An overview of fly-ash geopolymer composites in sustainable advance construction materials

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Fly-ash geopolymer composites are an exciting advancement in eco-friendly construction materials. Nowadays, the fly ash, has turned into a sustainable alternative to regular cement with the approach addresses critical concerns in construction, such as high energy use, excessive carbon emissions, and the challenge of managing industrial waste. In this comprehensive review, the 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 due, whereas the 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 industry's carbon footprint and contribute to global efforts to combat climate change. Additionally, by ongoing research aims to enhance the strength, heat resistance, and chemical durability of these composites, further promoting sustainable construction and supporting a circular economy by turning industrial waste into valuable construction materials.

Keywords: Fly ash; Geopolymer composite; Construction material; Waste material; Eco-friendly.

1. 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. This 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, thereby reducing waste and conserving resources, contributing to the reduction of carbon emissions. These characteristics make them suitable for a wide range of applications in fields like construction, infrastructure, transportation, and environmental engineering [1–14].

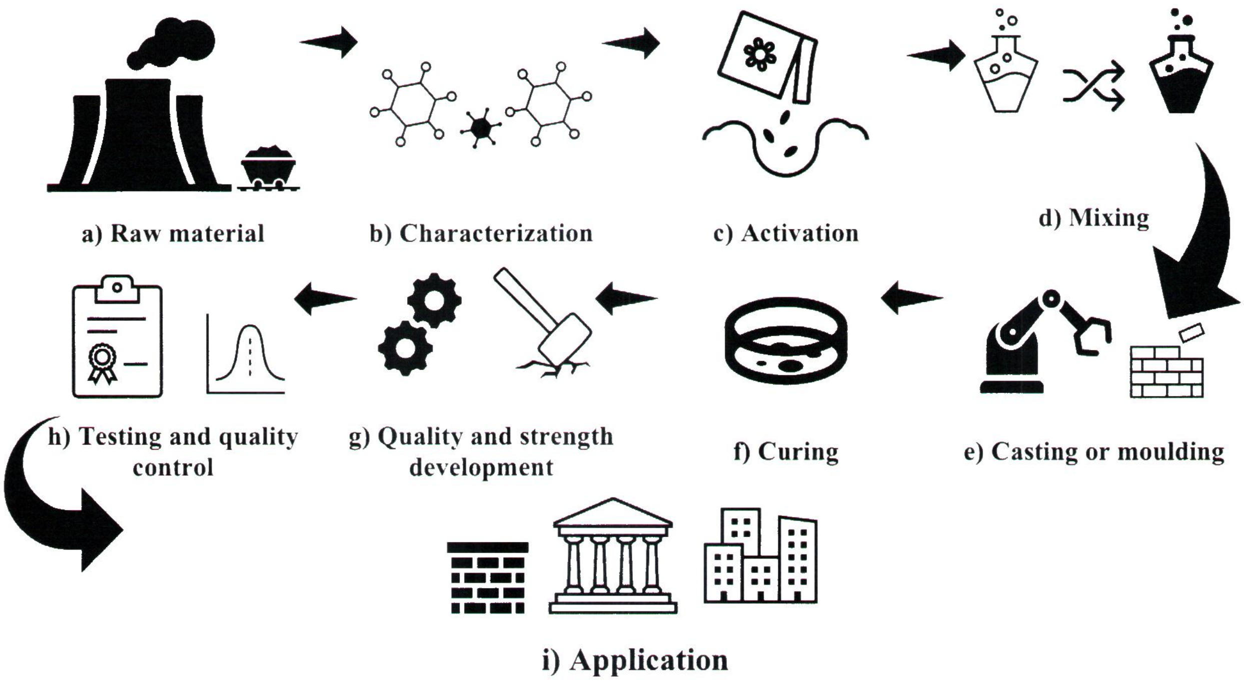

Figure 1: A schematic representation of the process involved in transforming fly ash into a geopolymer material, offering a sustainable alternative to traditional cement-based materials [15–18]; **a)** Commencing the process, fly ash is gathered as a byproduct from coal-fired power plants, **b)** Subsequently, the raw fly ash undergoes thorough analysis to determine its chemical composition and properties, **c)** To initiate the geopolymerization 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.

Furthermore, from Figure 1 has described that the fly ash, a byproduct of coal power plants is a global industrial waste [1,3,8,9,14,15]. When combined with alkalis, it forms geopolymer, a tough material known for its strength and resistance to chemicals. Geopolymer composites made from fly ash are an eco-friendly substitute for traditional binders like cement [9,11–14,18]. Researchers enhance these composites by adding materials like fibres or particles, improving their strength, thermal stability, and chemical resistance [4,10,15–17,19]. This sustainable process reduces reliance on traditional bindings and promotes eco-friendly construction. Fly ash geopolymer composites find promising applications across industries [10,14,16,20].

