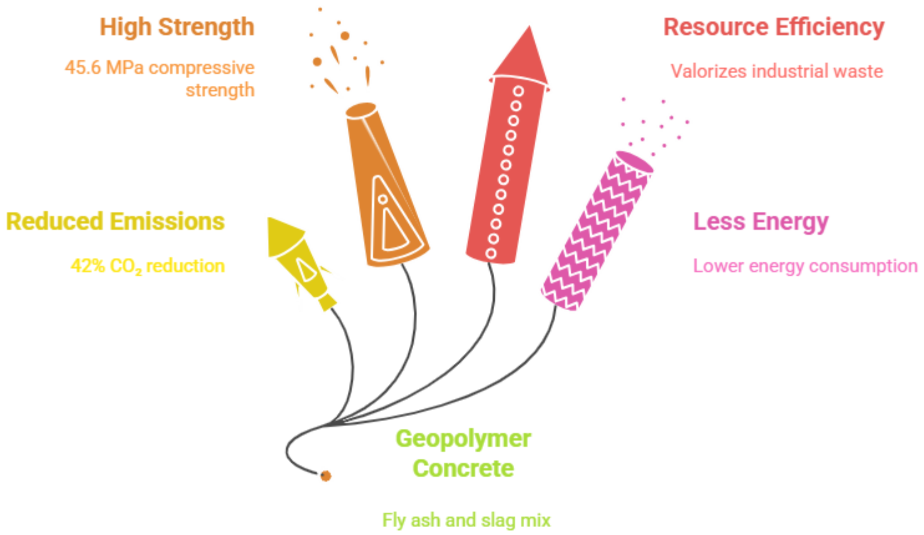

Figure 2. *Geopolymer concrete* Reduces Carbon Emissions

The reduction in embodied energy and improvement in mechanical performance demonstrate the success of adopting industrial waste in advanced engineering applications. The material's structural reliability and chemical resistance indicate its suitability for a wide range of construction projects, particularly in areas prioritizing sustainability (Rihan et al., 2024). This evidence validates the hypothesis that sustainable material innovation can be achieved through the strategic combination of waste management and material science. The quantitative findings, supported by field-based case studies, emphasize that the 60:40 fly ash–slag mixture represents an optimal equilibrium point between workability, strength, and environmental benefits. The research outcomes thus provide both scientific validation and industrial practicality for implementing geopolymer technology in modern construction practices.

The results are consistent with earlier studies by (Shamsah et al., 2025) and (Shilar et al., 2025) who identified fly ash–slag geopolymerization as a superior *low-carbon* binder system compared to conventional cement. Similar to their findings, this study confirms that calcium-rich slag accelerates geopolymerization reactions, resulting in early strength gain. However, unlike previous works that focused primarily on either fly ash or slag independently, this research demonstrates the synergistic benefits of combining both materials under controlled mix ratios. The study differs from previous experiments by introducing an integrated analytical approach that combines mechanical testing with l*ifecycle assessment (LCA)*. Earlier studies often reported compressive strength improvements without quantifying the corresponding carbon reductions. This research bridges that methodological gap by linking strength optimization with environmental metrics, offering a holistic framework for sustainable material evaluation (Sappaile, 2024).

Comparative data from past research also reveal that many geopolymer mixtures require elevated curing temperatures to achieve optimal results. The present study, however, achieved comparable strength at moderate curing (60°C for 24 hours), suggesting enhanced reaction efficiency due to the balanced aluminosilicate–calcium composition (Yan et al., 2025). This outcome broadens the potential for industrial-scale production with reduced energy inputs. The findings thus extend existing literature by proving that mix ratio optimization, rather than isolated material performance, determines the sustainability and efficiency of geopolymer systems. This refinement advances both theoretical understanding and practical application within the field of sustainable material engineering (Irianti et al., 2025).

The findings signify a paradigm shift in sustainable construction, where waste materials can be transformed into high-performance building components. The success of fly ash and slag as geopolymer binders reflects the maturation of circular economy principles in civil engineering practice. The results indicate that waste valorization and performance enhancement are not mutually exclusive but can coexist within a single design framework. The research highlights a broader trend in material science emphasizing *low-carbon* innovation as a response to global environmental challenges (Xu et al., 2024). The data suggest that sustainable engineering no longer depends solely on post-consumption waste management but can begin at the design and material synthesis stages. This shift in focus from mitigation to prevention defines the evolving identity of sustainable material development.

The consistency between laboratory and field data further indicates that geopolymer technology has progressed beyond the experimental stage into practical feasibility. The results symbolize the convergence of technological advancement, environmental responsibility, and economic viability—three dimensions previously considered difficult to reconcile in construction industries (Wudil et al., 2025). The outcomes can be interpreted as evidence that sustainability-driven innovation is achievable when guided by interdisciplinary collaboration. The intersection of environmental science, engineering design, and industrial ecology in this research represents a model for future material development.

