ISSN 2056-5860

INFLUENCE OF PRECURSOR COMPOSITION AND MIX-DESIGN PARAMETERS ON THE COMPRESSIVE STRENGTH OF AMBIENT-CURED GEOPOLYMER CONCRETE: A DATA-DRIVEN ANALYSIS

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ABSTRACT

The compressive strength of ambient-cured geopolymer concrete is influenced by interacting precursor, activator and mixture-design characteristics, making it difficult to generalise optimum conditions from individual experimental studies. This study employed a data-driven statistical approach to examine these relationships using 251 geopolymer concrete mixtures tested at 28 days under ambient curing. The database comprised fly ash-only, fly ash–ground-granulated blast-furnace slag (GGBS) blended and GGBS-only systems. Descriptive statistics, non-parametric comparisons, effect-size analysis and multivariable regression were used to evaluate relationships between mixture characteristics and compressive strength. Compressive strength increased progressively from fly ash-only through FA–GGBS blended to GGBS-only systems, while higher-strength mixtures were increasingly characterised by greater GGBS contribution. Differences among precursor systems remained significant after adjustment for selected activator and aggregate characteristics. Individual activator parameters did not consistently distinguish the high-strength group; however, NaOH molarity, sodium silicate-to-NaOH ratio and water-to-solids ratio showed significant associations with strength after multivariable adjustment. These findings indicate that precursor composition is a major discriminator of ambient-cured compressive strength, while activator effects depend on the broader mixture context. The results provide a basis for identifying promising mixture-design regions for subsequent experimental optimisation.

Keywords: Alkaline activator; ambient curing; compressive strength; data-driven analysis; fly ash; GGBS; geopolymer concrete; mix design.

1. Introduction

Geopolymer concrete has received increasing attention as a lower-carbon alternative to ordinary Portland cement concrete because it enables the utilisation of aluminosilicate-rich industrial by-products as binder materials. Among the most extensively investigated precursors are fly ash (FA) and ground-granulated blast-furnace slag (GGBS), which may be employed individually or in blended systems (Deb et al., 2014; Nath & Sarker, 2014; Provis, 2018). The compressive strength of these systems is influenced by several interrelated factors, including precursor composition and reactivity, alkaline activator characteristics, liquid content, aggregate proportions and curing conditions (Enoh & Ushie, 2023; Magugu et al., 2025; Provis, 2018; Ryu et al., 2015; Sunarsih et al., 2024)

Under ambient curing, low-calcium fly ash systems often exhibit relatively slow strength development because geopolymerisation proceeds less rapidly at room temperature. Incorporation of calcium-rich GGBS can improve ambient-cured strength by increasing precursor reactivity and promoting the formation of calcium-containing reaction products alongside the aluminosilicate geopolymer network (Deb et al., 2014; Ismail et al., 2014; Nath & Sarker, 2014). Consequently, FA–GGBS blends have been widely investigated as a means of achieving adequate strength without elevated-temperature curing (Ganesan & Ravichandran, 2026; Hadi et al., 2017). However, the extent of strength improvement depends on GGBS proportion, precursor characteristics and the composition of the alkaline activator.

Alkaline activator parameters are similarly important, but their effects are strongly dependent on the overall mixture composition. NaOH concentration influences precursor dissolution, while the sodium silicate-to-sodium hydroxide ratio (SS/SH), activator-to-binder ratio and water content affect soluble silicate availability, alkalinity, workability and pore development (Fernández-Jiménez & Palomo, 2005). Optimum values reported for these parameters vary considerably among experimental studies because precursor chemistry, material sources and mixture proportions differ (Adam et al., 2019; Albidah et al., 2021; Provis, 2018). This variability limits the direct transfer of optimum mixture proportions from one precursor system to another.