Moreover, the electricity generation has long relied on fossil fuels like coal, natural gas, and oil, but they come with environmental problems such as carbon emissions and pollution. The world is shifting towards cleaner energy sources like solar, wind, hydro, geothermal, and biomass power, which are more eco-friendly. Solar panels capture energy from the sun, wind turbines harness wind power, hydroelectric dams use flowing water, geothermal plants tap into the earth's heat, and biomass power comes from organic waste and wood. Nuclear power is another low-emission option. The term "global power generation capacity" refers to the various methods used worldwide to produce electricity. In 2008, renewable electricity capacity was 1 terawatt, less than the 3 terawatts from fossil fuels, as shown in Figure 2. But renewable energy has doubled over the past decade, becoming cheaper and more prevalent. The world is committed to cleaner, low-emission energy, and by 2035, renewables are expected to surpass fossil fuels, generating 15,000 terawatt-hours of electricity.

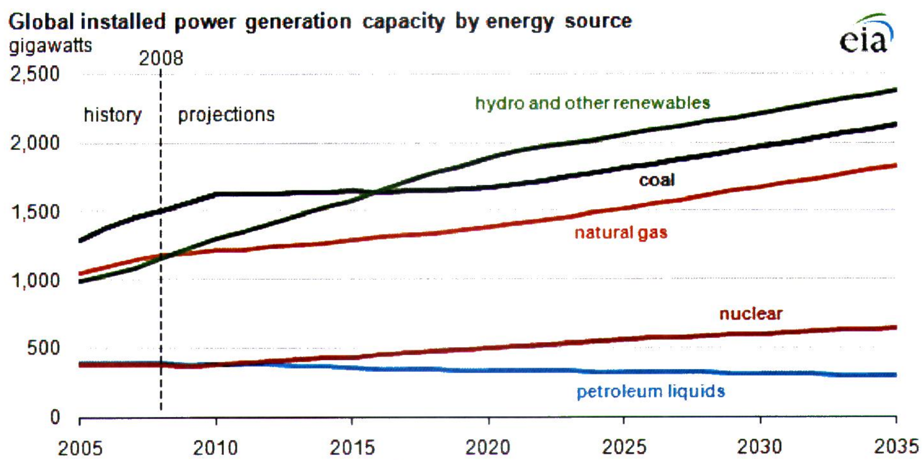

Figure 2: The source of global power generation capacity, (https://www.eia.gov/todayinenergy/detail.php?id=3270)

Meanwhile, from Figure 3 shows a reduction in solid byproduct production from burning fuel for electricity in the United States, mainly due to less coal use, a major source of these byproducts. In 2020, for the first time since data collection began in 2008, more of these byproducts were repurposed instead of being disposed of. These byproducts include fly ash (lighter ash in boiler flue gases), bottom ash (heavier ash at the bottom of boilers), and gypsum from flue gas desulphurization systems that control sulphur dioxide emissions. Each tonne of coal used for electricity in 2020 resulted in about 0.17 tonnes of these byproducts. They can be disposed of, used by power companies, sold for beneficial purposes, or occasionally stored for future use or sale.

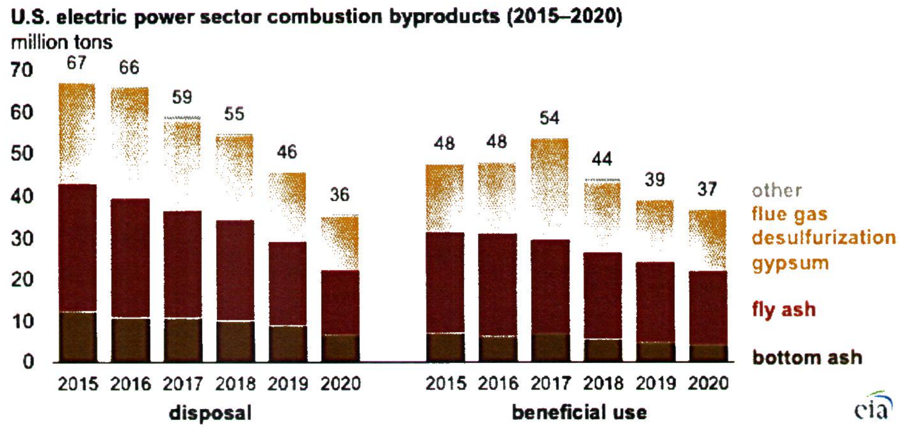

Figure 3: The U.S electric power sector combustion byproduct, (https://www.eia.gov/todayinenergy/detail.php?id=52518)

Moreover, between 2015 and 2020, the total production of combustion byproducts decreased by 36%, from 119 million tonnes to 76 million ns. This reduction corresponds to a 41% decrease in coal consumption in the electric power sector over the same five-year period. As the overall production of combustion byproducts has declined, their use has shifted from more expensive disposal methods to beneficial applications. These include manufacturing products like concrete and wallboard. Fly ash and bottom ash find use in concrete and structural fills, while flue gas desulfurization (FGD) wastes are employed in the production of gypsum wallboard.

Besides, this review underscores the exploration of fly ash's use as an eco-friendly substitute for traditional binding agents in the development of advanced composite materials, as found in the interdisciplinary domain of fly ash geopolymer composites. Researchers aim to enhance these composites' mechanical, thermal, and chemical properties by introducing reinforcing elements and optimising processing methods. These advancements carry significant implications for promoting sustainable construction practices and elevating the worth of industrial waste in applications that add value [2,4,21]. To contribute to this effort, Nayak and colleagues [2] assessed the advantages of concrete infused with fly ash, offering practical examples from the American Coal Ash Association. Thus, Zhang et al. [4] study on the treatment techniques of fly ash from municipal solid waste incineration has yielded economic benefits by characterising municipal solid waste incineration (MSWI) fly ash for sustainable management prospects and mechanisms.

