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Geopolymer Concrete Incorporating Fly Ash: A Comprehensive Review on Mix Design Strategies, Engineering Performance and Environmental Sustainability

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Abstract: Recent concern over the shortage of driving sustainable construction material has catalyzed the level of attention that has been given to Geopolymer concrete (GPC), especially those based on the use of fly ash which is a by-product of coal combustion as a major cementing agent. This review analyses the use of fly ash in Geopolymer concrete by critically looking into the mix design strategies, engineering performance as well as environmental sustainability. The underlying chemical composition of fly ash, size and shape of the particles and reactivity play an important role in Geopolymerization and end concrete properties. Important variable parameters including alkaline activator concentration Si/Al ratio and curing conditions are expounded on in regards to their role in the strength and endurance of the mechanical processes. Fly ash GPC shows high resistance to chemical attacks, low permeability as well as thermal performance over the conventional OPC concrete. In addition, production places tremendous benefits on the environment by way of carbon emission, energy requirement and efficient use of industrial wastes. Real life applications and case studies emphasize the implementation potential of best fly ash-based GPC, some obstacles being variable material, standardisation, and cost. Key gaps in current research and future directions are established in this review to provide future sense in terms of commercialization of Geopolymer concrete in supporting the construction of sustainable infrastructure.
Keywords: Geopolymer Concrete, Fly Ash, Alkali Activation, Sustainable Construction, Durability Performance.

I. INTRODUCTION

Construction is one of the biggest producers of carbon emissions in the world, and the manufacturing of Ordinary Portland Cement (OPC) alone makes up almost 7% of the total amount of CO_2 in the world. Due to the intensifying process of urbanization and the growing pressures on infrastructure, there is an urgent need to find alternative materials that will allow sustainable models of construction practices. In this regard, the Geopolymer concrete (GPC) has taken center stage and is a potentially good alternative to the conventional concrete because of its environmental friendliness. Geopolymer concrete is a non-organic inorganic aluminosilicate material created in the procedure of activation of precursors, such as fly ash with alkaline solutions. It does not use calcium silicate hydrate (C-S-H) to gain strength found in the OPC-based concrete. The binding process is, instead, based on the production of three-dimensional aluminosilicate gel, which provides significant mechanical strength as well as chemical resistance. GPC has early strength, fire resistance and environmental positives which include low heat emission, low CO_2 emission and low energy consumption. Fly ash representing the by-product of coal combustion in thermal power plants is one the mostly exploited precursors in Geopolymer systems because it contains significant proportions of silica as well as alumina. It is found mainly in two forms namely Class F and Class C with the former being much used in Geopolymer processes since it has less calcium content and is highly pozzolanic. The application of fly ash does not only solve the landfill problem but brings positive outcomes to the concept of a circular economy since industrial wastes can be transformed into high-performance construction materials. This chapter is an attempt to review the application of fly ash in Geopolymer-based concrete material in terms of material characteristics, mix design options, mechanical properties, eco-friendly advantages, and challenges. Further research on the characteristics of fly ash as the GPC also has the possibility of offering a more environmentally conscious construction that would comply with the environmental objectives of the entire world [1-2].

II. MIX DESIGN AND MATERIAL CONSTITUENTS

The Geopolymer concrete that involves the use of fly ash as a component is subject to various parameters that determine the end results and performance of the concrete after its design. The main ingredients are fly ash itself, alkaline activators (e.g., sodium hydroxide and sodium silicate), other additives or fillers (e.g., GGBS, metakaolin) and water. They each have a different function in the Geopolymerization process and have great influence on workability, strength, and durability.

Geopolymer chemistry depends on fly ash grade (Class F vs. Class C). SiO_2 and Al_2O_3 are abundant in Class F fly ash, suitable for low-calcium geopolymers, while Class C contains more CaO, promoting additional hydration reactions similar to OPC. The fineness and glassy phase content of fly ash also impact reactivity and setting time. Alkaline activators initiate the dissolution of aluminosilicate species from fly ash. The degree of polymerisation depends on the ratio and concentration of NaOH and Na_2SiO_3. Typically, a NaOH molarity between 8M–14M is used. The Na_2SiO_3 to NaOH ratio affects both workability and mechanical properties; higher silicate content generally improves strength but reduces flowability.

