

A Review on Performance Analysis of Geopolymers With Metakaolin and Fly ASH Blends Using A Dry Activator

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Abstract—

The construction industry plays a vital role in global infrastructure development; however, it is also one of the largest contributors to greenhouse gas emissions due to the extensive production and consumption of Ordinary Portland Cement (OPC). Cement manufacturing alone accounts for a significant percentage of global carbon dioxide (CO₂) emissions, creating an urgent need for sustainable and environmentally friendly alternatives. In this context, geopolymer technology has emerged as a promising solution that utilizes aluminosilicate-rich materials activated by alkaline solutions to produce high-performance binders with a substantially lower carbon footprint than conventional cement.

Among the various source materials used in geopolymer production, fly ash and metakaolin have gained considerable attention because of their high silica and alumina contents, excellent pozzolanic activity, widespread availability, and ability to enhance the mechanical and durability properties of geopolymer composites. Fly ash contributes to long-term strength development and improved workability, while metakaolin provides higher reactivity, accelerated geopolymerization, and superior early-age strength. The combination of these two materials in blended geopolymer systems has shown significant potential for producing sustainable construction materials with enhanced engineering performance.

This review paper presents a comprehensive assessment of recent advancements in fly ash–metakaolin-based geopolymers. The influence of precursor composition, alkaline activator concentration, activator-to-binder ratio, curing temperature, curing duration, and mix design parameters on fresh and hardened properties is critically analyzed. Furthermore, the effects of these parameters on workability, setting time, compressive strength, split tensile strength, flexural strength, durability, chemical resistance, thermal stability, and microstructural characteristics are thoroughly discussed. The review also highlights the role of advanced characterization techniques such as Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), and Energy Dispersive X-ray Spectroscopy (EDS) in understanding geopolymer formation and performance.

Additionally, the environmental benefits, economic feasibility, current limitations, and future research opportunities associated with fly ash–metakaolin geopolymer systems are examined. Based on the reviewed literature, it is concluded that the synergistic combination of fly ash and metakaolin significantly improves geopolymer performance by integrating the long-term strength contribution of fly ash with the high reactivity and early strength development of metakaolin. These blended geopolymers offer a viable and sustainable alternative to conventional cement-based materials, making them highly suitable for future structural and infrastructure applications.

Keywords — Geopolymer, Fly Ash, Metakaolin, Sustainable Construction, Alkali Activation, Mechanical Properties, Durability, Microstructure, Green Concrete, Environmental Sustainability.

1. INTRODUCTION

The rapid growth of urbanization, industrialization, and infrastructure development has significantly increased the demand for construction materials worldwide. Among these materials, Ordinary Portland Cement (OPC) remains the most widely used binder in the construction industry due to its availability, versatility, and well-established engineering performance. However, the manufacturing process of OPC is highly energy-intensive and environmentally detrimental. The calcination of limestone and the combustion of fossil fuels during cement production release substantial amounts of carbon dioxide (CO₂) into the atmosphere. It is estimated that

the cement industry contributes approximately 7–8% of global anthropogenic CO₂ emissions, making it one of the largest industrial sources of greenhouse gases. Additionally, the extraction of raw materials and high energy consumption associated with cement production have raised serious concerns regarding environmental sustainability and resource depletion.

In response to these challenges, researchers and engineers have increasingly focused on developing alternative binder systems that can reduce environmental impacts while maintaining or enhancing the performance characteristics of conventional cement-based materials. Among the various

alternatives investigated, geopolymer technology has emerged as one of the most promising and sustainable solutions. Geopolymers are inorganic polymeric materials formed through the reaction of aluminosilicate-rich source materials with alkaline activator solutions. Unlike OPC hydration, geopolymerization involves the dissolution of silica and alumina from precursor materials, followed by polycondensation reactions that produce a three-dimensional aluminosilicate network. This process results in the formation of durable and high-strength binders with significantly lower carbon emissions compared to traditional cement.

The concept of geopolymer technology was first introduced by Joseph Davidovits in the late 1970s as a means of developing environmentally friendly construction materials. Since then, extensive research has demonstrated that geopolymer binders can exhibit excellent mechanical properties, superior durability, low shrinkage, high resistance to chemical attack, and remarkable thermal stability. These advantages make geopolymer materials attractive for a wide range of structural and non-structural applications, including concrete production, precast elements, pavement construction, repair materials, and fire-resistant structures.