Table 1: Summary of fly ash geopolymer composites material development

Material used	**Reinforcements**	**Processing process**	**Parameter's**	**Reference**
Concrete	Fibre (glass steel, natural), aggregates, fabric, nano-and	Mixing, Moulding, and Curing	• Mixing (binder, aggregates, reinforcement & additive)	[15,22–29]
Mortar		Mixing,		

Tiles	micro particles, and additives	Moulding, Curing and Surface Treatment	• Thermal curing • Mechanical • Physical • Durability	
Coatings		Mixing, Application (brushing, spraying, rolling and dipping), and Curing	• Mixing (binder, aggregates, reinforcement & additive) • Application (brushing, spraying, rolling or dipping) • Thermal curing • Mechanical • Physical • Durability	[24,30–32]
Foam	Gas-forming agent (Aluminium powder, hydrogen peroxide, etc)	Mixing, Foaming, Moulding and Curing	• Mixing (binder, gas-binding agent, & additive) • Thermal curing • Mechanical • Physical • Durability	[33–36]
Bricks	Aggregates (Sand, and crushed stone), fibre and nanoparticles	Mixing, Moulding, Curing and Surface finishing	• Mixing (binder, aggregates, reinforcement & additive) • Thermal curing • Mechanical • Physical • Durability	[15,37–39]

2. PROPERTIES OF GEOPOLYMER COMPOSITES

2.1. Mechanical Properties of Fly Ash Geopolymer Composites

Fly ash is a fine material produced when coal is burned in power plants. It's separated from the smoke using special filters. This material, known for its pozzolanic properties, has found uses in many industries, from construction to automotive and packaging, due to its unique characteristics [8,40,41]. Researchers like Makgabutlane et al. [15] are exploring how to create sustainable and eco-friendly composite materials by combining plastic and fly ash waste. They aim to improve these materials' mechanical properties for various uses while reducing their impact on the environment.

Additionally, fly ash, a byproduct of coal burning in power plants, has drawn attention because it can interact with water and calcium hydroxide to create a geopolymer, a substance with binding properties similar to regular cement. Researchers have started mixing fly ash with biodegradable polymers and natural fibres like hemp, jute, or sisal to make eco-friendly and sturdy composite materials [13,30,42]. Studies like the one conducted by Zhang et al. [13] on fly ash/slag geopolymer concrete highlight the vital role of geopolymer materials in sustainable construction practices. These materials reduce the need for non-renewable resources and contribute to environmentally friendly composites.

Table 2: Mechanical properties of fly ash biocomposites

Properties	Description	Reference
Density, g/m^3	1.0 ~ 2.5	[29,43,44]
Porosity, %	10 ~ 50	[2,6,45]
Hardness, (Vickers) *HV*	10 ~ 100	[46–48]
Compressive strength, MPa	8 ~ 11	[21,49,50]
Flexural strength, MPa	4 ~ 6	[15,51,52]
Impact strength, Joule/cm	5 ~ 50	[53,54]

Besides, this review emphasises the importance of understanding how fly ash particles interact with biodegradable elements in creating sustainable materials. These interactions play a critical role in determining the overall mechanical performance of the composites. A summary of the mechanical characteristics of fly ash biocomposites is shown in Table 2. 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/m3, 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. In conclusion, this review promotes environmental sustainability and the development of eco-friendly materials by efficiently utilising waste resources to create valuable composites.

2.1.1. Morphological properties

Numerous investigations focused on the morphological properties of fly ash biocomposites" offer various insights in a specialized area of research that delves into the structure and constitution of composite materials derived from fly ash and biodegradable elements. Additionally, 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 constitutes the core objective in this field of research [23,25,55,56]. 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 the development of cutting-edge, sustainable materials with enhanced performance that can be applied across a wide spectrum of potential uses.

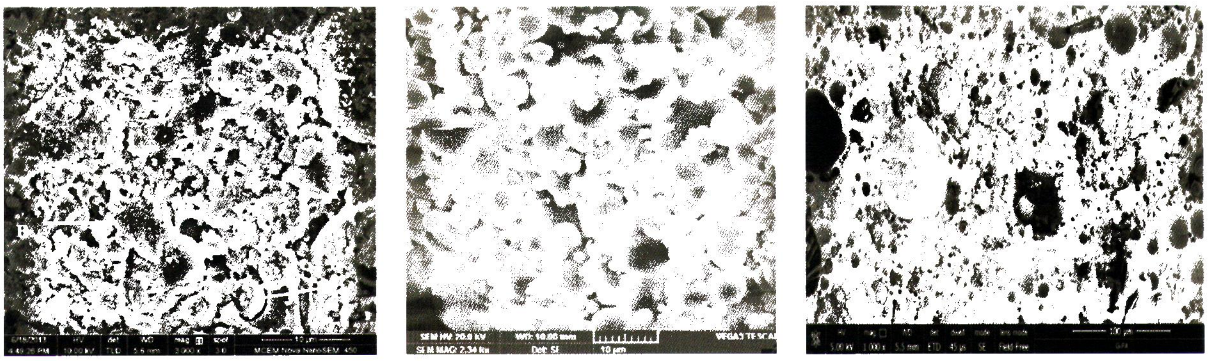

Figure 4: Morphology of fly ash geopolymer; **a)** Fly ash geopolymer cement [55], **b)** Fly ash geopolymer based [23], **c)** Fly ash geopolymer concrete [56]

