



Sustainable High-strength Geopolymer Concrete Incorporating Ultrafine Fly Ash and Ultrafine GGBS

Parah Salsabeel Jalal¹, Vikas Srivastava^{1*} and A. K. Tiwari²

¹Department of Civil Engineering, Sam Higginbottom University of Agriculture, Technology and Sciences, Prayagraj, UP, India

²RDC Concrete Limited, Lucknow, UP, India

Received: 29.08.2025 Accepted: 23.09.2025 Published: 30.12.2025

*vikas.srivastava@shiats.edu.in



ABSTRACT

The increasing global demand for Ordinary Portland Cement (OPC)-based concrete, driven by rapid urbanization and infrastructure development, poses significant environmental challenges, including high CO₂ emissions, depletion of natural aggregates, and reduced structural durability in aggressive environments. This study investigates an eco-sustainable alternative, ambient-cured geopolymer concrete (GPC), produced by partially replacing ultrafine fly ash (UFFA) with ultrafine ground granulated blast furnace slag (UFGGBS) in proportions ranging from 0% to 50% in 10% increments, with a total binder content fixed at 400 kg/m³ and activated with 10-molar sodium hydroxide and a sodium silicate-to-sodium hydroxide ratio of 2:1. This study distinguishes itself by utilizing ultrafine variants of industrial by-products to enhance reactivity and performance, representing a key advancement over conventional geopolymer mixes. Mechanical properties (compressive, flexural, and split-tensile strength) and durability indicators (water absorption and sorptivity) were evaluated. Results show that replacing UFFA with UFGGBS significantly enhanced early and long-term mechanical performance, with the F50G50 mix (50% UFFA and 50% UFGGBS) achieving the highest 28-day compressive strength (58.20 MPa), flexural strength (8.73 MPa), and split-tensile strength (6.54 MPa). Durability improved through reduced water absorption (28.74% lower than control) and sorptivity (57% reduction), attributed to the refined pore structure and denser aluminosilicate gel formation. This research supports the adoption of geopolymer technology as a viable pathway toward resource conservation, CO₂ emission reduction, and sustainable infrastructure development.

Keywords: Geopolymer concrete; Ultrafine fly ash; Ultrafine GGBS; Sustainable construction; Carbon footprint reduction; Waste utilization.

1. INTRODUCTION

Concrete construction plays a vital role in the growth of nations, irrespective of their stage of development. Developing nations prioritize new infrastructure for rapid urbanization, while developed nations focus on maintaining existing structures, highlighting diverse approaches (DeAzevedo *et al.* 2021). Concrete, the world's second most consumed material after water (Rihan and Abdalla, 2024), with 30 billion tonnes used annually (Monteiro *et al.* 2017), relies heavily on Ordinary Portland Cement (OPC) (Jalal *et al.* 2025b). Global OPC demand grows at ~3% annually (Imtiaz *et al.* 2020), reaching 4.1 billion tons in 2022 (IEA, 2024), and is projected to increase by 50% by 2050 (Monteiro *et al.* 2017). A world without concrete and OPC is hard to imagine (Imbabi *et al.* 2012). However, OPC production faces significant environmental challenges (Nilimaa, 2023). Manufacturing involves high-temperature limestone calcination, consuming vast energy (second only to steel/aluminum production (Rashad, 2020), using 7% of global industrial energy (Gopalakrishnan and Kaveri, 2021), and releasing substantial CO₂. The cement industry accounts for 5-9% of global CO₂ emissions (Kermeli *et al.* 2019; Benhelal

et al. 2021), contributing to climate change. Excessive production also links to cardio-respiratory diseases (Bildirici, 2020). Furthermore, concrete production consumes natural aggregates, causing resource depletion and unsustainable sand extraction (Schneider *et al.* 2011). OPC concrete durability is also concerning, often deteriorating significantly before its design life in corrosive environments (Mehta and Burrows, 2001; Thirukumaran *et al.* 2023; Yadav *et al.* 2025).

Rising cement demand, especially in countries with limited limestone reserves, necessitates alternatives like fly ash (FA) and ground granulated blast furnace slag (GGBS) to conserve resources (Jalal *et al.* 2025a). Recycled aggregates and waste materials can substitute for natural sand and gravel. Geopolymer concrete (GPC), utilizing industrial by-products (FA, GGBS, metakaolin) activated by alkalis (Chiranjeevi *et al.* 2023), offers a sustainable, clinker-less solution (Meskhi *et al.* 2023). Described as revolutionary (Nagaraju *et al.* 2023), GPC significantly reduces CO₂ emissions, utilizes waste, enhances durability, and provides excellent mechanical properties (such as higher compressive strength), lower water absorption, and chemical resistance (Verma *et al.* 2022; Philip and Nidhi, 2023; Rihan *et al.* 2024). Its

dense microstructure minimizes porosity and permeability (Alehyen *et al.* 2017), reducing carbon footprints by using industrial waste (Shilar *et al.* 2022).

Geopolymer chemistry involves the polymerization of aluminosilicate materials in alkaline activators (Almutairi *et al.* 2021), which fundamentally differs from the hydration of OPC (Raj *et al.* 2024). Geopolymers are amorphous aluminosilicate inorganic polymers with a tetrahedral SiO₂ and AlO₂ framework (Davidovits, 1991). The synthesis mechanism involves dissolution of aluminosilicate materials in alkali activators (e.g., NaOH, Na₂SiO₃) at room or elevated temperatures, forming an amorphous 3D silico-aluminate network (Cong and Cheng, 2021). This is followed by condensation and polycondensation, forming a 3D network of N-A-S-H (sodium aluminosilicate hydrate) gel (Amran *et al.* 2021), which is analogous to OPC's C-S-H gel.

While the benefits of conventional FA and GGBS in GPC are well-documented, research on the synergistic effects of their ultrafine counterparts (UFFA and UFGGBS) remains limited. This study aims to address this gap by systematically evaluating the mechanical and durability properties of ambient-cured GPC incorporating UFFA and UFGGBS. The novelty of this work lies in the utilization of these ultrafine materials to enhance reactivity, microstructure, and overall performance, providing a significant advancement towards high-strength, durable, and sustainable concrete alternatives.