A key factor influencing the performance of geopolymer materials is the selection of suitable precursor materials. Various industrial by-products and natural aluminosilicate sources have been utilized for geopolymer synthesis, including fly ash, metakaolin, ground granulated blast furnace slag (GGBS), rice husk ash, silica fume, and mine tailings. Among these materials, fly ash and metakaolin have received considerable attention due to their favorable chemical composition, high reactivity, and widespread availability.

Fly ash is a fine powder generated as a by-product during coal combustion in thermal power plants. Class F fly ash, characterized by high silica and alumina contents and low calcium content, is particularly suitable for geopolymer production. The utilization of fly ash in geopolymer systems offers several environmental and economic advantages, including waste management, landfill reduction, conservation of natural resources, and lower material costs. Fly ash-based geopolymers have demonstrated good long-term strength development, improved workability, and enhanced durability. However, fly ash often exhibits relatively slow reaction kinetics under ambient curing conditions, which may result in delayed strength development and the requirement for elevated-temperature curing.

Metakaolin, on the other hand, is a highly reactive aluminosilicate material produced through the controlled calcination of kaolin clay at temperatures ranging between 650°C and 850°C. Due to its amorphous structure and high purity, metakaolin exhibits excellent pozzolanic activity and rapid geopolymerization characteristics. Geopolymers produced using metakaolin generally achieve higher early-age strength, improved microstructural density, and enhanced mechanical performance compared to those produced solely from fly ash. Nevertheless, the use of metakaolin may increase material costs and reduce workability because of its fine particle size and higher water demand.

To overcome the individual limitations of fly ash and metakaolin while maximizing their respective benefits, researchers have increasingly explored blended geopolymer

systems incorporating both materials. The combination of fly ash and metakaolin has been found to produce synergistic effects that significantly improve the overall performance of geopolymer binders. Fly ash contributes to improved workability and long-term strength development, whereas metakaolin enhances early-age strength, accelerates geopolymerization, and refines the microstructure. The resulting blended geopolymer systems often exhibit superior compressive strength, reduced porosity, enhanced durability, and improved resistance to aggressive environmental conditions.

Several studies have investigated the influence of fly ash-to-metakaolin ratios on the fresh, mechanical, durability, and microstructural properties of geopolymers. Research findings indicate that replacement levels ranging from 20% to 40% metakaolin generally produce optimum performance characteristics. The incorporation of metakaolin improves the dissolution of aluminosilicate species, promotes the formation of dense geopolymer gels, and enhances the overall degree of polymerization. Furthermore, advances in characterization techniques such as Scanning Electron Microscopy (SEM), X-Ray Diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR), and Energy Dispersive X-ray Spectroscopy (EDS) have provided valuable insights into the reaction mechanisms and microstructural evolution of fly ash–metakaolin blended geopolymers.

Despite the substantial progress achieved in this field, several challenges remain regarding the optimization of mix designs, standardization of testing procedures, long-term durability assessment, large-scale implementation, and economic feasibility. The variability in raw material properties, differences in alkaline activator compositions, and diverse curing conditions reported in the literature often make direct comparisons difficult.

The primary objective of this review paper is to critically evaluate and synthesize recent research findings related to fly ash–metakaolin blended geopolymer systems. Particular emphasis is placed on the effects of precursor composition, alkaline activator characteristics, curing regimes, and mix design parameters on the fresh, mechanical, durability, thermal, and microstructural properties of geopolymers. The review also examines the environmental and sustainability benefits associated with the utilization of industrial by-products and alternative binders in construction. Furthermore, current limitations, practical challenges, and future research opportunities are discussed to facilitate the wider adoption of geopolymer technology in sustainable infrastructure development.

Through a comprehensive analysis of existing literature, this review aims to provide researchers, engineers, and industry professionals with a clear understanding of the behavior and potential of fly ash–metakaolin blended geopolymers as an environmentally friendly and high-performance alternative to conventional cement-based materials. The findings presented herein contribute to the ongoing effort toward achieving sustainable construction practices and reducing the environmental footprint of the global construction industry.

