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Technological, economic and environmental aspects of the production of sulfate-resistant Portland cement clinker based on the mineral resources of Karakalpakstan

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ABSTRACT
This study focuses on the production of sulfate-resistant Portland cement clinker using local raw materials found in the Aral Sea region of the Republic of Uzbekistan and on its properties. The obtained results highlight the technological, economic, and environmental advantages. The raw material mixtures consisted of limestone, barren sand, kaolin, and iron-containing industrial waste, resulting in a clinker with an optimized oxide composition (LSF = 0.82, SR = 2.15, AP = 0.94). X-ray phase analysis reveals a high content of alite ($C_3S \approx 38.6\%$) and belite ($C_2S \approx 41.0\%$) phases, which ensures high mechanical strength. Low tricalcium aluminate content (tricalcium aluminate < 5%) and sufficient ferrite content ($C_4AF \approx 16.2\%$) increased sulfate resistance and phase dominance. Sulfate resistance tests conducted in accordance with ASTM C1012/C1012M showed that sulfate-resistant Portland cement had the lowest swelling index among samples immersed in a 5% Na_2SO_4 solution, demonstrating its superior stability compared to conventional Portland cement and mixed cement types. The experimental results demonstrate the feasibility of producing high-quality sulfate-resistant Portland cement clinker using local raw materials and demonstrate its potential for use in the sulfate-rich conditions of the Aral Sea region. From an economic perspective, the use of local raw materials reduces production costs, the need for imports, and increases the competitiveness of the cement industry in our region. From an environmental perspective, the long service life of sulfate-resistant Portland cement and the ability to utilize industrial waste align with the principles of a "green economy" and promote waste reduction and sustainable growth.

Keywords: clinker synthesis, mineral resources, sulfate resistance, green economy, sustainability of sulfate-resistant Portland cement.

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Introduction

The rapid development of the construction industry—particularly the expansion of hydraulic structures, industrial facilities, and residential infrastructure—has significantly increased the global demand for strong and durable cements and concretes. However, in some regions, specific natural and geographical conditions pose particular challenges for building materials. In the Republic of Karakalpakstan, particularly in the Aral Sea region, soils and groundwater are characterized by high salinity: high concentrations of sulfate ions (SO_4^{2-}) pose a serious threat to concrete and reinforced concrete structures. In a sulfate environment, ordinary Portland cement quickly degrades: sulfate ions react with the three aluminate phases of calcium (C_3A), forming expanding ettringite, which leads to cracking and reduced strength. Therefore, the production of sulfate-resistant Portland cement has become a pressing technical challenge for this region.

According to UzM St 337:2024 and GOST 22266-2013, the C_3A content in cement clinker should not exceed 5%, and should be reduced to 3% under aggressive conditions. This limitation is due to the fact that C_3A reacts with sulfate ions, forming harmful expanding products. Reducing the amount of Al_2O_3 in the raw mix or increasing the amount of Fe_2O_3 are the most effective ways to suppress C_3A formation and improve sulfate resistance.

The Republic of Karakalpakstan possesses significant scientific and practical potential in this area. The region possesses reserves of raw materials necessary for cement production: limestone ($CaCO_3$ ≈ 85–90%), kaolin (Al_2O_3 ≈ 36–38%), basalt, and iron-rich rocks. Rational use of these resources not only ensures economic efficiency but also enables the production of high-quality sulfate-resistant Portland cement (SRC) clinker, adapted to the region's aggressive sulfate conditions. Therefore, the production and use of such cement has become an important requirement for the construction of reservoirs, sewer systems, and other engineering structures in the Aral Sea region.

International and regional standards set clear requirements for the mineralogical composition of cement clinker to ensure sulfate resistance. The C_3A content is one of the most important controlled parameters: the higher its proportion, the faster the sulfate attack and the greater the risk of expansive failure in concrete. Reducing C_3A by precisely adjusting the Al_2O_3/Fe_2O_3 ratio requires careful selection of raw materials and accurate calculation of batch ratios.

The main objective of this study is to synthesize sulfate-resistant Portland cement clinker from mineral raw materials from the Aral Sea region, determine its chemical and mineralogical composition, and examine the relationship between phase composition and sulfate resistance.

