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An Overview of Fly-ash Geopolymer Composites in Sustainable Advance Construction Materials

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ABSTRACT

Fly-ash geopolymer composites are an exciting advancement in eco-friendly construction materials. Fly-ash has become a sustainable alternative to regular cement because the approach addresses critical concerns in construction, such as high energy use, excessive carbon emissions and the challenge of managing industrial waste. In this review, a brief discussion on how fly-ash geopolymer composites could transform construction practices and reduce their impact on the environment. The construction industry is a major contributor to climate change, whereas industrial byproducts like fly-ash can also be an environmental challenge. Thus, the fly-ash geopolymer composites offer an innovative solution by reusing this waste to create environmentally friendly binding materials. Fly-ash can effectively replace traditional cement in construction, improving the durability and sustainability of buildings. By reducing our reliance on regular cement, these composites could revolutionise construction practices across various industries. Developing and widely adopting fly-ash geopolymer composites could bring substantial benefits. It could significantly reduce the construction

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industry's carbon footprint and contribute to global efforts to combat climate change. Additionally, ongoing research aims to enhance these composites' strength, heat resistance, and chemical durability, further promoting sustainable construction and supporting a circular economy by turning industrial waste into valuable construction materials.

Keywords: Construction material, eco-friendly, fly-ash, geopolymer composite, waste material

INTRODUCTION

Fly-ash geopolymer composites represent advanced materials formed by combining waste fly-ash generated from coal combustion with geopolymer technology. These composites, typified by the fly-ash geopolymer, act as composite binders that effectively reduce energy consumption and carbon emissions during cement production. It offers a sustainable solution with significant environmental advantages, helping mitigate climate change and health-related issues. Furthermore, they provide a robust and long-lasting substitute for typical cement-based products, reducing waste, conserving resources, and reducing carbon emissions. These characteristics make them suitable for a wide range of applications in fields like construction, infrastructure, transportation, and environmental engineering (Albidah, 2021; Amran et al., 2021; Cong & Cheng, 2021; Gollakota et al., 2019; Klima et al., 2022; X. Li et al., 2022; Z. Li et al., 2021; Moujoud et al., 2023; Nasir et al., 2022; Nayak et al., 2022; Qaidi et al., 2022; Zhang et al., 2020; Zhang et al., 2021; Zhu et al., 2021).

Figure 1 describes the schematic process in which fly-ash, a byproduct of coal power plants, is recognised as a global industrial waste (Gollakota et al., 2019; Z. Li et al., 2021; Makgabutlane et al., 2022; Moujoud et al., 2023; Zhu et al., 2021; Nasir et al., 2022). When combined with alkalis, fly-ash forms a geopolymer, a robust material noted for its strength and chemical resistance. Geopolymer composites derived from fly-ash serve as an eco-friendly alternative to traditional binders such as cement (Albidah, 2021; Z. Li et al., 2021; Nasir et al., 2023; Zhang et al., 2020; Qaidi et al., 2022; Zhu et al., 2021). Researchers enhance these composites by incorporating materials like fibres or particles, which improve their strength, thermal stability, and chemical resistance (Cong & Cheng, 2021; Grabias-Blicharz & Franus, 2023; Le Ping et al., 2022; Liu et al., 2022; Makgabutlane et al., 2022; Zhang et al., 2021). This sustainable approach reduces dependency on traditional bindings and promotes environmentally friendly construction practices. Consequently, fly-ash geopolymer composites exhibit promising applications across various industries (Cong & Cheng, 2021; Liu et al., 2022; Wu et al., 2019; Zhu et al., 2021).

Electricity generation has traditionally depended on fossil fuels such as coal, natural gas, and oil, which pose significant environmental challenges, including carbon emissions and pollution. The global shift towards cleaner energy sources—such as solar, wind, hydro, geothermal, and biomass power—reflects a growing commitment to eco-friendly

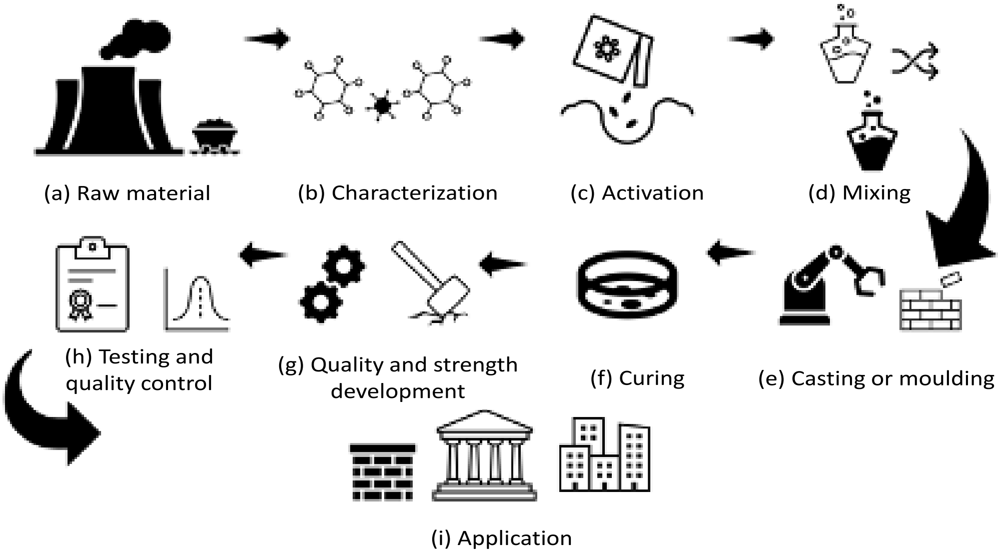

Figure 1. A schematic representation of the process involved in transforming fly-ash into a geopolymer material, offering a sustainable alternative to traditional cement-based materials: (a) Commencing the process, fly-ash is gathered as a byproduct from coal-fired power plants, (b) Subsequently, the raw fly-ash undergoes thorough analysis to determine its chemical composition and properties, (c) To initiate the geopolymerisation process, fly-ash must be activated, (d) The activated fly-ash is then mixed with water, resulting in the creation of a workable paste, (e) The geopolymer mixture is cast into moulds or shaped to achieve the desired form, (f) The geopolymer mixture undergoes a curing process, (g) Over time, the geopolymer cement or concrete gradually gains strength, (h) Samples of the geopolymer cement or concrete are subjected to various property tests, (i) Upon successful curing and testing, the geopolymer cement or concrete is considered ready for use (Grabias-Blicharz & Franus, 2023; Liu et al., 2022; Makgabutlane et al., 2022; Nasir et al., 2023)

alternatives. Solar panels harness energy from sunlight, wind turbines capture wind power, hydroelectric dams utilise flowing water, geothermal plants exploit the Earth's heat, and biomass power derives from organic waste and wood. Additionally, nuclear power offers a low-emission alternative.

