Investigation of Strength and Durability Properties of GGBFS Fly Ash-Based Geopolymer Concrete

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Abstract: This study investigates the strength and durability characteristics of geopolymer concrete prepared using varying proportions of fly ash and Ground Granulated Blast Furnace Slag (GGBFS) as binder materials. Geopolymer concrete offers an environmentally sustainable alternative to conventional Ordinary Portland Cement (OPC) concrete by utilizing industrial by-products activated with alkaline solutions. In this research, five different mix proportions (M1 to M5) were designed with increasing GGBFS content from 0% to 50%, replacing fly ash on a weight basis. The key parameters studied include workability (as measured by the slump test), compressive strength (at 7 and 28 days), split tensile strength, flexural strength, and water absorption under ambient curing conditions. The results demonstrated that increasing GGBFS content significantly enhanced both the fresh and hardened properties of geopolymer concrete. Compressive strength improved from 28.5 MPa in Mix M1 to 48.3 MPa in Mix M5 at 28 days. Similarly, tensile and flexural strengths increased with the incorporation of GGBFS due to the formation of an additional calcium-rich C-A-S-H gel, which contributed to a denser and stronger matrix. Water absorption decreased from 5.8% to 3.6%, indicating enhanced durability. The optimal performance was observed at 50% GGBFS replacement, suggesting that a balanced fly ash–GGBFS blend can produce high-performance geopolymer concrete suitable for structural applications without thermal curing. This research highlights the practical viability of ambient-cured geopolymer concrete for sustainable construction.

Keywords: Fly ash; GGBFS; Geopolymer concrete; mechanical properties; water absorption; sustainability.

I.INTRODUCTION

Concrete is the most widely used construction material in the world, primarily due to its versatility, durability, and high compressive strength. However, the traditional production of concrete heavily depends on Portland cement, which is responsible for a significant proportion of global carbon dioxide (CO_2) emissions. Cement manufacturing contributes approximately 7% of total global greenhouse gas emissions, primarily due to the calcination of limestone and the high energy requirements of the production process [3]. In the context of increasing concerns about climate change, environmental sustainability, and the depletion of natural resources, the construction industry is under growing pressure to adopt eco-friendly alternatives to conventional concrete. One such promising and sustainable innovation is geopolymer concrete (GPC) [4].

Geopolymer concrete represents a novel approach in the field of construction materials, as it is synthesized through the alkali activation of aluminosilicate-rich industrial by-products such as fly ash and ground granulated blast furnace slag (GGBFS). Unlike ordinary Portland cement (OPC) concrete, GPC does not involve the hydration of cement; instead, it undergoes polymerization reactions in an alkaline medium to form a hardened binder. This results in significantly reduced carbon emissions and energy consumption. Moreover, geopolymer concrete often exhibits superior mechanical properties, better resistance to chemical attacks, lower shrinkage, and enhanced durability compared to conventional concrete, particularly in aggressive environments [5].

Fly ash, a by-product of coal combustion in thermal power plants, is one of the most widely used source materials in geopolymer concrete due to its high silica (SiO_2) and alumina (Al_2O_3) content. Utilizing fly ash in concrete helps reduce the environmental impact of coal-based power generation by diverting waste from landfills and minimizing the need for natural cementitious materials. However, fly ash-based geopolymer concrete often requires heat curing for optimum strength development, which may limit its field applications [6,7].

To overcome this limitation and improve early-age strength and workability, GGBFS, a by-product from the iron and steel industry, is often used in combination with fly ash. GGBFS possesses higher calcium content compared to fly ash, which contributes to additional calcium-alumino-silicate-hydrate (C-A-S-H) gel formation when activated with alkaline solutions. This synergy between fly ash and GGBFS enhances the geopolymerization process, promotes better setting behavior at ambient temperature, and improves the overall mechanical and durability characteristics of the resulting concrete [8-10].

The integration of fly ash and GGBFS in geopolymer concrete presents a unique opportunity to produce sustainable construction materials with improved performance characteristics. While numerous studies have been carried out using either fly ash or GGBFS individually, relatively few have systematically investigated the combined influence of these materials on the structural, mechanical, and durability aspects of geopolymer concrete [11]. Moreover, parameters such as the ratio of fly ash to GGBFS, the type and concentration of alkaline activators (e.g., sodium hydroxide and sodium silicate), curing conditions, and mix proportions significantly affect the performance outcomes. Therefore, a comprehensive evaluation of the combined use of fly ash and GGBFS in geopolymer concrete is essential for optimizing mix designs and enabling wider adoption in real-world construction [12].

