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Sustainable Geopolymer Concrete: Performance Enhancement with Fly Ash, GGBS, and Zeolite Powder

S. Vijayan[1,*], D. Senthil Velan[2], Ahmed Bchatnia[3], S. Manikandan[4]

[1,2]Department of Civil Engineering, SRM Institute of Science and Technology, Ramapuram, Chennai, Tamil Nadu, India.
[3]Department of Mathematics, Tunis El Manar University, Tunis, Tunisia.
[4]Department of Robotics and Automation Engineering, Dhaanish Ahmed College of Engineering, Chennai, Tamil Nadu, India.
vijayans@srmist.edu.in[1], devsenvelan@gmail.com[2], ahmed.bchatnia@fst.utm.tn[3], manikandan@dhaanishcollege.in[4]

Abstract: Given the growing concerns over the environmental impact of Ordinary Portland Cement (OPC), this study explores geopolymer concrete (GPC) as a sustainable alternative. By utilising industrial byproducts such as fly ash, Ground Granulated Blast-Furnace Slag (GGBS), and Zeolite Powder, the research aims to develop an eco-friendly concrete mix that reduces carbon emissions without compromising performance. These alumino-silicate-rich materials were activated using a combination of sodium hydroxide and sodium silicate, forming a strong binder through geopolymerization. Various mix designs were prepared and tested under ambient curing conditions to reflect real-world practices. Key performance aspects, including compressive strength, workability, and water absorption, were evaluated. The study found that the right blend of materials significantly improves durability, reduces porosity, and enhances overall strength. The results show that geopolymer concrete can effectively replace OPC in many structural applications. Its use not only supports sustainable construction but also promotes the reuse of industrial waste, aligning with modern environmental goals. This research highlights GPC as a practical and high-performance alternative in today's construction industry.

Keywords: Geopolymer Concrete; Industrial Byproducts; Fly Ash; Zeolite Powder; Sustainable Construction; Ambient Curing; Structural Applications; Compressive Strength; Ordinary Portland Cement (OPC).

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1. Introduction

The construction industry plays a pivotal role in shaping modern infrastructure, but remains one of the most resource-intensive and environmentally damaging sectors. Among the various materials used, Ordinary Portland Cement (OPC) is a cornerstone of conventional concrete production [1]. However, OPC manufacturing is highly energy-intensive and emits large quantities of carbon dioxide (CO_2)—estimated to contribute around 8% of global CO_2 emissions. This environmental burden has prompted

*Corresponding author.

the urgent need for sustainable alternatives that can reduce the construction sector's carbon footprint without compromising structural performance. In recent years, Geopolymer Concrete (GPC) has gained significant attention as a viable substitute for OPC-based concrete [2]. Unlike traditional cement systems, geopolymer concrete is produced using alumino-silicate-rich industrial byproducts, such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), and zeolite powder. These materials, when activated by alkaline solutions like sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3), undergo a chemical reaction known as geopolymerization. This process forms a rigid three-dimensional network of calcium-alumino-silicate hydrate (C-A-S-H) or sodium-alumino-silicate hydrate (N-A-S-H) gels, which are responsible for the concrete's strength and durability. The use of geopolymer concrete offers several environmental and technical advantages. First, it reduces dependency on OPC, thereby lowering CO_2 emissions and energy consumption [3]. Second, it enables the reuse of industrial waste materials, supporting the goals of the circular economy and waste minimisation [14].

Technically, GPC displays excellent resistance to chemical attacks, reduced permeability, and superior thermal stability, making it highly suitable for aggressive environments. Furthermore, by avoiding the use of water in its binder activation, GPC contributes to the conservation of freshwater resources, which is increasingly important in arid regions [15]. Each binder material used in geopolymer concrete offers unique benefits [4]. Fly ash, a byproduct of coal combustion, improves workability and flowability of the mix. GGBS, a byproduct of the steel industry, significantly enhances both early-age compressive strength and long-term durability [6]. Meanwhile, zeolite powder, a naturally occurring pozzolan, refines the microstructure, reduces shrinkage, and improves resistance to sulfate and acid attacks. The strategic combination of these materials can produce a high-performance concrete mix; however, optimisation is essential, as excessive quantities of certain binders—especially zeolite—may increase porosity and reduce mechanical strength [7]. This study investigates the synergistic effect of combining fly ash, GGBS, and zeolite powder in various proportions to develop an optimised geopolymer mix.

