3rd World Conference on Architecture and Civil Engineering

Prague, Czech Republic 18 - 20 September 2025

Influence of Activator-to-Binder Ratio on the Mechanical Properties of One-Part Geopolymer Concrete

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Abstract

One-part geopolymer concrete (OPGC) has emerged as a promising sustainable alternative to Portland cement concrete due to the effective utilization of industrial by-products. This study investigates the influence of different activator-to-binder (a/b) ratios on the fresh and hardened properties of OPGC. The mixtures were prepared using 30% magnesium slag (MS) and 70% ground granulated blast-furnace slag (GGBS), with a constant water-to-binder (w/b) ratio of 0.47, and a/b ratio varied between 0.12 and 0.20. Fresh properties were evaluated through slump measurements, while hardened performance was assessed using density, ultrasonic pulse velocity (UPV), and compressive strength at multiple curing ages. The results demonstrated that increasing the activator dosage led to a noticeable reduction in slump, indicating reduced workability due to higher mixture viscosity. In contrast, mechanical performance improved substantially with higher activator contents, with compressive strength reaching 59.3 MPa at 90 days. Nevertheless, excessively high activator levels negatively impacted workability. Although the highest compressive strength was obtained at the 0.20 a/b ratio, the mixture with a 0.16 a/b ratio provided the best overall balance between workability and strength. At 0.20, the increased activator content led to higher viscosity and reduced workability, making the mixture more difficult to handle. In contrast, the 0.16 a/b ratio offered sufficient flowability while still achieving a high 90-day compressive strength of 46.07 MPa. Overall, the findings highlight the critical role of optimizing solid activator content in achieving a high-strength and workable OPGC suitable for modern construction applications.

Keywords: one-part geopolymer concrete, fresh properties of geopolymer concrete, compressive strength at different curing ages, activator to binder ratio, magnesium slag and ground granulated blast furnace slag based geopolymer concrete.

1 Introduction

The production of Portland cement-based concrete requires the consumption of large quantities of natural resources and contributes significantly to greenhouse gas emissions (El Mir et al.,2023). Scientists and researchers have continuously sought alternative materials that not only provide comparable or superior performance to cement-based concrete but also minimize environmental impacts (Guo et al., 2019). Such approaches aim to recycle industrial by-products, reduce CO_2 emissions, and preserve natural resources (Sumesh et al., 2017). Over the past two decades, increasing attention has been devoted to the development of eco-friendly construction materials through the incorporation of supplementary cementitious materials (SCMs) and fillers derived from industrial by-products. The superior performance of these materials is closely linked to their morphological characteristics and pozzolanic reactivity. These properties improve both the quality and quantity of hydration products in cementitious systems, leading to denser microstructures with reduced permeability. In particular, pozzolanic additives such as fly ash and ground-granulated blast-furnace slag react with calcium hydroxide to form secondary C-S-H and C-A-S-H gels, thereby enhancing strength and improving long-term durability (Meng et al., 2018), (Oderji et al., 2019). Furthermore, the use of such by-products reduces the exploitation of virgin resources and lowers greenhouse gas emissions, offering significant contributions to the development of sustainable construction materials (Pacheco-Torgal, 2015). Within this context, the valorisation of industrial waste has emerged as a strategic pathway to producing high-performance concrete that meets both technical and environmental requirements, while simultaneously enhancing the structural performance of conventional cement matrices (Zhang et al., 2010).

Geopolymer concrete has emerged as a promising innovation capable of replacing Ordinary Portland Cement based concrete (OPC). With appropriate mix design, geopolymer systems can achieve up to 80% reductions in CO_2 emissions and nearly 60% lower energy consumption compared to OPC (Oderji et al., 2019). Consequently, geopolymers have attracted increasing interest and recognition among researchers. The term “geopolymer” was first introduced by Davidovits in 1979 (Pacheco-Torgal, 2015). Conventional geopolymer formulations typically comprise a two-component system; a liquid alkali activator and a solid aluminosilicate precursor. These materials are widely acknowledged for their environmentally friendly nature, high workability, and superior compressive strength (Zhang, 2010). Nevertheless, the geopolymerization process is complex and difficult to control (Kong & Sanjayan, 2010). Additionally, practical challenges such as the transportation, storage, and handling of liquid alkaline activators—often viscous and difficult to store in large volumes—have limited large-scale applications (Luukkonen, 2018). This highlights the need for further advancements and optimisation of geopolymer concrete technologies.