Data-driven approaches provide an opportunity to examine geopolymer mixture parameters across broader experimental domains than are typically covered in individual experimental programmes. Previous studies have applied statistical and machine-learning approaches to investigate geopolymer compressive strength and the relative importance of mixture variables (Enoh, 2026; Rathnayaka et al., 2024; Tran, 2023). Tran (2023), for example, analysed 158 FA–slag geopolymer concrete mixtures and identified slag content, NaOH molarity, aggregate content and activator-to-binder ratio among important strength-related variables. Recent reviews have similarly demonstrated growing application of data-driven methods to geopolymer strength prediction while emphasising the importance of appropriate mixture and material descriptors (Rathnayaka et al., 2024). However, much of this work has focused on strength prediction and model performance, rather than direct statistical comparison of precursor systems and assessment of whether their strength differences persist after accounting for activator and mixture-design variables.

The present study therefore examines the relationships between precursor composition, alkaline activator characteristics, mixture-design parameters and 28-day compressive strength using a curated database of 251 ambient-cured geopolymer concrete mixtures comprising FA-only, FA–GGBS blended and GGBS-only systems. Descriptive statistics, non-parametric comparisons, effect-size analysis and multivariable regression are used to evaluate precursor-system differences and the influence of GGBS fraction, NaOH molarity, SS/SH ratio, activator-to-binder ratio, W/S ratio and aggregate characteristics. The study aims to identify the mixture characteristics most consistently associated with high ambient-cured compressive strength and to distinguish broad cross-study trends from conditions that remain dependent on the specific precursor–activator system.

2. Materials and Methods

2.1 Database Development

A multi-study database was compiled from published experimental studies on geopolymer concrete containing fly ash (FA), ground-granulated blast-furnace slag (GGBS), or combinations of both as precursor materials. The analysis was restricted to concrete mixtures containing coarse aggregate, thereby excluding geopolymer paste and mortar formulations. Only mixtures with reported 28-day compressive strength under ambient curing conditions were retained.

Relevant mixture-design information was extracted from the selected studies, including precursor quantities, alkaline activator characteristics, water content and aggregate proportions. Where a study reported multiple distinct mixture formulations, each formulation was treated as a separate observation. Mixture quantities were standardised to consistent units to enable comparison across studies.

The resulting database contained 251 mixtures with sufficient information for the variables considered in the present analysis.

2.2 Precursor Classification and Derived Mixture-Derived Parameters

The 251 mixtures were classified into three precursor systems according to their FA and GGBS contents: FA-only (n = 47), FA–GGBS blended (n = 100) and GGBS-only (n = 104). This classification was used for comparison of compressive-strength distributions among the precursor systems. To additionally represent precursor composition on a continuous scale, the relative contribution of GGBS was expressed as:

$$GGBS\ fraction, G_f = \frac{GGBS}{GGBS+FA} \quad (2.1)$$

Where a value of 0 represents an FA-only system and 1 represents a GGBS-only system

Other mixture-design parameters were derived from the reported constituent quantities as follows:

$$Sodium\ silicate - to - sodium\ hydroxide\ \ SS/SH = \frac{Na_2SiO_3}{NaOH} \qquad (2.2)$$

$$Total\ alkaline\ content, A = \ Na_2SiO_3 + NaOH \qquad (2.3$$

$$Activator - to - binder\ ratio, A/B = \frac{NaOH + Na_2SiO_2}{FA + GGBS}$$
(2.4)

$$Total\ aggregate, A_{ggT} = F_{Agg} + C_{Agg}$$
(2.5)

$$Fine\ aggregate\ fraction = \frac{FA_{gg}}{FA_{gg} + CA_{gg}}$$
(2.6)

Where FA_{gg} and CA_{gg} represent fine and coarse aggregate respectively

These derived parameters enabled precursor, activator and aggregate characteristics to be compared on a proportional basis rather than solely through their absolute constituent quantities.

2.3 Statistical Analysis of Precursor Systems

Descriptive statistics were calculated for the 28-day compressive strength of the FA-only, FA–GGBS and GGBS-only precursor systems. Normality of the strength distributions was assessed using the Shapiro–Wilk test. As the distributions did not satisfy the assumption of normality, differences among the three precursor systems were evaluated using the Kruskal–Wallis test.

Where a significant overall difference was identified, pairwise comparisons were performed using Mann–Whitney U tests, with Holm adjustment applied to account for multiple comparisons. Cliff's delta (δ) was calculated to quantify the magnitude of the pairwise differences between precursor systems. Statistical significance was evaluated at $p < 0.05$.

