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Experimental Investigation of the Influence of Fly Ash Fineness on the Mechanical Properties of M50 Grade Geopolymer Concrete

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Abstract: The manufacture of Ordinary Portland Cement (OPC) is a significant source of global carbon dioxide emissions, creating a strong need within the construction sector for more sustainable binder alternatives. Fly ash-based geopolymer concrete (FAGC) has developed as a potential sustainable alternative to conventional cement concrete by completely replacing OPC with Class F fly ash activated using sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3). Although many investigations have studied the effects of alkali-activator type, molarity, and proportion on geopolymer concrete, relatively limited attention has been given to the influence of fly ash fineness, expressed through particle size and specific surface area, on high-strength M50 geopolymer concrete. The present investigation compares two fineness levels from the same fly ash source—an as-received coarse fraction and a processed/ground fine fraction—to determine their effect on the mechanical behaviour of M50 geopolymer concrete while maintaining the alkali-activator composition and other mix parameters unchanged. Specimens are evaluated for compressive, split-tensile, flexural, shear, and pull-out strength in accordance with the applicable Indian Standard (IS) codes to identify the fly ash fineness that provides the most favourable overall mechanical performance. The findings are intended to contribute to the development of sustainable high-strength geopolymer concrete and promote its potential use as a structural substitute for conventional M50 grade cement concrete.
Keywords: Geopolymer Concrete; Fly Ash Fineness; M50 Grade Concrete; Mechanical Properties; Sustainable Construction

I. INTRODUCTION

1) Fly Ash-Based Geopolymer Concrete- Ordinary Portland Cement (OPC) manufacturing contributes substantially to human-induced CO_2 emissions, increasing the need for lower-carbon construction materials. Fly ash-based geopolymer concrete (FAGC) provides one such option by chemically activating the industrial by-product fly ash with an alkaline solution to create the binding matrix instead of OPC. Previous studies have reported that geopolymer concrete can achieve high compressive, split-tensile, and flexural strengths while also providing better durability than conventional concrete. The mechanical behaviour of FAGC is strongly influenced by the extent of geopolymerisation, which is dependent on fly ash reactivity and the characteristics of the alkaline activator system (Ahmed et al., 2022; Verma et al., 2022; Patil et al., 2023).
2) Role of Fly Ash Fineness in Geopolymer Concrete- Fly ash fineness, commonly represented by Blaine specific surface area or the residue retained on a standard sieve, influences the quantity of reactive silica and alumina available for dissolution during geopolymerisation. Because finer fly ash particles have greater surface area and reactivity, aluminosilicate phases can dissolve more rapidly in the alkaline environment, promoting a denser and more uniform geopolymer gel structure. Conversely, coarse fly ash tends to react at a slower rate and may leave more unreacted particles in the matrix, where they can behave mainly as filler rather than actively contributing to strength development. Thus, fly ash fineness is an important but relatively less-investigated mix parameter that can be varied independently of the alkaline_activator composition to affect strength, workability, and geopolymer microstructure (Patankar et al., 2014; Lokuge et al., 2018).
3) Mechanical Properties of High-Strength (M50 Grade) Fly Ash-Based Geopolymer Concrete-_Most of the reported literature on fly ash fineness has focused on low-to-medium grade geopolymer concrete (M25–M40) and has generally been limited to workability and compressive strength. However, the growing interest in using geopolymer concrete for structural applications requires its performance to be established at higher target grades, such as M50, and across the complete range of mechanical properties – compressive strength, split tensile strength, flexural strength, shear strength, and pull-out (bond) strength – that govern structural design. The present study therefore examines how fly ash fineness affects these mechanical properties in M50 grade geopolymer concrete, so that an optimum fineness level can be identified for high-strength structural applications (Gunasekara et al., 2021).

II. RESEARCH GAP

A considerable amount of research has established that fly ash-based geopolymer concrete is a viable sustainable alternative to OPC concrete, and that alkali activator type, molarity, and ratio strongly influence its mechanical performance. Comparatively fewer studies have isolated the effect of fly ash fineness itself, and those that exist have generally been restricted to workability and compressive strength at low-to-medium target grades, with little attention paid to split tensile, flexural, shear, and pull-out behaviour. Furthermore, very little published work addresses the effect of fineness specifically for M50 grade, high-strength geopolymer concrete, where the demand for a denser, more completely reacted binder matrix is greatest. Most of the available results are also difficult to compare directly, owing to differences in the source fly ash, grinding/processing method, alkali activator composition, and curing regime used across studies. A dedicated experimental investigation that isolates the effect of fineness – while holding the alkali activator composition, mix proportions, and curing regime constant – is therefore needed to establish its influence on the full range of mechanical properties of M50 grade fly ash-based geopolymer concrete.