2. MATERIALS AND METHODS

This study utilized the following materials:

- Natural Fine Aggregate (NFA) from the Yamuna River, India, conforming to Grading Zone II per IS:383-1970. It had a fineness modulus of 2.86, specific gravity of 2.55, and water absorption of 1.4%.
- Natural Coarse Aggregate (NCA) was locally sourced crushed stone in 12.5 mm and 20 mm sizes. The 12.5 mm aggregate had a fineness modulus of 7.80, specific gravity of 2.63, and absorption of 0.42%. The 20 mm aggregate had a fineness modulus of 8.21, specific gravity of 2.78, and absorption of 0.56%.
- A sulphonated naphthalene formaldehyde-based superplasticizer (conforming to IS:9103--1999/ASTM C494 Type G) was used, enabling 25-30% water reduction.
- Potable water conforming to IS:3025--1986/IS:456--2000 was used for mixing and curing.

- Supplementary cementitious materials included UFFA (specific surface area 526 m²/kg; specific gravity 2.34; conforming to IS 3812:2013) and UFGGBS (D50 3.90 µm; specific surface area 1822 m²/kg; specific gravity 2.82; conforming to IS:16715-2018).
- The alkaline activator consisted of NaOH flakes (98.8% purity) dissolved in water and a sodium silicate solution (Na₂O, 14.70%; SiO₂, 29.40%; specific gravity 1.27).

2.1 Mix Proportion

The concrete mix design was developed by the provisions of IS 10262:2009 for conventional concrete. The proportioning was finalized at 1:1.42:3.14 (binder: fine aggregate: coarse aggregate) with a water-to-binder ratio of 0.45. The total binder content was maintained constant at 400 kg/m³ for all mixes, with only the proportions of UFFA and UFGGBS varied. The calculated material quantities and corresponding mix proportions obtained from the design process are presented in Table 1. In the mix notation, F denotes UFFA and G denotes UFGGBS, where, for example, F100G0 represents a binder comprising 100% UFFA and 0% UFGGBS, F90G10 represents 90% UFFA and 10% UFGGBS, and so forth up to F50G50. The coarse aggregate fraction comprised 20 mm and 12.5 mm aggregates in a blend of 60% and 40%, respectively.

Table 1. Mix proportions for 1 kg/m³ for different blends of geopolymer concrete

Geopolymer Mixture	Fine Aggregate	Coarse Aggregate	Ultrafine Fly Ash	Ultrafine GGBS	NaOH Solution	SiO ₂
F100G0	568	1256	400	0	60	120
F90G10	568	1256	360	40	60	120
F80G20	568	1256	320	80	60	120
F70G30	568	1256	280	120	60	120
F60G40	568	1256	240	160	60	120
F50G50	568	1256	200	200	60	120

All geopolymer mixes were prepared using 10 M sodium hydroxide solution, with a constant sodium silicate-to-sodium hydroxide ratio of 2:1.

3. RESULTS AND DISCUSSION

3.1 Workability of Geopolymer Concrete

Workability refers to how readily fresh concrete can be mixed, transported, and placed into formwork while maintaining uniform composition (Shetty and Jain, 2019). The slump results, representing the workability of geopolymer concrete optimized with varying proportions of ultrafine fly ash (UFFA, F) and ultrafine GGBS (UFGGBS, G), demonstrate a clear trend relative to the control mix F100G0 (100% UFFA).

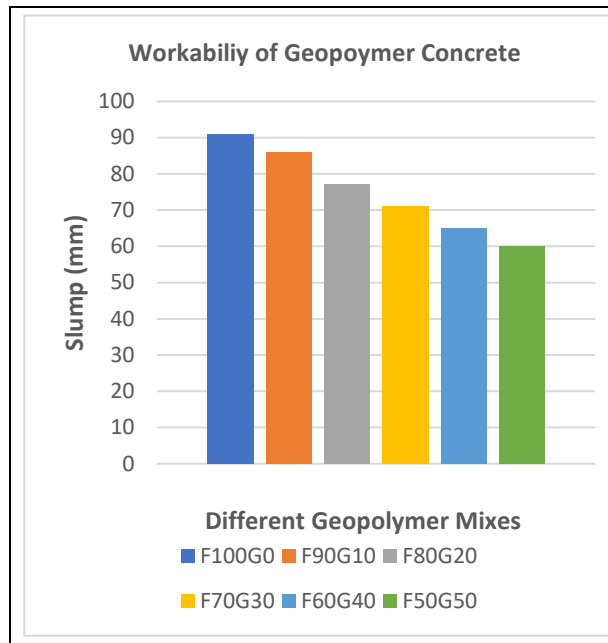


Fig. 1: Workability of different geopolymer mixtures

The control mix F100G0 exhibited a slump of 91 mm. As the proportion of UFGGBS increased from 10% to 50%, replacing UFFA, a progressive reduction in slump was observed: F90G10 (86 mm), F80G20 (77 mm), F70G30 (71 mm), F60G40 (65 mm), and F50G50 (60 mm). This consistent decrease in workability with increasing UFGGBS content is attributed to the intrinsic characteristics of UFGGBS. Compared to UFFA, UFGGBS possesses a lower plasticity and higher water demand due to its finer particle size and larger specific surface area. This is quantitatively supported by the larger specific surface area of UFGGBS (1822 m²/kg) compared to UFFA (526 m²/kg), necessitating additional water for lubrication to achieve consistency, consequently reducing slump.

In contrast, fly ash enhances workability due to its spherical particle shape and lower surface area, which promotes fluidity and reduces water demand. This observed trend of reduced workability with higher UFGGBS proportions aligns with findings reported by (Nath and Sarker, 2014; Bellum *et al.* 2020), reinforcing the relationship between increasing GGBS content and a decrease in slump in geopolymer concrete. Consequently, balancing the proportions of UFFA and UFGGBS is crucial to achieving the target workability while optimizing the mechanical and durability properties for specific applications.

3.2 Compressive Strength

The compressive strength development of geopolymer concrete incorporating UFFA and UFGGBS slag was evaluated over curing periods of 3, 7, 14, 28, 56, and 90 days under ambient conditions, using an alkaline activator solution (10 M NaOH, SS: SH = 2) for mixing, irrespective of water in conventional concrete.

