

# Evaluation of Strength and Durability Characteristics of Fly Ash and Silica Fume-Based Geopolymer Concrete

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**Abstract**—This study presents a detailed evaluation of the strength and durability characteristics of geopolymer concrete synthesized using fly ash and silica fume as primary alumino-silicate source materials. To promote sustainable and environmentally friendly construction practices, geopolymer concrete offers a promising alternative to traditional Portland cement concrete by utilizing industrial by-products and reducing CO<sub>2</sub> emissions. The binder in this study was activated using an alkaline solution composed of sodium hydroxide and sodium silicate. Various mix proportions were tested to optimize the mechanical properties and durability. Compressive strength, split tensile strength, and flexural strength were evaluated at different curing periods. Durability assessments included water absorption and chloride ion penetration. The results revealed that the inclusion of silica fume significantly improved the compressive and tensile strengths due to refined microstructure and enhanced geopolymerization. Furthermore, the geopolymer concrete exhibited excellent resistance to aggressive environments, with reduced permeability and superior chemical durability. The combination of fly ash and silica fume in geopolymer concrete not only enhances mechanical strength but also ensures long-term durability, making it a viable and sustainable construction material.

**Index Terms**—Fly ash; Silica fume; Geopolymer concrete; Mechanical properties; Durability studies; Environmental concerns.

## I. INTRODUCTION

Concrete is the most widely used construction material in the world due to its excellent compressive strength, ease of availability, and versatility.

However, the production of OPC, a key ingredient in conventional concrete, contributes significantly to global CO<sub>2</sub> emissions and environmental degradation. Roughly 7–8% of global greenhouse gas emissions are attributable to the cement industry alone. Investigating sustainable substitutes that reduce carbon emissions while preserving or enhancing the performance qualities of conventional concrete is crucial in this regard. Geopolymer concrete (GPC) has emerged as a potential solution to address these environmental concerns. Unlike OPC-based concrete, geopolymer concrete utilizes industrial by-products, such as fly ash, ground granulated blast-furnace slag (GGBS), and silica fume, as the binder material, which is activated by alkaline solutions. The concrete's longevity is increased by the polymerization process, which creates a robust alumino-silicate matrix that offers exceptional mechanical strength and resistance to chemical attacks [1].

Among the various alumino-silicate precursors, fly ash (a by-product of coal combustion in thermal power plants) and silica fume (a by-product of silicon and ferrosilicon alloy production) have shown considerable promise. Fly ash is rich in reactive silica and alumina, while silica fume provides ultra-fine particles that fill voids and enhance the densification of the matrix. When combined, these materials synergistically improve both the strength and durability characteristics of GPC.

Davidovits first introduced the concept of geopolymer concrete in the 1970s, coining the term “geopolymer” to describe inorganic alumino-silicate polymers formed through the reaction of

aluminosilicate oxides with alkali polysilicates [6]. Since then, considerable research has been conducted to develop and optimize geopolymer binders using various industrial byproducts. Geopolymer concrete is regarded as an environmentally friendly material due to its low energy consumption and minimal greenhouse gas emissions. According to Hardjito and Rangan (2005), fly ash-based geopolymer concrete requires significantly less energy during production compared to OPC and has the potential to reduce CO<sub>2</sub> emissions by up to 80%. The utilization of fly ash and silica fume in GPC not only diverts industrial waste from landfills but also contributes to a circular economy [8].

Fly ash is the most commonly used precursor in geopolymer concrete, especially Class F fly ash, which is rich in silica and alumina. Studies by Palomo et al. (1999) demonstrated that fly ash activated with sodium hydroxide and sodium silicate solution produces a binder with high compressive strength and early-age performance when cured at elevated temperatures [11]. Bakharev (2005) demonstrated that the mechanical strength of GPC is influenced by the alkali activator concentration, curing temperature, and the ratio of silica to alumina. The addition of silica fume further enhances the strength characteristics of GPC [2]. According to Nath and Sarker (2014), silica fume improves the microstructure by acting as a filler and promoting the formation of an additional polymeric gel. This results in higher compressive and tensile strength, as well as improved bond strength in reinforced applications [10].

One of the most attractive features of geopolymer concrete is its superior resistance to aggressive environments. Rangan (2008) reported that GPC shows excellent resistance to acid and sulfate attacks, making it suitable for marine and wastewater environments [12]. Komnitsas and Zaharaki (2007) found that the low calcium content in fly ash GPC limits the formation of expansive products, such as ettringite, which is responsible for sulfate-related deterioration in OPC concrete [9]. Chindaprasirt et al. (2009) examined the water absorption and chloride ion penetration in GPC and found that the dense matrix significantly reduces permeability, thereby enhancing durability [4]. The inclusion of silica fume was shown to reduce capillary pores further, as supported by research conducted by Singh et al.

(2015), who noted a clear correlation between silica content and decreased porosity [13].

The type and concentration of alkaline activators play a crucial role in the polymerization process. Temuujin et al. (2010) highlighted that the ratio of sodium silicate to sodium hydroxide affects the viscosity, setting time, and strength of the concrete. High alkali concentrations promote the dissolution of aluminosilicates and accelerate gel formation, although excessive alkali content can lead to efflorescence and reduced workability. The microstructural analysis provides valuable insights into the behaviour of geopolymer concrete [14]. SEM analysis by Criado et al. (2007) revealed the formation of dense N-A-S-H (sodium-alumino-silicate-hydrate) gel in fly ash-based geopolymer systems, which contributes to enhanced mechanical strength [5]. FTIR studies by Barbosa and MacKenzie (2003) confirmed the formation of Si-O-Al and Si-O-Si bonds, characteristic of the polymeric network. The use of silica fume intensifies this network, resulting in higher density and lower permeability [3].

