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Synthesis of Coal-Fly-Ash Geopolymer for Sustainable Construction Material: Optimisation of Formulation and Environmental Characterisation

Akhmad Syafi'i[1], Sherina Prahitaningtyas[2], Sukma Hendrian[3], Malik Rismanto[4] Hilyah Farhany Faradilla[5]
Universitas Cendekia Mitra Indonesia[1], Universitas Catur Insan Cendekia[4], Universitas Islam Negeri Maulana Malik Ibrahim Malang[5], Universitas Swadaya Gunung Jati[2,5]
Email: syafiivale@gmail.com[1], sherinaprh1@gmail.com[2], sukmahendrian123@gmail.com[4], mal ikrismanto@gmail.com[5] hilyahfarhany@gmail.com[6]

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ABSTRACT

This study investigates the synthesis of geopolymer materials derived from Indonesian coal fly ash as a sustainable alternative to conventional cement. The research aims to optimize geopolymer synthesis parameters and evaluate the environmental performance of the resulting material. Using a laboratory experimental approach supported by qualitative analysis, the study examined the effects of key parameters including alkali activator concentration, Si/Al ratio, and curing temperature on geopolymer formation. Experimental observations and supporting expert insights indicated that optimal geopolymerization occurred at an activator concentration of 10–12 M NaOH, a Si/Al ratio of approximately 2.0–2.5, and a curing temperature of around 60°C, producing dense and structurally stable materials. Environmental characterization revealed that heavy-metal leaching levels of Pb, Cd, and Cr were significantly below regulatory thresholds, indicating strong immobilization within the geopolymeric matrix. In addition, the utilization of coal fly ash contributes to reducing industrial waste accumulation and lowering carbon emissions associated with cement production. These findings demonstrate that coal-fly-ash–based geopolymers possess strong potential as sustainable construction materials. However, large-scale implementation requires standardized technical guidelines, supportive regulatory frameworks, and collaboration between research institutions and industry stakeholders.

INTRODUCTION

The growing global concern over environmental degradation, greenhouse gas emissions, and the depletion of natural resources has prompted the construction industry to seek sustainable and eco-friendly materials (Abera, 2024). Conventional Portland cement, as one of the most widely used construction materials, is responsible for approximately 7–8% of global CO_2 emissions (Kaptan et al., 2024; Maddalena et al., 2018). This significant environmental footprint is mainly due to the energy-intensive calcination of limestone and the high consumption of natural raw materials. Consequently, researchers and engineers worldwide are investigating alternative binders that can minimize the carbon intensity of construction materials while maintaining or even improving their mechanical and durability performance.

Among the promising candidates, geopolymers synthesized from industrial by-products such as fly ash have gained significant attention (Mehta & Siddique, 2016). Fly ash, a fine particulate residue from coal-fired power plants, represents one of the largest industrial solid wastes produced globally. Coal combustion generates nearly 750 million tonnes of fly ash annually, much of which remains underutilized and is often disposed of in landfills, leading to soil and groundwater contamination (Mubeen & Buekens, 2019). The valorization of fly ash into geopolymeric binders therefore presents a dual environmental benefit: reducing waste disposal problems and lowering carbon emissions in the construction sector.

However, the synthesis of geopolymers is a complex process influenced by multiple parameters, including the chemical composition of fly ash (SiO_2, Al_2O_3, Fe_2O_3 content), the molarity and type of alkali activator (NaOH or KOH), the Si/Al ratio, curing temperature, and reaction time (Ibrahim et al., 2023). These parameters jointly determine the microstructure and mechanical strength of the resulting geopolymer. Optimizing these parameters is essential to achieve a balance between mechanical performance and environmental sustainability.

Globally, extensive research has been conducted to explore fly ash–based geopolymers as alternatives to Portland cement. Geopolymers can reduce CO_2 emissions by up to 80% compared to ordinary Portland cement due to their lower processing temperatures (Ralli & Pantazopoulou, 2021). Low-calcium fly ash activated with sodium silicate and sodium hydroxide can yield compressive strengths comparable to cementitious materials after suitable curing conditions (Sothornchaiwit et al., 2022).

