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ASSESSMENT OF THE POTENTIAL OF FLY ASH AND BLAST FURNACE SLAG FOR THE PRODUCTION OF GEOPOLYMER BINDERS

ГЕОПОЛИМЕРЛІ БАЙЛАНЫСТЫРҒЫШТАРДЫ ӨНДІРУ ҮШІН ҰШАТЫН КҮЛІ МЕН ДОМНА ПЕШІ ҚОЖЫНЫҢ ӘЛЕУЕТІН БАҒАЛАУ

ОЦЕНКА ПОТЕНЦИАЛА ЗОЛЫ-УНОСА И ДОМЕННОГО ШЛАКА ДЛЯ ПОЛУЧЕНИЯ ГЕОПОЛИМЕРНЫХ ВЯЖУЩИХ

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geopolymer binders,
fly ash, blast furnace slag,
alkaline activation,
mechanical properties,
regression analysis,
cost-effectiveness.

ABSTRACT

This study presents a systematic review of 35 experimental publications (2014–2024) evaluating the potential of Kazakhstani fly ash (FA) and granulated blast furnace slag (GBFS) for the production of geopolymer binders. The chemical and mineralogical composition of raw materials, physical–mechanical properties (compressive strength, density, water absorption, frost resistance), and the influence of alkaline activation parameters (NaOH molarity, water glass modulus, curing temperature) on the formation of N-A-S-H and C-A-S-H gels were summarized and assessed using correlation and linear regression analysis. The results show that FA:GBFS ratios of 40:60–50:50 provide a synergistic effect, allowing compressive strength of 55–60 MPa under mild curing (25–60 °C) and reducing the cost of geopolymer concrete by 45–55% compared to ordinary Portland cement. The study confirms the high technical and economic viability of local industrial by-products for sustainable construction.

Түйінді сөздер:

геополимер
байланыстырғыштары,
ұшатын күл,
домна пешінің шлактары,
сілтілі белсендіру,
механикалық қасиеттері,
регрессиялық талдау,
шығын тиімділігі.

ТҮЙІНДЕМЕ

Бұл зерттеу қазақстандық ұшатын күлдің (FA) және гранулан-дырылған домна пеші шлақының (GBFS) геополимер байлаушы-ларын өндіру әлеуетін бағалайтын 35 эксперименттік жарияла-нымға (2014–2024) жүйелі шолу ұсынады. Шикізаттардың химия-лық және минералогиялық құрамы, физикалық-механикалық қасиеттері (сығу беріктігі, тығыздығы, су сіңіру, аязға төзімділік), сондай-ақ сілтілі активация параметрлерінің (NaOH молярлығы, су шыны модулі, қату температурасы) N-A-S-H және C-A-S-H гел-дерінің түзілуіне әсері корреляция мен сызықтық регрессиялық талдау арқылы қорытындыланып, бағаланды. Нәтижелер көрсеткен-



дей, FA:GBFS қатынастары 40:60–50:50 синергетикалық әсер береді, бұл жұмсақ қаттау кезінде (25–60 °C) 55–60 МПа қысу беріктігін қамтамасыз етеді және геополимерлі бетонның құнын кәдімгі портландцементпен салыстырғанда 45–55 %-ға төмендетеді. Зерттеу жергілікті өнеркәсіптік қосалқы өнімдердің тұрақты құрылыс үшін жоғары техникалық және экономикалық тиімділігін растайды.

Ключевые слова:

геополимерные вяжущие, зола-уноса, доменный шлак, щелочная активация, механические свойства, регрессионный анализ, экономическая эффективность.

АННОТАЦИЯ

В данном исследовании представлен систематический обзор 35 экспериментальных публикаций (2014–2024), оценивающих потенциал казахстанской летучей золы (FA) и гранулированного доменного шлака (GBFS) для производства связующих геополимеров. Химический и минералогический состав сырья, физико-механические свойства (прочность на сжатие, плотность, поглощение воды, морозостойкость) и влияние параметров активации щелочи (молярность NaOH, модуль стекла воды, температура отверждения) на образование гелей N-A-S-H и C-A-S-H были обобщены и оценены с помощью корреляционного и линейного регрессионного анализа. Результаты показывают, что соотношения FA:GBFS 40:60–50:50 обеспечивают синергетический эффект, позволяя сжимать 55–60 МПа при мягком отверждении (25–60 °C) и снижая стоимость геополимерного бетона на 45–55 % по сравнению с обычным портландцементом. Исследование подтверждает высокую техническую и экономическую жизнеспособность местных промышленных побочных продуктов для устойчивого строительства.

