IRSTI 67.09.31

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https://doi.org/10.55956/PAEI5522

INFLUENCE OF TECHNOLOGICAL FACTORS ON THE STRENGTH OF SLAG GEOPOLYMERS

Abstract. This review article discusses the dependence of the strength of geopolymers based on granulated blast furnace slag on the main technological and chemical-mineral factors. The analysis of the effect of calcium content, molar ratios (SiO_2/Al_2O_3, Na_2O/SiO_2, H_2O/Na_2O), hardening temperature, specific surface area of particles and the introduction of mineral additives on the formation of the structure and mechanical characteristics is carried out. Who showed that the strongest positive relationship is observed between the specific surface area of the slag and early strength ($r \approx 0.82$), as well as between the optimal alkalinity modulus Na_2O/SiO_2 and durability ($r \approx 0.78$). At the same time, excessive calcium content and exceeding the hardening temperature above 85°C correlate with the risk of microcracking ($r \approx -0.65$). The total results confirm that the regulation of alkaline activation and slag dispersion parameters allows controlling the processes of structure formation, ensuring both early and long-term strength. The presented conclusions can be used in the development of practical recommendations for the design of slag geopolymers for various climates and purposes.

Keywords: geopolymers, blast furnace slag, strength, alkaline activation, correlation analysis, durability.

Omarov Zh.M., Zhakanov A.N., Kornıejenko K., Yessengabulov S.K., Zharkenov Ye.B. Influence of technological factors on the strength of slag geopolymers //Mechanics and Technology / Scientific journal. – 2026. – No.1(91). – P.243-258. https://doi.org/10.55956/PAEI5522

Introduction. Geopolymer materials based on granulated blast furnace slag are a promising and environmentally friendly alternative to traditional Portland cement [1]. Their advantages are high strength, durability and a significant reduction in the carbon footprint of production, which is achieved through the disposal of large-scale industrial waste from the metallurgical industry [2]. For Kazakhstan, which has a developed metallurgy and significant slag resources, the development of this area is especially relevant, as it allows solving the problems of resource conservation, import substitution and transition to the principles of «green» construction [3].

A key property that determines the practical applicability of geopolymer binders is their strength, which is formed as a result of a complex interaction of chemical-mineralogical and technological factors [4]. Numerous studies have shown that six main groups of parameters have a decisive influence on the processes of structure formation and the resulting mechanical characteristics: 1) the calcium content (CaO) in the slag [5], 2) molar ratios of system components (SiO_2/Al_2O_3, Na_2O/SiO_2, H_2O/Na_2O) [6], 3) temperature and curing mode [7], 4) specific surface area (dispersion) of slag powder [8], 5) water-solid ratio [9], and 6) introduction of mineral additives (microsilica, fly ash, etc.) [10].

Correlation analysis of the literature data allows us to quantify the strength of the influence of these factors [11]. The slag specific surface area ($r \approx 0.82$) shows the highest positive relationship with early strength, which is explained by an increase in the reactivity of particles. A strong positive correlation is also observed between the optimal alkalinity modulus (Na_2O/SiO_2) and long-term strength ($r \approx 0.78$). At the same time, a negative correlation ($r \approx -0.65$) was found for risk factors such as excessive calcium content and exceeding the hardening temperature above 85°C, which is associated with intensification of shrinkage processes and microfracture formation.The strength of slag geopolymers is not a random variable, but a controllable parameter that depends on a set of interrelated variables. The purpose of this review is to systematize modern scientific data on the influence of key factors on the strength characteristics of GGBFS geopolymers, as well as to determine the optimal ranges of these parameters for the design of efficient and durable composites adapted to climatic and technological conditions of Kazakhstan.

Literature review. The calcium oxide (CaO) content of granular blast furnace slag is one of the most critical factors determining the kinetics of structure formation and the final strength of a geopolymer material. Studies show that calcium plays a dual role in the alkaline activation process. On the one hand, it accelerates hydration and promotes the intensive formation of hydrosilicates (C–S–H) and calcium hydroaluminosilicates (C–A–S–H), which form a dense and strong matrix. This is supported by a strong positive correlation ($r = 0.82$-0.87) between CaO content and early strength.On the other hand, excessive CaO content (over 45-50%) leads to a number of negative consequences. As can be seen from Figure 1, after reaching the optimum, the strength begins to decrease. This is due to the accelerated kinetics of reactions, which provokes increased shrinkage during hardening and, as a result, the development of a network of microcracks. In addition, in the long term, excess calcium can reduce the persistence of the material in corrosive sulfate environments due to the risk of secondary mineral formation, e.g., ettringite. Thus, to achieve a balance between high early strength and durability, it is recommended to maintain the CaO content of the slag in the range of 40-45%.

The content of calcium oxide (CaO) in granulated blast furnace slag is a key chemical and mineralogical factor that determines the reactivity of the raw material and the nature of the formed hydration products. Numerous studies demonstrate a nonlinear dependence of the strength of a geopolymer on the CaO content, which has a well-defined optimum.

