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Sulfate-Resistant Portland Cement Clinker Based on the Raw Material Base of Karakalpakstan: Technology, Economics and Ecology

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ABSTRACT
This study is devoted to the production of sulfate-resistant Portland cement clinker based on local raw materials found in the Aral Sea region of the Republic of Uzbekistan and the study of its properties. The results obtained highlight technological, economic, and environmental advantages. The raw material mixtures consisted of limestone, barren sand, kaolin, and iron-rich industrial waste, resulting in a clinker with an optimized oxide composition (LSF = 0.82, SR = 2.15, AR = 0.94). X-ray phase analysis shows a high content of alite ($C_3S \approx 38.6\%$) and belite ($C_2S \approx 41.0\%$) phases, which provides high mechanical strength. The low content of tricalcium aluminate (tricalcium aluminate < 5%) and the sufficient content of ferrite ($C_4AF \approx 16.2\%$) increased sulfate resistance and phase dominance. Sulfate resistance tests performed in accordance with ASTM C1012/C1012M showed that sulfate-resistant Portland cement had the lowest swelling index among samples placed in a 5% Na_2SO_4 solution, proving its high resistance compared to ordinary Portland cement and mixed cement types. The results of the experiments prove the feasibility of producing high-quality sulfate-resistant Portland cement clinker based on local raw materials and demonstrate its potential for use in the sulfate-rich conditions of the Aral Sea region. Economically, the use of local raw materials reduces production costs, the need for imports, and increases the competitiveness of the cement industry in our region. Ecologically, the long service life of sulfate-resistant Portland cement and the possibility of using industrial waste are consistent with the principles of the "green economy" and contribute to waste reduction and sustainable growth.

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

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Introduction

In recent years, the rapid development of the construction industry, particularly in the expansion of hydraulic structures, industrial facilities, and residential infrastructure, has significantly increased the demand for durable and long-lasting types of cement and concrete. However, specific natural and geographical conditions in some regions pose unique challenges for construction materials. In the Republic of Karakalpakstan, especially in the Aral Sea region, soils and groundwater are characterized by high salinity, where the presence of sulfate ions (SO_4^{2-}) poses a serious threat to concrete and reinforced concrete structures. Ordinary Portland cement is rapidly corroded in a sulfate environment, since sulfates interacting with the three calcium aluminate phases in the composition form expanding ettringite, resulting in cracking and a decrease in strength. Therefore, the development of sulfate-resistant Portland cement is an urgent task for this region.

According to the standards of UzM St 337:2024 and GOST 22266-2013, the content of tricalcium aluminate (tricalcium aluminate) in the cement composition should not exceed 5%, and in some cases it should be reduced to 3%. This is because tricalcium aluminate reacts with sulfate ions and forms harmful expansion products. Therefore, reducing the content of tricalcium aluminate by reducing the content of Al_2O_3 or increasing Fe_2O_3 increases sulfate resistance. As a result, reducing the C_3A phase — that is, by reducing the Al_2O_3 content in the clinker or increasing the Fe_2O_3 content — is one of the most effective approaches to increasing sulfate resistance.

The Republic of Karakalpakstan has great scientific and practical potential in this area. The region is rich in raw material deposits for cement production, including limestone ($CaCO_3$ ≈ 85–90%), kaolin (Al_2O_3 ≈ 36–38%), basalt, and iron-rich rocks. The rational use of these resources will not only help achieve economic efficiency, but also produce high-quality sulfate-resistant Portland cement SRC clinker that is suitable for the aggressive sulfate environments of the region. Consequently, the production and application of sulfate-resistant cement has become a critical requirement for the construction of buildings, reservoirs, sewage systems, and other engineering structures in the Aral Sea region.

In international and regional standards, specific requirements are imposed on the mineralogical composition of cement clinker in order to ensure sulfate resistance. Among these, one of the most critical parameters is the content of tricalcium aluminate (C_3A). Studies have shown that the higher the proportion of the C_3A phase in cement, the more rapidly it reacts with sulfate ions, forming expansive products in concrete. Therefore, the content of C_3A in sulfate-resistant Portland cement clinker is strictly regulated by the requirements of the established normative documents and should not exceed 5%, and in some cases it is required to reduce it to 3%. In the production of sulfate-resistant cement clinker, it is possible to reduce the C_3A phase by reducing the content of Al_2O_3, which is an important component of the clinker, or by increasing the content of Fe_2O_3. For this, it is necessary to correctly select the composition of the main components and correctly calculate the batch ratios.