III. PROBLEM STATEMENT

Due to the limited and fragmented understanding of how fly ash fineness affects the mechanical performance of high-strength geopolymer concrete, there is a need for a systematic experimental study that isolates fineness as the sole variable while keeping the alkali activator composition and mix design constant. This study assesses the effect of two fly ash fineness levels – as-received (coarser) fly ash and processed/ground (finer) fly ash – on the key mechanical properties (compressive strength, split-tensile strength, flexural strength, shear strength, and pull-out strength) of M50 grade fly ash-based geopolymer concrete, in order to determine the fineness level that provides the best overall mechanical performance.

IV. MATERIAL PROPERTIES

Table 1: Properties of Fine Aggregate

Property	Value
Type	Natural Sand
Specific Gravity	2.65
Fineness Modulus	2.8
Water Absorption	1.20%

Table 2: Properties of Coarse Aggregate

Property	Value
Type	Crushed Aggregate (20 mm Down)
Maximum Size	20 mm
Specific Gravity	2.85
Water Absorption	0.80%
Aggregate Impact Value	14.0%
Aggregate Crushing Value	11.5%

Table 3: Chemical Composition of Class F Fly Ash

Property	Value (%)
Silicon Dioxide (SiO_2)	56.20
Aluminium Oxide (Al_2O_3)	28.10
Iron Oxide (Fe_2O_3)	6.85
Titanium Dioxide (TiO_2)	2.10
Calcium Oxide (CaO)	3.60
Sodium Oxide (Na_2O)	0.48
Potassium Oxide (K_2O)	1.40

Table 4: Physical Properties of Fly Ash at the Two Fineness Levels Studied

Property	Coarse Fly Ash (As-Received, FA-C)	Fine Fly Ash (Processed, FA-F)
Blaine Specific Surface Area (m²/kg)	307	320
Residue on 45-micron Sieve	15%	8%
Specific Gravity	2.05	2.10
Colour	Grey	Light Grey

Table 5: Properties of Sodium Hydroxide (NaOH) Flakes

Property	Value
NaOH (Purity)	98.80%
Chloride	1.00%
Carbonate (CO_3)	0.01%
Silicate (SiO_2)	0.01%
Nitrate (NO_3)	0.005%
Size	3–6 mm
Colour	White

Table 6: Properties of Sodium Silicate (Na_2SiO_3) Solution

Property	Value
Sodium Oxide (Na_2O)	14.70%
Silicon Dioxide (SiO_2)	29.40%
Water (H_2O)	55.90%
Specific Gravity	1.27

V. PROPOSED METHODOLOGY

A. *Detailed Workflow*

1) *Literature Review*- Published research on fly ash-based geopolymer concrete was reviewed, with particular attention to the effect of fly ash fineness on mechanical performance, in order to identify the research gap and define the study objectives.
2) *Material Collection and Characterization*- Class F fly ash, fine aggregate, coarse aggregate, sodium hydroxide (NaOH) flakes, and sodium silicate (Na_2SiO_3) solution were collected. A single batch of fly ash was divided into two portions: one used as-received (coarser fraction) and one processed by grinding/sieving to a finer particle size. The physical and chemical properties of all materials, including the Blaine fineness and sieve residue of both fly ash fractions, were determined through standard laboratory tests.
3) *Mix Design*- The mix design for M50 grade fly ash-based geopolymer concrete was developed, keeping the NaOH molarity, the Na_2SiO_3-to-NaOH ratio, and the alkaline solution-to-fly ash ratio constant across both fineness levels, so that fineness remained the only variable between the two sets of mixes.
4) *Preparation of Specimens*- Geopolymer concrete was cast using the reference mix proportions for both the coarse and fine fly ash fractions, forming standard cube, cylinder, and beam specimens for evaluation of the mechanical properties.
5) *Curing of Specimens*- After casting, the specimens were placed in an oven and cured at a specific temperature for a predetermined duration to allow the geopolymerisation reaction to proceed and the target strength to develop.
6) *Mechanical Testing*- Compressive strength, splitting tensile strength, flexural strength, shear strength, and pull-out strength of the specimens from both fineness groups were determined after curing, following the applicable Indian Standard (IS) codes of practice.
7) *Data Analysis*- The experimental results were systematically recorded, tabulated, and analysed to establish the effect of fly ash fineness on the mechanical performance of M50 grade fly ash-based geopolymer concrete.
8) *Result Interpretation*- Results were presented in tabular form and compared between the coarse and fine fly ash mixes to determine the fineness level giving the best overall mechanical performance; conclusions were drawn on this basis.

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VI. RESULTS

Note: The compressive, split-tensile, and flexural strength results below are the actual laboratory results obtained for the trial batch (fly ash fineness of 320 m²/kg and 307 m²/kg, oven cured at 80°C).