Several researchers have explored the combination of fly ash and silica fume in GPC. Zhang et al. (2014) observed that replacing part of fly ash with 10–20% silica fume improves compressive strength and reduces porosity [15]. Similarly, Deb et al. (2015) found that hybrid geopolymer systems, incorporating fly ash and silica fume, offer improved resistance to chemical attack and enhanced durability compared to single-precursor systems [7]. While substantial work has been done on geopolymer concrete using fly ash and GGBS, there is limited comprehensive research combining fly ash and silica fume, focusing on both strength and durability aspects, especially under ambient curing conditions. Moreover, long-term performance under aggressive exposures remains an area requiring further exploration [16]. This study intends to close the gap by giving experimental insights into the mechanical properties, durability behavior, and microstructural characteristics of geopolymer concrete based on fly ash and silica fume.

## II. RESEARCH SIGNIFICANCE

This paper examines the impact of silica fume on the strength and durability properties of fly ash-based geopolymer concrete samples under various ambient

curing conditions. The strength properties, including compression, tensile, and flexural properties, were evaluated under controlled conditions. However, durability studies indicate that the life of the structure, as well as various properties, were determined, including water absorption and chloride permeability. On the other hand, compared the mechanical and durability properties to understand the influence of geopolymers on the same at various curing periods. At the same time, the influence of nano-particles on these properties were also explored and presented the reasons for increase or decrease in the strength and durability properties of the concrete.

### III. MATERIALS USED IN THIS STUDY

This study utilized various industrial by-products and chemicals to develop geopolymer concrete with enhanced strength and durability. The primary binder materials used in the present investigation were fly ash and silica fume, selected for their pozzolanic reactivity and environmental sustainability. Fly ash (low calcium), obtained from a local thermal power plant, was used as the primary alumino-silicate source material for geopolymerization. It is rich in silica (SiO<sub>2</sub>) and alumina (Al<sub>2</sub>O<sub>3</sub>) and contains low calcium content [16], making it suitable for geopolymer applications. The physical and chemical properties of the fly ash conformed to the requirements of IS: 3812 (Part 1) – 2013. Its spherical morphology helps improve workability, while its pozzolanic nature contributes to the long-term strength of the concrete. The fineness and low lime content of the fly ash contribute to the formation of a dense geopolymer matrix, enhancing both strength and chemical resistance.

Silica fume, also known as micro silica, was used as a secondary reactive component to enhance the densification of the matrix and the pore structure of the geopolymer concrete. It is a by-product of the silicon and ferrosilicon alloy industry, consisting of ultra-fine amorphous silicon dioxide (SiO<sub>2</sub>) with a particle size approximately 100 times smaller than that of cement. The high surface area and pozzolanic activity of silica fume contribute to improved strength, reduced permeability, and enhanced durability properties. Silica fume was used in partial replacement of fly ash in varying percentages (typically 5%–15% by weight) to study its synergistic

effect on mechanical and durability performance. It conforms to ASTM C1240 specifications and IS 15388:2003 for use in concrete.

The combination of fly ash and silica fume provides both a reactive matrix and ultra-fine filler particles that significantly refine the microstructure of the geopolymer concrete. Fly ash provides a long-term strength gain through geopolymerization, while silica fume enhances early-age strength and reduces the porosity of the concrete. This hybrid blend is particularly effective in resisting chemical attacks, minimizing chloride ion penetration, and reducing water absorption—thereby improving overall durability. Table 1 illustrates the chemical composition of fly ash and silica fume.

Table 1: Chemical composition of raw fly ash and silica fume

Oxide Component	Fly Ash	Silica Fume
SiO <sub>2</sub>	54.26	91.17
Al <sub>2</sub> O <sub>3</sub>	23.71	1.32
Fe <sub>2</sub> O <sub>3</sub>	7.19	0.76
CaO	4.94	0.85
MgO	1.45	0.68
SO <sub>3</sub>	2.73	0.89
Na <sub>2</sub> O	1.08	0.33
K <sub>2</sub> O	0.93	1.87
LOI	3.57	2.75

The physical properties of fly ash and silica fume have a significant influence on the behaviour and performance of geopolymer concrete. The fly ash used in this study was Class F type, appearing as a fine, grey, amorphous powder with a mean particle size of 30 µm and a specific gravity of 2.25. It had a bulk density of 950 kg/m<sup>3</sup> and a surface area (Blaine) of approximately 350 m<sup>2</sup>/kg, indicating moderate fineness. The fineness, determined by the residue retained on a 45 µm sieve, was 24%, confirming compliance with IS: 3812 (Part 1) – 2013. The colour was dark grey, typical of fly ash with moderate iron content.