INTRODUCTION

The global construction industry faces increasing pressure to reduce CO₂ emissions since cement production accounts for nearly 8% of total anthropogenic output. Alkali-activated aluminosilicate materials (geopolymers) present an environmentally efficient alternative, offering comparable or enhanced mechanical performance with significantly reduced carbon footprint.

Kazakhstan fly ash (class F, ASTM C618) contains high amounts of amorphous SiO₂, while granulated blast furnace slag is rich in reactive CaO phases. Their combined application enhances the formation of N-A-S-H and C-A-S-H gels.

The relevance of this study lies in the lack of complex analyses that simultaneously address the chemical composition of raw materials, mechanical properties of composite systems, activation parameters, structural formation mechanisms, and economic feasibility of using local materials.

The purpose of the study is to systematize the results of research from 2014–2024 and assess the potential of Kazakhstan's fly ash and granulated blast furnace slag for producing geopolymer binders.

Scientific novelty consists in a comprehensive assessment of chemical, mineralogical, physical, mechanical, microstructural, and economic parameters as an integrated system, allowing identification of optimal technological conditions.

To achieve this goal, the study was carried out in several stages:

1. Systematization of scientific sources – analysis of publications of 2014–2024 with experimental data on the composition, strength and hardening conditions of geopolymer materials.
2. Comparative analysis of physicochemical and mechanical properties – assessment of fly ash, granulated slag and their combinations in terms of strength, density, water absorption and frost resistance.
3. Correlation and regression analysis – quantitative assessment of the effect of the composition and parameters of alkaline activation on the strength and economic efficiency of geopolymer concrete.

Stages of research. To achieve this goal, the following was carried out in several consecutive stages:

– Systematization of scientific sources. The search and selection of publications for 2014–2024 in the Scopus, ScienceDirect, Google Scholar and RSCI databases using the keywords based on the following keywords: geopolymer, fly ash, blast furnace slag, alkali activation, sustainability. Articles with experimental data on strength, chemical composition and hardening conditions were included.

– Analysis of physicochemical and mechanical properties. The compositions of fly ash and blast furnace slag, the features of their alkaline activation, as well as the physical and mechanical characteristics of geopolymers (strength, density, water absorption, frost resistance) based on them are compared.

– Construction of a regression model «strength – cost». Based on the literature and calculated data, the equations of dependence of the cost of 1 m³ of concrete on strength, taking into account the prices of components, are determined. The economic indicators of geopolymer and cement concrete are compared.

Systematization of scientific sources by strength, chemical composition and hardening conditions.

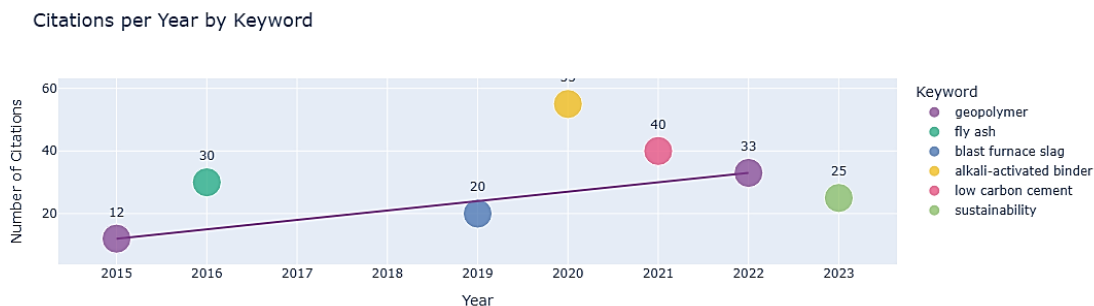


Figure 1. Keyword citation frequency (2014–2024)

Note – compiled by the author

MATERIALS AND METHODS

At the first stage of the study, a targeted analysis of scientific publications on geopolymer binders based on fly ash and granulated blast furnace slag was carried out. The distribution of keyword citations by topic is shown in Figure 1. The main attention is paid to the comparison of data on strength characteristics (compression, bending, modulus of elasticity), chemical composition of raw materials (in particular, SiO₂, Al₂O₃, CaO content), hardening conditions (temperature, time, type and concentration of alkaline activators).

