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Comparative Life-Cycle and Performance Assessment of Fly Ash-Based Geopolymer Binders versus Ordinary Portland Cement for Energy-Efficient Building Applications

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Abstract- The construction industry is a major contributor to global CO_2 emissions, primarily due to the energy-intensive production of Ordinary Portland Cement (OPC). This paper presents a comparative case study comparing the environmental, mechanical, and durability performance of OPC (Conventional) and Fly Ash-Based Geopolymer Binders (Sustainable). Using data extracted from past research, this study demonstrates the significant sustainable effect of fly ash-based geopolymer binders. These green binders offer a considerably reduced embodied carbon and energy footprint, while maintaining comparable or superior performance indicators. Fly ash-based geopolymer binders exhibit an embodied carbon of 242.87 kg CO_2e compared to 552.22 kg CO_2e for OPC per kg binder or m^3 concrete. Furthermore, their end-of-life assessment reveals greater potential for recycling and reuse, aligning with circular economic principles. The findings strongly advocate for the increased adoption of green cement, such as fly ash-based geopolymer binders, as a key strategy for developing energy-efficient and sustainable constructions.

Key Words- Green Building Materials, Low-Carbon Construction, Sustainable Cement Alternatives, Sustainable Construction

1 INTRODUCTION

The construction industry plays a major role in global economic development. However, it is also one of the largest contributors to environmental degradation and climate change. Buildings account for a significant share of global energy consumption and greenhouse gas emissions throughout their life cycle, from material extraction and production to construction, operation, and demolition. Among construction materials, Ordinary Portland Cement (OPC) is recognized as a significant source of carbon dioxide emissions due to its highly energy-intensive manufacturing process and the release of chemically bound CO_2 during the calcination of limestone [1],[2]. It is estimated that cement production alone contributes approximately 7-8% of total global CO_2 emissions, making it a critical target for sustainability-driven innovation in the construction environment [3],[4].

As global concerns over climate change, resource depletion, and energy efficiency intensify, there is increasing pressure on the construction sector to adopt environmentally responsible materials and practices. Green material design has therefore emerged as a key strategy to reduce the environmental footprint of buildings while maintaining structural safety and performance. In this context, alternativorus materials that can replace or partially substitute OPC have gained considerable research and industrial interest.

Geopolymer binders represent one of the most promising sustainable alternatives to conventional cement. Unlike OPC, geopolymers are produced through the alkali activation of aluminosilicate-rich materials, such as fly ash, rice husk ash, or slag, which are often industrial by-products [5],[6],[7]. The use of fly ash not only reduces the demand for virgin raw materials but also offers an effective pathway for waste valorization, diverting large quantities of industrial waste from landfills [8][9]. Furthermore, geopolymer production typically requires lower processing temperatures than OPC manufacturing, resulting in reduced energy consumption and greenhouse gas emissions.

Beyond environmental benefits, geopolymer binders have demonstrated competitive mechanical properties and superior durability in aggressive environments, such as sulphate or chloride-rich conditions. These characteristics make them particularly suitable for energy-efficient and long-lasting building applications [10],[11],[12]. However, despite their potential advantages, the large-scale adoption of geopolymer binders is still limited due to concerns related to material variability, lack of standardized design codes, and uncertainties regarding long-term performance and end-of-life behavior.

Fig. 1. Carbon-intensive cement production and low-carbon geopolymer alternatives.

Against this background, a systematic comparison between conventional OPC and sustainable fly ash-based geopolymer binders is essential to support informed material selection in green building design (Fig.1). This study presents a comparative case study based on synthesized data from existing literature, focusing on key performance indicators including environmental impact, mechanical strength, durability, and end-of-life potential. By highlighting the strengths and limitations of both binder types, this research aims to demonstrate the role of green cements in enabling energy-efficient, low-carbon, and sustainable construction practices aligned with circular economy principles.

2 METHODOLOGY

This research is based on a comprehensive literature review and data synthesis from past peer-reviewed research papers, technical reports, and case studies as shown in Fig.2. This approach was selected to enable a comparative case study between Ordinary Portland Cement (OPC) and Fly Ash-Based Geopolymer Binders without conducting new experimental work, making the study cost-effective and suitable for assessing broader sustainability trends [2],[13].