The Si/Al ratio (ideally between 2 and 3.5) governs the molecular structure of the gel network formed. The Na_2O/binder ratio, liquid-to-binder ratio, and curing conditions (ambient vs. thermal) also significantly influence performance. Heat curing at 60–90°C is often recommended to enhance early strength, especially when using low-calcium fly ash. Additives like GGBS, rice husk ash or metakaolin can be blended with fly ash to accelerate setting and improve performance. However, these additions must be balanced carefully to prevent rapid stiffening or adverse microstructural changes. Thus, the Geopolymer concrete mix design of fly ash based optimisation is multi-variable process that requires thorough understanding of material interactions, chemistry, and processing conditions to achieve targeted performance and durability (Fig.1) [3-4].

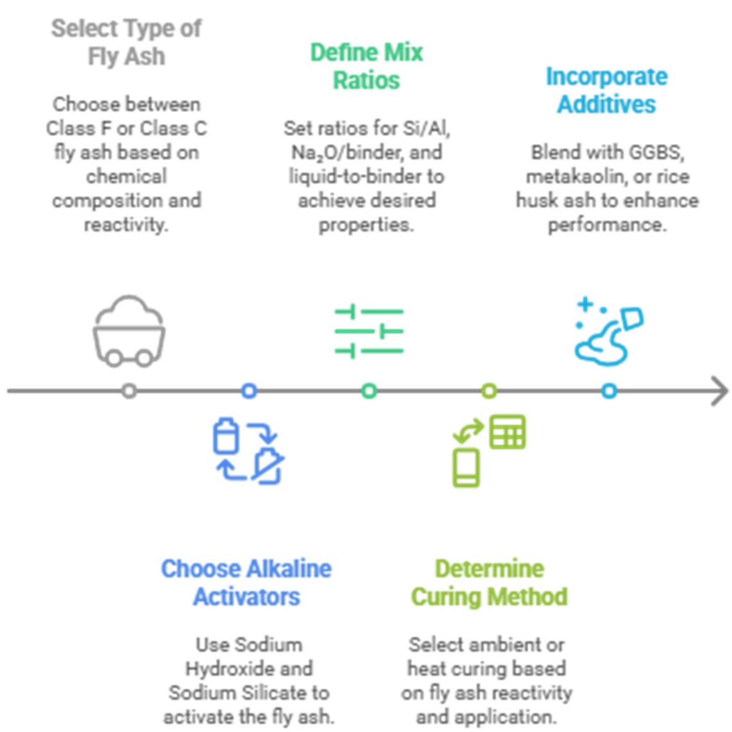

Fig-1: Mixed design process for fly ash based Geopolymer concrete

III. MECHANICAL AND DURABILITY PROPERTIES

The mechanical properties of Geopolymer concrete of fly ash are influenced by several mix parameters, including fly ash type, alkali activator concentration, curing regime, and water content. Among the key mechanical indicators, compressive strength is the most widely studied. Research shows that geopolymer concrete can achieve compressive strengths exceeding 40–60 MPa under proper thermal curing, allowing it to be used in structural contexts. Tensile and flexural strengths of geopolymer concrete typically range between 8–15% of its compressive strength. Due to the brittle nature of geopolymer binders, these parameters can be enhanced by fiber reinforcement (e.g., steel, basalt, polypropylene). The inclusion of fine fillers or reactive pozzolans can further improve strength and density. Durability owns the advantages of Geopolymer concrete over OPC concrete. GPC demonstrates high resistance to acid and sulfate attacks, low chloride ion permeability, and excellent performance under thermal stress. Its low calcium content prevents deleterious reactions like alkali-silica reaction and delaying ettringite development. Water absorption and permeability tests show that GPC has a denser microstructure, contributing to lower porosity and better impermeability. This is particularly beneficial in aggressive environments such as marine structures, sewage systems, or industrial foundations. Moreover, geopolymer concrete has been shown to retain strength and integrity under fire exposure due to its ceramic-like structure. Microstructural analysis using SEM, XRD, and FTIR techniques reveals that the sodium-aluminosilicate-hydrate is primary binding phase. Fly ash particles undergo partial dissolution and are embedded in the gel matrix, contributing to densification. The crystalline and amorphous phases vary depending on curing conditions and mix design, affecting long-term performance. Fly ash-based GPC sometimes outperforms OPC concrete in mechanical and durability, particularly when the mix design is carefully optimized (Fig.2) [5-8].