Compressive strength tests were performed on 100 mm cube specimens compliant with IS: 516-1959, and the resultant data are illustrated in Fig. 2. The control mix, F100G0, exhibited poor early-age strength due to the inherently slower reaction kinetics of UFFA under ambient curing, achieving only 8.22 MPa at 3 days. While strength improved progressively over time (reaching 31.51 MPa at 90 days), F100G0 consistently demonstrated the lowest strength across all ages. The introduction of UFGGBS significantly enhanced the performance. The F90G10 mix showed marked improvement (12.24 MPa at 3 days, 41.40 MPa at 90 days), a trend that continued with increasing GGBS content: F80G20 (14.70 MPa at 3 days, 47.46 MPa at 90 days), F70G30 (19.78 MPa at 3 days, 54.84 MPa at 90 days), and F60G40 (22.08 MPa at 3 days, 57.24 MPa at 90 days). The balanced F50G50 mix demonstrated notably high early strength (23.28 MPa at 3 days) and achieved the highest strength within this defined range, reaching 58.20 MPa at 28 days and 61.11 MPa at 56 and 90 days.

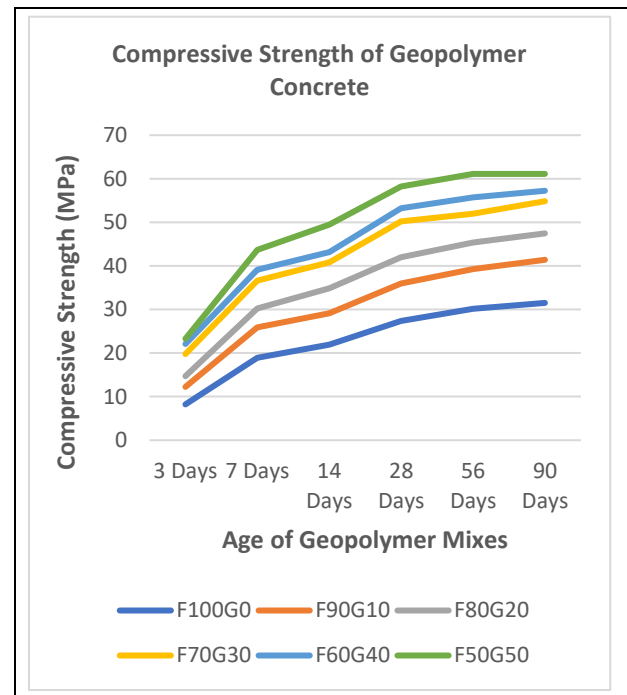


Fig. 2: Compressive strengths of geopolymer mixes

The results demonstrate a systematic increase in compressive strength **across** all curing ages, with increasing proportions of UFGGBS relative to UFFA, from F100G0 up to F50G50. This enhancement is attributed to the higher calcium content in GGBS, which accelerates the geopolymerization reaction under ambient conditions (Jalal and Srivastava, 2025). It contributes to the formation of calcium-aluminate-silicate-hydrate (C-A-S-H) gels alongside the sodium-aluminosilicate-hydrate (N-A-S-H) gel, leading to a denser and stronger microstructure (Jalal *et al.* 2025). Consequently, mixes with higher GGBS content

exhibited more significant early strength gains. All mixes showed progressive strength development with extended curing, highlighting the importance of curing duration for ongoing geopolymerization. The superior performance of mixes like F50G50 aligns with observations by (Ahamed *et al.* 2024; Bellum *et al.* 2020; Rajini and Rao, 2014) regarding the positive correlation between GGBS content and compressive strength in geopolymer systems. However, the use of ultrafine materials in this study (UFFA and UFGGBS) likely enhances reactivity compared to coarser materials used in some referenced works, potentially contributing to the strong performance observed, particularly in the F50G50 mix, and underscoring the critical role of material fineness. This observation also highlights the complexity of the relationship where factors like precursor fineness significantly influence the geopolymerization process and resultant strength.

3.3 Flexural Strength

Flexural strength of ambient-cured geopolymer concrete (incorporating UFFA and GGBS blends from F100G0 to F50G50) was evaluated using $100 \times 100 \times 500$ mm beams tested via three-point bending per IS:516-1959 at 14 and 28 days. Using the fly ash-dominant mix F100G0 as the control (2.98 MPa at 14 days; 3.72 MPa at 28 days), a significant progressive enhancement in flexural strength was observed with increasing UFGGBS content. This control mix exhibited the lowest strength, attributable to the slower reaction kinetics of fly ash under ambient curing conditions. Introducing 10% GGBS (F90G10) substantially improved strength to 4.20 MPa (14 days) and 5.04 MPa (28 days). Further increments in GGBS proportion yielded consistent gains: F80G20 reached 4.88 MPa (14 days) and 5.88 MPa (28 days), F70G30 achieved 5.92 MPa (14 days) and 7.27 MPa (28 days), and F60G40 attained 6.30 MPa (14 days) and 7.6 MPa (28 days). The balanced mix F50G50 demonstrated the highest strength within this evaluated range, achieving 7.42 MPa at 14 days and 8.73 MPa at 28 days.

These results reinforced that increasing the proportion of ultrafine GGBS within the ultrafine fly ash-ultrafine GGBS binder matrix significantly enhances flexural strength. This trend aligns with findings reported by (Nath and Sarker, 2017; Ahamed *et al.* 2024) for geopolymers using conventional fly ash and GGBS, underscoring the beneficial impact of higher GGBS content, particularly in its ultrafine form, on the mechanical performance of GPC. The optimal performance of the F50G50 mix highlights its potential as a favorable formulation for general construction applications requiring reliable strength under ambient curing.