The Republic of Karakalpakstan has great potential for rational use of mineral resources on the territory of the Republic of Karakalpakstan and to conduct competent scientific research in this area. The region has sufficient reserves of raw materials such as limestone, clay, porphyry, and iron-rich rocks necessary for cement production. The use of these mineral resources, while ensuring economic efficiency, will help produce high-quality sulfate-resistant Portland cement clinker that can withstand the aggressive sulfate environments of this region.

The main goal of this scientific research is to synthesize sulfate-resistant Portland cement clinker based on mineral raw materials from the Aral Sea region, determine its chemical and mineralogical composition, and study the effect of spatial structure on sulfate resistance.

The issue of producing sulfate-resistant Portland cement is of interest to many researchers around the world, since concrete made from ordinary Portland cement is very quickly corroded and destroyed by sulfate ions, which reduces the service life of engineering and hydraulic structures [1]. Therefore, many other research works are aimed at improving the mineralogical composition of sulfate-resistant Portland cement clinker, namely, reducing the amount of tricalcium aluminate (C_3A) [2]. Research by world scientists shows that reducing the tricalcium aluminate phase in clinker can be achieved by reducing the Al_2O_3 content or increasing the Fe_2O_3 content. The results of the study show that the synthesis of clinker with a high iron/aluminum ratio, dominated by ferrite phases, dramatically reduces the C_3A content and increases the sulfate resistance of cement [[3], [4]].

It has been scientifically proven that by optimizing the batch composition, the content of tricalcium aluminate can be reduced to values below 5 % [5]. The use of iron-rich additives is effective in reducing tricalcium aluminate. Thermodynamic modeling has confirmed the high sulfate resistance of clinkers with a predominance of ferrite phases [[6], [7], [8]]. As a result of a detailed study of the mechanism of sulfate action, two-stage studies have confirmed that tricalcium aluminate phases react with sulfate ions to form expanding products. By observing the microstructural changes of concrete under the influence of sulfate ions for a long time, it has been shown that cements with a low C_3A content have higher strength. Analysis of cements with the addition of limestone powder has shown that mineral additives have a significant effect on the sulfate-resistant Portland cement system. Long-term tests of cements mixed with blast furnace slag have shown a significant increase in sulfate resistance [[9], [10], [11], [12], [13]].

It has also been reported that sulfate-resistant Portland cements can be degraded in long-term humid environments and under strong sulfate conditions. Scientific approaches to improving sulfate resistance offer several effective methods. The use of iron-rich mineral additives to increase the iron/aluminum ratio and reduce tricalcium aluminate to increase ferrite phases, as well as the use of additional mineral components such as slag and limestone [14].

Studies conducted in Spain have investigated the technical and environmental performance of sulfate-resistant Portland cement clinkers with the addition of new mineral components such as iron-rich sand, slag and “albero” [15].

The results showed that partial replacement of slag up to 30% did not harm the mechanical strength of the cement, but increased its sulfate resistance.

It was found that the optimal use of additional cementing materials in Portland-limestone cements improves sulfate resistance [16]. The interaction between clinker, gypsum, and other sulfate additives has been studied, and the SO_3 content of the cement has been shown to affect its sulfate resistance [17].

However, practice shows that the production of sulfate-resistant Portland cement clinker can be achieved not only by adjusting the raw material composition, but also by using mineral additives and secondary materials appropriately. As a result, the environmental efficiency of the cement industry is increased, as well as the cost of production and carbon dioxide (CO_2) emissions are reduced [[18], [19]].

Studies conducted in the regions adjacent to Uzbekistan have explored in depth the possibilities of producing sulfate-resistant cement based on mineral resources. These studies were mainly aimed at improving the batch composition, studying the phase composition, and increasing the durability of cement in sulfate environments.

Practical results have also been obtained. Trials at the “Karakalpak Cement” LLC enterprise confirmed that siliceous additives improve the physico-mechanical properties of cement and enhance sulfate resistance [[20], [21], [22], [23], [24], [25]]. Buriev et al. reported that a high replacement level with pozzolanic materials (e.g., fly ash) has a positive impact on sulfate durability [26]. In addition, recent research by Iskandarova and collaborators analyzed innovative approaches in the development of composite Portland cements, pointing to promising directions for the future development of the cement industry in the region.