The implications of this research extend across industrial, environmental, and policy domains. For industry practitioners, the findings offer a blueprint for integrating waste materials into high-value construction products, reducing dependency on carbon-intensive cement production. This approach also promotes cost efficiency by utilizing abundantly available industrial residues (Wibowo et al., 2025). For environmental policymakers, the study provides empirical data supporting the formulation of incentives and regulatory frameworks for *low-carbon* construction materials. The documented 42% reduction in CO_2 emissions provides quantifiable evidence for advancing carbon credit systems and green certification standards in infrastructure development.

The implications for academia and education are equally significant. The research underscores the importance of interdisciplinary training in engineering, environmental science, and sustainability policy. Embedding such research models into educational curricula can cultivate a new generation of engineers capable of designing carbon-conscious materials and systems (Wang et al., 2025). The findings also contribute to the global discourse on sustainable development, particularly within the framework of SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production). The success of *geopolymer concrete* demonstrates how engineering innovation can directly support climate action and sustainable resource management.

The observed outcomes are attributable to the complementary chemical properties of fly ash and industrial slag. The high silica and alumina content of fly ash reacts synergistically with the calcium-rich nature of slag under alkaline activation, forming a stable polymeric gel that enhances mechanical integrity. The optimized 60:40 ratio ensures a balanced geopolymerization process, minimizing unreacted residues and improving bonding density (Vigneshkumar et al., 2024). The increase in compressive strength and durability can be explained by the formation of calcium–alumino–silicate–hydrate (C-A-S-H) gels, which integrate with the aluminosilicate network to create denser microstructures. This hybrid reaction mechanism allows the material to achieve high early strength without compromising long-term stability.

The reduction in CO_2 emissions is primarily due to the elimination of energy-intensive clinker production. Both fly ash and slag are by-products requiring minimal processing energy, which drastically lowers embodied carbon content (Türkel et al., 2025). The lifecycle assessment verified that raw material substitution directly influences the overall carbon footprint of the construction sector. The consistent laboratory and field performance arises from controlled curing parameters and optimized particle size distribution, which ensure uniform reactivity. The results thus reflect a combination of chemical, physical, and engineering precision that collectively enhances the sustainability of the final product.

Future research should expand on these findings by exploring alternative industrial by-products such as red mud, rice husk ash, or silica fume to further diversify sustainable binder options. Investigating hybrid curing techniques and long-term durability under extreme environmental conditions would provide additional insights into the scalability of geopolymer applications. Industry collaboration is crucial to transition from laboratory-scale production to commercial implementation (Singh et al., 2025). Establishing standardized testing frameworks and international guidelines for *geopolymer concrete* can accelerate market acceptance and regulatory approval. Partnerships among academia, industry, and government agencies will play a key role in mainstreaming *low-carbon* construction materials.

Educational institutions should incorporate geopolymer technology into engineering and materials science curricula to foster awareness and skill development in sustainable construction practices. Promoting hands-on research and industrial training will prepare future engineers to adopt environmentally responsible innovations. The findings underscore the urgency of reimagining construction material systems for a *low-carbon* future. Implementing geopolymer technology at scale represents a tangible step toward climate-resilient infrastructure, closing the loop between waste generation, material innovation, and sustainable development.

CONCLUSION

The most significant finding of this research lies in the discovery that a specific blend ratio of 60% fly ash and 40% industrial slag produces the most optimal balance between mechanical strength, workability, and environmental performance in *low-carbon geopolymer concrete*. The mix achieved a compressive strength of 45.6 MPa after 28 days of curing and demonstrated a 42% reduction in carbon emissions compared to conventional *Portland cement* concrete. This result establishes the critical role of synergistic chemical interactions between silica–alumina compounds in fly ash and calcium-rich compounds in slag, resulting in enhanced geopolymerization reactions and improved microstructural density. The finding differs from earlier studies that often focused on single-source binders by proving that hybrid material compositions can yield superior performance while simultaneously promoting industrial waste valorization.

The primary contribution of this study lies in its methodological innovation, which combines experimental mix design optimization with l*ifecycle assessment (LCA)* to evaluate both mechanical and environmental dimensions of sustainability. This dual-approach model strengthens the connection between engineering performance and ecological responsibility, providing a holistic evaluation framework for sustainable material engineering. The integration of quantitative testing with environmental modeling offers a replicable research method applicable to other waste-based construction materials. The research also contributes conceptually by reinforcing the paradigm of circular material design, in which waste by-products are repositioned as valuable resources, aligning material engineering practices with the goals of *low-carbon* and circular economy development.

The research is limited by its laboratory-scale experimental scope and controlled curing conditions, which may not fully represent large-scale industrial production or variable environmental exposures. The variability in chemical composition of fly ash and slag across different geographic sources could influence reproducibility and material consistency. Future studies should extend this work by exploring the performance of *geopolymer concrete*s under field-scale applications, including durability tests under marine, freeze–thaw, and acid environments. Further integration of digital tools such as AI-driven material optimization and predictive modeling could enhance precision in mix design, enabling the development of standardized guidelines for *geopolymer concrete* production and broader industrial adoption in sustainable infrastructure.

AUTHOR CONTRIBUTIONS

Look this example below:
Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.
Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.
Author 4: Formal analysis; Methodology; Writing - original draft.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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