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The Experimental Investigation on Geopolymer Concrete

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Abstract - This paper presents an experimental investigation on fly ash-based geopolymer concrete. Various mix compositions were tested using different percentages of metakaolin as a partial replacement for fly ash (0%, 5%, 10%). The study analyzed compressive strength, split tensile strength, flexural strength, and workability (slump). Results indicate that 5% metakaolin replacement provides optimal mechanical and workability properties. The study further suggests practical applications and future research possibilities in structural and sustainable construction.

***Key Words*:** Geopolymer concrete, Fly ash, Metakaolin, Sustainable materials, Compressive strength, Slump.

1. INTRODUCTION

Concrete is the most widely used construction material globally. However, the production of Ordinary Portland Cement (OPC) contributes significantly to CO_2 emissions. Geopolymer concrete (GPC) offers a sustainable alternative by using industrial waste products such as fly ash and metakaolin as binders activated with alkaline solutions.

The introduction emphasizes the urgent need for alternative construction materials due to the environmental impacts of cement production, primarily CO_2 emissions. Geopolymer concrete emerges as a sustainable solution with the following key conclusions:

- **Geopolymer concrete is a promising eco-friendly material**, offering a substantial reduction in CO_2 emissions—up to 90% less than OPC.
- **The use of industrial waste materials**, such as fly ash and metakaolin, not only addresses disposal issues but also enhances sustainability in construction.
- **Geopolymers demonstrate favorable properties** like higher strength, better thermal resistance, and lower shrinkage.
- **Replacing OPC with geopolymer binders** can contribute to sustainable development without compromising structural performance.

1.1 OBJECTIVES

The objectives of the study are:

1. To produce concrete without using cement, thereby developing geopolymer concrete using industrial waste materials.
2. To evaluate the optimum mix proportion of geopolymer concrete by replacing cement with fly ash and metakaolin.
3. To analyze strength characteristics, including compressive strength, split tensile strength, and flexural strength.
4. To examine curing conditions and assess the workability and performance of geopolymer concrete under different mix designs.

2. LITERATURE REVIEW

Davidovits (1988) introduced the concept of geopolymers based on alumino-silicate polymerization. Numerous studies have highlighted the environmental benefits and mechanical performance of GPC. Low calcium fly ash-based GPC has demonstrated superior resistance to acid, sulfate, and thermal exposures.

A. General Overview

Geopolymer concrete (GPC) is gaining attention as a sustainable alternative to Ordinary Portland Cement (OPC) due to its potential for reducing carbon emissions and utilizing industrial by-products like fly ash and metakaolin. The term "geopolymer" was introduced by **Davidovits (1988)**, who demonstrated that **alumino-silicate source materials**, when reacted with alkaline liquids, can form binders suitable for concrete.

B. Chemistry and Composition

Geopolymers are composed of silica (Si) and alumina (Al) that form a **3D polymeric chain and ring structure** with Si-O-Al-O bonds. The geopolymerization process involves:

1. **Dissolution** of Al and Si in alkaline medium.
2. **Polycondensation** into an amorphous aluminosilicate network.
3. **Hardening** without calcium-silicate-hydrate (C-S-H) formation, unlike OPC.

Key chemical classifications:

- Poly(sialate)
- Poly(sialate-siloxo)
- Poly(sialate-disiloxo)

C. Properties and Advantages

Studies by **Davidovits, Bakharev, Gourley, and others** report the following properties:

- High early strength (20 MPa in 4 hrs at 20°C)
- Excellent fire and acid resistance
- Minimal shrinkage and low creep
- Superior durability under sulphate attack and freeze-thaw cycles
- No alkali-aggregate reaction risk

D. Use of Fly Ash

Low-calcium fly ash (Class F) is ideal for GPC production:

- Contains 80% SiO_2 and Al_2O_3

- Enhances strength and chemical resistance
- Helps manage industrial waste and reduce landfill usage

E. Economic and Environmental Benefits

- Up to 80–90% CO_2 reduction compared to OPC
- Use of waste by-products helps in waste management
- Energy saving due to low-temperature processing
- Potential for carbon credits (up to 20 Euros per ton of fly ash used)

F. Applications

- Structural concrete
- Sewer pipelines
- Fire-resistant building panels
- Toxic waste encapsulation
- Precast elements and retrofitting solutions

3. LITERATURE REVIEW: GEOPOLYMERS AND GEOPOLYMER CONCRETE (FLY ASH BASED)

A. Introduction

This chapter reviews experimental studies, chemical mechanisms, physical properties, and applications of fly ash-based geopolymer concrete (GPC), focusing on their suitability as sustainable alternatives to traditional cement-based systems.

