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Diabase-porphyrite crushing screenings as an alternative aluminosilicate component for Portland cement clinker production

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ABSTRACT

This study evaluates the feasibility of using diabase–porphyrite crushing screenings from the Shekhjeli deposit, generated as a by-product of crushed-stone production, as an alternative aluminosilicate component in the raw meal for Portland cement clinker production. The raw materials were characterized by chemical and mineralogical analyses, and raw meal compositions were evaluated through calculation and laboratory firing. The phase composition and microstructure of the obtained clinker were examined by X-ray diffraction and SEM–EDS, while the technological and mechanical properties of the resulting cement were also determined. A three-component raw mix containing 20.73 wt.% diabase–porphyrite screenings was selected, and firing at 1420 °C resulted in the formation of the principal Portland cement clinker phases. SEM–EDS observations showed a relatively homogeneous clinker microstructure comparable to that of industrial clinker. Cement prepared from the experimental clinker exhibited normal hydration behaviour and reached a compressive strength of 39.5 MPa after 28 days of curing. These results demonstrate that diabase–porphyrite crushing screenings can serve as an alternative to the conventional clay component, contributing to the utilization of local mineral waste and expansion of the raw-material base for cement production.

Keywords: diabase–porphyrite crushing screenings, waste utilization, Portland cement clinker, clinker phase formation, cement hydration, mechanical strength.

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Introduction

Currently, the construction industry is growing rapidly around the world, and the demand for building materials, especially Portland cement, continues to increase. At the same time, cement production requires large amounts of natural mineral raw materials and considerable energy. The intensive development of traditional deposits is gradually reducing their reserves and, in some cases, may lead to the depletion of the raw-material base. For this reason, the Development Strategy of New Uzbekistan for 2022–2026 gives special attention to increasing the production of building materials, using unconventional non-metallic minerals and secondary resources, and developing waste-free technologies as part of the transition to a green economy [1].

Accordingly, reducing the use of conventional mineral raw materials and the cost of Portland cement production by partially replacing natural components with industrial wastes and secondary resources is of both scientific and practical interest. This approach can help conserve natural resources, reduce accumulated waste and, with proper selection of the composition, maintain or improve the technological and performance properties of cement-based materials. Therefore, the development of energy- and resource-efficient cement production technologies using alternative raw materials remains an important area of research [[2], [3], [4]]. Particular attention has been devoted to the use of industrial by-products as raw-meal components, mineralizers, setting regulators, supplementary cementitious materials, and clinker substitutes [[5], [6]].

A number of studies have shown that industrial waste can be effectively used in the production of cement-based materials. Kuzmenkov et al. [7] found that phosphogypsum can be used as a component to regulate the setting time of Portland cement. Barinkova et al. [8] studied the possibility of obtaining building materials with properties similar to traditional Portland cement materials based on red mud. Panova et al. [9] studied the use of metallurgical and other industrial wastes as alternative raw materials and functional additives in cement production. Ren et al. [[10], [11]] showed that sulfoaluminate binders can be obtained completely from solid industrial wastes. The resulting materials had high compressive strength, required lower firing temperatures, and reduced CO_2 emissions by approximately 58% compared to traditional production methods. Esenbayeva et al. [12] studied phase changes associated with the formation of nanostructures in materials obtained from industrial waste. According to the results of the study, the mechanical effect during the rapid cooling and solidification process increased the degree of crystallization and contributed to the formation of a dense submicron and nanoscale structure of hydrate phases.

Scientific research has also been conducted on the use of industrial waste in the production of low-clinker composite cements. Begzhanova et al. [13] found that complex additives consisting of fly ash, microsilica, and steelmaking slag can be used to produce low-clinker composite cements. By adding up to 45% of the fly ash component to the composition of the composite cement, the clinker content was reduced to 55%, while the mechanical strength was not lower than that of traditional Portland cements. The use of fly ash and microsilica together increased the pozzolanic activity of the composite additive.

Natural and technogenic aluminosilicate materials, including magmatic rocks, are also being considered as alternative components of cement raw meals. Zhanikulov et al. [[14], [15]] showed that tephritobasalt, coal-mining waste, and lead slag can partially substitute conventional clay and iron-bearing components. The use of these materials enabled Portland cement clinker formation at 1350°C, thereby reducing the consumption of natural raw materials and energy. In a later study, Zhanikulov et al. [16] developed raw-meal compositions for more energy- and resource-efficient Portland cement clinker production and examined clinker formation at high temperatures, as well as the hydration and hardening of cement systems containing technogenic materials. Bahriev et al. [17] used coal-mining waste and iron ore as mineralizing components and reported a decrease in free CaO content and a reduction in clinker firing temperature by 100–150 °C. According to the authors' calculations, this approach could reduce CO_2 emissions by 12–15%. Mironyuk et al. [18] showed that local igneous rocks can serve as aluminosilicate raw materials and flux-mineralizing components, contributing to lower heat consumption and accelerated clinker formation.