II. LITERATURE REVIEW

1) *Salim Barbhuiya et al.*

Salim Barbhuiya et al. investigated the potential of fly ash and fly ash–metakaolin blended geopolymers as sustainable alternatives to Ordinary Portland Cement (OPC). The authors highlighted that Portland cement production contributes approximately 6–7% of global carbon dioxide emissions, creating an urgent need for environmentally friendly construction materials. Their research focused on evaluating the compressive strength and microstructural characteristics of geopolymer systems prepared using fly ash and blended fly ash–metakaolin precursors. Compressive strength tests were performed at 7, 14, and 28 days, while Scanning Electron Microscopy (SEM) and X-Ray Diffraction (XRD) analyses were used to investigate microstructural development. The study demonstrated that the incorporation of metakaolin significantly enhanced geopolymerization, resulting in denser microstructures and improved mechanical performance. The findings confirmed the suitability of fly ash–metakaolin geopolymers as sustainable high-performance construction materials.

2) *Masoud Bahrami et al.*

Masoud Bahrami et al. explored the application of geopolymer binders as formaldehyde-free adhesives for plywood production. The geopolymer binder was synthesized using kaolin and metakaolin as primary aluminosilicate sources, while silica fume was incorporated at varying percentages to improve performance. The study revealed that replacing up to 20% of the aluminosilicate content with silica fume enhanced geopolymerization and increased the formation of amorphous gel phases. Consequently, the binder exhibited improved cohesion, reduced viscosity, shorter curing times, and enhanced penetration into wood cells. Mechanical testing showed increased shear strength and bending strength of plywood panels. The research demonstrated the versatility of geopolymer technology beyond construction materials and highlighted the beneficial role of metakaolin in improving geopolymer binder properties.

3) *Sherin Khadeeja Rahman et al.*

Sherin Khadeeja Rahman et al. developed a novel self-compacting geopolymer concrete designed for ambient curing conditions. The study addressed two major limitations of conventional geopolymer systems: the requirement for elevated curing temperatures and the use of multiple chemical activators. Eight geopolymer concrete mixtures containing fly ash, slag, and micro fly ash were evaluated. The results indicated that the optimized self-compacting geopolymer concrete achieved a compressive strength of approximately 40 MPa after 28 days under ambient curing conditions without the use of cement or superplasticizers. The research provided a significant contribution toward the practical implementation of geopolymer concrete in field applications.

4) *Sood et al.*

Sood et al. investigated the fresh-state and mechanical properties of geopolymer pastes prepared using a dry-mixing technique. The study incorporated supplementary cementitious

materials (SCMs) and powder-based alkaline activators to develop ambient-cured geopolymer systems. Various combinations of fly ash, GGBS, calcium hydroxide, and sodium metasilicate were evaluated. The findings indicated that fly ash and GGBS activated with calcium hydroxide and sodium metasilicate produced superior workability and compressive strength. The research demonstrated the feasibility of producing geopolymer materials through dry-mixing approaches, which could simplify large-scale construction practices.

5) *H.A. Abdel-Gawad et al.*

H.A. Abdel-Gawad et al. focused on the development of one-part geopolymer cement using dry alkaline activators. The researchers prepared a dry activator by reacting sodium hydroxide with calcium carbonate and subsequently blending it with granulated blast furnace slag. The study evaluated the effects of water-to-cement ratio and activator content on the mechanical and physical properties of geopolymer pastes. The optimum activator composition was identified as 4% sodium hydroxide and 5% calcium carbonate by weight of slag. Microstructural analyses using SEM, TGA, DTG, and FTIR confirmed the successful formation of geopolymer reaction products. The study demonstrated the commercial potential of one-part geopolymer systems.

6) *Ridho Bayuaji et al.*

Ridho Bayuaji et al. proposed the concept of geopolymer cement produced through a dry mixing method. The study aimed to overcome practical difficulties associated with conventional liquid-activated geopolymer systems. By incorporating solid alkaline activators directly into the geopolymer powder, the resulting product could be used similarly to ordinary Portland cement. The authors concluded that dry geopolymer cement could facilitate industrial-scale production and improve the commercial acceptance of geopolymer technology.

7) *Arie Wardhono et al.*

Arie Wardhono et al. investigated the influence of water-to-binder ratio on the strength development of fly ash-based geopolymer mortar prepared using dry geopolymer powder. Five water-to-binder ratios ranging from 0.30 to 0.50 were examined. The results indicated that the water-to-binder ratio significantly affected compressive strength development, with a ratio of 0.40 producing the highest 28-day compressive strength of 10.3 MPa. The study highlighted the importance of moisture optimization in dry geopolymer systems.