The term 'global power generation capacity' encompasses the various methods employed worldwide to produce electricity. In 2008, the capacity for renewable electricity stood at 1 terawatt, compared to 3 terawatts from fossil fuels, as depicted in Figure 2. Over the past decade, renewable energy capacity has doubled, driven by decreasing costs and increasing adoption. By 2035, renewables are projected to surpass fossil fuels, generating approximately 15,000 terawatt-hours of electricity. This transition underscores the global commitment to cleaner, low-emission energy sources.

Figure 3 illustrates a decline in the production of solid byproducts from fuel combustion for electricity generation in the United States, primarily attributed to the decreased use of coal, a significant source of these byproducts. Notably, in 2020, for the first time since data collection commenced in 2008, a greater proportion of these byproducts were repurposed rather than disposed of. The solid byproducts include fly-ash (fine particles captured from boiler flue gases), bottom ash (coarser particles collected at the bottom of boilers), and gypsum produced from flue gas desulphurisation systems designed to control sulphur dioxide emissions. In 2020, each tonne of coal burned for electricity generation yielded approximately 0.17 tonnes of these byproducts. These byproducts can be disposed of, utilised by power companies, sold for beneficial uses, or occasionally stored for future utilisation or sale.

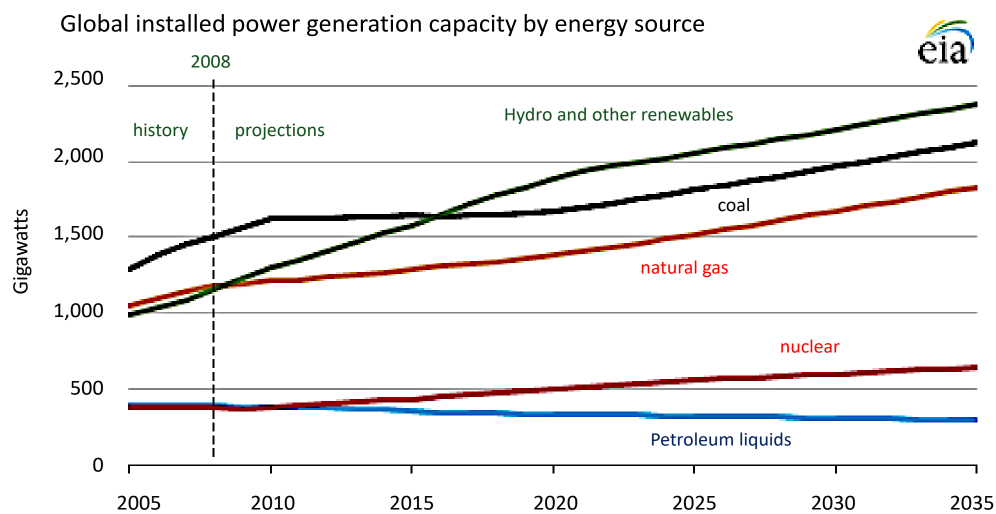

Figure 2. The source of global power generation capacity (U.S. Energy Information Administration, 2011)

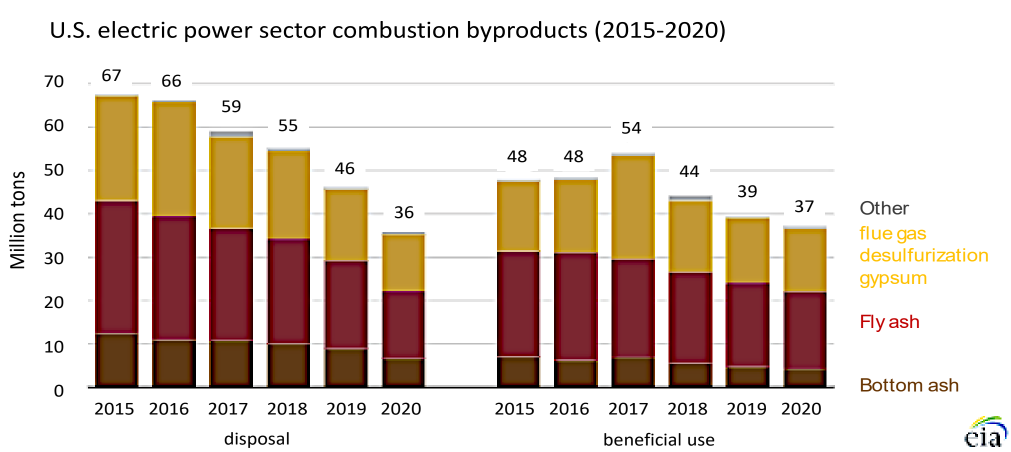

Figure 3. The U.S electric power sector combustion byproduct (year 2015–2020) (U.S. Energy Information Administration, 2022)

Between 2015 and 2020, the total production of combustion byproducts decreased by 36%, from 119 million metric tonnes to 76 million metric tonnes. This reduction is consistent with a 41% decrease in coal consumption in the electric power sector over the same period. As the overall production of combustion byproducts has declined, their utilisation has shifted from more costly disposal methods to beneficial applications. These applications include the manufacturing of products such as concrete and wallboard. Specifically, fly-ash and bottom ash are used in concrete and structural fills, while flue gas desulfurisation (FGD) wastes are employed to produce gypsum wallboard.

Furthermore, this review highlights the potential of fly-ash as an eco-friendly substitute for traditional binding agents in developing advanced composite materials within the interdisciplinary field of fly-ash geopolymer composites. Researchers aim to enhance these composites' mechanical, thermal, and chemical properties by incorporating reinforcing elements and optimising processing methods. These advancements hold significant implications for promoting sustainable construction practices and increasing the value of industrial waste through beneficial applications (Nayak et al., 2022; Zhang et al., 2021; Zhuang et al., 2016). For instance, Nayak et al. (2022) evaluated the advantages of concrete infused with fly-ash, providing practical examples from the American Coal Ash Association. Additionally, the study by Zhang et al. (2021) on the treatment techniques of fly-ash from municipal solid waste incineration has demonstrated economic benefits by characterising municipal solid waste incineration (MSWI) fly-ash for sustainable management prospects and mechanisms. Therefore, Table 1 provides a comprehensive summary of the various developments in fly-ash geopolymer composites.