2.4 Strength-Group Analysis

To examine mixture characteristics associated with different levels of compressive strength, the 251 observations were divided into low-, medium-, and high-strength groups based on tertiles of the 28-day compressive-strength distribution. Selected precursor, activator and aggregate parameters were then compared across the three groups. These included GGBS fraction, NaOH molarity, SS/SH ratio, activator-to-binder ratio, W/S ratio, total aggregate content and fine aggregate fraction.

Differences among the three strength groups were evaluated using the Kruskal–Wallis test. Where significant differences were identified, pairwise comparisons were performed using Mann–Whitney U tests with Holm adjustment for multiple comparisons.

2.5 Multivariable Analysis

A multivariable linear regression model was used to examine the association between mixture characteristics and 28-day compressive strength. The predictors included precursor system, NaOH molarity, SS/SH ratio, activator-to-binder ratio, W/S ratio, total aggregate content and fine aggregate fraction.

Precursor system was included as a categorical variable, with FA-only mixtures as the reference category. Continuous predictors were standardised prior to analysis to facilitate comparison of their regression coefficients. Heteroscedasticity-consistent HC3 robust standard errors were used for statistical inference.

Regression coefficients (β), robust standard errors, 95% confidence intervals and *p*-values were reported for each predictor. Model performance was summarised using R2 and adjusted R2. A significance level of $\alpha=0.05$ was adopted.

2.6 Parameter Interaction and Scope of Analysis

Selected mixture parameters were examined jointly to explore relationships that might not be evident from individual-variable comparisons. Particular attention was given to the relationship between precursor composition and NaOH molarity, as well as the continuous relationship between GGBS fraction and compressive strength. NaOH molarity was grouped into concentration intervals to compare mean compressive strength across the three precursor systems, while locally weighted smoothing (LOESS) was used to examine possible nonlinear variation in compressive strength with GGBS fraction.

The analyses were interpreted within the range of mixtures represented in the database. Because the observations originated from different experimental programmes, differences in precursor chemistry, particle characteristics, sodium silicate composition and other inconsistently reported material properties could not be incorporated. The statistical relationships therefore represent associations within the compiled database rather than causal effects or universal optimum mixture proportions.

3. Results and Discussion

3.1 Characteristics of the Database and Precursor Systems

The 28-day compressive strength of the 251 mixtures ranged from 8.00 to 81.24 MPa, with an overall mean of 41.20 MPa. Clear differences were observed among the precursor systems (Table 1). FA-only mixtures exhibited the lowest mean compressive strength (26.07 MPa), followed by FA–GGBS blends (39.78 MPa), while GGBS-only mixtures recorded the highest mean strength (49.56 MPa). Median values followed the same trend.

Table 1: Compressive-strength characteristics of the precursor systems

Precursor system	n	Mean (MPa)	SD (MPa)	Median (MPa)	Minimum (MPa)	Maximum (MPa)
Fly ash only	47	26.07	12.28	25.00	10.00	56.90
FA-GGBS blend	100	39.78	17.99	37.50	8.00	80.00
GGBS only	104	49.56	15.47	47.92	16.69	81.24

The differences among the three precursor systems were statistically significant (Kruskal–Wallis, $p < 0.001$). The higher strengths associated with GGBS-containing systems are consistent with experimental studies showing improved ambient-cured strength following GGBS incorporation into fly ash geopolymer concrete (Deb et al., 2014; Nath & Sarker, 2014). Nath and Sarker specifically investigated GGBFS additions up to 30% under ambient curing at approximately 20–23 °C and reported enhanced strength development, while Deb et al. similarly found increasing strength with GGBFS incorporation under ambient curing.

Despite the overall progression in mean strength, the distributions overlapped considerably. FA–GGBS blends reached 80.00 MPa, close to the maximum of 81.24 MPa for GGBS-only mixtures, while FA-only mixtures reached 56.90 MPa. The results therefore indicate a strong association between precursor system and compressive strength, rather than an absolute separation among the three systems.