As discussed previously, 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. Meanwhile, diverse research focused on morphological properties, microscopic examination techniques, such as scanning electron microscopy (SEM), as depicted in Figure 4, are used. 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 [23,55–57].

Besides, the investigating on 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. Through the enhancement of the mechanical performance of composites based on fly ash and gaining a comprehensive understanding of how fly ash particles interact with biodegradable constituents, this research endeavours to produce durable and environmentally responsible materials. Researchers employ methods like 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 through the examination of 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.

2.1.2. Thermal properties of fly ash geopolymer composite

Learning the behaviour and performance of fly ash biocomposites within the realm of geopolymer composites is heavily reliant on their thermal characteristics. The geopolymerization 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 [34,58]. Furthermore, fly ash biocomposites exhibit noteworthy attributes in various thermal aspects. Their thermal conductivity is subject to influence by several factors, 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 in comparison to traditional cement-based composites. In a review study conducted by Klima and colleagues [5], 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 [59] 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	[34,58,60–63]
Coefficient thermal expansion, 10^{-6}/°C	5 ~ 20	Construction material, infrastructure material, electronic packaging, automotive, aerospace, optical device, industrial equipment (thermal stress),	[59,64–66]
Melting temperature, °C	600 ~ 1200	Furnace, coating, aerospace, industrial equipment (thermal stress), power plant, energy storage system	[3,5,18,22,44,65]

Table 3 provides a comprehensive summary of 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 the regulation of thermal stress, benefiting industrial equipment as well as 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.

Consequently, 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 creation of energy-efficient construction materials. In doing so, they offer promising solutions for the development of sustainable and versatile materials across numerous industries.

2.1.3. Physical properties

A pivotal determinant of the performance and applicability of geopolymer composites are their physical attributes. 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. The discussion below elucidates some key physical properties of geopolymer composites.

Geopolymer composites boast a multitude of noteworthy characteristics. Their density aligns closely with that of conventional cement-based materials, offering advantages like enhanced energy efficiency and resilience in adverse conditions, rendering them well-suited for applications in insulation, construction, and aerospace. The mechanical strength they exhibit is intricately linked with their porosity; lower porosity correlates with increased wear resistance and durability. Hardness is a pivotal factor in the creation of durable and reliable components, as it quantifies a material's capacity to withstand deformation and abrasion. Nonetheless, it's important to note that a study by Mohd Nasir et al. [18] 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	[5,9,15–18,23,44,50,52,62,67–75]
Texture	Silt loam	
Specific surface area	2500 to 4000 cm2g-1	
Specific gravity	1.6 - 2.6 g cm-3	
Bulk density	0.9 - 1.3 g cm-3	

Water holding capacity	40 – 60 %	
colour	White/yellow-orange/black	

Therefore, the fundamental physical properties of fly ash biocomposites are comprehensively outlined in Table 4. These properties include texture categorized as silt loam, particle diameters ranging from 0.01 to 100 m, specific gravity within the range of 1.6 to 2.6 g/cm3, a specific surface area spanning from 2500 to 4000 cm2/g, a water retention capacity of 40%–60%, and bulk densities ranging from 0.9 to 1.3 g/cm3. 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. [50], focusing on fly ash-geopolymer concrete has unveiled a noteworthy observation. It underscores the potential of environmentally friendly materials such as fly ash to not only match but 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 the 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.

3. CONCLUSION

Fly ash geopolymer composites, such as fly ash geopolymer, represent advanced materials created by combining waste fly ash from coal combustion with geopolymer technology. These composites serve as eco-friendly binders that reduce energy consumption and carbon emissions during cement production, offering significant environmental benefits for sustainability and climate mitigation. They provide durable alternatives to traditional cement-based products, reducing waste and conserving resources, thus contributing to carbon emission reduction. These properties make them suitable for various applications in construction, infrastructure, transportation, and environmental engineering. Fly ash, a substantial global industrial waste can be transformed into geopolymers by reacting with alkalis, producing materials with exceptional mechanical properties and durability. These geopolymer composites offer a sustainable alternative to traditional binders like Portland cement. Researchers aim to enhance their properties by incorporating reinforcing materials and optimising the geopolymerization process.

In terms of thermal properties, fly ash biocomposites offer lower thermal conductivity compared to traditional cement-based materials, making them suitable for various applications, including insulation and fire-resistant construction. They exhibit promising physical characteristics like density, porosity, hardness, and strength, which are important for their performance in specific applications. In summary, fly ash geopolymer composites are environmentally friendly materials with diverse properties that can be tailored for various applications, from construction to industrial equipment. They offer sustainable solutions to contemporary engineering challenges and hold great promise for advancing eco-friendly materials and reducing waste.