In contrast, silica fume was a highly reactive pozzolanic material, appearing as an ultra-fine, light grey powder with a mean particle size of 0.15 µm, which is significantly finer than fly ash. It had a specific gravity of 2.20, a bulk density of 250 kg/m<sup>3</sup>, and an exceptionally high specific surface area of

over 20,000 m<sup>2</sup>/kg, which enhances its filler effect and pozzolanic reactivity. The fineness, with less than 5% retained on the 45 μm sieve, confirms its suitability for densifying the concrete matrix and improving durability properties. Table 2 presents the physical properties of fly ash and silica fume.

Table 2: Physical properties of fly ash and silica fume

Property	Fly Ash	Silica Fume
Appearance	Grey, fine powder	Light grey, ultra-fine powder
Physical State	Amorphous, glassy	Amorphous, highly reactive
Mean Particle Size	30 μm	0.15 μm
Specific Gravity	2.25	2.2
Bulk Density	950 kg/m <sup>3</sup>	250 kg/m <sup>3</sup>
Surface Area (Blaine)	350 m <sup>2</sup> /kg	20,000 m <sup>2</sup> /kg
Fineness (Retained on 45 μm)	24%	5%

The mix proportions for fly ash and silica fume-based geopolymer concrete were designed by maintaining a constant total binder content of 400 kg/m<sup>3</sup>, with silica fume partially replacing fly ash by weight in varying percentages across six mixes (M1 to M6). Mix M1

served as the control mix containing 100% fly ash, while mixes M2 through M6 included incremental silica fume replacements of 2.5%, 5%, 7.5%, 10%, and 15%, respectively. Accordingly, the fly ash content decreased from 400 kg in M1 to 340 kg in M6, while the silica fume content increased from 0 kg to 60 kg.

In all mixes, the fine aggregate (river sand) and coarse aggregate (crushed stone with a maximum size of 20 mm) were fixed at 600 kg/m<sup>3</sup> and 1200 kg/m<sup>3</sup>, respectively. The alkaline activator solution, a key component in polymerisation, consisted of sodium hydroxide (NaOH) and sodium silicate (Na<sub>2</sub>SiO<sub>3</sub>) with a constant mass ratio of 2.5:1. The masses of NaOH and Na<sub>2</sub>SiO<sub>3</sub> were kept consistent at 40 kg and 100 kg, respectively, for all mixes. The liquid-to-binder ratio was maintained at 0.45 to ensure uniformity in workability and reactivity.

All specimens were cured at an elevated temperature of 60°C for 24 hours in a controlled environment to promote effective polymerization. This curing regime was selected based on previous studies indicating enhanced strength and densification of the geopolymer matrix under thermal curing. The designed mix proportions facilitated a comparative analysis of the influence of silica fume on the mechanical and durability properties of geopolymer concrete.

Table 3: Mix proportions in kg/m<sup>3</sup>

Mix ID	Fly Ash	Silica Fume	Fine Aggregate	Coarse Aggregate	NaOH (8M)	Na <sub>2</sub> SiO <sub>3</sub>	L/B Ratio	Na <sub>2</sub> SiO <sub>3</sub> :NaOH Ratio
M1	400	0	600	1200	40	100	0.45	2.5:1
M2	390	10 (2.5%)	600	1200	40	100	0.45	2.5:1
M3	380	20 (5%)	600	1200	40	100	0.45	2.5:1
M4	370	30 (7.5%)	600	1200	40	100	0.45	2.5:1
M5	360	40 (10%)	600	1200	40	100	0.45	2.5:1
M6	340	60 (15%)	600	1200	40	100	0.45	2.5:1

#### IV. TEST METHODS

##### 4.1. Slump Cone Test (Workability Test)

The slump cone test is conducted to determine the workability and consistency of freshly mixed concrete. The apparatus consists of a metallic frustum-shaped slump cone, 300 mm in height, with a bottom diameter of 200 mm and a top diameter of

100 mm. The cone is placed on a flat, non-absorbent surface and filled with freshly mixed concrete in three layers, each tamped 25 times using a standard tamping rod. After leveling the top, the cone is slowly lifted vertically, allowing the concrete to subside or "slump." The difference in height between the top of the cone and the highest point of the slumped concrete is measured in millimeters and reported as the slump value. This test is performed in accordance

with IS: 1199 – 1959 or ASTM C143/C143M. A high slump indicates higher workability, whereas a low slump indicates stiffer concrete. The slump test provides quick insight into the behavior of fresh geopolymer concrete, especially when comparing mixes containing fly ash and silica fume. It is important to perform the test within 5–10 minutes after mixing to ensure reliable results.

#### 4.2. Compressive Strength

The compressive strength test is one of the most critical tests for evaluating the mechanical properties of concrete. It is performed on standard cube specimens, typically 150 mm × 150 mm × 150 mm in size, in accordance with IS: 516 – 1959 or ASTM C39/C39M. After casting, the specimens are cured under specific conditions (ambient, steam, or oven curing) for 7, 14, 28, 56, and 90 days. The test is conducted using a calibrated compression testing machine (CTM) by applying a gradually increasing axial load until the specimen fails. The maximum load applied to the specimen before failure is recorded, and the compressive strength is calculated by dividing this load by the cross-sectional area of the cube. For geopolymer concrete, this test helps in assessing the effects of activator concentration, curing regime, and binder composition (fly ash and silica fume) on strength development. The results provide vital information for structural design and quality control. Care must be taken to ensure proper alignment and surface contact during testing to avoid eccentric loading and inaccurate results.