Table 1
Summary of fly-ash geopolymer composite material development

Material used	Reinforcements	Processing process	Parameter's	Reference
Concrete	Fibre (glass steel, natural), aggregates, fabric, nano-and microparticles, and additives	Mixing, Moulding, and Curing	• Mixing (binder, aggregates, reinforcement and additive) • Thermal curing • Mechanical • Physical • Durability	Al-Majidi et al. (2016); Durak (2022); Mahmoodi et al. (2021); Makgabutlane et al. (2022); Marvila et al. (2021); Poloju et al. (2023); Sotelo-Piña et al. (2019); Wazien et al. (2016); Balakumaran et al., (2015)
Mortar		Mixing, Moulding, Curing and Surface Treatment		
Tiles				

Table 1 *(Continue)*

Material used	Reinforcements	Processing process	Parameter's	Reference
Coatings		Mixing, Application (brushing, spraying, rolling, and dipping), and Curing	• Mixing (binder, aggregates, reinforcement and additive) • Application (brushing, spraying, rolling, or dipping) • Thermal curing • Mechanical • Physical • Durability	Al Bakri Abdullah et al. (2013); Biondi et al. (2019); Hamidi et al. (2022); Sotelo-Piña et al. (2019)
Foam	Gas-forming agent (Aluminium powder, hydrogen peroxide)	Mixing, Foaming, Moulding and Curing	• Mixing (binder, gas-binding agent and additive) • Thermal curing • Mechanical • Physical • Durability	Al Bakri Abdullah et al. (2012); Atienza et al. (2023); Ducman and Korat (2016); Radina et al. (2023)
Bricks	Aggregates (Sand and crushed stone), fibre and nanoparticles	Mixing, Moulding, Curing and Surface finishing	• Mixing (binder, aggregates, reinforcement and additive) • Thermal curing • Mechanical • Physical • Durability	Ibrahim et al. (2014); Lavanya et al. (2020); Makgabutlane et al. (2022); Wan Ibrahim et al. (2015)

PROPERTIES OF FLY-ASH GEOPOLYMER COMPOSITES

Fly-Ash Geopolymer

Fly ash is a fine particulate material generated as a byproduct during the combustion of coal in power plants. This material is collected from the flue gases using electrostatic precipitators or filter bags, which effectively separate it from the smoke. Moreover, fly-ash is known for its pozzolanic properties, meaning it can react with calcium hydroxide in the presence of water to form compounds that possess cementitious characteristics. These unique properties make fly-ash a valuable resource in various industries, including construction, automotive, and packaging, where it is utilised to enhance the strength and durability of materials. In the construction industry, fly-ash improves the mechanical properties of concrete and other building materials, contributing to stronger and more durable structures. In the automotive sector, fly-ash creates lighter and stronger composite materials, enhancing vehicle performance and efficiency. Additionally, fly-ash is incorporated into the packaging industry to increase structural integrity and reduce environmental impact. The versatility and beneficial characteristics of fly-ash make it significant for promoting sustainability and innovation across these industries (Fediuk & Yushin, 2015; Nasir et al., 2022; Zierold & Odoh, 2020). Researchers such as Makgabutlane et al. (2022) are exploring the potential of creating sustainable and eco-friendly composite materials by combining plastic and fly-ash waste. The goal of this research is to enhance the mechanical properties of these materials for a variety of applications while also reducing their environmental impact.

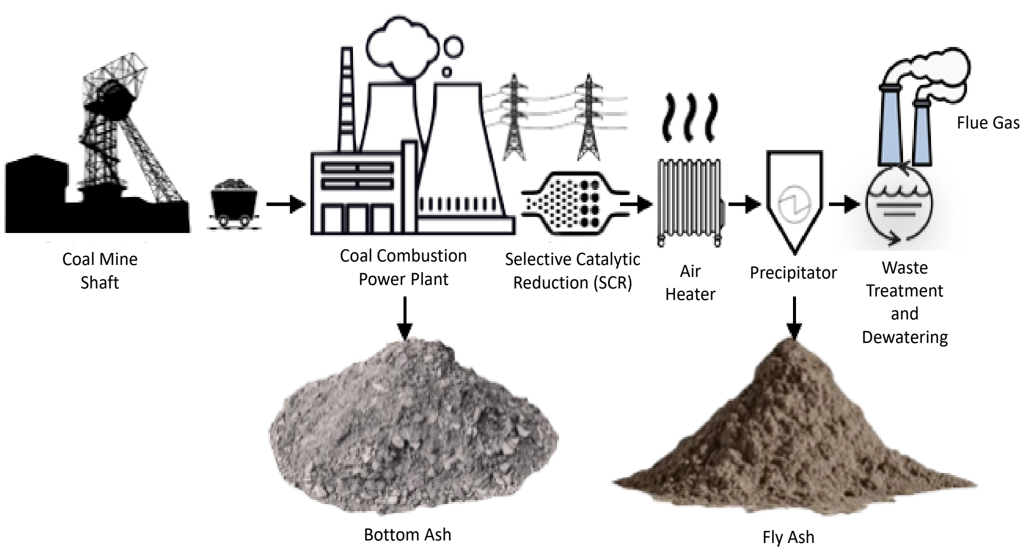

Figure 4. The production process of fly-ash and bottom ash (Baranwal et al., 2021; Sabarinath & Vittala, 2015)

Fly-ash, a byproduct of coal combustion can form a geopolymer when it interacts with water and calcium hydroxide. Geopolymers are materials with binding properties similar to those of conventional cement. This geopolymerisation process involves the polymerisation of silicon and aluminium species into a three-dimensional network, resulting in a material with excellent binding and structural properties. Researchers have been investigating the combination of fly-ash with biodegradable polymers and natural fibres such as hemp, jute, and sisal to produce eco-friendly and durable composite materials (Hamidi et al., 2022;

Khatib et al., 2009; Zhang et al., 2020). Studies such as those conducted by Zhang et al. (2020) on fly ash/slag geopolymer concrete emphasise the crucial role of geopolymer materials in promoting sustainable construction practices. These materials reduce the dependency on non-renewable resources and contribute to developing environmentally friendly composites, offering significant environmental benefits. As a result, Figure 4 illustrates a better understanding of the raw materials, characteristics, and processing methods used to obtain fly-ash, as well as its application and potential for sustainable development.