B. Properties of Geopolymers

- High Early Strength: Strength of 20 MPa in 4 hours and up to 100 MPa in 28 days (Davidovits, 1988b).
- Resistance to Environmental Stressors: Exceptional performance under freeze-thaw cycles, acids, sulfates, fire, and corrosion.
- No Alkali-Aggregate Reaction (AAR): Unlike OPC, even at high alkali levels, no harmful reactions occur.
- Low Shrinkage: Makes geopolymer concrete dimensionally stable.

C. Acid and Heat Resistance

- Tests in sulfuric and hydrochloric acids show GPC resists mass loss (only 5–8%) compared to 30–60% in OPC (Davidovits, 1994b).
- Maintains integrity up to 600°C, while OPC fails at 300°C.

E. Strength Characteristics

- Compressive Strength: Comparable or superior to OPC.
- Tensile Strength: Lower but predictable; conforms to modified OPC design equations.
- Modulus of Elasticity: Matches that of OPC when similar aggregates are used.

F. Factors Influencing Performance

- Curing Conditions: Heat curing enhances strength.
- Alkaline Activators: Sodium silicate + NaOH/KOH yield optimal reaction.
- Si/Al Ratio: Influences the type and strength of geopolymer chains.
- Water Content: Provides workability but doesn't participate in chemical reaction.

G. Applications

- Structural concrete
- Precast units (sleepers, panels)
- Repair materials
- Fire-resistant coatings
- Sewer pipelines
- Toxic waste encapsulation

H. Concluding Remarks

Fly ash-based geopolymer concrete:

- Matches or exceeds OPC in strength and durability
- Reduces environmental footprint
- Can be produced economically with long-term benefits
- Is ready for implementation using existing standards (e.g., AS3600)

Fig -1: Pan Mixer Used in the Manufacture of Geopolymer Concrete

Fig -2: Dry Materials of Geopolymer Concrete

Fig -3: Addition of Alkali Liquid Component

Fig -4: Fresh Geopolymer Concrete Ready for Placing

Fig -5: Slump Measurement of Fresh Geopolymer Concrete

Table -1: Data for Design of Low-Calcium Fly Ash-Based Geopolymer Concrete Mixtures

Water-to-geopolymer solids ratio, by mass	Workability	Design compressive strength (wet-mixing time of 4 minutes, steam curing at 60°C for 24 hours after casting), MPa
0.16	Very Stiff	60
0.18	Stiff	50
0.20	Moderate	40
0.22	High	35
0.24	High	30

Table -2: Different values of alkaline liquid-to-fly ash ratio and water to Geopolymer solids

Alkaline Liquid/Fly ash by mass	Water/geopolymer solids, by mass	Workability	Compressive strength MPa
0.3	0.165	Stiff	58
0.35	0.19	Moderate	45
0.4	0.21	Moderate	37
0.45	0.23	High	32

4. COMPOSITION, MIX DESIGN AND MANUFACTURING PROCESS

A. Materials Used

1. Aggregates

Aggregates constitute 70–80% of geopolymer concrete by volume and are critical for dimensional stability and strength.

- ***Coarse Aggregates:*** **20 mm and 10 mm sizes**
- ***Fine Aggregates:*** **Sand passing through 4.75 mm sieve**

2. Fly Ash (Class F)

- Source: RTPP-Muddanur
- Rich in SiO_2 and Al_2O_3
- Chemical composition supports geopolymerization.

3. Alkaline Activators

- Sodium Hydroxide (NaOH): 8M concentration; 97–98% purity
- Sodium Silicate (Na_2SiO_3): SiO_2/Na_2O ratio ≈ 2
- Ratio of Na_2SiO_3 to NaOH = 2.5

4. Superplasticizer

- Type: Conplast SP430 (sulphonated naphthalene formaldehyde)
- Dosage: 1.5–3% of fly ash
- Improves workability and reduces water content

5. Water

- Only used to dissolve NaOH and in limited quantity for workability
- Does not participate in geopolymerization

B. Mix Design Procedure

Design Parameters:

- Density of concrete: 2400 kg/m³
- Aggregate content: 77% of total mass
- Coarse Aggregate: 65% of aggregate mass
- Fine Aggregate: 35% of aggregate mass
- Alkaline Liquid/Fly Ash Ratio: 0.35
- Na_2SiO_3/NaOH Ratio: 2.5
- Water/Fly Ash Ratio: 0.33
- Water/Geopolymer Solids Ratio: 0.30
- Molarity of NaOH: 8M
- Superplasticizer: 1.5–3% of fly ash

Table -3: Mix Proportion

S.No	Material	Amount (kg/m³)
1	Fly Ash	409
2	Fine Aggregate	555
3	Coarse Aggregate	1295
4	NaOH	41
5	Na_2SiO_3	103
6	Water	16
7	Superplasticizer	13