Recently, “one-part geopolymers,” also referred to as “just add water” systems, have attracted increasing attention as an alternative to conventional two-part formulations due to their improved safety, portability, and ease of use (Bernal et al., 2014). Unlike conventional systems, where alkaline solutions and aluminosilicate binders are prepared separately, one-part systems are composed of dry powders containing both solid aluminosilicate precursors and solid activators, which are subsequently activated by the addition of water (Luukkonen et al., 2018). The key distinction lies in the use of solid-state alkali activators (e.g., solid sodium hydroxide or sodium metasilicate) rather than liquid activator solutions. This approach simplifies field applications while reducing safety concerns (Provis, 2018).

A wide range of industrial by-products, including fly ash, GGBS, MS and metakaolin, have been successfully utilised in one-part geopolymer systems (Sunarsih et al., 2024). The compressive strength of these binders depends on multiple interrelated parameters, including:

- Type and fineness of aluminosilicate precursors: The reactivity of fly ash or slag plays a decisive role (Qu et al., 2021).
- Activator composition and dosage: The chemical type and quantity of solid activators influence dissolution and gel formation (Yip & Van Deventer, 2003).
- Water-to-solid ratio: Lower ratios enhance strength but can reduce workability (Dong et al., 2023).
- Curing conditions: Although ambient curing is possible, thermal curing is known to accelerate early strength development (Rabie et al., 2022).
- Aggregate properties: Larger aggregates have been reported to enhance thermal stability (Zhang et al., 2020).

Early studies revealed that one-part geopolymer concretes sometimes exhibited relatively low compressive strengths, raising concerns regarding their load-bearing capacity and increased risks of cracking or brittle failure (Kloušek et al., 2007). Other investigations also highlighted limitations in tensile, flexural, and elastic behaviour at initial stages (Peng et al., 2015). As a result, improving the mechanical performance of one-part geopolymer systems has become a prominent focus in recent literature. Several studies have identified solid sodium metasilicate as a highly effective powdered activator in these systems (Ma et al., 2018). For instance, Hai-Yan Zhang reported that anhydrous sodium metasilicate outperformed the conventional combination of liquid sodium silicate and sodium hydroxide in metakaolin-fly ash blends (Zhang et al., 2014). Similarly, Lao et al. demonstrated that hybrid mixtures containing sodium metasilicate and sodium carbonate provided the best balance of mechanical performance, energy efficiency, environmental impact, and economic viability (Lao et al., 2023).

Several researchers have investigated the influence of the activator-to-binder (a/b) ratio on the performance of geopolymer systems. Thokchom et al. studied fly ash-based geopolymer mortars in sulphate environments and reported that variations in the a/b ratio had a direct effect on compressive strength development (Thokchom et al., 2010). Similarly, a study published in the Journal of Civil Engineering Forum examined the combined effects of water-to-solid ratio, activator-to-binder ratio, and lime addition, finding that an A/B ratio in the range of 0.50–0.55 was optimal for achieving high compressive strength (Rahman & Mahmud, 2016). In fly ash and slag-based systems, Rahman et al. observed that increasing the a/b ratio improved workability and compressive strength up to an optimum value, after which further increases resulted in higher porosity and reduced strength (Rahman et al., 2017). Shilar et al. optimised alkaline activator content in geopolymer concretes and confirmed that excessive activator dosage led to diminished long-term performance despite early strength gains (Shilar et al., 2022). Another study by Rajan & AnuPriya demonstrated that varying Na_2SiO_3/NaOH ratios, closely linked to the overall a/b proportion, strongly influenced mechanical properties such as tensile strength and porosity (Rajan & AnuPriya, 2005). More recently, Zhang et al. highlighted that binder type and activator composition jointly determined the fresh and hardened properties of slag- and lime-based geopolymers, underlining the necessity of optimising the a/b ratio for both durability and mechanical performance (Zhang et al., 2014). Collectively, these studies emphasise that the a/b ratio is a critical parameter, directly affecting workability and strength development of OPGC.