The search was carried out in the Scopus, ScienceDirect, Google Scholar and RSCI databases for 2014–2024. For the convenience of comparing information, classification by main parameters is carried out.

Fly ash, when used in its pure form, requires heating to 60–80 °C to achieve a strength above 35–40 MPa. However, with a sufficient molarity of the alkaline solution (NaOH ≥ 10 M), partial activation is possible at room temperature.

Granulated blast furnace slag, due to its high CaO content, makes it possible to obtain a strength of up to 60–70 MPa already when curing at 25 °C, especially with a high content of the vitreous phase.

The combination of fly ash and granulated blast furnace slag in a ratio of 50:50 or 45:55 provides a synergistic effect: high initial strength (up to 55–60 MPa) and structure stability without mandatory heating.

The concentration of NaOH in the range of 8–10 M, the activator-to-binder ratio of 0.4–0.6, and the addition of water glass (Na_2SiO_3) increase the efficiency of geopolymerization.

At the second stage of the study, a comparative analysis of literature sources was carried out, which presented experimental data on the strength, density, water absorption and frost resistance of geopolymer binders based on fly ash, granulated blast furnace slag and their combinations.

In his work, Taarrini (2014) found that pure fly ash provides a strength of 30–42 MPa when heated to 70 °C, but without heat treatment, such indicators are unattainable. Dhivya and Venkatasubramani (2016) showed that the 50:50 mixture of fly ash and slag at 60–80 °C reaches 58 MPa, and water absorption is reduced to 5–7% due to a decrease in capillary porosity. He, Jie, Zhang, Yu, and Zhang (2020) noted that 100% slag at 85 °C yields up to 60 MPa due to active CaO, which forms a strong C-A-S-H gel. Zawrah, Khattab, Gado, and El Sayed (2021) proved that with an optimal composition ($\text{SiO}_2/\text{Al}_2\text{O}_3 \approx 2.2$) and the right activator, it is possible to obtain 32–38 MPa even at room temperature; slag and Na_2SiO_3 additionally compact the structure. Wang, Wang, Li, Liu, and Wang (2022) found that slag increases the density of the geopolymer to 2300–2400 kg/m^3 versus 2200 kg/m^3 for a single-ash system. Li, Zhang, Cao, Li, and He (2023) showed that the 45:55 mixture (fly ash, slag) gains 45–55 MPa in 7 days, reaching 77% of the 28-day strength in the first week. Noushini, Castel, and Aldred (2018) established that fly ash–slag can withstand up to F200 without noticeable loss of strength, while only ash loses up to 20% after 100 cycles. Komljenović, Bašćarević, and Bradić (2016) proved that with 8–10 M NaOH and the addition of Na_2SiO_3 , water absorption is reduced to 5.2%, making the material resistant to external conditions. Azad, Lin, and Cheng (2022) found that slag increases frost resistance due to its compacted microstructure and strong gel bonds. Tleubayeva (2023) demonstrated that the optimization of the composition of fly ash and slag makes it possible to achieve water absorption of <6% and frost resistance of F200 due to the dense structure. Zhang, Cheng, Li, and Xu (2022) showed that the durability and microstructure of fly ash–slag geopolymer concrete are highly dependent on the applied curing regimes. Kumar, Singh, and Roy (2022) established the significant influence of the alkali activator ratio and curing temperature on the strength development of geopolymer concrete. Santos, Pacheco-Torgal, and Jalali (2023) confirmed a substantial reduction in CO_2 emissions through the use of geopolymer concrete compared to ordinary Portland cement. Mehta and Siddique (2023) showed the high resistance of fly ash–slag-based geopolymer composites when exposed to aggressive environments. Gao, Wang, and Chen (2024) proposed a multi-objective optimization model for designing geopolymer mixes balancing strength, cost, and environmental impact.

Table 1. Comparison of physical and mechanical characteristics of geopolymer binders

№	Source	Composition	Strength (MPa)	Density (kg/m^3)	Water absorption (%)	Frost resistance
1	Taarrini D., 2014	100:0	30–42	2200	10–12	F100
2	Dhivya S., 2016	50:50	up to 58	2300–2350	5–7	F150–F200
3	He J., 2020	0:100	40–60	2400	<6	F200
4	Zawrah M., 2021	100:0	32–38	2200	8–11	F100
5	Li M., 2023	45:55	45–55	2350	5–6	F150
6	Komljenović M., 2016	70:30	48–54	2300	5.2	–

Note – compiled by the author

The best physical and mechanical properties are achieved by combining ash and slag in a ratio of 40:60 – 50:50, which allows to achieve high strength (up to 60 MPa), density (up to 2400 kg/m^3) and resistance to external influences.