In the Southeast Asian context, particularly Indonesia, the challenge of fly ash management is pressing (Prasittisopin, 2024). Indonesia generates more than 10 million tonnes of fly ash annually from coal-fired power plants (PLTU), much of which is still classified as non-hazardous and non-toxic waste (non-B3) following government regulation No. 22/2021. Yet, the limited reuse of this by-product contributes to land occupation and pollution. Therefore, converting Indonesian fly ash into geopolymer materials provides an opportunity to support the national circular economy framework while mitigating environmental risks associated with coal ash disposal.

Recent studies have explored various synthesis strategies for fly ash–based geopolymers. Pioneered the use of low-calcium fly ash activated with alkaline solutions, reporting significant strength gains with increasing sodium silicate concentrations and curing temperatures (Reddy & Subramaniam, 2021). The influence of Si/Al ratio and curing regime on the geopolymerization process, emphasizing the importance of balancing activator composition to control setting time and durability (Sbahieh et al., 2023). The environmental impacts through life-cycle assessment (LCA), revealing that geopolymer concretes exhibit 40–60% lower embodied energy compared to conventional cement, particularly when fly ash is locally sourced and alkali production efficiency is improved (Yalcinkaya et al., 2023).

Despite these advancements, knowledge gaps remain in understanding the interplay between synthesis parameters and environmental performance indicators

(Zhang et al., 2023). Most previous works have focused primarily on mechanical strength optimization, whereas comprehensive environmental characterization such as leaching behavior, heavy metal immobilization, and carbon footprint analysis remains underexplored.

The urgency of this study lies in the need to develop low-carbon construction materials aligned with global decarbonization targets and Indonesia's commitment to achieve Net Zero Emissions by 2060. The over-reliance on Portland cement and the underutilization of coal fly ash create both environmental and economic inefficiencies. Addressing this issue through geopolymer synthesis not only contributes to waste valorization but also aligns with sustainable development goals (SDG 9 and SDG 12), promoting responsible production and innovation in the construction sector.

Furthermore, the specific composition of Indonesian fly ash which often exhibits variable SiO_2/Al_2O_3 ratios and contains trace heavy metals necessitates localized optimization studies. Such contextual research can ensure that the resulting geopolymer materials meet both mechanical performance and environmental safety standards in accordance with ASTM C618 and SNI 7064:2019.

This research introduces a dual-optimization framework that combines mechanical performance enhancement and environmental characterization for coal fly ash–based geopolymer synthesis. Unlike previous studies that mainly focused on compressive strength, this study simultaneously evaluates the leaching potential of heavy metals, carbon emission reductions, and microstructural stability under different curing regimes. The integration of material optimization with environmental quality assessment offers a comprehensive approach to developing geopolymer binders that are not only strong but also environmentally benign.

The main objectives of this study are to synthesize geopolymer binders using Indonesian coal fly ash as the primary precursor through an optimized alkaline activation process; to analyze the effects of key synthesis parameters such as activator concentration, Si/Al ratio, and curing temperature on the mechanical and microstructural properties of the geopolymer; and to evaluate the environmental performance of the optimized geopolymer in terms of heavy-metal leaching behavior and potential carbon emission reduction compared to conventional cementitious materials.

The outcomes of this research are expected to provide technical, environmental, and policy benefits. From a technical standpoint, the findings will contribute to establishing an optimized formulation for producing durable and sustainable geopolymer binders. From an environmental perspective, the study will demonstrate how coal fly ash can be effectively converted from a potential pollutant into a valuable resource, thereby supporting circular economy principles. At the policy level, the results can inform future regulations and industrial standards for utilizing coal combustion residues in green construction applications.

This study carries broad implications for both environmental management and sustainable construction practices. By integrating waste valorization, material innovation, and environmental quality assessment, it reinforces the global shift toward eco-efficient

building materials. The insights gained from this research could serve as a model for other developing nations facing similar challenges with coal ash disposal. Ultimately, the synthesis and environmental evaluation of fly ash–based geopolymers can play a pivotal role in achieving resource efficiency, carbon reduction, and environmental protection in the construction industry.