Mechanical Properties of Fly-ash Geopolymer Composites

Understanding how fly-ash particles interact with biodegradable elements is critical for creating sustainable materials. These interactions play a pivotal role in determining the overall mechanical performance of the composites. Table 2 summarises the mechanical characteristics of fly-ash biocomposites. The properties discussed include porosity (10% to 50%), indicating the presence of empty spaces within the material. Density ranges from 1.0 to 2.5 g/cm^3, and hardness (measured on the Vickers scale) varies from 10 to 100. The ability of the material to withstand compression is measured by its compressive strength (8 to 11 MPa), while its resistance to bending is represented by its flexural strength (4 to 6 MPa). Impact strength (5 to 50 joules per centimetre) measures how much energy the material can absorb during impacts. This review promotes environmental sustainability and the development of eco-friendly materials by efficiently utilising waste resources to create valuable composites.

Table 2
Physical and mechanical properties of fly-ash biocomposites

Properties	Description	Reference
Density, g/m^3	1.0 – 2.5	Hager et al. (2021); Wan Mastura et al., (2013); Wazien et al. (2016)
Porosity, %	10 – 50	Alehyen et al. (2017); X. Li et al. (2022); Nayak et al. (2022)
Hardness, (Vickers) *HV*	10 – 100	Estrada-Arreola et al. (2014); Gohatre et al., (2020); Luhar and Luhar (2022)
Compressive strength, MPa	8 – 11	Qaidi et al. (2022); Wang et al. (2022); Zhuang et al. (2016)
Flexural strength, MPa	4 – 6	Korniejenko et al. (2016); Makgabutlane et al. (2022); Yu and Jia, (2022)
Impact strength, Joule/cm	5 – 50	Bajpai et al. (2020); Shi et al.(2021)

Morphological Properties

Investigations into the morphological properties of fly ash biocomposites offer various insights into the structure and constitution of composite materials derived from fly-ash and biodegradable elements. These reviews contribute to the comprehension of the physical organisation, configuration, and interactions between fly-ash particles and biodegradable components within the composite matrix, which is a core objective in this field of research (Al-Majidi et al., 2016; Nasvi et al., 2016; Poloju et al., 2023; Roviello et al., 2016). By scrutinising the inner morphology of the components and how it influences the characteristics of the composite through an analysis of the physical arrangement, dispersion, and interactions of these elements within the composite, the aim is to develop cutting-edge, sustainable materials with enhanced performance that can be applied across a wide spectrum of potential uses.

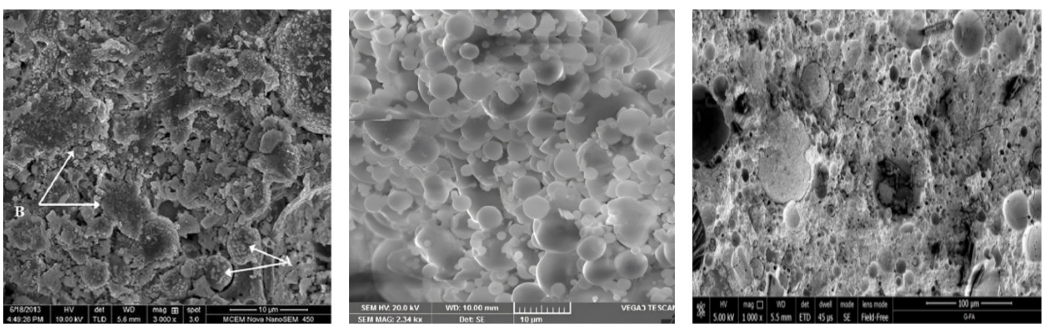

Figure 5. Morphology of fly-ash geopolymer; a) Fly-ash geopolymer cement (Nasvi et al., 2016), b) Fly-ash geopolymer based (Poloju et al., 2023), c) Fly-ash geopolymer concrete (Roviello et al., 2016)

As previously discussed, the combustion of coal results in the creation of a fine powder referred to as fly-ash. This fine powder comprises minute spherical particles with the potential to chemically interact with water and calcium hydroxide, thereby giving rise to a cementitious binding agent known as "geopolymer." These particles possess distinct pozzolanic properties, and as such, the distribution and arrangement of these particles within the composite matrix play a pivotal role in influencing the overall performance and characteristics of the material. In diverse research on morphological properties, microscopic examination techniques, such as scanning electron microscopy (SEM), are used (Figure 5). These techniques enable the exploration of the inner structure, the formation of bonds, and the dispersion of particles within the matrix, consequently affecting the composite's overall mechanical behaviour. Additionally, the morphological attributes are of paramount importance as they determine the mechanical strength and load-bearing capacity through an optimised and uniform distribution of fly-ash particles within the matrix (Luna-Galiano et al., 2016; Nasvi et al., 2016; Poloju et al., 2023; Roviello et al., 2016).

Besides investigating the morphological characteristics of fly-ash biocomposites, it becomes feasible to tailor their mechanical properties to meet specific application requirements by manipulating the arrangement and interaction of fly-ash particles with biodegradable components. By enhancing the mechanical performance of composites based on fly-ash and understanding how fly-ash particles interact with biodegradable constituents, this research endeavours to produce durable and environmentally responsible materials. Researchers employ scanning electron microscopy (SEM) or transmission electron microscopy (TEM) to explore microstructural arrangements, examining how these elements interconnect and establish bonds within the matrix. Recognising uneven distribution or clustering is crucial in preventing performance degradation and the loss of strength. An understanding of these interfacial interactions aids in load transfer and the prevention of crack formation within the composite. Researchers gain profound insights into how microstructure impacts the macroscopic behaviour of fly-ash biocomposites by examining morphological traits across various scales, thereby facilitating the design and technological optimisation of specific attributes. The investigation of morphological features ultimately contributes to the advancement of materials science by fostering the creation of innovative, environmentally friendly composites suitable for a diverse range of applications.