The problem of sulfate corrosion in cement-based materials has attracted extensive research attention internationally, as concrete made from ordinary Portland cement rapidly deteriorates in a sulfate environment, significantly reducing the service life of engineering and hydraulic structures [1]. Many studies are aimed at improving the mineralogical composition of sulfate-resistant clinker, in particular, minimizing the C_3A phase [2]. Studies have shown that reducing the amount of Al_2O_3 or increasing the amount of Fe_2O_3 effectively suppresses the formation of C_3A. Clinkers with a high iron-to-aluminum ratio and a predominance of the ferrite phase demonstrated a sharp reduction in C_3A content and an increase in sulfate resistance [[3], [4]].

It has been shown that optimization of batch composition can reduce the C_3A content below 5% [5], with iron-rich admixtures shown to be particularly effective. Thermodynamic modeling has confirmed the high sulfate resistance of clinkers with a predominance of ferrite phases [[6], [7], [8]]. Mechanistic studies have shown that C_3A phases form expanding products in a two-stage reaction with sulfate ions; long-term observations of the microstructure of sulfate-exposed concrete have confirmed that low-C_3A cements have high strength. The addition of mineral admixtures such as limestone powder, upper kiln slag, and pozolanic materials has also been noted to significantly improve sulfate resistance [[9], [10], [11], [12], [13]].

It has also been noted that sulfate-resistant Portland cement can deteriorate under prolonged moisture conditions and exposure to highly aggressive sulfate. Among the proposed strategies for combating this problem, increasing the Fe/Al ratio with iron-rich mineral additives and using additional cementitious materials such as slag and limestone have been shown to be the most effective [14].

Research conducted in Spain examined the technical and environmental performance of sulfate-resistant clinkers containing new mineral components such as iron-rich sand, slag, and "albero" [15]. The results showed that partial replacement with slag (up to 30%) increases sulfate resistance without compromising mechanical strength. Additional research has confirmed that optimal use of additional cementitious materials in Portland cements improves sulfate resistance [16]; the amount of SO_3 generated by the clinker-gypsum interaction has been found to have a measurable effect on sulfate resistance [17].

In addition to compositional optimization, the use of mineral additives and recycled materials in clinker production improves environmental performance, reduces production costs, and lowers CO_2 emissions [18].

Research conducted in regions neighboring Uzbekistan also explored the potential for producing sulfate-resistant cement using local mineral resources, focusing on batch optimization, phase analysis, and durability testing in sulfate environments. Practical trials conducted at Karakalpak Cement LLC confirmed that silicon additives improve physical and mechanical properties and enhance sulfate resistance [[19], [20], [21], [22], [23]]. Buriev et al. noted that a high degree of substitution with pozolane materials—for example, fly ash—has a positive effect on sulfate resistance [[24], [25]]. Iskandarova and her colleagues identified innovative directions for the development of composite Portland cement in the region. Kazakhstani scientists who synthesized ferrite-phase cements using manganese- and iron-rich ores confirmed that increasing the C_4AF content reduces C_3A, improving sulfate resistance [26].

From an economic perspective, the use of local limestone, loose sand, kaolin, and iron-rich industrial waste reduces dependence on imported raw materials and lowers production costs, strengthening the competitiveness of the cement industry in the region. Rational use of local resources not only improves technological efficiency but also reduces production costs, contributing to the sustainable development of industry in the Aral Sea region [27].

From an environmental perspective, sulfate-resistant Portland cement clinker, by resisting sulfate corrosion, extends the service life of hydraulic and civil engineering structures, reduces the need for repairs and reconstruction, thereby reducing resource consumption and environmental impacts. These principles are fully consistent with the concepts of a "green economy" and "circular economy," which prioritize sustainability and the efficient use of industrial waste [28]. The inclusion of iron-rich industrial waste in the batch further supports waste recycling and helps reduce CO_2 emissions in the cement industry.

Overall, sulfate-resistant Portland cement clinker synthesized from local raw materials from Karakalpakstan offers a harmonious combination of technological advantages, cost efficiency, and environmental sustainability, making it a material of high practical importance for the Aral Sea region.