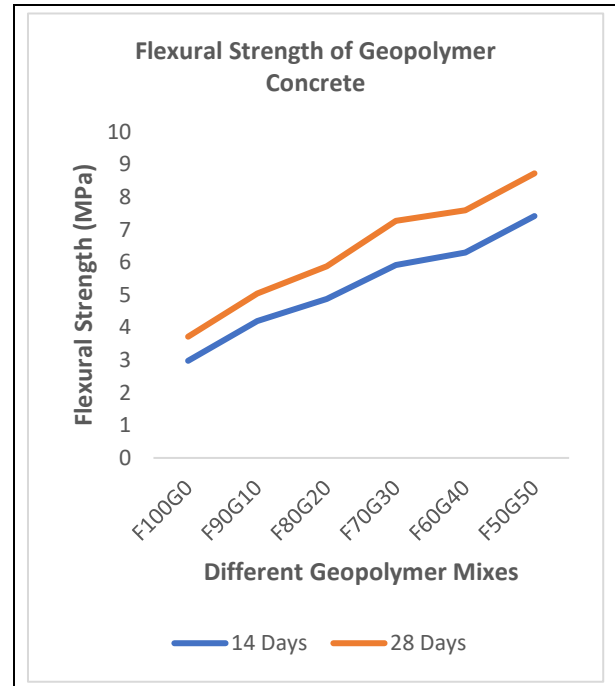


Fig. 3: Flexural strengths of geopolymer mixes

3.4 Split-tensile Strength

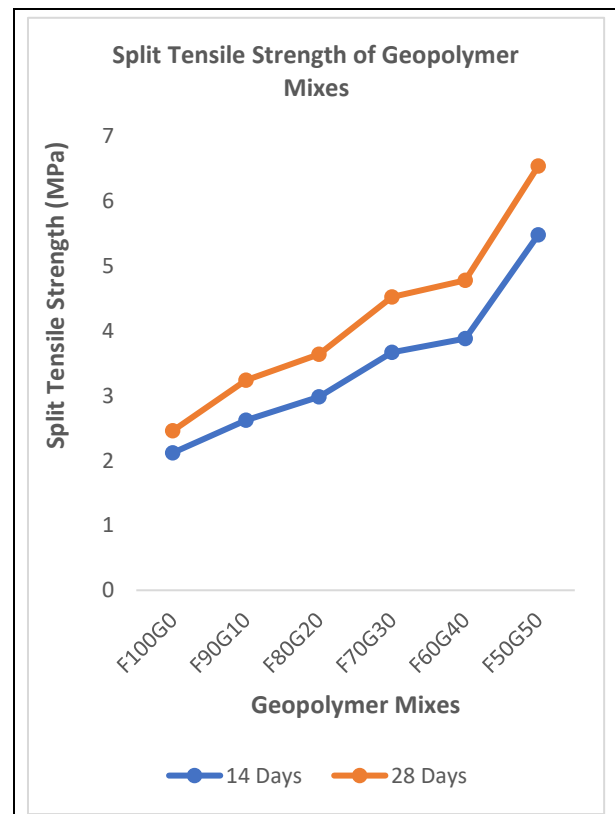


Fig. 4: Split-tensile strengths of UFFA-UFGGBS geopolymer concrete mixtures

Split-tensile strength was tested on 100×200 mm cylinders according to IS:5816 (1999) at 14 and 28 days of curing. The control mixture (F100G0)

demonstrated the lowest split-tensile strength of 2.46 MPa at 28 days, due to the slow pozzolanic reactivity of UFFA in the absence of UFGGBS. Incremental replacement of UFFA with UFGGBS significantly improved strength, with F90G10 (10% UFGGBS) showing a 32% increase to 3.24 MPa, F80G20 (20% UFGGBS) achieving a 48% rise to 3.64 MPa, and F70G30 (30% UFGGBS) exhibiting an 84% surge to 4.52 MPa, exceeding the control by 1.84 times. These results demonstrate a strong positive correlation between UFGGBS content and split-tensile strength (Figure 4). The acceleration in geopolymerization kinetics and refined microstructure due to UFGGBS's high reactivity (Ahamed *et al.* 2024) underpins this trend. Notably, mixtures with $\geq 30\%$ UFGGBS (F70G30–F50G50) outperformed the control by $\geq 84\%$, highlighting UFGGBS's critical role in optimizing tensile properties.

The findings align with a study linking slag content to strength augmentation in geopolymer systems (Rajini and Rao, 2014). However, this study specifically establishes the efficacy of ultrafine precursors (UFFA-UFGGBS) in enhancing tensile performance, with F50G50 emerging as the optimal blend.

3.5 Water Absorption

This study evaluated the 24-hour water absorption of geopolymer concrete blends incorporating ultrafine binders. ASTM C 642-13 guidelines were followed for the water absorption test. Concrete cubes (100 mm) were oven-dried, cooled to room temperature, and submerged in water for 24 hours. Results demonstrate a systematic reduction in water absorption with increasing GGBS content relative to the fly ash-based control mix (F100G0).

The control mix (F100G0) exhibited 4.28% water absorption. Progressive substitution of fly ash with ultrafine GGBS significantly reduced absorption, with F50G50 achieving the lowest value (3.05%), representing a 28.74% reduction vs. the control. This inverse relationship between GGBS content and water absorption is visually consolidated in Figure 5.

The enhanced impermeability correlates with microstructural refinement from ultrafine GGBS. Its particles efficiently fill capillary pores, reducing matrix permeability (Niyazuddin and Umesh, 2023). The denser geopolymer matrix results from GGBS-driven pozzolanic reactions, yielding superior microstructural refinement compared to fly ash-dominated systems (Nagajothi and Elavenil, 2021). These findings align with (Ahamed *et al.* 2024), who reported reduced absorption in GGBS-incorporated geopolymers, though material fineness and mix designs differ.