8) *Kamal Neupane et al.*

Kamal Neupane et al. reviewed the engineering and durability characteristics of geopolymer binders. The study highlighted the superior resistance of geopolymers to sulfate attack, acid attack, and elevated temperatures compared to OPC-based systems. The authors emphasized that while liquid-activated geopolymers exhibit excellent properties, difficulties in handling alkaline solutions remain a significant challenge for large-scale implementation.

9) *Ricardo A.M. Figueiredo et al.*

Ricardo A.M. Figueiredo et al. investigated the use of iron ore tailings as an alternative silica source for producing sodium silicate activators in one-part geopolymer systems. Geopolymers synthesized using tailings-derived sodium silicate achieved compressive strengths of approximately 32 MPa, compared with 40 MPa obtained using commercial sodium silicate. The study demonstrated the feasibility of utilizing mining waste materials in geopolymer production, contributing to circular economy principles.

10) *Subhash V. Patankar et al.*

Subhash V. Patankar et al. developed a mix design methodology for fly ash-based geopolymer concrete. The study evaluated the effects of fly ash fineness, aggregate grading, water content, and activator composition on concrete performance. Using a constant 13 M sodium hydroxide solution and sodium silicate activator, the researchers proposed a systematic mix design approach for achieving desired strength and workability characteristics.

11) *Diyar N. Qader et al.*

Diyar N. Qader et al. conducted a comprehensive review on the use of metakaolin in alkali-activated materials and conventional concrete. The study analyzed the influence of metakaolin when combined with fly ash, GGBS, silica fume, and rice husk ash. The review concluded that metakaolin significantly improves compressive strength, durability, and microstructural development due to its high pozzolanic reactivity.

12) *Midhin A. Khaleel et al.*

Midhin A. Khaleel et al. investigated geopolymer concrete incorporating wastepaper ash and high-density polyethylene (HDPE) waste as sustainable replacement materials. The study found that replacing 30% of metakaolin with wastepaper ash increased compressive strength from 31.62 MPa to 35.38 MPa. Additionally, the incorporation of 3% HDPE further enhanced compressive strength to 36.54 MPa. The research demonstrated the potential of integrating multiple waste streams into geopolymer systems.

13) *Al Mashhadani Duraid Ali Jasim et al.*

The authors investigated metakaolin-based geopolymer concrete activated using calcium hydroxide and sodium silicate solutions. The study aimed to reduce the corrosiveness and handling difficulties associated with conventional sodium hydroxide-based activators. The results demonstrated that the alternative activator system successfully produced geopolymer concrete with satisfactory mechanical and durability properties.

14) *S. Gambo et al.*

S. Gambo et al. evaluated the performance of metakaolin-based geopolymer concrete exposed to elevated temperatures. Specimens cured at 60°C for 24 hours were subjected to high-temperature exposure, and their compressive strength, water absorption, and abrasion resistance were measured. The study demonstrated excellent thermal stability and residual strength retention, confirming the suitability of metakaolin geopolymers for fire-resistant applications.

15) *Khairunnisa Zulkifly et al.*

Khairunnisa Zulkifly et al. examined the thermal performance of fly ash–metakaolin blended geopolymers subjected to elevated temperatures. The results indicated that the blended geopolymer systems maintained superior physical and mechanical properties after thermal exposure. The synergistic interaction between fly ash and metakaolin contributed to enhanced thermal stability and structural integrity.

16) *Peng Wang et al.*

Peng Wang et al. conducted a bibliometric analysis of metakaolin-based geopolymer research using 1,553 publications from 2003–2023. The study identified major research trends, leading countries, influential institutions, and emerging topics. The findings revealed a rapid increase in research activity, particularly after 2019, highlighting the growing importance of metakaolin geopolymers in sustainable construction.

17) *Hai Yan Zhang et al.*

Hai Yan Zhang et al. investigated fly ash–metakaolin blended geopolymers for fire-resistant applications. The study found that metakaolin improves early-age strength, whereas fly ash enhances high-temperature performance. The combined use of both materials produced geopolymer systems with balanced mechanical properties and superior thermal resistance.