Thermal Properties of Fly-Ash Geopolymer Composite

Understanding the behaviour and performance of fly-ash biocomposites within the realm of geopolymer composites is heavily reliant on their thermal characteristics. The geopolymerisation process that gives rise to materials known as geopolymer composites involves a chemical reaction between fly-ash and alkali activators, such as sodium or potassium silicates, culminating in the formation of a three-dimensional, inorganic polymer network (Atienza et al., 2023; Narattha et al., 2022). Fly-ash biocomposites exhibit noteworthy attributes in various thermal aspects. Several factors influence their thermal conductivity, including the type and quantity of fly-ash, the presence of biodegradable materials, and the nature of the geopolymer adhesive. The outcome is lower thermal conductivity compared to traditional cement-based composites. In a review study conducted by Klima et al. (2022), a substantial focus was placed on exploring the thermal characteristics of fly ash-based geopolymers in high-temperature settings. The review underscored the significance of factors such as pore interconnectivity in preventing damage, the impact of mix design and curing techniques, and the role of alkali sources in bolstering heat resistance. These properties find utility in applications like fire-resistant construction materials, high-temperature insulation, and protective coatings for industrial equipment operating in exceedingly challenging thermal conditions. Moreover, Kaya and Köksal (2022) have highlighted the vital need for a comprehensive examination of mix design and curing methods, the influence of alkali sources on thermal resistance, and the role of pore interconnectivity in averting damage, especially in the construction sector. For applications exposed to high temperatures, the careful management of thermal degradation is imperative to ensure performance under demanding conditions.

Table 3
Principal thermal properties of fly-ash biocomposites

Properties	Description	Application	Reference
Thermal conductivity, W/mK	0.1 – 4.0	• Insulation • Building material • Coating • Electronic enclosure • Industrial equipment • Solar panel • Cryogenic	Atienza et al. (2023); Feng et al. (2015); Karakaş et al. (2023); Narattha et al. (2022); Novais et al. (2016); Shao et al. (2018)
Coefficient thermal expansion, 10^{-6}/°C	5 – 20	• Construction material • Infrastructure material • Electronic packaging • Automotive • Aerospace • Optical device • Industrial equipment	Ali and Vijayalakshmi Natrajan (2021); He et al. (2020); Kaya and Köksal (2022); Ma and Dehn (2017)
Melting temperature, °C	600 – 1200	• Furnace • Coating • Aerospace • Industrial equipment • Power plant • Energy storage system	Durak (2022); Hager et al. (2021); He et al. (2020); Klima et al. (2022); Moujoud et al. (2023); Nasir et al. (2023)

Table 3 summarises the key thermal attributes of fly-ash biocomposites, along with their descriptions and existing applications. These characteristics encompass a thermal conductivity spanning from 0.1 to 4.0 W/mK, making them suitable for a wide range of uses such as cryogenic conditions, solar panels, construction materials, coatings, electronic enclosures, and insulation. The coefficient of thermal expansion, falling within the range of 5 to 20 x 10^{-6} °C, plays a pivotal role in regulating thermal stress, benefiting industrial equipment and materials in buildings and infrastructure, electronic packaging, and the automotive and aerospace sectors. The melting temperature, ranging from 600 to 1200°C, is a critical parameter for various applications, including furnaces, coatings, aerospace components, industrial equipment designed to manage thermal stress, power plants, and energy storage systems. This extensive table furnishes valuable insights into the adaptable thermal properties of fly-ash biocomposites and their diverse utility across multiple sectors.

Fly-ash biocomposites possess crucial thermal properties that render them invaluable for a multitude of applications, from thermal insulation to the mitigation of thermal expansion. They can also be formulated to serve as natural fire retardants or enhance fire resistance. These versatile materials can be customised for specific purposes, ranging from high-temperature industrial environments to the design of energy-efficient construction materials. In doing so, they offer promising solutions developing sustainable and versatile materials across numerous industries.

Physical Properties

Geopolymer composites' physical attributes significantly influence their performance and applicability. These attributes encompass a spectrum of observable traits, such as density, porosity, hardness, strength, thermal conductivity, and more. These traits play a critical role in shaping the behaviour and performance of geopolymer composites, ultimately influencing their suitability for diverse applications.

Geopolymer composites boast a multitude of noteworthy characteristics. Their density aligns closely with conventional cement-based materials, offering advantages like enhanced energy efficiency and resilience in adverse conditions, rendering them well-suited for insulation, construction, and aerospace applications. The mechanical strength they exhibit is intricately linked with their porosity; lower porosity correlates with increased wear resistance and durability. Hardness is pivotal in creating durable and reliable components, as it quantifies a material's capacity to withstand deformation and abrasion. Nonetheless, a study by Nasir et al. (2023) concerning recycled polyethene terephthalate (rPET) and industrial waste fly-ash, in response to environmental concerns, investigated the thermal behaviour and microstructure of the composite. Excessive fly-ash was found to induce degradation, leading to voids and clustering, ultimately affecting thermal performance.

Table 4
Physical properties of fly-ash biocomposites

Parameter	Description	Reference
Particle diameter (µm)	0.01–100	Akid et al. (2023); Al-Nini et al. (2020); Alterary and Marei (2021); Ferdous et al. (2020); Grabias-Blicharz and Franus, (2023); Hager et al. (2021); Harihanandh et al. (2021); Klima et al. (2022); Korniejenko et al. (2016); Li et al. (2021); Liu et al. (2022), Maiti and Prasad (2016); Makgabutlane et al. (2022); Nasir et al. (2023); Poloju et al. (2023); Poyyamozhi et al. (2023); Prusty and Patro (2015); Qaidi et al. (2022); Shao et al. (2018); Sonebi et al. (2022)

Table 4 *(Continue)*

Parameter	Description	Reference
Texture	Silt loam	Al-Nini et al. (2020)
Specific surface area (cm^2g^{-1})	2500–4000	Grabias-Blicharz and Franus (2023)
Specific gravity ($g\ cm^{-3}$)	1.6–2.6	Hager et al. (2021)
Bulk density ($g\ cm^{-3}$)	0.9–1.3	Harihanandh et al. (2021)
Water holding capacity (%)	40–60	Makgabutlane et al. (2022)
Colour	White/yellow-orange/black	Klima et al. (2022)

The fundamental physical properties of fly-ash biocomposites are outlined in Table 4. These properties include texture categorised as silt loam, particle diameters ranging from 0.01 to 100 μm, specific gravity within the range of 1.6 to 2.6 g/cm^3, a specific surface area spanning from 2500 to 4000 cm^2/g, a water retention capacity of 40%–60%, and bulk densities ranging from 0.9 to 1.3 g/cm^3. These biocomposites exhibit diverse colours, including white, yellow-orange, and black. This table furnishes detailed information regarding the particle size, texture, density, water-holding capacity, and colour variations, encompassing the primary physical characteristics of fly-ash biocomposites.