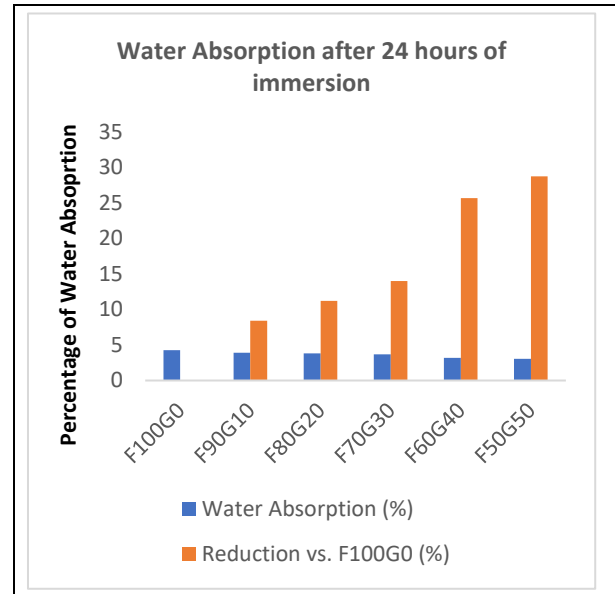


Fig. 5: Water absorption of UFFA-UFGGBS geopolymer blends

3.6 Sorptivity

Cylindrical specimens (100 mm × 50 mm) were preconditioned by oven-drying at 50 °C for 7 days. Electrician's tape sealed the circumferential surfaces, while the two end faces remained unsealed for suction testing. Sorptivity analysis revealed distinct water absorption behaviors between the control mix (F100G0) and slag-modified geopolymer concretes (F90G10–F50G50). Cumulative water absorption (I) in cm and sorptivity coefficients in ($\text{mm}/\text{min}^{0.5}$) decreased progressively with increasing slag substitution (Figure 6).

The control mix (F100G0) exhibited the highest absorption ($I = 0.175$ cm at 120 min) and sorptivity ($0.149 \text{ mm}/\text{min}^{0.5}$). A marked reduction occurred with incremental slag addition: F50G50 showed 43% lower absorption and 57% lower sorptivity vs. F100G0. This inverse relationship between slag content and water ingress is further illustrated in Figure 7, which integrates all sorptivity data.

The enhanced impermeability with slag content is attributed to microstructural refinement, where finer slag particles reduce pore connectivity more effectively than fly ash (Yilmazoglu *et al.* 2024), and reaction chemistry, where slag-rich geopolymers form denser aluminosilicate gels compared to the porous C-S-H phases in OPC systems (Hossain *et al.* 2020). These results demonstrate that slag content critically governs sorptivity by densifying the matrix, highlighting geopolymer concretes' suitability for durability-critical applications such as marine infrastructure.

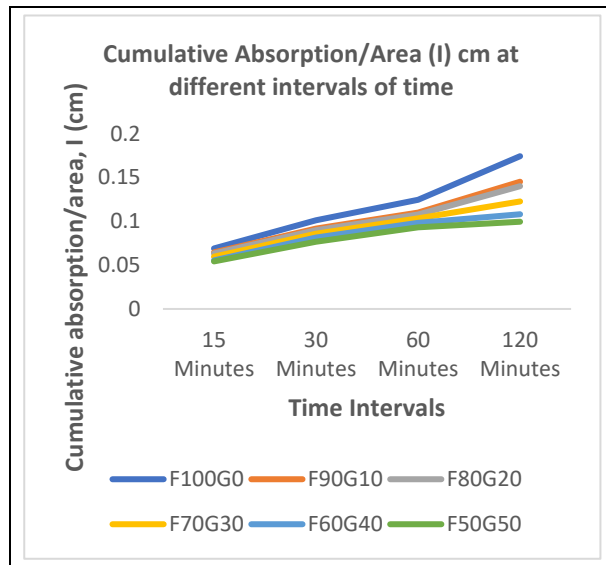


Fig. 6: Cumulative absorption/area (I) at various time intervals

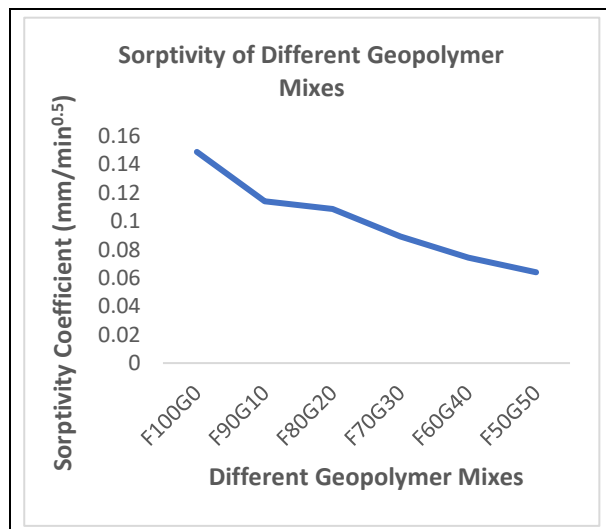


Fig. 7: Sorptivity of different geopolymer concrete mixtures

4. CORRELATION OF MECHANICAL PROPERTIES

4.1 Relationship Between Compressive and Flexural Strength

The 28-day compressive and flexural strengths of geopolymer concrete mixes were experimentally evaluated. Results demonstrate a consistent increase in both properties with compositional changes (e.g., higher compressive/flexural strength in F50G50 vs. F100G0).

A predictive model for flexural strength was evaluated against experimental results. The percentage error was calculated using the formula:

$$\text{Error (\%)} = \frac{[(\text{Predicted Value} - \text{Experimental Value}) / \text{Experimental Value}] \times 100}{\dots} \quad (1)$$

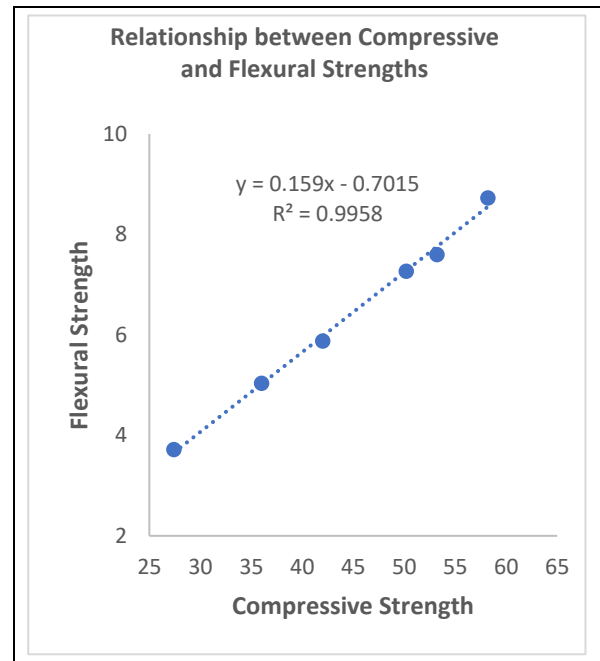


Fig. 8: Relationship between compressive and flexural strengths

The results show very low deviations for all mixes, with errors remaining within $\pm 2.1\%$. The maximum error was observed for the control mix (F100G0) at 1.88%, while the minimum occurred for F70G30 at -0.14% , indicating excellent predictive accuracy across the range of compositions under study.

