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INNOVATION IN FLY ASH–GGBS BASED GEOPOLYMER CEMENT FOR ENHANCED DURABILITY AND STRUCTURAL APPLICATIONS

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Abstract

Contemporary mission practice faces unprecedented complexity due to social, cultural, ecological, and technological transformations. Traditional diagnostic frameworks often fail to address the underlying worldviews and ontologies that shape institutional and societal behavior. This article introduces the Tripolar Systemic Analysis (TSA), a diagnostic methodology built upon the Moleka Grid, which integrates symptomatic, paradigmatic, and ontological analyses. Drawing upon ontorics, philosophy, and leadership studies, TSA enables mission leaders and researchers to engage with systemic transformation holistically. Comparative analysis with classical models such as the Iceberg Model and Three Horizons Framework demonstrates TSA's novel contribution: a multi-level, philosophically grounded, and actionable framework for transformational leadership and systemic mission intervention.

1. Introduction

Concrete is the most widely used construction material in the world, and ordinary Portland cement (OPC) is its primary binding component. However, the production of OPC is energy-intensive and contributes significantly to global carbon dioxide emissions, which has led to serious environmental concerns. The increasing demand for sustainable and eco-friendly construction materials has motivated researchers to explore alternative binders that can reduce the carbon footprint of the construction industry. Geopolymer cement has emerged as a promising sustainable alternative to OPC due to its low carbon emissions and its ability to utilize industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS). These materials are rich in alumino-silicate compounds and can be activated using alkaline solutions to form geopolymer binders with excellent mechanical and durability properties. Compared to conventional cement, geopolymer cement offers advantages such as high early strength, superior resistance to chemical attack, low shrinkage, and improved thermal stability. In recent years, innovative developments in geopolymer cement technology have focused on optimizing mix proportions, improving curing methods, and enhancing durability and structural performance. The combined use of fly ash and GGBS has been shown to improve setting characteristics and strength development while ensuring better long-term durability. Moreover, geopolymer cement contributes to effective waste management by converting industrial by-products into value-added construction materials.

1.1 Materials Used in Geopolymer Concrete (No-Cement System)

1.Source Materials

- Fly ash (Class F), Ground Granulated Blast Furnace Slag (GGBS), Metakaolin
- Rice Husk Ash (RHA)

2.Alkaline Activators

- Sodium Hydroxide (NaOH), Sodium Silicate (Na_2SiO_3)

3.Aggregates

- Fine aggregate (river sand or manufactured sand) , Coarse aggregate

1.2 Geopolymerization Mechanism

Dissolution of silica and alumina in alkaline solution , Transportation and orientation of dissolved species, Polycondensation reaction, Formation of geopolymeric gel (N-A-S-H / C-A-S-H) and Hardening and strength development

1.3 Advantages of No-Cement Geopolymer Concrete

- Zero cement usage, Up to 80–90% reduction in CO_2 emissions
- High early and ultimate compressive strength, Excellent resistance to sulphate and acid attack
- Low shrinkage and creep, Superior fire and thermal resistance
- Effective utilization of industrial waste materials

1.4 Limitations and Challenges

- Lack of universal design codes , Handling issues related to alkaline solutions
- Dependency on quality and availability of fly ash and GGBS
- Need for temperature-controlled curing (in some mixes)

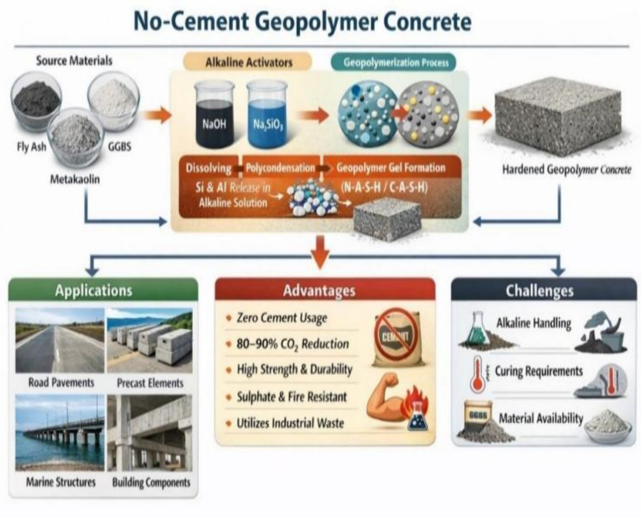

Fig.1 No Cement of Geopolymer Concrete

2. AI and ML Applications in Geopolymer Concrete

Artificial Intelligence (AI) and Machine Learning (ML) have emerged as powerful tools for optimizing material design, predicting performance, and enhancing sustainability in the construction industry.