The primary objective is to achieve a concrete that not only meets or exceeds the mechanical performance of conventional OPC concrete but also offers enhanced durability and environmental sustainability. The mixes are activated using a 10M NaOH solution and sodium silicate, with a fixed alkaline ratio [5]. Curing is conducted at ambient temperature (27±2°C) to replicate real-world field conditions, making the results more applicable to actual construction practices [13]. The performance of each mix is evaluated based on compressive strength, workability (as measured by the slump test), water absorption, and durability indicators [11]. By analysing these parameters, this research aims to identify the most effective combination of industrial byproducts that can replace OPC, reduce construction-related emissions, and promote long-term structural integrity. Ultimately, this study contributes to the growing body of knowledge on sustainable construction materials and supports the global transition toward greener, more resilient infrastructure solutions.

2. Role of Experimental Testing and Performance Evaluation

In the development of advanced construction materials such as geopolymer concrete (GPC), experimental testing plays a pivotal role in validating performance and optimising material combinations. Unlike theoretical mix design approaches or simulation models alone, laboratory-based experimental evaluation provides tangible, real-world data on mechanical and durability characteristics under controlled conditions [1]. This process is essential when dealing with alternative binders, such as fly ash, GGBS, and zeolite powder, whose properties can vary based on source, fineness, and chemical composition. For geopolymer concrete, evaluating key parameters—such as compressive strength, flexural strength, slump value, and water absorption—offers critical insights into the behaviour of the mix under practical scenarios [5]. These tests not only confirm whether the mix meets structural requirements but also provide insight into its workability, durability, and resistance to environmental stressors [8]. By testing specimens at multiple curing intervals (7, 14, and 28 days), the study captures the strength development curve, which is especially important for GPC due to its unique geopolymerization process.

One of the major advantages of experimental testing in this context is its ability to identify optimal proportions of binder components that strike a balance between performance and sustainability [2]. For instance, excessive zeolite may reduce strength due to increased porosity, while a well-proportioned blend can lead to denser microstructures and higher strength. Furthermore, real-world testing under ambient curing conditions— as used in this study—adds practical relevance, simulating typical site environments without requiring specialised heat treatment. Through structured experimentation, this research not only validates the feasibility of replacing OPC with industrial byproducts but also provides a roadmap for scaling GPC into mainstream construction [9]; [10]. The results serve as a benchmark for future innovations, enabling data-driven improvements and fostering confidence in adopting sustainable alternatives in the structural engineering community [12].

3. Methodology

Figure 1 shows a flow chart that shows the methodical design process used in this work. The method starts with a thorough assessment of the literature to learn about past research results, locate gaps in the current research, and set specific research goals. After that, the right materials are carefully chosen and gathered based on their ease of finding and their relevance to the study. Then, material characterisation is done to test the materials' physical, chemical, and mechanical properties. After the materials have been described, an alkaline solution is prepared in the correct proportions for the blend. During the mix design development stage, the best ratios of all the parts are found to get the desired strength and performance. Then, the prepared materials are thoroughly combined and poured into moulds in a controlled manner.

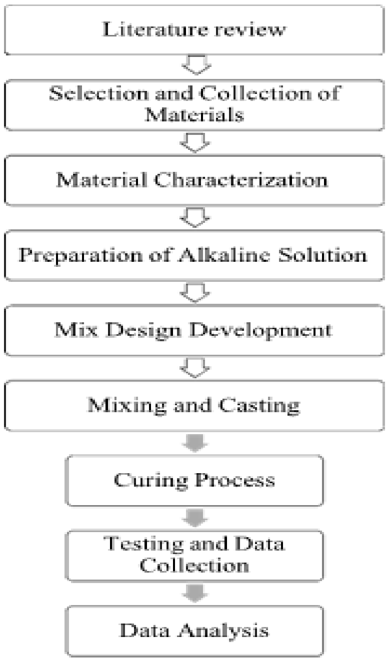

Figure 1: Flow chart for design methodology

4. Experimental Setup and Analysis

This paper is rooted in practical, laboratory-based experimentation rather than software modelling or simulation. The primary aim is to evaluate the behaviour and performance of geopolymer concrete using fly ash, Ground Granulated Blast Furnace Slag (GGBS), and zeolite powder under varying proportions. The testing methodology follows Indian Standards (IS) and replicates real construction environments as closely as possible to ensure the relevance and reliability of the results.

