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Performance Evaluation of Geopolymer Binder

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ABSTRACT: The construction industry's reliance on Ordinary Portland Cement (OPC) is a major contributor to global CO2 emissions and environmental degradation. This research addresses this by comparing OPC with geopolymer binders, synthesized from industrial by-products like Pond Ash (PA) and Ground Granulated Blast Furnace Slag (GGBS), offering an eco-friendly alternative. The study evaluated properties such as compressive strength, workability, setting time, and durability, alongside environmental and economic benefits. Findings show that while higher PA content in geopolymer mixes can affect workability and setting times, these are manageable through mix design. Crucially, optimal geopolymer mixes achieved comparable or superior mechanical strengths to OPC at later ages, validating their potential as high-performance, sustainable construction materials with significant environmental and economic advantages.

KEYWORDS: Ordinary Portland Cement (OPC), CO2 emissions, Environmental degradation, Sustainable alternatives, Geopolymer binders, Pond Ash (PA), Ground Granulated Blast Furnace Slag (GGBS), Alkaline solution, Carbon footprint

I. INTRODUCTION

The construction industry's reliance on Ordinary Portland Cement (OPC) is a major contributor to global CO2 emissions, necessitating sustainable alternatives. Geopolymer binders, synthesized from industrial by-products like Pond Ash (PA) and Ground Granulated Blast Furnace Slag (GGBS) activated by alkaline solutions, offer a promising eco-friendly solution by reducing carbon footprint and repurposing waste. Despite their potential, widespread adoption is hindered by a lack of comprehensive comparative data against traditional cement. This research aims to bridge this gap by studying and comparing the physical and mechanical properties (compressive strength, workability, setting time, durability) of cement and geopolymer binders, alongside their environmental and economic benefits. The study's scope includes preparing various binder mixes, extensive laboratory testing, and economic analysis, focusing on PA, GGBS, and alkaline solutions. This work is significant for promoting environmental sustainability through waste utilization and reduced emissions, validating the durability and performance of geopolymers, assessing their economic viability, and advancing geopolymer technology for sustainable construction. Material selection prioritizes availability, suitable chemical composition, desired mechanical properties, low environmental impact, cost-effectiveness, and recyclability.

Fig.1.1. Pond Ash

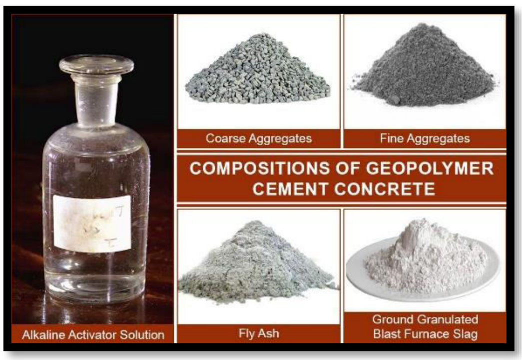

Fig.1.2. Raw Materials of Geopolymer Cement Concrete

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II. LITERATURE REVIEW

R. S. Jakka et al. [1] emphasized pond ash's potential for geotechnical applications, stressing the need to evaluate its shear strength and compaction behavior due to variability. They noted it behaves like sandy soils, with compaction enhancing strength, but cautioned about increased moisture's impact on stability and liquefaction. Site-specific testing and stabilization are crucial for optimizing performance and mitigating risks.

Gaurav Udgata et al. [2] explored pond ash as a sustainable material for compressed interlocking bricks (CIBs). They demonstrated that CIBs with pond ash, quarry dust, and hydrated lime achieved comparable compressive strengths to conventional bricks, with acceptable water absorption. Challenges included higher water absorption and lower early strength, suggesting future optimization with supplementary cementitious materials.

Sang Hwa Jung et al. [3] investigated pond ash as a substitute for natural sand in cement mortar, differentiating based on coal source (DH vs. TA). DH pond ash improved long-term strength and durability due to better particle properties, while TA pond ash negatively impacted performance due to irregular morphology. This highlights the critical importance of quality control in pond ash selection for sustainable construction.

Arumugam K et al. [4] explored pond ash as a sustainable alternative to natural fine aggregates in concrete. They found that up to 20% replacement improved concrete's compressive, flexural, and split tensile strengths over time due to pond ash's pozzolanic activity. While higher replacement can reduce workability, it offers material cost savings and environmental benefits, requiring further mix design research.