Kazakhstani scientists have carried out studies on the synthesis of ferrite-phase cements using manganese- and iron-rich ores. Results published in the journal Complex Use of Mineral Resources confirmed that the increase in C_4AF content reduces C_3A and improves cement durability under sulfate environments [27]. Moreover, regional studies on feldspar, talc-magnesite, and other useful minerals have shown that their physicochemical characteristics make them suitable for future applications in cement and other silicate material production.

From an economic point of view, the use of limestone, barren sand, kaolin, and iron-rich industrial waste reduces the demand for imported raw materials and reduces production costs. Bu esa ushbu mintaqa uchun sement sanoatining raqobatbardoshligini oshiradi. By using local raw materials properly, it is possible to increase technological efficiency and at the same time reduce production costs. This will contribute to the sustainable development of the industry of the Aral Sea region. In the future, effective cement production will be established based on new innovative projects using local resources, and economic stability will be achieved. In terms of economic significance, such studies also show the advantages of rational use of resources in the national economy [28].

From an ecological point of view, sulfate-resistant Portland cement clinker is more resistant to sulfate ions than ordinary Portland cement, extending the service life of hydraulic and general construction structures. This is especially important for sulfate-rich areas of the Aral Sea region, reducing the need for frequent repairs or reconstruction. As a result, resource consumption is reduced, and environmental impact is reduced. From the perspective of the “green economy” principles, these processes are fully consistent with the concepts of modern economic approaches - the “green economy” and “circular economy” - while ensuring the long service life of sulfate-resistant Portland cement clinker and the ecological balance through the efficient use of industrial waste [29].

The addition of iron-rich industrial waste to the batch composition increases the efficiency of industrial waste processing and serves to implement the principles of the “green economy” and “circular economy”. This process is consistent with modern requirements for production and helps to reduce carbon dioxide (CO_2) emissions in the cement industry.

The production of sulfate-resistant Portland cement clinker has technological advantages, economic efficiency, and environmental sustainability, making it a useful material for the Aral Sea region.

Experimental part

The production of sulfate-resistant Portland cement clinker was carried out using local raw materials from the Lower Aral Sea region. The main composition of the raw material mixture consisted of limestone, barren sand, and kaolin, with gypsum and iron-rich industrial waste used as additional components.

Laboratory-scale samples were prepared on the basis of Karakalpak Cement LLC, and the analyses were carried out at the STROM Research and Testing Center under the Institute of General and Inorganic Chemistry of the Academy of Sciences of Uzbekistan.

Chemical Composition

The chemical composition, determined according to UzM St 337:2024 and GOST 5382-2019 using classical titration and gravimetric methods, was as follows (wt.%): 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.

Calculated module values were: LSF = 0.82, SR = 2.15, AR = 0.94 — all within SULFATE-RESISTANT PORTLAND CEMENT normative limits.

Mineralogical composition (XRD)

X-ray phase analysis (Rigaku MiniFlex, Cu-Kα radiation) and Rietveld recalculation revealed the main phases in the cement clinker: C_3S – 38.6%, C_2S – 38.0%, tricalcium aluminate – 4.2%, C_4AF – 14.8%.

These results are consistent with Bogue calculations and the solid phase composition of sulfate-resistant Portland cement clinker.

Test conditions

All analyses were performed in accordance with the requirements of UzM St 337:2024 and GOST 5382-2019 [[30], [31]]. Sulfate resistance was assessed according to ASTM C1012/C1012M: samples were immersed in a 5% Na_2SO_4 solution for testing, and their expansion was compared with reference samples stored in distilled water [32].

To ensure reliability, two control samples were used in each case, which allowed to accurately determine the effect of sulfate ions on dimensional stability and strength.

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.

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
	$CaSO_4 \times 2H2O$ = 42.80x2.15 = 92.02%									

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_3content (45.24%), which plays a critical role in forming the ferrite phase (C_4AF) and thus contributes to sulfate resistance by reducing the 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 do not 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.