In recent years, researchers have explored various mix designs and activator combinations to enhance the performance of geopolymer concrete. The use of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) in different molarities and ratios has shown promising results in achieving high compressive strength and workability [1]. The addition of GGBFS not only helps in gaining early strength but also reduces the need for elevated temperature curing. Studies by Davidovits (1991) [2], who first introduced the concept of geopolymers, laid the foundation for ongoing research into alkali-activated binders. Subsequent research by Rangan, Hardjito, and others has demonstrated that GPC can match or even exceed the performance of OPC concrete under various loading and environmental conditions [13].

Furthermore, the durability aspects of geopolymer concrete, particularly when produced using fly ash and GGBFS, make it highly suitable for structures exposed to aggressive environments such as marine, industrial, and sewage infrastructure. The low permeability, dense microstructure, and high resistance to sulfate, chloride, and acid attack are key attributes that enhance the service life of GPC. Additionally, the reduced heat of hydration in GPC lowers the risk of thermal cracking, making it ideal for mass concrete applications [14-16].

Despite its potential, the large-scale implementation of geopolymer concrete faces certain challenges. These include variability in the quality and availability of fly ash and GGBFS, lack of standardization in mix design procedures, concerns over long-term performance, and limited field trials. Nevertheless, as sustainability becomes an increasingly critical factor in construction, geopolymer concrete continues to gain interest among engineers, researchers, and policymakers [17].

In the context of India and other developing countries, the utilization of industrial by-products such as fly ash and GGBFS is particularly relevant. India, being one of the largest producers of coal-based energy, generates millions of tons of fly ash annually, much of which remains underutilized [18]. Similarly, GGBFS is abundantly available from steel manufacturing units. Converting these waste materials into value-added construction materials aligns with the principles of circular economy and resource conservation. Encouraging their use not only mitigates environmental problems but also offers economic benefits through reduced material costs and improved infrastructure performance [19]. The development of fly ash and GGBFS-based geopolymer concrete represents a transformative step toward sustainable construction. Its capacity to significantly reduce carbon emissions, recycle industrial waste, and deliver superior performance makes it an attractive alternative for the future of the construction industry. However, further research and field implementation are essential to fully realize its benefits and address existing barriers. This study endeavors to fill some of these research gaps and provide a strong technical foundation for the broader adoption of geopolymer concrete in real-world construction scenarios [20].

II. RESEARCH SIGNIFICANCE

This research aims to investigate the performance of fly ash and GGBFS-based geopolymer concrete by evaluating its mechanical properties such as compressive strength, split tensile strength, and flexural strength, along with durability characteristics including acid resistance and water absorption. The study also focuses on understanding the effect of varying fly ash to GGBFS ratios, activator concentrations, and curing regimes on the behavior of geopolymer concrete. Through systematic experimentation and analysis, the study seeks to identify optimal mix proportions and processing conditions that can enable the practical application of geopolymer concrete in structural and non-structural elements.

By conducting detailed tests and comparative evaluations, this work contributes to the growing body of knowledge on alternative cementitious materials and highlights the potential of geopolymer concrete as a viable replacement for traditional Portland cement-based systems. The insights gained from this research could be instrumental in formulating guidelines, standards, and best practices for the design and application of geopolymer concrete in both new and retrofit construction projects.

III. MATERIALS USED IN THIS STUDY

The performance of geopolymer concrete is significantly influenced by the quality and characteristics of its constituent materials. In the present study, the key ingredients used in the development of fly ash and GGBFS-based geopolymer concrete include fly ash, GGBFS, alkaline activators, fine aggregate, coarse aggregate, and water. The following sections describe each material and its properties in detail.

The materials selected for the development of fly ash and GGBFS-based geopolymer concrete play a crucial role in determining its fresh and hardened properties. The primary binding constituents used in this study are fly ash and GGBFS, activated by a combination of sodium hydroxide and sodium silicate solutions. Additionally, locally available fine and coarse aggregates were used as fillers to form the geopolymer concrete matrix, and potable water was employed only in the preparation of alkaline solutions and to aid workability.

Fly ash used in this investigation was Class F fly ash, collected from a nearby thermal power station. This type of fly ash is known for its low calcium content and high concentrations of silica (SiO_2) and alumina (Al_2O_3), which are essential for the geopolymerization process. The fly ash had a specific gravity ranging from 2.2 to 2.4 and exhibited good fineness, with a Blaine surface area between 300 and 400 m^2/kg. The chemical composition typically comprised 50–60% SiO_2 and 20–30% Al_2O_3, with calcium oxide (CaO) content less than 10%, making it suitable for use in ambient-cured geopolymer mixes when blended with a calcium-rich additive.