This study aims to investigate the mechanical performance of OPGC incorporating MS and GGBS under different activator-to-binder ratios. Despite the growing interest in one-part geopolymer concrete systems, the effects of varying activator-to-binder combinations on compressive strength development have not yet been comprehensively addressed in the literature. In this context, the novelty of the present work lies in demonstrating one-part geopolymer concrete systems that can achieve optimum performance under different activator-to-binder conditions while simultaneously highlighting the environmental advantages of sustainable binder materials. Thus, the study seeks to contribute both to reducing environmental impacts and to advancing the development of high-strength infrastructure systems.

2 Materials and Methods

Concrete mixtures were developed using alternative binders instead of traditional Portland cement. The binder system consisted of MS and GGBS as a precursor, a solid sodium metasilicate as the chemical activator, and both fine and coarse aggregates. All materials were weighed and mixed under controlled laboratory conditions to ensure consistency and repeatability.

2.1 Materials

In this study, one-part geopolymer concretes were designed to evaluate the influence of different activator-to-binder (a/b) ratios on compressive strength. The mixtures were prepared using 30% magnesium slag and 70% ground granulated blast-furnace slag as aluminosilicate precursors were supplied by Kar Mineral Mining Inc. Table 1 presents the chemical compositions of the materials as obtained from the supplier's X-ray fluorescence (XRF) analysis, while the specific densities of MS and GGBS employed in the experimental programme were measured as 2.14 and 2.83 g/cm³, respectively.

Table 1. Chemical compositions of MS and GGBS

Component name	MS (mass % as oxides)	GGBS (mass % as oxides)
SiO_2	26,58	37,4
Al_2O_3	1,91	10,38
Fe_2O_3	3,29	1,3
CaO	61,85	30,93
MgO	3,83	7,21
SO_3	0,09	0,77
Na_2O	0,21	0,39

Component name	MS (mass % as oxides)	GGBS (mass % as oxides)
K_2O	0,02	0,69
Cl	0	0,048

Sodium metasilicate (Na_2SiO_3), serving as the solid activator, was obtained from Songen Biotechnology and Laboratory Materials Ltd. Co., and its physical properties are summarized in Table 2. Based on the manufacturer's technical data sheet, the anhydrous sodium metasilicate activator used in this study contains 50% SiO_2 and 50% Na_2O by mass and was dissolved in water prior to mixing. The solid activator was dissolved in water prior to mixing in order to facilitate its dissolution and to achieve a more homogeneous concrete mixture. This operational choice was informed by the authors' previous experimental studies, in which the solid activator was added directly to the dry mix and resulted in non-uniform distribution of activator. Dissolving the activator in water was therefore adopted to improve homogeneity within the mix, leading to a more uniform and effective activation, as observed experimentally. All aggregates and binders were dry-mixed for 2 minutes, followed by the gradual addition of the activator solution and an additional 3 minutes of mixing at 280 rpm to ensure homogeneity. After casting, specimens were cured at 60 °C for 24 hours and subsequently stored under ambient conditions until testing at 7, 28, and 90 days.

Table 2. The physical properties of the solid activator sodium metasilicate

Properties	Value
Molecular structure	Composed of Sodium (Na), Silicon (Si), and Oxygen (O) atoms
Components	Sodium Oxide (Na_2O): Provides alkaline structure Silica (SiO_2): Promotes the formation of reactive phases
Physical form	White granules
Density (solid)	2.5 g/cm^3
Solubility	Easily dissolves in water; dissociates into Na^+ and SiO_3^{2-} ions
Reactivity	Initiates the alkaline activation process Supports the formation of C-S-H and N-A-S-H gel phases in geopolymer concrete production
Moisture absorption	Rapidly absorbs moisture from the air; should be stored in a dry environment
Thermal stability	Stable up to 1088°C

The fine and coarse aggregates employed in this research were provided by KÇS Cement, Turkey, and processed in accordance with the specifications of EN 12620. Coarse aggregates had a maximum nominal size of 16 mm, whereas the fine aggregates were characterized by a fineness modulus of 4.35. The aggregates used in this study exhibited a dry specific gravity of 2.58, a saturated surface-dry specific gravity of 2.68, and a water absorption capacity of 1.2%. The aggregates were separated into categories using sieve analyses that defined specific size ranges, and their gradation was adjusted to ensure uniform distribution. The particle size distributions of the aggregates used in the concrete mixes complied with the limits specified in the EN 12620 standard, as illustrated in Figure 1.