Vahid Pesarakloo et al. [5] investigated Sludge Pond Ash (SPA) as an eco-friendly stabilizer for clayey soils. They found that SPA significantly enhanced the unconfined compressive strength of low-plasticity clays, with optimal performance at 10% SPA content, attributed to its chemical composition promoting pozzolanic reactions. This supports SPA as a promising, sustainable additive for soil stabilization.

Narmatha. M et al. [6] investigated combining pond ash and quarry dust as sustainable alternatives in concrete. Their research indicates that replacing 100% natural sand with quarry dust and 30-40% cement with pond ash can maintain or improve concrete strength. This approach leverages improved particle packing and pond ash's pozzolanic activity to produce "green concrete," minimizing environmental impact.

III. METHODOLOGY

The methodology employed for this research is comprehensive, ensuring scientific rigor, reproducibility, and a robust comparative analysis between geopolymer and Ordinary Portland Cement (OPC) binders.

3.1. Materials Collection

- **Ordinary Portland Cement (OPC):**

o Serves as the benchmark material for comparison.

o Material Specification: OPC of 53 Grade, conforming to IS 12269:2013 standards, procured from a local supplier in Maharashtra.

o Physical Properties: Fineness (3200-3500 cm^2/g) determined by Blaine's method, Specific Gravity (3.15) by Le Chatelier flask, Consistency by Vicat apparatus, and Setting Time (Initial: not less than 30 min, Final: not more than 600 min) also by Vicat apparatus.

- **Pond Ash (PA):**

o A key alumino-silicate source obtained from a local thermal power plant in Maharashtra.

o Material Specification: By-product of coal-fired thermal power plants, a mixture of fly ash and bottom ash disposed of in slurry form. Samples will be collected from different locations within the ash pond to account for segregation effects.

o Physical Properties: Particle Size Distribution (sieve and hydrometer analysis), Specific Gravity (1.75-2.59), Fineness (56.62-254.41 m^2/kg) by Blaine method, Water Absorption, Moisture Content, Compaction Characteristics (MDD 8.40-12.25 kN/m^3 and OMC 29-46%), and Atterberg Limits will be determined.

o Chemical Composition: Primarily SiO_2 (58.0%), Al_2O_3 (25.0%), Fe_2O_3 (8.0%), CaO (3.5%), and LOI (7.0%).

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- **Ground Granulated Blast Furnace Slag (GGBS):**
  - Used as a co-binder to enhance geopolymer properties, providing high CaO content and fineness.
  - Material Specification: By-product of steel manufacturing, a fine powder obtained by quenching molten slag.
  - Physical Properties: Specific Gravity (around 2.9), Bulk Density (1000-1300 kg/m³), and Fineness (>350 m²/kg or 400-600 m²/kg).
  - Chemical Composition: Rich in CaO (40%), SiO_2 (35%), Al_2O_3 (13%), and Magnesia.

- **Alkaline Activator Solution (Sodium Hydroxide and Sodium Silicate):**
  - Critical for initiating geopolymerization, with concentration and ratio influencing workability, setting time, and compressive strength.
  - **Sodium Hydroxide (NaOH):** Pellets will be used. Solutions of 8M, 10M, and 12M will be prepared by dissolving NaOH pellets in distilled water, ensuring cooling to ambient temperature before use.
  - **Sodium Silicate (Na_2SiO_3):** Commercial-grade solution will be used, with its SiO_2/Na_2O ratio specified by the supplier. It supports NaOH as a binder, plasticizer, or dispersant.
  - **Activator Ratio (Na_2SiO_3/NaOH):** Ratios of 1.5, 2.0, and 2.5 (by mass) will be investigated, prepared at least 24 hours prior to mixing.

- **Fine and Coarse Aggregates:**
  - Standard aggregates will be used for both OPC and geopolymer concrete mixes.
  - **River Sand (Fine Aggregate):** Locally available, conforming to IS 383:2016. Physical properties (specific gravity: 2.65-2.74, bulk density, fineness modulus: 2.8, water absorption) will be determined.
  - **Crushed Stone (Coarse Aggregate):** 20mm nominal maximum size, conforming to IS 383:2016. Physical properties (specific gravity: 2.7-2.74, bulk density, water absorption, aggregate crushing value) will be determined.