4.1. Material Selection and Preparation

The first step involved sourcing and verifying the materials required for the study. Class F fly ash, GGBS, and zeolite powder were selected as binder materials. River sand was used as fine aggregate, and crushed granite stone was used as coarse aggregate, both conforming to IS: 383 specifications. The alkaline activator was prepared using a 10 M sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) solution in a fixed ratio of 2.5:1 (Figure 2).

Figure 2: Material selection

4.2. Mix Design and Trial Batching

Various trial mixes were formulated by varying the proportions of fly ash, GGBS, and zeolite powder while maintaining a constant binder content (Figure 3).

Figure 3: Mixing the raw materials

The alkaline liquid-to-binder ratio was set at 0.45 for all mixes. Each component was measured accurately to ensure consistency across different batches (Figure 4).

Figure 4: Trial batching

Mixes were prepared in a pan mixer to ensure uniform distribution of materials (Figure 5).

Figure 5: Trial batching

4.3. Casting of Specimens

Concrete cubes of size 150 mm × 150 mm × 150 mm were cast in steel moulds in three layers, with each layer compacted using a vibrating Table to remove air voids. In addition to the cubes, flexural beam specimens measuring 100 mm × 100 mm × 500 mm were also cast using the same procedure. After demolding at 24 hours, all specimens were cured at ambient room temperature (27 ± 2°C) to simulate field conditions without thermal curing (Figure 6).

Figure 6: Concrete cubes and beams cast

4.4. Curing Schedule of Specimens

Tables 1 and 2 show the curing schedule and duration that were used for the specimens in this experimental study. Table 1 shows the full curing plan for two kinds of specimens: a cube and a flexural beam. The cube specimens were 150 mm on each side, while the flexural beam specimens were 100 mm on each side and 500 mm long. Both types of specimens were cured at room temperature, which was kept at 27 ± 2°C. The curing method used was ambient chamber curing, which creates a stable and regulated environment for building strength. The specimens underwent curing periods of 7, 14, 28, and 56 days to assess the temporal evolution of mechanical characteristics.

Table 1: Curing schedule for specimens

Specimen Type	Dimensions (mm)	Curing Temperature (°C)	Curing Method	Curing Duration (days)
Cube	150 × 150 × 150	27 ± 2	Ambient room curing	7, 14, 28, 56
Flexural Beam	100 × 100 × 500	27 ± 2	Ambient room curing	7, 14, 28, 56

Table 2 shows how long the curing process should last for each type of test. We did the compressive strength testing on cube samples and the flexural strength tests on flexural beam samples. Both tests were done at 7, 14, 28, and 56 days of cure to see how the strength changed over time. The repeated curing intervals made it possible to compare how strength developed at different stages. These curing conditions ensured the testing process was consistent and reliable, allowing for accurate measurement of the performance characteristics of the materials used in the study.

Table 2: Curing duration for specimens

Test Type	Specimen Type	Curing Age (days)	Test Type	Specimen Type
Compressive Strength	Cube	7, 14, 28, 56	Compressive Strength	Cube
Flexural Strength	Flexural Beam	7, 14, 28, 56	Flexural Strength	Flexural Beam

Figures 7 and 8 show how the compressive and flexural strength of samples change over time as they cure. As the curing time goes on, Figure 7 indicates that the compressive strength increases significantly. The strength gain happens quickly in the first few days and continues to increase steadily as the curing time gets longer. This shows that the material is getting hydrated and bonded well. The pattern shows that longer curing times improve the material's compressibility by helping the microstructure form better.