The potential of basaltic materials as alternative raw materials for Portland cement clinker production has also been demonstrated in several studies. Hassaan [19] investigated basalt as an alternative aluminosilicate raw material replacing the conventional clay component. However, an additional silica-bearing component was required to adjust the raw-meal composition. Andrade et al. [20] investigated basalt quarry fines generated during aggregate production and demonstrated their suitability as components of Portland clinker raw mixtures by adjusting the proportions of limestone, clay, and iron-bearing corrective material. El-Didamony et al. [21] investigated basalt additions to conventional kiln feed and showed that the material could improve raw-meal burnability through its fluxing and mineralizing action. Ahmed et al. [22] further demonstrated the possibility of using basalt to replace silica- and iron-bearing corrective components and, in selected formulations, the clay component as well. Abdel-Latief et al. [23] investigated weathered basalt as a partial or complete substitute for clay and reported improved raw-meal burnability and clinker-phase formation.

The potential of basaltic and diabase-derived materials as alternative raw materials for Portland cement clinker production has also been demonstrated in several studies. Hassaan [19] investigated basalt as an alternative aluminosilicate raw material replacing the conventional clay component. However, an additional silica-bearing component was required to adjust the raw-meal composition. Andrade et al. [20] investigated basalt quarry fines generated during aggregate production and demonstrated their suitability as components of Portland clinker raw mixtures by adjusting the proportions of limestone, clay, and iron-bearing corrective material. El-Didamony et al. [21] investigated basalt additions to conventional kiln feed and showed that the material could improve raw-meal burnability through its fluxing and mineralizing action. Ahmed et al. [22] further demonstrated the possibility of using basalt to replace silica- and iron-bearing corrective components and, in selected formulations, the clay component as well. Abdel-Latief et al. [23] investigated weathered basalt as a partial or complete substitute for clay and reported improved raw-meal burnability and clinker-phase formation. Lyubomirskii et al. [24] investigated diabase-washing waste as a clay component in Portland cement clinker raw mixtures. Their results showed that the limestone–diabase system required an additional high-silica corrective component to obtain suitable raw-meal modulus values.

Taken together, these studies demonstrate that industrial wastes and igneous materials, particularly basaltic and diabase-derived raw materials, have considerable potential for Portland cement clinker production. However, their technological functions vary substantially depending on their chemical and mineralogical composition. Such materials may act as aluminosilicate substitutes for clay, replacements for silica- or iron-bearing corrective components, or as fluxing and mineralizing additives. Consequently, their suitability for clinker production cannot be generalized solely on the basis of geological classification and should be evaluated individually for each specific source.

This issue is particularly relevant to the Republic of Karakalpakstan, which possesses considerable mineral and technogenic resources that could potentially be utilized by the construction-materials industry. Several Portland cement plants operate in the region, and expansion of their production requires substantial quantities of limestone, clay, and corrective mineral components. At the same time, the industrial utilization of local unconventional raw materials remains limited because their chemical and mineralogical characteristics, behaviour during clinker formation, and influence on cement properties have not been sufficiently investigated. The use of quarrying and crushed-stone production wastes as alternative raw materials could therefore contribute to expanding the regional raw-material base while reducing the accumulation of industrial waste. Government initiatives aimed at the more efficient use of mineral resources and the recycling of technogenic waste within the green-economy framework further reinforce the relevance of this approach [25].

Within this regional context, the diabase–porphyrite crushing screenings generated during crushed-stone production at the Shekhjeli deposit are of particular interest. Unlike virgin igneous rocks specifically quarried as raw materials, these screenings represent an already accumulated quarry-processing by-product whose large-scale utilization has not yet been established. Their potential use as an aluminosilicate component of Portland cement raw meal is therefore relevant from both technological and resource-utilization perspectives. The Shekhjeli quarry is located in the Karaozak district, approximately 3 km northwest of Karaozak railway station, which may also facilitate transportation of the material to cement plants in the region.

To further substantiate the selection of this material, its chemical composition and technological role were compared with those of basaltic and diabase-derived materials previously investigated for Portland cement clinker production. The results of this comparative assessment are presented in the Results and Discussion section (Table 2).

Accordingly, this study aimed to assess the feasibility of using Shekhjeli diabase–porphyrite crushing screenings as an alternative aluminosilicate component of Portland cement raw meal and to evaluate their influence on clinker formation, firing behaviour, phase composition, hydration, and the principal technological and mechanical properties of the resulting cement.

Materials and methods

Raw materials

Portland cement clinker was produced using limestone from the Daruazatau deposit in the Republic of Karakalpakstan as the principal calcium-bearing component, diabase–porphyrite crushing screenings (DP screenings) from the Shekhzheli deposit as an alternative aluminosilicate component replacing conventional clay, and copper-smelting slag from JSC Almalyk Mining and Metallurgical Complex (Iron-rich slag) as an iron-bearing corrective component. The diabase–porphyrite screenings are generated during the crushing and size classification of rock in the production of construction aggregates and constitute a polydisperse material with a particle size of 0–5 mm. According to data provided by the enterprise, approximately 30–40 thousand tonnes of this material are generated annually, while the accumulated quantity in waste dumps exceeds 5.5 million tonnes. The substantial volume of the material and the absence of its large-scale industrial utilization make its application in Portland cement clinker production of considerable practical interest. The oxide composition of the diabase–porphyrite screenings indicates their potential use as a source of silica and alumina in clinker raw meals. To evaluate the feasibility of replacing the conventional clay component, the chemical and mineralogical compositions of the raw materials were characterized, and raw meal formulations with specified values of the lime saturation factor, silica modulus, and alumina modulus were designed. The clinker-forming processes and the properties of the resulting clinker were subsequently investigated.