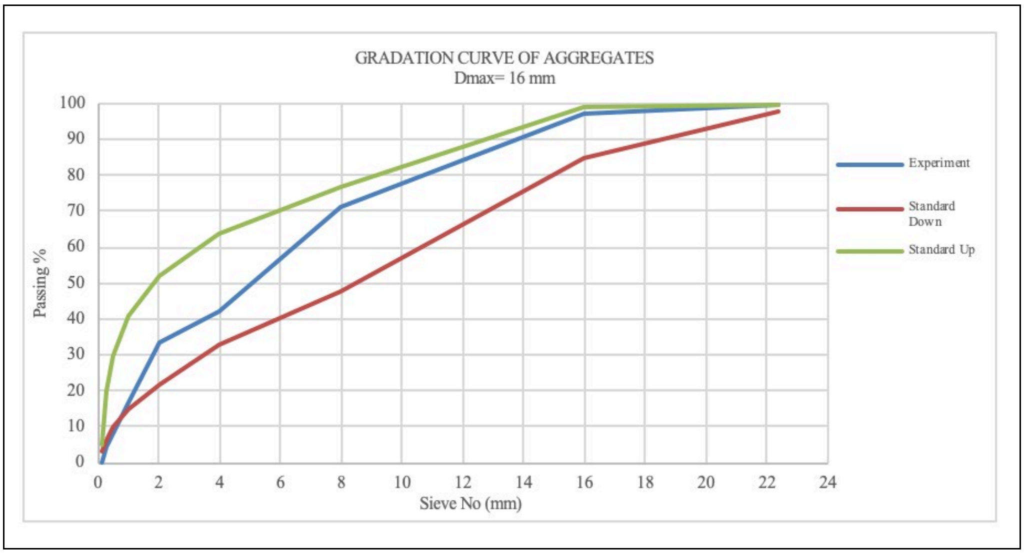

Figure 1. The particle size distribution curve of the aggregates employed in the experiment

2.2 Mix Design

OPGC was produced using water, coarse and fine aggregates, and an alternative binder composed of raw materials and a solid activator. The primary raw materials were MS and GGBS, while solid Na_2SiO_3 was used as the activator. Owing to the similarities between conventional concrete and OPGC, the mix design approach was adapted from previous research (Peng et al., 2015). The quantities used in the OPGC mixtures are summarised in Table 3. In this experimental programme, the total aggregate content was fixed at 70% by mass, consisting of 60% coarse aggregate and 40% fine aggregate. The water-to-binder ratio was kept constant at 0.47 for all mixtures. All mixes were prepared under laboratory ambient conditions, with an average temperature of approximately 22 °C and relative humidity of 50%. No chemical admixtures such as superplasticisers were used in order to isolate the effect of the activator-to-binder ratio on the fresh and hardened properties of the geopolymer concrete. Workability was assessed using the slump test, which was considered adequate for comparing the flow behaviour of the mixtures. Although detailed rheological measurements were not conducted, variations in slump were used as an indicator of changes in flow characteristics resulting from different activator contents. Initial and final setting times were not explicitly measured; however, no abnormal setting behaviour was observed during mixing and casting.

The primary objective of this study was to investigate the influence of different activator-to-binder (a/b) ratios on the strength development of geopolymer concrete. Accordingly, the experimental specimens were prepared with varying activator contents while keeping all other parameters constant. In this context, GC12 denotes a mixture with an activator-to-binder ratio of 0.12. Similarly, GC14, GC16, GC18, and GC20 represent mixtures with a/b ratios of 0.14, 0.16, 0.18, and 0.20, respectively. The detailed mixture proportions are presented in Table 4.

After casting, all specimens were subjected to heat curing at 60 °C for 24 h, followed by storage under laboratory conditions until testing. This curing regime was selected to ensure sufficient early-age activation of the MS–GGBS-based binder system, which is known to benefit from elevated-temperature curing. While such curing conditions may differ from typical field practices, they provide a controlled framework for evaluating the intrinsic effects of activator dosage on geopolymerization and strength development.