2.1 Mix Design Optimization

ML algorithms such as Artificial Neural Networks (ANNs), Support Vector Machines (SVMs), and Genetic Algorithms (GA) are used to predict the optimal proportion of fly ash, GGBS, activators, and aggregates.

These models can reduce the need for extensive experimental trials, saving time, cost, and resources.

AI-based systems can tailor geopolymer mixes for specific performance requirements, such as compressive strength, workability, or durability.

2.2 Predicting Mechanical Properties

ML models can accurately predict compressive strength, tensile strength, flexural strength, and durability of GPC based on input parameters like material composition, curing method, and temperature.

This allows engineers to forecast performance under different environmental conditions without extensive lab testing.

2.3 Curing and Performance Analysis

AI techniques can model the effects of curing temperature, curing time, and ambient conditions on geopolymerization.

Predictive models help in selecting suitable curing regimes to maximize strength and minimize defects like efflorescence or cracking.

2.4 Structural Behavior Simulation

ML combined with Finite Element Analysis (FEA) can simulate structural performance of geopolymer concrete elements under flexural, compressive, or seismic loads.

AI-assisted modeling reduces computational time and provides more accurate predictions for reinforced geopolymer concrete elements.

2.5 Sustainability and Cost Analysis

AI models can optimize material selection and energy consumption, leading to cost-effective and environmentally sustainable GPC formulations.

Multi-objective optimization algorithms can balance strength, durability, CO_2 reduction, and cost, facilitating green construction practices.

2.6. Quality Control and Defect Detection

ML models integrated with image processing and sensor data can detect cracks, voids, or inconsistencies in geopolymer concrete during or after curing.

This allows for real-time quality control and ensures reliability in structural applications.

AI and ML provide significant advantages in advancing geopolymer concrete technology by reducing experimental workload, predicting performance, optimizing mix designs, and promoting sustainable construction. These technologies enable engineers and researchers to accelerate the adoption of geopolymer concrete in practical applications.

3.Literature Review

Peem Nuaklong, Vanchai Sata and Prinya Chandrasiri (2015). The properties of fly ash - based Geoploymer concrete incorporated with recycled concrete aggregates. It have been studied by the samples were prepared using high calcium fly ash, activator solution, and fine aggregate and coarse aggregate. In study, two types of aggregates namely recycled concrete aggregates and crushed limestone coarse aggregates were used in the mix. It was found that the compressive strength of recycled coarse aggregate Geopolymer concrete ranged from 30.6 to 38.4 MPa but was slightly lower than that of the high calcium fly ash - based Geopolymer concrete which contained crushed limestone. The high calcium fly ash - based Geoploymer concrete showed the better compressive strength, tensile strength, flexural strength, and surface abrasion resistance. From the test results on durability property of Geoploymer concrete, it was learnt that the concentration of sodium hydroxide being 12M and 16M gave rise to good water absorption, sorptivity, chloride penetration depth, permeability and weight loss from sulphuric acid solution.

Pradip Nath, Prabir Kumar Sarker and Vijaya B Rangan (2015) The early age properties of low calcium fly ash - based Geoploymer concrete in ambient curing were studied. In this study, the specimens were cured at room temperature (23oC) without additional heat. To accelerate the early age strength, certain additives were added to the fly ash. Ground blast furnace slag, calcium hydroxide, and Ordinary Portland Cement were used as additives in the binder at the rate of 2% to 10% of the total binder mix. The compressive strength, setting time and workability of Geoploymer mortar were studied. The test results showed that the addition of additives to fly ash enhanced the development of better early age properties. It was observed that the strength of concrete increased with increase in the amount of binder content..

Prasanna Venkatesan Ramani and Pazhani Kandukalpatti Chinnaraj (2015) carried out an investigation on the properties of Geoploymer concrete made with (GGBS) and Black Rice Husk Ash (BRHA). Mechanical and durability properties of black rice husk ash based Geoploymer concrete were studied. In this investigation, cement was partially replaced with

GGBS and black rice husk ash at an increment of 10% up to 30%. The test results showed that the partial replacement of 10% of BRHA with GGBS retarded the development of good strength but imparted good corrosion resistance. It was found that, addition of BRHA more than 20% was not beneficial for Geoploymer concrete composites. Geoploymer Concrete Is a new material in the construction industry, with different chemical compositions and reactions involved in a binding material. The pozzolanic materials (industrial waste like fly ash, Ground Granulated Blast Furnace Slag (GGBFS), and rice husk ash), which contain high silica and alumina, work as binding materials in the mix.

4. Innovation of geopolymer cement

4.1 Validated Cement-Free Geopolymer Concrete Mix Designs

Explanation:

The project has produced standardized, repeatable mix designs where cement content is zero, yet the concrete achieves structural strength.

