An Experimental Study on GGBS-Fly Ash Geopolymer Concrete: Mechanical Properties and Structural Performance of Reinforced Deep Beams

Nguyen Thien Thanh
Faculty of Civil Engineering, Ho Chi Minh City University of Technology (HCMUT), Ho Chi Minh City, Vietnam | Vietnam National University Ho Chi Minh City, Ho Chi Minh City, Vietnam
ntthanh.sdh21@hcmut.edu.vn

Tran Cao Thanh Ngoc
School of Civil Engineering and Management, International University, Ho Chi Minh City, Vietnam
tctngoc@hcmiu.edu.vn

Nguyen Tan Khoa
Institute of Research and Development, Duy Tan University, Da Nang, Vietnam | Faculty of Civil Engineering, Duy Tan University, Da Nang, Vietnam
nguyentankhoa@duytan.edu.vn

Le Anh Tuan
Faculty of Civil Engineering, Ho Chi Minh City University of Technology (HCMUT), Ho Chi Minh City, Vietnam | Vietnam National University Ho Chi Minh City, Ho Chi Minh City, Vietnam
latuan@hcmut.edu.vn (corresponding author)

Received: 19 April 2026 | Revised: 28 May 2026 | Accepted: 5 June 2026

ABSTRACT

The shift from Ordinary Portland Cement (OPC) to geopolymer concrete offers significant environmental advantages. However, its application to shear-critical structural elements, such as reinforced deep beams, remains insufficiently researched. This experimental study investigates the mechanical properties and structural performance of Ground Granulated Blast-furnace Slag (GGBS)-fly ash geopolymer concrete with alkaline liquid-to-geopolymer (AL/GS) ratios of 0.7, 0.8, and 0.9. The compressive strength, indirect tensile strength, and behavior of reinforced deep beams were evaluated under ambient and heat-cured conditions. The results showed that an AL/GS ratio of 0.7 yielded the highest compressive strength, 65.7 MPa at 90 days, under ambient curing. The deep beam tests revealed that a reduction in the 28-day compressive strength from 59 MPa (AL/GS = 0.7) to 42 MPa (AL/GS = 0.9) caused a dramatic 68% drop in the ultimate load-carrying capacity (from 325 to 108 kN). This pronounced sensitivity is attributed to the primary strut-and-tie mechanism, where higher compressive strength significantly enhances the efficiency of the concrete strut. The geopolymer concrete also exhibited more brittle tensile behavior compared to conventional predictive models. These findings highlight the importance of optimizing the AL/GS ratio to achieve high and uniform compressive strength for the safe structural application of GGBS-fly ash geopolymer concrete in shear-critical structural members.

Keywords-geopolymer concrete; compressive strength; indirect tensile strength; structural performance; deep beam

I. INTRODUCTION

The conceptual framework for geopolymers was first introduced in 1979 by Professor Davidovits [1]. He introduced the term to describe a group of mineral binders possessing a polymeric silicon-oxygen-aluminum framework. Unlike Ordinary Portland Cement (OPC), which relies on the hydration of calcium silicates, geopolymer concrete is synthesized through the polycondensation of aluminosilicate-rich source materials activated by highly alkaline solutions, typically a mixture of sodium hydroxide and sodium silicate [2]. This chemical process creates an amorphous to semi-crystalline three-dimensional polymeric structure that binds aggregates together with extreme efficiency [3].

Compared with traditional OPC concrete, geopolymer concrete has numerous advantages. Geopolymer binders offer major environmental benefits by reducing greenhouse gas emissions through the utilization of industrial waste rather than relying on limestone calcination [4]. In terms of mechanical behavior, geopolymer concrete is characterized by rapid early-age strength development [5], negligible creep and shrinkage [6, 7], and exceptional stability at elevated temperatures [8]. Additionally, the unique chemistry of geopolymers makes them highly resistant to sulfates and acids [9, 10], ensuring durability in demanding infrastructure applications [11].

Despite their superior properties, the commercial viability of early geopolymer concrete was historically limited by the necessity of specific curing regimes. Because the polymerization process requires thermal activation, geopolymers formulated solely with Class F fly ash must typically be cured at elevated temperatures [12]. While feasible for precast concrete elements, this thermal requirement renders pure fly ash geopolymers impractical for cast-in-situ construction. To overcome this limitation, research has focused on blended precursor systems, particularly combining Ground Granulated Blast-furnace Slag (GGBS) with fly ash.