Chemical Composition

The chemical composition of the raw materials was determined in accordance with UzM St 337:2024 and GOST 5382-2019 using conventional titrimetric and gravimetric methods. The results of the chemical analysis are presented in Table 1.

The chemical composition of the limestone was typical of relatively pure carbonate raw materials, with CaO as the predominant component. The DP screenings contained comparatively high amounts of Al_2O_3 and Fe_2O_3, together with a noticeable content of alkali oxides ($R_2O = Na_2O + K_2O$). The iron-rich slag was characterized by an Fe_2O_3 content exceeding 50 wt.% and a SiO_2 content of approximately 34 wt.%, while appreciable amounts of Al_2O_3 and CaO were also present.

Mineralogical composition (XRD)

The phase compositions of the raw materials and synthesized samples were determined by X-ray diffraction (XRD) using a Rigaku MiniFlex diffractometer (Japan) with Cu Kα radiation. Quantitative phase analysis was performed by the Rietveld refinement method using the ICDD PDF-2 database (2007 release).

The raw materials used for Portland cement clinker production were analyzed by X-ray diffraction, and the resulting patterns are shown in Figs. 1–3.

X-ray diffraction analysis revealed distinct differences in the mineralogical composition of the raw materials. The limestone was composed predominantly of calcite (Fig. 1), as indicated by characteristic reflections at d = 0.381, 0.303, 0.247, 0.227, 0.208, 0.190, 0.186, 0.162, 0.160, 0.152, 0.151, 0.143, and 0.141 nm. The diabase–porphyrite crushing screenings contained mainly quartz and feldspar (Fig. 2). Quartz was identified by reflections at d = 0.425, 0.333, 0.244, 0.212, 0.181, 0.180, 0.153, 0.138, and 0.137 nm. The reflections observed at d = 0.699, 0.631, 0.402, 0.385, 0.377, 0.365, 0.350, 0.309, 0.295, 0.291, 0.285, 0.268, 0.263, 0.255, 0.231, 0.227, 0.218, 0.178, 0.146, and 0.143 nm were attributed to feldspar. A different phase assemblage was observed in the iron-rich slag (Fig. 3), where fayalite and magnetite were the main crystalline phases, together with a minor amount of quartz. Fayalite was identified by reflections at d = 0.355, 0.282, 0.262, 0.256, 0.251, 0.241, 0.230, 0.177, 0.170, 0.161, and 0.152 nm, whereas magnetite was characterized by reflections at d = 0.295, 0.253, 0.208, 0.184, and 0.148 nm. Weak peaks at d = 0.425 and 0.334 nm were assigned to quartz.

Table 1 - Chemical composition of the raw materials

Raw material	Oxide content (wt.%)							LOI (wt.%)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	R_2O	
Limestone	0.65	0.21	0.10	54.88	0.28	0.10	0.06	42.94
DP screenings	60.23	21.80	8.56	1.02	0.45	0.10	4.42	3.20
Iron-rich slag	34.31	6.85	50.55	3.04	1.8	0.01	1.6	1.24