Additionally, a review study conducted by Qaidi et al. (2022) focusing on fly ash geopolymer concrete has unveiled a noteworthy observation. It underscores the potential of environmentally friendly materials such as fly ash to match and often surpass the mechanical properties of polymer concrete in aspects like the production process, mix design, compressive strength, and microstructure of fly ash-geopolymer concrete. Consequently, their commendable compressive strength renders them exceptionally suitable for load-bearing constructions, ensuring stability and cost-effective maintenance. Equally significant is flexural strength, which plays a vital role in structural components such as beams and panels, particularly when subjected to bending loads. In summation, it is imperative to grasp and optimise the physical characteristics of geopolymer composites to tailor the material for specific applications. Geopolymer composites, as high-performing materials, offer a more environmentally friendly and efficient solution to contemporary engineering challenges across a spectrum of high-technology industries.

ADVANCED APPLICATION OF FLY-ASH GEOPOLYMER COMPOSITES

Fly-ash geopolymer composites have garnered significant interest as sustainable advanced construction materials due to their superior mechanical properties, environmental benefits, and versatility. These composites are utilised in various applications, from infrastructure development to specialised industrial uses, promoting sustainable construction practices. Their enhanced functionalities include improving electrical conductivity for structural health monitoring, utilising industrial byproducts for superior properties, and serving as efficient repair materials for infrastructure.

Furthermore, fly-ash geopolymer composites represent a significant advancement in sustainable construction materials, offering a wide range of applications across various sectors. Their superior mechanical properties, environmental benefits, and versatility make them crucial in developing sustainable infrastructure. As research and innovation continue to advance, the scope and potential of fly-ash geopolymer composites are expected to expand, further cementing their role in the future of construction technology. These attributes underscore the versatility and sustainability of fly-ash geopolymer composites. As research expands, the applications of these composites are expected to grow, contributing to the development of smart, durable, and eco-friendly construction solutions (Bijeljić & Ristić, 2023; Mizerová et al., 2019; Wang et al., 2023).

Infrastructure and Building Construction

Structural Components

Fly-ash geopolymer composites are extensively used to fabricate structural components such as beams, columns, and slabs. Their high compressive strength, durability, and resistance to environmental degradation make them suitable for load-bearing applications. Studies have demonstrated that fly-ash-based geopolymer concrete can achieve mechanical properties comparable to or even exceeding those of traditional Portland cement concrete, making it a viable alternative for reinforced concrete structures.

The use of fly-ash geopolymer composites in precast concrete elements is gaining popularity due to the reduced curing times and lower energy requirements during production (Figure 6). Precast geopolymer elements, such as panels, blocks, and pipes, offer enhanced performance characteristics, including improved thermal insulation, fire resistance, and a reduced carbon footprint.

Transportation Infrastructure

Road Construction

Fly-ash geopolymer composites are being utilised in the construction of roadways and pavements. The material's superior resistance to freeze-thaw cycles, chemical attacks, and abrasion makes it ideal for such applications. Geopolymer-based road construction not only enhances the longevity and durability of road surfaces but also contributes to the reduction of greenhouse gas emissions associated with traditional asphalt and cement-based materials (Bellum et al., 2020; Y. Li et al., 2023; Parcesepe et al., 2022; Sarath Chandra & Krishnaiah, 2022; Sofri et al., 2022).

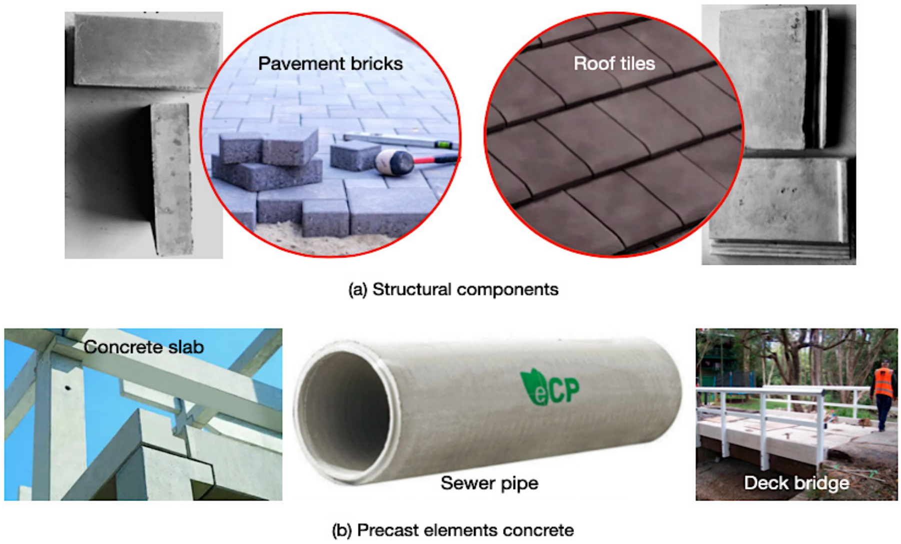

Figure 6. Various applications from fly-ash geopolymer composites: (a) Structural components, (b) Precast elements (Imtiaz et al., 2020; Selim et al., 2024; Shehata et al., 2022)

Railway Sleepers

The railway industry is exploring the use of fly-ash geopolymer composites for manufacturing railway sleepers. These sleepers exhibit excellent mechanical properties, such as high strength and durability, essential for supporting heavy rail traffic. Additionally, the adoption of geopolymer composites helps mitigate the environmental impact associated with the production and disposal of conventional concrete sleepers (Gourley, 2014; Jokubaitis et al., 2020; Salih et al., 2021; Zakeri & Sadeghi, 2007).

Figure 7 illustrates the advanced applications of fly-ash geopolymer composites in transportation infrastructure, highlighting their use in road construction and railway sleepers. For road construction, these composites offer enhanced durability through resistance to freeze-thaw cycles and chemical attacks, along with sustainability benefits such as a reduced carbon footprint and lower energy consumption. In the context of railway sleepers, fly-ash geopolymer composites provide high strength, impact resistance, and environmental benefits by utilising waste materials and reducing carbon emissions. Their low maintenance requirements and extended service life make them a superior alternative to traditional materials in both applications, contributing to developing eco-friendly and resilient transportation infrastructure systems.