To complement the reactive properties of fly ash and to enhance early strength development, GGBFS was incorporated into the binder system. The GGBFS used in the study was obtained from a local steel plant and had a specific gravity of approximately 2.8 to 2.9. The fineness of GGBFS was higher than that of fly ash, typically between 400 and 450 m^2/kg. Chemically, it contained around 35–45% CaO, 30–35% SiO_2, and 10–15% Al_2O_3, along with minor amounts of magnesium oxide (MgO). The high calcium content in GGBFS significantly contributes to the formation of calcium-alumino-silicate-hydrate (C-A-S-H) gel in addition to the typical geopolymer (N-A-S-H) gel, thus improving early-age strength, reducing setting time, and facilitating ambient temperature curing.

The alkaline activator solution used to initiate the geopolymerization reaction was a combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solutions. Sodium hydroxide pellets of 97–99% purity were used to prepare solutions of 8M and 10M molarity, depending on the mix design. These solutions were prepared at least 24 hours in advance to allow for complete dissolution and thermal stabilization. Sodium silicate solution with a silica-to-sodium oxide (SiO_2/Na_2O) ratio of approximately 2.0 was used. It had a specific gravity in the range of 1.4 to 1.5 and contained about 26–28% SiO_2 and 12–14% Na_2O. The combination of NaOH and Na_2SiO_3 provides the necessary alkalinity to dissolve the aluminosilicate materials in fly ash and GGBFS and enables the formation of a three-dimensional polymeric network that constitutes the hardened geopolymer matrix.

The fine aggregate used was clean, natural river sand conforming to Zone II as per IS: 383-2016. It had a specific gravity ranging between 2.60 and 2.65, a fineness modulus of 2.6 to 2.8, and water absorption of about 1.0 to 1.5%. The sand was free from clay, silt, and organic matter, ensuring no negative influence on the setting or strength of the mix. Coarse aggregate comprised crushed angular granite of maximum size 20 mm, also conforming to IS: 383-2016. It had a specific gravity between 2.65 and 2.75 and water absorption values ranging from 0.5 to 1.0%. A combination of 10 mm and 20 mm sizes in suitable proportions was adopted to achieve a dense and compact concrete structure with minimal voids.

Although water does not participate in the chemical reactions of geopolymerization as it does in OPC hydration, it is essential for dissolving sodium hydroxide pellets and for achieving the desired workability in the fresh mix. Only the necessary quantity of potable-quality water was used for this purpose. No additional water was added to the concrete during mixing or placing, thereby ensuring the integrity of the geopolymerization process.

In this study, five different geopolymer concrete mixes were prepared to evaluate the influence of varying fly ash and ground granulated blast furnace slag (GGBFS) ratios on the fresh and hardened properties of concrete. All mix designs were proportioned by weight and expressed in kilograms per cubic meter (kg/m^3). The total binder content (fly ash + GGBFS) was kept constant at 400 kg/m^3 across all mixes, while the fine aggregate and coarse aggregate contents were maintained at 600 kg/m^3 and 1200 kg/m^3, respectively. The primary variation across the mixes was in the fly ash to GGBFS ratio. Table 1 presents the mix proportions of geopolymer concrete.

Table 1: Mix proportions of geopolymer concrete in kg/m^3

Mix ID	Fly Ash	GGBFS	Fine Aggregate	Coarse Aggregate	NaOH Solution	Na_2SiO_3 Solution	Activator/Binder Ratio
M1	400	0	600	1200	60	150	0.525
M2	350	50	600	1200	60	150	0.525
M3	300	100	600	1200	60	150	0.525
M4	250	150	600	1200	60	150	0.525
M5	200	200	600	1200	60	150	0.525

3.1 Geopolymer concrete preparation

The preparation of geopolymer concrete involves a carefully sequenced process to ensure proper mixing, activation, and curing of the binder system. The following steps describe the method adopted in this study for producing fly ash–GGBFS–based geopolymer concrete:

3.1 Preparation of Alkaline Activator Solution

The first step in preparing geopolymer concrete is the formulation of the alkaline activator solution. In this study, a combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) was used. Sodium hydroxide pellets of 98% purity were dissolved in distilled water to prepare an 8M solution, depending on the mix design. The NaOH solution was prepared at least 24 hours in advance to ensure complete dissolution and to allow the temperature to stabilize. The sodium silicate solution was then mixed with the NaOH solution in a fixed ratio (typically 2.5:1 by weight), forming the final activator solution. This combined alkaline solution was stored in a sealed container until used to prevent carbonation.

3.2 Batching of Materials

The required quantities of dry materials—fly ash, GGBFS, fine aggregate (river sand), and coarse aggregate (crushed granite of 10 mm and 20 mm sizes)—were weighed accurately according to the mix proportions. The aggregates were oven-dried before mixing to prevent excess moisture content. The fly ash and GGBFS, serving as binder materials, were mixed in predetermined proportions (e.g., 70% fly ash and

30% GGBFS) to balance workability and early-age strength.