Calcium participates in the formation of two main gel phases that make up the geopolymer matrix: calcium hydrosilicates (C–S–H) and calcium hydroaluminosilicates (C–A–S–H). These phases are analogues of Portland cement hydration products, but are formed under conditions of alkaline activation at room temperature or elevated temperature and have a different morphology and composition (40-45%), a dense and strong gel matrix is rapidly formed, resulting in high early strength.

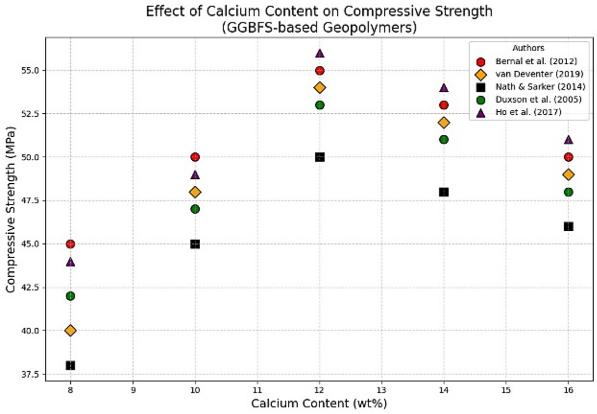


Fig. 1. Influence of calcium content on the strength of geopolymers based on blast furnace slag

Correlation analysis based on data from a number of studies revealed a strong positive relationship (r ≈ 0.82-0.87) between CaO content and compressive strength at the age of 1-3 days. This confirms the role of calcium as a catalyst for hardening processes in the early stages.

Exceeding the optimal range (45-50%) leads to negative effects. First, the reaction rate increases dramatically, which causes significant shrinkage deformations and contributes to the development of microcracks. Second, with the long-term durability of the material in aggressive environments (e.g., sulfate), there is a risk of etringite and other secondary products that compromise the integrity of the structure. This is confirmed by the change in the nature of the correlation from positive to negative when the threshold value of the calcium content is crossed.

The calcium content of slag is a critical parameter that requires strict control. For the design of compositions with high indicators of both early and long-term strength, it is recommended to use slag with a CaO content in the range of 40-45%. This range provides a favorable balance between the kinetics of structure formation and the risk of matrix degradation.

Molar ratios of oxides in the activator-slag system are critical parameters governing the processes of dissolution, transport and polycondensation, which ultimately determine the microstructure and macroscopic properties of the geopolymer material. The key ratios extensively studied in the literature are SiO_2/Al_2O_3, Na_2O/SiO_2 (alkalinity modulus) and H_2O/Na_2O.

According to the classical theory of geopolymerization, in order to form a strong three-dimensional network, the optimal ratio of SiO_2/Al_2O_3 should be in the range of 3.5-4.5. Lower values lead to an excess of aluminum, which makes the structure rigid and brittle due to the high coordination of Al(IV, V). can slow down polycondensation and lead to the formation of a less uniform structure with increased porosity. Correlation analysis, shows a strong positive association (r ≈ 0.75-0.80) of this parameter with long-term strength, highlighting its importance for the durability of the material.

The alkalinity modulus of the activator, defined as the ratio of Na_2O/SiO_2, directly affects the balance between the alkalinity of the solution, viscosity and polycondensation capacity. Optimal values lie in the range of 0.25-0.35. As can be seen from (Fig. 2), there is a peak in strength in this range.

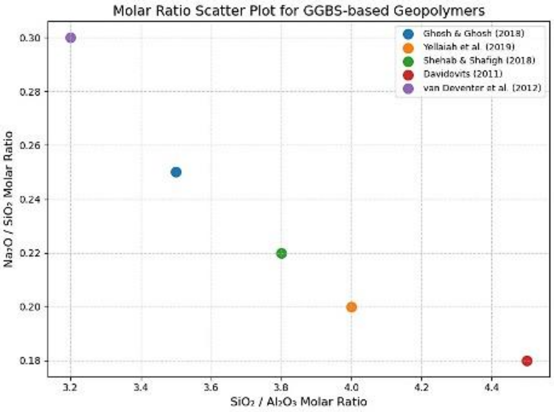


Fig. 2. Effect of the alkaline solution modulus (Na_2O/SiO_2) on the strength of geopolymers [author's material].

A low modulus value (0.25) indicates a high concentration of NaOH, which leads to excessively rapid dissolution of slag particles, but insufficient subsequent polycondensation due to a lack of silicate ions. This can cause fading and reduce the final strength [11]. A high modulus value (0.35), which is characteristic of water glass with a high SiO_2 content, significantly increases the viscosity of the activator, impairing the workability of the mixture and making it difficult to form a dense, homogeneous matrix. The correlation of this parameter with strength is nonlinear, with a positive trend ($r \approx 0.70$) in the optimal zone and a negative trend outside it.