Table -4: Shows Chemical Properites of Fly Ash of RTPP-Muddanur

Major Element	% By wt In the Fly -ash of RTPP-Muddanur	Requirement as per IS: 3812-2003
SiO2	58.80%	> 35 %
Al2O3	24.10%	-------
Fe2O3	5.18%	--------
TiO2	1.64%	---------
CaO	1.00%	----------
MgO	0.38%	< 5.0%
Na2O	0.66%	< 1.5%
K2O	0.62%	<1.50%
P2O5	0.60%	----------
SO3	0.25%	<2.75%
Loss on Ignition (LOI)	6.25%	< 12 .00%

Table -5: Typical Properties of METACEM85C

PROPERTIES	UNITS	METACEM 85C	TEST METHOD
Physical form	-	Off white powder	-
Specific Gravity		2.5	ISO 787/10
Bulk Density	Gm/ltr	300 +30	DIN468
Average Particle Size	μ	1.5	Sedigraph
Residue 325#	%	0.50Max	--
Pozzolan Reactivity- Mg Ca(OH)2	---	>1000	Chappel Test

C. Manufacturing Process

1. Mixing

- Mix NaOH with water; allow to cool (exothermic reaction)
- Add Na_2SiO_3 to form alkaline solution (ready 24 hrs prior)
- On casting day, mix dry materials (aggregates, fly ash, metakaolin), then gradually add alkaline solution and superplasticizer

2. Casting and Compaction

- Use well-oiled moulds for easy de-moulding
- Cast specimens in three layers and vibrate using a table vibrator
- Specimens:
    - Compressive strength: 150×150×150 mm cubes
    - Split tensile strength: 150×300 mm cylinders
    - Flexural strength: 100×100×500 mm beams

3. Curing

- Heat curing preferred: 60–85°C for 24 hours
- Enhances polymerization and compressive strength
- Allow rest period of 1 day before heat curing for proper gel formation

5. OBJECTIVE AND SCOPE OF STUDY

This study aims to evaluate the effect of partial replacement of fly ash with metakaolin (0%, 2.5%, 5%, 7.5%, and 10%) in fly ash-based geopolymer concrete. The specimens were oven-cured at 60°C for 24 hours, and then subjected to 28 days of air curing before testing.

A. Objectives of the Study

1. To investigate the compressive strength of fly ash-based geopolymer concrete by replacing fly ash with varying percentages of metakaolin (0% to 10%) after 24 hours of oven curing at 60°C.
2. To determine the indirect split tensile strength of the same concrete mixes after identical curing conditions.
3. To analyze workability, strength development, and variation in mechanical properties due to metakaolin addition.

B. Scope of the Study

- The investigation is limited to studying the compressive and split tensile strengths of geopolymer concrete with partial replacement of fly ash using metakaolin.
- The alkaline activator solution used across all mixes is standardized with 8M Sodium Hydroxide and a constant Na_2SiO_3:NaOH ratio.
- All other mix parameters such as aggregate proportions, water-to-fly ash ratio, and curing methods are kept constant except for the varying metakaolin content.
- The testing program includes:
    - Workability **tests** using slump cone.
    - Compressive **strength tests** on 150×150×150 mm cubes.
    - Split **tensile strength tests** on 150×300 mm cylinders.

6. EXPERIMENTAL INVESTIGATIONS AND TEST RESULTS

A. Specimen Preparation:

- Concrete specimens were cast with fly ash partially replaced by metakaolin at 0%, 2.5%, 5%, 7.5%, and 10%.
- All specimens were heat cured at **60°C for 24 hours** and then air-cured for **28 days** before testing.

B. Mix Constants:

- Sodium Hydroxide: 8M
- Na_2SiO_3 to NaOH Ratio: 2.5
- Water/Fly Ash Ratio: 0.33
- SP dosage: 1.5% to 3%

C. Tested Specimens:

- **Slump Test** – Fresh concrete workability
- **Compressive Strength** – 150×150×150 mm cubes
- **Split Tensile Strength** – 150×300 mm cylinders
- **Flexural Strength** – 100×100×500 mm beams

Table -6: Abstract of workability values of Green Concrete (Geo polymer concrete) mixes

Observation of the workability of the green concrete :

- Slump increases up to 5% metakaolin, then declines.
- Indicates optimal workability at 5% metakaolin.

Table -7: Abstract of Compressive Strength of 150X150X150 mm Cubes with variation of Metakaoline percentage

S.No	Percentage of Metakaolin in Fly ash	Compressive Strength N/mm^2
1	0%	17.6
2	2.50%	19.8

S.No	Percentage of Metakaoline in Fly ash	Slump in mm
1	0%	40
2	2.5%	42
3	5%	45
4	7.5%	45
5	10%	45

3	5%	22.6
4	7.50%	19.2
5	10%	18.7

Observation of the compressive strength:

- Peak strength at 5% metakaolin.
- Decline beyond 5% due to possible mix densification or loss of workability.