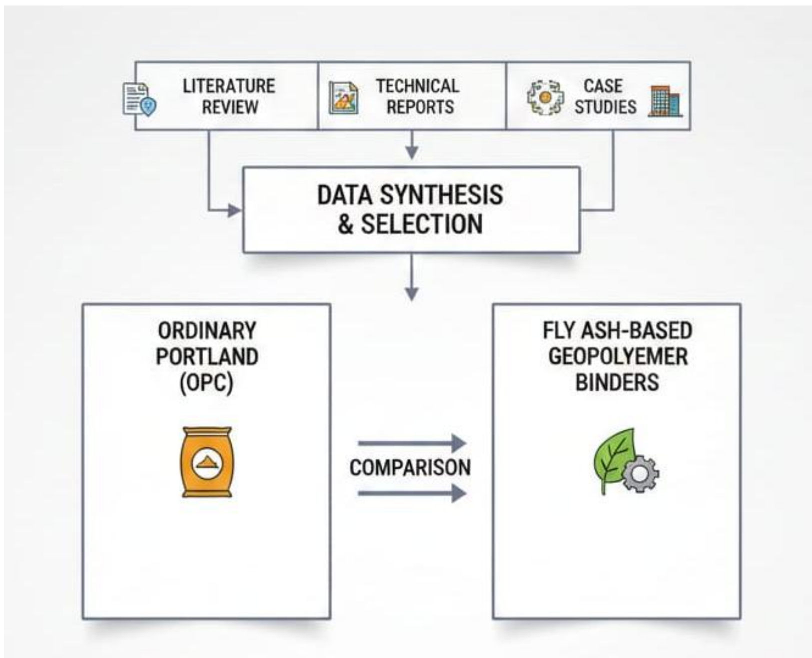

Fig. 2. Research Methodology

To ensure a meaningful and balanced comparison, specific evaluation factors were carefully selected based on their relevance to sustainable construction and energy-efficient building design. The collected data were systematically organized into a comparative framework, as presented in Table 1, under the following key categories:

2.1. Material Identity

This factor describes the fundamental nature of each binder, including binder type and primary raw materials. Understanding material identity is important because it directly influences resource consumption, manufacturing processes, and environmental impact. OPC relies on non-renewable natural resources such as limestone and clay, while geopolymer binders utilize industrial by-products like fly ash, highlighting their potential for waste reduction and resource efficiency.

2.2. Environmental Performance

Environmental performance is a critical indicator of sustainability and was evaluated using embodied carbon and embodied energy [14].

- Embodied carbon represents the total greenhouse gas emissions associated with material production and is essential for assessing a material's contribution to climate change.
- Embodied energy reflects the total energy consumed during manufacturing and processing. Lower embodied energy indicates higher energy efficiency and reduced dependence on fossil fuels.

2.3. Mechanical Performance

Mechanical performance, particularly compressive strength at 28 days, was included to assess structural applicability. Compressive strength is one of the most important properties for cement-based materials, as it determines their ability to withstand structural loads. Including this factor ensures that sustainability benefits are evaluated alongside practical engineering requirements [15].

2.4. Durability Indicators

Durability plays a vital role in determining the service life and long-term sustainability of buildings. Sulphate resistance was selected as a representative durability indicator because sulphate attack is a common cause of concrete degradation, especially in aggressive soil and groundwater conditions. Materials with higher sulphate resistance require less maintenance and repair, reducing resource consumption over the building's life cycle [16].

2.5. End-of-Life Options

An end-of-life assessment evaluates what happens to materials after demolition, which is essential for considering circular economy principles. This factor was included to compare the potential for recycling, reuse, and landfill disposal. Materials with higher recyclability and reuse potential contribute to reduced construction and demolition waste and promote sustainable material loops [17],[18].

The selected factors collectively provide a holistic comparison of OPC and fly ash-based geopolymer binders, covering environmental, technical, durability, and circular economy perspectives. The analysis and discussion are based on reported data trends rather than isolated values, allowing for a realistic and balanced assessment of the advantages and limitations of green cement alternatives.