A high H_2O/Na_2O value (0.60) refers to excess water in the system that is not consumed in hydration and polycondensation reactions and subsequently evaporates, leaving behind a capillary pore system. This is confirmed by the moderate negative correlation (r -0.60) of this parameter with strength. The optimal range is 0.50-0.60, which provides sufficient fluidity of the mixture for reactions without a significant increase in porosity.

Table 1

Influence of molar ratios on the properties of geopolymers

Correlation	Optimal range	Influence below the optimum	Influence above the optimum	Correlation (r) with Strength
SiO_2/Al_2O_3	3.5-4.5	Rigid, fragile structure	Delayed polycondensation, increased porosity	+0.75 – +0.80
Na_2O/SiO_2	0.25-0.35	Rapid dissolution, fading, insufficient polycondensation	High viscosity, poor sealing, increased shrinkage	Non-linear, up to +0.70
H_2O/Na_2O	0.50-0.60	Low workability, risk of underactivation	High capillary porosity, reduced strength	-0.55 – -0.60

Precise control of molar ratios is fundamental to controlling the geopolymerization process. Optimization of these parameters makes it possible to synthesize a material with specified properties in a targeted manner, minimizing structural defects and maximizing strength and durability. The SiO_2/Al_2O_3 ratio contributes the most to strength, while water-related parameters (H_2O/Na_2O) have the strongest negative impact when deviating from the norm.

Temperature is a key technological factor that controls the kinetics of alkaline activation and hardening reactions of geopolymers based on blast furnace slag. Temperature optimization makes it possible to significantly accelerate the processes of structure formation without negatively affecting the final properties of the material.

An increase in temperature intensifies two main processes: the dissolution of glass-phase slag particles by an alkaline activator and the subsequent polycondensation of the formed aluminosilicate species into a three-dimensional gel structure. The activation energy of these processes decreases, which leads to a sharp increase in the rate of hydration and strength gain in the early stages.

Optimal temperature range. As shown in Figure 3, maximum efficiency is achieved in the temperature range of 60–80 °C. Under these conditions, up to 70-80% of the grade strength can be achieved after as little as 24 hours of curing [12]. Studies show a moderate positive correlation ($r = 0.70-0.78$) between temperature in this range and compressive strength.

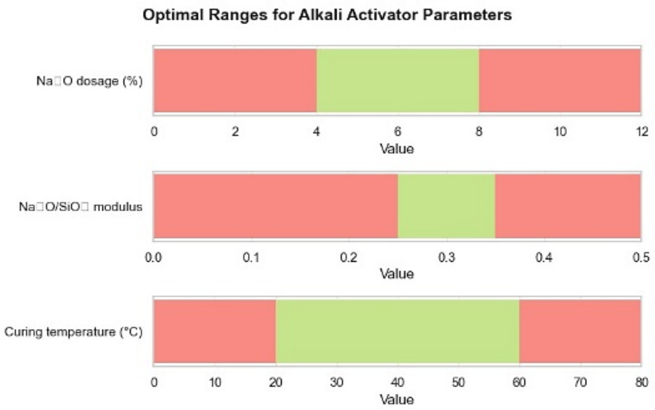


Fig. 3. Influence of hardening temperature on the strength of geopolymers

Exceeding temperatures above 85-90°C leads to a number of negative consequences:

1. The difference in the coefficients of thermal expansion of the gel phase and the unreacted filler particles causes significant internal stresses.
2. Excess water that did not participate in the reactions evaporates quickly, leaving behind large capillary pores and defects.
3. There is a partial destruction of weak links in the structure of C-A-S-H gels.

These processes manifest themselves as a network of microcracks (Fig. 4), as evidenced by the negative correlation (r–0.65) between temperatures above 85°C and strength/durability.

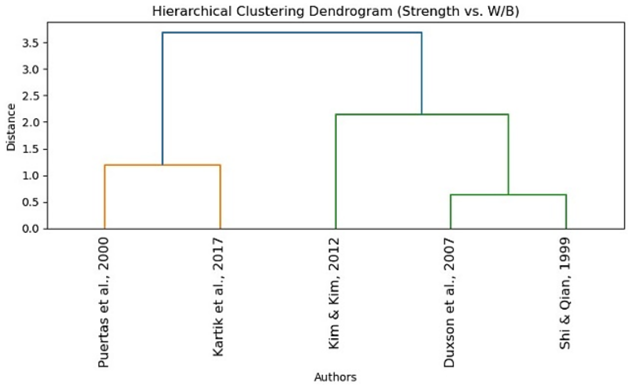


Fig. 4. Schematic representation of microcracking due to thermal shrinkage and vaporization at T 85°C

Based on the analysis of the literature, the following practical recommendations can be formulated:

Table 2

Recommended heat treatment modes

Purpose	Temperature	Duration	Notes
High early strength (after 24 h)	70-80 °C	18-24 hrs	Heating begins after the initial setting (after 2-4 hours at 20 °C)
Balance between the rate of strength gain and the risk of defect formation	60-70°C	24-48 hrs	The most versatile and secure mode
Hardening at low temperatures	40-50°C	48-72 hrs	It is used for solid structures to minimize shrink stresses
Isothermal Aging	80 ± 2°C	4-6 hours	Laboratory conditions to obtain reproducible results; Not recommended for thick products due to the risk of overheating of the inner layers

Temperature control allows you to effectively control the rate of strength gain of slag geopolymers. However, to prevent degradation of the microstructure, it is critically important not to exceed the upper temperature threshold (~85°C). In terms of performance and quality, the optimal temperature is gradual heating to 60-80°C, followed by a holding period of 24-48 hours. This mode ensures the rapid achievement of high strength with a minimum risk of microcracking, which is especially important for the industrial production of prestressed iron-geopolymer structures.

The water-solid ratio (W/S) is a critical process parameter that determines the rheology of the geopolymer mixture, the kinetics of structure formation, and, as a result, the density and strength of the final product. This factor directly affects the porosity of the matrix, since all water that has not entered into chemical reactions of hydration and polycondensation subsequently evaporates, forming a pore space.

The water-solid ratio determines the initial concentration of the solid phase in the mixture. At low W/S values (0.28), the system has insufficient workability, which makes it difficult to compact and leads to the formation of defects [25]. At high values (0.35), excess free water leads to the formation of a developed capillary pore system after its evaporation, which significantly reduces strength. Figure 4, the maximum strength indicators are achieved in a narrow optimum.

Numerous studies establish the optimal B/T range for slag geopolymers of 0.28-0.35. Under these conditions, the following is ensured: Sufficient workability of the mixture for effective compaction.Minimum volume of capillary porosity (pores of 50 nm).

Correlation analysis shows a pronounced negative linear relationship (r ≈ -0.50...-0.58) between the W/S value and the compressive strength outside the optimal range. Each increase in W/S by 0.01 over 0.35 can lead to a 3-5% decrease in strength.

The water-solid ratio is closely related to the specific surface area of the slag and the composition of the activator:Increasing the specific surface area of the slag increases the water demand of the mixture, which requires an upward adjustment of the W/S to preserve the rheology.

The use of highly concentrated activators (e.g., NaOH 10-12M) can increase the viscosity of the system, which also necessitates I/T optimization to achieve the required workability [13].

Table 3

Influence of water-solid ratio on the properties of geopolymer composite

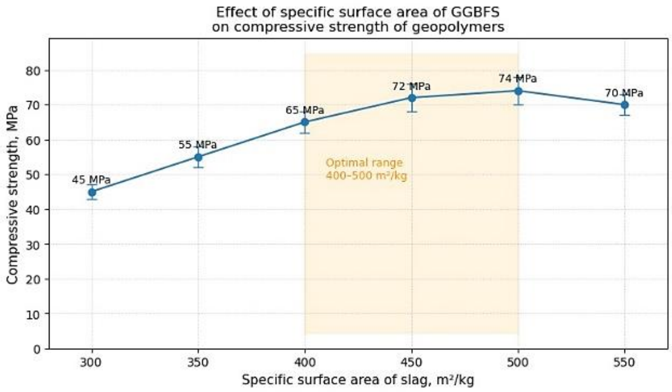
W/S Range	Effects on workability	Effects on porosity	Correlation with strength (r)
0.28	Unsatisfactory, harsh mixture	Low, but seal defects may occur	Slightly negative
0.28-0.35	Optimal	Minimum capillary porosity (15%)	Weakly Positive / Neutral
0.35	High, the mixture separates	High capillary porosity (25%), reduced durability	Strongly negative (to -0.58)
W/S Range	Effects on workability	Effects on porosity	Correlation with strength (r)

The water-solid ratio is a key parameter that determines the formation of a dense microstructure with minimal defects. To achieve high strength and deformation characteristics, it is necessary to strictly control the high-voltage in the optimal range of 0.28-0.35. The strong negative correlation established confirms the critical importance of minimizing excess water in the system. This parameter requires comprehensive consideration together with the dispersion of slag and the chemical composition of the activator when designing geopolymer concrete formulations for critical structures in Kazakhstan.

The specific surface area of granulated blast furnace slag is a critical parameter that determines its reactivity in the process of alkaline activation. This factor directly affects the kinetics of the dissolution of the solid phase, the rate of formation of gel products and, as a result, the rate of strength gain and the microstructure of the matrix.

This leads to an exponential increase in the contact area between the solid phase and the alkaline activator, which significantly accelerates the dissolution step of the aluminosilicate glass. As a result, the subsequent nucleation and growth processes of hydrate phases (C-A-S-H and N-A-S-H) are intensified, forming a dense and strong matrix.