Table 7: Result of Compressive Strength (N/mm²) – Trial Batch

Day	GPC – Coarse Fly Ash (FA-C) (N/mm²)	GPC – Fine Fly Ash (FA-F) (N/mm²)
3	32.64	34.62
7	42.71	48.15
28	50.37	56.81

The stress is given by "$\boldsymbol{\sigma = P/A}$" where, P is load applied A is cross sectional area

Fig. 1: Cube compressive strength testing

Table 8: Result of Split Tensile Strength (N/mm²) – Trial Batch

Day	Convention concrete (N/mm²)	GPC – Fine Fly Ash (FA-F) (N/mm²)
3	3.05	3.20
7	4.25	4.56
28	5.20	5.0

It is computed using the fst = 2P/(πLD), where P is the applied load, L is the cylinder length and D is the diameter. This test provides a reliable estimate of tensile capacity, generally ranging between 8–12% of the compressive strength.

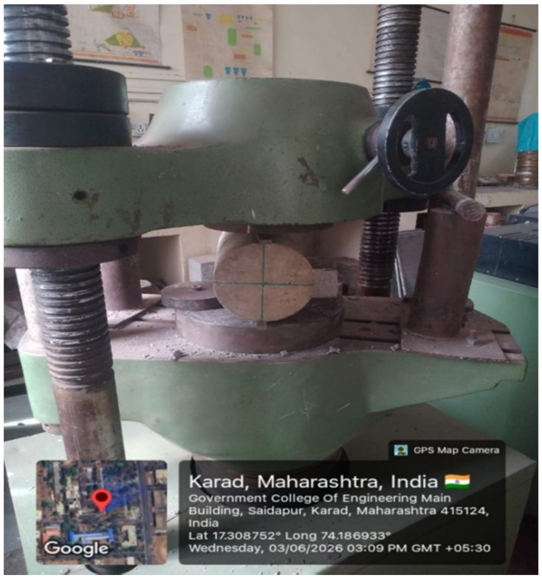

Fig. 2: Cylinder split tensile strength testing

Table 9: Result of Flexural Strength (N/mm²) – Trial Batch

Day	Conventional concrete (N/mm²)	GPC – Fine Fly Ash (FA-F) (N/mm²)
3	3.20	3.00
7	4.60	4.70
28	6.20	5.90

As per IS 516:1959. It is calculated as $R = PL/(bd^2)$ when fracture occurs within the central part, otherwise $R = 3Pa/(bd^2)$, where R is modulus of rapture, P is load applied on beam, L is span, b is breadth, d is depth, and a is the distance from support to crack location.

Fig. 3: Beam flexural strength testing

1) *Compressive Strength*- The 28-day compressive strength of the fine fly ash (FA-F, 320 m²/kg) mix reached 56.81 N/mm², compared with 50.37 N/mm² for the coarse fly ash (FA-C, 307 m²/kg) mix. The finer fly ash produced higher compressive strength at all three curing ages tested (3, 7, and 28 days), consistent with the trend reported in the literature for finer fly ash.
2) *Split Tensile Strength*- The split tensile strength followed the same pattern: the fine fly ash mix reached 5.20 N/mm² at 28 days against 4.95 N/mm² for the coarse fly ash mix, with FA-F ahead of FA-C at all three ages tested.
3) *Flexural Strength*- The flexural strength of the fine fly ash mix (5.90 N/mm² at 28 days) exceeded that of the coarse fly ash mix (5.40 N/mm²) at both 7 and 28 days. At 3 days the trend was briefly reversed (FA-C 3.20 N/mm² vs. FA-F 3.00 N/mm²), suggesting the finer fly ash's advantage becomes clearer as the geopolymerisation reaction progresses rather than at very early age.

A. *Cost Comparison*

Table no:- 10

Material	Unit	Rate (₹)	OPC&GPC Qty		OPC&GPC Amount (₹)	
Cement	kg	7.8	396	3088.80	-	-
Fly Ash	kg	3	-	-	231.08	693.24
Coarse Aggregate	m³	2500	0.79	1975.00	0.80	2000.00
Fine Aggregate	m³	4300	0.59	2537.00	0.40	1720.00
NaOH	kg	50	-	-	40.35	2017.50
Na_2SiO_3	kg	40	-	-	40.35	1614.00
Total				₹7600.80		₹8044.74

B. *Inference*

The cost for conventional concrete is 7600 Rs and for geopolymer concrete are 8044 Rs for 1 m3 respectively. The cost comparison between Ordinary Portland Cement (OPC) and Geopolymer Concrete (GPC) shows that GPC is approximately ₹443.94 more expensive per cubic meter than OPC. While the initial material cost of GPC is slightly higher due to the inclusion of alkaline activators (NaOH and Na_2SiO_3), it offers potential benefits in terms of sustainability, durability, and reduced carbon footprint, making it a viable alternative for long-term infrastructure.