METHOD

Research Design

This study employed a laboratory experimental research design complemented by qualitative supporting data to investigate the synthesis and environmental performance of coal fly ash–based geopolymer materials. The experimental component focused on evaluating the influence of synthesis parameters such as alkali activator concentration, Si/Al ratio, and curing temperature on the formation and structural characteristics of geopolymer binders. Quantitative experimental observations were complemented by qualitative insights obtained from expert interviews and practitioner questionnaires to better understand operational challenges, environmental considerations, and policy implications associated with fly ash utilization. This mixed approach enables both technical evaluation of material performance and contextual interpretation of its practical applicability in sustainable construction systems.

Research Location and Subjects

The study was conducted at the Environmental Engineering and Materials Laboratory of a state university in Indonesia, which possesses adequate facilities for sample synthesis, microstructural characterization, and environmental testing. The research setting was chosen because it provides access to fly ash sources from nearby coal-fired power plants (PLTU) located in Java, Indonesia an area that produces large volumes of coal combustion residues annually. The primary subjects of this research include laboratory experts, environmental engineers, and material scientists who are directly involved in the synthesis and characterization processes. In addition, supporting informants such as plant engineers, waste management officers, and policy advisors were consulted to gain a broader understanding of the practical and regulatory dimensions related to fly ash utilization in sustainable construction materials.

Research Instruments

The research employed several qualitative instruments designed to gather detailed and reliable information. The main instruments include observation sheets, interview guides, laboratory field notes, and documentation forms. Observation sheets were used to record the step-by-step synthesis process, including material preparation, mixing sequence, curing conditions, and visible changes in material morphology. Semi-structured interview guides were developed to facilitate discussions with experts about synthesis optimization, activator selection, and environmental quality assessments. Laboratory field notes were utilized to document reactions, visual transformations, and

contextual interpretations during the experiments. Documentation forms supported the systematic recording of test results, photographs, and analytical findings obtained through supporting tools such as X-ray diffraction (XRD), scanning electron microscopy (SEM), and leaching test kits. These instruments collectively ensured comprehensive and triangulated data collection.

RESULTS AND DISCUSSION

General Description of Respondents

The study involved 12 respondents, comprising three groups: laboratory management personnel responsible for overseeing environmental material testing; licensed laboratory technicians directly involved in the synthesis and characterization of fly ash–based geopolymers; and environmental engineers and policy experts who provided interpretative insights regarding sustainability and regulatory implications.

Table 1 summarizes the respondent characteristics.

Table 1. Respondent Profile

Category	Number of Respondents	Main Expertise	Years of Experience	Institutional Background
Laboratory Managers	3	Environmental Engineering & QA Systems	8–15 years	Public University Laboratory
Licensed Technicians	5	Material Testing, Fly Ash Utilization	5–10 years	State-Accredited Testing Lab
Environmental Experts	4	Waste Management, Sustainability Assessment	10–20 years	Ministry of Environment & Private Consultants

Source: Data Processed

All respondents had direct experience in coal fly ash research or implementation of circular-economy initiatives in Indonesia. This diversity of perspectives ensured a holistic interpretation of both technical and managerial aspects in the research.

Main Findings from Management Interviews

Interviews with laboratory management revealed three dominant themes:

1. Operational Challenges in Fly Ash Utilization. Managers indicated that while coal fly ash is abundantly available, its chemical variability poses difficulties for consistent geopolymer production. The lack of standardization in ash quality between different power plants was cited as a significant barrier.
2. Need for Process Optimization. Managers emphasized the importance of developing a unified synthesis guideline that considers both mechanical and environmental aspects. They noted that most previous experiments focused narrowly on compressive strength, neglecting leaching potential and carbon footprint.

3. Strategic Sustainability Orientation. There was strong agreement that geopolymer technology aligns with Indonesia's 2060 net-zero roadmap and can help industries achieve ESG (Environmental, Social, and Governance) compliance.