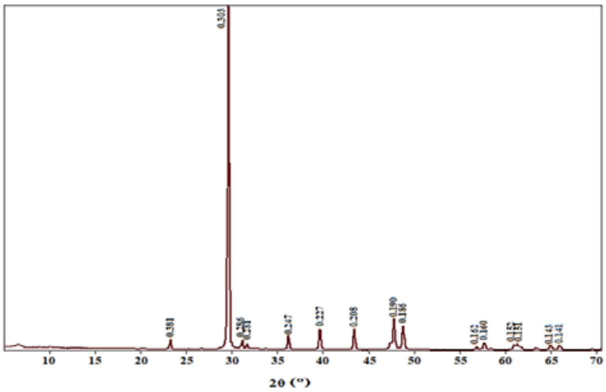

Figure 1 - XRD pattern of limestone

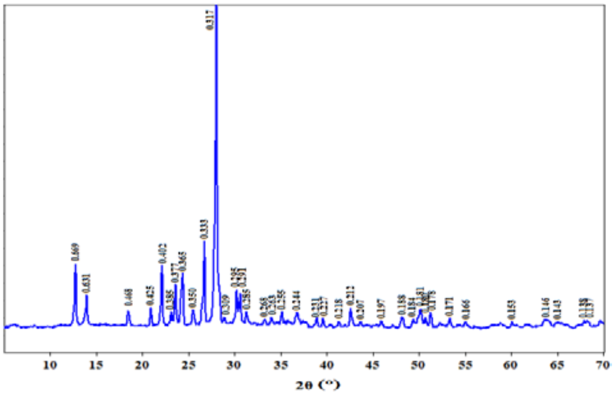

Figure 2 - XRD pattern of DP screenings

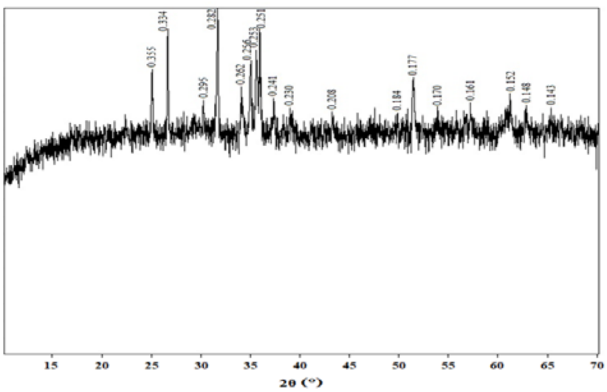

Figure 3 - XRD pattern of slag

SEM-EDS analysis

The surface morphology and microstructure of the samples were examined by scanning electron microscopy (SEM) using a JSM-IT210 microscope (JEOL Ltd., Japan) operated in high-vacuum mode with a secondary electron detector (SED), at an accelerating voltage of 20 kV and a working distance of 9.0 mm. The elemental composition was determined by energy-dispersive X-ray spectroscopy (EDS) using the integrated analytical system [26].

Test conditions and sample preparations

The suitability of the raw materials for Portland cement production and the selection of the appropriate processing route were assessed through a comprehensive examination of their chemical and mineralogical compositions and physicomechanical properties. The properties of the resulting cement were evaluated for compliance with the requirements of O'zDSt 2950:2015 and GOST 31108–2020 [[27], [28]].

Based on the chemical analysis results, raw meal calculations and laboratory clinker-burnability tests were carried out to establish the theoretical basis for selecting suitable proportions of the raw materials [[29], [30]]. Representative samples of limestone, diabase–porphyrite crushing screenings, and iron-rich slag were used to prepare the clinker raw meals.

The proportions of the raw mixtures were calculated from the chemical compositions of the individual raw materials given in Table 1. Before the calculations, the oxide composition of each component was normalized to 100 wt.%. A series of raw mixtures was designed with lime saturation factor (LSF) values ranging from 0.80 to 0.95 and silica modulus (SM) values ranging from 1.8 to 3.5. For the preparation of the Portland cement raw meals, the limestone was initially crushed in a jaw crusher to a particle size of 1–5 mm. The crushed limestone, diabase–porphyrite screenings, and iron-rich slag were then proportioned according to the calculated compositions and jointly ground in a ball mill. Grinding was continued until the residue on a 0.08 mm sieve was within the range of 10–15%, resulting in homogeneous raw meals suitable for clinker firing. The prepared raw meals were mixed with 5 – 10 wt.% water and pressed into cylindrical pellets with a diameter of 20 mm and a mass of approximately 10 g. The forming pressure was maintained within the range of 1.5–2.0 MPa. The pellets were subsequently dried either at room temperature for 24 h or in a drying oven at 50–60 °C for 3 h. The dried pellets were fired in a laboratory muffle furnace at selected temperatures between 1350 and 1420 °C. The total firing cycle was approximately 3 h and included heating to the target temperature followed by a holding period of 30 min at the maximum temperature. After firing, the clinker samples were rapidly cooled to room temperature.

Results and Discussion

Comparative assessment of diabase–porphyrite screenings as an aluminosilicate raw material

To evaluate the compositional characteristics of the Shekhjeli DP screenings and to substantiate their use as an aluminosilicate component of the raw meal, their chemical composition was compared with those of basaltic and diabase-derived materials previously investigated for Portland cement clinker production. In such raw-material systems, igneous rocks are of particular interest primarily as sources of SiO_2, Al_2O_3, and Fe_2O_3, which are required for the formation of silicate, aluminate, and aluminoferrite clinker phases, and they can partially or completely replace conventional clay raw materials. At the same time, variations in the contents of CaO, MgO, Fe_2O_3, and alkali oxides may additionally affect raw-meal proportioning, burnability, and the intensity of clinker-forming reactions. Comparative data on the chemical composition of the investigated DP screenings and previously studied basaltic and diabase-derived materials are presented in Table 2.

The comparative data in Table 2 demonstrate that the chemical compositions of igneous materials previously investigated as raw components for Portland cement clinker production vary over a relatively wide range. The SiO_2 contents of the considered basaltic and diabase-derived materials range from 44.86 to 58.50 wt.%, while Al_2O_3 ranges from 12.50 to 22.14 wt.%. In most cases, their CaO and MgO contents are considerably higher than those of the Shekhjeli diabase–porphyrite screenings. These materials have generally been used as sources of silica, alumina, and iron-bearing constituents to partially or completely replace conventional clay raw materials, while differences in their chemical composition also influence raw-meal formulation and clinker-forming reactions.