Table 3: The quantities used in the experiment

Materials	**%**	**kg/ m^3**
Coarse aggregate	60	961
Fine aggregate	40	693
Magnesium slag (MS)	30	119,61
GGBS	70	279,09
Water/ binder ratio	47	217,37

Table 4: Mix design

Materials	**Material ID**				
	GC12	*GC14*	*GC16*	*GC18*	*GC20*
Activator/ binder ratio	0,12	0,14	0,16	0,18	0,20
Coarse aggregate (kg/ m^3)	961	961	961	961	961
Fine aggregate (kg/ m^3)	693	693	693	693	693
Magnesium slag (MS) (kg/ m^3)	119,61	119,61	119,61	119,61	119,61
Ground granulated blast furnace slag (GGBS) (kg/ m^3)	279,09	279,09	279,09	279,09	279,09
Activator (Sodium metasilicate) (kg/ m^3)	23,922	27,909	31,896	35,883	39,87
Water (kg/ m^3)	217,37	217,37	217,37	217,37	217,37

2.3 Test Procedure

Five different mixture design resulting in a total of 45 specimens were developed to understand the effect of activator/ binder ratio on strength development in OPGC. For each 7-day, 28-day and 90-day testing, three identical cube specimens (150mm x 150mm x 150mm) as seen in Figure 2 were prepared to enable averaging of the test results. The concrete mixtures were prepared in HOBART mixer with 60-L capacity, operating at a speed of 280 rpm as seen in Figure 2. In the first step, coarse and fine aggregates were combined in a dry state and blended for around two minutes. Following this, MS and GGBS were incorporated, and mixing was continued for a further two minutes to obtain an even distribution of the powders. After a uniform dry blend was reached, the solid sodium metasilicate activator was added by dissolving it in the mixing water as seen in Figure 3.

Figure 2: Cube specimens and materials in Hobart mixer

Figure 3: Solid activator and dissolution of the solid activator in water

After mixing, slump tests were performed in compliance with EN 12350-2 to assess the workability of the fresh concrete as seen in Figure 4. These tests were carried out under ambient conditions at 20 ± 2 °C. The fresh geopolymer concrete, prepared through a procedure resembling that of conventional concrete and therefore providing advantages in handling, was then placed into pre-oiled cube molds for testing as seen in Figure 4.

Figure 4: Slump test and placing concrete to molds

Following placement into the molds, the specimens were compacted using a vibrating device to achieve adequate consolidation and to remove trapped air. After vibration and casting, the specimens were wrapped with heat-resistant plastic film to minimise moisture evaporation and subsequently placed in a furnace maintained at 60 °C for thermal curing that was considered necessary to achieve proper setting in one-part geopolymer concrete (Abdollahnejad et al., 2019). This treatment aimed to accelerate the chemical reactions within the geopolymer matrix and to promote appropriate setting. The specimens were kept in the furnace for 24 hours. Once the curing period ended, they were taken out, unwrapped, and sealed in plastic bags to preserve internal moisture. Thereafter, they were stored under ambient conditions until the designated testing ages of 7 days, 28 days and 90 days. The curing and storage procedure for MS-based OPGC specimens is illustrated in Figure 5.

Figure 5: Experiment furnace, placing concrete samples to furnace, samples after furnace and samples waiting for test day

3 Results

3.1 Slump

To evaluate the workability properties of fresh geopolymer concrete, the slump test was performed in accordance with EN 12350-2. Table 5 shows the slump test results of five different a/b ratio geopolymer concrete specimens. According to results, the concrete exhibited a medium level of workability, providing sufficient flowability during placement and compaction especially in 0,16 a/b ratio. Beyond this value, workability decreases and the viscosity of the mixture increases, making the concrete more difficult to place as seen in Table 5 values as 0,18 and 0,20 a/b ratios 8 cm and 5 cm accordingly. Previous studies emphasize that there is a relationship between rheological behavior and slump value in fresh concrete (White & Lees, 2025). Therefore, the slump values of fresh geopolymer concrete are directly related to its placement performance and susceptibility to segregation (Tanigawa, 1992). Accordingly, the obtained slump values demonstrate that the risk of segregation and bleeding in the concrete was effectively controlled. These results confirm that the adopted mix design provided a suitable balance of consistency for the performance of fresh geopolymer concrete.