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Reference

[1] Gollakota ARK, Volli V, Shu CM. Progressive utilisation prospects of coal fly ash: A review. Sci Total Environ 2019;672:951–89. https://doi.org/10.1016/j.scitotenv.2019.03.337.

[2] Nayak DK, Abhilash PP, Singh R, Kumar R, Kumar V. Fly ash for sustainable construction: A review of fly ash concrete and its beneficial use case studies. Clean Mater 2022;6:100143. https://doi.org/10.1016/j.clema.2022.100143.

[3] Moujoud Z, Sair S, Ait Ousaleh H, Ayouch I, El Bouari A, Tanane O. Geopolymer composites reinforced with natural Fibers: A review of recent advances in processing and properties. Constr Build Mater 2023;388:131666. https://doi.org/10.1016/j.conbuildmat.2023.131666.

[4] Zhang Y, Wang L, Chen L, Ma B, Zhang Y, Ni W, et al. Treatment of municipal solid waste incineration fly ash: State-of-the-art technologies and future perspectives. J Hazard Mater 2021;411:125132. https://doi.org/10.1016/j.jhazmat.2021.125132.

[5] Klima KM, Schollbach K, Brouwers HJH, Yu Q. Thermal and fire resistance of Class F fly ash based geopolymers – A review. Constr Build Mater 2022;323:126529. https://doi.org/10.1016/j.conbuildmat.2022.126529.

[6] Li X, Bai C, Qiao Y, Wang X, Yang K, Colombo P. Preparation, properties and applications of fly ash-based porous geopolymers: A review. J Clean Prod 2022;359:132043. https://doi.org/10.1016/j.jclepro.2022.132043.

[7] Amran M, Debbarma S, Ozbakkaloglu T. Fly ash-based eco-friendly geopolymer concrete: A critical review of the long-term durability properties. Constr Build Mater 2021;270:121857. https://doi.org/10.1016/j.conbuildmat.2020.121857.

[8] Mohd Nasir NH, Usman F, Saggaf A, Saloma. Development of composite material from Recycled Polyethylene Terephthalate and fly ash: Four decades progress review. Curr Res Green Sustain Chem 2022;5:100280.

https://doi.org/10.1016/j.crgsc.2022.100280.

[9] Li Z, Fei ME, Huyan C, Shi X. Nano-engineered, Fly Ash-Based Geopolymer Composites: An Overview. Resour Conserv Recycl 2021;168:105334. https://doi.org/10.1016/j.resconrec.2020.105334.

[10] Cong P, Cheng Y. Advances in geopolymer materials: A comprehensive review. J Traffic Transp Eng (English Ed 2021;8:283–314. https://doi.org/10.1016/j.jtte.2021.03.004.

[11] Albidah AS. Effect of partial replacement of geopolymer binder materials on the fresh and mechanical properties: A review. Ceram Int 2021;47:14923–43. https://doi.org/10.1016/j.ceramint.2021.02.127.

[12] Qaidi SMA, Tayeh BA, Ahmed HU, Emad W. A review of the sustainable utilisation of red mud and fly ash for the production of geopolymer composites. Constr Build Mater 2022;350:128892. https://doi.org/10.1016/j.conbuildmat.2022.128892.

[13] Zhang P, Gao Z, Wang J, Guo J, Hu S, Ling Y. Properties of fresh and hardened fly ash/slag based geopolymer concrete: A review. J Clean Prod 2020;270:122389. https://doi.org/10.1016/j.jclepro.2020.122389.

[14] Zhu J, Wei Z, Luo Z, Yu L, Yin K. Phase changes during various treatment processes for incineration bottom ash from municipal solid wastes: A review in the application-environment nexus. Environ Pollut 2021;287:117618. https://doi.org/10.1016/j.envpol.2021.117618.

[15] Makgabutlane B, Maubane-Nkadimeng MS, Coville NJ, Mhlanga SD. Plastic-fly ash waste composites reinforced with carbon nanotubes for sustainable building and construction applications: A review. Results Chem 2022;4:100405. https://doi.org/10.1016/j.rechem.2022.100405.

[16] Liu Y, Mo Z, Su Y, Chen Y. State-of-the-art controlled low-strength materials using incineration industrial by-products as cementitious materials. Constr Build Mater 2022;345:128391. https://doi.org/10.1016/j.conbuildmat.2022.128391.

[17] Grabias-Blicharz E, Franus W. A critical review on mechanochemical processing of fly ash and fly ash-derived materials. Sci Total Environ 2023;860:160529. https://doi.org/10.1016/j.scitotenv.2022.160529.

[18] Mohd Nasir NH, Usman F, Woen EL, Ansari MNM, Supian ABM, Saloma. Microstructural and Thermal Behaviour of Composite Material from Recycled Polyethylene Terephthalate and Fly Ash. Recycling 2023;8. https://doi.org/10.3390/recycling8010011.