Both compressive and flexural strengths demonstrated consistent growth with increasing UFGGBS content, rising from 27.40 MPa to 58.20 MPa for compressive strength and from 3.72 MPa to 8.73 MPa for flexural strength between the lowest and highest grades. The predicted values closely matched the experimental data for all mixes (errors $\leq \pm 2.1\%$), confirming the reliability of the model. The marginally higher errors in the control and high-strength extremes suggest slight compositional sensitivity, but the overall strong correlation between compressive and flexural strength supports the robustness of the model for intermediate to high-strength geopolymer concretes. This confirms a strong correlation between compressive and flexural strength in geopolymer concrete, with the predictive model being robust for intermediate to high-strength formulations. Further refinement is recommended for low-strength mixes.

4.2 Relationship Between Compressive and Split-tensile Strengths

Experimental results for 28-day compressive and split-tensile strengths of geopolymer concrete blends show a clear ascending trend in both properties with increasing GGBS content. Compressive strength increased from 27.40 MPa for F100G0 to 58.20 MPa for F50G50, indicating an enhancement of

112%. Split-tensile strength increased from 2.46 MPa for F100G0 to 6.54 MPa for F50G50, registering a 166% improvement.

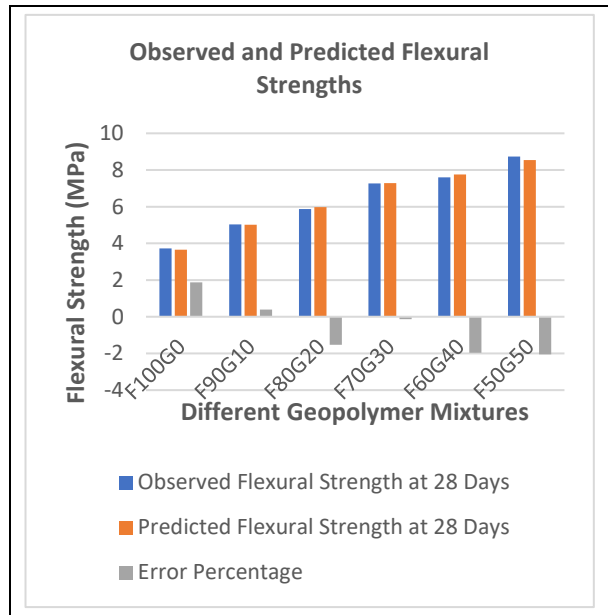


Fig. 9: Observed and predicted flexural strengths and % errors

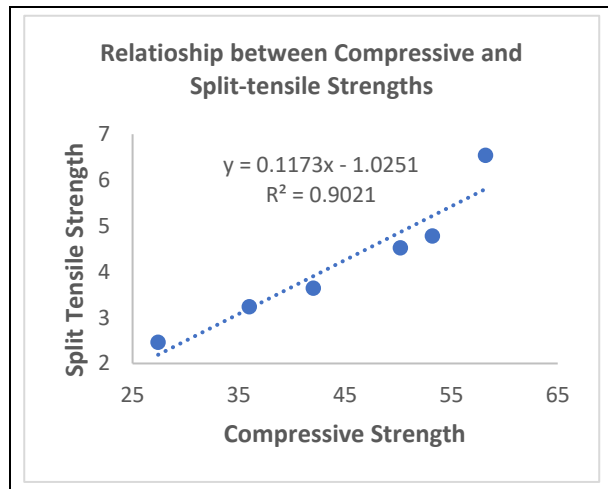


Fig. 10: Relationship between compressive and split-tensile strengths

Predictions of split-tensile strength were derived from empirical models based on compressive strength. Error analysis revealed that predictions for mixes F90G10 (1.54% error) and F100G0 (28% error) were the least and most deviant, respectively. Moderate under-prediction occurred for F80G20 (-7.14%), F70G30 (-7.52%), and F60G40 (-8.99%), while F50G50 was over-predicted (11.31%).

Split-tensile strength exhibited a near-linear relationship with compressive strength ($R^2 = 0.93$), following the trend. GGBS incorporation significantly enhanced both compressive and tensile properties due to improved microstructure and binding phases. The steep

rise in split-tensile strength (166%) relative to compressive strength (112%) suggests GGBS disproportionately improves tensile resistance, likely due to refined interfacial transition zones. Empirical models underestimated the tensile strength for mid-range blends (F60G40–F80G20) by 7–9% but overestimated fly-ash-dominant mixes (F100G0). This highlights the need for mix-specific calibration when predicting tensile strength from compressive strength in geopolymer systems. These results underscore the importance of binder composition in optimizing the mechanical synergy between compressive and tensile properties in geopolymer concrete.