Table 5: Slump test results of each OPGC mixture

a/b (%)	Slump (cm)
0,12	15
0,14	13
0,16	10
0,18	8
0,20	5

3.2 Density

The influence of the a/b ratio on the density of OPGC mixtures is summarized in Table 6. As the a/b ratio increased from 0.12 to 0.20, the weight of specimens with a fixed volume of 1000 cm³ rose from 2.07 to 2.19 g/cm³. This incremental rise in density with higher a/b ratios reflects a denser microstructure and improved packing of the solid constituents. Similar observations have been reported in previous studies, where higher activator contents enhanced dissolution of aluminosilicate precursors, thereby facilitating the formation of more compact C–S–H and N–A–S–H gel phases (Zhang et al., 2014), (Nath & Sarker, 2014). According to Provis and Van Deventer, this densification effect is linked to the increased availability of alkali ions, which promote faster geopolymerization and contribute to reduced porosity (Provis & Van Deventer, 2009). However, excessive activator content has been associated with increased viscosity and reduced workability, potentially leading to microstructural defects (Bernal et al., 2014).

Table 6: Density results of each OPGC mixture

a/b (%)	Weight (gr)	Volume (cm^3)	Density (gr/cm^3)
0,12	2070	1000	2,07
0,14	2090	1000	2,09
0,16	2150	1000	2,15
0,18	2180	1000	2,18
0,20	2180	1000	2,19

3.3 UPV Test

The UPV test results revealed distinct variations in the internal quality of OPGC mixtures depending on the activator-to-binder (a/b) ratio as seen in Table 7. As the a/b ratio increased, the UPV values consistently rose, reaching peak levels between 4400 m/s and 4660 m/s. These elevated values reflect the development of a dense and homogeneous matrix with minimal voids, attributed to improved dissolution of aluminosilicate precursors, enhanced workability, and effective compaction at these ratios. Similar findings have been reported in previous studies, where increasing activator content promoted the formation of compact reaction products such as C–S–H and N–A–S–H gels, thereby improving the microstructural integrity and ultrasonic pulse transmission of geopolymer concretes (Zhang et al., 2014), (Nath & Sarker, 2014). Nevertheless, as noted by Bernal et al., excessive activator dosage can also increase viscosity, reduce flowability, and introduce internal discontinuities (Bernal et al., 2014). Overall, the results of this study confirm that the activator-to-binder ratio is a decisive parameter for achieving superior internal quality and optimized UPV performance in OPGC systems.

Table 7: UPV test results of each OPGC mixture

a/b (%)	**UPV (m/s)**
0,12	4400
0,14	4450
0,16	4480
0,18	4550
0,20	4660

Moreover, since all mixtures were prepared with the same aggregate proportion and identical water-to-binder ratio, the differences in measured bulk density among the mixtures can be interpreted as differences in porosity. Accordingly, the mixture with the highest measured density, representing the most compact structure, was taken as the reference state (ρ_{ref} = 2.19 g/cm^3, corresponding to an a/b ratio of 0.20). The relative porosity of each mixture was then estimated by comparing its bulk density to the reference density using the following expression and showed in Table 8:

Porosity (%)$=(1-\rho/\rho_{ref\rho})\times 100$

*Table 8: D*ensity, UPV and estimated porosity of OPGC mixtures with different a/b ratio.

a/b (%)	**Density (gr/cm^3)**	**UPV (m/s)**	**Estimated Porosity (%)**
0,12	2,07	4400	5,48
0,14	2,09	4450	4,57
0,16	2,15	4480	1,83
0,18	2,18	4550	0,46
0,20	2,19	4660	0,00

The relationship between density, UPV, and porosity was quantitatively assessed by estimating porosity from bulk density measurements using a relative porosity approach. As the activator-to-binder ratio increased, the estimated porosity decreased from 5.48% to 0%, while UPV increased from 4400 to 4660 m/s. Linear regression analysis revealed a strong inverse relationship between UPV and estimated porosity (R^2 = 0.81), indicating that mixtures with lower porosity exhibited higher ultrasonic pulse velocity. This trend reflects improved matrix compactness and reduced internal discontinuities, which facilitate more efficient transmission of ultrasonic waves.