[19] Khaw Le Ping K, Cheah CB, Liew JJ, Siddique R, Tangchirapat W, Megat Johari MA Bin. Coal bottom ash as constituent binder and aggregate replacement in cementitious and geopolymer composites: A review. J Build Eng 2022;52:104369.

https://doi.org/10.1016/j.jobe.2022.104369.

[20] Wu Y, Lu B, Bai T, Wang H, Du F, Zhang Y, et al. Geopolymer, green alkali activated cementitious material: Synthesis, applications and challenges. Constr Build Mater 2019;224:930–49. https://doi.org/10.1016/j.conbuildmat.2019.07.112.

[21] Zhuang XY, Chen L, Komarneni S, Zhou CH, Tong DS, Yang HM, et al. Fly ash-based geopolymer: Clean production, properties and applications. J Clean Prod 2016;125:253–67. https://doi.org/10.1016/j.jclepro.2016.03.019.

[22] Durak U. Effect of short-term elevated temperature curing on strength properties and microstructure of fresh fly ash geopolymer mortar. Arab J Geosci 2022;15:1–11. https://doi.org/10.1007/s12517-022-10050-4.

[23] Poloju KK, Annadurai S, Manchiryal RK, Goriparthi MR, Baskar P, Prabakaran M, et al. Analysis of Rheological Characteristic Studies of Fly-Ash-Based Geopolymer Concrete. Buildings 2023;13. https://doi.org/10.3390/buildings13030811.

[24] Sotelo-Piña C, Aguilera-González EN, Martínez-Luévanos A. Geopolymers: Past, present, and future of low carbon footprint eco-materials. Handb Ecomater 2019;4:2765–85. https://doi.org/10.1007/978-3-319-68255-6_54.

[25] Al-Majidi MH, Lampropoulos A, Cundy A, Meikle S. Development of geopolymer mortar under ambient temperature for in situ applications. Constr Build Mater 2016;120:198–211. https://doi.org/10.1016/j.conbuildmat.2016.05.085.

[26] Xavier CT, Kumar PP, Kumar PJ, Kumar GM. Comparative Studies on Floor Tiles using Geopolymer Concrete and Cement Concrete 2015;3:1–4.

[27] Marvila MT, Azevedo ARG, Delaqua GCG, Mendes BC, Pedroti LG, Vieira CMF. Performance of geopolymer tiles in high temperature and saturation conditions. Constr Build Mater 2021;286:122994. https://doi.org/10.1016/j.conbuildmat.2021.122994.

[28] Mahmoodi O, Siad H, Lachemi M, Dadsetan S, Sahmaran M. Development of optimized binary ceramic tile and concrete wastes geopolymer binders for in-situ applications. J Build Eng 2021;43:102906. https://doi.org/10.1016/j.jobe.2021.102906.

[29] Wazien AZW, Abdullah MMAB, Abd Razak R, Rozainy MAZMR, Tahir MFM. Strength and Density of Geopolymer Mortar Cured at Ambient Temperature for Use as Repair Material. IOP Conf Ser Mater Sci Eng 2016;133. https://doi.org/10.1088/1757-899X/133/1/012042.

[30] Hamidi RM, Siyal AA, Luukkonen T, Shamsuddin RM, Moniruzzaman M. Fly ash geopolymer as a coating material for controlled-release fertilizer based on granulated urea. RSC Adv 2022;12:33187–99. https://doi.org/10.1039/d2ra06056f.

[31] Al Bakri Abdullah MM, Jamaludin L, Kamarudin H, Binhussain M, Ruzaidi Ghazali CM, Ahmad MI. Study on fly ash based geopolymer for coating applications. Adv Mater Res 2013;686:227–33.

https://doi.org/10.4028/www.scientific.net/AMR.686.227.

[32] Biondi L, Perry M, Vlachakis C, Wu Z, Hamilton A, McAlorum J. Ambient cured fly ash geopolymer coatings for concrete. Materials (Basel) 2019;12:1–24. https://doi.org/10.3390/ma12060923.

[33] Ducman V, Korat L. Characterization of geopolymer fly-ash based foams obtained with the addition of Al powder or H2O2 as foaming agents. Mater Charact 2016;113:207–13. https://doi.org/10.1016/j.matchar.2016.01.019.

[34] Atienza EM, De Jesus RM, Ongpeng JMC. Development of Foam Fly Ash Geopolymer with Recycled High-Density Polyethylene (HDPE) Plastics. Polymers (Basel) 2023;15. https://doi.org/10.3390/polym15112413.

[35] Radina L, Sprince A, Pakrastins L, Gailitis R, Sakale G. Foamed geopolymers: a review of recent studies. J Phys Conf Ser 2023;2423. https://doi.org/10.1088/1742-6596/2423/1/012032.

[36] Al Bakri Abdullah MM, Hussin K, Bnhussain M, Ismail KN, Yahya Z, Razak RA. Fly ash-based geopolymer lightweight concrete using foaming agent. Int J Mol Sci 2012;13:7186–98. https://doi.org/10.3390/ijms13067186.

[37] Lavanya B, Kuriya PD, Suganesh S, Indrajith R, Chokkalingam RB. Properties of geopolymer bricks made with flyash and GGBS. IOP Conf Ser Mater Sci Eng 2020;872. https://doi.org/10.1088/1757-899X/872/1/012141.