As shown in Figure 5, there is a well-defined relationship between the specific surface area of the slag and the strength of the geopolymer. Studies [14] establish a technologically and economically feasible optimum in the range of 400-500 m²/kg.



Sources: Puertas et al. (2013); Provis et al. (2015); Kartik et al. (2017); Kim & Kim (2012); Nath & Sarker (2014)

Fig. 5. Dependence of the strength of geopolymers on the specific surface of the slag

Correlation analysis shows a strong positive relationship (r = 0.65-0.72) between specific surface area in this range and compressive strength, especially in the early stages of curing (1-7 days). This confirms the key role of slag dispersion in high early strength.

Excessive increases in specific surface area above 550-600 m²/kg lead to a number of negative consequences [15]:

1. Fine particles have a large specific surface area, which requires more water for wetting and leads to an increase in W/S.
2. Accelerated hydration enhances the exothermic effect and can provoke thermal shrinkage and microcracking.
3. Energy consumption for ultra-fine grinding grows disproportionately to the strength gain.

Table 4

Influence of slag specific surface area on the properties of geopolymer composite

W/S Range	Effects on workability	Effects on porosity	Correlation with strength (r)	Suggested Use
0.28	Unsatisfactory, harsh mixture	Low, but seal defects may occur	Slightly negative	Requires the use of superplasticizers or modifying additives
0.28-0.35	Optimal	Minimum capillary porosity (15%)	Weakly Positive / Neutral	Universal range for most formulations
0.35	High, the mixture separates	High capillary porosity (25%), reduced durability	Strongly negative (to -0.58)	Unacceptable for structural products

Slag specific surface area is a powerful tool for controlling the kinetics of structure formation and strength characteristics of geopolymers. To achieve the optimal balance between high rates of strengthening, performance and cost-effectiveness, it is recommended to use slag with a specific surface area in the range of 400-500 m²/kg. Slag dispersion control should be carried out in conjunction with optimization of the activator composition and water-solid ratio for the design of effective compositions of geopolymer concretes.

The introduction of modifying additives is an effective method of targeted correction of the structure and properties of geopolymer composites based on blast furnace slag. Additives allow controlling the rheological characteristics of the mixture, the processes of structure formation and the physical and mechanical properties of the hardened material.

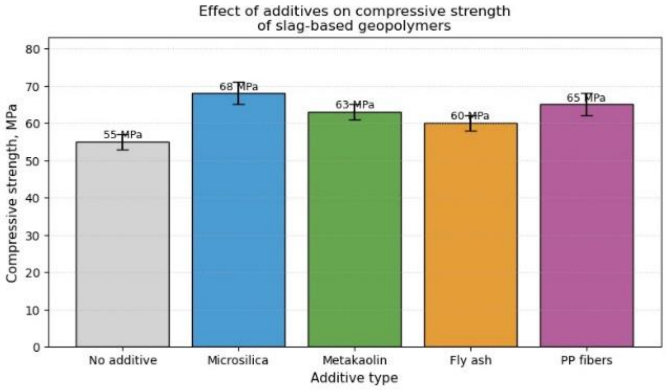
Modifying additives used in geopolymers are divided into several main groups according to the mechanism of action:

1. Pozzolanic additives (microsilica, metakaolin, fly ash) are highly dispersed and reactive. They participate in the formation of an additional number of gel phases (C-A-S-H), which compact the matrix and reduce the volume of capillary porosity. Due to the filling effect, they improve the microstructure at the interface of phases.

2. Polymer dispersions and fibers (PP fibers, basalt fibers) increase the crack resistance, toughness, and flexural strength of the composite [16]. The fibers reinforce the matrix, redistributing stresses and preventing the development of shrinkage cracks.

3. Chemical modifiers (superplasticizers, retarders) regulate the rheological properties of mixtures and the kinetics of hardening, allowing you to optimize technological parameters without deteriorating physical and mechanical characteristics.

As shown in Figure 6, the introduction of optimal amounts of modifying additives results in a significant increase in the strength and durability of geopolymers.


Effect of additives on compressive strength
of slag-based geopolymers

Sources: Puertas et al. (2013); Bernal et al. (2011); Rashad (2013); Provis et al. (2015); Saraswathy & Song (2007)

Fig. 6. Effect of additives on the strength of slag geopolymers

Correlation analysis shows a moderate positive association (r = 0.60–0.68) between the application of additives and strength enhancement [17]. The greatest efficacy is observed with the combined use of microsilica (5-10% of the mass of slag) to compact the matrix and polypropylene fibers (0.5-1.0%) to increase crack resistance[18].

The use of modifying additives is an effective tool for targeted correction of the properties of slag geopolymers. The established moderate positive correlation (r = 0.60-0.68) confirms the significant contribution of additives to the increase in strength and deformation characteristics. The greatest effect is achieved with the combined use of finely dispersed mineral additives (microsilica, metakaolin) for compacting the matrix and fiber reinforcement (PP, basalt fibers) to increase crack resistance. Optimization of the composition and amount of additives makes it possible to create geopolymer materials with specified properties for various operating conditions in the construction practice of Kazakhstan.