#### 4.3. Splitting Tensile Strength

The splitting tensile strength test is conducted to evaluate the tensile strength of concrete, which is crucial for understanding its behavior under axial tension. The test is performed on cylindrical specimens, typically 150 mm in diameter and 300 mm in height, as per IS: 5816 – 1999 or ASTM C496/C496M. The cylinder is placed horizontally between the platens of a compression testing machine, and a line load is applied along the length of the cylinder. This loading configuration creates a uniform tensile stress along the vertical diameter. Failure typically occurs along the vertical plane passing through the center of the cylinder. The splitting tensile strength is calculated using the formula:

$$f_t = \frac{2P}{\pi DL}$$

Where  $P$  is the applied load,  $D$  is the diameter, and  $L$  is the length of the cylinder.

This test is especially important for geopolymer concrete since it helps evaluate the effectiveness of pozzolanic materials like silica fume in enhancing tensile capacity. Proper specimen alignment and gradual load application are essential to avoid premature failure or uneven stress distribution.

#### 4.4. Flexural Strength

The flexural strength test measures the concrete's resistance to bending and is critical in applications such as pavements and beams. It is conducted using a prism specimen, typically 100 mm × 100 mm × 500 mm, in accordance with IS: 516 – 1959 or ASTM C78/C78M. The specimen is simply supported at both ends and subjected to two-point loading at one-third spans. The flexural strength, or modulus of rupture, is calculated using the formula:

$$f_f = \frac{PL}{bd^2}$$

Where  $P$  is the applied load,  $L$  is the span length,  $b$  is the specimen width, and  $d$  is the depth.

This test is highly sensitive to specimen size, curing conditions, and loading rate. In geopolymer concrete incorporating fly ash and silica fume, flexural strength can be influenced by the dense matrix and improved bonding between particles. Uniform curing and precise load application are crucial to minimize experimental error. Flexural strength testing helps in evaluating the suitability of concrete for structural elements subjected to bending and tensile stresses.

#### 4.5. Water Absorption Test

The water absorption test is used to determine the porosity and durability of concrete by measuring the amount of water absorbed under partial immersion. The test is conducted in accordance with ASTM C642 or IS: 2185 (Part 1) – 2005. Cube specimens are oven-dried at  $105 \pm 5^\circ\text{C}$  until they attain a constant mass and are then cooled to room temperature. After cooling, the specimens are immersed in water for 24 hours. The increase in mass due to water absorption is recorded, and the percentage of water absorbed is calculated using the formula:

$$\text{Water Absorption} = \frac{W_2 - W_1}{W_1} \times 100$$

Where  $W_1$  is the dry weight and  $W_2$  is the wet weight. This test provides a direct indication of the concrete's pore structure and its ability to resist moisture ingress. For geopolymer concrete, the test reflects the efficiency of fly ash and silica fume in reducing capillary porosity. Lower water absorption generally indicates higher durability and resistance to freeze-thaw cycles, sulfate attack, and chloride penetration.

#### 4.6. Rapid Chloride Permeability Test (RCPT)

The RCPT is a standard test for assessing the resistance of concrete to chloride ion penetration, which is a critical factor in evaluating its durability in aggressive environments. This test is performed as per ASTM C1202. A 50 mm thick disc is cut from a concrete cylinder (usually 100 mm in diameter), dried, and vacuum saturated. The specimen is then placed in a test cell, with one side exposed to a 3% NaCl solution and the other side to a 0.3 N NaOH solution. A constant voltage of 60 V DC is applied across the specimen for a period of 6 hours. The total charge passed in coulombs is recorded, which indicates the permeability of the concrete to chloride ions. A lower charge indicates higher resistance to chloride ingress. The test is particularly relevant for geopolymer concrete, as the dense alumino-silicate matrix formed by fly ash and silica fume can significantly reduce permeability. This test is essential for infrastructure exposed to marine

environments or deicing salts. Care must be taken to maintain the temperature during testing, as increased heat can falsely elevate charge readings.

## V. RESULTS AND DISCUSSION

### 5.1 Workability

The slump cone test results revealed a gradual reduction in workability as the percentage of silica fume increased from 0% to 15%. Mix M1, which contained 100% fly ash, showed the highest slump value of 105 mm, indicating good workability due to the spherical shape and smooth surface texture of fly ash particles. As silica fume was incrementally added (M2 to M6), the slump values decreased progressively to 80 mm in M6. This decline is attributed to the extremely fine particle size and high surface area of silica fume, which increases water demand and decreases fluidity. The denser particle packing due to silica fume leads to a stiff mix, which although reduces workability, contributes positively to mechanical strength and durability. Therefore, while the workability reduces with increasing silica fume content, it sets the stage for improved performance in strength and permeability-related properties due to better matrix densification and reduced porosity, as seen in the subsequent tests. Figure 1 presents the workability of geopolymer concrete with different replacement levels of fly ash with silica fume.