The incorporation of GGBS into a fly ash-based geopolymer matrix yields a highly synergistic effect. Due to its high calcium content, GGBS fundamentally modifies the reaction kinetics; the dissolution of calcium ions in the alkaline medium facilitates the co-precipitation of both aluminosilicate (N-A-S-H) and calcium silicate hydrate (C-A-S-H) gels [13]. This dual-gel system enables ambient curing while creating a denser and less permeable matrix. Consequently, GGBS-fly ash geopolymer concrete is practical for on-site applications and often exhibits mechanical properties that are superior to those of high-strength OPC [14].

While the basic material and microstructural properties of GGBS-fly ash geopolymers are well understood, their use in complex structural applications demands rigorous macro-scale testing. In modern heavy civil engineering, reinforced deep beams serve as critical load-bearing elements in structures such as pile caps and transfer girders. Distinguished by their low span-to-depth ratios, these beams are governed by non-linear strain profiles and transmit loads primarily through a strut-and-tie mechanism, deviating significantly from conventional flexural behavior.

Due to this complex internal stress distribution, the overall structural performance of deep beams is intrinsically linked to the shear capacity, compressive strength, and cracking resistance of the constituent concrete matrix. Currently, the literature lacks comprehensive studies on reinforced deep beams cast from GGBS-fly ash geopolymer concrete. Although the shear and flexural mechanisms of OPC deep beams have been thoroughly codified, extrapolating these models to geopolymer elements is theoretically flawed, given their distinct chemical matrices, variable strength ratios, and unique reinforcement bonding behavior. Existing research has focused on low-calcium geopolymer flexure, leaving a gap regarding shear-critical deep beams cast from high-slag, single-activator Na_2SiO_3 only binders. Because altered microstructural cracking makes standard findings invalid for these systems, this study investigates how high alkaline liquid-to-geopolymer solid (AL/GS) ratios dictate the internal concrete compressive strut mechanism under severe shear. Therefore, the present experimental study was designed to systematically address this significant research gap. This research aims to characterize the mechanical properties of an optimized GGBS-fly ash geopolymer mix (such as compressive strength and indirect tensile strength) and, more importantly, to evaluate the flexural and shear behaviors of the corresponding reinforced deep beams.

II. EXPERIMENTAL PROGRAM

A. Material and Mixture Proportions

The experimental work was performed using fly ash and GGBS as binders, an alkali solution, and fine and coarse aggregates. The specific gravity and fineness of GGBS were 2.55 g/cm^3 and 3600 cm^2/g, respectively. Class F fly ash with a specific gravity of 2.5 g/cm^3 was used. The chemical compositions of fly ash and GGBS are shown in Table I.

TABLE I. CHEMICAL COMPOSITION OF FLY ASH AND GGBS

Oxide (%)	Fly ash	GGBS
SiO_2	51.7	35.9
Al^2O_3	31.9	13
Fe_2O_3	3.48	-
CaO	1.21	38.13
K_2O & Na_2O	1.02	1.01
MgO	0.81	7.5
SO_3	0.25	-
Loss on Ignition (LOI)	9.63	1.15

The alkali solution is usually a combination of sodium silicate and sodium hydroxide solutions. However, in the current study, only sodium silicate (Na_2SiO_3) solution was used for mixing with the solid. The modulus ratio ($Ms = SiO_2/Na_2O$, $Na_2O=8.37\%$, $SiO_2=27.63\%$) of the Na_2SiO_3 solution was 3.3. Aggregates, including stone as Coarse Aggregates (CA) of 15 mm and river sand as Fine Aggregates (FA), were mixed at a 2:1 mass ratio. The specific gravity of CA is 2700 kg/m^3 and 2650 kg/m^3 for FA. The details of the mixture proportions by mass ratio are provided in Table II. The three geopolymer concrete mixtures are designated as GCB1, GCB2, and GCB3, corresponding to AL/GS ratios of 0.7, 0.8, and 0.9, respectively. The mix design was developed based on extensive preliminary trials aimed at achieving high compressive strength >50 MPa after 28 days, while maintaining acceptable workability for structural applications. The fly ash:GGBS ratio was fixed at 20:80 by mass. The AL/GS ratio was systematically varied (0.7, 0.8, and 0.9) to investigate its influence on both fresh and hardened properties. This range was selected because ratios below 0.7 resulted in poor workability, whereas ratios above 0.9 led to excessive bleeding and strength reduction in the trial mixes.

