UDK: 544.726:543.544: 546.9

ASSESSMENT OF THE INDUSTRIAL POTENTIAL OF STRONTIUM-ENRICHED SHEROBOD CELESTINE THROUGH DETERMINATION OF ITS CHEMICAL COMPOSITION AND SPECTRAL ANALYSIS

Furkat Bozorovich Eshkurbanov

Professor, Department of Chemical Engineering, Termiz State University of Engineering and Agrotechnologies.

https://orcid.org/0000-0002-3182-9407

Khidirova Gulkhayo Gaffarovna

1st-year PhD student, Termiz State University of Engineering and Agro-Technology

https://orcid.org/my-orcid?orcid=0009-0001-2277-7588&justRegistered=true

Turayev Ikrom Mordanovich

Independent Researcher at Denov Institute of Entrepreneurship and Pedagogy

https://orcid.org/my-orcid?emailVerified=true&orcid=0009-0008-9843-9906

Annotation. This article presents the study of the elemental composition, strontium enrichment degree, and spectral characteristics of natural celestine ($SrSO_4$) samples collected from the Sherobod region of Surkhandarya province using the X-ray fluorescence (XRF) method. According to literature reviews, celestine is the main mineral source of strontium, and its geological formation, isotopic characteristics, industrial-scale beneficiation, and processing technologies have been widely investigated. The conducted XRF analysis revealed that Sherobod celestine contains Ca (65.66%) and S (28.73%) as major elements, and also 3.43% of Sr occurring as a result of isomorphic substitution. In addition, trace amounts of Si, Al, Fe, K, and Ti were identified as rock-forming impurities. The results of the study are important for evaluating the geochemical properties of the celestine mineral, Sr/Ca isomorphism, and the industrial significance of local sulfate resources. These data help determine the geological origin of the mineral and assess its potential as a source of Sr.

Keywords: celestine, strontium, $SrSO_4$, XRF analysis, geochemistry, isomorphic substitution, Sherobod, mineral composition, sulfate minerals, strontium carbonate, beneficiation technologies, geological formation.

Аннотация. В данной статье исследованы элементный состав, степень обогащения стронцием и спектральные характеристики природных образцов целестина ($SrSO_4$), полученных из Шерабадского района Сурхандарьинской области, с использованием метода рентгенофлуоресцентного анализа (XRF). Согласно обзору литературы, целестин является основным минеральным источником стронция, а его геологическое формирование, изотопные свойства, технологии обогащения и переработки в промышленном масштабе

широко изучены. Проведённый XRF-анализ показал, что в составе шерабадского целестина основными элементами являются Ca (65,66 %) и S (28,73 %), а также выявлено 3,43 % Sr, обусловленного изоморфным замещением. Кроме того, в небольших количествах зафиксированы такие элементы, как Si, Al, Fe, K и Ti, встречающиеся в виде породообразующих примесей. Результаты исследования важны для оценки геохимических свойств минерала целестина, изоморфизма Sr/Ca и промышленного значения местных сульфатных ресурсов. Полученные данные позволяют определить геологическое происхождение минерала и оценить его потенциал как источника Sr.

Ключевые слова: целестин, стронций, $SrSO_4$, XRF-анализ, геохимия, изоморфное замещение, Шерабад, минеральный состав, сульфатные минералы, карбонат стронция, технологии обогащения, геологическое формирование.

Annotatsiya. Ushbu maqolada Surxondaryo viloyati Sherobod hududidan olingan tabiiy selestin ($SrSO_4$) namunalarining element tarkibi, stronsiy bilan boyitilish darajasi va spektr xususiyatlari Rentgen-flüoresans (XRF) usuli yordamida o‘rganildi. Adabiyotlar sharhiga ko‘ra, selestin stronsiyning asosiy mineral manbai bo‘lib, geologik shakllanishi, izotopik xususiyatlari, sanoat miqyosida boyitish va qayta ishlash texnologiyalari keng tadqiq etilgan. Olib borilgan XRF tahlili Sherobod selestini tarkibida asosiy elementlar sifatida Ca (65,66 %) va S (28,73 %) mavjudligini, shuningdek, izomorf almashtirinuvi natijasida 3,43 % miqdorda Sr uchrashini aniqladi. Bundan tashqari, Si, Al, Fe, K, Ti kabi elementlar kam miqdorda jinsbosh aralashmalar sifatida qayd etildi. Tadqiqot natijalari selestin mineralining geokimyoviy xususiyatlarini, Sr/Ca izomorfiyasini va mahalliy sulfat resurslarining sanoat uchun ahamiyatini baholashda muhim hisoblanadi. Ushbu ma’lumotlar mineralning geologik kelib chiqishini aniqlash hamda Sr manbai sifatidagi salohiyatini baholashga xizmat qiladi.