Experimental part

Materials and Methods

Sulfate-resistant Portland cement clinker was synthesized using local raw materials sourced from the Lower Aral Sea region. The base raw material mixture included limestone, barren sand, and kaolin, while gypsum and iron-containing industrial waste were used as adjusting components to achieve the target oxide balance. Laboratory samples were prepared at Karakalpak Cement LLC, and all analytical measurements were conducted at the STROM Research and Testing Center of the Institute of General and Inorganic Chemistry of the Academy of Sciences of Uzbekistan.

Chemical Composition

The chemical composition of the synthesized clinker was determined in accordance with UzM St 337:2024 and GOST 5382-2019 by classical titration and gravimetric methods [[28], [29]]. The results (wt.%) were as follows: CaO - 61.09; SiO_2 22.10; Al_2O_3 - 4.98; Fe_2O_3 5.32; MgO - 2.07; SO_3 - 0.80; LOI - 1.14; Free CaO - 0.94. The calculated modulus values (LSF = 0.82; SR = 2.15; AR = 0.94) were within the standard values established for sulfate-resistant Portland cement clinker.

Mineralogical composition (XRD)

X-ray diffraction (XRD) analysis was performed using a Rigaku MiniFlex diffractometer (Cu-Kα radiation), and phase quantification was carried out using the Rietveld refining method. The main mineralogical phases identified in the clinker were: C_3S - 38.6%; C_2S - 38.0%; C_3A - 4.2%; C_4AF - 14.8%. These results are in close agreement with Bogue's calculations and meet the standard requirements for the phase composition of sulfate-resistant Portland cement clinker.

Sulfate Resistance Testing

Sulfate resistance was assessed in accordance with ASTM C1012/C1012M [31]. Test specimens were immersed in a 5% Na_2SO_4 solution, their dimensional expansion was measured, and they were compared to reference specimens stored in distilled water. To ensure the reliability of the results and accurately quantify the effect of sulfate ions on dimensional stability and mechanical strength, two control specimens were used for each test condition. All analyses were conducted in full compliance with the requirements of UzM St 337:2024 and GOST 5382-2019 [[29], [30]].

Results and Discussion

The selection of raw materials for the production of sulfate-resistant Portland cement clinker is of particular scientific and practical importance. Therefore, the economical use of local raw materials is an urgent issue. In the Republic of Karakalpakstan, dune sands, kaolin, iron-rich industrial waste and limestone deposits are considered promising sources of raw materials. By analyzing their chemical composition, it is possible to determine the mineralogical composition of sulfate-resistant Portland cement clinker.

The ratio of the main oxides in the raw material mixture is an important factor in the synthesis of sulfate-resistant Portland cement clinker. Calcium oxide (CaO) serves to form alite (C_3S) and belite (C_2S) phases, and silicon dioxide (SiO_2) is the basis for silicate phases; aluminum oxide (Al_2O_3) serves to form tricalcium aluminate (tricalcium aluminate). Also, to ensure sulfate resistance, it is necessary to reduce the content of tricalcium aluminate to ≤5%, preferably to 3%. Iron oxide (Fe_2O_3) is part of the ferrite phase (C_4AF) and is important in reducing the content of tricalcium aluminate.

Also, achieving the correct distribution of oxides is an important factor in ensuring the strength and long-term stability of cement in sulfate environments. The chemical composition of local raw materials in the Republic of Karakalpakstan by main oxides is presented in (Table 1).

The chemical composition of these raw materials is suitable for ensuring the optimal balance required in the synthesis of sulfate-resistant Portland cement clinker. Barkhan sands are characterized by a very high SiO_2 content (89.22%), which provides a primary source for silicate phases (e.g., C_3S and C_2S) and contributes to improved mechanical strength of clinker. However, due to their relatively low Al_2O_3 (3.15%) and Fe_2O_3 (0.97%) contents, these sands are mainly useful for increasing the silica modulus (SM).