The Shekhjeli diabase–porphyrite screenings are characterized by a combination of relatively high SiO_2 (60.23 wt.%) and Al_2O_3 (21.80 wt.%) contents and comparatively low CaO (1.02 wt.%) and MgO (0.45 wt.%) contents. The combined SiO_2 + Al_2O_3 content reaches 82.03 wt.%, whereas the combined CaO + MgO content is only 1.47 wt.%. This oxide balance indicates the predominantly aluminosilicate character of the material and supports its use primarily as a source of silica and alumina for Portland cement clinker formation.

Table 2 - Comparison of the chemical composition of basaltic and diabase-derived materials investigated for Portland cement clinker production

Material / Reference	Oxide content, (wt.%)							
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	R_2O	$SiO_2 + Al_2O_3$	CaO + MgO
Shekhjeli DP screenings / present study	60.23	21.80	8.56	1.02	0.45	4.42	82.03	1.47
Basalt rock [19]	45.30	16.90	12.70	9.70	6.90	2.80	62.20	16.60
Basalt quarry fines[20]	50.90	12.50	15.20	8.99	5.32	4.32	63.40	14.31
Basalt [21]	50.35	14.43	12.75	10.18	6.05	2.92	64.78	16.23
Basalt [22]	58.50	14.43	8.57	4.70	4.35	3.27	72.93	9.05
Weathered basalt [23]	49.59	14.74	12.57	9.64	5.29	4.59	64.33	14.93
Diabase-washing wastes [24]	44.86-46.21	16.74-22.14	12.10-15.67	9.65-10.14	4.87-7.85	3.26-4.23	61.60-67.70	14.94-17.50

Note. *Ranges for Lyubomirskii et al. [24] correspond to three investigated diabase-washing waste samples.

Table 3 - Chemical composition of the experimental clinker

Clinker	Oxide content, (wt.%)							LOI (wt.%)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	R_2O	
Experimental. KH=0.91. n=2.2	21.94	5.25	4.05	66.10	0.45	0.10	1.31	0.65
Karakalpakcement LLC	21.45	5.22	3.94	65.77	0.63	1.13	1.53	0.31

Therefore, the selection of the Shekhjeli diabase–porphyrite screenings was based not merely on their igneous origin, but on the favorable proportion of the principal clinker-forming oxides. Compared with the basaltic and diabase-derived materials reported in previous studies, the investigated screenings contain a higher proportion of silica–alumina components and relatively low amounts of CaO and MgO, making them a suitable alternative aluminosilicate component for replacing conventional clay raw material. An additional practical advantage is that this material is a by-product of crushed-stone production that has already accumulated in substantial quantities. Its utilization in clinker production may therefore simultaneously expand the local raw-material base and contribute to the recycling of mineral waste.

Optimization of Portland cement raw meal composition

Analysis of compositions No. 1 (LSF = 0.80, SM = 1.8), No. 2 (LSF = 0.89, SM = 2.7), No. 3 (LSF = 0.90, SM = 1.8), No. 6 (LSF = 0.91, SM = 2.75), and other experimental Portland cement raw mixes with different LSF and SM values showed that, although compositions No. 1, No. 2, No. 3, and No. 6 began to melt at relatively lower temperatures, X-ray diffraction analysis did not indicate complete formation of the principal clinker minerals. In addition, the free CaO content remained within the range of 2.2–2.9 wt.%, which does not meet the requirements of the applicable standards.

The analysis of the optimal compositions No. 4 (LSF = 0.91, SM = 2.2) and No. 5 (LSF = 0.91, SM = 2.5) showed that the free CaO contents were 0.85 and 0.97 wt.%, respectively, while their mineralogical compositions also complied with the requirements of O‘zDSt 2801:2013. Therefore, further evaluation of the properties of the experimental clinker was carried out using the composition with LSF = 0.91 and SM = 2.2 (Table 3).

The calculated clinker phase composition was consistent with the requirements of O‘z MSt 337:2024 [31] and GOST 34850–2022 [32]. The calculated clinker composition contained 61.25 wt.% tricalcium silicate (C_3S), 16.71 wt.% dicalcium silicate (C_2S), 7.03 wt.% tricalcium aluminate (C_3A), and 12.31 wt.% tetracalcium aluminoferrite (C_4AF). Recalculation confirmed that the selected proportions provided the target LSF and SM values of 0.91 and 2.2, respectively. The selected raw mixture consisted of 77.62 wt.% limestone, 20.73 wt.% diabase–porphyrite crushing screenings, and 1.65 wt.% iron-rich slag. After proportioning, joint grinding, and homogenization, the resulting raw meal was fired to produce the experimental clinker.

Thus, comparison of the chemical and mineralogical compositions and the modulus characteristics of the experimental Portland cement clinker showed that the measured parameters were within the permissible limits specified in O‘z MSt 337:2024 and GOST 34850–2022.

The relatively high alkali content may influence both the mineral-forming processes during Portland cement clinker firing and the subsequent hydration of cement. The diabase–porphyrite screenings contained 4.42 wt.% total alkalis, expressed as R_2O (Na_2O + K_2O), while the experimental clinker contained 1.31 wt.% R_2O. According to O‘zDSt 2801:2013, for general-purpose cements, the mass fraction of alkali oxides expressed as Na_2O equivalent (Na_2O_{eq}=Na_2O+0.658K_2O) is established in agreement with the consumer, taking into account the intended service conditions. Since only the total R_2O content was determined in the experimental clinker, without separate determination of Na_2O and K_2O, the exact Na_2O-equivalent alkali content was not calculated.