[38] Wan Ibrahim WM, Hussin K, Al Bakri Abdullah MM, Abdul Kadir A, Binhussain M. A Review of Fly Ash-Based Geopolymer Lightweight Bricks. Appl Mech Mater 2015;754–755:452–6. https://doi.org/10.4028/www.scientific.net/amm.754-755.452.

[39] Ibrahim WMW, Al Bakri Abdullah MM, Sandu AV, Hussin K, Sandu IG, Ismail KN, et al. Processing and characterization of fly ash-based geopolymer bricks. Rev Chim 2014;65:1340–5.

[40] Zierold KM, Odoh C. A review on fly ash from coal-fired power plants: Chemical composition, regulations, and health evidence. Rev Environ Health 2020;35:401–18. https://doi.org/10.1515/reveh-2019-0039.

[41] Fediuk RS, Yushin AM. The use of fly ash the thermal power plants in the construction. IOP Conf Ser Mater Sci Eng 2015;93. https://doi.org/10.1088/1757-899X/93/1/012070.

[42] Khatib JM, Kayali O, Siddique R. Dimensional Change and Strength of Mortars Containing Fly Ash and Metakaolin. J Mater Civ Eng 2009;21:523–8. https://doi.org/10.1061/(asce)0899-1561(2009)21:9(523).

[43] Wan Mastura WI, Kamarudin H, Nizar IK, Al Bakri AMM. Mechanical performances of fly ash geopolymer bricks. Adv Sci Lett 2013;19:186–9. https://doi.org/10.1166/asl.2013.4679.

[44] Hager I, Sitarz M, Mróz K. Fly-ash based geopolymer mortar for high-temperature application – Effect of slag addition. J Clean Prod 2021;316. https://doi.org/10.1016/j.jclepro.2021.128168.

[45] Alehyen S, Zerzouri M, El Alouani M, El Achouri M, Taibi M. Porosity and fire resistance of fly ash based geopolymer. J Mater Environ Sci 2017;8:3676–89.

[46] Gohatre OK, Biswal M, Mohanty S, Nayak SK. Study on thermal, mechanical and morphological properties of recycled poly(vinyl chloride)/fly ash composites. Polym Int 2020;69:552–63. https://doi.org/10.1002/pi.5988.

[47] Estrada-Arreola F, Pérez-Bueno JJ, Flores-Ruiz FJ, León-Sarabia E, Espinoza-Beltrán FJ. The effect of temperature on micro-mechanical properties of fly ash based geopolymers activated with nano-SiO2 solution by sol-gel technique. Microsc Adv Sci Res Educ 2014:5.

[48] Luhar I, Luhar S. A Comprehensive Review on Fly Ash-Based Geopolymer. J Compos Sci 2022;6:1–59. https://doi.org/10.3390/jcs6080219.

[49] Wang M, Kang J, Liu W, Su J, Li M. Research on prediction of compressive strength of fly ash and slag mixed concrete based on machine learning. PLoS One 2022;17:1–18. https://doi.org/10.1371/journal.pone.0279293.

[50] Qaidi S, Najm HM, Abed SM, Ahmed HU, Al Dughaishi H, Al Lawati J, et al. Fly Ash-Based Geopolymer Composites: A Review of the Compressive Strength and Microstructure Analysis. Materials (Basel) 2022;15. https://doi.org/10.3390/ma15207098.

[51] Yu G, Jia Y. Microstructure and Mechanical Properties of Fly Ash-Based Geopolymer Cementitious Composites. Minerals 2022;12. https://doi.org/10.3390/min12070853.

[52] Korniejenko K, Fr??czek E, Pytlak E, Adamski M. Mechanical Properties of Geopolymer Composites Reinforced with Natural Fibers. Procedia Eng 2016;151:388–93. https://doi.org/10.1016/j.proeng.2016.07.395.

[53] Shi X, Zhang C, Liang Y, Luo J, Wang X, Feng Y, et al. Life cycle assessment and impact correlation analysis of fly ash geopolymer concrete. Materials (Basel) 2021;14:1–13. https://doi.org/10.3390/ma14237375.

[54] Bajpai R, Choudhary K, Srivastava A, Sangwan KS, Singh M. Environmental impact assessment of fly ash and silica fume based geopolymer concrete. J Clean Prod 2020;254:120147. https://doi.org/10.1016/j.jclepro.2020.120147.

[55] Nasvi MCM, Rathnaweera TD, Padmanabhan E. Geopolymer as well cement and its mechanical integrity under deep down-hole stress conditions: application for carbon capture and storage wells. Geomech Geophys Geo-Energy Geo-Resources 2016;2:245–56. https://doi.org/10.1007/s40948-016-0034-2.

[56] Roviello G, Ricciotti L, Tarallo O, Ferone C, Colangelo F, Roviello V, et al.

Innovative fly ash geopolymer-epoxy composites: Preparation, microstructure and mechanical properties. Materials (Basel) 2016;9. https://doi.org/10.3390/ma9060461.

[57] Luna-Galiano Y, Fernández-Pereira C, Izquierdo M. Contributions to the study of porosity in fly ash-based geopolymers. Relationship between degree of reaction, porosity and compressive strength. Mater Constr 2016;66. https://doi.org/10.3989/mc.2016.10215.