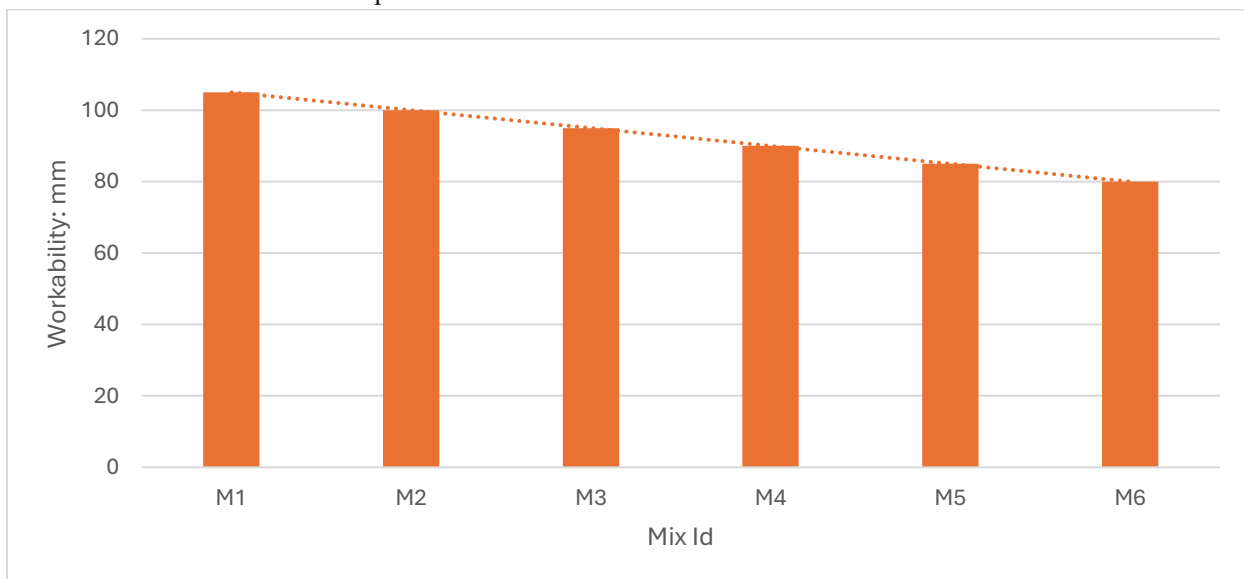


Figure 1: Workability of geopolymer concrete in 'mm'

### 5.2 Compressive strength

The compressive strength results showed a consistent increase with the addition of silica fume up to 10%, peaking at 53.4 MPa in Mix M5 at 28 days. Mix M1, which contained only fly ash, recorded a 28-day strength of 45.2 MPa. The enhancement in strength is due to the synergistic effect of silica fume, which reacts with excess calcium and forms additional binding gel (N-A-S-H and C-A-S-H), thereby densifying the geopolymer matrix. However, a slight reduction in strength was observed in Mix M6 (15% SF), indicating that beyond an optimal point, excessive silica fume can hinder geopolymerization

due to high water demand and potential agglomeration. These results correlate with the slump test, where reduced workability may have led to inadequate compaction in higher SF mixes. Furthermore, the improved compressive strength directly influences durability, as denser concrete is more resistant to ingress of water and harmful ions, as confirmed by water absorption and RCPT results. Figure 2 shows the compressive strength of geopolymer concrete with different replacement levels of fly ash with silica fume.

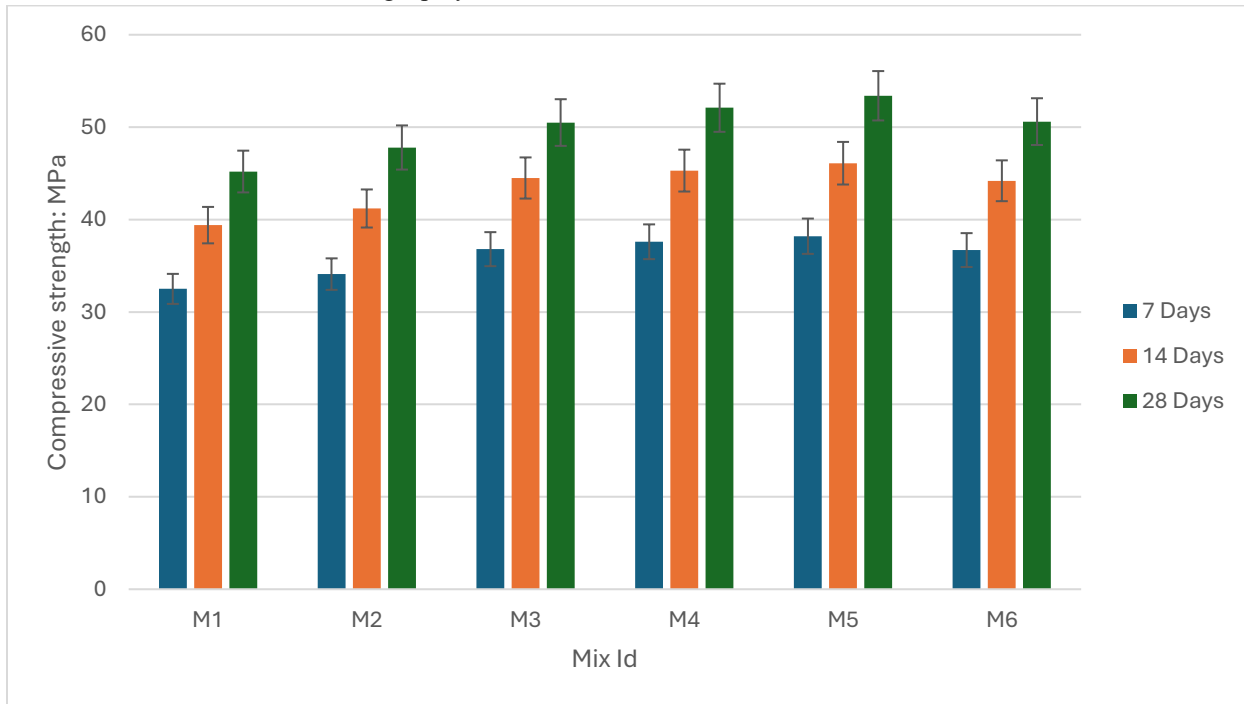


Figure 2: Presents the compressive strength of geopolymer concrete for 7, 14 and 28 days of ambient curing