3.2 Pairwise Differences Between Precursor Systems

Pairwise analysis confirmed differences among the three precursor systems *Table 2*. GGBS-only mixtures exhibited a mean compressive strength 23.50 MPa higher than FA-only mixtures and 9.79 MPa higher than FA–GGBS blends, while FA–GGBS blends were 13.71 MPa higher than FA-only mixtures. All pairwise differences remained statistically significant after Holm adjustment ($p < 0.001$).

Table 2: Pairwise comparison of compressive strength among precursor systems

Comparison	Mean difference (MPa)	Cliff's δ	Holm-adjusted p
GGBS only vs FA-GGBS blend	+9.79	0.311	< 0.001
GGBS only vs fly ash only	+23.50	0.760	< 0.001
FA-GGBS blend vs fly ash only	+13.71	0.515	< 0.001

The largest effect size was observed between GGBS-only and FA-only mixtures ($\delta = 0.760$), followed by FA–GGBS and FA-only mixtures ($\delta = 0.515$), while the GGBS-only versus FA–GGBS comparison

showed a smaller effect (δ = 0.311). This indicates a greater distinction between FA-only and GGBS-containing systems than between blended and GGBS-only systems.
The observed pattern is consistent with experimental studies showing that GGBS incorporation can enhance the compressive strength of FA-based geopolymer concrete, while the resulting performance also depends on precursor proportion and other mixture-design parameters. Rao & Rao (2018), for example, identified GGBS content, alkaline solution-to-binder ratio and curing condition as influential parameters in FA–GGBS geopolymer concrete.

3.3 Influence of GGBS Fraction on Compressive Strength

The categorical comparison of precursor systems does not capture compositional variation within FA–GGBS blended mixtures. GGBS fraction was therefore examined as a continuous measure of precursor composition, ranging from 0 for FA-only mixtures to 1 for GGBS-only mixtures. As shown in Figure 1 compressive strength generally increased with increasing GGBS fraction, although considerable variation was observed across the composition range.
The observed trend indicates that greater GGBS contribution was generally associated with higher ambient-cured compressive strength, but the substantial scatter shows that precursor composition alone does not account for the observed strength variation. This agrees with controlled experimental studies in which increasing GGBS proportion improved the compressive strength of FA–GGBS geopolymer concrete under ambient curing (Verma & Dev, 2021). Similar increases have been reported across mixtures containing progressively greater GGBS proportions, although the resulting strength remains dependent on the overall mixture and curing conditions.

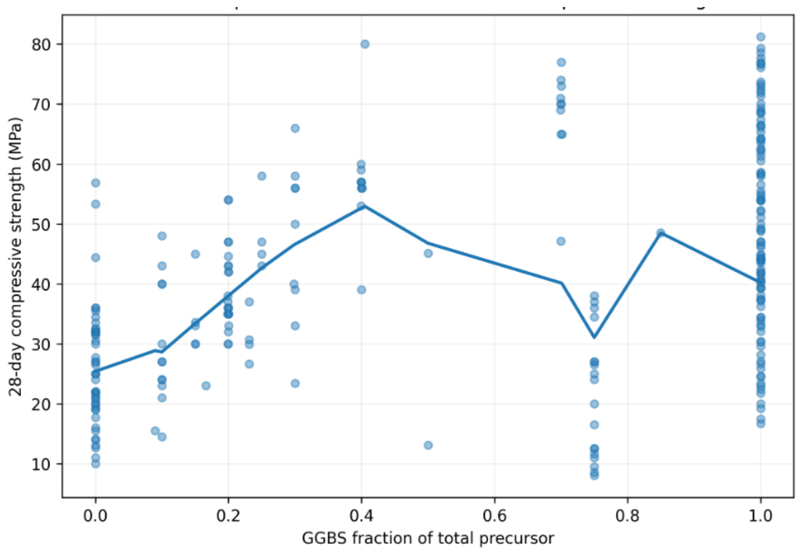

Figure 1: Relationship between GGBS fraction and 28-day compressive strength. The fitted LOESS curve illustrates the overall trend within the database.