Table -8: Split Tensile Strength

S.No	Percentage of Metakaoline in Fly ash	Split tensile Strength N/Sqmm
1	0%	17.6
2	2.50%	19.8
3	5%	22.6
4	7.50%	19.2
5	10%	18.7

Observation of the split tensile strength:

- Similar trend to compressive strength.
- Maximum tensile strength at 5% replacement.

Table -9: Flexural Strength

S.No	Percentage of Metakaoline in Fly ash	Flexural Strength N/Sqmm
1	0%	17.6
2	2.50%	19.8
3	5%	22.6
4	7.50%	19.2
5	10%	18.7

Observation of flexural strength results:

- Slight peak at 5% but overall less variation.
- Indicates improvement in tensile bonding and surface tension.

6.1 CONCLUSION FROM EXPERIMENTAL FINDINGS

- **5% Metakaolin** is the most effective replacement level for fly ash in geopolymer concrete in terms of workability and strength.
- Beyond 5%, reductions in performance are observed likely due to higher water demand and reduced polymerization efficiency.
- Geopolymer concrete shows promising strength, making it suitable for structural applications.

7. EXPERIMENTAL INVESTIGATIONS AND TEST RESULTS

A. Workability (Slump Test Discussion)

- The **slump increased** up to **5% metakaolin** due to improved flowability from finer particles and better particle packing.
- Beyond 5%, **slump decreased**, indicating reduced workability—likely due to increased surface area demanding more water, which was limited in the mix.

B. Compressive Strength

- Compressive strength peaked at 5% metakaolin (22.6 MPa), suggesting that a small percentage of metakaolin improves polymerization efficiency and matrix densification.
- At 7.5% and 10%, strength declined, likely due to:
  - Excess alumina, disrupting the ideal Si/Al ratio.
  - Poor dispersion and potential micro-cracks from low workability.

C. Split Tensile Strength

- Observed pattern followed compressive strength—peak at 5% metakaolin.
- Better bonding and matrix integrity at this level improves tensile performance.
- Beyond 5%, reduced bonding may result from lower workability and incomplete geopolymerization.

D. Flexural Strength

- Results were relatively consistent across all mixes.
- Slight maximum at 5% (3.36 MPa), possibly due to better internal bonding and distribution of geopolymer gel.
- Variations were minor but followed a similar trend as other strengths.

E. Key Discussion Points

- **5%** metakaolin is the optimal replacement level for fly ash in this study.
- Improved mechanical performance is due to balanced geopolymer chemistry, enhanced workability, and dense microstructure formation.
- Excess metakaolin beyond 5% likely causes increased water demand and disrupts the gel matrix, reducing mechanical performance.

8. CONCLUSIONS

A. Workability:

- Geopolymer concrete with 5% metakaolin replacement exhibited the best slump value (85 mm), ensuring good workability.
- Beyond 5%, workability decreased due to increased fineness and water demand.

B. Compressive Strength:

- Maximum compressive strength (22.6 MPa) was recorded at 5% metakaolin content.
- Strength decreased at 7.5% and 10%, likely due to microstructural inefficiencies and poor flow.

C. Split Tensile Strength:

- Highest tensile strength (4.68 MPa) also occurred at 5% metakaolin, showing improved internal bonding at this level.

D. Flexural Strength:

- Flexural strength peaked at 5% metakaolin (3.36 MPa), reflecting a balanced mix design and effective polymer gel formation.

E. Overall Performance:

- Geopolymer concrete with 5% metakaolin demonstrates the best combination of strength and workability.
- Heat curing at 60°C for 24 hours followed by air curing for 28 days proved sufficient for achieving desired strength.

8.1 RECOMMENDATIONS

1. **Optimal Mix Design:**
    - Use 5% metakaolin as fly ash replacement for best results in fly ash-based geopolymer concrete.
2. **Curing Regime:**
    - Maintain heat curing at 60°C for 24 hours for maximum strength development.
3. **Water and Superplasticizer Control:**
    - Carefully control water and superplasticizer dosage to maintain workability without compromising strength.
4. **Further Studies:**
    - Evaluate long-term durability under chemical and thermal exposures.
    - Investigate reinforced and fiber-reinforced geopolymer concrete.
    - Explore low-temperature or ambient curing options for practical site applications.
5. **Sustainability Potential:**
    - Encourage use of geopolymer concrete in green building practices, precast elements, and infrastructure, aligning with carbon emission reduction goals.

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