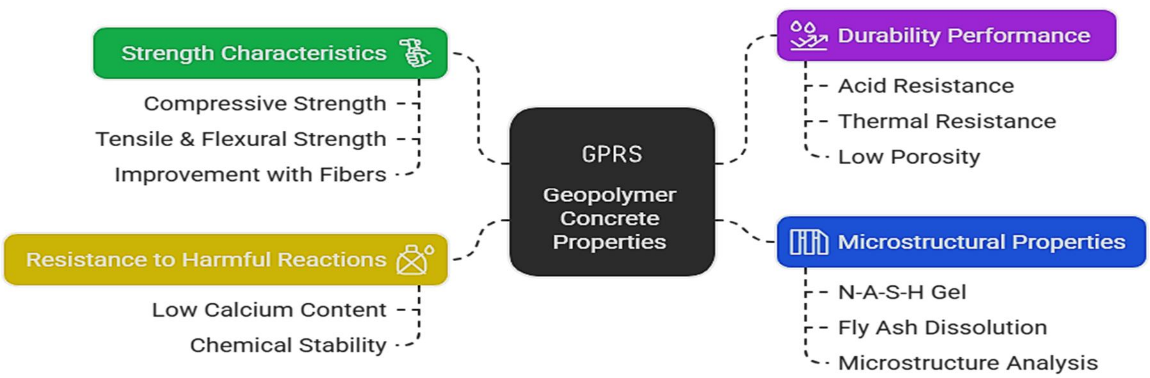

Fig-2: Properties of Geopolymer Concrete

IV. ENVIRONMENTAL IMPACT AND SUSTAINABILITY

Fly ash with Geopolymer concrete can substantially minimise construction materials' environmental impact, which is a major draw. The production of OPC is energy-intensive and releases significant CO_2 from limestone calcination and fossil fuel combustion. In contrast, geopolymer concrete made from fly ash utilizes industrial waste and avoids the calcination process, leading to up to 80–90% reduction in CO_2 emissions. The environmental load of Geopolymer concrete, as regularly reported by the Life Cycle Assessment (LCA) studies, is much lower in a range of indicators: global warming potential (GWP), embodied energy, and resource depletion. This makes it a favorable alternative in green building certifications such as LEED and BREEAM. Coal combustion releases fly ash which represents a major waste management challenge [9-12]. Its use in GPC not only diverts waste from landfills but also adds economic value to a waste stream. Also, Geopolymer concrete does not involve the use of kiln operations at high temperatures compared to ordinary concrete, thus resulting in a lower number of energy use overall during its manufacture. The production of Geopolymer concrete also uses relatively little water because it does not undergo hydration reactions which demand the use of water as is the case in OPC. This may be of great advantage in the areas where there is scarcity of water. Furthermore, Fly ash-based GPC improves interior quality of air by eliminating VOCs that can be present in other construction materials. Despite these advantages, the environmental benefits depend on factors such as transport distances, fly ash availability, and activator production. Sodium hydroxide and sodium silicate are energy-intensive chemicals, and their manufacturing impacts need to be considered in a full LCA. In summary, Geopolymer concrete of fly ash represents a step forward in sustainable construction, aligning well with global carbon neutrality targets and the circular economy model [13-19].