TABLE II. MIXTURE PROPORTIONS GIVEN IN MASS RATIOS

Mixture	Fly ash	GGBS	AL	CA	FA
GCB1	1	4	3.5	10	5
GCB2	1	4	4	10	5
GCB3	1	4	4.5	10	5

B. Sample Preparation and Test Methods

Fly ash and GGBS were quantified as a mix proportion, as depicted in Table II. These two components were mixed for 5 min. Na_2SiO_3 solution was poured into the solids and mixed for 5 min. Finally, CA and FA were added to the slurry and mixed for 3 more min. Fresh geopolymer concrete was cast and compacted into the molds. A series of 45 concrete cylinders with a diameter of 150 mm and a height of 300 mm were cured under ambient conditions to determine the concrete strength with aging. In addition, a series of 18 cylindrical specimens (150 mm × 300 mm) were cured in an oven at 80 °C for 24 h to determine the compressive strength and indirect tensile strength.

The testing program for investigating the mechanical properties and structural performance of the short geopolymer beams is illustrated in Figure 1. Compressive strength tests followed the ASTM C39 [15], whereas the indirect tensile tests were based on the ASTM C496 [16]. Both tests were performed on three 150 × 300 mm cylindrical specimens for each mixture after 28 days of curing.

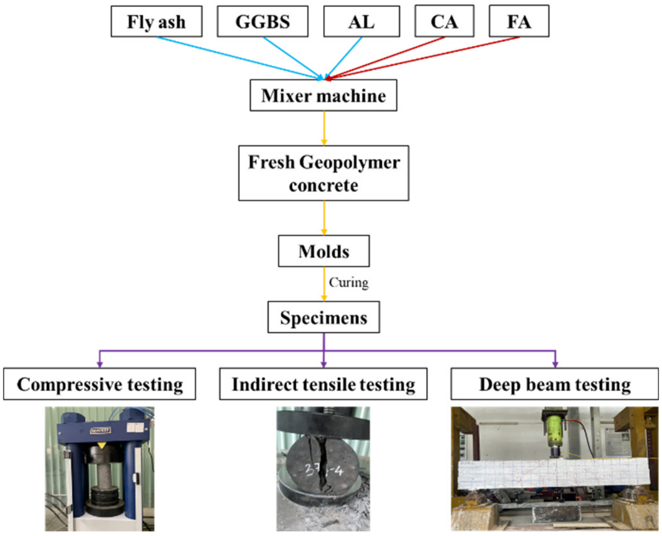

Fig. 1. Experimental process of this study.

The deep geopolymer concrete beams were 200 mm (b) × 400 mm (h) × 2000 mm (L). Geopolymer beams were cast in steel molds and cured in an oven at 80 °C for 24 h. Heat curing was chosen for the deep geopolymer concrete beam to ensure rapid and uniform strength for testing purposes. Besides, the final target of this study was to produce precast articles; thus, this testing program simulated specific precast industry conditions. Prior to casting the fresh geopolymer concrete into the cylinder and beam molds, the workability of each batch was evaluated using a standard slump test in accordance with ASTM C143. The GCB1 mixture (AL/GS = 0.7) exhibited a highly viscous, cohesive, and stiff consistency, yielding a slump value of approximately 50 mm. This limited workability is attributed to the high specific surface area (3600 cm^2/g) and angular morphology of the GGBS particles, which rapidly absorbed free liquid, and early-stage flocculation was accelerated. Conversely, increasing the AL/GS ratio to 0.8 (GCB2) and 0.9 (GCB3) progressively augmented the volume of the fluid phase, resulting in measured slump values of 85 mm and 140 mm, respectively. While GCB3 offered the most effortless placement and compaction around the dense reinforcement cages, it introduced an excess of free water that ultimately compromised the hardened matrix properties. After curing, the beam was placed under ambient conditions and tested at 28 days. The details of the beam are presented in Figure 2. The internal reinforcement layout of the deep geopolymer concrete beams was designed using two distinct types of steel bars, as illustrated in the schematic detailing (Figure 2). High-yield deformed steel bars with a nominal diameter of 22 mm (D22) were utilized for the primary longitudinal tension reinforcement, while 18 mm (D18) bars were used in the compression zone. Deformed steel bars with a nominal diameter of 8 mm spaced at 100 mm centers (D8@100) served as the shear stirrups. Uniaxial tensile testing was performed on representative steel coupons to establish their actual mechanical profiles. The reinforcement steel exhibited a nominal yield strength (f_y) of ≥ 300 MPa and a minimum ultimate tensile strength (f_u) ≥ 450 MPa. These material properties ensured that the internal steel links (ties) possessed adequate capacity to sustain the structural truss mechanism without premature yielding before the concrete compressive strut reached its ultimate capacity.

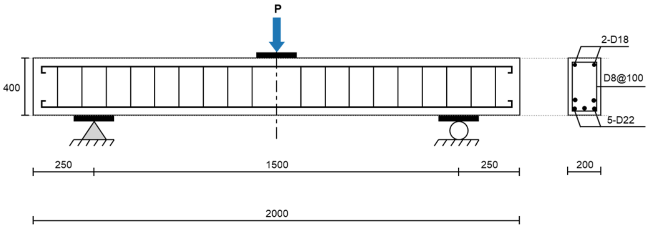

Fig. 2. Details of the short geopolymer concrete beam.