3.4 Influence of Alkaline Activator Parameters

NaOH molarity in the database ranged from 1 to 20 M, with a mean of approximately 8.35 M. Unlike GGBS fraction, NaOH molarity showed no clear monotonic relationship with compressive strength across the complete database. When considered across the three precursor systems (Figure 3), substantial strength variation remained within similar molarity ranges, indicating that the relationship between NaOH concentration and strength varied with precursor composition.
Experimental studies similarly indicate that increasing NaOH concentration does not necessarily produce a continuous increase in strength. For ambient-cured FA–GGBS concrete, Ghafoor et al. (2024), reported increasing compressive strength between 8 and 12 M NaOH, followed by lower strength at 14 M. Niş (2019), likewise demonstrated that compressive strength varied with both NaOH concentration and SS/SH ratio in FA–GGBS concrete. These findings support the variation observed in

the present database and indicate that NaOH molarity is better considered in relation to the overall activator and precursor composition.

The SS/SH ratio showed a negative adjusted association with compressive strength in the multivariable analysis. However, this relationship occurred across mixtures with different precursor proportions and activator quantities and therefore represents the overall pattern within the compiled database. Experimental investigations have similarly shown that the influence of SS/SH varies with NaOH concentration and precursor composition (Niş, 2019; Sunarsih et al., 2024).
In contrast, activator-to-binder ratio was not significantly associated with compressive strength after multivariable adjustment. Although sufficient activator is required for precursor dissolution and reaction, its influence depends on the amount and characteristics of the precursor and the composition of the activating solution. Consequently, the results indicate that the strength relationships associated with alkaline activation arise from the combined mixture composition rather than from a single activator parameter.

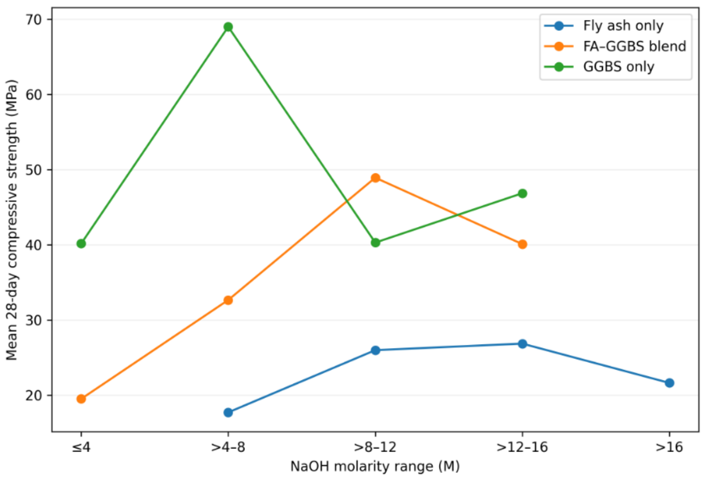

Figure 2: Variation in mean 28-day compressive strength with NaOH molarity across fly ash-only, FA–GGBS blended and GGBS-only precursor systems.

3.5 Influence of Water-to-Solids Ratio

The W/S ratio ranged from approximately 0.18 to 0.53 within the database. No clear decrease in compressive strength with increasing W/S was observed across the complete dataset. In the multivariable analysis, W/S instead showed a positive adjusted association with compressive strength. This contrasts with controlled experimental studies in which increasing W/S generally reduced compressive strength. Rafeet et al. (2017), demonstrated the importance of water content in FA–GGBS alkali-activated concrete, while Adam et al. (2019),reported higher compressive strength at lower W/S ratios in ambient-cured fly ash geopolymer concrete.
The positive association observed in the present database may reflect the heterogeneous mixture composition, where W/S varied simultaneously with precursor type, activator characteristics and other mixture parameters. Water-related effects may also vary with the binder system and investigated composition range. Consequently, the observed relationship appears to reflect differences among the represented mixture systems rather than a direct strength-enhancing influence of increasing water content.