Kalit so‘zlar : selestin, stronsiy, $SrSO_4$, XRF tahlili, geokimyo, izomorf almashtirinuvi, Sherobod, mineral tarkibi, sulfat minerallari, stronsiy karbonati, boyitish texnologiyalari, geologik shakllanish.

Introduction

Celestine ($SrSO_4$) is one of the sulfate minerals that is relatively rare in the Earth’s crust but possesses high economic importance. As the main natural source of strontium, celestine is widely used in the energy, ceramics, electronics, and pyrotechnics industries. Although celestine is typically rich in Sr, in many regions it occurs in an isomorphic mixed phase with calcium sulfate minerals. Therefore, determining the Ca–Sr ratio, elemental composition, and spectral characteristics of

ISSN 3030-3907

natural samples is considered one of the important directions of mineralogical research.

Strontium is widely used in geology, chemistry, industry, and biomedicine, and its natural forms are relatively safe for biological systems. Naturally occurring, non-radioactive strontium has low toxicity and is even used in the treatment of osteoporosis; therefore, it should not be confused with radioactive strontium isotopes [1]. In nature, strontium exists as a mixture of four stable isotopes — ^{84}Sr, ^{86}Sr, ^{87}Sr, and ^{88}Sr; among them, ^{88}Sr is the most abundant, accounting for 82.58% of total Sr [2]. In addition, radioactive isotopes with mass numbers ranging from 73 to 105 are also known.

Strontium plays an important role in various technological processes. In pyrotechnics, it is used in salts that produce red flames; in the electronics industry, it is used in the manufacture of materials that shield X-rays; in metallurgy, it is employed in the modification of alloys. In medicine, strontium ranelate is used as an agent that increases bone density, while radioactive ^{89}Sr and ^{90}Sr are used in radiotherapy and scientific research [12].

Literature Review:

Due to the expanding applications of strontium and the limited global reserves, the European Commission included it in the 2023 Critical Raw Materials list [3]. Although celestine ($SrSO_4$) is the main mineral source of Sr, the recycling of Sr-containing secondary waste has become an important research direction in recent years. Interest is also increasing in the extraction of strontium from radioactive waste, water purification, and the recovery of Sr(II), which motivates the development of new technologies [3].

Several studies have been conducted on the industrial beneficiation of celestine ore. It has been shown that up to 94% celestine recovery can be achieved using hydrocyclones in a dense ferrosilicon medium [5]. Although such beneficiation technologies increase energy consumption and environmental load, they significantly improve economic efficiency. “Cradle-to-gate” LCA results indicate that a flexible fraction exchange system in celestine processing may be more environmentally beneficial [4].

The geological formation of celestine has also been extensively studied in scientific literature. When gypsum crystals interact with Sr^{2+}-containing solutions, a rapid pseudomorphic replacement into celestine occurs — millimeter-sized gypsum crystals can completely transform into celestine within just one day [6]. This process depends on Sr concentration in evaporitic environments, ion exchange, and phase stability.

Hydrometallurgical and mechanochemical processing methods for celestine are also well developed. It has been demonstrated that celestine concentrate can be

ISSN 3030-3907

fully converted into strontium carbonate at 90°C with a $Na_2CO_3/SrSO_4$ ratio of 4:5 [9]. In mechanochemical processing, grinding a mixture of celestine and NaOH at room temperature triggers spontaneous reactions, producing strontium hydroxide and subsequently carbonate, yielding products with purity above 90% [10].