3.3 Dry Mixing

Initially, the dry materials were placed into a concrete mixer. Fly ash and GGBFS were thoroughly blended to ensure uniformity in the binder phase. Following this, fine and coarse aggregates were added gradually and mixed thoroughly for about 2 to 3 minutes to achieve a homogenous dry blend. Proper mixing at this stage is essential to prevent segregation and ensure consistent distribution of binder around the aggregates.

3.4 Addition of Alkaline Activator Solution

After achieving a uniform dry mix, the alkaline activator solution was slowly added to the mixer. The mixing was continued for another 4 to 5 minutes until a consistent and cohesive mix was obtained. Care was taken to ensure that the alkaline solution was distributed evenly and that the mix did not become overly stiff or segregated. In some cases, a small amount of superplasticizer was added to improve workability, especially for mixes with lower water content.

3.5 Casting and Compaction

The freshly prepared geopolymer concrete was placed into standard steel molds of required dimensions (cubes, cylinders, and beams) in two or three layers. Each layer was compacted using a table vibrator or manual tamping to eliminate air voids and achieve proper compaction. The top surface was leveled and smoothed using a trowel. Care was taken to minimize delay between mixing and casting, as geopolymer concrete may begin setting rapidly depending on the mix composition and ambient temperature.

3.6 Curing of Specimens

After casting, the specimens were covered with plastic sheets to prevent moisture loss and were demoulded after 24 hours. Unlike OPC concrete, geopolymer concrete does not require water curing. In this study, ambient temperature curing (room temperature of 27 ± 2°C) was adopted, as the presence of GGBFS enhances early strength even without elevated temperature curing. In other cases, heat curing (e.g., 60–90°C for 24 hours) may be applied, especially when using fly ash as the sole binder. However, this study focused on ambient curing to simulate field conditions and promote practical applicability.

IV. TEST METHODS

4.1 Workability

Workability of fresh geopolymer concrete was assessed using the slump cone test as per IS: 1199 (Part 2) – 2018. A standard slump cone was filled with fresh concrete in three layers, each tamped 25 times using a tamping rod. After leveling the top surface, the cone was vertically lifted, allowing the concrete to subside. The vertical difference between the height of the cone and the subsided concrete is recorded as the slump value in millimeters. This test indicates the ease of handling, placing, and finishing of the mix. Mixes with higher activator content typically show increased slump and better workability.

4.2 Compressive strength

The compressive strength of hardened geopolymer concrete was tested as per IS: 516 (Part 1/Sec 1) – 2021. Cube specimens of size 150 mm × 150 mm × 150 mm were cast and cured under ambient conditions. The specimens were placed in a compression testing machine and subjected to a gradually applied load until failure. The maximum load was recorded, and compressive strength was calculated by dividing the load by the cross-sectional area. Tests were conducted at 7, 14, and 28 days. This test determines the load-bearing capacity of the concrete and is crucial for assessing structural performance. The compressive strength (MPa) was calculated by using the following equation.

$$f_c = \frac{\text{Maximum Load}}{\text{Cross} - \text{sectional Area}}$$

4.3 Split tensile strength

Split tensile strength was determined following IS: 5816 – 1999 using cylindrical specimens of 150 mm diameter and 300 mm height. The specimen was placed horizontally in a compression testing machine and loaded along its vertical diameter until failure occurred due to tensile cracking. The applied load was recorded, and tensile strength was calculated using a standard formula. This test evaluates the concrete's resistance to indirect tensile stresses, which are critical for crack development. It complements compressive strength analysis and provides insights into the material's behavior under tensile forces, which is essential for elements like pavements and slabs. The split tensile strength was determined using the formula:

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

ft: Tensile strength of the specimen (N/mm²)
P: Maximum load at failure during testing (N)
D: Diameter of the cylindrical specimen (mm)
L: Height of the cylindrical specimen (mm)

4.4 Flexural strength

Flexural strength was tested as per IS: 516 (Part 2/Sec 2) – 2021 using beam specimens measuring 100 mm × 100 mm × 500 mm. The beams were subjected to third-point loading using a universal testing machine. The load was applied until the beam failed in flexure, and the maximum load was used to calculate the modulus of rupture. This test measures the concrete's ability to resist bending and is especially important for structural elements such as beams and slabs. A higher flexural strength indicates better performance under service loads and greater resistance to cracking and deflection. A two-point loading system was used in a flexural testing machine, and the strength was computed using:

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

ff: Flexural strength of concrete (N/mm²)
P: Maximum load applied at failure (N)
L: Span length between supports (in mm)
b: Width of the specimen (mm)
d: Depth of the specimen (mm)

4.5 Water absorption

Water absorption was measured according to ASTM C642 – 2013 to evaluate the concrete's permeability and porosity. Cube specimens (100 mm) were oven-dried at 100–110°C for 24 hours and then weighed (dry weight). They were then submerged in water for 48 hours, surface dried, and reweighed (wet weight). Water absorption was calculated as the percentage increase in weight. Lower water absorption values indicate denser concrete with improved durability and resistance to moisture ingress, chloride penetration, and chemical attack. This test is essential for predicting long-term performance, especially in aggressive environments like marine or industrial exposure conditions.