The iron-rich by-product contains a high Fe_2O_3 content (45.24%), which plays a critical role in forming the ferrite phase (C_4AF) and thus contributes to sulfate resistance by reducing three calcium aluminate content. Meanwhile, its SiO_2 (40.40%) and Al_2O_3 (6.00%) levels are moderate, allowing adjustment of the iron modulus (IM) in the raw mix. Low levels of alkaline oxides such as Na_2O and K_2O ensure that adverse effects occur during clinker hydration. Kaolin is high in Al_2O_3 (16.47%) and SiO_2 (54.07%), and acts as the main raw material for the formation of aluminate phases. However, due to the relatively high Al_2O_3 content, kaolin consumption must be carefully controlled, otherwise the tricalcium aluminate content in the clinker may exceed 5%. Kaolin has moderate Fe_2O_3 (9.93%) and Na_2O (1.72%) levels, and it is suitable for adjusting the aluminum modulus (AM). The low content of SO_2 (0%) and TiO_2 (0.17%) does not adversely affect the quality of sulfate-resistant clinker.

Limestone is the main source of CaO (53.14%), which is essential for the formation of alite and belite phases. The almost complete absence of SiO_2 and Al_2O_3 (0% and 0.15%) in it proves that it is a pure calcium source. The low content of MgO (2.56%) and Fe_2O_3 (0.12%) does not cause problems during the clinker hydration process. The loss on heat (LOI, ≈ 42.49%) proves the carbonate nature of the limestone and indicates the release of CO_2 during the calcination process.

In general, the mixture of these raw materials provides the ratio of oxides necessary for the synthesis of sulfate-resistant Portland cement clinker. It is recommended to conduct laboratory tests to determine the main composition. According to preliminary calculations, the optimal batch composition may be as follows: barren sand 15–20%, iron-rich industrial waste 5–10%, kaolin 10–15% and limestone 60–70%. This approach allows for the maximum use of local raw materials and increases the resistance of cement to sulfate environments by 20–30%. In addition to these raw materials, gypsum plays an important role in the cement production process. It is mainly used as a component that regulates the rate of hardening at the cement setting stage.

Table 1 - Chemical composition of local raw materials selected for the synthesis of sulfate-resistant portland cement

Raw Material	Chemical composition by major oxides (wt.%)									
	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	Na_2O	K_2O	TiO_2	SO_2	LOI
Limestone	–	0.15	53.14	2.56	0.12	–	–	–	–	42.49
Barxan sand	89.22	3.15	0.68	2.32	0.97	0.94	0.70	0.24	0.20	1.61
Kaolin	54.07	16.47	0.85	2.57	9.93	1.72	–	0.17	–	9.23
Iron-rich by-product	40.40	6.00	2.05	4.00	45.24	–	0.40	–	0.22	3.10
gypsum stone	2.80	0.49	30.98	–	–	–	2.63	2.80	42.80	20.30
	$CaSO4 \times 2H_2O = 42.80 \times 2.15 = 85.6\%$									

According to the results of chemical analysis, gypsum from the Tashaba deposit in the Republic of Karakalpakstan contains 42.80% SO_3, which is approximately 85.6% $CaSO_4 \cdot 2H_2O$. Such a very high purity and very low content of SiO_2 (2.80%), Al_2O_3 (0.49%), MgO and Fe_2O_3 indicate that Tashaba gypsum is an ideal raw material for the cement industry. Such a pure chemical composition of Tashaba gypsum ensures the stable formation of ettringite during the hydration process, prevents secondary reactions and increases the sulfate resistance of cement. The low content of impurities in the mixture has a positive effect on the friability, color and stability of the composition of the cement. Therefore, the use of Tashaba gypsum in the production process of sulfate-resistant clinker not only improves the quality of cement, but also serves to effectively use local mineral resources, reduce production costs, and ensure the environmental sustainability of the cement industry (Fig. 1).

Figure 1 - gypsum stone sourced from the Tashaba deposit, Karakalpakstan

The successful balance of the above raw material components is reflected in the mineralogical composition of the synthesized sulfate-resistant Portland cement clinker, since the ratio of oxides directly affects the phases formed (Table 2).

According to the data from the table, the clinker contains CaO (61.09%). It is mainly derived from limestone and is important in the formation of the main part of the alite (C_3S) and belite (C_2S) phases, which determine the strength of the cement and the hydration process. The SiO_2 content (22.1%) is moderate, which plays an important role in the formation of silicate phases in particular. This oxide is mainly derived from barren sands and kaolin. The amounts of Al_2O_3 (4.98%) and Fe_2O_3 (5.32%) serve to form the aluminate and ferrite phases in the clinker due to kaolin and iron-rich industrial waste. Small amounts of oxides such as MgO (2.07%) and SO_3 (0.80%) improve the stability of the clinker in sulfate environments and at the same time prevent undesirable reactions. The absence of Cl^- (0.0%) and the low content of free CaO (0.935%) greatly increase corrosion resistance. The low heat loss (1.14%) confirms the very good quality of the raw materials. The total oxide content of 100.0% indicates that the clinker composition is optimal and fully balanced.