The deep beam internal reinforcement configuration was designed to ensure an explicit shear-critical failure mode while preventing premature flexural or anchorage debonding. The longitudinal tension steel consisted of 5-D22 bars, whereas the compression zone utilized 2-D18 bars. To combat severe local shear stresses along the short span, web reinforcement was provided via tight D8 stirrups spaced uniformly at 100 mm centers. To prevent anchorage pull-out failure within the short shear span, all longitudinal bars were detailed with 90° standard structural hooks anchored securely past the support centerlines, ensuring perfect strain transfer within the strut-and-tie zone.

III. RESULTS AND DISCUSSION

A. Influence of AL/GS Ratio on Compressive Strength of Geopolymer Concrete

Figure 3 demonstrates the development of compressive strength over time for fly ash and GGBS-based geopolymer concrete cured under ambient conditions. The compressive strength was evaluated across three mixtures, GCB1, GCB2, and GCB3, with different AL/GS ratios of 0.7, 0.8, and 0.9, respectively.

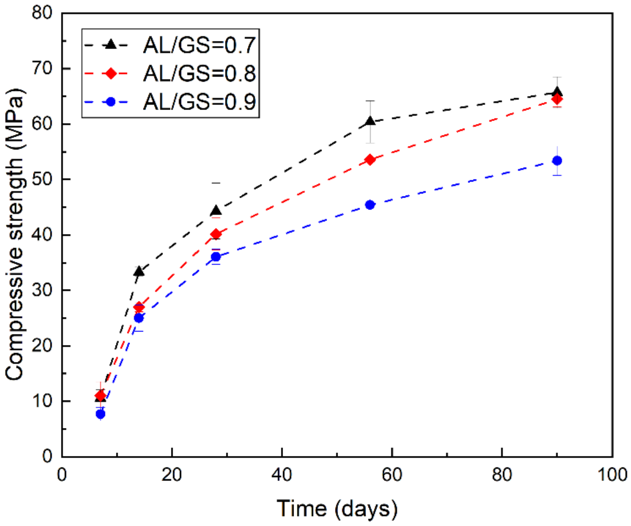

Fig. 3. Relationship between AL/GS ratio and compressive strength of the geopolymer concrete.

As shown in Figure 3, all mixtures exhibited a rapid strength gain during the early curing period (particularly from 7 to 28 days), followed by a slower but continued increase up to 90 days. The GCB1 (AL/GS = 0.7) mixture consistently achieved the highest compressive strength at all testing ages, reaching approximately 65.7 MPa at 90 days. In comparison, the GCB2 (AL/GS = 0.8) and GCB2 (AL/GS = 0.9) mixtures attained lower strengths of about 64.5 MPa and 53.4 MPa, respectively, at the same age. In the case of an AL/GS = 0.7 mixture, the compressive strength increased by 22.8 MPa from 7 to 14 days and by 11 MPa from 14 to 28 days. After 28 days, the strength growth slowed significantly, with only a 16.1 MPa increase from 28 to 56 days and a 5.3 MPa increase from 56 to 90 days, ultimately reaching about 65.7 MPa at 90 days.

Similarly, the AL/GS = 0.8 mixture exhibited a sharp rise of 16 MPa between 7 and 14 days and 13.15 MPa between 14 and 28 days. Later stages showed slower development, with increases of 13.43 MPa (28–56 days) and 10.9 MPa (56–90 days), achieving approximately 64.5 MPa at 90 days.

For the AL/GS = 0.9 mixture, the strength rose to 17.3 MPa after 7-14 days and 11 MPa from 14 to 28 days, followed by modest gains of 18.36 MPa (28-56 days) and 8 MPa (56-90 days), resulting in a final strength of about 53.4 MPa at 90 days.

The superior performance at AL/GS = 0.7 can be attributed to the optimal balance of alkalinity and silicate content, which promotes the efficient dissolution of aluminosilicates from the precursors and facilitates the formation of a dense, highly cross-linked N-A-S-H and C-(A)-S-H gel network. At higher AL/GS ratios (0.8 and 0.9), excess alkaline activator leads to several detrimental effects: (1) overly rapid geopolymerization reaction, resulting in a less homogeneous microstructure with increased porosity and microcracks, (2) potential formation of crystalline zeolitic phases instead of amorphous binding gels, which reduces the binding efficiency, and (3) surplus free alkali that may remain unreacted, causing efflorescence or weakening the gel structure over time. Consequently, increasing the AL/GS ratio beyond the optimum value of 0.7 resulted in a noticeable decline in both early-age and long-term compressive strength.