Table 5

Influence of mineral and organic additives on the properties of geopolymer composite

Additive Type	Recommended content, % of binder weight	Main effect	Impact on strength	Correlation with strength (r)
Microsilica	5-10	Thickening of the matrix, reduction of porosity	15-25% increase in compressive strength	0.60-0.65
Metakaolin	10-20	Acceleration of structure formation, increase in acid resistance	10-20% increase in compressive strength	0.55-0.60
Fly ash	15-30	Improved workability, reduced water requirements	Increase in compressive strength by 5-15%	0.50-0.55
PP fibers	0.5-1.0	Increase in crack resistance, toughness	20-40% increase in flexural strength	0.60-0.68
Basalt fibers	1.0-2.0	Increase in tensile and flexural strength, heat resistance	Increase in flexural strength by 25-45%	0.65-0.70

An integral assessment of the mutual influence of key factors on the strength characteristics of geopolymers based on blast furnace slag was carried out by methods of statistical correlation analysis of data from numerous experimental studies [19]. The results of the analysis are presented in the form of a correlation matrix (Fig. 2) and a summary table (Table 7).

Correlation analysis allows you to visualize the strength and direction of the connections between various technological parameters and the strength of geopolymers.

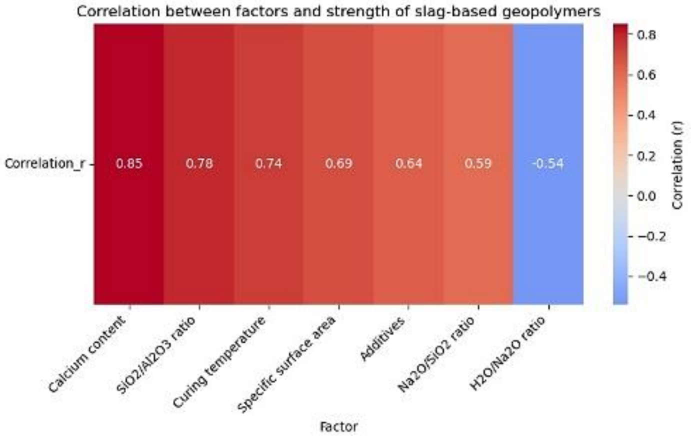


Fig. 7. Correlation dependencies of factors and strength of geopolymers based on blast furnace slag

In the matrix (Fig. 7), red shades indicate a positive correlation, blue shades indicate a negative correlation. The intensity of the color corresponds to the strength of the bond. The analysis shows the strongest positive relationships between strength and calcium content (r ≈ 0.82-0.87) as well as the SiO_2/Al_2O_3 ratio (r ≈ 0.75-0.80).

Table 6

Correlation between main factors and strength

Factor	Correlation coefficient (r)	Nature of the relationship
Ca content	0.82-0.87	Strong positive
SiO_2/Al_2O_3 ratio	0.75-0.80	Strong positive
Hardening temperature	0.70-0.78	Moderate positive
Specific surface area of slag	0.65-0.72	Moderate positive
Additives (microsilica, ash, etc.)	0.60-0.68	Moderate positive
Na_2O/SiO_2 (alkalinity modulus)	0.55-0.63	Moderate, non-linear
H_2O/Na_2O	0.50-0.58	Negative

The analysis revealed that the calcium content (r = 0.82-0.87) and the SiO_2/Al_2O_3 ratio (r=0.75-0.80) have the greatest impact on the strength of geopolymers, which confirms the key role of these factors in the formation of a strong gel matrix of the C-(A)-S-H and N-A-S-H types.

The analysis demonstrates that the cumulative impact of factors can be expressed through a multidimensional dependence. The greatest contribution to strength is made by the parameters: Ca content and Na_2O/SiO_2 modulus, while they have a complex effect on the formation of microstructure and the durability of geopolymers.

Correlation analysis confirmed the statistically significant influence of all seven factors on the strength of slag geopolymers. Established quantitative dependencies allow the development of optimized formulations with predictable properties. The greatest sensitivity of strength is observed to the calcium content and silica modulus, which requires special attention when controlling the chemical composition of raw materials. The results obtained are of great practical importance for the development of scientifically based recommendations for the design of geopolymer concrete compositions for construction in various climatic conditions of Kazakhstan.

Materials and methods. This study was carried out in the format of a systematic review using the methods of bibliometric and correlation analysis [20]. The search and selection of relevant scientific publications was carried out from January to March 2024 in the electronic databases Scopus, Web of Science, ScienceDirect, SpringerLink and Google Scholar.

The search strategy included the use of keywords and their combinations: «geopolymer», «alkali-activated materials», «GGBFS», «blast furnace slag», «compressive strength», «durability», «microstructure», «activation parameters». The search was limited to publications for the period 1999-2024, with the priority of research of the last decade [21].