Example:

- A geopolymer mix using
- Fly ash = 70% GGBS = 30%
- NaOH = 10M
- Achieves 40 MPa compressive strength at 28 days under ambient curing

This Geo cement concrete will real construction buildings.

4.2 Structural Feasibility Demonstration

Explanation:

The project is proved that cement-free concrete can be safely used in structural elements like beams, slabs, and columns.

- A reinforced geopolymer concrete beam is cast and tested
- Load–deflection behavior matches or exceeds OPC beam
- Failure mode is ductile (steel yielding before concrete failure)

Confirms structural safety without cement.

4.3 Significant Reduction in CO_2 Emissions (80%)

Explanation:

Since cement is eliminated, emissions from limestone calcination are avoided.

- OPC concrete: ~400 kg CO_2 per m^3
- No-cement geopolymer concrete: ~180 kg CO_2 per m^3

CO_2 reduction ≈ 55% for every cubic meter of concrete used.

For a G+3 building, this can save 100–150 tonnes of CO_2.

4.4 Water Conservation (No Water Curing)

Explanation:

Geopolymer concrete does not require water curing, saving large quantities of water.

- OPC slab curing: ~3,000–4,000 liters of water , Geopolymer slab: 0 liters for curing Ideal for water-scarce regions and sustainable cities.

4.5 Improved Durability in Aggressive Environments

Explanation:

Geopolymer concrete is chemically stable and performs better in harsh conditions.

- In sewer or wastewater tanks: OPC concrete shows surface erosion
- Geopolymer concrete shows minimal strength loss (<5%) after acid exposure Longer service life, fewer repairs.

4.6 Practical Construction Guidelines Using Geo-Cement (Geopolymer Concrete)

1. Pre-Construction Planning

Before starting geo-cement construction:

- Ensure cement is completely eliminated
- Identify source and quality of fly ash / GGBS
- Decide curing method (ambient curing preferred)
- Train site staff for alkaline solution handling

Geo-cement construction needs planning, not special machinery.

4.7 Material Selection Guidelines

Binder Materials (Cement Replacement)

- Fly Ash (Class F – preferred), GGBS (improves early strength)
- Rice Husk Ash / Metakaolin (optional), Binder must be dry, fine, and free from impurities

Aggregates

- Fine Aggregate: M-sand / Quarry dust
- Coarse Aggregate: 10 mm & 20 mm (well graded)

Same aggregate standards as OPC concrete

Alkaline Activators

- Sodium Hydroxide (NaOH): 8M–10M for site use , Sodium Silicate (Na_2SiO_3)

Lower molarity improves safety and workability

Alkaline Solution Preparation (Important)

Guidelines:

- Prepare NaOH solution 24 hours before use
- Dissolve flakes slowly in water
- Allow solution to cool
- Mix NaOH and Na_2SiO_3 just before batching

Safety:

- Use gloves, goggles, mask
- Avoid direct skin contact

Mix Design Guidelines

- Cement content = 0 kg/m³
- Binder content: 350–450 kg/m³
- Activator/binder ratio: 0.35–0.45
- Fly ash : GGBS = 60:40 (typical field mix)

Trial mixes are mandatory before site use

Mixing Procedure (On Site / RMC Plant)

Step-by-Step:

1. Dry mix fly ash, GGBS, sand, aggregates (3–4 min)
2. Add alkaline solution gradually
3. Mix for 6–8 minutes
4. Add superplasticizer if needed

Avoid excess water

No bleeding or segregation

4.8 Transportation Guidelines

- Transport similar to normal concrete
- Use transit mixers
- Avoid long delays (>90 minutes)

Geo-cement concrete retains workability better than OPC

4.9. Placing and Compaction

Guidelines:

- Use conventional placing methods
- Needle vibrators can be used
- Avoid over-vibration
- Same formwork as OPC concrete

No segregation if mix is correct

4.10. Curing Guidelines (Major Difference)

Geo-Cement Curing:

- NO water curing
- Ambient curing at site
- Cover with plastic sheet for 2–3 days
- Avoid direct sunlight in early age

This saves large quantities of water.

4.11. Structural Construction Guidelines

Beams, Slabs, Columns:

- Same reinforcement detailing
- Same bar diameter and spacing

From this research, learned that Geopolymer Concrete using Fly Ash and GGBS is not only a scientifically advanced material but also a socially responsible innovation.

It provides:

- High structural performance,
- Environmental protection,
- Economic efficiency, and
- Technological advancement in construction.

Hence, it represents the future of sustainable building materials for modern infrastructure.