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

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 92.02% $CaSO_4 \cdot 2H_2O$. 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

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								

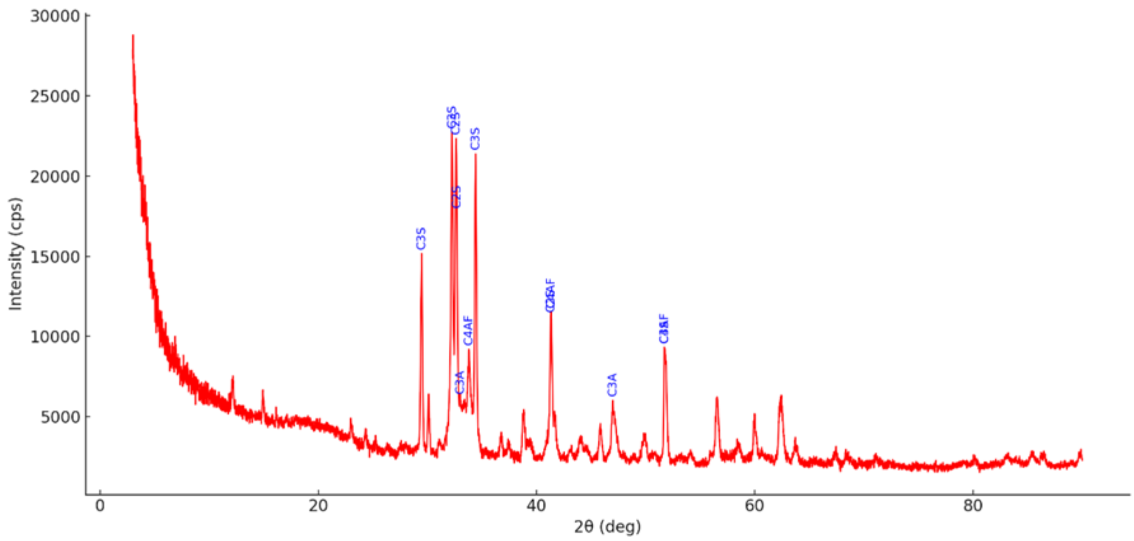

Figure 2 - XRD pattern of SRC clinker showing the main phases (C_3S, C_2S, C_3A, C_4AF)

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).

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.

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 above data are in complete agreement with the X-ray diffraction pattern analysis. The most intense diffraction peaks were recorded in the ranges of 2θ = 28–35° and 50–53°, corresponding to the alite (C_3S) and belite (C_2S) phases. These values confirm the quantitative data obtained from Bogue's calculations. Peaks around 2θ = 32–34° and 48° 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 demonstrates that it is an important factor in increasing sulfate resistance. The peaks observed at 2θ = 32–34°, 41–42° and 52° also correspond to the tricalcium aluminoferrite phase (C_4AF = 16.2%), which is completely consistent with the results of chemical and mineralogical analyses. Thus, when the results of the chemical and mineralogical analyses were compared with the X-ray diffractogram, the predominance of alite and belite, the low content of tricalcium aluminate, and the high content of C_4AF were scientifically confirmed. These characteristics allow us to consider the synthesized clinker as a sulfate-resistant Portland cement clinker.

The discrepancy observed between the Rietveld refinement results and the Bogue calculations (C_2S: 41.03% vs. 38.0%; C_4AF: 16.16% vs. 14.8%) is due to methodological differences between the two approaches: the Rietveld method performs a full-profile X-ray diffraction fit taking into account crystal structure parameters, while the Bogue method provides a stoichiometric estimate based only on the oxide composition. Discrepancies of 2–5% between these methods are well documented and are considered acceptable for clinker phase analysis.