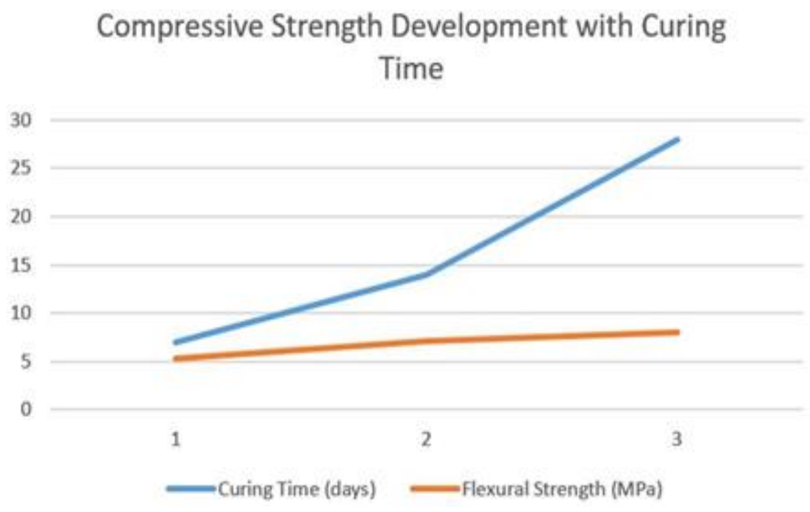

Figure 7: Curing compressive strength

Figure 8 shows how the flexural strength similarly changes with cure time. The results show that the flexural strength gets better over time, but not as quickly as the compressive strength. This implies that flexural properties evolve progressively as the material acquires stiffness and cohesiveness. Both figures clearly illustrate that longer curing times improve the overall mechanical properties of the samples. The steady rise in strength indicates that appropriate curing is crucial for ensuring the tested materials operate as intended.

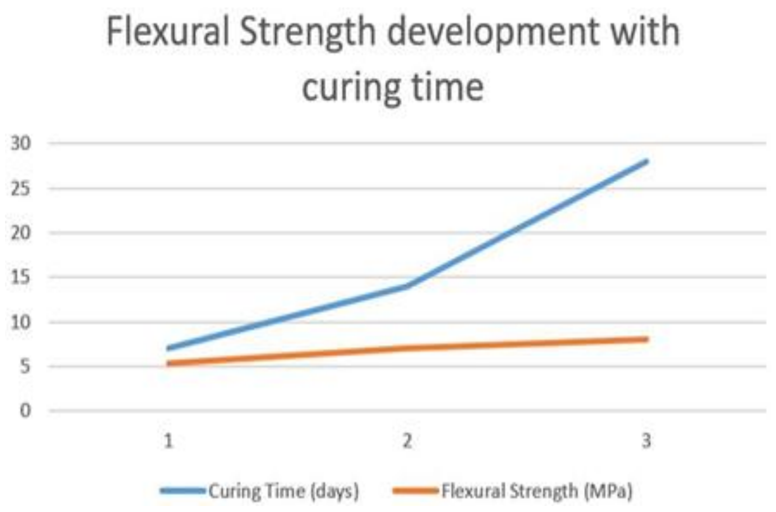

Figure 8: Curing flexural strength

4.5. Testing Procedures

Each mix was tested at 7, 14, and 28 days to evaluate the development of mechanical properties and durability. The following tests were conducted:

- Compressive Strength Test as per IS 516:1959 using a compression testing machine.
- Slump Test to assess the workability of fresh concrete as per IS 1199:1959.
- The Water Absorption Test is used to evaluate porosity and durability.
- Flexural Strength Test as per IS 516:1959 using a flexural testing setup.
- Rebound Hammer Test to assess surface hardness and estimate in-situ concrete strength.

All tests were performed in triplicate to ensure accuracy and repeatability of results (Figures 9 to 11).

Figure 9: Slump cone test

Figure 10: Water absorption test

Figure 11: Cube compression test

4.6. Data Analysis and Interpretation

The experimental data were tabulated and analysed to identify trends across different mix proportions. Graphs were used to compare strength gain over time, workability differences, and absorption rates. The results were interpreted to determine the most effective binder combination in terms of both mechanical performance and sustainability. This experimental approach ensures that findings are grounded in real material behaviour, offering practical insights for future implementation of geopolymer concrete in structural applications.

5. Comparison of (GPC) and (OPC)

The development and application of Geopolymer Concrete (GPC) mark a significant advancement in sustainable construction practices. While Ordinary Portland Cement (OPC) has been the benchmark in the construction industry for decades, GPC offers a compelling alternative that addresses key limitations of conventional concrete. This section presents a detailed comparative analysis between GPC and OPC concrete in terms of composition, performance, environmental impact, and practical usability.

5.1. Binder Composition

OPC concrete primarily uses clinker-based cement, which requires high-temperature processes such as calcination and grinding, resulting in significant energy consumption and CO_2 emissions. GPC, on the other hand, utilises alumino-silicate-rich industrial byproducts, such as fly ash, Ground Granulated Blast Furnace Slag (GGBS), and zeolite powder, which are activated by alkaline solutions like sodium hydroxide and sodium silicate. This eliminates the need for cement, supporting waste recycling and circular economy goals.