V. APPLICATIONS, CHALLENGES AND FUTURE PROSPECTS

Geopolymer concrete of Fly ash has found increasing adoption in structural and non-structural applications. Its high strength, durability, and environmental benefits make it suitable for use in precast elements, paving blocks, retaining walls, sewer pipes, and marine structures. Prestressed bridge girders and railway sleepers have also been successfully produced using GPC, especially in countries like Australia and India, where large volumes of fly ash are available. Several field trials and pilot projects have demonstrated the viability of GPC in real-world conditions. Notably, infrastructure projects in India have employed fly ash-based GPC for road pavements and precast concrete components. The use of ambient-cured GPC has further expanded its applicability in tropical climates where heat curing can be naturally achieved. However, several challenges remain. Standardization in mix design and performance prediction is lacking, limiting widespread acceptance in building codes. The high cost and handling difficulties of alkaline activators also hinder large-scale commercial use. Moreover, variability in fly ash composition across different power plants affects consistency in performance. Workability and setting time control are also concerns, especially for in-situ casting. Unlike OPC, GPC lacks a universal admixture solution, and research into compatible plasticizers, retarders, and accelerators is still ongoing. Also, the long-term performance data under varying climate and load conditions are still being gathered (Fig.3).

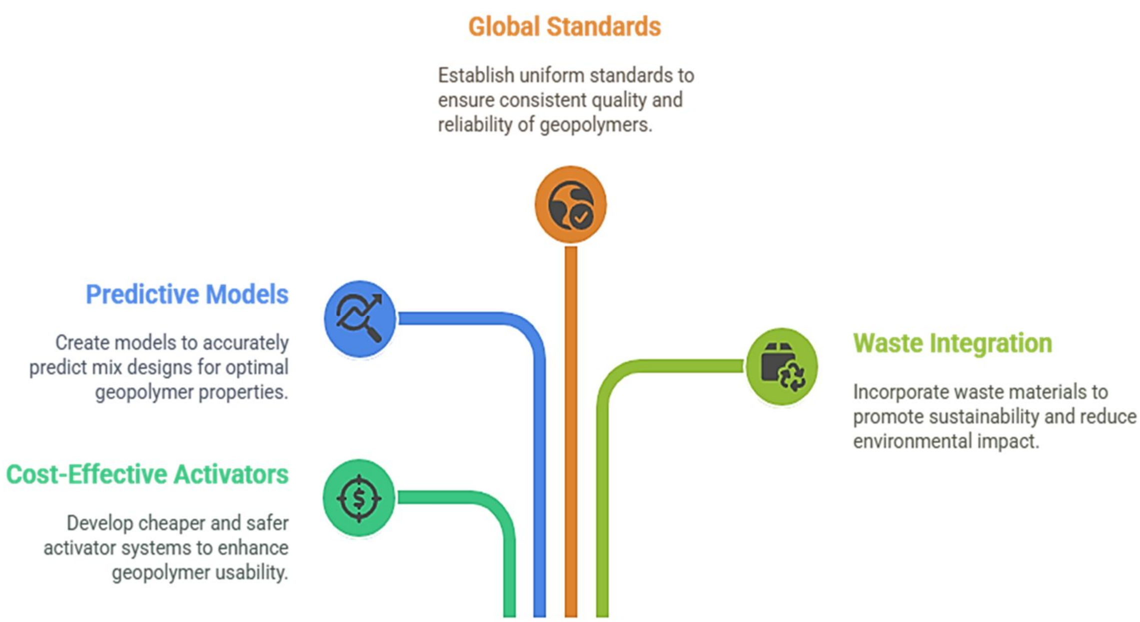

Fig-3: Future Outlook of Fly Ash-Based Geopolymer Concrete

VI. OBJECTIVES

Based on the literature review, the following Research objectives have been formulated to address the identified research gaps, and future research should focus on achieving these objectives.

- Creating economical alternatives and safer activator systems.
- Creating predictive mix design models.
- Establishing global standards and specifications for GPC.
- Integrating supplementary waste materials for hybrid geopolymers.