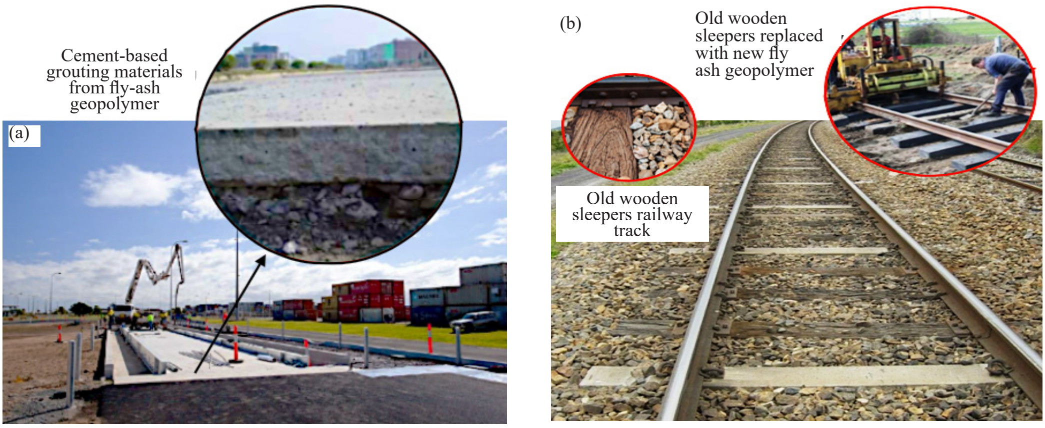

Figure 7. Advanced applications of fly-ash geopolymer composites in transportation infrastructure: (a) Geopolymer fly-ash used for concrete road pavement, (b) Railway sleeper with fly-ash geopolymer concrete (J. Li et al., 2023; Kerchof & Wu, 2012; Parcesepe et al., 2022; Plastic News, 2017)

Marine and Coastal Applications

Fly-ash geopolymer composites are highly resistant to the aggressive marine environment, making them suitable for marine and coastal construction projects. Applications include seawalls, breakwaters, and underwater pipelines. The material's inherent resistance to chloride and sulphate attacks and low permeability ensures prolonged service life and reduced maintenance costs in harsh marine conditions.

Figure 8 illustrates the advanced applications of fly-ash geopolymer composites in marine and coastal environments. These composites are ideal for constructing seawalls and breakwaters due to their excellent resistance to chloride and sulphate attacks, low permeability, and reduced carbon footprint (Latham et al., 2008; Pasupathy et al., 2021; van Gent, 2021). In underwater pipeline construction, their high compressive and flexural strength, along with erosion resistance, ensure durability and longevity. Additionally, fly-ash geopolymer composites are used in marine construction elements such as piers, docks, and offshore platforms, offering superior durability, fire resistance, and sustainability. Using recycled materials and lower energy consumption during production further contribute to their environmental benefits, making them a preferred choice for eco-friendly and resilient marine infrastructure.

Industrial Applications

Waste Containment

Fly-ash geopolymer composites are employed to contain and stabilise hazardous wastes. Their ability to immobilise heavy metals and other contaminants makes them an effective material for lining landfills, encapsulating waste materials, and constructing containment

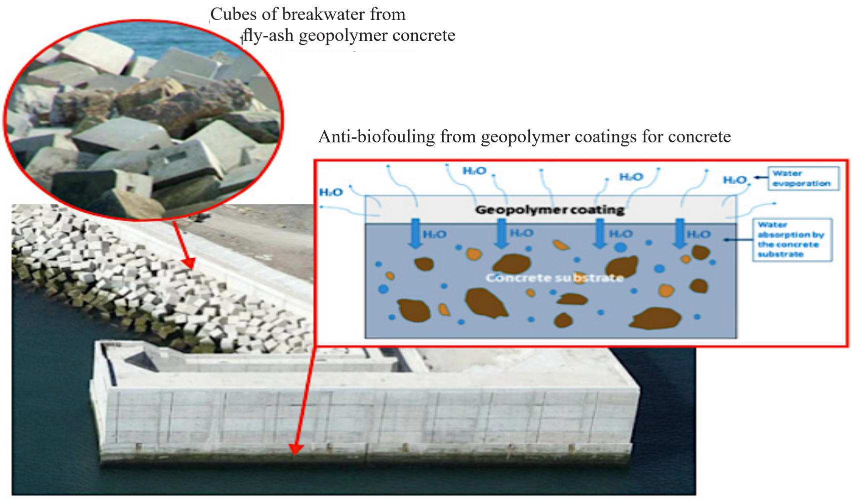

Figure 8. Advanced applications of fly-ash geopolymer composites in the marina and coastal applications (Biondi et al., 2019; Latham et al., 2008; Pasupathy et al., 2021; van Gent, 2021)

barriers. This application addresses environmental pollution and provides a sustainable solution for waste management. The advanced application of fly-ash geopolymer composites in waste containment is an exciting development in environmental science and industrial practices. Synthesis of these geopolymers from industrial byproducts like fly-ash mitigates waste and creates valuable materials for environmental remediation. Their use in adsorptive processes for removing heavy metals and dyes from wastewater exemplifies a sustainable approach to managing industrial pollutants.

Future research should focus on enhancing the performance of geopolymer-based adsorbents, expanding their application to a broader range of contaminants, and verifying their effectiveness in real-world wastewater treatment scenarios. Fly ash geopolymers' economic and environmental benefits underscore their potential to revolutionise waste containment practices and support a circular economy. By advancing these technologies, researchers and industry can work towards a more sustainable future with reduced reliance on traditional, less eco-friendly materials. Subsequently, Table 5 emphasises the materials, applications, and significant insights from a variety of studies on fly-ash-based geopolymers, thereby expounding their potential for sustainable waste management and environmental remediation.

Heat-Resistant Materials

The thermal stability and fire-resistant properties of fly-ash geopolymer composites make them suitable for applications requiring high-temperature resistance. Industries use these composites to manufacture fireproof panels, insulation materials, and refractory linings. The ability to withstand extreme temperatures without significant loss of structural integrity is a key advantage in such applications. Figure 9 illustrates the advanced applications of fly-ash geopolymer composites in industrial settings, focusing on waste containment and heat-resistant materials. For waste containment, these composites provide excellent chemical resistance, low permeability, and the ability to stabilise and solidify hazardous materials, ensuring environmental protection and structural integrity. In high-temperature applications, fly-ash geopolymer composites are used in refractory linings, fireproofing, thermal insulation panels, and heat shields due to their superior thermal stability and fire resistance. These properties make them ideal for enhancing safety, durability, and efficiency in various industrial processes.