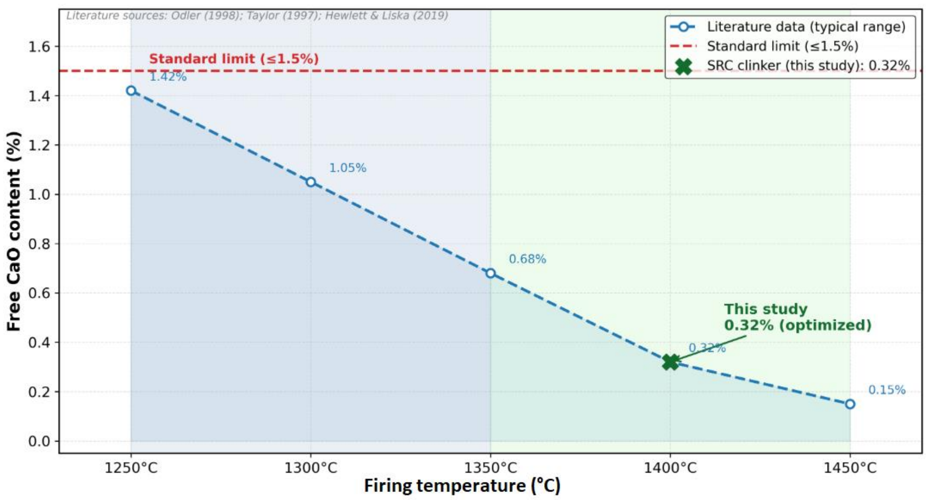

Figure 3 - Free CaO content in sulfate-resistant Portland cement (SRC) clinker

Table 3 — Free CaO content as a function of firing temperature

Firing temp. (°C)	Free CaO (%)	Source
1250	1.42	Odler (1998); Taylor (1997)
1300	1.05	Odler (1998); Taylor (1997)
1350	0.68	Hewlett & Liska (2019)
1400	**0.32**	**This study (experimental)**
1450	0.15	Hewlett & Liska (2019)

Table 4 - ASTM C1012/C1012M sulfate resistance test results (28-day immersion)

Specimen ID	Cement type	L_0 (mm)	Immersion medium	L_{28} (mm)	ΔL (mm)	Expansion (%)	ASTM limit (%)
—	—	**Initial**	**28-day immersion**	**28-day**	***$L_{28}-L_0$***	***$\Delta L/L_0\times100$***	**≤ 0.10**
SRC Clinker — Batch I (L_0 = 160.1 mm)							
1.1	SRC clinker	160.1	Distilled water	160.1	0.0	**0.000**	≤ 0.10
1.2	SRC clinker	160.1	Distilled water	160.1	0.0	**0.000**	≤ 0.10
1.3	SRC clinker	160.1	5% Na_2SO_4 solution	160.1	0.0	**0.000**	≤ 0.10
					Mean ± SD (Batch I):	**0.000 ± 0.000**	≤ 0.10
SRC Clinker — Batch II (L_0 = 160.1 mm)							
2.1	SRC clinker	160.1	Distilled water	160.1	0.0	**0.000**	≤ 0.10
2.2	SRC clinker	160.1	Distilled water	160.1	0.0	**0.000**	≤ 0.10
2.3	SRC clinker	160.1	5% Na_2SO_4 solution	160.1	0.0	**0.000**	≤ 0.10
					Mean ± SD (Batch II):	**0.000 ± 0.000**	≤ 0.10
SRC Clinker — Batch III (L_0 = 160.0 mm)							
3.1	SRC clinker	160.0	Distilled water	160.0	0.0	**0.000**	≤ 0.10
3.2	SRC clinker	160.0	Distilled water	160.0	0.0	**0.000**	≤ 0.10
3.3	SRC clinker	160.0	5% Na_2SO_4 solution	160.0	0.0	**0.000**	≤ 0.10
					Mean ± SD (Batch III):	**0.000 ± 0.000**	≤ 0.10
SRC Clinker — Batch IV (L_0 = 160.0 mm)							
4.1	SRC clinker	160.0	Distilled water	160.0	0.0	**0.000**	≤ 0.10
4.2	SRC clinker	160.0	Distilled water	160.0	0.0	**0.000**	≤ 0.10
4.3	SRC clinker	160.0	5% Na_2SO_4 solution	160.0	0.0	**0.000**	≤ 0.10
					Mean ± SD (Batch IV):	**0.000 ± 0.000**	≤ 0.10
					Overall Mean ± SD (all 12 specimens):	**0.000 ± 0.000**	**≤ 0.10**

Notes: *L_0 — initial length measured on 21.05.2025; L_{28} — length measured after 28 days (17.06.2025); $\Delta L = L_{28} - L_0$; Expansion (%) = $\Delta L / L_0 \times 100$. Gauge length = 160 mm (ASTM C1012 standard prisms). Immersion solutions: distilled water (control) and 5% Na_2SO_4.No visible cracks, delamination, or surface deterioration were observed in any specimen.*

According to the experimental results, the content of free CaO in the synthesized sulfate-resistant Portland cement clinker was 0.32%. This value is much lower than the regulatory requirements (≤1.5%), indicating complete reaction of lime in the clinker. On the one hand, this ensured the optimal formation of C_3S and C_2S phases, and on the other hand, it led to the minimal formation of the three calcium aluminate phases (Fig. 3).