### 5.3 Splitting tensile strength

The splitting tensile strength followed a similar trend as compressive strength, improving with silica fume addition up to 10%. The 28-day tensile strength increased from 3.12 MPa in Mix M1 to 3.60 MPa in Mix M5, representing a notable improvement in the concrete's ability to resist cracking under tension. The pozzolanic reactivity of silica fume plays a critical role in enhancing the interfacial transition zone (ITZ) between the binder matrix and aggregates, which is typically the weakest zone in concrete. Better bonding and reduced porosity due to filler effects lead to improved tensile characteristics. Mix M6

showed a slight reduction in tensile strength (3.42 MPa), echoing the trend seen in compressive strength. The enhanced tensile strength not only complements the compressive strength but also supports improved flexural performance, which is critical for structural elements like beams and slabs subjected to bending and cracking. This behavior is consistent with the reduced water absorption and chloride permeability results, suggesting a more durable microstructure. Figure 2 shows the splitting tensile strength of geopolymer concrete for 7, 14 and 28 days of ambient curing.

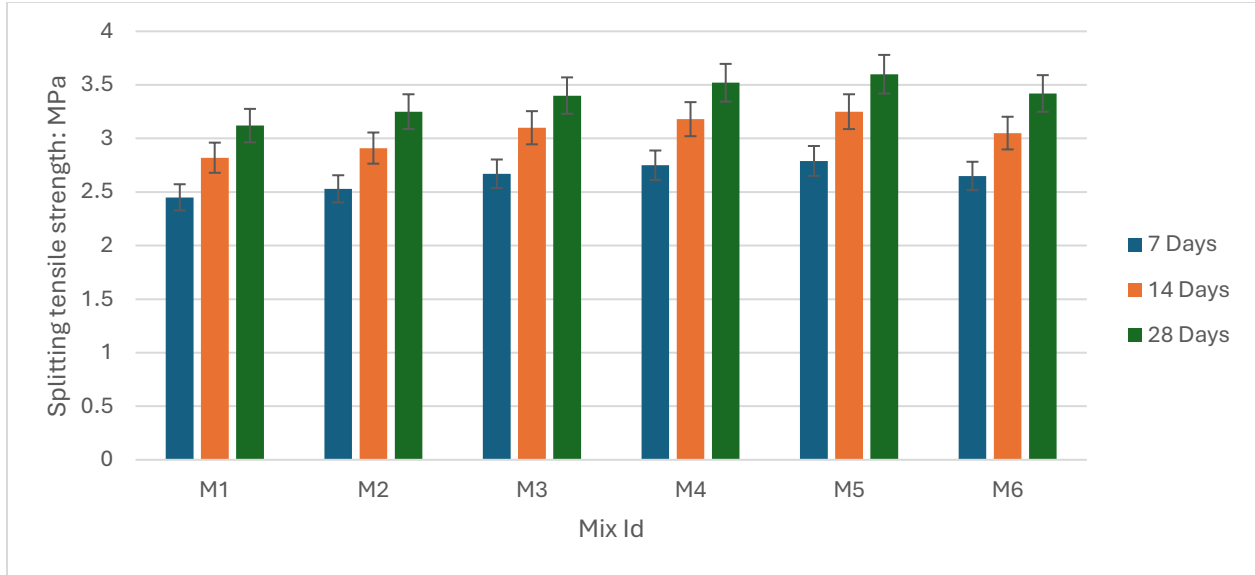


Figure 3: The splitting tensile strength of geopolymer concrete for 7, 14 and 28 days of ambient curing

#### 5.4 Flexural strength

The flexural strength values also demonstrated improvement with increasing silica fume content, peaking at 5.15 MPa in Mix M5 at 28 days. This represents a significant increase over the control mix (M1), which recorded 4.45 MPa. Flexural strength is closely related to both compressive and tensile strength, and this test further confirms the structural benefits of silica fume in the geopolymer matrix. The ultra-fine silica fume particles fill micro-voids and contribute to the continuous gel phase, enhancing stress distribution and crack-bridging capacity. The slight decline in Mix M6 (15% SF) may be attributed

to reduced workability and difficulty in achieving uniform compaction. The flexural behavior benefits from improved ITZ and matrix densification, which are also responsible for lower water permeability, as seen in the water absorption and RCPT tests. In structural design, enhanced flexural capacity is critical for serviceability, indicating that Mix M5 offers the best combination of strength and workability without compromising durability. Figure 4 presents the flexural strength of geopolymer concrete for 7, 14 and 28 days of ambient curing.