3.4 Compressive Strength

The measured values and their corresponding averages for each age are presented in the Table 9, Table 10, and Table 11. The experimental results clearly demonstrate that the increase of a/b ratio in OPGC has a significant influence on compressive strength, as also shown in Figure 6. As the a/b ratio increased from 0.12 to 0.20, both early- and late-age compressive strengths exhibited a distinct upward trend. The highest strength was obtained at the 0.20 a/b ratio, reaching 55.4 MPa at 7 days, 56.82 MPa at 28 days, and 59.30 MPa at 90 days. These findings are consistent with previous research, which has shown that the dosage of alkali activators plays a critical role in controlling the dissolution of aluminosilicate phases and the subsequent formation of binding gels such as C–S–H, N–A–S–H, and C–A–S–H (Provis & Van Deventer, 2009). Nath and Sarker reported that increasing activator content enhances the reactivity of geopolymer systems resulting in significant improvements in compressive strength, particularly at early ages (Nath & Sarker, 2014). Similarly, Zhang et al. highlighted that the availability of sufficient activator dosage accelerates geopolymerization kinetics, leading to denser microstructures and higher strength development (Zhang et al., 2014). However, excessive activator content has also been associated with increased viscosity, poor workability, and microstructural defects, which can eventually limit further strength gains (Waqas et al., 2021).

Table 9: The compressive strength test results at 7. days

a/b (%)	Sample 1 (MPa)	Sample 2 (MPa)	Sample 3 (MPa)	Average (MPa)
0,12	17,10	16,80	17,07	16,99
0,14	23,50	23,80	23,59	23,63
0,16	41,40	41,70	41,46	41,52
0,18	53,40	53,80	53,51	53,57
0,20	55,20	55,60	55,40	55,40

Table 10: The compressive strength test results at 28. days

a/b (%)	Sample 1 (MPa)	Sample 2 (MPa)	Sample 3 (MPa)	Average (MPa)
0,12	18,90	19,20	18,96	19,02
0,14	27,50	27,80	27,59	27,63
0,16	43,40	43,70	43,55	43,55
0,18	54,40	54,80	54,60	54,60
0,20	56,70	57,00	56,76	56,82

Table 11: The compressive strength test results at 90. days

a/b (%)	Sample 1 (MPa)	Sample 2 (MPa)	Sample 3 (MPa)	Average (MPa)
0,12	20,10	20,40	20,10	20,20
0,14	30,50	30,80	30,56	30,62
0,16	45,90	46,30	46,01	46,07
0,18	56,50	56,90	56,64	56,68
0,20	59,10	59,50	59,30	59,30

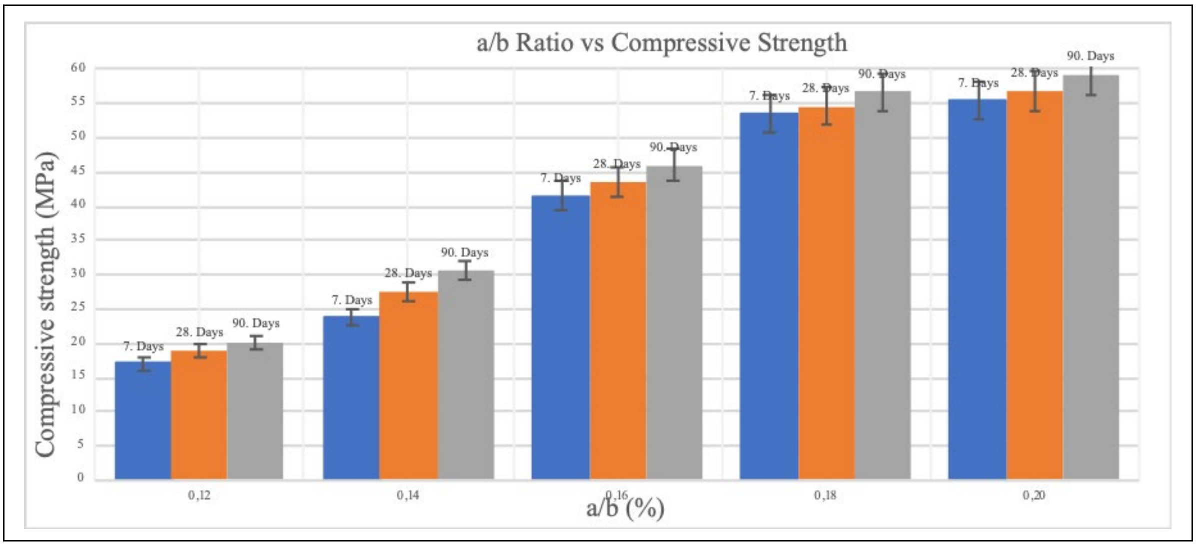

Figure 6: Compressive strength test results at 7-days, 28-days and 90 days

Overall, the results of this experimental study confirm that optimizing the activator-to-binder ratio is essential to achieving a balance between workability and mechanical performance, with moderate increases in activator content providing substantial improvements in compressive strength without compromising mixture integrity.