B. Influence of AL/GS Ratio on Indirect Tensile Strength of Geopolymer Concrete

The GCB1, GCB2, and GCB3 mixtures were employed with curing conditions of 80 °C for 24 h to assess the impact of the alkaline liquid to geopolymer solid ratio on the indirect tensile strength of fly ash and GGBS-based geopolymer concrete. Figure 4 portrays the correlation between the indirect tensile strength of the geopolymer concrete and the AL/GS ratio.

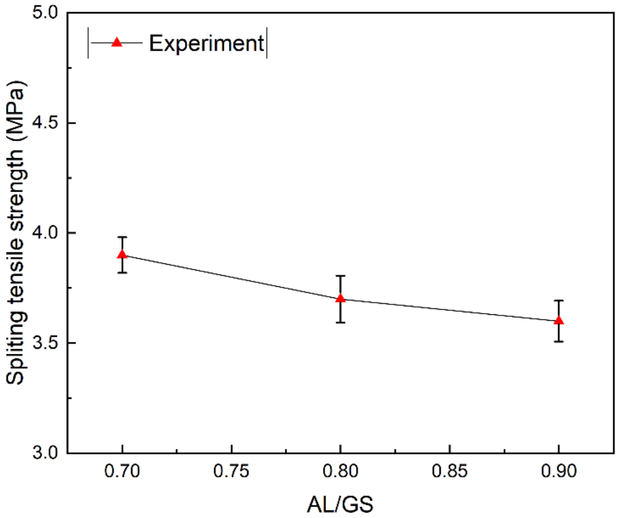

Fig. 4. Relationship between AL/GS ratio and indirect tensile strength of geopolymer concrete.

In Figure 4, the experimental results demonstrate a distinct inverse relationship between the AL/GS ratio and the indirect tensile strength of the fly ash-GGBS geopolymer concrete. As the AL/GS ratio increases from 0.7 to 0.9, the tensile strength decreases from approximately 3.9 MPa to 3.6 MPa. This degradation is fundamentally tied to the microstructural evolution of the geopolymer matrix. Higher AL/GS ratios introduce a larger volume of liquid into the mixture; the excess water that is not consumed during geopolymerization eventually evaporates, leaving behind a network of capillary pores that compromises matrix density and facilitates tensile crack propagation. Furthermore, an elevated liquid content dilutes the alkaline activator, which retards the dissolution of aluminosilicate precursors and reduces the efficiency of N-A-S-H and C-(A)-S-H gel formation. Conversely, the optimized ratio of 0.7 promotes a highly concentrated alkaline environment, resulting in a dense, highly cross-linked binder that effectively bridges the aggregates.

A comparative analysis of the experimental data and established predictive models was conducted. Authors in [17] proposed a formula to predict the indirect tensile strength:

$$f_{ct} = 0.7\sqrt{f_{cm}} \text{ (MPa)} \tag{1}$$

According to the AS 3600-2009 standard [18], the relation between the indirect tensile strength and the compressive strength of OPC concrete can be expressed as:

$$f_{ct} = 0.4\sqrt{f_{cm}} \text{ (MPa)} \tag{2}$$

Authors in [19] proposed using (3) to calculate the indirect tensile strength of geopolymer concrete:

$$f_{ct} = 0.858(f_{cm})^{0.41} \text{ (MPa)} \tag{3}$$

where f_{ct} (MPa) is the tensile strength, and f_{cm} (MPa) is the compressive strength.

A comparison between the current and previous studies is shown in Figure 5. For compressive strengths ranging from 42 MPa to 59 MPa, the experimental indirect tensile strengths were consistently lower than those predicted in [17, 19] but higher than those in [18]. On average, the measured tensile strengths were 24.2% lower than the values calculated from (1), 12.2% lower than the values using (3), and 32.7% higher when (2) was used. This underperformance in tensile strength can be attributed to the activator-to-precursor ratio (AL/GS) optimized primarily for the maximum compressive strength. At AL/GS = 0.7 (corresponding to the highest compressive strength of 59 MPa), the formation of a dense and highly cross-linked N-A-S-H and C-(A)-S-H gel network significantly enhances the compressive capacity but results in a more brittle Interfacial Transition Zone (ITZ) between the paste and aggregates. Under indirect tensile fields, this brittle ITZ lacks the micro-ductility found in low-calcium, fly ash-dominated matrices, causing rapid crack propagation at lower macroscopic tensile thresholds. Higher AL/GS ratios (0.8 and 0.9) further exacerbate this issue by promoting overly rapid geopolymerization, leading to increased microporosity and microcracks within the matrix. Thus, the geopolymer concrete in this study exhibited more brittle tensile behavior compared to low-calcium fly ash-based geopolymers and conventional Portland cement concrete. These findings suggest that separate optimization of the AL/GS ratio or the incorporation of fibers may be necessary to improve the tensile properties of geopolymer concrete for structural applications.