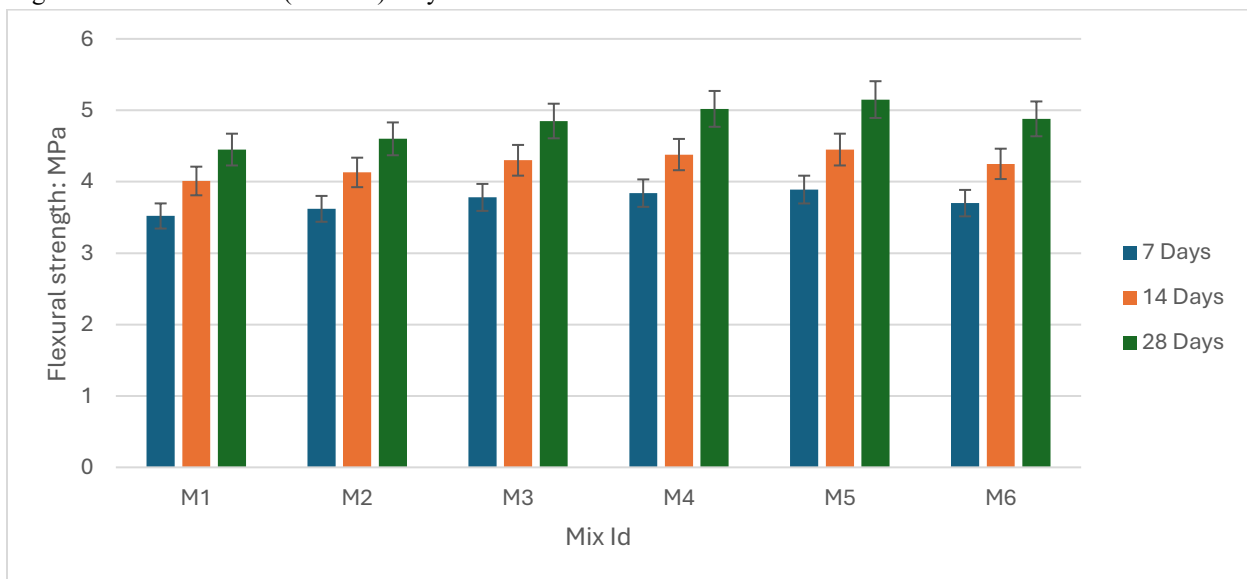


Figure 4: The flexural strength of geopolymer concrete for 7, 14 and 28 days of ambient curing

5.5 Water absorption

Water absorption decreased progressively with the addition of silica fume, reaching the lowest value of 3.33% in Mix M5. This is a direct result of the pore refinement and densification achieved through the incorporation of highly reactive and fine silica fume particles. Mix M1 had the highest absorption (4.52%), indicating a more porous matrix due to sole reliance on fly ash. The decreased porosity limits the ingress of moisture and deleterious chemicals, enhancing the durability of the concrete. Interestingly, Mix M6 showed a slight increase in water absorption (3.45%) compared to M5, which may be due to the difficulty in achieving adequate compaction and increased water demand at higher SF levels. These findings are consistent with the trends in strength properties, where optimal silica fume content improved matrix integrity. The reduced water absorption is also reflected in the RCPT results, where lower permeability directly corresponds with reduced moisture transport, supporting long-term performance in aggressive environments. Table 4 represents the water absorption of fly ash and silica fume-based geopolymer concrete.

Table 4: Water absorption test results

Mix ID	Silica Fume (%)	Water Absorption (%)
M1	0	4.52
M2	2.5	4.12
M3	5	3.82
M4	7.5	3.55
M5	10	3.33
M6	15	3.45

5.6 RCPT

The RCPT results exhibited a significant decrease in chloride ion permeability with increasing silica fume content, reflecting the densification of the geopolymer matrix. The control mix (M1) had a moderate charge passed value of 2600 coulombs, while Mix M5 showed the lowest charge passed at 1825 coulombs, indicating low permeability. The improvement in chloride resistance is attributed to silica fume’s ability to reduce capillary pores and refine the pore structure, thus restricting ionic transport. Although Mix M6 maintained a low permeability rating (1900 coulombs), a slight increase over M5 suggests that excess SF may lead to

agglomeration or reduced compactability. These results align well with water absorption findings and validate the structural benefits observed in mechanical tests. Reduced chloride permeability is vital for structures exposed to marine or deicing environments, as it delays reinforcement corrosion and enhances service life. The RCPT outcome effectively confirms the comprehensive improvements brought by silica fume up to the optimal level of 10%. Table 5 presents the RCPT test results of geopolymer concrete with various replacement levels of silica fume

Table 5: RCPT results of geopolymer concrete with various replacement levels of silica fume

Mix ID	Silica Fume (%)	Charge Passed (Coulombs)	Permeability Rating
M1	0	2600	Moderate
M2	2.5	2400	Moderate
M3	5	2150	Low
M4	7.5	1980	Low
M5	10	1825	Low
M6	15	1900	Low

The interconnected results demonstrate that silica fume, when used up to an optimal replacement level of 10%, significantly enhances the strength (compressive, tensile, and flexural), reduces water absorption, and improves chloride resistance in fly ash-based geopolymer concrete. While workability decreases with increasing SF, the trade-off leads to superior durability and structural performance. All tests consistently point to Mix M5 (10% SF) as the most balanced and high-performing blend. Excess silica fume beyond this threshold slightly compromises workability and performance, reaffirming the importance of optimized mix design for sustainable and durable concrete structures.