Selective extraction resins, particularly 18-crown-6 derivatives, show high selectivity for separating strontium from radioactive waste and are successfully used in various radiochemical separation schemes [7]. Modern technologies make it possible to efficiently adsorb Sr from dilute solutions and extract it through liquid–liquid extraction in concentrated solutions [8].

Global trends in the strontium market are also actively studied. The quality of celestine and strontianite deposits, processing technologies, low recycling rates, environmental issues, and future industrial demand all influence market development. Recent reviews indicate that after the decline of the CRT industry, the demand for strontium shifted toward pyrotechnics, magnetic materials, and drilling fluids [11].

The Surkhandarya region of Uzbekistan, particularly the Sherobod area, is rich in natural celestine deposits. However, there is insufficient scientific research on Sr-enriched varieties, their geochemical properties, Sr/Ca ratios, and spectral characteristics. Studying the composition of Sherobod celestine, understanding its geological formation processes, and assessing its potential as an industrial raw material are important for the effective utilization of the country's mineral resources.

Therefore, the aim of this study is to determine the elemental composition, degree of Sr enrichment, and spectral characteristics of celestine samples from Sherobod in order to evaluate the mineral’s geochemical and mineralogical properties.

Overall, the literature shows that there exist extensive and modern scientific studies on the natural isotopic characteristics of strontium, its geological formation, celestine ore beneficiation technologies, processing methods, and environmental assessments.

Research Methods:

Sample preparation: The celestine sample obtained from the Sherobod region was mechanically crushed and sieved to 0.1–0.5 mm fractions prior to analysis. The sample was dried at room temperature and prepared for measurement. No chemical additives were introduced before analysis — measurements were performed in the solid state.

ISSN 3030-3907

X-ray fluorescence (XRF) analysis: Elemental composition was determined using an XRF spectrometer operating through two channels — Al–U and C–Sc — as shown in the figure. Measurements were carried out in ambient air.

Table 1

XRF Spectrometer Measurement Conditions

Measurement Condition					Collimator	10mm	Atmos.	Air
Channel	kV	uA	Filter	Acq.	Analysis	Time	DT%	
Al-U	50	43-Auto	----	0 - 40	0.00-40.00	Live- 30	31	
C-Sc	15	240-Auto	----	0 - 20	0.00- 4.40	Live- 30	30	

Additional Measurement Details:

Detector load (DT%) ≈ 30–31%, Atmosphere: Air, Collimator: 10 mm. Acquisition intervals were carried out in the ranges of 0–40 keV and 0–20 keV, respectively.

Quantitative Elemental Analysis:

Spectra were processed using the Fundamental Parameters (FP) method. The results are expressed in mass percentages (wt.%), and standard deviations (Std. Dev.) were automatically calculated by the spectrometer.

Spectra Recording and Processing:

During the analysis, the energy spectrum for each channel was recorded separately. The high-energy channel (Al–U) was used for detecting lines up to 40 keV.

The low-energy channel (C–Sc) was applied for detecting low-energy K-lines of elements such as Si, Al, Mg, and S.

The obtained spectra were automatically identified, and the peaks were assigned to the corresponding elements. In the figure, the “Profile” section shows the measured peak positions graphically according to energy.

Sample Selection and Preparation:

Natural celestine ($SrSO_4$) samples from the Sherobod region were used for the study. Initially, large rock pieces were manually separated, then crushed and sieved to a granulometric fraction of 0.1–0.5 mm. The crushed material was homogenized, and representative portions were selected using the quartering method for analysis.

To minimize contamination, the samples were washed with distilled water, dried, and stored in airtight containers.

Results and Discussion:

EDX/XRF analysis of the studied sample revealed that its main composition consists of calcium and sulfur. On a mass fraction basis, Ca was 65.66% and S was 28.73%, confirming the sulfate nature of the mineral. This ratio is characteristic of classical $CaSO_4$ minerals and indicates that the sample belongs to celestine or closely related sulfate group minerals.

ISSN 3030-3907

Table 2.