In the mineralogical composition, the clinker is dominated by C_3S (38.64%) and C_2S (41.03%) phases, which primarily determine its mechanical properties. The relatively low content of tricalcium aluminate (4.17%, ≤5%) is the main indicator of sulfate resistance, since it greatly reduces the formation of ettringite. This is directly related to the low content of Al_2O_3 in the raw materials. The presence of the C_4AF (16.16%) phase indicated a high ferrite content in the clinker. This phase is formed due to Fe_2O_3 introduced through iron-rich industrial waste and, replacing part of the tricalcium aluminate, increases the strength of sulfate-resistant cement clinker. The calculated modulus values once again prove that the raw material mixture is in equilibrium. The CaO/SiO_2 ratio (2.76) — the silicon modulus — provides high mechanical strength of the cement. The lime saturation factor (LSF = 0.86) indicates that the firing process was carried out under optimal conditions. The aluminum modulus n (2.15) and iron modulus p (0.94) confirm that the oxides have a stable ratio. These results prove that it is possible to effectively produce sulfate-resistant Portland cement clinker based on local raw materials such as barren sand, iron-rich industrial waste, kaolin and limestone.

Table 2 - Chemical and mineralogical composition of sulfate-resistant portland cement clinker

Material name	**LOI**	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**MgO**	**SO_3**	**Cl^-**	**CaO (Free CaO)**	**Σ**
Portland cement clinker	1.14	22.1	4.98	5.32	61.09	2.07	0.8	0.0	0.935	100.0
	Mineralogical composition (%) and module indices									
		C_3S=38.64; C_2S=41.03; C_3A=4.17; C_4AF=16.16; CaO/SiO_2=2.76; LSF=0.86; SR=2.15; AR=0.94								

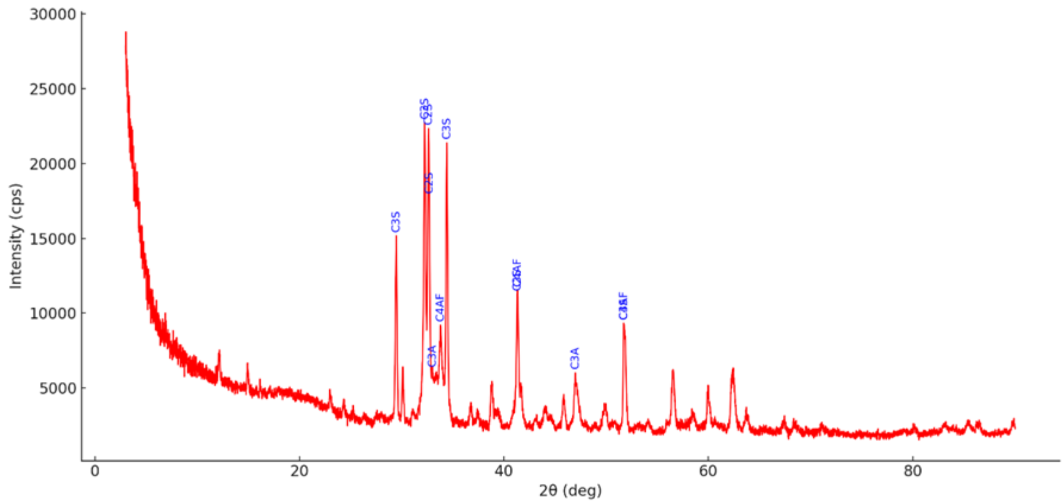

Figure 2 - XRD pattern of SRC clinker showing the main phases (C_3S, C_2S, C_3A, C_4AF)

Reducing the amount of tricalcium aluminate can reduce the expansion and erosion of cement in sulfate environments by 15–25%, resulting in increased long-term durability of structures. However, to maintain optimal modulus values, it is necessary to precisely control the firing temperature in the range of 1350–1450 °C, as well as the time of burning the clinker in the kiln. In future studies, it is proposed to study the mineralogy of the raw material mixture in depth, analyze the hydration kinetics, and conduct mechanical tests in order to improve the efficiency of the synthesized clinker. The chemical composition and phase structure of the clinker were evaluated by X-ray phase analysis along with tabular data. The XRD diffractogram showed clear peaks corresponding to the main crystal phases, the presence of which confirmed the results obtained by the Bogue method (Fig. 2). The strongest diffraction peaks observed between 2θ ≈ 29–34° and 51–52° indicate the dominance of the C_3S and C_2S phases.