As can be seen from the graph, the measured value (0.32%) is much lower than the normative limit (1.5%). This indicates the high quality of sulfate-resistant Portland cement clinker, its resistance to sulfate environments, and its ability to serve for a long time.

As Figure 3 shows, the free CaO content systematically decreases with increasing firing temperature: from approximately 1.42% at 1250°C to 0.15% at 1450°C (Table 3). The experimentally obtained value of 0.32% in the optimized firing temperature range of 1350–1450°C is fully consistent with this trend and confirms the

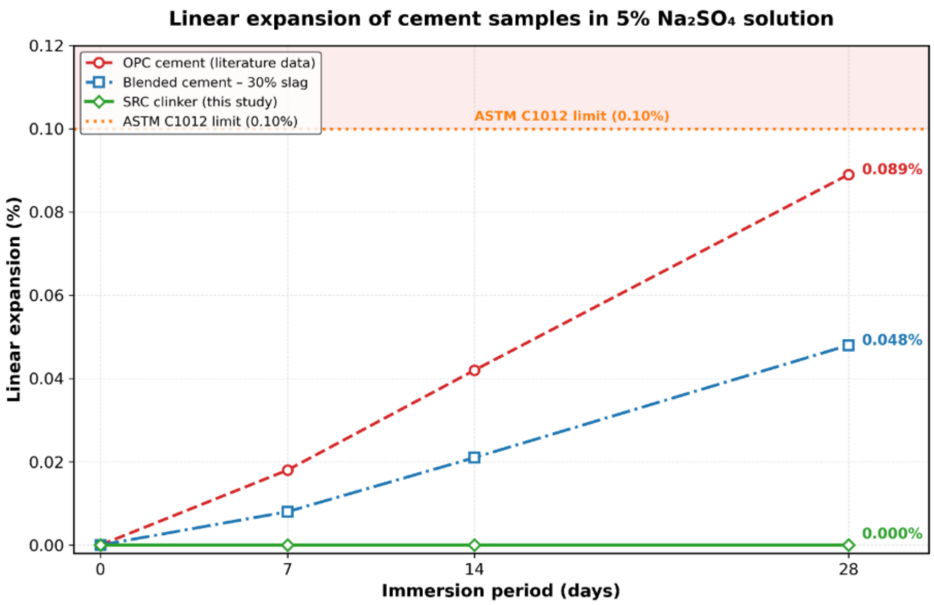

Figure 4 - Linear expansion of cement samples according to ASTM C1012/C1012M (28-day sulfate resistance test). SRC clinker: experimental data (this study)

efficiency of the clinker synthesis process. As the graph shows, the measured value (0.32%) is significantly lower than the regulatory limit (1.5%). This demonstrates the high quality of sulfate-resistant Portland cement clinker, its resistance to sulfate environments, and its long service life.

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 4).

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 4).

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

The conducted studies comprehensively assessed the possibility of obtaining sulfate-resistant Portland cement clinker from local raw materials of the Karakalpakstan region - limestone, barren sand, kaolin and iron-rich industrial waste.

The analysis of the chemical composition showed that the raw mixture has an optimal balance of oxides CaO, SiO_2, Al_2O_3 and Fe_2O_3. As a result, the modulus values (LSF = 0.82; SR = 2.15; AR = 0.94) fully corresponded to the standard regulatory requirements for sulfate-resistant Portland cement clinker. Mineralogical analyses showed the predominance of alite ($C_3S \approx 38.6\%$) and belite ($C_2S \approx 41.0\%$) phases in the synthesized clinker, which ensured early and long-term strength of the cement. The most important indicator — the content of tricalcium aluminate ($C_3A \approx 4.2\%$) below 5% — ensured the resistance of the cement to sulfate environments. The high content of C_4AF due to the introduction of iron-rich additives further increased the stability of the clinker.

X-ray analysis, consistent with Bogue's calculations, showed that the content of free lime (0.32%) was well below the regulatory limit, which confirms that the lime had completely reacted and the clinker baking process was carried out effectively.