Table 5
Advanced applications of fly-ash geopolymer composites for industrial waste containment

Materials	Applications	Significant insight	Reference
Fly-ash-based aluminosilicate	• Environmental applications • Adsorbents • Catalysts	• Low-cost, eco-friendly • Immobilises toxic or radioactive metals • Potential to adsorb liquid or gas contaminants • Provides significant economic benefits from resource recycling	Adewuyi (2021)
Geopolymers	• Adsorption of heavy metals and dyes	• High efficiency • Cost-effectiveness • Similar performance to other materials • Adsorption is spontaneous and endothermic • Future research on performance enhancement and real wastewater testing	Siyal et al. (2018)
Fly ash-based geopolymer, Polyethersulfone (PES)	• Adsorption of Heavy Metal Ions	• Convenient, low-cost and eco-friendly • High adsorption capacity for Pb^{2+}, Cu^{2+}, Cd^{2+}, and Ni^{2+} • Porous structure with significant surface area	Onutai et al. (2023)
Biomass fly-ash-based geopolymers	• Adsorption of methylene blue	• Highly porous and lightweight • Superior adsorption capacity • Potential for use in packed beds as membranes, • Reduces the environmental footprint	Novais et al. (2018)

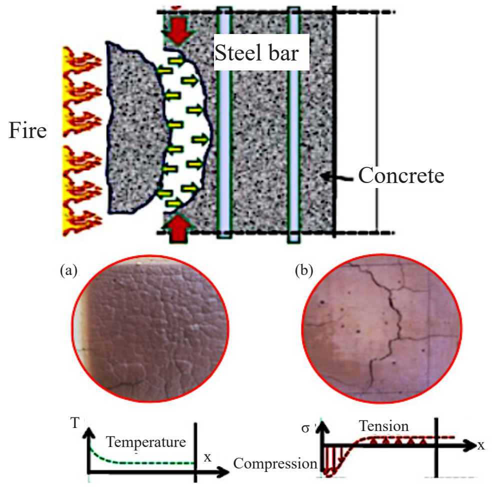

Figure 9. Fly-ash geopolymer used in the construction industry as fire resistance of geopolymer concrete deterioration due to fire damage is generally caused by two mechanisms: (a) thermal dilation and (b) Vapor pressure (Amran et al., 2022; Vickers et al., 2016)

Innovative and Future Applications

3D Printing

Advancements in 3D printing technology have opened new avenues for the use of fly-ash geopolymer composites. The material's excellent printability and rapid setting time make it ideal for additive manufacturing. 3D-printed geopolymer structures can be used in various applications, including custom architectural elements, complex geometrical forms, and rapid prototyping.

Space Construction

Research is being conducted on using fly-ash geopolymer composites for construction in extraterrestrial environments, such as the Moon and Mars. The material's ability to be synthesised from locally available resources and its strength and durability make it a promising candidate for building habitats and infrastructure on space exploration missions.

Thus, Figure 10 describes the fly-ash geopolymer composites emerging as a transformative material for innovative and future applications in 3D printing and space construction. Their mechanical properties, sustainability, and adaptability make them ideal for creating complex, durable, and eco-friendly structures. As technological advancements continue, the potential of fly-ash geopolymer composites in these cutting-edge fields is expected to grow, contributing to revolutionary developments in construction methodologies both on Earth and beyond.

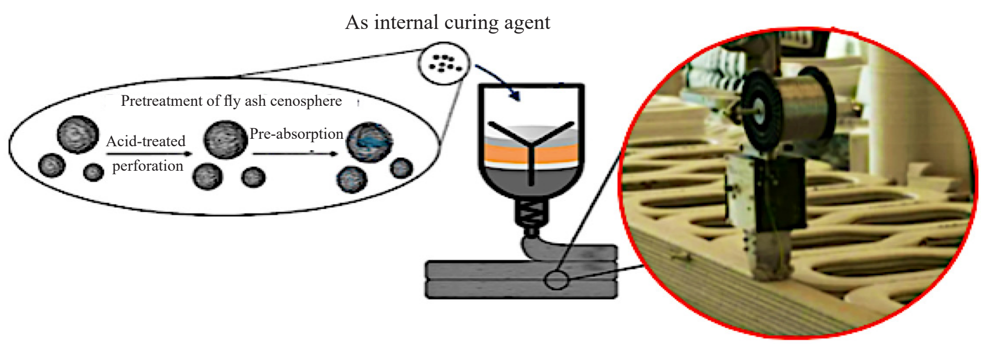

Figure 10. Pioneering the future: fly-ash geopolymer composites in 3D printing and space construction. Harnessing the power of sustainable materials for innovative applications on Earth and beyond (Tao et al., 2022)

CONCLUSION

In conclusion, the literature review underscores the transformative potential of fly-ash geopolymer composites in reshaping the construction industry while advancing environmental sustainability. A comprehensive analysis of their mechanical, morphological, thermal, and physical properties shows that these composites hold promise across diverse sectors, including the aerospace and automotive industries. Key findings suggest optimal percentages for properties crucial to their performance, laying a foundation for informed material selection and application. Moreover, ongoing research endeavours focus on enhancing the strength, heat resistance, and chemical durability of fly-ash geopolymer composites. Innovations such as incorporating reinforcing elements and refined processing techniques are driving advancements in their mechanical properties. Additionally, insights gained from morphological analyses, particularly through techniques like scanning electron microscopy (SEM), contribute to developing sustainable materials with enhanced performance characteristics.

The environmental advantages of fly-ash geopolymer composites, including reduced carbon emissions and waste generation, underscore their significance in promoting sustainable construction practices and fostering a circular economy. By repurposing industrial byproducts like fly-ash, these composites offer a viable alternative to conventional binding agents, mitigating the environmental footprint of construction activities. Overall, the literature highlights the pivotal role of fly-ash geopolymer composites in driving sustainable construction practices and supporting a circular economy model. Future research should prioritise further exploration into optimising these materials' properties and expanding their applications to address the evolving challenges of the 21st-century construction industry.

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