18) *Mohamed Amin et al.*

Mohamed Amin et al. evaluated high-strength geopolymer concrete produced using fly ash, metakaolin, and slag. The study reported excellent workability, compressive strength, tensile strength, flexural strength, and durability. SEM and EDX analyses confirmed the formation of dense geopolymer matrices with improved microstructural characteristics.

19) *Tao Bai et al.*

Tao Bai et al. investigated metakaolin geopolymer modified with fly ash, steel slag, and brake pad waste. The results showed that incorporating industrial wastes significantly improved flexural strength and chemical resistance while maintaining satisfactory compressive strength. The study demonstrated the capability of geopolymers to immobilize heavy metals and recycle industrial waste streams.

20) *E. Papa et al.*

E. Papa et al. synthesized geopolymers using metakaolin and coal combustion ashes. The resulting materials achieved compressive strengths of approximately 30 MPa and exhibited excellent thermal performance. The study demonstrated the feasibility of utilizing coal ashes as reactive fillers in geopolymer composites.

21) *Muhammad Hassan Ashfaq et al.*

Muhammad Hassan Ashfaq et al. investigated the binary effect of fly ash and metakaolin in geopolymer concrete. By varying metakaolin replacement levels from 10% to 40%, the study identified optimum combinations that significantly enhanced mechanical performance under both ambient and heat-curing conditions. The research highlighted the synergistic interaction between fly ash and metakaolin in geopolymer systems.

22) *Khairunnisa Zulkifly et al.*

The authors evaluated the influence of NaOH concentration, solid-to-liquid ratio, and sodium silicate-to-sodium hydroxide ratio on fly ash–metakaolin blended geopolymers. The optimum formulation achieved a compressive strength of 54.7 MPa after 28 days. The addition of aluminum phosphate compounds further increased strength to over 63 MPa, demonstrating the effectiveness of chemical modifications.

23) *SaiKrishna Chelluri et al.*

SaiKrishna Chelluri et al. reviewed the evolution of geopolymer technology and highlighted the importance of precursor selection, activator concentration, curing temperature, and mix design optimization. The study emphasized the growing interest in blended geopolymer systems due to their superior performance and environmental benefits.

24) *M.A. Gómez-Casero et al.*

M.A. Gómez-Casero et al. investigated geopolymer systems synthesized from varying proportions of metakaolin and fly ash. Microstructural analyses confirmed the formation of N-A-S-H and (N,C)-A-S-H gels. Although the blended systems exhibited slightly lower compressive strength than pure metakaolin geopolymers, they demonstrated satisfactory thermal properties and sustainable utilization of industrial by-products.

25) *Mehena Oualit et al.*

Mehena Oualit et al. explored the incorporation of multi-walled carbon nanotubes (MWCNTs) into metakaolin-based geopolymer mortar. The study reported significant improvements in compressive strength, flexural strength, and toughness. The nanotubes effectively bridged microcracks and enhanced load transfer mechanisms, reducing the brittle behavior commonly associated with geopolymer materials.

Summary

The reviewed literature demonstrates that fly ash and metakaolin are among the most effective precursor materials for geopolymer production. Their combined use provides synergistic improvements in workability, compressive strength, tensile strength, durability, thermal stability, and microstructural development. Although significant progress has been achieved, challenges related to standardization, ambient curing, large-scale implementation, and long-term durability remain areas requiring further investigation.

II. ENVIRONMENTAL SUSTAINABILITY

1) *Fly Ash–Metakaolin Geopolymers*

One of the most significant advantages of geopolymer technology is its contribution to environmental sustainability. The increasing demand for infrastructure and construction activities worldwide has led to a substantial rise in the consumption of Ordinary Portland Cement (OPC), which is responsible for considerable carbon dioxide (CO₂) emissions and depletion of natural resources. In contrast, geopolymer

binders produced from fly ash and metakaolin offer an eco-friendly alternative that supports sustainable development goals while maintaining excellent engineering performance.

2) *Reduction in CO₂ Emissions*

The production of Ordinary Portland Cement is highly energy-intensive and involves the calcination of limestone at temperatures exceeding 1450°C. This process releases large quantities of carbon dioxide both from fuel combustion and the decomposition of limestone. It is estimated that approximately 0.8–0.9 tonnes of CO₂ are emitted for every tonne of cement produced.