3 COMPARATIVE DATA SYNTHESIS

Table 1 presents the key comparative data used in this study, synthesized from past research. Comparison data were analyzed under different property categories to evaluate the effect of each binder type.

Table 1: Property comparison of conventional (OPC) and sustainable (fly ash-based geopolymer) Binders

Property Category	Property Name	Unit	OPC (Conventional)	Fly Ash–Based Geopolymer Binder	Ref.
Material Identity	Binder type	-	Portland clinker-based cement	Alkali-activated aluminosilicate	[19],[20]
	Main raw materials	-	Limestone, clay	Fly ash, alkaline activator	[19],[20]
Environmental Performance	Embodied carbon	kg CO_2 / kg binder or kg CO_2 / m^3 concrete	552.22 kg CO_2e	242.87 kg CO_2e	[21]
	Embodied energy	MJ / kg or MJ / m^3	Between +4.6 MJ/kg and +6.4 MJ/kg	0.9 MJ/kg	[22],[23]
Mechanical Performance	Compressive strength (28 days)	MPa	20.68 MPa (28 Days)	25.81 MPa (28 Days)	[24]
Durability Indicators	Sulphate resistance	% of change in mass	+0.6 (within 90 days)	-0.1 (within 90 days)	[25]
End-of-Life	End-of-life option	Qualitative	Recycling / landfill	Recycling / reuse potential	[26]

4 DISCUSSION

4.1. Material Identity and Resource Efficiency

OPC is a Portland clinker-based cement requiring non-renewable resources like limestone and clay. The production involves high-temperature calcination, which is energy-intensive and CO2-releasing.

In contrast, the Fly Ash-Based Geopolymer Binder is an alkali-activated aluminosilicate. It primarily utilizes industrial waste products, specifically fly ash, along with an alkaline activator. By replacing raw materials with industrial by-products, green cement inherently promote resource efficiency and waste valorization. This core difference is the foundation for the superior environmental performance of geopolymers.

4.2. Environmental Performance: Embodied Carbon and Energy

This is arguably the most critical area where green cement demonstrates a clear advantage.

- Embodied Carbon: OPC has a high embodied carbon of 552.22 kg CO_2e. Fly ash-based geopolymer binders significantly cut this down to 242.87 kg CO_2e per kg binder or m^3 concrete. This represents a reduction of over 50%, directly contributing to lower CO_2 footprints for entire structures.
- Embodied Energy: Similarly, the embodied energy of OPC is high, ranging from +4.6 MJ/kg to +6.4 MJ/kg. The geopolymer binder has a dramatically lower embodied energy level of 0.9 MJ/kg. The

lower energy demand in the manufacturing process directly correlates to the increased energy efficiency of buildings over their full life cycle.