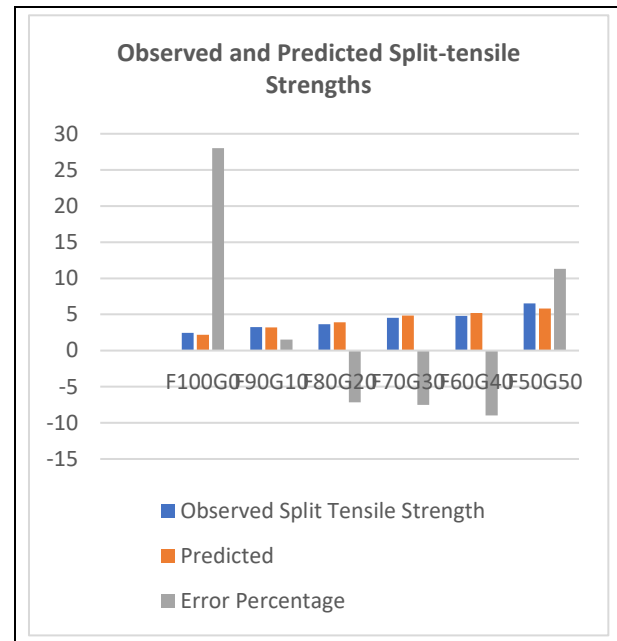


Fig. 11: Observed and predicted split-tensile strengths and % errors

5. CONCLUSION

This study demonstrates that ultrafine fly ash–ultrafine GGBS-based geopolymer concrete, cured under ambient conditions, is a high-strength, durable, and eco-efficient alternative to OPC, with the potential for substantial CO₂ reduction and resource conservation. Compared to ultrafine fly ash-only mixes, the inclusion of ultrafine GGBS significantly enhanced performance, with a balanced 50:50 UFFA–UFGGBS blend achieving the highest 28-day compressive, flexural, and split-tensile strengths and lowering water absorption and sorptivity markedly. These improvements are attributed to refined pore structure and the formation of dense N-A-S-H and C-A-S-H gels. Strong correlations among compressive, flexural, and tensile strengths underscore the mechanical synergy attainable through optimized binder composition, confirming ultrafine precursor-based GPC as a viable solution for sustainable, high-

performance construction. Future research could explore the long-term durability under various aggressive environments, the economic feasibility of large-scale production, and the use of other ultrafine industrial wastes.

FUNDING

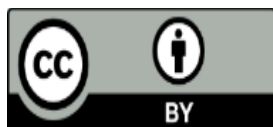
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).



REFERENCES

- Ahamed, S., Islam, M. H., Rafiq, F., Hossain, M. N. and Islam, M. B., Utilization of GGBS, Fly Ash, and Recycled Aggregates for Sustainable Geopolymer Concrete: A Carbon Reduction Approach, *Int. Conf. Adv. Civ. Infrastruct. Constr. Mater.*, 512, 177-185(2024).
https://doi.org/10.1007/978-3-031-63280-8_19
- Alehyen, S., Achouri, M. E. and Taibi, M., Characterization, microstructure and properties of fly ash-based geopolymer, *J. Mater. Environ. Sci.*, 8(5), 1783-1796(2017).
- Almutairi, A. L., Tayeh, B. A., Adesina, A., Isleem, H. F. and Zeyad, A. M., Potential applications of geopolymer concrete in construction: A review, *Case Stud. Constr. Mater.*, 15, e00733(2021).
<https://doi.org/10.1016/j.cscm.2021.e00733>
- Bellum, R. R., Muniraj, K. and Madduru, S. R. C., Exploration of mechanical and durability characteristics of fly ash-GGBFS based green geopolymer concrete, *SN Appl. Sci.*, 2(5), 919(2020).
<https://doi.org/10.1007/s42452-020-2720-5>
- Benhelal, E., Shamsaei, E. and Rashid, M. I., Challenges against CO₂ abatement strategies in cement industry: A review, *J. Environ. Sci.*, 104, 84-101(2021).
<https://doi.org/10.1016/j.jes.2020.11.020>
- Bildirici, M. E., The relationship between cement production, mortality rate, air quality, and economic growth for China, India, Brazil, Turkey, and the USA: MScBVAR and MScBGC analysis, *Environ. Sci. Pollut. Res.*, 27(2), 2248-2263(2020).
<https://doi.org/10.1007/s11356-019-06586-w>
- Chiranjeevi, K., Abraham, M., Rath, B. and Praveenkumar, T. R., Enhancing the properties of geopolymer concrete using nano-silica and microstructure assessment: a sustainable approach, *Sci. Rep.*, 13(1), 17302(2023).
<https://doi.org/10.1038/s41598-023-44491-y>
- Cong, P. and Cheng, Y., Advances in geopolymer materials: A comprehensive review, *J. Traffic Transp. Eng.*, 8(3), 283-314(2021).
<https://doi.org/10.1016/j.jtte.2021.03.004>
- Davidovits, J., Geopolymers: inorganic polymeric new materials, *J. Therm. Anal. Calorim.*, 37(8), 1633-1656(1991).
<https://doi.org/10.1007/bf01912193>
- DeAzevedo, A. R. G., Marvila, M. T., Tayeh, B. A., Cecchin, D., Pereira, A. C. and Monteiro, S. N., Technological performance of açai natural fibre reinforced cement-based mortars, *J. Build. Eng.*, 33, 101675(2021).
<https://doi.org/10.1016/j.jobbe.2020.101675>
- Gopalakrishnan, R. and Kaveri, R., Using graphene oxide to improve the mechanical and electrical properties of fiber-reinforced high-volume sugarcane bagasse ash cement mortar, *Eur. Phys. J. Plus.*, 136(2), 202(2021).
<https://doi.org/10.1140/epjp/s13360-021-01179-4>
- Hossain, M. M., Karim, M. R., A Elahi, M. M. and Zain, M. F. M., Water absorption and sorptivity of alkali-activated ternary blended composite binder, *J. Build. Eng.*, 31, 101370(2020).
<https://doi.org/10.1016/j.jobbe.2020.101370>
- Imbabi, M. S., Carrigan, C. and McKenna, S., Trends and developments in green cement and concrete technology, *Int. J. Sustainable Built Environ.*, 1(2), 194-216(2012).
<https://doi.org/10.1016/j.ijbsbe.2013.05.001>
- Imtiaz, L., Rehman, S. K. U., Memon, S. A., Khan, M. K. and Javed, M. F., A review of recent developments and advances in eco-friendly geopolymer concrete, *Appl. Sci.*, 10(21), 7838(2020).
<https://doi.org/10.3390/app10217838>
- Jalal, P. S. and Srivastava, V., Exploring the Synergy of Fly Ash and GGBS in Geopolymer Concrete: A Review, *Int. J. Adv. Eng. Manage.*, 7(4), 714-728(2025).
<https://doi.org/10.35629/5252-0704714728>
- Jalal, P. S., Srivastava, V. and Tiwari, A. K., A Critical Review of Geopolymer Concrete: Mechanisms, Mix Design Methodologies, and Circular Economy Potentials, *J. Archit. Civ. Eng.*, 10(7), 84-95(2025a).
<https://doi.org/10.35629/8193-10078495>
- Jalal, P. S., Srivastava, V. and Tiwari, A. K., Geopolymer Concrete: An Alternative to Conventional Concrete for Sustainable Construction, *J. Environ.*