It is well established that elevated alkali contents may increase the susceptibility to alkali–silica reaction when reactive aggregates containing active forms of silica are used, particularly under conditions of sufficient moisture. However, the potential ASR risk is governed not only by the alkali content of the cement, but also by the mineralogical and chemical reactivity of the aggregate, the availability of alkalis in the pore solution, and the exposure conditions of the concrete. Therefore, the R_2O content of 1.31 wt.% in the clinker alone is insufficient to provide an unambiguous assessment of the susceptibility of the cementitious system to alkali–silica reaction.

The developed cement is intended for general construction applications. Concrete specimens prepared using the experimental cement showed satisfactory frost resistance after 200 freeze–thaw cycles in accordance with GOST 10060–2012. This result characterizes the resistance of the concrete to cyclic freezing and thawing, but it is not regarded as direct evidence of resistance to alkali–silica reaction. When this cement is used with potentially reactive aggregates, the alkali content and the intended service conditions should therefore be taken into account in concrete mix design and material selection.

The phase composition of the clinker was examined by X-ray diffraction (Fig. 4). The diffraction pattern contained reflections corresponding to the main Portland cement clinker phases. Tricalcium silicate (C_3S) was identified by reflections at d = 0.592, 0.386, 0.302, 0.296, 0.277, 0.260, 0.231, 0.197, 0.193, and 0.182 nm, while dicalcium silicate (C_2S) with reflections at d = 0.318, 0.274, 0.270, 0.244, 0.218, 0.148, and 0.138 nm. The reflections at d = 0.268, 0.244, 0.218, 0.197, 0.193, and 0.183 nm were assigned to tricalcium aluminate (C_3A), whereas those at d = 0.731, 0.386, 0.268, 0.193, 0.153, 0.148, and 0.138 nm were attributed to tetracalcium aluminoferrite (C_4AF). These results confirm the formation of the principal clinker phases during firing.

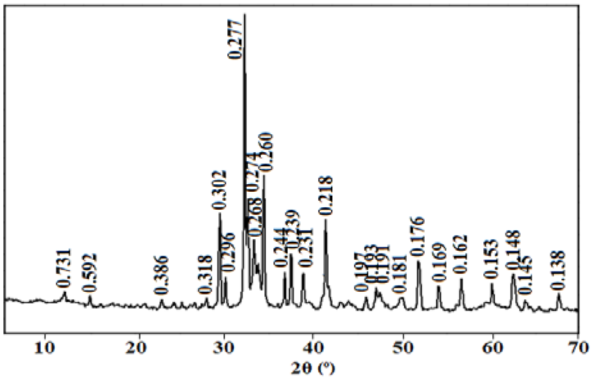

Figure 4 - XRD pattern of obtained clinker at 1420°C

The SEM images and corresponding EDS spectrum of the experimental clinker (Fig. 5) showed that its elemental composition was generally comparable to that of the industrial clinker produced by Karakalpakcement LLC (Fig. 6). The analyzed areas contained Ca, Si, Al, and Fe in proportions consistent with the formation of the principal Portland cement clinker phases. Combined with the XRD results, the SEM–EDS observations indicate that the clinker produced using diabase–porphyrite crushing screenings developed a relatively homogeneous microstructure containing calcium silicate and aluminate–ferrite phases. Their distribution was broadly similar to that observed in the industrial clinker produced by Karakalpakcement LLC.

In the next stage of the study, Portland cement was produced from the experimental clinker, and its physicomechanical properties were evaluated. To regulate the setting time, 5 wt.% gypsum from the Tashaba deposit in the Republic of Karakalpakstan was added to the clinker. The gypsum contained 93.25 wt.% $CaSO_4 \cdot 2H_2O$.

Hydration reactions govern the setting behaviour of cement paste and influence the subsequent development of the physicomechanical properties of hardened cement. Therefore, the normal consistency and setting times of the prepared cement paste were determined, and the results are presented in Table 4.

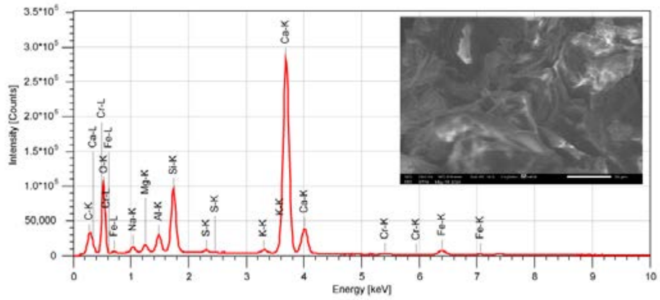

Figure 5 - SEM image and EDS spectrum of the clinker obtained at 1420 °C

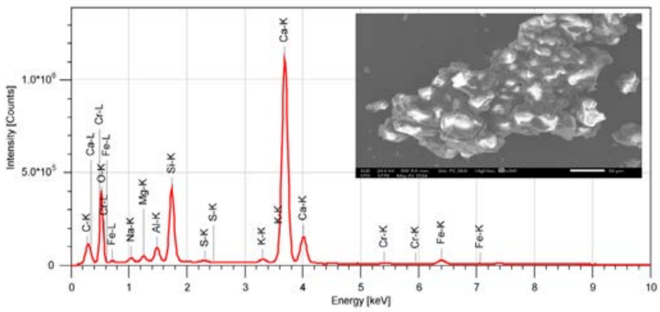

Figure 6 - SEM image and EDS spectrum of the industrial clinker produced by Karakalpakcement LLC