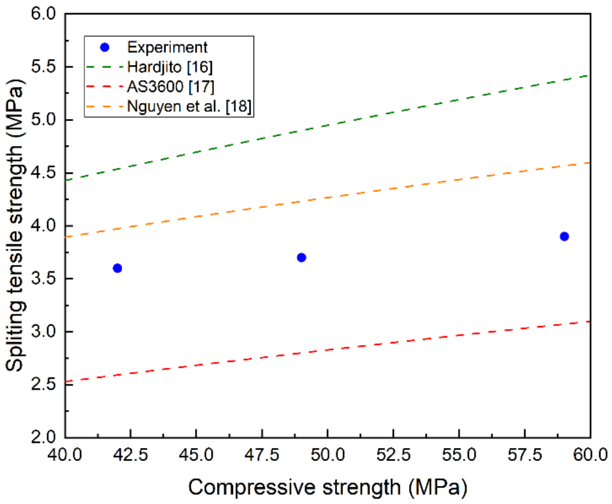

Fig. 5. Comparison between the results of this study and previous studies.

C. Beam Results

The structural behavior of deep geopolymer concrete beams was evaluated by employing three mixtures, GCB1, GCB2, and GCB3, to conduct a three-point bending test. All three beams with identical geometry (b = 200 mm, h = 400 mm, d = 375 mm) and shear span-to-depth ratio (a/d = 2.0) were cured at 80 °C for 24 h and then tested after 28 days. The 28-day compressive strengths varied significantly: 59 MPa (GCB1 with AL/GS=0.7), 49 MPa (GCB2 with AL/GS=0.8), and 42 MPa (GCB3 with AL/GS=0.9). The load-deflection curves of the three deep geopolymer concrete beams are presented in Figure 6.

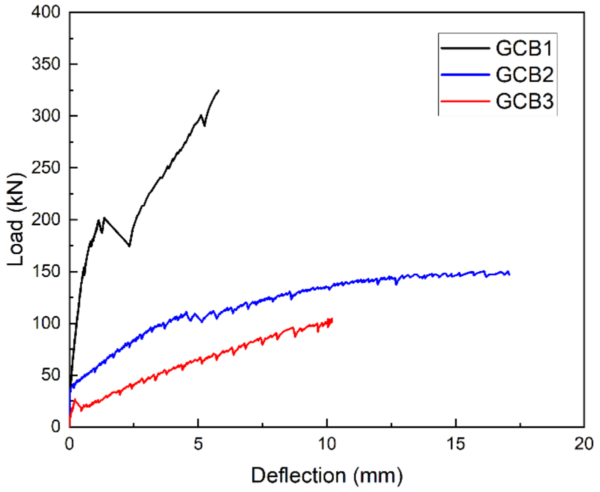

Fig. 6. Load deflection curves of three deep geopolymer concrete beams.

According to Figure 6, the experimental results revealed a strong correlation between compressive strength and beam performance. Beam GCB1, possessing the highest compressive strength of 59 MPa, exhibited superior load-carrying capacity, reaching an ultimate load of approximately 325 kN at a relatively small mid-span deflection of about 5.8 mm. In contrast, GCB2 and GCB3 achieved considerably lower ultimate loads of 150 kN and 108 kN, respectively. This represents a dramatic reduction of more than 68% in ultimate capacity when the compressive strength decreased from 59 MPa to 42 MPa. Although the compressive strength decreased by only 28.8%, the ultimate load capacity reduced by approximately 66.8%, indicating a strongly nonlinear structural response. This disproportionate deterioration demonstrates that deep beam behavior is extremely sensitive to concrete compressive strength because failure is governed primarily by compressive strut integrity rather than reinforcement yielding.

This pronounced effect can be attributed to the dominant strut-and-tie mechanism governing the behavior of deep beams with a low shear span-to-effective depth (a/d) ratio. Here, a represents the shear span (the distance from the application point of the concentrated load to the centerline of the support, measuring 750 mm), and d is the effective depth of the longitudinal tensile reinforcement (375 mm), yielding an a/d ratio of 2.0. Higher compressive strength significantly enhances the capacity of the concrete strut, leading to markedly higher shear resistance and overall stiffness, as evidenced by the steep load-deflection response of GCB1. In contrast, the beams with lower compressive strengths (GCB2 and GCB3) exhibited reduced strut efficiency, resulting in lower ultimate loads and greater reliance on the stirrups and longitudinal reinforcement for post-cracking resistance. Consequently, these beams demonstrated more ductile behavior with larger ultimate deflections.