The high content of alite and belite phases is an mportant factor determining the main mechanical properties of clinker. The Alite mineral, which makes up the mineralogical composition of clinker, actively participates in the early days of the hydration process, ensuring rapid hardening of the cement stone from the first days. Belite, on the other hand, exhibits a very slow hydration property compared to allite and serves to increase the long-term strength of the cement stone in the period of 28 days and beyond. The high content of these two phases is the main reason for the rapid and very high-quality mechanical strengthening of the cement.

The results of the above data were found to be in full agreement with the analysis of the X-ray diffractogram. The most intense diffraction peaks were recorded in the range of 2θ = 28–350 and 50–530, which were found to correspond to the alite (C_3S) and belite (C_2S) phases. These indicators confirm the quantitative data obtained from Bogue calculations. The peaks around 2θ = 32–340 and 480 correspond very well to the tricalcium aluminate phase (C_3A = 4.2%) and indicate that its content in the clinker is very low. The low content of tricalcium aluminate clearly indicates that it is an important factor in increasing sulfate resistance. The peaks observed at 2θ = 32–340, 41–420 and 520 also correspond to the tricalcium aluminoferrite phase (C_4AF = 16.2%), which is in full agreement with the results of chemical and mineralogical analyses.

The fact that free CaO is lower than the required standard indicates the efficiency of the synthesis process. These results scientifically justify the possibility of using the obtained sulfate-resistant Portland cement clinker in the production of sulfate-resistant cement in accordance with the standards of the Republic of Uzbekistan St 337:2024 and GOST 22266-2013.

Sulfate resistance tests conducted according to the ASTM C1012/C1012M standard showed significant differences in cement samples. The degree of expansion observed in a Na_2SO_4 solution for 28 days was directly related to the composition of the mineral phases of the cement (Table 3).

Table 3 - ASTM C1012 sulfate resistance test – 28-day results

Sample	Medium	Length (mm)
1.1	Distilled Water	16.1
1.2	Distilled Water	16.1
1.3	5% Na_2SO_4	16.1
2.1	Distilled Water	16.1
2.2	Distilled Water	16.1
2.3	5% Na_2SO_4	16.1
3.1	Distilled Water	16.0
3.2	Distilled Water	16.0
3.3	5% Na_2SO_4	16.0

The 28-day exposure results clearly show that the cement based on sulfate-resistant Portland cement clinker showed significantly higher durability than OPC (ordinary Portland cement) and blended cements (Figure 3).

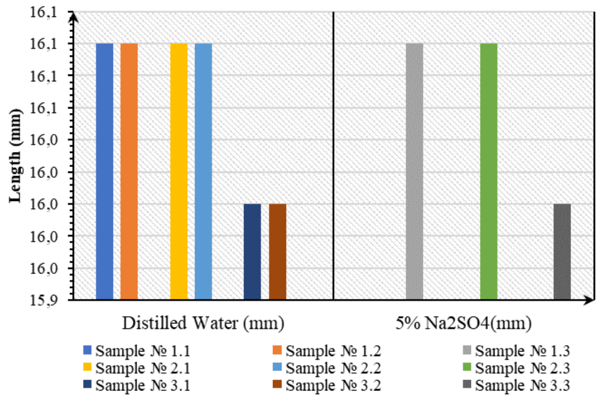

Figure 3 - Expansion of cement samples (SULFATE RESISTANT PORTLAND CEMENT, OPC, and blended cement) after 28 days of exposure to 5% Na_2SO_4 solution

First, the cement based on sulfate-resistant Portland cement clinker had the lowest expansion values. This is explained by the limited content of tricalcium aluminate in the composition (tricalcium aluminate ≤ 5%). Due to the low calcium aluminate, it reduces the reaction with sulfate ions and reduces the formation of excess ettringite or secondary gypsum. As a result, sulfate-resistant Portland cement exhibits long-term durability.