3.6 Adjusted Influence of Precursor System

Multivariable analysis was used to examine whether differences among precursor systems persisted after accounting for selected activator and aggregate characteristics. With FA-only mixtures as the reference category, FA–GGBS blends showed an adjusted strength difference of approximately +19.5 MPa, while GGBS-only mixtures showed a difference of approximately +36.6 MPa; both were statistically significant ($p < 0.001$) (*Table 3*).
The persistence of the precursor-system differences after adjustment confirms that precursor composition was strongly associated with compressive strength within the investigated database. This

agrees with experimental evidence showing improved ambient-cured strength with increasing GGBS contribution in FA–GGBS systems (Rafeet et al., 2017; Verma & Dev, 2021). Data-driven evidence also supports the importance of slag content: Tran (2023), using 158 FA–slag geopolymer concrete mixtures, identified slag content among the most influential variables affecting compressive strength.
NaOH molarity, SS/SH ratio and W/S ratio also showed significant adjusted associations, whereas activator-to-binder ratio and the aggregate variables were not significant after adjustment. The model explained approximately 40% of the observed strength variation (adjusted $R^2 \approx 0.397$), indicating that substantial variability remained unaccounted for by the included mixture parameters.

Table 3: Multivariable regression of mixture-design parameters on 28-day compressive strength

Predictor	Coefficient, β (MPa)	Robust SE	95% CI	p-value
Intercept	18.30	2.72	12.98 to 23.63	<0.001
FA-GGBS blend	19.52	2.90	13.84 to 25.21	<0.001
GGBS only	36.64	4.64	27.56 to 45.73	<0.001
NaOH molarity	8.42	1.93	4.65 to 12.19	<0.001
W/S ratio	4.22	1.61	1.07 to 7.37	0.009
SS/SH ratio	-5.42	1.12	-7.62 to -3.23	<0.001
Activator/binder ratio	-0.66	1.11	-2.83 to 1.51	0.550
Total aggregate	-0.93	1.32	-3.51 to 1.65	0.480
Fine aggregate fraction	-0.09	1.88	-3.78 to 3.59	0.961

Model statistics: n = 251: R^2 =0.416; adjusted R^2 = 0.397; overall model $p < 0.001$
FA-only was the reference precursor category. Continuous predictors were standardised before regression; their coefficients therefore represent the estimated change in compressive strength associated with a one-standard-deviation increase in the predictor. HC3 robust standard errors were used.

3.7 Mixture Characteristics Associated with High Compressive Strength

The database was divided into low-, medium- and high-strength groups to identify mixture characteristics associated with increasing compressive strength. The groups contained 88, 79 and 84 mixtures, respectively. Their selected mixture characteristics are compared in Table 4.
The clearest difference among the strength groups was GGBS fraction, which increased from 0.352 in the low-strength group to 0.787 in the high-strength group ($p < 0.001$). This confirms the greater representation of GGBS-rich mixtures at higher strength levels. Similar relationships between increasing GGBS content and compressive strength have been reported in FA–GGBS alkali-activated concrete (Rafeet et al., 2017; Verma & Dev, 2021). Rafeet et al. (2017), for example, found that increasing GGBS content increased compressive strength, although other mixture characteristics also influenced performance.
In contrast, NaOH molarity, SS/SH ratio, activator-to-binder ratio and W/S ratio did not differ significantly among the three strength groups. Thus, the high-strength mixtures were not characterised by a single range of these activator parameters. This is consistent with experimental mix-design studies showing that geopolymer strength depends on combinations of precursor content, activator proportion and other mixture parameters rather than any single mixture variable (Rafeet et al., 2017; Rao & Rao, 2018).
Total aggregate content and fine aggregate fraction also differed significantly among the strength groups ($p = 0.003$ and $p = 0.016$, respectively). However, their differences were smaller than the progression observed for GGBS fraction and may partly reflect variation in the mix-design approaches represented in the source studies. Aggregate proportion forms part of the overall geopolymer concrete mix design and operates together with binder and activator quantities rather than as an isolated strength-controlling parameter.
Overall, the high-strength region of the database was most clearly characterised by greater GGBS contribution, while no comparable high-strength range emerged for the individual activator parameters. Pairwise comparison of the high- and low-strength groups confirmed significant differences in GGBS fraction ($p < 0.001$) and total aggregate content ($p = 0.023$) after Holm adjustment, while differences in the individual activator parameters were not significant.