Table 4 - Comparative properties of the experimental and industrial cements

Cement	Cement Residue on a 0.08 mm sieve, %	Specific surface area, cm^2/g	Normal consistency, %	Water-to-cement ratio	Setting time, min	
					Initial	Final
Experimental cement	11.0	3150	26.5	0.26	130	155
Industrial cement produced by Karakalpakcement LLC	10.5	3150	26.5	0.26	160	175

Table 5 - Physicomechanical properties of the obtained cement at different curing ages

Hydrothermal curing at 95 ± 5 °C		Normal curing			
		3 days		28 days	
Flexural strength, MPa	Compressive strength, MPa	Flexural strength, MPa	Compressive strength, MPa	Flexural strength, MPa	Compressive strength, MPa
2.5	24.5	2.8	28.4	4.5	39.5

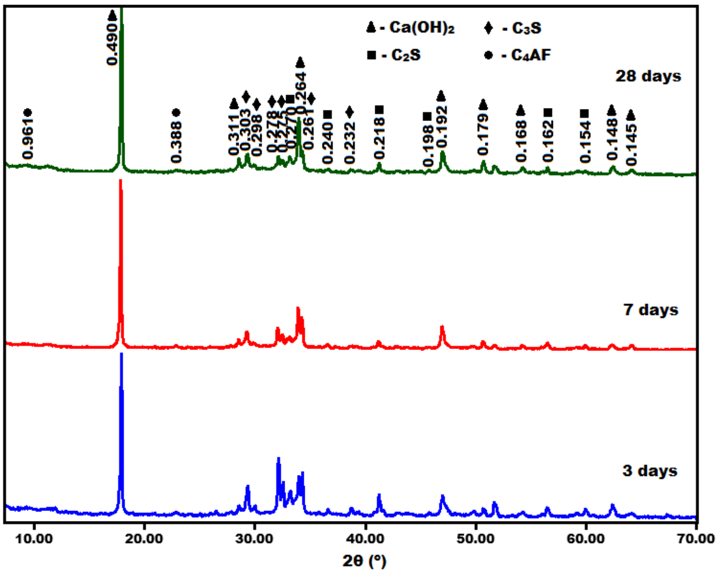

Figure 7 - XRD patterns of the experimental cement at different curing ages

The setting-time measurements showed that the initial and final setting times of the experimental cement were comparable to those of the industrial cement and remained within the permissible limits specified by the applicable standards.

Many researchers worldwide have extensively studied the hydration processes that govern the performance of hardened cement paste. The hydration and hardening of Portland cement involve a complex sequence of physicochemical reactions that determine its technological behaviour and the development of its functional properties [[33], [34], [35], [36]]. In the present study, the hydration behaviour and phase evolution of the experimental cement were examined by X-ray diffraction at different curing ages (Fig. 7).

The XRD patterns show a gradual decrease in the intensity of the reflections attributed to alite (C_3S) and belite (C_2S) with increasing curing time from 3 to 28 days. This indicates the progressive consumption of the residual clinker phases during cement hydration. At the same time, the reflections of portlandite, $Ca(OH)_2$, remain clearly visible in the hydrated samples. These changes confirm the continued hydration of the experimental cement with increasing curing age. Because C–S–H is poorly crystalline [[37], [38]], it was not identified directly from individual sharp diffraction peaks.

Flexural and compressive strengths are among the principal physicomechanical characteristics of Portland cement. To determine the strength properties of the experimental cement produced using diabase–porphyrite crushing screenings, prismatic mortar specimens measuring 40 × 40 × 160 mm were prepared. The specimens were cured under standard conditions: they were initially stored in a moist-air environment for 24 h and subsequently immersed in water at room temperature for up to 28 days.

The physicomechanical properties of the prepared Portland cement specimens were determined in accordance with GOST 30744–2001 [39]. As shown in Table 5, the cement produced from the three-component raw mixture attained a flexural strength of 4.5 MPa and a compressive strength of 39.5 MPa after 28 days of curing under standard conditions.

Steam curing at 95 ± 5 °C, performed in accordance with GOST 10178–85 [40], resulted in the development of approximately 50–60% of the 28-day strength. This indicates that the experimental cement was capable of achieving appreciable early strength under accelerated curing conditions.