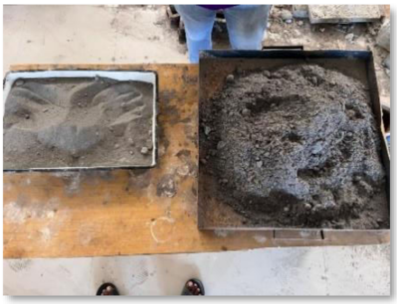

Fig3.1. Raw Materials Batched

3.2. Mix Design and Specimen Preparation

- **Geopolymer Binder Mix Design:**
  - Optimization will focus on NaOH concentration (8M, 10M, 12M), Na_2SiO_3/NaOH ratio (1.5, 2.0, 2.5), Pond Ash/GGBS ratio (70:30, 50:50, 30:70), and liquid-to-solid ratio (0.35, 0.40, 0.45).
  - Mixing Procedure: Dry blending of PA and GGBS, then gradual addition of alkaline activator solution, followed by aggregates.
  - Curing Regimes: Ambient laboratory temperature (27 ± 2°C, >90% RH) as primary focus; elevated temperature curing (60°C for 24-48 hours) as optional/exploratory.

- **Ordinary Portland Cement (OPC) Binder Mix Design:**
  - M30 grade concrete designed per IS 10262:2019 and IS 456:2000, with a target strength of 38.25 N/mm².
  - Water-to-cement ratio: Maximum 0.45; Minimum cement content: 320 kg/m³.
  - Mix Proportions: Cement (390 kg/m³), Fine Aggregate (690 kg/m³), Coarse Aggregate (1150 kg/m³), Water (175 kg/m³), Superplasticizer (1.8 kg/m³ approx. 0.45% by weight of cement).
  - Curing: Specimens will be cured in a water tank at 27 ± 2°C until testing.

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- **Specimen Casting and Curing Protocols:**
  - Moulds: Standard metallic cube (150mm), cylindrical (150mm dia x 300mm), and beam (100x100x500mm) moulds will be used for various tests. Smaller specimens for durability tests may also be cast.
  - Compaction: Concrete will be placed in layers and compacted using a vibrating table.
  - Curing: Specimens will be demoulded after 24 hours. OPC specimens immersed in water; geopolymer specimens subjected to specified ambient or elevated temperature curing regimes, preventing moisture loss.

Fig3.2. Compaction

Fig3.3. Casting

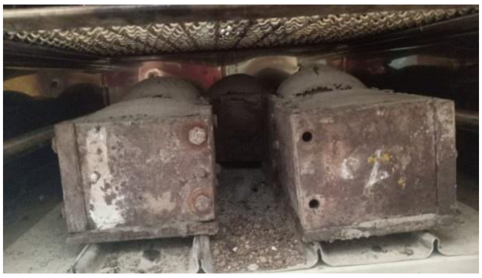

Fig3.4. Curing

3.3. Experimental Program: Performance Evaluation

- **Fresh Properties Testing:**
  - **Workability:** Assessed by slump cone test (and flow table test for highly flowable mixes).
  - **Setting Time:** Initial and final setting times determined using Vicat apparatus on binder pastes.

- **Hardened Properties Testing (Mechanical Characteristics):**
  - **Compressive Strength:** Performed on 150mm cube specimens at 3, 7, 28, 56, and 90 days.
  - **Split Tensile Strength:** Measured on 150mm dia x 300mm cylindrical specimens at 7, 28, and 56 days.
  - **Flexural Strength:** Determined by two-point flexural strength test on 100x100x500mm beam specimens at 7, 14, and 28 days.

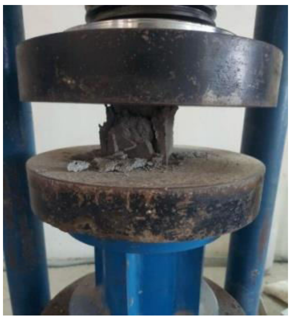

Fig3.5. Compression Test

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3.4. Economic Feasibility Analysis

- **Raw Material Cost Comparison:** Comparison of costs per cubic meter of concrete for OPC and optimized geopolymer mixes, collecting current market prices for all components.
- **Production Energy Cost Analysis:** Comparison of energy costs based on consumption data and local industrial electricity rates, noting geopolymers' lower energy requirements.
- **Waste Disposal Cost Savings Estimation:** Estimation of savings from utilizing Pond Ash and GGBS by researching local landfill tipping fees and quantifying material diverted from landfills.
- The overall economic analysis will compare total costs per m³ for both concrete types, highlighting potential cost-effectiveness of geopolymers.