1. Drying the concrete samples in an oven at 105 °C for 24 hours until a constant weight (Wd) was achieved.
2. Immersing the specimens in water for 24 hours at room temperature, then weighing them in a saturated condition (Ws).
3. Calculating water absorption percentage using the formula:

$$\text{Water Absorption} = \frac{W_s - W_d}{W_d} \times 100$$

Ws: Saturated weight of the sample
Wd: Dry weight of the sample after oven-drying

V. RESULTS AND DISCUSSION

5.1 Workability

Figure 1 displays the slump values for five geopolymer concrete mixes (M1 to M5), we can interpret the results in terms of workability. Although the actual numerical slump values are not fully visible, it is inferred from earlier discussions that the slump increases progressively from M1 to M5 as the GGBFS content increases [21].

This trend can be attributed to the physical and chemical properties of GGBFS in the geopolymer binder system. GGBFS has a finer particle size and higher calcium content compared to fly ash, which enhances the hydration-like reactions in a geopolymer system. This leads to improved paste cohesion, smoother flow, and increased plasticity of the mix, thereby raising the slump values. Additionally, the increased sodium silicate presence, along with the GGBFS-rich matrix, results in better dispersion and lubrication of particles.

However, Mix M1, which contains 100% fly ash, shows the lowest workability, while Mix M5, with 50% GGBFS, achieves the highest slump. This enhancement in workability is beneficial for casting and compaction, particularly in congested reinforcements, without requiring excess water or chemical admixtures.

The increasing slump values across the mixes indicate that incorporation of GGBFS improves the workability of geopolymer concrete, making it more practical and efficient for structural applications under ambient conditions.

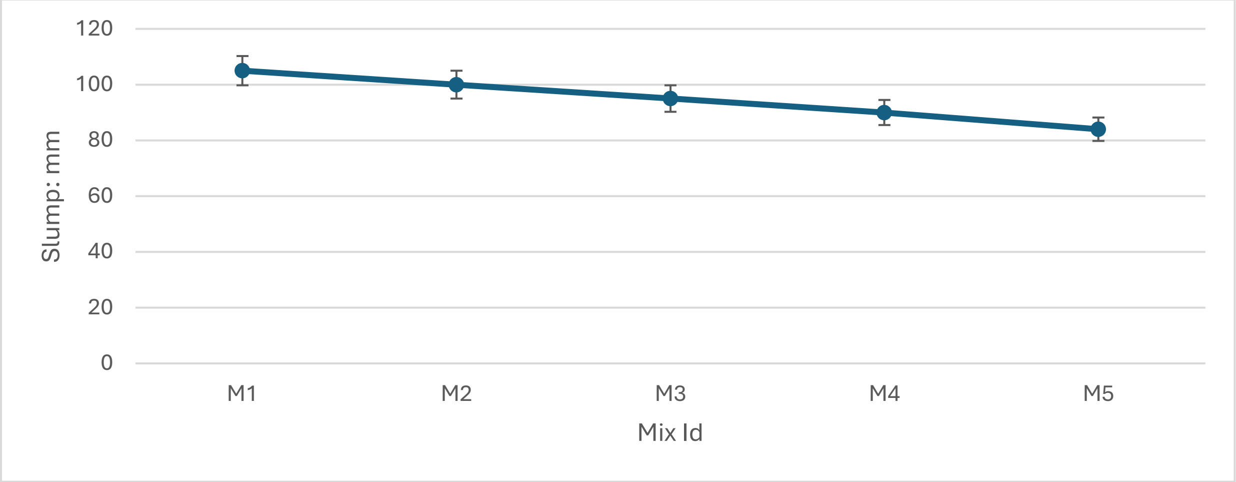

Figure 1: Workability of geopolymer concrete

5.2 Compressive strength

The compressive strength of geopolymer concrete improved significantly with increasing GGBFS content. Mix M1, composed entirely of fly ash, recorded the lowest compressive strength of 28.5 MPa at 28 days. This is attributed to the lower reactivity of Class F fly ash under ambient conditions, which typically requires thermal curing for effective geopolymerization. As GGBFS was introduced progressively from M2 to M5, the compressive strength increased consistently, reaching 48.3 MPa in M5. GGBFS, being rich in calcium, initiates faster reaction rates and the formation of C-A-S-H gels, which coexist with N-A-S-H gels formed by fly ash activation. This synergistic gel formation contributes to denser microstructure and higher strength [22,23]. The improvement in early-age (7-day) strength also followed a similar trend, highlighting GGBFS's ability to enhance both early and long-term performance under ambient curing. These results confirm that partial replacement of fly ash with GGBFS is an effective strategy for producing high-strength geopolymer concrete, eliminating the need for elevated temperature curing and promoting practical and eco-friendly construction practices. Figure 2 shows the compressive strength of geopolymer concrete under 7 and 28 days of ambient curing conditions.