4 Limitations

Microstructural characterization using SEM/EDX was not performed in this study and is therefore recognized as a limitation. As a result, the interpretation of the experimental results is primarily based on macroscopic properties such as density, ultrasonic pulse velocity (UPV), and mechanical performance. While these parameters provide indirect insight into pore structure and matrix compactness, detailed microstructural evidence would allow for a more comprehensive understanding of the geopolymerization mechanisms and phase development. Future research will therefore focus on comprehensive microstructural analyses to more clearly elucidate the relationship between pore structure and the observed mechanical and durability-related properties.

5 Conclusion and Future Studies

This study has demonstrated the critical influence of mix design parameters, particularly the activator-to-binder ratio on the fresh and hardened performance of OPGC incorporating MS and GGBS. The following statements were obtained with this experimental study;

- The slump test results confirmed that the mixtures achieved a good workability level at 0,16 a/b ratio, ensuring sufficient flowability during casting and compaction without segregation risks.
- Density measurements indicated a steady increase with higher activator-to-binder ratios, reflecting improved packing and matrix consolidation.
- The UPV results showed a clear increasing trend with higher a/b ratios, exhibiting a pattern that closely paralleled the improvements observed in compressive strength. This indicates that mixtures with higher a/b ratios developed denser and more homogeneous microstructures, supporting more effective wave transmission.
- The quantitative correlation between UPV and estimated porosity confirms that the observed increase in UPV with increasing activator content is primarily associated with matrix densification and pore structure refinement.
- Compressive strength development followed a similar trend, with both early and late strength values significantly enhanced as the a/b ratio increased, achieving peak performance at 0.20. Despite the high strength achieved at this ratio, its poor workability makes it less practical for casting and compaction. Hence, evaluating both mechanical performance and fresh-state behavior, the 0.16 a/b ratio emerges as the most suitable balance. The findings highlight the importance of balancing activator dosage to maximize reactivity and strength while maintaining adequate workability.

Overall, the results underline that optimized proportions of activator content can provide one-part geopolymer concretes with high strength and practical workability. The outcomes of this research confirm the potential of OPGC as a high-performance alternative to conventional cement-based binders, while emphasizing the necessity of careful proportioning in activator dosage to ensure long-term performance. Nevertheless, the study also highlights that the use of MS in OPGC still requires a more comprehensive evaluation of its environmental impacts and carbon footprint, suggesting that a dedicated life cycle assessment (LCA) should be undertaken to fully understand its sustainability potential.

Furthermore, future studies should extend this work by incorporating detailed microstructural analyses. SEM and EDX results would provide valuable insights into the morphology, reaction products, and elemental composition of the geopolymer matrix. Integrating these microstructural observations with the mechanical findings would allow for a more comprehensive understanding of the material behavior and would help validate the mechanisms responsible for strength development in OPGC. Such analyses would ultimately lead to more conclusive results.

6 Practical Design Recommendations

Based on the findings, the following practical recommendations can guide the use of MS in OPGC mixtures in real construction applications:

- Use a 0.16 a/b ratio to achieve the best balance between workability and mechanical strength.
- Dissolve the solid activator in mixing water before adding it to dry materials to ensure uniform dispersion.
- Mix at moderate speed to achieve a homogeneous mixture and prevent incomplete dissolution of the activator.
- Avoid high activator contents, as these increase viscosity and reduce workability, making casting more difficult.
- Compact the mixture adequately to eliminate entrapped air and avoid microstructural defects, especially in stiffer mixes.
- Apply thermal curing at around 60 °C for 24 hours, if feasible, to enhance early strength development and reaction efficiency.
- Store and handle aggregates in controlled moisture conditions to maintain consistency in fresh-state behavior.

Acknowledgment

The authors would like to express their sincere gratitude to Scientific Research Projects Programme of Gaziantep University under Project No: MF. HZP. 24. 13., and YOK 100/2000 fellowship which enabled the mobility of the researchers and contributed to the successful execution of this research.

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