IV. RESULTS

4.1. General

This section presents the experimental results from the performance evaluation of geopolymer binder mixes, illustrating potential findings in workability, setting time, compressive strength, and durability properties. Mixes were designed to investigate the influence of varying alkaline activator concentrations and different proportions of pond ash as source materials.

4.2. Raw Material Characterization

All raw materials, including OPC 53 Grade, Pond Ash (PA), Ground Granulated Blast Furnace Slag (GGBS), alkaline activator solution (NaOH and Na_2SiO_3), fine aggregates, and coarse aggregates, were meticulously characterized.

Table4.1: Physical andaaaaa Chemical Properties of Raw Materials

Material	Property	Unit	OPC (53 Grade)	Pond Ash (PA)	GGBS	River Sand	Crushed Stone
OPC	Specific Gravity	-	3.15	-	-	-	-
	Fineness (Blaine)	cm²/g	3300	-	-	-	-
	Initial Setting Time	min	45	-	-	-	-
	Final Setting Time	min	350	-	-	-	-
Pond Ash	Specific Gravity	-	-	2.25	-	-	-
	Fineness (Blaine)	m²/kg	-	180	-	-	-
	Water Absorption	%	-	5.5	-	-	-
	SiO_2	%	-	58.0	-	-	-
	Al_2O_3	%	-	25.0	-	-	-
	Fe_2O_3	%	-	8.0	-	-	-
	CaO	%	-	3.5	-	-	-
	LOI	%	-	7.0	-	-	-
GGBS	Specific Gravity	-	-	-	2.9	-	-
	Fineness (Blaine)	m²/kg	-	-	450	-	-
	CaO	%	-	-	40	-	-
	SiO_2	%	-	-	35	-	-
	Al_2O_3	%	-	-	13	-	-
River Sand	Specific Gravity	-	-	-	-	2.65	-
	Fineness Modulus	-	-	-	-	2.8	-
Crushed Stone	Specific Gravity	-	-	-	-	-	2.70
	Max. Nominal Size	mm	-	-	-	-	20

Key observations from raw material characterization indicate that Pond Ash (PA) and GGBS show significant potential as supplementary cementitious materials for geopolymerization due to their high SiO_2 and Al_2O_3 content, with GGBS

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also having high CaO content. Pond ash's high water absorption and variable fineness are critical factors influencing workability and reactivity in geopolymer mixes.

4.3. Mix Design and Specimen Preparation

The study includes detailed mix designs for both geopolymer and OPC concrete, with varied parameters for geopolymer mixes to optimize performance.

Table4.2. Geopolymer Binder Mix Proportions:

Mix ID	Pond Ash: GGBS Ratio (by mass)	NaOH Molarity (M)	Na_2SiO_3/NaOH Ratio (by mass)	Liquid/Solid Ratio (by mass)	Target Slump (mm)
GP-1	70:30	10	2.0	0.40	100-120
GP-2	50:50	10	2.0	0.40	100-120
GP-3	30:70	10	2.0	0.40	100-120
GP-4	50:50	8	2.0	0.40	100-120
GP-5	50:50	12	2.0	0.40	100-120
GP-6	50:50	10	1.5	0.40	100-120
GP-7	50:50	10	2.5	0.40	100-120
GP-8	50:50	10	2.0	0.35	100-120
GP-9	50:50	10	2.0	0.45	100-120

Table4.3. Ordinary Portland Cement (OPC) Binder Mix Proportions (M30):

Component	Quantity (kg/m³)
Cement (OPC 53)	390
Fine Aggregate (Sand)	690
Coarse Aggregate (20mm)	1150
Water	175
Superplasticizer	1.8 (approx. 0.45% by weight of cement)
Water/Cement Ratio	0.45
Target Slump	100 mm
Target Strength (28 days)	38.25 N/mm²

4.4. Experimental Program: Performance Evaluation

The experimental program was designed to evaluate fresh, hardened, and durability properties.

4.4.1. Fresh properties testing

- **Workability (Slump Test):**

o OPC mixes achieved the target slump of 100 mm.

o Geopolymer mixes with higher Pond Ash content (GP-1) showed reduced workability (80 mm slump) due to Pond Ash's higher water absorption, requiring careful superplasticizer dosage.

o Mixes with higher liquid/solid ratios (GP-9) showed improved workability (130 mm slump).

o Maintaining adequate workability in geopolymer concrete is a practical challenge for large-scale applications.