Second, ordinary Portland cement (OPC) showed high expansion. At the end of 28 days, the deformation values approached or exceeded the limit values specified in the ASTM C1012 standard. This is explained by the high content of three calcium aluminates in the OPC composition. Tricalcium aluminate actively reacts with sulfate ions, forming expansive ettringite.

Third, the mixed cements obtained from local raw materials showed lower expansion than OPC, but did not reach the level of sulfate-resistant Portland cement. This indicates that local mineral additives (kaolin, clay derivatives, iron-rich additives) have a partially limiting effect on the reaction with sulfate ions.

In general, experiments have shown that sulfate-resistant Portland cement, which can be produced in Karakalpakstan, has significantly higher resistance to sulfate-rich conditions - in particular, in the conditions of high-sulfate groundwater of the Aral Sea region - than ordinary Portland cement. These scientific results confirm the increased resistance of sulfate-resistant Portland cement to the effects of sulfate ions and its possible use as a promising construction material in aggressive environments.

Conclusions

This study comprehensively assessed the feasibility of producing sulfate-resistant Portland cement clinker from local raw materials in Karakalpakstan, specifically limestone, barren sand, kaolin, and iron-containing industrial waste. This represents a new use for regionally available resources, which have not previously been explored in combination for this purpose.

Chemical analysis confirmed that the raw mix achieved an optimal oxide balance of CaO, SiO2, Al2O3, and Fe2O3, resulting in modulus values (LSF = 0.82; SR = 2.15; AR = 0.94) fully compliant with standard regulatory requirements for sulfate-resistant Portland cement clinker. The significant belite content is particularly significant, as C2S promotes long-term strength development and a reduction in the heat of hydration—properties particularly beneficial in sulfate-resistant systems. Critically, the tricalcium aluminate (C3A ≈ 4.2%) content remained below the 5% regulatory threshold, which is the primary mineralogical basis for sulfate resistance. The increased C4AF content, achieved through the intentional inclusion of iron-rich industrial waste, further enhanced clinker stability.

X-ray diffraction analysis, consistent with Bogue's calculations, confirmed that the free lime content (0.32%) was significantly below the regulatory level, indicating that the clinkerization process was complete and thermally efficient.

Sulfate resistance tests conducted in accordance with ASTM C1012/C1012M demonstrated clear differences in performance between cement types. Ordinary Portland cement demonstrated the highest expansion (approaching the standard limit after 28 days), the blended cements yielded intermediate results, and the sulfate-resistant Portland cement clinker synthesized in this study achieved the lowest expansion value, confirming its excellent resistance to sulfate attack. The exact expansion values for all cement types tested are presented in Table 3.

In conclusion, sulfate-resistant Portland cement clinker of standard quality can be successfully synthesized from local raw materials from Karakalpakstan, with optimized modulus values specifically tailored to the mineral properties of these regional resources. The use of iron-containing industrial waste as a corrective additive not only met the compositional requirements but also facilitated the recycling of industrial waste, reduced dependence on primary raw material extraction, and minimized emissions associated with the transportation of imported raw materials. These results demonstrate both the technical viability and the environmental and economic benefits of localized sulfate-resistant cement production.

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

CRediT author statement: **A. Khadzhiev**: Conceptualization, Methodology, Software; **A. Khadzhiev**: Data curation, Writing draft preparation; **L Wang**: Visualization, Investigation; **F. Atabaev**: Supervision; **N. Makhsudova**: Software, Validation; **E. Atashev**: Reviewing and Editing.