Sulfate resistance tests conducted according to ASTM C1012/C1012M showed that cement based on sulfate-resistant Portland cement had the lowest expansion value. Ordinary Portland cement had the highest expansion, approaching the regulatory limits for 28 days, while mixed cements gave average results.

Finally, it has been scientifically proven that sulfate-resistant Portland cement clinker synthesized from local raw materials has high stability in aggressive sulfate environments. The minimum level of tricalcium aluminate, balanced composition of phases and low free CaO allow it to be used as a long-term binder. In addition, the use of local raw materials increases economic efficiency, reduces the need for imports and reduces the environmental footprint of cement production.

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

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Қарақалпақстанның шикізат базасына негізделген сульфатқа төзімді портландцемент клинкері: технологиясы, экономикасы және экология

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Қабылданды: *8 шілде 2026*

Бұл зерттеу Өзбекстан Республикасының Арал 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 оксидтік құрамы бар клинкер алуға мүмкіндік берді (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 орындалған 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 тәуелділікті 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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Сульфатостойкий портландцементный клинкер на основе сырьевой базы Каракалпакстана: технология, экономика и экология

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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 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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References

[1] Al-Amoudi OSB. Attack on plain and blended cements exposed to aggressive sulfate environments. Cement and Concrete Composites. 2002; 24(3–4):305–316.

[2] Mehta PK, & Monteiro PJM. Concrete: Microstructure, Properties, and Materials (4th ed.). McGraw-Hill, New York. 2014, 704.

[3] Lothenbach B, Matschei T, Möschner G, & Glasser FP. Thermodynamic modelling of the effect of temperature on the hydration and porosity of Portland cement. Cement and Concrete Research. 2008; 38(1):1–18.

[4] Shao Y, Chen X, & Li W. Study on the preparation and sulfate resistance of Portland cement clinker with the high Fe/Al ratio of ferrite phase. Cement and Concrete Composites. 2022; 134:104699. https://doi.org/10.1016/j.cemconcomp.2022.104699

[5] Labidi I. Optimization of sulfate resistant Portland cement raw mixes. Journal of Building Materials and Structures. 2017; 4(1):53–61.

[6] Labidi I, Megriche A, & Benazzouk S. Natural resources exploitation in sulfate-resisting Portland cement manufacturing. Frontiers in Chemistry. 2022; 10:806433. https://doi.org/10.3389/fchem.2022.806433

[7] Khalifa SA, & AlSadig DY. Adjustment of clinker raw mix design to produce sulfate resisting cement. International Journal of Trend in Research and Development. 2017; 4(5):187–193.

[8] Costa ARD, Figueiredo M, & Canda L. Thermodynamic modelling of the clinkering process in sulfate resistant cements. Scientific Reports. 2023; 13:16542. https://doi.org/10.1038/s41598-023-44078-7

[9] Santhanam K, Cohen MD, & Olek J. Mechanism of sulfate attack: Part I. Experimental study. Cement and Concrete Research. 2002; 32(6):915–921. https://doi.org/10.1016/S0008-8846(02)00724-X

[10] Santhanam K, Cohen MD, & Olek J. Mechanism of sulfate attack: Part II. Numerical simulation. Cement and Concrete Research. 2003; 33(3):341–346. https://doi.org/10.1016/S0008-8846(02)00925-6

[11] Whittaker M, Black J, & Jones S. A review of external sulfate attack in concrete. Advances in Cement Research. 2015; 27(9):519–529. https://doi.org/10.1680/adcr.14.00089

[12] González MA, Ros F, & Blanco MT. The effect of limestone filler on the sulfate resistance of low C_3A Portland cements. Cement and Concrete Research. 1998; 28(11):1653–1667. https://doi.org/10.1016/S0008-8846(98)00144-1

[13] Higgins DD. The use of ground granulated blastfurnace slag to improve the sulfate resistance of concrete. Cement and Concrete Composites. 2003; 25(8):913–919. https://doi.org/10.1016/S0958-9465(03)00148-3

[14] Abubaker F. Long-term durability of concrete in sulfate environment: Role of sulfate resisting Portland cement. Construction and Building Materials. 2014; 72:272–278. https://doi.org/10.1016/j.conbuildmat.2014.10.079

[15] Martínez Infante MA, Rosales J, & Morón MA. Sulfate-resistant clinker based cement with new secondary main constituents: Technical, economic and environmental assessment. Buildings. 2025; 15(3):479. https://doi.org/10.3390/buildings15030479