- Nanotechnol.*, 13(4), 218-225(2025).
<https://doi.org/10.13074/jent.2024.12.2441122>
- Jalal, P. S., Srivastava, V. and Tiwari, A. K., Portland Cement at the Crossroads: Environmental Imperatives and Pathways to Sustainable Production, *J. Mech. Civ. Eng.*, 22(4), 1–10(2025b).
<https://doi.org/10.9790/1684-2204010110>
- Kermeli, K., Edelenbosch, O. Y., Graus, W. C., Ruijven, B. J. V., Mima, S., Vuuren, D. P. V. and Worrell, E., The scope for better industry representation in long-term energy models: Modeling the cement industry, *Appl. Energy*, 240, 964-985(2019).
<https://doi.org/10.1016/j.apenergy.2019.01.252>
- Meskhii, B., Beskopylny, A. N., Stel'makh, S. A., Shcherban', E. M., Mailyan, L. R., Shilov, A. A., El'shaeva, D., Shilova, K., Karalar, M., Aksoylu, C. and Özkılıç, Y. O., Analytical review of geopolymers concrete: Retrospective and current issues, *Mater.*, 16(10), 3792(2023).
<https://doi.org/10.3390/ma16103792>
- Monteiro, P. J. M., Miller, S. A. and Horvath, A., Towards sustainable concrete, *Nat. Mater.*, 16(7), 698-699(2017).
<https://doi.org/10.1038/nmat4930>
- Nagajothi, S. and Elavenil, S., Effect of GGBS addition on reactivity and microstructure properties of ambient cured fly ash-based geopolymer concrete, *Silicon*, 13(2), 507-516(2021).
<https://doi.org/10.1007/s12633-020-00470-w>
- Nagaraju, T. V., Bahrami, A., Azab, M. and Naskar, S., Development of sustainable high performance geopolymer concrete and mortar using agricultural biomass—a strength performance and sustainability analysis, *Front. Mater.*, 10, 1128095(2023).
<https://doi.org/10.3389/fmats.2023.1128095>
- Nath, P. and Sarker, P. K., Effect of GGBFS on setting, workability and early strength properties of fly ash geopolymer concrete cured in ambient condition, *Constr. Build. Mater.*, 66, 163-171(2014).
<https://doi.org/10.1016/j.conbuildmat.2014.05.080>
- Nilimaa, J., Smart materials and technologies for sustainable concrete construction, *Dev. Built Environ.*, 15, 100177(2023).
<https://doi.org/10.1016/j.dibe.2023.100177>
- Niyazuddin and Umesh, B., Mechanical and durability properties of standard and high strength geopolymer concrete using particle packing theory, *Constr. Build. Mater.*, 400, 132722(2023).
<https://doi.org/10.1016/j.conbuildmat.2023.132722>
- Philip, S. and Nidhi, M., A review on the material performance of geopolymer concrete as green building materials, *Mater. Today: Proc.*, XXXX, S221478532301996X(2023).
<https://doi.org/10.1016/j.matpr.2023.04.110>
- Rajini, B. and Rao, A. V. N., Mechanical properties of geopolymer concrete with fly ash and GGBS as source materials, *Int. J. Innovative Res. Sci., Eng. Technol.*, 3(9), 15944-15953(2014).
<https://doi.org/10.15680/IJIRSET.2014.0309023>
- Rashad, A. M., Effect of steel fibers on geopolymer properties—the best synopsis for civil engineer, *Constr. Build. Mater.*, 246, 118534((2020)).
<https://doi.org/10.1016/j.conbuildmat.2020.118534>
- Rihan, M. A. M. and Abdalla, T. A., Factors influencing compressive strength in fly ash-based geopolymer concrete: a comprehensive review, *Iran. J. Sci. Technol. Trans. Civ. Eng.*, 48(6), 3853-3869(2024).
<https://doi.org/10.1007/s40996-024-01413-w>
- Rihan, M. A. M., Onchiri, R. O., Gathimba, N. and Sabuni, B., Assessing the durability performance of geopolymer concrete utilizing fly ash and sugarcane bagasse ash as sustainable binders, *Open Ceram.*, 20, 100687(2024).
<https://doi.org/10.1016/j.oceram.2024.100687>
- Schneider, M., Romer, M., Tschudin, M. and Bolio, H., Sustainable cement production—present and future, *Cem. Concr. Res.*, 41(7), 642-650(2011).
<https://doi.org/10.1016/j.cemconres.2011.03.019>
- Shilar, F. A., Ganachari, S. V., Patil, V. B. and Nisar, K. S., Evaluation of structural performances of metakaolin based geopolymer concrete, *J. Mater. Res. Technol.*, 20, 3208-3228(2022).
<https://doi.org/10.1016/j.jmrt.2022.08.020>
- Thirukumaran, T., Krishnapriya, S., Priya, V., Britto, A. S. F., Anandhalakshmi, R., Dinesh, S., Poomalai, R., Vivek, S. and Saravanan, S., Utilizing rice husk ash as a bio-waste material in geopolymer composites with aluminium oxide, *Global NEST J.*, 25(6), 119-129(2023).
<https://doi.org/10.30955/gnj.004694>
- Verma, M., Dev, N., Rahman, I., Nigam, M., Ahmed, M. and Mallick, J., Geopolymer concrete: a material for sustainable development in Indian construction industries, *Cryst.*, 12(4), 514(2022).
<https://doi.org/10.3390/cryst12040514>
- Yadav, A., Srivastava, V., Tiwari, A. K. and Jalal, A. K., Comparative Study on the Durability of Geopolymer and Conventional Concrete under Harsh Environmental and Chemical Exposure Conditions, *J. Archit. Civ. Eng.*, 10(6), 253–264(2025).
<https://doi.org/10.35629/8193-10062534>
- Yilmazoglu, A., Yildirim, S. T., Yıldız, S. and Behçet, O. F., Effect of GGBS content and water/geopolymer solid ratio on the mechanical, elevated temperature resistance, and sorptivity properties of FA/GGBS-based geopolymer concrete, *J. Mater. Civ. Eng.*, 36(4), 04024032(2024).
<https://doi.org/10.1061/JMCEE>