Geopolymer technology significantly reduces these emissions because it does not require clinker production, which is the primary source of carbon emissions in cement manufacturing. Instead, geopolymers utilize aluminosilicate-rich materials such as fly ash and metakaolin that react with alkaline activators to form binding gels. Various life-cycle assessment studies have reported that geopolymer concrete can reduce carbon emissions by approximately 40–80% compared with conventional OPC concrete, depending on the source materials, activators, transportation distances, and curing methods employed. Consequently, widespread adoption of geopolymer technology can contribute significantly to mitigating climate change and achieving carbon-neutral construction practices.

3) *Utilization of Industrial Waste Materials*

Fly ash, one of the primary raw materials used in geopolymer production, is generated as a by-product of coal combustion in thermal power plants. Millions of tonnes of fly ash are produced annually worldwide, and a significant portion remains unused, creating serious disposal and environmental challenges.

The incorporation of fly ash into geopolymer binders transforms an industrial waste product into a valuable construction material. This approach not only reduces waste accumulation but also promotes resource efficiency by converting by-products into high-performance engineering materials. In addition to fly ash, geopolymers can accommodate other industrial wastes such as ground granulated blast furnace slag (GGBS), silica fume, red mud, rice husk ash, mine tailings, and waste glass powder. Such utilization supports sustainable waste management practices and reduces dependence on virgin raw materials.

4) *Conservation of Natural Resources*

Traditional cement production requires extensive extraction of natural resources, including limestone, clay, shale, and gypsum. Continuous mining of these materials contributes to environmental degradation, habitat destruction, land-use changes, and depletion of finite natural reserves.

Geopolymer technology reduces the need for these raw materials by utilizing industrial by-products and processed aluminosilicate materials. The replacement of cement with fly ash–metakaolin blends decreases the demand for limestone quarrying and associated processing activities. Furthermore, the use of waste-derived materials helps preserve natural ecosystems and reduces the environmental footprint of construction projects.

5) *Reduced Landfill Burden*

Industrial waste disposal remains a major environmental concern worldwide. Large quantities of fly ash, slag, mining residues, and other industrial by-products are commonly disposed of in landfills or ash ponds, occupying valuable land resources and posing risks of soil, groundwater, and air pollution.

The use of fly ash and other industrial wastes in geopolymer production diverts substantial amounts of waste from landfills. This reduces the burden on waste disposal facilities, minimizes land occupation, and decreases environmental contamination risks. By converting waste materials into useful construction products, geopolymer technology supports more efficient and sustainable waste management systems.

6) *Promotion of Circular Economy Principles*

The circular economy model emphasizes minimizing waste generation, maximizing resource utilization, and continuously recycling materials within productive systems. Geopolymer technology aligns closely with these principles by converting industrial by-products into durable construction materials rather than treating them as waste.

The utilization of fly ash, slag, silica fume, mine tailings, and other secondary resources creates a closed-loop system in which waste generated by one industry becomes a valuable input for another. This approach improves resource efficiency, reduces environmental impacts, lowers disposal costs, and promotes sustainable industrial development. Furthermore, the longer service life and enhanced durability of geopolymer structures reduce maintenance requirements and lifecycle resource consumption, further supporting circular economy objectives.

7) *Life-Cycle Environmental Benefits*

Beyond reducing carbon emissions during production, geopolymer materials offer additional environmental advantages throughout their service life. Their superior durability, resistance to chemical attack, low permeability, and enhanced thermal stability contribute to longer structural lifespans and reduced repair and replacement needs. Consequently, fewer resources, less energy, and lower maintenance costs are required over the lifecycle of geopolymer-based structures.

Life-cycle assessment studies have consistently demonstrated that fly ash–metakaolin geopolymers possess lower embodied energy and environmental impacts than conventional cement-based materials. These benefits make geopolymer technology a key component of sustainable infrastructure development and green building initiatives.

8) *Summary*

The adoption of fly ash–metakaolin geopolymer technology offers substantial environmental benefits, including significant reductions in CO₂ emissions, effective utilization of industrial waste materials, conservation of natural resources, minimization of landfill disposal, and promotion of circular economy principles. Studies have reported carbon footprint reductions ranging from 40% to 80% compared with conventional Portland cement systems. Combined with their excellent mechanical and durability performance, these

sustainability advantages position geopolymers as one of the most promising construction materials for achieving environmentally responsible and sustainable infrastructure development in the future.