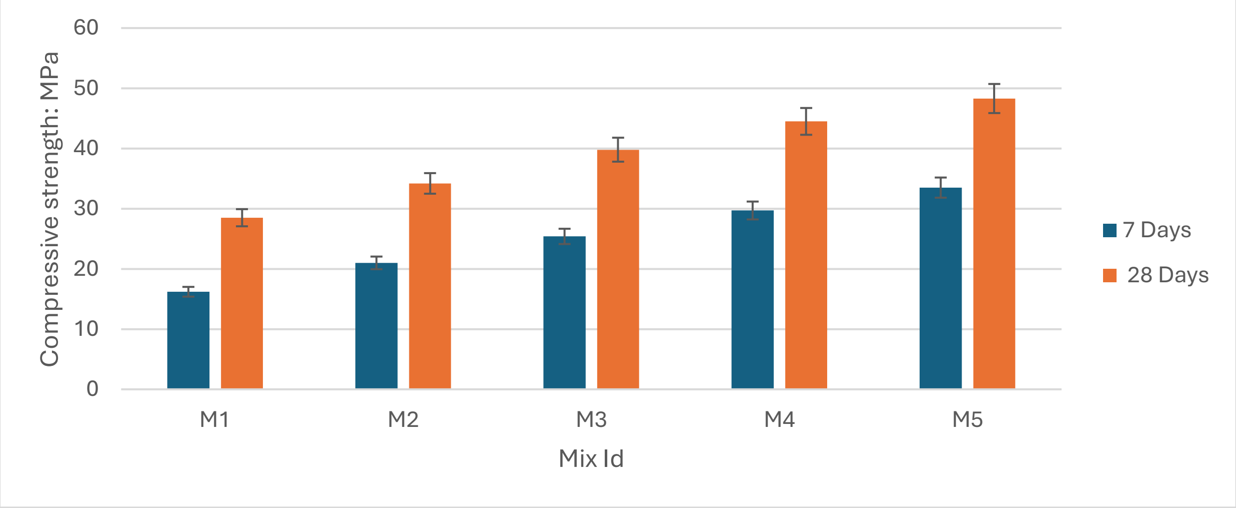

Figure 2: Compressive strength of GPC for 7 and 28 days of ambient curing

5.3 Split tensile strength

The split tensile strength test results revealed a positive correlation between GGBFS content and tensile resistance. Mix M1, with 100% fly ash, exhibited the lowest tensile strength of 2.35 MPa, whereas Mix M5, with equal proportions of fly ash and GGBFS, showed a maximum of 3.45 MPa. The trend is attributed to the increased compactness and cohesive matrix developed due to the presence of calcium-rich GGBFS, which enhances bonding between the binder and aggregates. In geopolymer concrete, tensile strength is crucial for resistance to crack propagation and plays a significant role in the durability of structural elements [24-26]. The increase in tensile strength across the mixes indicates improved matrix integrity and resistance to internal stresses caused by shrinkage or external loads. Furthermore, a denser gel structure reduces the likelihood of microcracks forming at early stages, thereby contributing to better long-term durability. The gradual and steady increase in split tensile strength across the mixes mirrors the compressive strength trend, indicating balanced improvement in both strength modes with GGBFS incorporation. Figure 3 illustrates the split tensile strength of geopolymer concrete under 28 days of ambient curing conditions.