[58] Narattha C, Wattanasiriwech S, Wattanasiriwech D. Thermal and mechanical characterization of fly ash geopolymer with aluminium chloride and potassium hydroxide treated hemp shiv lightweight aggregate. Constr Build Mater 2022;331:127206. https://doi.org/10.1016/j.conbuildmat.2022.127206.

[59] Kaya M, Köksal F. Physical and mechanical properties of C class fly ash based light-weight geopolymer mortar produced with expanded vermiculite aggregate. Rev La Constr 2022;21:21–35. https://doi.org/10.7764/RDLC.21.1.21.

[60] Novais RM, Buruberri LH, Ascensão G, Seabra MP, Labrincha JA. Porous biomass fly ash-based geopolymers with tailored thermal conductivity. J Clean Prod 2016;119:99–107. https://doi.org/10.1016/j.jclepro.2016.01.083.

[61] Karakaş H, İlkentapar S, Durak U, Örklemez E, Özuzun S, Karahan O, et al. Properties of fly ash-based lightweight-geopolymer mortars containing perlite aggregates: Mechanical, microstructure, and thermal conductivity coefficient. Constr Build Mater 2023;362:27–33. https://doi.org/10.1016/j.conbuildmat.2022.129717.

[62] Shao N ning, Zhang Y bo, Liu Z, Wang D min, Zhang Z tai. Fabrication of hollow microspheres filled fly ash based foam geopolymers with ultra-low thermal conductivity and relative high strength. Constr Build Mater 2018;185:567–73. https://doi.org/10.1016/j.conbuildmat.2018.07.077.

[63] Feng J, Zhang R, Gong L, Li Y, Cao W, Cheng X. Development of porous fly ash-based geopolymer with low thermal conductivity. Mater Des 2015;65:529–33. https://doi.org/10.1016/j.matdes.2014.09.024.

[64] Ali MF, Vijayalakshmi Natrajan MM. A Review of Geopolymer Composite Thermal Properties. IOP Conf Ser Earth Environ Sci 2021;822. https://doi.org/10.1088/1755-1315/822/1/012051.

[65] He R, Dai N, Wang Z. Thermal and Mechanical Properties of Geopolymers Exposed to High Temperature: A Literature Review. Adv Civ Eng 2020;2020. https://doi.org/10.1155/2020/7532703.

[66] Ma J, Dehn F. Investigations on the coefficient of thermal expansion of a low-calcium fly ash-based geopolymer concrete. Struct Concr 2017;18:781–91. https://doi.org/10.1002/suco.201600211.

[67] Maiti D, Prasad B. Revegetation of fly ash A review with emphasis on grass-legume

plantation and bioaccumulation of metals. Appl Ecol Environ Res 2016;14:185–212. https://doi.org/10.15666/aeer/1402_185212.

[68] Alterary SS, Marei NH. Fly ash properties, characterization, and applications: A review. J King Saud Univ - Sci 2021;33:101536. https://doi.org/10.1016/j.jksus.2021.101536.

[69] Prusty JK, Patro SK. Properties of fresh and hardened concrete using agro-waste as partial replacement of coarse aggregate - A review. Constr Build Mater 2015;82:101–13. https://doi.org/10.1016/j.conbuildmat.2015.02.063.

[70] Sonebi M, Abdalqader A, Fayyad T, Amziane S, El-Khatib J. Effect of fly ash and metakaolin on the properties of fiber-reinforced cementitious composites: A factorial design approach. Comput Concr 2022;29:347–60. https://doi.org/10.12989/cac.2022.29.5.347.

[71] Harihanandh M, Viswanathan KE, Krishnaraja AR. Comparative study on chemical and morphology properties of nano fly ash in concrete. Mater Today Proc 2021;45:3132–6. https://doi.org/10.1016/j.matpr.2020.12.217.

[72] Poyyamozhi M, Murugesan B, Rajamanickam N. Integrated solar PV and piezoelectric based torched fly ash tiles for smart building applications with machine learning forecasting. Sol Energy 2023;258:404–17. https://doi.org/10.1016/j.solener.2023.04.053.

[73] Akid ASM, Hossain S, Munshi MIU, Elahi MMA, Sobuz MHR, Tam VWY, et al. Assessing the influence of fly ash and polypropylene fiber on fresh, mechanical and durability properties of concrete. J King Saud Univ - Eng Sci 2021. https://doi.org/10.1016/j.jksues.2021.06.005.

[74] Al-Nini A, Nikbakht E, Syamsir A, Shafiq N, Mohammed BS, Al-Fakih A, et al. Flexural behavior of double-skin steel tube beams filled with fiber-reinforced cementitious composite and strengthened with CFRP sheets. Materials (Basel) 2020;13. https://doi.org/10.3390/ma13143064.

[75] Ferdous W, Manalo A, Wong HS, Abousnina R, AlAjarmeh OS, Zhuge Y, et al. Optimal design for epoxy polymer concrete based on mechanical properties and durability aspects. Constr Build Mater 2020;232:117229. https://doi.org/10.1016/j.conbuildmat.2019.117229.