VII. CONCLUSIONS

This paper has set out a systematic experimental framework for evaluating the effect of fly ash fineness on the mechanical properties of M50 grade fly ash-based geopolymer concrete, isolating fineness as the sole variable while holding the alkali activator composition and mix design constant. Based on the trends reported in the wider literature on fly ash fineness, it is anticipated that the finer fly ash fraction will produce a denser aluminosilicate gel matrix due to its greater specific surface area and reactivity, resulting in improved compressive, split-tensile, flexural, shear, and pull-out strength relative to the coarser, as-received fly ash. Once the proposed experimental programmed has been carried out, the actual results should be substituted into the tables in Section 6 to confirm the optimum fly ash fineness for producing high-strength, sustainable M50 grade geopolymer concrete, supporting its wider adoption as a structural alternative to conventional cement concrete.

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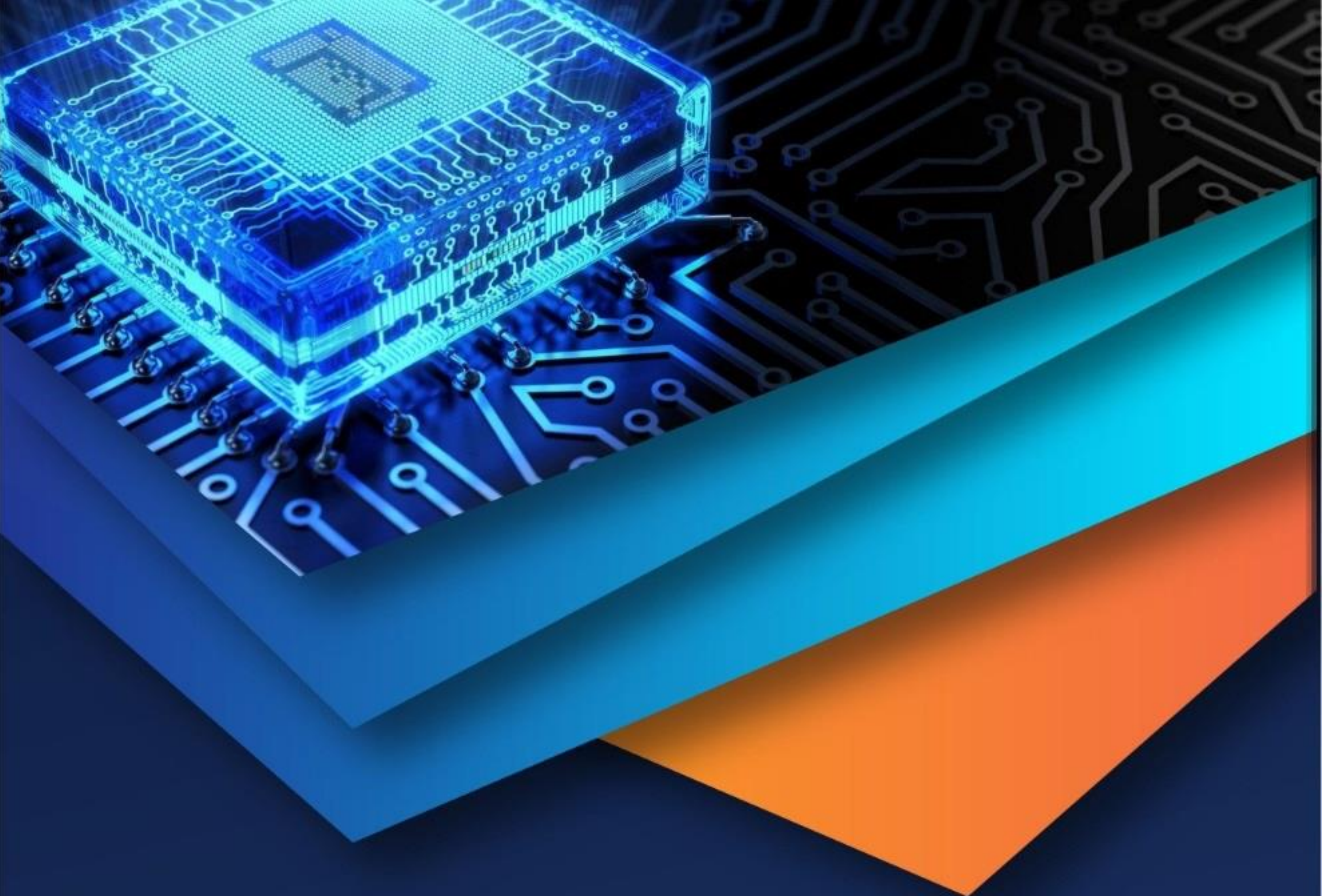

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