5.2. Environmental Impact

A major advantage of GPC is its significantly reduced carbon footprint. While OPC production emits approximately 0.9 tons of CO_2 per ton of cement, GPC emits far less due to its reliance on industrial waste and absence of high-temperature manufacturing processes. Additionally, GPC reduces landfill waste by making productive use of otherwise discarded byproducts.

5.3. Mechanical Properties

The compressive strength of GPC is often comparable to or greater than that of OPC, especially when GGBS is used. It also demonstrates superior chemical resistance, particularly in environments exposed to acids or sulfates. GPC shows lower shrinkage and better long-term performance, although it may experience slower early-age strength development, depending on the curing method and mix proportions.

5.4. Curing Process

OPC concrete develops strength through hydration and is typically cured using water immersion or moist curing methods. In contrast, GPC relies on geopolymerization, a process that can be enhanced through thermal curing but is also effective under ambient curing conditions, as applied in this study. This flexibility makes GPC suitable for real-world site applications where energy-intensive curing methods are impractical.

5.5. Workability and Handling

Fly ash in GPC contributes to good workability, often negating the need for plasticisers. In OPC concrete, chemical admixtures are frequently required to achieve similar performance. However, the use of alkaline activators in GPC requires strict safety measures, including protective gear and careful mixing, to prevent handling hazards.

5.6. Cost and Availability

While the raw materials for GPC—such as fly ash and GGBS—are often cost-effective or available as industrial waste, the cost of alkaline activators (NaOH and Na_2SiO_3) can make the initial mix slightly more expensive. However, due to its enhanced durability and reduced maintenance needs, GPC can prove to be more economical in the long term. OPC remains more widely available, supported by established codes and industry familiarity (Table 3).

Table 3: Comparison of geopolymer concrete and OPC

Parameter	Geopolymer Concrete (GPC)	OPC Concrete
Binder Material	Industrial byproducts (Fly Ash, GGBS, Zeolite)	Clinker-based Ordinary Portland Cement
CO_2 Emissions (approx.)	Low (up to 80% reduction)	High (~0.9 tons CO_2 per ton of cement)
Energy Consumption	Lower (no calcination required)	High (energy-intensive clinker production)
Compressive Strength	Comparable to or greater than OPC	Good, depends on grade and curing
Chemical Resistance	Excellent (resistant to acid/sulfate attacks)	Moderate to poor (needs additives for harsh environments)
Curing Requirement	Ambient or thermal curing (mix-dependent)	Water curing under standard conditions
Early Strength Gain	Slower (especially with high fly ash content)	Faster (depending on grade and curing)
Workability	Good (especially with fly ash inclusion)	Often needs admixtures for better flow
Durability and Shrinkage	Higher durability, lower shrinkage and permeability	Prone to shrinkage and long-term cracking
Handling & Safety	Requires care due to alkaline activators (NaOH, Na_2SiO_3)	Easier and safer to handle
Material Cost	Lower binders, higher activator cost	Higher binder cost, lower additional chemicals
Long-Term Cost Efficiency	High (due to lower maintenance and longer life)	Moderate (frequent repairs and degradation in harsh environmental conditions)
Code Availability	Limited or under development in many regions	Widely available and standardised globally

6. Results and Discussion

6.1. Compressive Strength Analysis

To assess the strength performance of various geopolymer concrete (GPC) mixes, cube specimens were tested at 7, 14, and 28 days. The results are summarised in the following Table 4.

Table 4: Compressive strength of different mixes

Mix ID	Composition	7-Day (MPa)	14-Day (MPa)	28-Day (MPa)
Mix 1	50% GGBS + 40% Fly Ash + 10% Zeolite	35.8	42.6	46.9
Mix 2	60% GGBS + 30% Fly Ash + 10% Zeolite	39.5	47.2	51.8
Mix 3	55% GGBS + 35% Fly Ash + 10% Zeolite	36.7	44.0	48.3

Observation: Mix 2 yielded the highest compressive strength across all testing intervals, confirming the beneficial influence of increased GGBS content on strength gain under ambient curing (Figure 12).