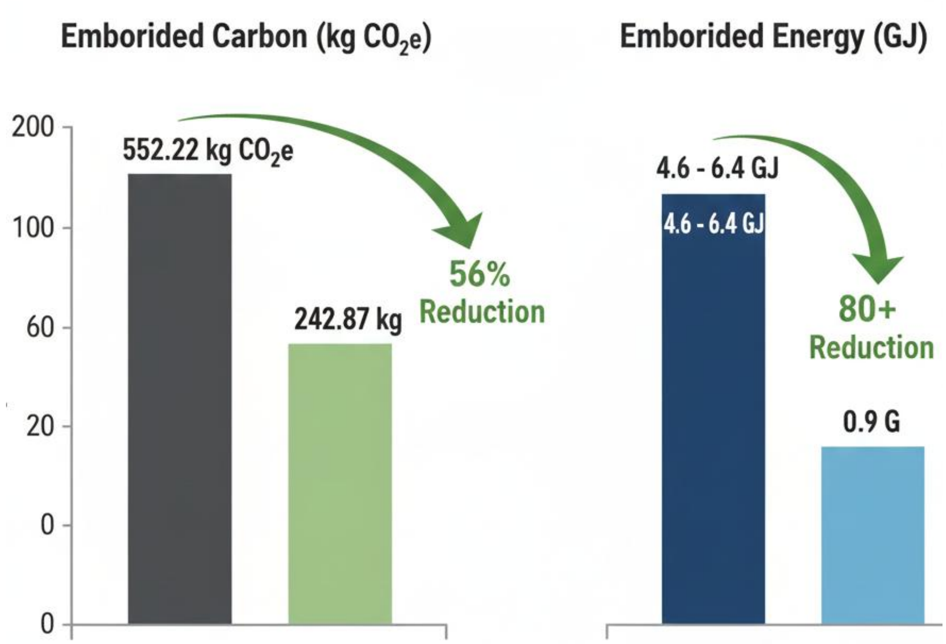

Fig. 3. Side-by-side comparison of Embodied Carbon and Embodied Energy by Geopolymer concrete versus OPC.

4.3. Mechanical Performance and Applicability

While environmental metrics are key, a material's practical use depends on its mechanical performance. The 28-day compressive strength for the sampled OPC is 20.68 MPa, while fly ash-based geopolymer samples show 25.81 MPa.

In this specific comparison, the fly ash-based geopolymer samples exhibit higher compressive strength values. This 25.81 MPa value is adequate for many structural applications, particularly in residential and low-rise commercial buildings, and is comparable to or exceeds many OPC grades. Furthermore, geopolymer concrete can be engineered to achieve even higher strengths depending on the formulation and curing conditions. This indicates that geopolymer binders are a viable, performance-ready alternative for a significant portion of construction needs [27],[28].

4.4. Durability Indicators

Durability is a major factor in determining a building's service life and long-term sustainability. The comparison of sulphate resistance, a key indicator of material degradation, shows an advantage for the geopolymer binder.

- Sulphate Resistance: OPC shows a +0.6 change in mass (a measure of expansion or degradation) within 90 days, indicating susceptibility to sulphate attack. The geopolymer binder shows a -0.1 change in mass within 90 days, suggesting higher resistance and stability in sulphate-rich environments. This enhanced durability can lead to a longer lifespan for geopolymer-based structures, further enhancing their sustainability profile by reducing the need for maintenance and replacement.

4.5. End-of-Life Assessment and Circular Economy Potential

The transition to a circular economy is a central goal for green material design. The End-of-Life (EoL) options differ significantly for the two binder types.

- OPC End-of-Life: The primary EoL options for OPC concrete are recycling (as crushed aggregates) and landfilling. While recycling into Recycled Concrete Aggregate (RCA) is common, OPC concrete still contributes heavily to Construction and Demolition Waste (CDW), and a significant amount is landfilled. Advanced recycling methods like cement reclinkering are challenging due to the difficulty of separating the hardened paste from aggregates [29].
- Geopolymer End-of-Life: Geopolymer concrete offers a greater recycling/reuse potential. Studies indicate that Recycled Aggregate Geopolymer Concrete (RAGC) can better incorporate high percentages of RCA (sometimes up to 100% replacement) without the same performance loss issues seen with OPC. This ability for better integration of recycled materials makes geopolymer binders perfectly aligned with a circular economy model [30].

A primary environmental challenge for geopolymers, however, is the presence of alkaline activators in their life cycle, which can increase the ecotoxicity potential impacts (marine, freshwater, human). Despite this, incorporating RCA in geopolymer production has been shown to minimize the leaching of toxic elements.

5 CONCLUSIONS

The comparative case study clearly demonstrates that sustainable fly ash–based geopolymer binders offer significant and quantifiable advantages over conventional Ordinary Portland Cement, positioning them as a critical material for the future of energy-efficient and green building design. The most compelling findings of this comparative study are geopolymers offer a dramatically lower embodied carbon (242.87 kg CO_2e vs. 552.22 kg CO_2e) and embodied energy (0.9 MJ/kg vs. +4.6 MJ/kg to +6.4 MJ/kg. Geopolymers exhibit superior sulphate resistance (-0.1 change in mass) compared to OPC (+0.6 change in mass), suggesting a longer structural lifespan with enhanced durability. Further, geopolymer concrete integrates better with Recycled Concrete Aggregate, promoting a higher reuse potential and reducing landfill dependency.

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