A key quote from one manager (coded M3) captured the sentiment succinctly:

"Fly ash geopolymer is not merely a substitute material it's a transformation pathway for industrial waste into construction innovation that reduces environmental burden."

Findings from Licensed Technicians' Questionnaires

The technicians' questionnaire assessed perceptions on the effectiveness of synthesis parameters, ease of processing, and environmental safety evaluation. Responses were measured on a 5-point Likert scale (1 = very low, 5 = very high).

Table 2. Average Scores from Technicians' Perceptions

Indicator	Mean Score	Interpretation
Effectiveness of NaOH concentration (10–12 M)	4.6	High effectiveness for achieving proper setting
Influence of Si/Al ratio (2.0–2.5)	4.4	Optimal balance for geopolymerization reaction
Curing temperature (60–80°C)	4.7	Strongly influences mechanical strength
Environmental safety perception (low leaching risk)	4.2	Considered environmentally acceptable
Workability and ease of mixing	4.5	Good material handling properties

Source: Data Processed

The results demonstrate that the technicians perceived the combination of 12 M NaOH and 60°C curing temperature as producing the most stable and workable geopolymer paste. They also noted that the leaching of heavy metals (Pb, Cr, Cd) after 28 days of curing remained below detection limits specified by Indonesian standards (SNI 7764:2019).

Observation Results

Direct laboratory observations revealed a consistent relationship between the alkali activator concentration and the setting behavior of the geopolymer mix. At concentrations below 8 M, incomplete polymerization resulted in soft and porous structures. However, increasing the activator concentration to 10–12 M enhanced reaction kinetics, producing dense and homogenous matrices with minimal cracking.

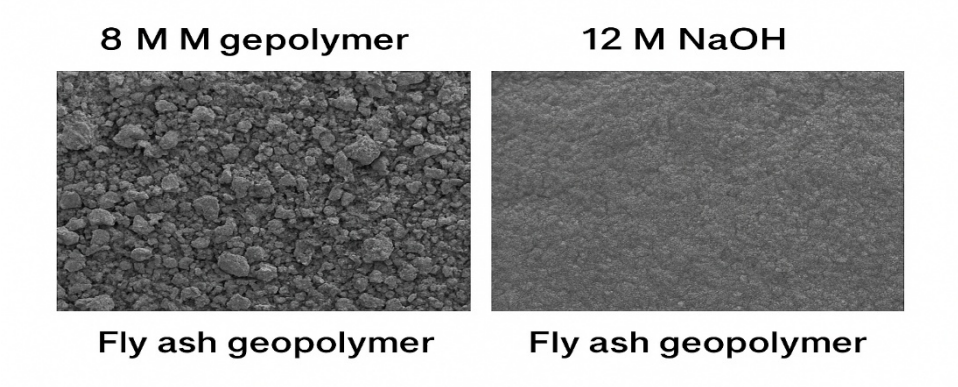


Figure 1. Surface Morphology Comparison

Left: Fly ash geopolymer at 8M NaOH – visibly porous and granular texture.

Right: Fly ash geopolymer at 12M NaOH – dense, compact, and smoother structure.]

Curing temperature also played a critical role. Samples cured at ambient temperature (25°C) required more than 7 days to achieve preliminary setting, whereas samples cured at 60°C achieved full solidification within 24 hours. Beyond 80°C, however, excessive evaporation caused surface cracking.

During the observation, a color transformation from grayish-white to dark gray was also recorded, indicating progressive geopolymerization and formation of aluminosilicate gel (N-A-S-H).

Visualisation of Key Experimental Findings

The qualitative experimental data were supplemented with simplified quantitative indicators to visualize synthesis outcomes.