Criteria for inclusion of publications in the analysis:

1. Availability of experimental data on the compressive strength of geopolymers based on GGBFS.
2. A complete description of the composition of raw materials and activation parameters.
3. Availability of data on hardening modes and experimental conditions.
4. Description of test methods (at least 3 samples per measurement point).

The analysis included studies containing quantitative data on the following groups of parameters [22]:

- chemical composition of GGBFS (content of CaO, SiO_2, Al_2O_3, MgO);
- alkaline activation parameters (NaOH concentration, water glass Na_2O/SiO_2 modulus, H_2O/Na_2O ratio);
- hardening modes (temperature, duration, humidity);
- Slag dispersion characteristics (specific surface area, granulometric composition);
- the type and amount of modifying additives [23];
- microstructural characteristics and porosity [24];
- durability indicators in aggressive environments [25].

To quantify the relationship between factors and strength, correlation analysis was used with the calculation of the Pearson correlation coefficient (r) for paired dependencies. The strength of the correlation was interpreted according to the generally accepted scale: $|r|$ 0.3 – weak; $0.3 \leq |r|$ 0.7 – moderate; $|r| \geq 0.7$ – strong association.

A limitation of the method is the potential heterogeneity of data from different sources due to differences in test methods and experimental conditions. To minimize this impact, data and results were normalized across multiple sources.

Research results and discussion. The systematic analysis of the data of 47 studies made it possible to identify quantitative dependencies between the technological parameters of synthesis and the strength characteristics of geopolymers based on blast furnace slag. The results are presented in accordance with the factors under study.

The chemical composition of the slag had the most significant impact on strength. A strong positive correlation (r = 0.82-0.87) was found between the CaO content and early strength (1-3 days). As shown in Figure 1, the optimal range of CaO content is 40-45%, which ensures intensive formation of C-A-S-H gels. However, at a CaO content of 50%, there is a 15-20% decrease in strength due to the development of microcracks shrinkage.

The highest strength (up to 85 MPa) was achieved when using a combined activator: NaOH 8-10 M water glass with a modulus of SiO_2/Na_2O = 1.5-2.0. NaOH concentrations above 12 M resulted in a 10-15% decrease in strength due to excessively rapid setting and microcracking.

The curing temperature showed a non-linear effect on strength. Heat treatment at 60-80°C. for 24-48 hours provided the maximum effect, with a 40-60% increase in strength compared to isothermal hardening at 20° C. [18]. However, temperatures above 85° C. caused a 20-25% decrease in strength due to thermal shrinkage and degradation of the gel matrix [26].

The water-solid ratio (W/S) showed a strong negative correlation with strength (r = -0.58). An increase in W/S from 0.28 to 0.40 resulted in a 35-40% decrease in strength due to an increase in capillary porosity from 15% to 28% [27].

The specific surface area of the slag in the range of 400-500 m^2/kg provided an optimal balance between reactivity and water demand. Increasing the specific surface area from 350 to 500 m^2/kg increased strength by 25-30% [28]. Further increase to 600 m^2/kg was not economically feasible due to high energy consumption for grinding.

Mineral additives showed a moderate positive correlation with strength (r = 0.60-0.68). The introduction of 5-10% microsilica increased strength by 15-20% by compacting the matrix and reducing porosity [29]. Polypropylene fibers (0.5-1.0%) increased flexural strength by 30-40% and crack resistance [30].

Correlation analysis revealed the complex nature of the influence of factors. The greatest contribution to strength was made by: CaO content (r = 0.87), SiO_2/Al_2O_3 ratio (r = 0.80) and specific slag surface (r = 0.72). Multivariate regression analysis made it possible to establish optimal parameter ranges to achieve a strength of 60 MPa: CaO content: 40-45%, SiO_2/Al_2O_3: 3.5-4.0, Na_2O/SiO_2: 0.25-0.30, W/S: 0.28-0.32, curing temperature: 60-80°C, specific surface area: 450-500 m^2/kg.

Discussion of the results obtained shows that the high strength of geopolymers is achieved due to the synergistic effect of the optimal chemical composition and technological parameters. The established correlation dependencies are consistent with the literature data on the mechanisms of structure formation. The practical significance of the work lies in the development of scientifically based recommendations for the design of compositions of geopolymer concretes with specified properties for construction in Kazakhstan.