Conclusions

The results demonstrate that diabase–porphyrite crushing screenings from the Shekhjeli deposit can be used as an alternative aluminosilicate raw material for Portland cement clinker production. In the selected three-component raw meal, the screenings constituted 20.73 wt.% of the total mixture and served as the aluminosilicate component in place of conventional clay, together with 77.62 wt.% limestone and 1.65 wt.% iron-rich slag. Thus, the value of 20.73 wt.% should be regarded as the proportion established for the specific raw-meal formulation investigated in this study rather than as a general recommended addition rate. The selected composition with LSF = 0.91 and SM = 2.2 provided satisfactory clinker formation at 1420 °C.

XRD and SEM–EDS analyses confirmed the formation of the principal Portland cement clinker phases and a relatively homogeneous clinker microstructure. During cement hydration, the gradual decrease in the intensity of residual alite and belite reflections, together with the presence of portlandite, indicated continued hydration from 3 to 28 days. The cement produced from the experimental clinker showed technological properties comparable to those of the industrial reference cement and reached a compressive strength of 39.5 MPa after 28 days under standard curing conditions.

From a practical perspective, the use of Shekhjeli diabase–porphyrite screenings may contribute to expanding the local raw-material base for cement production while simultaneously reducing the accumulation of crushed-stone production waste. However, the relatively high alkali content of the experimental clinker should be considered when the cement is intended for use with potentially reactive aggregates. The present results were obtained under laboratory conditions; therefore, further work should focus on industrial-scale validation, assessment of raw-material compositional variability, and long-term durability, including alkali–silica reaction under relevant service conditions.

Conflicts of interest. On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Қиыршық тас өндірісінің диабаз-порфиритті қалдығы – портландцемент өндіруге арналған перспективалы компонент

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АННОТАЦИЯ
Осы зерттеуде қиыршық тас өндірісінің жанама өнімі ретінде түзілетін Шехжелі кен орнының диабаз-порфиритті ұсақтау елендiлерін портландцемент клинкерін өндіруге арналған шикізат қоспасының баламалы алюмосиликатты компоненті ретінде пайдалану мүмкіндігі бағаланды. Бастапқы шикізат материалдары химиялық және минералогиялық талдау әдістерімен сипатталды, ал шикізат қоспаларының құрамдары есептеулер және зертханалық күйдіру нәтижелері негізінде бағаланды. Алынған клинкердің фазалық құрамы мен микроқұрылымы рентгенфазалық талдау және СЭМ–ЭДС әдістерімен зерттеліп, алынған цементтің технологиялық және механикалық қасиеттері анықталды. Құрамында 20,73 масс. % диабаз-порфиритті ұсақтау елендiлері бар үшкомпонентті шикізат қоспасы таңдалды; оны 1420 °С температурада күйдіру нәтижесінде портландцемент клинкерінің негізгі минералдық фазалары қалыптасты. СЭМ–ЭДС нәтижелері эксперименттік клинкердің микроқұрылымы салыстырмалы түрде біртекті және өнеркәсіптік клинкердің микроқұрылымымен салыстырмалы екенін көрсетті. Эксперименттік клинкер негізінде алынған цемент қалыпты гидратация үдерісімен сипатталып, 28 тәулік қатайғаннан кейін сығылу беріктігі 39,5 МПа-ға жетті. Алынған нәтижелер диабаз-порфиритті ұсақтау елендiлерін дәстүрлі сазды компонентке балама ретінде пайдалануға болатынын және бұл жергілікті минералдық қалдықтарды кәдеге жаратуға әрі цемент өндірісінің шикізат базасын кеңейтуге мүмкіндік беретінін көрсетеді.

Түйін сөздер: диабаз-порфиритті ұсақтау елендiсі, қалдықтарды кәдеге жарату, портландцемент клинкері, клинкерлік фазалардың түзілуі, цементтің гидратациясы, механикалық беріктік.

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АННОТАЦИЯ
В работе оценена возможность использования отсевов дробления диабаз-порфирита Шехжелинского месторождения, образующихся как побочный продукт производства щебня, в качестве альтернативного алюмосиликатного компонента сырьевой смеси для получения портландцементного клинкера. Исходные материалы были охарактеризованы методами химического и минералогического анализа, а составы сырьевых смесей оценены на основе расчётов и лабораторного обжига. Фазовый состав и микроструктуру полученного клинкера исследовали методами рентгенофазового анализа и СЭМ–ЭДС, также были определены технологические и механические свойства полученного цемента. Была выбрана трёхкомпонентная сырьевая смесь, содержащая 20,73 мас. % отсевов диабаз-порфирита; её обжиг при 1420 °С обеспечил формирование основных минералов портландцементного клинкера. По данным СЭМ–ЭДС экспериментальный клинкер характеризовался относительно однородной микроструктурой, сопоставимой с микроструктурой промышленного клинкера. Цемент, полученный из экспериментального клинкера, характеризовался нормальным протеканием процессов гидратации и достиг прочности при сжатии 39,5 МПа после 28 суток твердения. Полученные результаты показывают, что отсевы дробления диабаз-порфирита могут использоваться в качестве альтернативы традиционному глинистому компоненту, способствуя утилизации местных минеральных отходов и расширению сырьевой базы цементного производства.

Ключевые слова: отсев дробления диабаз-порфирита, утилизация отходов, портландцементный клинкер, формирование клинкерных фаз, гидратация цемента, механическая прочность.

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