The experimental results indicate that the compressive strength is a significant parameter that controls both the strength and deformation characteristics of deep geopolymer beams. A relatively small variation in compressive strength can lead to substantial changes in the load-carrying capacity owing to the high sensitivity of the strut-and-tie mechanism to concrete strength. These findings highlight the importance of achieving uniform and high compressive strength in geopolymer concrete when designing shear-critical structures.

Based on the experimental structural performance observed, several practical rules are proposed for structural engineering practice:

- AL/GS control in precast elements: When manufacturing precast shear elements (such as pile caps or transfer girders) using green single-activator geopolymers, the AL/GS mass ratio must be strictly capped at 0.7. Allowing the liquid ratio to drift to 0.9 to ease factory pouring will degrade the structural shear capacity by up to 68%.
- Minimum web reinforcement: Because high-calcium geopolymer matrices show a more brittle tensile failure mode than standard OPC, structural designers should increase the minimum horizontal and vertical web reinforcement ratios by roughly 15–20% above standard ACI 318 baselines to ensure reliable post-cracking load redistribution across the diagonal concrete struts.

IV. CONCLUSIONS

In this study, the mechanical properties of an optimized Ground Granulated Blast furnace Slag (GGBS)-fly ash geopolymer concrete and the structural performance of corresponding reinforced deep beams were systematically evaluated. Based on the experimental results, the following key conclusions can be drawn.

The alkaline liquid to geopolymer solid (AL/GS) ratio significantly influences compressive strength, with the optimal ratio identified as 0.7 (GCB1). This mixture achieved the highest compressive strength at all testing ages, reaching approximately 65.7 MPa at 90 days. Increasing the AL/GS ratio beyond this optimum (to 0.8 or 0.9) leads to a noticeable decline in both early-age and long-term compressive strength. This reduction is due to an overly rapid geopolymerization reaction caused by the excess alkaline activator, resulting in a less homogeneous microstructure with increased porosity and microcracks.

There is a distinct inverse relationship between the AL/GS ratio and the indirect tensile strength of the geopolymer concrete. As the ratio increased from 0.7 to 0.9, the tensile strength decreased from approximately 3.9 MPa to 3.6 MPa. The experimental indirect tensile strengths recorded were consistently lower than the predictive models proposed in [17, 19] but remained higher than the AS 3600 prediction [18]. The geopolymer concrete exhibited more brittle tensile behavior compared to Ordinary Portland Cement (OPC) concrete. This indicates that improving the tensile properties for structural applications may require separate optimization of the AL/GS ratio or the incorporation of fibers.

There is a strong correlation between the concrete's compressive strength and the overall performance of the deep beams. Beam GCB1, cast with the optimal AL/GS ratio of 0.7, demonstrated superior load-carrying capacity, achieving an ultimate load of roughly 325 kN at a mid-span deflection of about 5.8 mm. A decrease in compressive strength resulted in a dramatic reduction of more than 68% in ultimate capacity.

The structural behavior of deep geopolymer beams with a low shear span-to-depth (a/d) ratio is heavily governed by a strut-and-tie mechanism. A higher compressive strength improves the capacity of the concrete strut, leading to increased shear resistance and stiffness. Conversely, beams with lower compressive strength showed reduced strut efficiency, resulting in a greater reliance on longitudinal reinforcement and stirrups for post-cracking resistance.

Compressive strength serves as a crucial parameter controlling the strength and deformation characteristics of deep geopolymer beams. Due to the high sensitivity of the strut-and-tie mechanism to concrete strength, achieving uniform and high compressive strength is essential when designing shear-critical structural members.

DECLARATION OF COMPETING INTERESTS

The authors declare that they have no competing interests.

ACKNOWLEDGMENT

The authors acknowledge the Ho Chi Minh City University of Technology (HCMUT) and VNU-HCM for supporting this study.

DATA AVAILABILITY

The data supporting the findings of this study are available within this paper.

AI USE AND DECLARATION OF GENERATIVE AI USE

The authors used generative AI solely for language improvement and editorial assistance during the preparation of this manuscript. All generated output was carefully reviewed and edited by the authors, who take full responsibility for the content of the final manuscript.

REFERENCES

[1] J. Davidovits and S. A. Cordi, "Synthesis of new high temperature geo-polymers for reinforced plastics/composites," presented at the *Plastics Technology-Recent Developments & Trends*, 1979, vol. 79, pp. 151–154.