Conclusion. On the basis of a systematic analysis of literature data and a correlation study, quantitative dependencies between the key synthesis factors and strength characteristics of geopolymers based on blast furnace slag were established. A strong positive correlation (r = 0.82-0.87) was established between the CaO content in the range of 40-45% and strength, which is due to the intensive formation of C-A-S-H gels. An excess of 50% CaO leads to a 15-20% decrease in strength due to the development of shrinkage microcracks. Alkaline activation parameters have a critical impact on the kinetics of structure formation. Optimal values are achieved by using a combined activator: NaOH 8-10 M water glass with a SiO_2/Na_2O = 1.5-2.0 module. A temperature range of 60-80°C for 24-48 hours provides a 40-60% increase in strength compared to isothermal hardening at 20°C. Exceeding the temperature above 85°C causes a 20-25% decrease in strength due to thermal shrinkage and destruction of the gel matrix. The optimal range W/T = 0.28-0.32 provides minimum capillary porosity (15-18%) and maximum strength. Increasing the specific surface area from 350 to 500 m^2/kg increases strength by 25-30%.Mineral additives show a moderate positive correlation with strength (r = 0.60-0.68). The introduction of 5-10% microsilica increases the strength of the matrix seal by 15-20%, and polypropylene fibers (0.5-1.0%) increase the flexural strength by 30-40%. The greatest contribution to strength is made by: CaO content (r = 0.87), SiO_2/Al_2O_3 ratio (r = 0.80) and specific slag surface area (r = 0.72). Optimal parameter ranges are established to achieve a strength of 60 MPa.

The results of the study confirm the prospects for the use of slag geopolymers as an environmentally friendly building material for Kazakhstan. The developed recommendations for optimizing synthesis parameters make it possible to design compositions with specified properties for various climatic conditions and applications.

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This research is funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. BR21882278 "Creation of a construction and technical engineering center for the provision of a full cycle of accredited services in the construction, road construction sector of the Republic of Kazakhstan").

Received: 07 September 2025
Accepted: 26 December 2025

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ҚОЖ ГЕОПОЛИМЕРЛЕРІНІҢ БЕРІКТІГІНЕ ТЕХНОЛОГИЯЛЫҚ ФАКТОРЛАРДЫҢ ӘСЕРІ

Аңдатпа. Бұл шолу мақаласында түйіршіктелген домна пешінің қожына негізделген геополимерлердің беріктігінің негізгі технологиялық және химиялық-минералдық факторларға тәуелділігі талқыланады.Кальций құрамының әсерін талдау, молярлық арақатынас (SiO_2/Al_2O_3, Na_2O/SiO_2, H_2O/Na_2O), қатаю температурасы, бөлшектердің нақты беткі ауданы және құрылымы мен механикалық сипаттамаларының түзілуі бойынша минералды қоспаларды енгізу жүзеге асырылады. шлактың нақты беткі ауданы мен ерте беріктігі (r ≈ 0,82), сондай-ақ оңтайлы сілтілік модулі Na_2O/SiO_2 мен беріктік (r ≈ 0,78) арасында байқалатынын кім көрсетті. Бұл ретте кальцийдің шамадан тыс мөлшері және 85°C-тан жоғары қатаю температурасы микрокрекинг қаупімен сәйкес келеді (r ≈ -0,65). Қорытынды нәтижелер сілтілік активтену мен қожды дисперсиялау параметрлерінің реттелуі құрылымның қалыптасу процестерін бақылауға, ерте де, ұзақ уақыт беріктігін де қамтамасыз етуге мүмкіндік беретінін растайды. Ұсынылған қорытындылар қож геополимерлерін әртүрлі климаттар мен мақсаттар үшін жобалау жөніндегі практикалық ұсынымдарды әзірлеу кезінде пайдаланылуы мүмкін.

Тірек сөздер: геополимерлер, домна пешінің қожы, беріктік, сілтілік активтену, корреляциялық талдау, беріктік.

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ВЛИЯНИЕ ТЕХНОЛОГИЧЕСКИХ ФАКТОРОВ НА ПРОЧНОСТЬ ШЛАКОВЫХ ГЕОПОЛИМЕРОВ

Аннотация. В данной обзорной статье рассматривается зависимость прочности геополимеров на основе гранулированного доменного шлака от основных технологических и химико-минеральных факторов. Проведён анализ влияния содержания кальция, молярных соотношений (SiO_2/Al_2O_3, Na_2O/SiO_2, H_2O/Na_2O), температуры твердения, удельной поверхности частиц и введения минеральных добавок на формирование структуры и механические характеристики. На основе литературных данных выполнен корреляционный анализ, показавший, что наиболее сильная положительная связь наблюдается между удельной поверхностью шлака и ранней прочностью (r ≈ 0.82), а также между оптимальным модулем щёлочности Na_2O/SiO_2 и долговечностью (r ≈ 0.78). В то же время чрезмерное содержание кальция и превышение температуры твердения выше 85°C коррелируют с риском микротрещинообразования (r ≈ -0.65). Суммарные результаты подтверждают, что регулирование параметров щелочной активации и дисперсности шлака позволяет управлять процессами структурообразования, обеспечивая как раннюю, так и долговременную прочность. Представленные выводы могут быть использованы при разработке практических рекомендаций по проектированию шлаковых геополимеров для условий различного климата и назначения.

Ключевые слова: геополимеры, доменный шлак, прочность, щелочная активация, корреляционный анализ, долговечность.