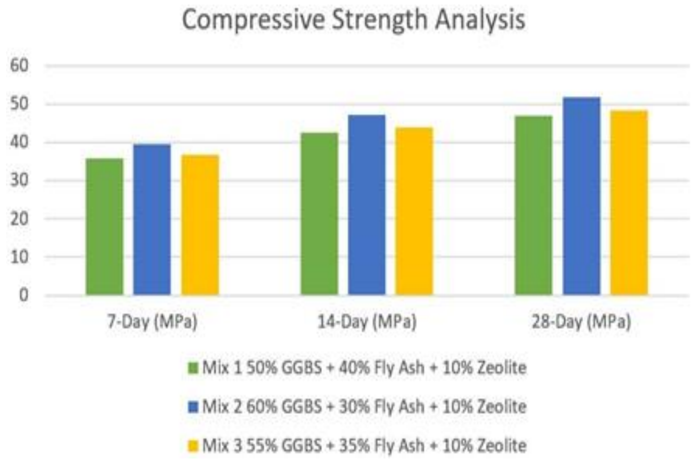

Figure 12: Flexural strength

6.2. Flexural Strength Performance

Flexural strength was assessed to understand tensile capacity and crack resistance (Table 5). The results are shown below:

Table 5: Flexural strength of GPC mixes

Mix ID	7-Day (MPa)	14-Day (MPa)	28-Day (MPa)	Failure Mode
Mix 1	5.0	6.5	7.0	Bending
Mix 2	5.3	7.1	8.0	Mid-span cracking
Mix 3	5.1	6.7	7.5	Flexural fracture

Interpretation: The flexural strength followed a similar trend to compressive strength, with Mix 2 again outperforming. Cracks typically initiated at mid-span, consistent with flexural loading behaviour (Figure 13).

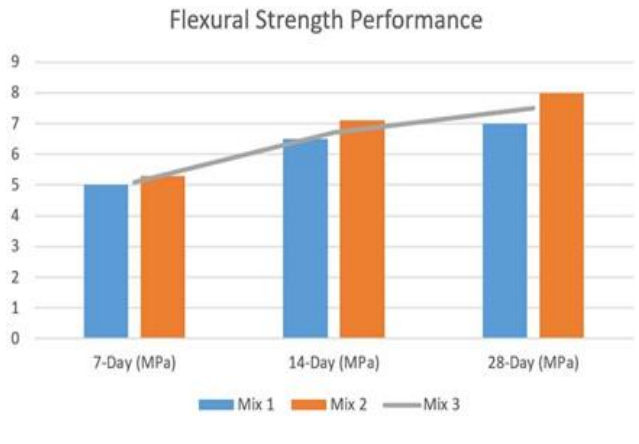

Figure 13: Compressive strength

6.3. Surface Hardness – Rebound Hammer Test

The rebound hammer test was conducted to estimate surface hardness, which correlates with compressive strength (Table 6).

Table 6: Rebound hammer results

Mix ID	7-Day Value	14-Day Value	28-Day Value	Surface Condition
Mix 1	35	39	41	Smooth
Mix 2	36	40	43	Slightly rough
Mix 3	34	38	40	Slightly rough

Insight: Rebound values increased with age and correlated well with compressive strength data. Surface condition played a minor role in the readings (Figure 14).

14-Day Value	28-Day Value	Surface Condition
39	41	Smooth
40	43	Slightly rough
38	40	Slightly rough

Figure 14: Rebound hammer test

6.4. Workability and Durability

Slump Test Results: Workability was evaluated using the slump test on fresh concrete mixes (Table 7).

Table 7: Slump values

Mix ID	Slump (mm)
Mix 1	75
Mix 2	72
Mix 3	74

Comment: All mixes displayed satisfactory workability for structural applications, with Fly Ash contributing to smoother mixing and easier compaction (Figure 15).

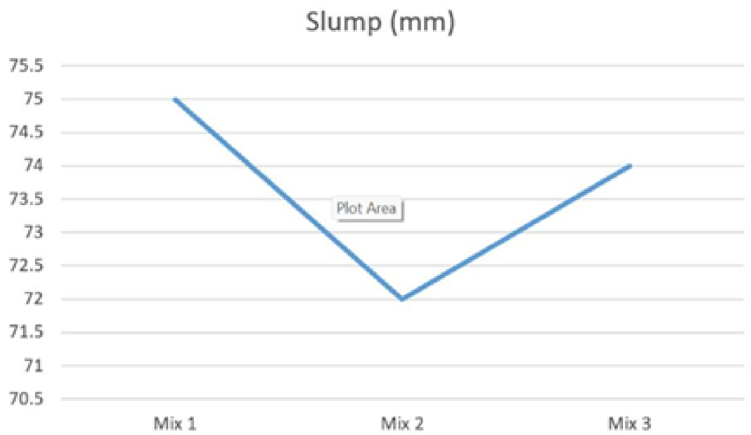

Figure 15: Slump value

Water Absorption: Porosity and durability were assessed through water absorption tests (Table 8).