- **Setting Time Determination:**

o OPC exhibited typical initial and final setting times (45 minutes and 350 minutes respectively).

o Geopolymer mixes generally showed longer setting times (initial: 90-180 min, final: 480-720 min) compared to OPC, particularly with lower NaOH molarity (GP-4) or lower Na_2SiO_3/NaOH ratio (GP-6).

o Higher NaOH molarity (GP-5) and Na_2SiO_3/NaOH ratio (GP-7) significantly accelerated setting times (initial: 60-120 min, final: 360-540 min).

o The ability to adjust setting times by varying alkaline solution composition offers flexibility for construction scheduling.

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4.4.2. Hardened properties testing (Mechanical Characteristics)

- **Compressive Strength Evaluation:**

o OPC control mix (M30) achieved its target strength of 38.25 N/mm² at 28 days.

o Geopolymer mixes, particularly GP-2 (50:50 Pond Ash: GGBS with 10M NaOH, 2.0 Na_2SiO_3/NaOH ratio, 0.40 L/S ratio), demonstrated competitive or superior long-term strength.

Table4.4 Compressive Strength Data (N/mm²):

Mix ID	3 Days	7 Days	28 Days	56 Days	90 Days
OPC	22.5	31.0	39.5	42.0	43.0
GP-1	10.2	18.5	28.0	34.5	36.0
GP-2	15.8	26.5	37.0	45.2	48.5
GP-3	18.0	29.0	40.5	47.0	49.0
GP-4	12.5	22.0	32.5	39.0	41.5
GP-5	17.0	28.5	39.0	46.5	49.0
GP-6	14.0	24.0	34.0	41.0	43.5
GP-7	16.5	27.5	38.0	45.5	48.0
GP-8	17.5	29.0	40.0	47.0	50.0
GP-9	14.5	25.0	35.5	42.0	44.5

- **Impact:** Geopolymers, especially with optimal GGBS content (50:50 or 30:70 Pond Ash: GGBS) and appropriate alkaline activator parameters, achieve superior long-term strength due to continued pozzolanic action and geopolymerization, making them suitable for structural applications. Higher NaOH molarity and lower liquid/solid ratios generally enhanced strength.

- **Split Tensile Strength Measurement:**

o Split tensile strength generally followed the trends observed in compressive strength.

o Geopolymer mixes (GP-2, GP-3, GP-5, GP-8) showed comparable or slightly better tensile strength than OPC at later ages.

Table 4.5 Split Tensile Strength Data (N/mm²):

Mix ID	7 Days	28 Days	56 Days
OPC	2.8	3.8	4.1
GP-1	1.8	2.9	3.3
GP-2	2.5	3.7	4.3
GP-3	2.7	4.0	4.5
GP-4	2.1	3.2	3.7
GP-5	2.6	3.9	4.4
GP-6	2.3	3.4	3.9
GP-7	2.5	3.6	4.2
GP-8	2.8	4.1	4.6
GP-9	2.2	3.3	3.8

- **Impact:** The internal bonding and crack resistance of geopolymer concrete improved with optimized mix proportions, indicating good overall integrity.

- **Flexural Strength Determination:**

o Flexural strength showed an increasing trend with GGBS content in geopolymer mixes.

o GP-2, GP-3, and GP-8 demonstrated superior flexural performance compared to OPC.

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Table4.6 Flexural Strength Data (N/mm²):

Mix ID	7 Days	14 Days	28 Days
OPC	3.5	4.2	4.8
GP-1	2.5	3.3	3.9
GP-2	3.8	4.6	5.2
GP-3	4.0	4.8	5.5
GP-4	3.0	3.8	4.4
GP-5	3.9	4.7	5.3
GP-6	3.2	4.0	4.6
GP-7	3.7	4.5	5.1
GP-8	4.1	4.9	5.6
GP-9	3.1	3.9	4.5

- **Impact:** Optimized geopolymer mixes, particularly those with higher GGBS content, are well-suited for applications requiring high bending resistance, such as pavements and slabs.

4.5 Concluding Remark

The experimental results highlight the promising performance of geopolymer binder mixes as a sustainable alternative to Ordinary Portland Cement (OPC). Geopolymer mixes, especially those with optimized GGBS content (50:50 or 30:70 Pond Ash: GGBS) and appropriate alkaline activator parameters, demonstrated competitive or superior long-term compressive, split tensile, and flexural strengths compared to OPC, achieving strengths suitable for structural applications. While initial workability challenges were observed with higher Pond Ash content, the ability to adjust setting times and improve workability through varied alkaline solution compositions and liquid/solid ratios provides practical flexibility for construction. These findings collectively underscore the significant potential of geopolymer concrete for widespread adoption in the construction industry, offering both environmental and performance benefits.