VI. CONCLUSIONS

Based on the comprehensive experimental investigation, it is concluded that the incorporation of silica fume as a partial replacement for fly ash significantly enhances the strength and durability characteristics of geopolymer concrete. An optimum replacement level of 10% silica fume (Mix M5) resulted in the highest compressive, tensile, and

flexural strengths due to improved geopolymer gel formation and matrix densification. Silica fume also contributed to substantial reductions in water absorption and chloride ion permeability, indicating enhanced resistance to moisture ingress and aggressive environments. Although workability decreased with increasing silica fume content, the trade-off was justified by notable gains in performance. Beyond 10% replacement, slight reductions in workability and strength were observed, highlighting the importance of optimal dosage. Overall, the combination of fly ash and silica fume in geopolymer concrete presents a viable, eco-friendly alternative to conventional cement concrete, with improved mechanical and durability performance suitable for sustainable infrastructure applications.

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#### DECLARATIONS

The authors declared that there is no conflict of interest statement to publish this paper.

#### CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

#### REFERENCES

- [1] Consoli, N., Miranda, T., & Cristelo, N. (2021). Live-Scale Testing of Granular Materials Stabilized with Alkali-Activated Waste Glass and Carbide Lime. *Applied Sciences*, 11(23), 11286.
- [2] Bakharev, T. (2005). Durability of geopolymer materials in sodium and magnesium sulfate solutions. *Cement and Concrete Research*, 35(6), 1233–1246. <https://doi.org/10.1016/j.cemconres.2004.09.002>
- [3] Barbosa, V. F. F., & MacKenzie, K. J. D. (2003). Thermal behaviour of inorganic geopolymers and composites derived from sodium polysialate. *Materials Research Bulletin*, 38(2), 319–331. [https://doi.org/10.1016/S0025-5408\(02\)00941-8](https://doi.org/10.1016/S0025-5408(02)00941-8)
- [4] Chindaprasirt, P., Chareerat, T., & Sirivivatnanon, V. (2007). Workability and strength of coarse high calcium fly ash geopolymer. *Cement and Concrete Composites*, 29(3), 224–229. <https://doi.org/10.1016/j.cemconcomp.2006.11.002>
- [5] Criado, M., Fernández-Jiménez, A., & Palomo, A. (2007). Alkaline activation of fly ash: Effect of the SiO<sub>2</sub>/Na<sub>2</sub>O ratio. Part I: FTIR study. *Microporous and Mesoporous Materials*, 106(1–3), 180–191. <https://doi.org/10.1016/j.micromeso.2007.02.055>
- [6] Davidovits, J. (1991). Geopolymers: Inorganic polymeric new materials. *Journal of Thermal Analysis*, 37, 1633–1656. <https://doi.org/10.1007/BF01912193>
- [7] Deb, P. S., Nath, P., & Sarker, P. K. (2015). The effects of ground granulated blast-furnace slag blending with fly ash and activator content on the workability and strength properties of geopolymer concrete cured at room temperature. *Materials & Design*, 62, 32–39. <https://doi.org/10.1016/j.matdes.2014.05.001>
- [8] Hardjito, D., & Rangan, B. V. (2005). Development and properties of low-calcium fly ash-based geopolymer concrete. *Curtin University of Technology, Perth*. <https://doi.org/10.13140/RG.2.1.4298.5764>
- [9] Komnitsas, K., & Zaharaki, D. (2007). Geopolymerisation: A review and prospects for the minerals industry. *Minerals Engineering*, 20(14), 1261–1277. <https://doi.org/10.1016/j.mineng.2007.07.011>
- [10] Nath, P., & Sarker, P. K. (2014). Effect of fly ash on the durability properties of high strength concrete. *Procedia Engineering*, 90, 765–770. <https://doi.org/10.1016/j.proeng.2014.11.803>
- [11] Palomo, A., Grutzeck, M. W., & Blanco, M. T. (1999). Alkali-activated fly ashes: A cement for the future. *Cement and Concrete Research*, 29(8), 1323–1329. [https://doi.org/10.1016/S0008-8846\(98\)00243-9](https://doi.org/10.1016/S0008-8846(98)00243-9)
- [12] Rangan, B. V. (2008). Low-calcium fly ash-based geopolymer concrete. *Concrete Construction Engineering Handbook (2nd ed., Chapter 26)*, CRC Press.
- [13] Singh, B., Ishwarya, G., Gupta, M., & Bhattacharyya, S. K. (2015). Geopolymer

concrete: A review of some recent developments. *Construction and Building Materials*, 85, 78–90. <https://doi.org/10.1016/j.conbuildmat.2015.03.036>

- [14] Temuujin, J., Minjigmaa, A., Lee, M., Chen-Tan, N., & van Riessen, A. (2010). Characterization of class F fly ash geopolymer pastes immersed in acid and alkaline solutions. *Cement and Concrete Composites*, 33(10), 1086–1091. <https://doi.org/10.1016/j.cemconcomp.2011.08.005>
- [15] Zhang, Z., Yao, X., & Zhu, H. (2014). Potential application of geopolymers as protection coatings for marine concrete. *Advances in Materials Science and Engineering*, 2014, Article ID 928732. <https://doi.org/10.1155/2014/928732>
- [16] Popovics, S. (1991). *A Model for Estimation of the Contribution of Fly Ash to Concrete Strength*. CRC Press eBooks. <https://doi.org/10.1201/9781482296631-20>.