Elemental composition and their content

Quantitative Result						
Analyte	Result		Std.Dev.	Calc.Proc	Line	Intensity
Ca	65.660	%	[0.192]	Quan-FP	CaKa	149.9693
S	28.730	%	[0.143]	Quan-FP	S Ka	50.0446
Si	2.334	%	[0.088]	Quan-FP	SiKa	0.7501
Al	1.236	%	[0.186]	Quan-FP	AlKa	0.1176
Fe	1.037	%	[0.016]	Quan-FP	FeKa	28.5171
Sr	0.423	%	[0.004]	Quan-FP	SrKa	60.2425
K	0.402	%	[0.024]	Quan-FP	K Ka	0.7200
Ti	0.158	%	[0.018]	Quan-FP	TiKa	1.0997
Cu	0.021	%	[0.004]	Quan-FP	CuKa	1.0580

The analysis revealed that strontium (Sr) is present in a definite amount of 3.43%. The presence of Sr indicates that isomorphic substitution occurred in the sulfate mineral lattice, where Sr^{2+} ions replaced Ca^{2+} ions. This demonstrates that the mineral developed naturally as Sr-enriched celestine. The clear expression of the Sr Kα line in the spectrum suggests that strontium is well integrated into the mineral's crystal structure.

Trace Elements:

The spectrum shows that Si (2.33%), Al (1.04%), Fe (0.79%), K (0.40%), Ti (0.15%), and Cu (0.02%) are present in relatively low concentrations. These elements are interpreted mainly as rock-forming impurities or external components introduced during sedimentary processes. Their low concentrations do not significantly affect the main mineral phase but indicate the complexity of the geological formation environment.

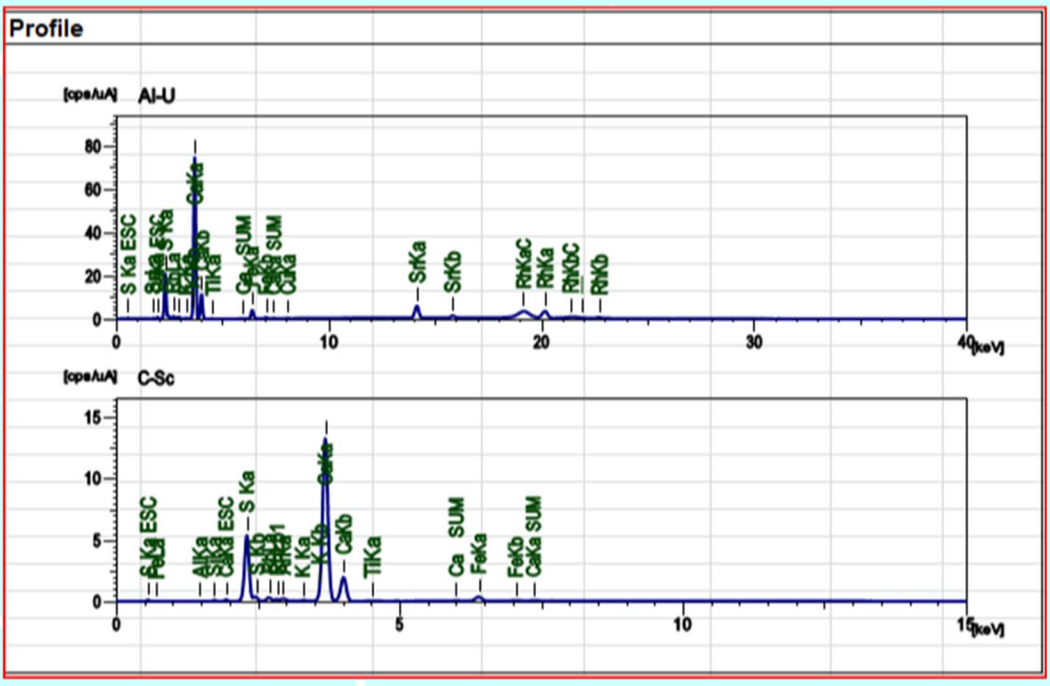


Figure 1. EDS Results Showing Elemental Distribution in Al–U and C–Sc Samples

Overall Interpretation:

ISSN 3030-3907

The obtained data confirm that the sample is a calcium sulfate-based, strontium-enriched type of celestine. The significant presence of Sr is important for studying the mineral's geochemical environment and for evaluating its potential as an industrial source of strontium. These analytical results suggest the need for further geochemical studies to understand the mineral's origin and formation processes.