Hardening conditions (temperature, humidity, type of activator) significantly affect the properties of the final product. All of the above formulations are technologically achievable in industrial conditions without the need for autoclaving.

Chemical and mineralogical composition of fly ash and granulated blast furnace slag.

Fly ash: SiO₂ – 45–60%, Al₂O₃ – 20–35%, CaO < 10%, vitreous structure, spherical particles. Forms N-A-S-H gel when activated.

Blast furnace slag: CaO – 35–45%, SiO₂ – 30–40%, Al₂O₃ – 7–15%, MgO – up to 8%, high reactivity. With accelerated strengthening, it forms C-A-S-H gel.

The compressive strength of geopolymers on pure fly ash is limited (~35–40 MPa) without heat treatment. When combined with granulated blast furnace slag and hardened at 25–60 °C, the strength increases to 55–60 MPa and above, even without autoclaving.

The density of the mixture increases due to the active formation of C-A-S-H gel and a decrease in porosity. Optimal values are achieved with an ash-fly ratio: granulated blast furnace slag from 40:60 to 50:50.

At the third stage of the study, the strength of concrete mixtures was analyzed with changes in their cost, and a regression linear analysis of the dependence of strength on cost for geopolymer and Portland cement concrete was carried out. This made it possible to determine which of the materials provides the best efficiency at the same level of strength.

The article provides a detailed regression linear analysis of the relationship between the strength and cost of geopolymer concrete and cement concrete (OPC). The analysis was carried out on two groups of materials with the construction and interpretation of linear models.

Table 2. Geopolymer concrete (according to Taarrini D. – cost of sales of geopolymer compositions in terms of tenge (at the exchange rate of 1 INR ≈ 5.4 KZT)

№	Composition	Cost (KZT/m ³)	Strength
1	Mix A	15 390	24
2	Mix B	15 930	30
3	Mix C	16 470	36
4	Mix D	17 280	40
5	Mix E	17 820	42

Note – compiled by the author

Table 3. Ordinary Portland cement market data of Kazakhstan, approximate

Concrete Class	Strength	Cost
M200	15	17000
M300	25	18500
M350	30	19500
M400	35	21000
M450	40	22500

Note – compiled by the author

Regression analysis.

Regression analysis shows:

Geopolymer concrete: $CS = 0.0072 \cdot \text{Cost} - 87.4$

OPC concrete: $CS = 0.0054 \cdot \text{Cost} - 76.5$

At equal cost increase, geopolymer concrete gains more strength (7.2 vs 5.4 MPa per 1000 KZT).

Economic analysis.

Table 4. Cost of raw materials in Kazakhstan

Component	Price, tenge/ton	Note
Fly ash	500-1000	Including transport
Granulated slag	2000-3500	Including transport
NaOH (100%)	150 000-180 000	Technical
Liquid glass (Na_2SiO_3)	45 000-60 000	Module 2.5-3.0
Portland cement M500	70 000-85 000	RK Production
Sand	3 000-5 000	Local
Macadam	8 000-12 000	Fraction 5-20 mm
<i>Note – compiled by the author</i>		

Fly ash and slag significantly reduce production cost. Geopolymer concrete (40 MPa) costs ~21,360 KZT/m³, while OPC M400 costs ~44,400 KZT/m³. Savings: 45–55%.

CONCLUSION

The analysis confirms that fly ash and granulated blast furnace slag of Kazakhstan are highly reactive and can be effectively used to produce geopolymer binders. The optimal ratio of components (40:60-50:50) ensures the formation of strong N-A-S-H and C-A-S-H gels, which leads to an increase in strength up to 55-60 MPa, a decrease in water absorption and an increase in the density of the material. The main factors affecting the properties of geopolymers are the chemical composition of the raw material, the concentration of NaOH, the module of water glass and the curing conditions. The use of correlation and regression analysis made it possible to quantify the contribution of each parameter to the formation of strength. An economic assessment has shown that the use of local raw materials reduces the cost of geopolymer concrete by 45-55% compared to cement materials. Thus, Kazakhstan's fly ash and blast furnace slag have a high potential for industrial applications, providing both technical and environmental benefits.

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