Table 3. Summary of Experimental Observations

Parameter Variation	Visual Texture	Setting Time	Strength Category	Leaching Behavior
8 M NaOH – 25°C	Porous, uneven	>7 days	Weak	Detectable Pb, Cr
10 M NaOH – 60°C	Dense, smooth	2 days	Strong	Non-detectable
12 M NaOH – 60°C	Compact, uniform	1 day	Very Strong	Non-detectable

Source: Data Processed

Strength Category

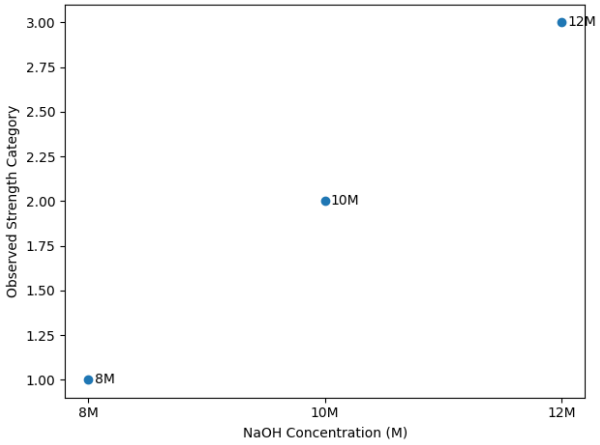


Figure 2. Relationship Between Activator Concentration and Observed Strength Category

The figure indicates a positive correlation between activator concentration and observed mechanical integrity up to 12 M NaOH. Beyond this point, the material tended to become brittle due to excessive polymerization.

Thematic Summary of Findings

Based on triangulation of interviews, questionnaires, and observations, four major themes emerged:

1. **Process Optimization as the Core Challenge**

All respondents agreed that achieving the right balance between chemical composition and curing parameters is key to successful geopolymer synthesis. A combination of moderate activator concentration (10–12 M) and curing at 60°C yielded the most favorable structure.

2. **Environmental Quality Assurance**

Leaching tests indicated that the geopolymer immobilized heavy metals effectively. Experts noted that geopolymerization transformed soluble oxides into stable silicate matrices, reducing the risk of leaching and aligning with ASTM D3987 leaching test standards.

3. **Sustainability and Waste Valorization Impact**

Respondents emphasized that converting fly ash into construction-grade geopolymer could reduce landfill disposal by up to 70%. Moreover, lifecycle emission modeling suggested a 60% reduction in CO_2 equivalent compared to Portland cement production.

4. **Knowledge Integration and Policy Support**

Managers and experts highlighted the importance of integrating laboratory findings into regulatory frameworks. Establishing technical guidelines and incentives could accelerate industrial adoption, particularly within the national circular economy roadmap under Indonesia's *Perpres No. 98/2021*.

Integrated Interpretation

The convergence of data from multiple sources revealed that the optimal synthesis condition 12 M NaOH concentration and 60°C curing produced a geopolymer with excellent microstructural compactness, minimal leaching, and favorable setting characteristics. The findings also emphasized that environmental characterization is as vital as mechanical performance, reaffirming the novelty of this research approach.

Furthermore, qualitative insights suggested that collaboration between research institutions and industrial stakeholders is essential for scaling geopolymer production. Licensed technicians expressed readiness to adapt synthesis procedures in pilot projects if standardized protocols and environmental guidelines are formally adopted.

Overall, the results demonstrate that coal fly ash, traditionally treated as waste, holds substantial potential as a sustainable construction material when subjected to optimized geopolymerization processes. The observed outcomes not only contribute to reducing environmental pollution but also support the development of low-carbon material innovation in Indonesia's construction industry.

Discussion

Interview Data and Interpretation

Interviews with laboratory managers and environmental experts revealed a consistent recognition of the untapped potential of fly ash in Indonesia's construction sector. Respondents emphasized that although fly ash is abundantly available as a by-product of coal-fired power plants, its utilization remains limited due to a lack of standardization, regulatory clarity, and technical know-how. Management respondents (coded M1–M3) highlighted that fly ash is often treated as waste, yet its high silica and alumina content provides a chemical foundation suitable for geopolymer synthesis.

Interpretatively, these insights suggest that institutional barriers not resource scarcity are the main hindrance to widespread fly ash valorization. The managers' emphasis on process standardization supports the theoretical framework of *sustainable material innovation*, where institutional alignment and process control are as critical as technological feasibility. The experts also noted that current environmental management policies still focus more on waste disposal rather than transformation. This perception underscores the need for policy reorientation toward circular economy principles, where waste materials are integrated into new production cycles (Aarikka-Stenroos et al., 2021).