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Қарақалпақстанның минералдық ресурстары негізінде сульфатқа төзімді портландцемент клинкерін өндірудің технологиялық, экономикалық және экологиялық аспектілері

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Бұл зерттеу Өзбекстан Республикасының Арал теңізі өңірінен табылған жергілікті шикізат негізінде сульфатқа төзімді портландцемент клинкерін өндіруге және оның қасиеттерін зерттеуге арналған. Алынған нәтижелер технологиялық, экономикалық және экологиялық артықшылықтарды көрсетеді. Шикізат қоспалары әктас, құнарсыз құм, каолин және темірге бай өндірістік қалдықтардан тұрды, нәтижесінде оңтайландырылған оксидті құрамы бар клинкер алынды (LSF = 0,82, SR = 2,15, AR = 0,94). Рентгендік фазалық талдау жоғары механикалық беріктікті қамтамасыз ететін алит (C_3S ≈ 38,6%) және белит (C_2S ≈ 41,0%) фазаларының жоғары құрамын көрсетеді. Үшкальций алюминатының төмен мөлшері (үшкальций алюминатының < 5%) және ферриттің жеткілікті мөлшері (C_4AF ≈ 16,2%) сульфатқа төзімділігі мен фазалық басымдылығын арттырды. ASTM C1012/C1012M стандартына сәйкес жүргізілген сульфатқа төзімділік сынақтары сульфатқа төзімді портландцементтің 5% Na_2SO_4 ерітіндісіне салынған үлгілер арасында ісіну индексінің ең төмен екенін көрсетті, бұл қарапайым портландцемент пен аралас цемент түрлерімен салыстырғанда оның жоғары төзімділігін дәлелдеді. Алынған нәтижелер жергілікті шикізат негізінде сульфатқа төзімді жоғары сапалы портландцемент клинкерін шығаруға және оның Орал өңірінің сульфатқа бай жағдайларына жарамдылығын көрсетуге мүмкіндік береді. Экономикалық тұрғыдан жергілікті шикізатты пайдалану өндіріс шығындарын азайтады, импортқа қажеттілікті азайтады, цемент өнеркәсібінің бәсекеге қабілеттілігін арттырады. Экологиялық тұрғыдан алғанда, сульфатқа төзімді портландцементтің ұзақ қызмет ету мерзімі және өнеркәсіптік қалдықтарды пайдалану жасыл экономикаға сәйкес келеді, қалдықтарды азайтуға көмектеседі және тұрақты дамуға ықпал етеді.

Түйінді сөздер: сульфатқа төзімді портландцемент, клинкер синтезі, минералды ресурстар, сульфатқа төзімділік, жасыл экономика, тұрақтылық.

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Технологические, экономические и экологические аспекты производства сульфатостойкого портландцементного клинкера на основе минеральных ресурсов Каракалпакстана

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АННОТАЦИЯ

Данное исследование посвящено получению сульфатостойкого портландцементного клинкера на основе местного сырья, обнаруженного в регионе Аральского моря Республики Узбекистан, и изучению его свойств. Полученные результаты подчеркивают технологические, экономические и экологические преимущества. В качестве сырьевых смесей использовались известняк, пустые пески, каолин и богатые железом промышленные отходы, что позволило получить клинкер с оптимизированным оксидным составом (LSF = 0,82, SR = 2,15, AR = 0,94). Рентгенофазовый анализ показывает высокое содержание фаз алита (C_3S ≈ 38,6%) и белита (C_2S ≈ 41,0%), что обеспечивает высокую механическую прочность. Низкое содержание трикальцийалюмината (трикальцийалюминат < 5%) и достаточное содержание феррита (C_4AF ≈ 16,2%) повысили сульфатостойкость и фазовое доминирование. Испытания на сульфатостойкость, проведенные в соответствии со стандартами ASTM C1012/C1012M, показали, что сульфатостойкий портландцемент имел самый низкий индекс набухания среди образцов, помещенных в 5% раствор Na_2SO_4, что подтверждает его высокую стойкость по сравнению с обычным портландцементом и смешанными видами цемента. Полученные результаты открывают возможность производства высококачественного сульфатостойкого портландцементного клинкера на основе местного сырья и демонстрируют его пригодность для условий региона Орал с высоким содержанием сульфатов. С экономической точки зрения использование местного сырья снижает производственные затраты, уменьшает потребность в импорте и повышает конкурентоспособность цементной промышленности. С экологической точки зрения длительный срок службы сульфатостойкого портландцемента и использование промышленных отходов совместимы с «зеленой» экономикой, способствуют сокращению отходов и устойчивому развитию.

Ключевые слова: сульфатостойкий портландцемент, синтез клинкера, минеральные ресурсы, сульфатостойкость, зелёная экономика, устойчивое развитие.

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