[2] J. Davidovits, *Geopolymer Chemistry and Applications*, 3rd ed. Geopolymer Institute, 2011.

[3] J. Davidovits, "Geopolymers: Inorganic polymeric new materials," *Journal of Thermal Analysis*, vol. 37, no. 8, pp. 1633–1656, Aug. 1991, https://doi.org/10.1007/BF01912193.

[4] J. Davidovits, "Global warming impact on the cement and aggregates industries," *World Resource Review*, vol. 6, no. 2, pp. 263–278, 1994.

[5] S. Muthukrishnan, S. Ramakrishnan, and J. Sanjayan, "Rapid early age strength development of in-line activated geopolymer for concrete 3D printing," *Construction and Building Materials*, vol. 406, Nov. 2023, Art. no. 133312, https://doi.org/10.1016/j.conbuildmat.2023.133312.

[6] A. Castel, S. J. Foster, T. Ng, J. G. Sanjayan, and R. I. Gilbert, "Creep and drying shrinkage of a blended slag and low calcium fly ash geopolymer Concrete," *Materials and Structures*, vol. 49, no. 5, pp. 1619–1628, May 2016, https://doi.org/10.1617/s11527-015-0599-1.

[7] R. Olayinka, R. Jafari, and M. Fiset, "Shrinkage Characteristics of Geopolymer Concrete: A Comprehensive Review," *Materials*, vol. 18, no. 19, Sept. 2025, Art. no. 4528, https://doi.org/10.3390/ma18194528.

[8] T. Manzoor, J. A. Bhat, and A. H. Shah, "Performance of geopolymer concrete at elevated temperature − A critical review," *Construction and Building Materials*, vol. 420, Mar. 2024, Art. no. 135578, https://doi.org/10.1016/j.conbuildmat.2024.135578.

[9] J. Xie, J. Zhao, J. Wang, C. Wang, P. Huang, and C. Fang, "Sulfate Resistance of Recycled Aggregate Concrete with GGBS and Fly Ash-Based Geopolymer," *Materials*, vol. 12, no. 8, Apr. 2019, Art. no. 1247, https://doi.org/10.3390/ma12081247.

[10] Y. Patrisia, D. W. Law, C. Gunasekara, and A. Wardhono, "Fly ash geopolymer concrete durability to sulphate, acid and peat attack," *MATEC Web of Conferences*, vol. 364, 2022, Art. no. 02003, https://doi.org/10.1051/matecconf/202236402003.

[11] L. S. Wong, "Durability Performance of Geopolymer Concrete: A Review," *Polymers*, vol. 14, no. 5, Feb. 2022, Art. no. 868, https://doi.org/10.3390/polym14050868.

[12] V. Ray, K. Sekhar, N. G. Reddy, and B. H. Rao, "Beneficial utilization of waste heat for developing fly ash based geopolymer mortar," *Discover Civil Engineering*, vol. 2, June 2025, Art. no. 104, https://doi.org/10.1007/s44290-025-00262-4.

[13] J. Xie, J. Wang, R. Rao, C. Wang, and C. Fang, "Effects of combined usage of GGBS and fly ash on workability and mechanical properties of alkali activated geopolymer concrete with recycled aggregate," *Composites Part B: Engineering*, vol. 164, pp. 179–190, May 2019, https://doi.org/10.1016/j.compositesb.2018.11.067.

[14] A. Kumar, . Rajkishor, N. Kumar, A. K. Chhotu, and B. Kumar, "Effect of Ground Granulated Blast Slag and Temperature Curing on the Strength of Fly Ash-based Geopolymer Concrete," *Engineering, Technology & Applied Science Research*, vol. 14, no. 2, pp. 13319–13323, Apr. 2024, https://doi.org/10.48084/etasr.6874.

[15] *ASTM C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. West Conshohocken, PA, USA: ASTM International, 2008.

[16] *ASTM C496/C496M-11 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. West Conshohocken, PA, USA: ASTM International, 2011.

[17] D. Hardjito and B. V. Rangan, *Development and Properties of Low-Calcium Fly Ash-Based Geopolymer Concrete*. Perth, Australia: Curtin University of Technology, 2005.

[18] *AS 3600-2009 Concrete Structures*. Australia: Standards Australia, 2009.

[19] K. T. Nguyen, N. Ahn, T. A. Le, and K. Lee, "Theoretical and experimental study on mechanical properties and flexural strength of fly ash-geopolymer concrete," *Construction and Building Materials*, vol. 106, pp. 65–77, Mar. 2016, https://doi.org/10.1016/j.conbuildmat.2015.12.033.