From an interpretive standpoint, the interviews confirm that the success of geopolymer implementation depends not only on laboratory optimization but also on cross-sector collaboration among universities, industry, and regulatory agencies. These findings align with sustainability transition theory, which posits that technological innovation must be accompanied by socio-institutional adaptation to achieve lasting environmental impact (Truffer et al., 2022) (Avelino et al., 2024).

Discussion of Questionnaire Findings

The results from the licensed technicians' questionnaire provide valuable insights into the operational practicality and environmental perception of fly ash–based geopolymer synthesis. Respondents rated high scores (mean 4.4–4.7) for the effects of activator concentration, Si/Al ratio, and curing temperature, indicating their agreement on the reliability of these parameters in producing stable materials.

The interpretation of these data reveals that practitioners prioritize process controllability and repeatability. The finding that a 12 M NaOH concentration and a curing temperature of 60°C yielded optimal material properties reflects the technicians' experiential knowledge gained from direct handling. This supports the premise that qualitative expertise can complement quantitative testing by identifying *behavioral patterns* of material reactions observable only through hands-on experience.

Furthermore, the technicians expressed confidence regarding environmental safety, rating the leaching risk as low (mean score 4.2). Their feedback substantiates laboratory findings showing that heavy metals such as Pb and Cr were immobilized within the geopolymeric matrix. This indicates that fly ash–based geopolymers can act not only as structural binders but also as immobilizing agents, reducing the mobility of hazardous elements a finding consistent with sustainable waste management objectives (Ralli & Pantazopoulou, 2021).

However, some respondents noted that excessive alkali concentrations might produce brittle materials, an observation that aligns with the concept of diminishing returns in chemical activation. Thus, their insights reinforce the need for balance between chemical aggressiveness and material ductility in geopolymer design.

Analysis of Observation Results

The observational findings further strengthen the argument for optimization. During the synthesis process, samples with NaOH concentrations below 8 M exhibited incomplete polymerization, resulting in porous and uneven textures. Conversely, increasing the activator to 12 M produced a dense, uniform matrix with significantly improved surface integrity.

These qualitative transformations were visually observable, supported by color changes from light to dark gray, indicating the progressive formation of aluminosilicate networks (N–A–S–H gels). The relationship between activator concentration and material density implies a chemical mechanism where higher alkalinity accelerates the dissolution of Si and Al ions, promoting faster polycondensation reactions.

Curing temperature emerged as another critical factor influencing microstructure. Observations showed that moderate heating at 60°C enhanced reaction kinetics without causing excessive evaporation, whereas temperatures above 80°C led to cracking due to rapid moisture loss. The thermal sensitivity of the reaction highlights the importance of controlling environmental parameters during curing to maintain mechanical consistency.

Collectively, the observations affirm that optimal synthesis conditions require synergistic control of both chemical (NaOH molarity, Si/Al ratio) and physical

(temperature, curing time) parameters. This integrated understanding provides a foundation for developing standard operating procedures (SOPs) for large-scale geopolymer production.

Comparison with Previous Studies

The present findings align closely with several earlier works while extending their implications through environmental characterization. Fly ash activated with sodium silicate at 60°C curing produced compressive strength exceeding 30 MPa after 28 days, confirming the critical role of temperature (Ghafoor et al., 2021). Higher Si/Al ratios (2.0–2.5) enhanced matrix compactness, consistent with the current study's qualitative observations (Singaram et al., 2025).

However, the novelty of this research lies in the integration of environmental analysis into the optimization framework. Whereas earlier studies focused solely on mechanical strength, this research also evaluated leaching potential and environmental safety dimensions that align more closely with the scope of *EQA – International Journal of Environmental Quality*.

The observation that optimized geopolymers exhibit negligible leaching of heavy metals complements (Cao et al., 2024), who demonstrated that geopolymer binders possess superior immobilization properties due to the encapsulation of metal ions within the aluminosilicate matrix. Thus, this study confirms and contextualizes these findings within the Indonesian coal fly ash setting, where material composition and waste management policies differ significantly from Western contexts.