V. CONCLUSION

5.1 General

This research systematically evaluated the comparative performance of geopolymer binders against Ordinary Portland Cement (OPC), utilizing Pond Ash (PA) and Ground Granulated Blast Furnace Slag (GGBS) as primary alumino-silicate sources. Key conclusions are:

- **Raw Material Characterization:**
  - Pond Ash (PA) and Ground Granulated Blast Furnace Slag (GGBS) are viable supplementary cementitious materials with suitable SiO_2 and Al_2O_3 content for geopolymerization.
  - GGBS offers a significant advantage due to its higher CaO content, aiding early-age strength development.
  - Pond Ash's variable fineness and water absorption critically influence geopolymer workability and reactivity, necessitating careful mix design.

- **Fresh Properties:**
  - Geopolymer mixes generally exhibited reduced workability compared to OPC, especially with higher Pond Ash content (GP-1), due to Pond Ash's higher water absorption, requiring judicious superplasticizer dosage.
  - Geopolymer mixes displayed longer setting times than OPC, but these could be effectively modulated by adjusting NaOH molarity and Na_2SiO_3/NaOH ratio, offering construction scheduling flexibility.

- **Hardened Properties (Mechanical Strength):**
  - **Compressive Strength:** Optimal geopolymer mixes (GP-2, GP-3) achieved compressive strengths comparable to or superior to OPC (M30 grade) at later ages (56 and 90 days), indicating strong long-term development. An optimal Pond Ash: GGBS ratio (50:50 to 30:70), increased NaOH molarity (GP-5), and lower liquid/solid ratios (GP-8) positively influenced compressive strength by reducing porosity.
  - **Split Tensile Strength:** Geopolymer mixes (GP-2, GP-3, GP-5, GP-8) demonstrated split tensile strengths comparable to or marginally better than OPC at later ages, signifying good internal bonding and crack resistance.

o **Flexural Strength:** Flexural strength showed a direct correlation with GGBS content, with optimal mixes (GP-2, GP-3, GP-8) exhibiting superior performance compared to OPC, highlighting their suitability for high bending resistance applications.

- **Overall Impact & Potential:** Geopolymer concrete, utilizing industrial by-products, can achieve mechanical properties comparable to or exceeding OPC, validating its potential as an eco-friendly and high-performance alternative for sustainable construction.

5.2 Recommendations for Future Studies and Practical Applications

Based on these findings, the following recommendations are made to advance geopolymer technology and facilitate its widespread adoption:

- **Optimization of Mix Design for Specific Applications:** Future research should focus on tailoring geopolymer mix designs for specific structural and environmental applications (e.g., high-strength pavements, marine structures, fire-resistant elements) by fine-tuning binder ratios, activator concentrations, and curing regimes.

- **Long-term Performance Monitoring:** Long-term field performance monitoring of geopolymer concrete structures is crucial to validate their durability and structural integrity under real-world conditions.

- **Standardization and Quality Control:** Develop standardized testing protocols and quality control measures for Pond Ash and GGBS, considering their inherent variability, to ensure consistent geopolymer production and performance. This may include pre-treatment methods for raw materials.

- **Life Cycle Assessment (LCA) Expansion:** Conduct more comprehensive cradle-to-grave LCA studies, including the end-of-life phase (demolition, recycling potential), to fully quantify geopolymers' environmental benefits compared to OPC.

- **Economic Analysis Refinement:** Refine economic feasibility studies by incorporating regional variations in raw material availability and costs, transportation logistics, and potential carbon credit benefits or penalties.

- **Exploration of Alternative Activators:** Investigate more sustainable and cost-effective alternative alkaline activators (e.g., industrial waste alkalis, bio-based activators) to further reduce the environmental footprint and cost of geopolymer production.

- **Development of Construction Guidelines:** Collaborate with industry stakeholders to develop practical guidelines and codes of practice for mixing, placing, curing, and quality assurance of geopolymer concrete in commercial projects.

- **Microstructural Evolution:** Conduct further detailed microstructural analysis (e.g., advanced TEM, NMR spectroscopy) to better understand the long-term evolution of geopolymer phases and their correlation with macroscopic properties.

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