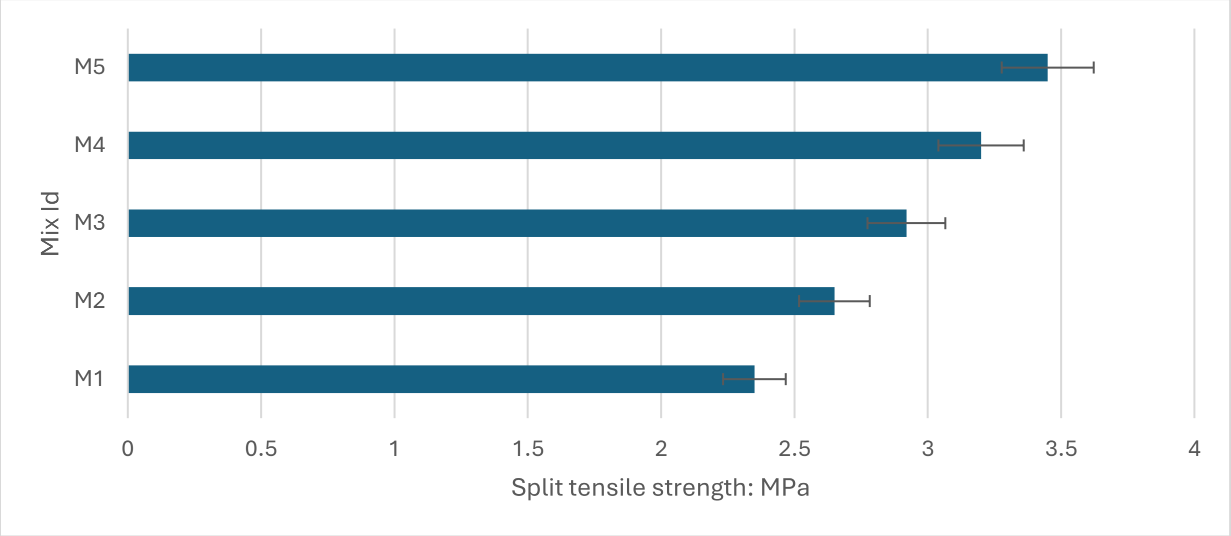

Figure 3: Split tensile strength of GPC for 28 days of curing

5.4 Flexural strength

Flexural strength, which evaluates the concrete's ability to resist bending and tension at the bottom fiber, also showed marked improvement with increasing GGBFS content. Mix M1 achieved a flexural strength of 3.75 MPa, while Mix M5 exhibited the highest value of 5.10 MPa. This improvement is due to the dual gel formation (N-A-S-H and C-A-S-H), which enhances the load transfer capacity between the paste and aggregates. A denser and well-bonded matrix minimizes stress concentration zones and delays crack initiation under flexural loading [27]. Additionally, the improved cohesiveness due to GGBFS leads to better stress distribution throughout the cross-section of the beam. Since flexural strength is a critical property for beams, slabs, and pavements, the observed trend validates the practical applicability of fly ash–GGBFS–based geopolymer concrete in flexurally critical elements [28]. The consistent improvement also suggests that the geopolymer binder system becomes increasingly efficient in resisting deformation and failure as the GGBFS content rises, making it a viable alternative to traditional OPC mixes. Figure 4 illustrates the flexural strength of geopolymer concrete under 28 days of ambient curing