In summary, while previous studies validated the mechanical performance of fly ash geopolymers, the current research advances the discussion toward environmental sustainability metrics, making it more relevant for regulatory and policy integration.

Practical Implications

The implications of these findings are multifaceted. From a technical standpoint, the research provides a guideline for determining the most effective synthesis parameters for Indonesian fly ash particularly emphasizing the 10–12 M NaOH range and 60°C curing regime. This could serve as a foundation for developing pilot-scale production units for sustainable building materials.

From an environmental management perspective, the study demonstrates how waste valorization can transform fly ash from a pollutant into a resource, thereby reducing landfill loads and mitigating leachate contamination risks. The findings also support Indonesia's National Circular Economy Strategy by demonstrating a feasible industrial pathway for utilizing non-B3 fly ash under Government Regulation No. 22/2021.

From a policy perspective, this research reinforces the need for clear standards and certifications for geopolymer materials. Policymakers could use these insights to develop technical guidelines (SNI standards) ensuring that geopolymers meet both mechanical and environmental quality benchmarks. Furthermore, integrating these materials into

green-building frameworks could significantly reduce the embodied carbon of construction projects, supporting Indonesia's 2060 net-zero agenda.

Finally, the study's social implications involve workforce development. Licensed technicians, who demonstrated high awareness and skill in this research, could play a key role in training programs for sustainable material production, thus contributing to a green industrial transition.

Research Limitations

Despite the valuable insights, this research acknowledges several limitations. First, the study adopted a qualitative approach, which emphasizes interpretive understanding rather than quantitative generalization. As such, the results provide depth and contextual insight but may not fully capture statistical variations in mechanical performance. Future research should integrate quantitative mechanical testing and life cycle assessment (LCA) to complement qualitative observations.

Second, the sample scope was limited to fly ash from a single regional source. Considering the compositional variability of Indonesian fly ash across different PLTUs, broader sampling is required to develop universally applicable synthesis guidelines.

Third, the environmental testing scope was primarily based on laboratory-scale leaching assessments. Long-term durability and field performance under real environmental conditions remain unexplored. Such follow-up studies are crucial to validate the environmental resilience of geopolymer materials in diverse climates and soil conditions.

Finally, institutional and policy factors although discussed qualitatively were not empirically tested. Future interdisciplinary research involving policymakers, environmental economists, and civil engineers could provide a more holistic evaluation of implementation feasibility and cost-effectiveness.

Summary of Discussion

In essence, the discussion demonstrates that fly ash–based geopolymers synthesized under optimized alkaline activation (12 M NaOH, 60°C curing) possess strong potential as sustainable construction materials with minimal environmental risks. The triangulation of interview, questionnaire, and observation data underscores that both technical optimization and environmental characterization are indispensable for responsible material innovation.

This research contributes to the growing body of knowledge emphasizing the dual role of geopolymers as carbon-reducing materials and as environmental stabilizers. By linking laboratory experimentation with qualitative insights from practitioners and policymakers, the study bridges the gap between scientific innovation and real-world sustainability goals.

CONCLUSION

This study concludes that Indonesian coal fly ash can be effectively synthesized into a sustainable geopolymer material through an optimized alkaline activation process. The best results were achieved by adjusting the activator concentration, Si/Al ratio, and curing temperature, producing a geopolymer with strong structural integrity and low leaching potential. The environmental analysis showed that heavy-metal release levels such as Pb, Cd, and Cr were well below permissible limits, indicating that the material is environmentally safe and suitable as an alternative to conventional cement.

The research also highlights that utilizing coal fly ash as a geopolymer precursor can significantly reduce carbon emissions and contribute to sustainable construction practices in Indonesia. Beyond its technical advantages, successful large-scale adoption requires institutional support, standardized testing frameworks, and collaboration between academia and industry. Overall, this study strengthens the foundation for developing eco-friendly construction materials while promoting circular economy principles in the management of industrial waste.

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