With continued research and policy support, geopolymer concrete incorporating fly ash can transform from a niche innovation to a mainstream sustainable building material, playing a pivotal role in low-carbon construction [19-27].

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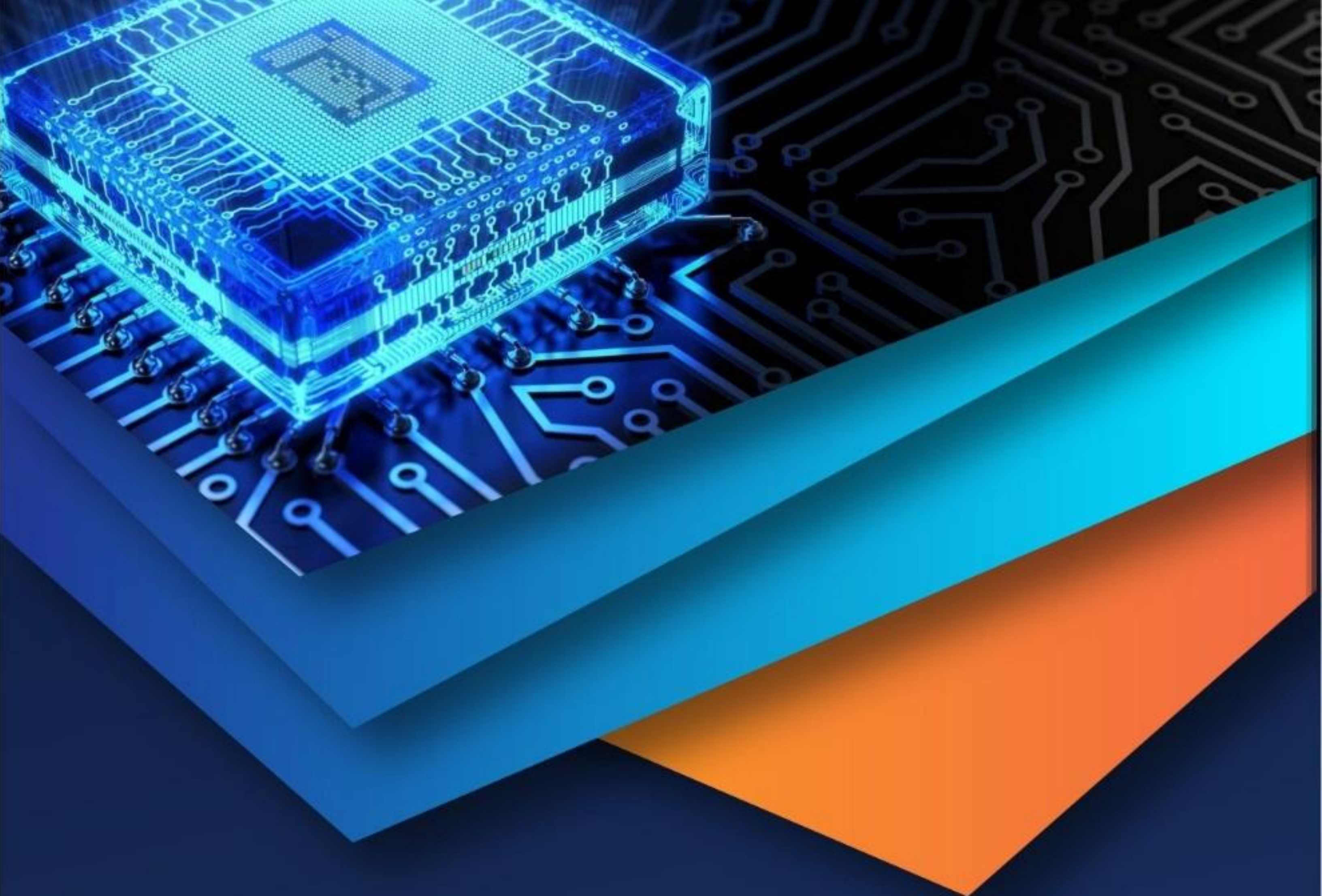

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