III. CHALLENGES AND LIMITATIONS OF FLY ASH–METAKAOLIN GEOPOLYMERS

Despite the significant environmental and engineering advantages offered by fly ash–metakaolin geopolymer technology, several challenges continue to limit its widespread adoption in the construction industry. Although extensive laboratory research has demonstrated the potential of geopolymers as sustainable alternatives to Ordinary Portland Cement (OPC), practical implementation on a large scale remains constrained by technical, economic, and regulatory barriers. Addressing these limitations is essential for achieving broader industrial acceptance and commercialization of geopolymer materials.

3.1 Lack of Standardized Mix Design Procedures

One of the most significant challenges facing geopolymer technology is the absence of universally accepted mix design methodologies. Unlike conventional concrete, which follows well-established standards such as ACI, IS, BS, and Eurocode guidelines, geopolymer concrete lacks comprehensive design specifications and standard procedures.

The performance of geopolymer materials depends on numerous interrelated factors, including:

- Type and chemical composition of precursor materials
- Alkaline activator concentration
- Sodium silicate-to-sodium hydroxide ratio
- Activator-to-binder ratio
- Water content
- Curing temperature and duration
- Aggregate characteristics

Because of these variables, researchers often use different mix proportions and experimental procedures, making direct comparison of results difficult. The absence of standardized design methods creates uncertainty among engineers, contractors, and regulatory authorities regarding material performance and quality control. Consequently, the development of comprehensive mix design guidelines remains a critical requirement for large-scale implementation.

3.2 Variability in Fly Ash Composition

Fly ash is one of the most widely used geopolymer precursor materials due to its high silica and alumina content. However, its chemical and physical properties vary significantly depending on several factors, including:

- Coal source
- Combustion technology
- Operating conditions of thermal power plants
- Collection and storage methods

Variations in fly ash composition can substantially influence geopolymerization reactions and final material properties. Differences in silica, alumina, calcium oxide, iron oxide, and unburnt carbon content often lead to inconsistent strength development and durability performance.

For example, Class F fly ash generally produces superior geopolymer properties due to its high aluminosilicate content and low calcium levels, whereas Class C fly ash may exhibit different reaction mechanisms because of its higher calcium concentration. Such inconsistencies make it difficult to establish universal geopolymer formulations and often require extensive material characterization before mix design optimization.

Furthermore, as many countries gradually reduce coal-based power generation in favor of renewable energy sources, the long-term availability of high-quality fly ash may become increasingly limited, creating additional challenges for future geopolymer production.

3.3 Handling and Safety Issues of Alkaline Activators

Geopolymer synthesis typically requires highly alkaline solutions such as:

- Sodium Hydroxide (NaOH)
- Potassium Hydroxide (KOH)
- Sodium Silicate (Na_2SiO_3)
- Potassium Silicate (K_2SiO_3)

These chemicals are highly corrosive and require careful handling during storage, transportation, and mixing operations. Exposure to concentrated alkaline solutions may cause:

- Skin burns
- Eye injuries
- Respiratory irritation
- Workplace safety hazards

In addition, preparation of alkaline activator solutions often requires precise control of concentration and temperature. Improper preparation can lead to inconsistent geopolymerization, reduced mechanical performance, and quality control issues.

From a construction perspective, the handling of liquid alkaline activators complicates field operations and increases labor training requirements. Contractors and construction personnel may be reluctant to adopt geopolymer technology due to unfamiliarity with these chemicals and associated safety concerns.

To overcome this challenge, researchers have recently focused on developing one-part or "just add water" geopolymer systems using dry activators. Although promising, these technologies still require further optimization before widespread commercial adoption.

3.4 Limited Field Implementation and Commercial Adoption

While thousands of laboratory studies have demonstrated the potential of geopolymer materials, relatively few large-scale construction projects have utilized geopolymer concrete in real-world applications.

Several factors contribute to this limitation:

1) Lack of Industry Awareness

Many engineers, architects, contractors, and policymakers remain unfamiliar with geopolymer technology and its benefits. The construction industry is traditionally conservative and tends to rely on well-established materials with proven performance histories.