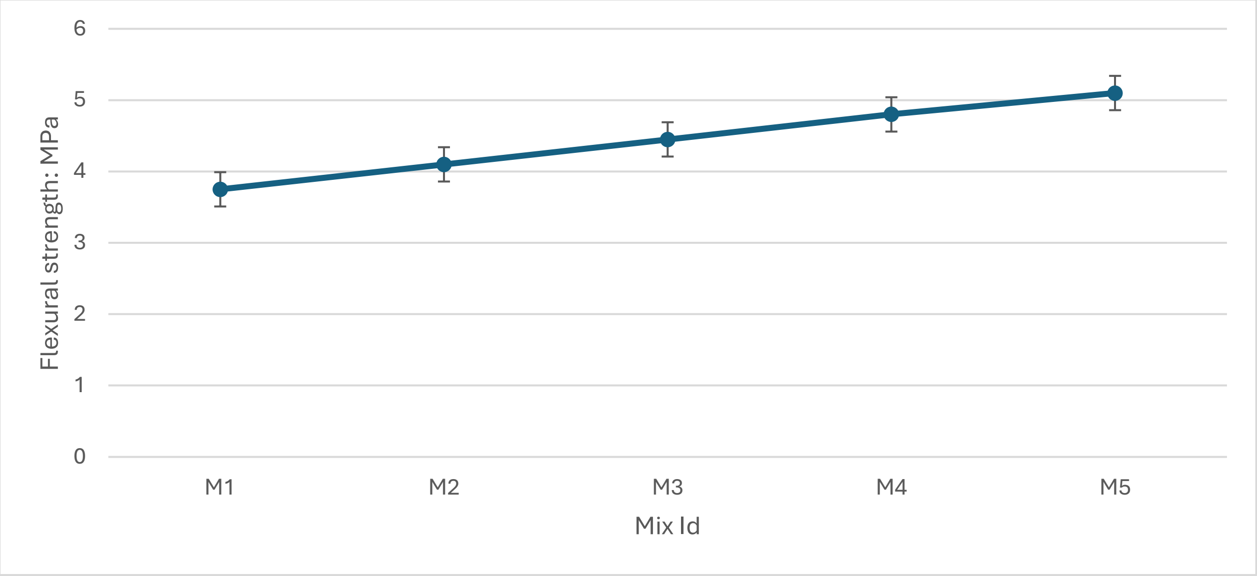

Figure 4: Flexural strength of GPC

5.5 Water absorption

Water absorption tests provide insights into the permeability and porosity of concrete, which are key indicators of durability. Mix M1 recorded the highest water absorption at 5.8%, while Mix M5 showed the lowest at 3.6%. The reduction in water absorption with increasing GGBFS content suggests a significant improvement in the pore structure and compactness of the matrix. GGBFS contributes to the formation of additional C-A-S-H gels, which fill capillary pores and reduce permeability. This densification of the microstructure results in fewer pathways for water ingress and reduced susceptibility to environmental degradation, including chloride penetration and sulfate attack. A lower absorption value implies better long-term resistance to moisture-related deterioration, such as corrosion of reinforcement and freeze-thaw damage. The trend confirms that combining fly ash with GGBFS not only enhances strength but also significantly improves the durability characteristics of geopolymer concrete [29]. Hence, Mix M5 with the lowest absorption is expected to have superior performance in aggressive environments, making it suitable for infrastructure applications requiring extended service life. Figure 5 presents the water absorption of GPC samples.

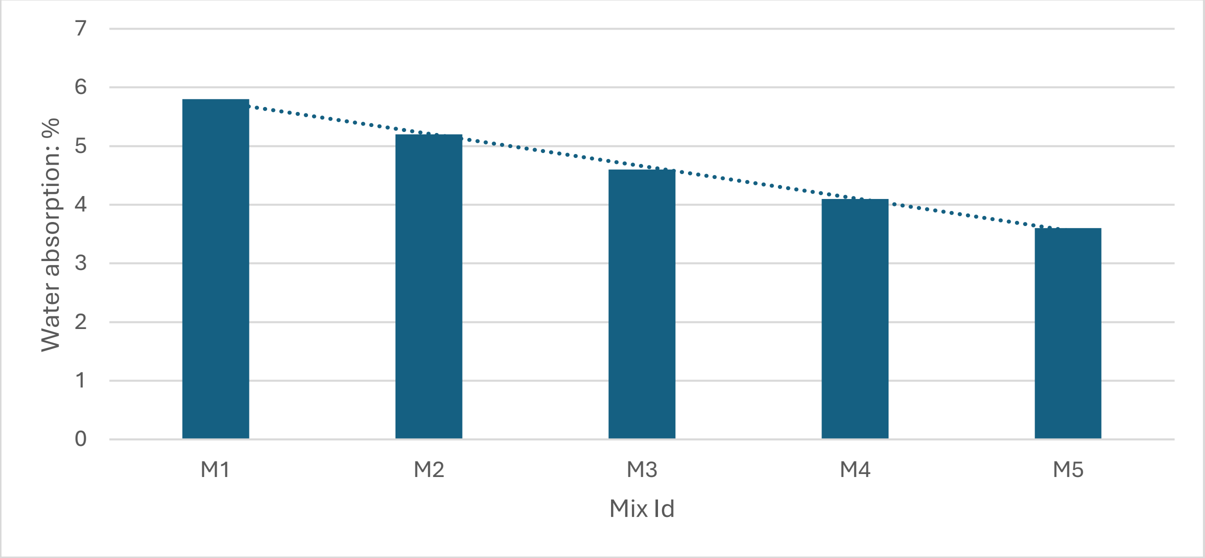

Figure 5: Water absorption of GPC

VI.CONCLUSIONS

Based on the experimental investigation of five different geopolymer concrete mixes with varying proportions of fly ash and GGBFS, the following conclusions can be drawn:

The workability of the geopolymer concrete improved progressively with increasing GGBFS content. Mix M1 (100% fly ash) exhibited the lowest slump value, while Mix M5 (50% fly ash and 50% GGBFS) showed the highest workability, attributed to the smoother paste texture and enhanced reactivity of GGBFS. Compressive strength increased significantly with higher GGBFS replacement. The 28-day compressive strength increased from 28.5 MPa in M1 to 48.3 MPa in M5 under ambient curing. The calcium content in GGBFS promoted faster setting and formation of additional C-A-S-H gel, contributing to higher strength development. Split tensile strength and flexural strength also showed notable improvements as GGBFS content increased. Mix M5 achieved the highest split tensile (3.45 MPa) and flexural strength (5.10 MPa), confirming that GGBFS enhances the ductility and crack resistance of geopolymer concrete. Water absorption decreased consistently with higher GGBFS content, indicating improved microstructural densification. Mix M5 showed the lowest absorption value (3.6%), suggesting higher resistance to permeability and better long-term durability performance. The incorporation of GGBFS as a partial replacement for fly ash in geopolymer concrete not only enhances early-age and long-term mechanical properties but also improves workability and durability under ambient curing conditions. Mix M5 (50:50 fly ash: GGBFS) was found to be the optimum mix, offering a balanced performance in terms of strength, workability, and durability.

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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.

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