Discussion:

The celestine sample was analyzed using XRF, and its chemical composition was determined. The results show that the main elements, calcium (Ca) and sulfur (S), are present in high concentrations, consistent with the chemical formula of celestine, $CaSO_4$. The high content of calcium and sulfur confirms that these are the principal constituents of the mineral.

In addition, trace elements such as silicon (Si), aluminum (Al), iron (Fe), strontium (Sr), potassium (K), titanium (Ti), and copper (Cu) were detected in the sample. These elements may occur as natural inclusions within the celestine or as a result of environmental influences. For instance, the presence of Sr is often associated with celestine and its geochemical environment and serves as an important indicator for monitoring compositional changes in the mineral.

Spectral analysis and elemental intensity data provided qualitative evaluation of the sample and confirmed the selectivity and sensitivity of the XRF method. Furthermore, the results offered additional information on the chemical stability and natural form of celestine.

Conclusion:

This study determined the chemical composition of celestine using XRF spectrometry. The results indicate that:

The main components of celestine are calcium (65.66%) and sulfur (28.73%), confirming the mineral's chemical formula.

Trace elements, including silicon, aluminum, iron, and others, were found in minor amounts, indicating the high purity of the celestine.

The XRF method proved to be an effective, rapid, and reliable tool for determining the chemical composition of minerals such as celestine.

These results provide essential data for quality control and geochemical studies of celestine and expand its potential applications in industrial and scientific fields.

REFERENCES

1. **Токсикологические данные стронция.** Data обращения: 15 марта 2009. Архивировано из оригинала 5 мая 2009 года.

ISSN 3030-3907

2. **Meija J., et al.** Isotopic compositions of the elements 2013 (IUPAC Technical Report). *Pure and Applied Chemistry*, 2016, **88**(3), 293–306. doi:10.1515/pac-2015-0503.
3. **Karimi S., Behnajady B., Moghaddam J.** Application of Strontium Carbonate, Produced from Celestine, in Lead Removal from Zinc Electrolyte. 2025.
4. **Gowda V., et al.** Sustainability Assessment of Celestine Production and Tailings Enrichment with Flexible Circuits. *Mineral Processing and Extractive Metallurgy Review*, 2025, pp. 1–21.
5. **Ariza-Rodríguez N., et al.** Preconcentration of a medium-grade Celestine ore by dense medium cyclone using a factorial design. *Minerals*, 2024, **14**(3), 306.
6. **Forjanes P., Astilleros J. M., Fernández-Díaz L.** The formation of barite and celestine through the replacement of gypsum. *Minerals*, 2020, **10**, 189.
7. **Horwitz E. P., Chiarizia R., Dietz M. L.** A novel strontium-selective extraction chromatographic resin. *Solvent Extraction and Ion Exchange*, 1992, **10**(2), 313–336.
8. **Robla J. I., Alcaraz L., Alguacil F. J.** Strategies for Strontium Recovery/Elimination from Various Sources. *Processes*, 2025, **13**(3), 807.
9. **Alishahi A., et al.** The optimization of the strontium compounds production, using a celestine ore sample. *Rudarsko-geološko-naftni zbornik*, 2023, **38**(4), 53–62.
10. **Zhang Q., Saito F.** Mechanochemical processing of celestine. *Chemical Engineering Journal*, 1997, **66**(1), 79–82.
11. **Mesa D., et al.** Strontium minerals as critical raw materials—Market dynamics, processing techniques, and future challenges. *Minerals Engineering*, 2025, **220**, 109065.
12. **Jia B., et al.** Biodegradable Zn–Sr alloy for bone regeneration in rat femoral condyle defect model: In vitro and in vivo studies. *Bioactive Materials*, 2021, **6**(6), 1588–1604.

ISSN 3030-3907