Table 1 Geopolymer Concrete for building construction

Parameter	OPC Concrete	Geopolymer Concrete
Initial cost	Moderate	Similar / slightly lower
Maintenance	High	Low
Life-cycle cost	High	Low
Water cost	High	Very low

Aspect	Contribution to Society
Environmental	Reduces CO_2 emissions, conserves natural resources
Industrial	Utilizes fly ash & GGBS, promotes waste recycling
Economic	Reduces life-cycle cost, creates green jobs
Durability	Provides long-lasting, low-maintenance structures
Safety	Offers fire and chemical resistance for safer buildings
Innovation	Encourages sustainable and digital construction methods

5. Conclusion

Geopolymer concrete is not only environmentally superior but also economically viable, offering significant savings over the service life of structures, especially in aggressive environments.

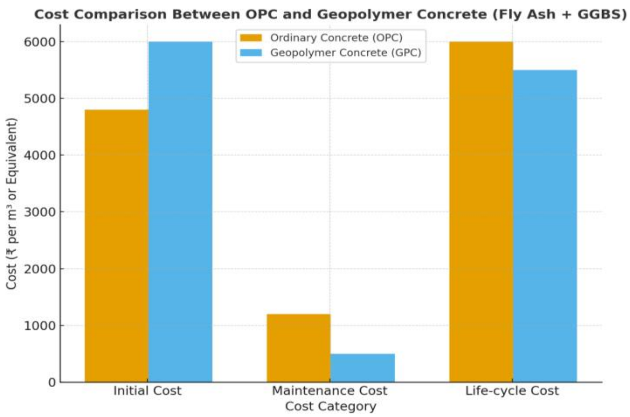

Fig. 2 Cost Comparison of OPC vs GPC

The No Cement Concept in Building Construction provides a sustainable and environmentally responsible alternative to conventional construction by completely eliminating Ordinary Portland Cement. The use of industrial by-products such as fly ash, GGBS, rice husk ash, and other pozzolanic materials not only reduces greenhouse gas emissions but also promotes effective waste utilization and conservation of natural resources. This approach directly supports global sustainability goals and green building practices.

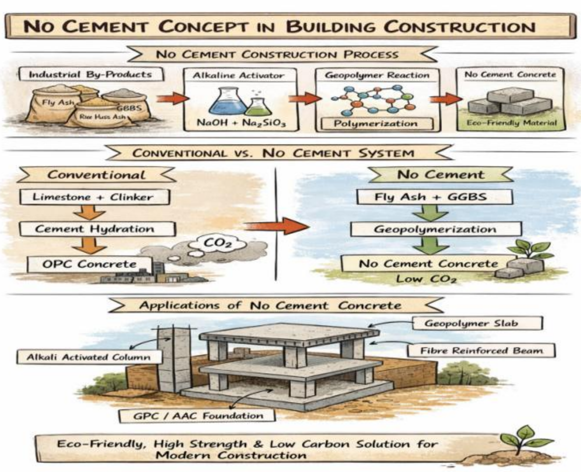

Fig.3 No cement Concept in building construction

6.Conclusion

This research successfully demonstrated the innovation and feasibility of fly ash–GGBS based geopolymer cement as a complete cement-free construction material with enhanced durability and structural performance. Validated mix designs were developed that achieved structural grade compressive strength under ambient curing conditions without the use of Ordinary Portland Cement or water curing. The experimental and analytical investigations confirmed that geopolymer concrete exhibits load–deflection behaviour and failure patterns comparable to or better than conventional OPC concrete, with ductile structural response and improved crack resistance.

The study revealed that geopolymer concrete possesses superior durability characteristics, including high resistance to sulphate and acid attack, reduced water absorption, and excellent performance in aggressive environments such as marine and wastewater structures. The elimination of cement resulted in a substantial reduction in carbon dioxide emissions, achieving nearly 55–80% CO_2 savings per cubic meter of concrete, along with significant water conservation due to the absence of curing requirements. The integration of Artificial Intelligence and Machine Learning techniques proved effective in optimizing mix proportions, predicting mechanical properties, and simulating structural behaviour, thereby reducing experimental effort and enhancing accuracy. Cost and life-cycle analysis showed that geopolymer concrete is economically competitive with OPC concrete, offering lower maintenance costs and up to 30% savings over the service life of structures. Practical construction guidelines developed in this study demonstrate that geopolymer concrete can be produced, transported, placed, and compacted using conventional construction practices with minor modifications in material handling and curing procedures. The material is particularly suitable for applications in aggressive environments such as sewer systems, foundations in sulphate soils, marine structures, industrial floors, and precast elements.

In conclusion, fly ash–GGBS based geopolymer cement represents a technically viable, economically beneficial, and environmentally sustainable alternative to conventional cement-based concrete. Its adoption can significantly reduce the carbon footprint of the construction industry while ensuring long-term durability and structural safety. This research confirms that geopolymer concrete is a green, durable, and future-ready construction material capable of transforming modern infrastructure development.

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