Table 4:Mixture characteristics across compressive-strength groups

Parameter	Low strength	Medium strength	High strength	p
GGBS fraction	0.352	0.569	0.787	<0.001
NaOH molarity	8.46	8.24	8.12	0.742
SS/SH ratio	6.04	2.73	2.33	0.254
Activator/Binder ratio	0.454	0.421	0.437	0.178
W/S ratio	0.329	0.322	0.331	0.590
Total aggregate	1718.10	1807.33	1818.85	0.003
Fine aggregate fraction	0.411	0.407	0.431	0.016

Values are group means; p-values were obtained from Kruskal–Wallis tests.

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3.8 Engineering Implications and Limitations

The findings highlight the importance of precursor composition in the design of ambient-cured geopolymer concrete. The greater representation of GGBS-rich systems at higher strength levels indicates that GGBS incorporation provides a practical route to improved 28-day strength where elevated-temperature curing is undesirable. However, the high strengths achieved by several FA–GGBS blends show that complete replacement of fly ash by GGBS is not necessary for favourable performance. Effective mixture design therefore requires appropriate combinations of precursor and activator characteristics rather than reliance on a single precursor proportion.

The results also demonstrate that individual activator parameters cannot be used alone to define high-strength mixtures. Although NaOH molarity, SS/SH ratio and W/S showed significant adjusted associations with compressive strength, these variables did not individually distinguish the high-strength group. This reinforces the need to consider precursor and activator characteristics together during mixture optimisation. Recent mix-design studies similarly emphasise the combined influence of precursor type, activator composition and other mixture parameters on geopolymer performance.

The study is limited by the heterogeneous nature of the literature-derived database. The 251 mixtures originated from different experimental programmes and therefore varied in material sources, mixture proportions and testing conditions. Important characteristics such as precursor chemical composition, fineness, amorphous content and sodium silicate modulus were not consistently available and could not be incorporated into the analysis. The importance of such additional material descriptors is supported by recent literature-derived modelling, where inclusion of fly-ash oxide composition, curing conditions and activator characteristics substantially improved strength prediction (Rathnayaka et al., 2024). The present findings are also restricted to 28-day ambient-cured geopolymer concrete and may not apply directly to other curing conditions or ages.

Within these limitations, the analysis identifies broad mixture-design relationships across FA-only, FA–GGBS and GGBS-only systems and provides a basis for selecting promising composition ranges for subsequent controlled experimental optimisation.

4. Conclusions

This study examined the relationships between precursor composition, alkaline activator characteristics, mixture-design parameters and 28-day compressive strength using a database of 251 ambient-cured geopolymer concrete mixtures. The principal findings are:

1. Precursor composition was a major discriminator of compressive strength. Strength increased progressively from FA-only to FA–GGBS blended and GGBS-only systems, with significant differences among all three precursor groups.
2. Higher-strength mixtures were increasingly associated with greater GGBS contribution. The continuous GGBS-fraction analysis and strength-group comparison both showed greater representation of GGBS-rich systems at higher compressive strengths.
3. Individual activator parameters did not define a universal high-strength mixture range. NaOH molarity, SS/SH ratio, activator-to-binder ratio and W/S ratio did not significantly distinguish the low-, medium- and high-strength groups. However, NaOH molarity, SS/SH and W/S showed significant associations after multivariable adjustment, indicating that their relationships with strength depend on the broader mixture composition.

4. Precursor-system differences persisted after multivariable adjustment. FA–GGBS and GGBS-only systems remained significantly associated with higher compressive strength relative to FA-only mixtures after accounting for selected activator and aggregate characteristics.
5. GGBS-only mixtures did not represent a universal optimum. Several FA–GGBS blends achieved strengths approaching the upper range of the GGBS-only systems, demonstrating that high ambient-cured strength can also be achieved through suitable precursor–activator combinations.

Overall, the findings identify precursor composition, particularly GGBS contribution, as an important characteristic associated with higher 28-day ambient-cured compressive strength, while the relationships of individual activator parameters remain dependent on the overall mixture context. Future database studies incorporating precursor chemistry, fineness, amorphous content and detailed activator characteristics could provide a stronger basis for transferable geopolymer mix-design relationships. These material descriptors are well established as relevant to geopolymer reactivity and strength

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