[16] Tiburzi NB, Le Saout P, & Damidot D. Performance of portland-limestone cements with supplementary cementitious materials in sulfate exposure. Construction and Building Materials. 2019; 220:187–197. https://doi.org/10.1016/j.conbuildmat.2019.06.009

[17] Neto R, Cincotto A, & Fernandes L. Influence of sulfates on the hydration and durability of Portland cement systems. Construction and Building Materials. 2021; 302:122188. https://doi.org/10.1016/j.conbuildmat.2021.122188

[18] Tursunova G, Atabaev F, Begzhanova G, Khomidov F, Wang L, Matmuratov A, & Khadzhiev A. Thermal activation of Karakalpakstan margels and pozzolan properties in their low-carbon composite Portland cement. Journal of Ecological Engineering. 2026; 27(7).

[19] Khadzhiev A, Atabaev F, & Tursunova G. Influence of sandstone on physical and chemical processes of interaction of components and genetic formation of cement composite. E3S Web of Conferences. 2024; 563:02027. https://doi.org/10.1051/e3sconf/202456302027

[20] Iskandarova MI, Atabaev FB, Yakubzhanova ZB, Kahhorov U, Hadjiev ASh. Development of Technology for Obtaining Portland Cement with New Types of Composite Additives. AIP Conference Proceedings. 2022; 2432:050063 https://doi.org/10.1063/5.0090576

[21] Iskandarova M, Atabaev F, Tursunova G, Tursunov Z, Khadzhiev A. Composite Portland cements: Innovations and future directions in cement technology. Innovative Infrastructure Solutions. 2025. https://doi.org/10.1007/s41062-025-02067-x

[22] Iskandarova MI, Atabaev FB, Khadzhiev AS. Utilization of natural silicate rocks to reduce the carbon footprint in the cement industry. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2026; 338(3):40–50. https://doi.org/10.31643/2026/6445.27

[23] Khadzhiev A, Abdullaev M, Yakubov Y, Jumaniyozov J. The effect of hybrid mineral additives on the genetic formation and physico-chemical processes of cement composites. E3S Web of Conferences. 2025; 633:08003. https://doi.org/10.1051/e3sconf/202563308003

[24] Atabaev FB, Aripova MKh, Khadzhiev ASh, Tursunova GR, Tursunov ZR. Effect of multicomponent mineral additives on the microstructure and strength of composite cement. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2025; 1(322):45–57. https://doi.org/10.31643/2027/6445.05

[25] Khadzhiev A, & Atabaev F. Influence of silica-containing additives on physical and mechanical properties of Portland Cement Co. Ltd Karakalpaksement. E3S Web of Conferences. 2023; 401:05051. https://doi.org/10.1051/e3sconf/202340105051

[26] Buriev AI, Iskandarova MI, & Begzhanova GB. Influence of a high degree of filling on the properties of pozzolanic cement. RA Journal of Applied Research. 2023; 9(2):60–65. https://doi.org/10.47191/rajar/v9i2.02

[27] Bagdaulet B, & Aitkulov N. Application of regional mineral resources for the synthesis of sulfate resisting cements. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2023; 4:33–42. https://doi.org/10.31643/2023/6445.18

[28] Habert G, et al. Cement production technology improvement compared to factor 4 objectives: can we reach individually based targets? Journal of Cleaner Production. 2011; 17(12):1179–1187.

[29] Lotfi S, et al. Circular economy as a strategy for sustainable development of the cement industry. Construction and Building Materials. 2020; 255:119397.

[30] OʻzM St 337:2024. Sulfatga chidamli portlandsement. Texnik shartlar [Sulfate-resistant Portland cement. Technical conditions]. Uzbekistan National Standard. 2024. (in Uzbek).

[31] GOST 22266-2013. Sulfatstoykiy portlandtsement i shlakoportlandtsement. Tekhnicheskiye usloviya [Sulfate-resistant Portland cement and slag Portland cement. Technical conditions]. Mezhgosudarstvennyy standart. 2013. (in Russ.). https://meganorm.ru/Data/592/59275.pdf

[32] ASTM International. ASTM C1012/C1012M–24: Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution. West Conshohocken, PA: ASTM International. 2024. https://www.astm.org/c1012_c1012m-24.html