2) Regulatory Constraints

Most building codes and construction standards are specifically designed for Portland cement-based materials. The absence of dedicated geopolymer standards often prevents their use in critical structural applications.

3) Economic Considerations

Although fly ash itself is relatively inexpensive, the cost of alkaline activators can be significant. Transportation, storage, and handling expenses may further increase production costs in certain regions.

4) Limited Commercial Production Facilities

The infrastructure required for large-scale geopolymer production remains underdeveloped in many countries. Consequently, commercial availability is still limited compared with OPC.

As a result, despite strong laboratory evidence supporting geopolymer performance, large-scale industrial implementation remains relatively rare.

3.5 Scarcity of Long-Term Durability Data

Durability is one of the most important requirements for construction materials because infrastructure is expected to remain functional for several decades. Although short-term laboratory studies have consistently demonstrated excellent durability characteristics of geopolymer materials, long-term field data remain limited.

Most published studies evaluate durability over periods ranging from several months to a few years. However, there is insufficient information regarding geopolymer performance over service lives of 30–100 years under actual environmental conditions.

Important aspects requiring further investigation include:

- Long-term carbonation resistance
- Chloride penetration behavior
- Sulfate attack resistance
- Freeze-thaw durability
- Creep and shrinkage characteristics
- Reinforcement corrosion behavior
- Performance under cyclic loading
- Weathering and environmental degradation

Without extensive long-term performance records, infrastructure owners and regulatory agencies may hesitate to approve geopolymer materials for critical structural applications.

Therefore, continuous monitoring of existing geopolymer structures and long-term durability studies are essential to establish confidence in the material's service-life performance.

3.6 Additional Challenges

Apart from the primary limitations discussed above, several other issues require attention:

5) High Energy Requirement for Heat Curing

Many fly ash-based geopolymer systems require elevated-temperature curing (60–80°C) to achieve optimum strength development. This requirement may limit practical application in large-scale cast-in-place construction.

6) Material Availability

The availability of high-quality precursor materials such as fly ash and metakaolin varies geographically, which may affect production consistency and transportation costs.

7) Environmental Impact of Activator Production

Although geopolymers reduce CO₂ emissions compared with OPC, the manufacture of sodium hydroxide and sodium silicate still consumes energy and contributes to environmental impacts. Therefore, efforts are needed to develop more sustainable activator systems.

8) Quality Control Issues

The sensitivity of geopolymer systems to raw material composition and processing conditions necessitates stringent quality control measures during production.

IV. FUTURE RE RESEARCH DIRECTIONS

Future investigations should focus on:

1. Ambient-cured geopolymer systems.
2. One-part geopolymer binders.
3. Fiber-reinforced geopolymer composites.
4. AI-based geopolymer mix optimization.
5. Life-cycle assessment studies.
6. Large-scale structural applications.
7. Long-term durability evaluation.

V. CONCLUSION

Fly ash–metakaolin blended geopolymers have emerged as a promising and sustainable alternative to Ordinary Portland Cement (OPC) in the construction industry. The combination of fly ash and metakaolin enhances the geopolymerization process, resulting in improved mechanical properties, durability, and thermal resistance. Fly ash contributes to long-term strength and workability, while metakaolin provides higher reactivity and early-age strength, creating a synergistic effect that improves overall performance.

The reviewed literature indicates that blends containing approximately 20–30% metakaolin and 70–80% fly ash generally provide the optimum balance between strength, durability, and workability. These geopolymer systems have demonstrated excellent compressive strength, resistance to chemical attack, low permeability, and superior fire resistance, making them suitable for structural and infrastructure applications.

In addition to their engineering benefits, fly ash–metakaolin geopolymers offer significant environmental advantages by reducing CO₂ emissions, utilizing industrial waste materials, conserving natural resources, and supporting circular economy principles. Studies have reported carbon footprint reductions of 40–80% compared with conventional OPC-based concrete. Despite these advantages, challenges such as the lack of standardized mix design procedures, variability in raw material properties, handling of alkaline activators, and limited long-term field data still need to be addressed. Further research and large-scale implementation are necessary to overcome these limitations and promote wider adoption.

Overall, fly ash–metakaolin blended geopolymers represent a viable, eco-friendly, and high-performance construction

material that can play a crucial role in achieving sustainable and low-carbon infrastructure development in the future.

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