Table 8: Water absorption percentages

Mix ID	Water Absorption (%)
Mix 1	4.0
Mix 2	3.6
Mix 3	3.8

Figure 16 shows how three different concrete mixes compare in terms of water absorption and slump values. The orange line represents the slump values, while the blue bars indicate the percentage of water absorption. Mix 1 and Mix 3 both absorb about 4% of water, making them almost identical. Mix 2, on the other hand, shows a clear drop in both water absorption and slump value. Overall, the figure shows that Mix 2 works best because it absorbs less water and has a lower slump.

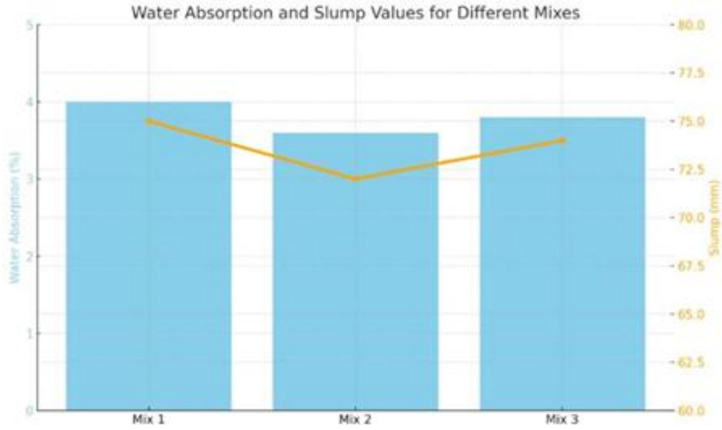

Figure 16: Water absorption test

Observation: Mix 2 again demonstrated superior performance, with reduced water absorption indicating a denser and more durable matrix (Table 9).

Table 9: Summary of key results

Parameter	Best Performing Mix (60% GGBS + 30% FA + 10% Zeolite)
Compressive Strength	51.8 MPa at 28 days
Flexural Strength	8.0 MPa at 28 days
Water Absorption	3.6%
Slump Value	72 mm
Rebound Value	43

6.5. Interpretation and Implications

- GGBS played a crucial role in strength enhancement due to its latent hydraulic properties.
- Fly Ash improved the mix's flowability, aiding workability.
- Zeolite Powder, in limited quantities, helped reduce shrinkage and refine the pore structure but required careful control to avoid excess porosity.
- The optimal mix design (Mix 2) demonstrated balanced performance, delivering strength, workability, and durability under ambient curing conditions—making it a viable candidate for practical, eco-conscious construction.

7. Conclusion

The study successfully explored the development and optimisation of geopolymer concrete (GPC) using a sustainable blend of industrial byproducts—Fly Ash, Ground Granulated Blast Furnace Slag (GGBS), and Zeolite Powder. The paper aimed to reduce reliance on Ordinary Portland Cement (OPC) while improving the mechanical and durability characteristics of concrete under ambient curing conditions. Key conclusions drawn from this research are outlined as the optimal mix proportion of 60% GGBS, 30% Fly Ash, and 10% Zeolite Powder demonstrated the best overall performance, achieving a compressive strength of 51.8 MPa, flexural strength of 8.0 MPa, and low water absorption (3.6%)—indicating superior strength and durability compared to conventional mixes. Workability results from slump tests showed all GPC mixes were easily placeable, with slump values ranging between 72 mm and 75 mm, confirming suitability for practical field applications. The inclusion of Fly Ash enhanced the mix's flowability, making it easier to handle during casting.

The Rebound Hammer test confirmed the improved surface hardness of the optimised mix, with a 28-day rebound value of 43, further validating the strength development under ambient conditions. Zeolite powder contributed to pore refinement and chemical resistance when used in moderate amounts (10%), but higher contents led to increased porosity. This underscores the importance of proportion control for long-term performance. Environmental sustainability was a major achievement, as the mix design reduced cement usage, lowered CO_2 emissions, and promoted the circular economy through the reuse of industrial waste materials. This research clearly demonstrates that ambient-cured GPC can effectively replace OPC-based concrete for structural applications without compromising performance, offering a cost-effective and greener alternative.

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