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# Policy Pathways for Scaling Geopolymer Concrete: Lessons from Global Practices and Future Directions

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**Abstract:** This study explores policy pathways to accelerate the adoption of geopolymer concrete (GPC) as a sustainable alternative to Portland cement. Through comparative analysis of regulatory frameworks in India and the EU, and life cycle assessment modeling, it identifies fiscal incentives, procurement reforms, and institutional support as key enablers. Despite technical advantages, GPC faces challenges such as carbonation risks and fly ash variability. Future research must address long-term durability, market readiness in developing countries, and global material databases. Findings emphasize that integrated policy frameworks are essential to scale GPC and unlock its potential for reducing construction sector emissions.

**Keywords:** geopolymer concrete, fly ash, low-carbon construction, policy frameworks, public procurement, waste-derived activators, sustainability transition.

## Introduction

Fly ash waste from coal combustion has become a critical global environmental issue. Recent estimates indicate that global fly ash production exceeds 500 million tons annually, yet less than 30% is repurposed in a beneficial manner (Mathapati et al., 2022). The remainder is typically disposed of in landfills, where it poses a risk of contaminating groundwater through the leaching of heavy metals such as arsenic (As), mercury (Hg), and lead (Pb) (Du et al., 2025).

Simultaneously, the construction industry is responsible for approximately 8–10% of global $CO_2$ emissions, with around 90% of these emissions attributed to Portland cement production (Andrew, 2019). One promising alternative is geopolymer concrete (GPC), which utilizes fly ash as a binder activated through an alkali polymerization process. This technology has the potential to reduce $CO_2$ emissions by 70–80% compared to conventional cement (Davidovits, 2021). However, broader adoption is hampered by a lack of specific policy frameworks and institutional infrastructure (European Commission, 2022).

## Research Objectives and Research Questions

**Objective:**

To examine policy instruments, regulatory frameworks, and strategic approaches for accelerating the adoption of geopolymer concrete.

**Research Questions:**

1. What policy models have proven effective in advancing GPC adoption?
2. How can public procurement and fiscal incentives drive the use of low-carbon materials?
3. What institutional frameworks are needed to support scale-up in developing countries?

## Policy Analysis

A comparative policy study conducted by the authors identified three key approaches. First, India's Ministry of Environment issued a regulation requiring a minimum of 35% fly ash usage in all public construction projects (Ministry of Environment, Forest and Climate Change, 2021). While this marks progress, the regulation does not distinguish between conventional fly ash use as an additive and more innovative applications such as GPC. As a result, its impact is largely limited to waste diversion rather than deep decarbonization (European Commission, 2022).

Second, the European Union's experience, particularly the Netherlands' 'Green Public Procurement' (GPP) scheme, offers a fiscal model. Projects using materials with a carbon footprint below 50% of the standard receive a 15% tax credit. Between 2019 and 2023, this initiative led to a 40% increase in low-carbon material usage and a 300% growth in GPC implementation in infrastructure projects (European Commission, 2022).

Life Cycle Assessment (LCA) analyses support these policy approaches. With economies of scale, GPC costs could fall from USD 200/m³ to USD 135/m³ by 2030 through mass production of waste-derived alkali activators, USD 50/ton $CO_2$ carbon subsidies, and streamlined material approval procedures (Astuti et al., 2024).

## Strategic and Institutional Recommendations

To facilitate large-scale adoption of GPC, we recommend the following policy instruments:

- A 'Carbon Discount' in public procurement: 5% bid reduction for every 10% reduction in material carbon footprint
- Creation of a National Fly Ash Database to link suppliers with construction demand
- Establishment of GPC Competency Centers offering technical training and certification

As shown by a research before, despite GPC's advantages, its carbonation rate can be five times higher than that of ordinary concrete (Zhao et al., 2024). Hence, regulatory standards must include durability metrics. Similarly, the compositional variability of fly ash across power plants—particularly in the $SiO_2$ (40–45%) and $Al_2O_3$ (15–30%) content—necessitates tailored mix formulations and customized approval processes (Putra et al., 2024).

## Future Research Directions

- **Durability testing of GPC for >50 years using accelerated aging models and AI-based prediction tools**
  Due to variations in testing methodologies, certain research findings remain contentious. For example, (Zhao et al., 2024) reported that the carbonation rate of GPC is substantially higher than that of ordinary Portland concrete, raising concerns regarding its long-term durability in specific environments.
- **Socioeconomic studies on market readiness in developing countries**
  (Aiman et al., 2024) used survey and factor analysis to reveal that "standards and knowledge significantly influence the adoption of geopolymer concrete. Furthermore, scientometric reviews highlight that policy gaps and low awareness in developing regions have left geopolymer adoption lagging behind that in Europe, Australia, and China. Geopolymer demand in the Asia Pacific region is being driven by urbanization and green policies, yet fragmented regulations (e.g. in Southeast Asia and parts of Africa) remain significant barriers .
- **Development of an international fly ash composition database and formulation guide**
  Data obtained from multiple coal-fired power plants across different countries reveal considerable variability in the $SiO_2$ and $Al_2O_3$ content of fly ash (Putra et al., 2024), which has direct implications for its use in geopolymer concrete formulations.

## Conclusions

This study concludes that effective policy frameworks are critical to scaling up GPC adoption. A coordinated approach involving carbon incentives, data infrastructure, and institutional capacity can transform fly ash from an environmental burden into a strategic asset for sustainable development.

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