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Study of the physical and chemical properties of aluminum slags

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ABSTRACT

The paper presents the results of a study of the physicochemical and mineralogical properties of primary and secondary aluminum slags. It was found that the primary aluminum slags contain 67.8% Al_2O_3, 12.4% SiO_2, 4.58% MgO, 4.59% CaO, and 0.52% Fe_2O_3. The main phases are spinel (25.4%), sapphirine (26.0%), corundum (25.0%), enstatite (11.9%), and mullite (11.7%). These high-temperature aluminosilicate and oxide phases have high thermodynamic stability and low chemical activity, which significantly complicates the processing of primary slags. The secondary aluminum slags contain 34.9% Al_2O_3, 4.61% SiO_2, 34.7% CaO, 5.70% MgO, and 4.71% Fe_2O_3. The mineral composition comprises spinel (20.5%), quartz (10.5%), mullite (8.0%), corundum (13.1%), calcite (27.0%), and breyite (20.9%). Complex aluminosilicate compounds were not detected in the secondary slags, which determines their higher reactivity. The potential of using secondary aluminum slags in metallurgical processing is demonstrated, in particular in the production of ferrosilicon in the form of pellets with the addition of ferrosilicon metal fines, which allows for a reduction in the consumption of natural silica materials and an increase in the resource efficiency of production. The results obtained can be used in the development of energy- and resource-saving technologies for processing aluminum waste.

Keywords: Aluminum slag, aluminosilicates, X-ray phase analysis, mineral composition, microanalysis.

INTRODUCTION

Aluminum slags, formed during the processing of primary and, especially, secondary aluminum, are a complex multicomponent system comprising metallic aluminum, oxide phases (primarily Al_2O_3 and aluminates), salt components (NaCl, KCl, fluorides), and aluminum nitride, which is the main environmentally hazardous component due to the release of ammonia during hydrolysis. Their composition and properties depend significantly on smelting conditions, the type of fluxes added, and the cooling regime, so processing requires an individual approach [1]. During primary production and secondary processing, approximately 30–50 kg and 100–150 kg of slag are released from a ton of aluminium, respectively [[2], [3], [4]].

The development of aluminum slag processing technologies is aimed at maximizing the extraction of metallic aluminum, neutralizing harmful components, and producing useful products such as alumina, fillers, and building materials. Traditionally, mechanical methods based on grinding, screening, and gravity separation have been used in industry to recover droplet or coarsely dispersed aluminum. These methods are effective when the metallic phase content is significant, but they leave unresolved the problem of salt and nitride components in the non-metallic residue [5].

Pyrometallurgical approaches, including high-temperature reduction and thermal neutralization, reduce the AlN content and partially remove halogen-containing phases. However, they are associated with high energy consumption and require strict control of emissions of NH3, HCl, and HF. Modern modifications of pyrometallurgy, such as thermal-alkaline processing, are aimed at converting solid phases into more reactive forms, facilitating subsequent hydrometallurgical extraction of aluminum [6].

Hydrometallurgical processing is the most rapidly developing area. Alkaline leaching in NaOH solutions followed by the production of $NaAlO_2$ and the isolation of aluminum hydroxide allows for the efficient use of even slags containing minimal amounts of metallic aluminum. After carbonation or acid precipitation, hydroxide is released into solution, and subsequent calcination produces high-purity Al_2O_3. Research shows that preliminary growth or mechanical activation significantly increase the degree of aluminum extraction and reduce the influence of salt phases and AlN [7]. One of the key issues in hydrometallurgy remains the kinetics and control of aluminum nitride hydrolysis: its decomposition is accompanied by the release of ammonia, which requires capture and neutralization. The kinetics of AlN hydrolysis have been studied in detail in investigations of its phase transformations and interactions with water under various temperature conditions [[8],[9]].

Along with chemical methods, physical methods for extracting metal fractions are actively developing. For example, mechanical activation combined with separation in supergravity fields allows for the highly efficient extraction of dispersed metallic aluminum without significant thermal load or the formation of harmful gases. Such technologies are promising in applications requiring the minimization of energy costs and environmental risks [11].

A separate area of development is the processing of salt slags into materials suitable for construction or chemical applications. Due to its high Al2O3 and salt contents, such waste can serve as a raw material for producing zeolites, fillers, and components for cement systems. Recent research shows that controlled leaching of salts, subsequent heat treatment, and modification yield a stable and environmentally safe product with market value [[12],[13],[14]]. Overall, global trends in the development of aluminum slag processing technologies indicate a shift from the simple extraction of metallic aluminum to complex integrated processes that combine mechanical, pyrometallurgical, and hydrometallurgical methods. This approach not only increases aluminum recovery but also significantly expands the range of useful products, reduces waste volume, and minimizes environmental impact. Combined schemes that include preliminary thermochemical treatment, selective leaching, and subsequent metallization of non-metallic residues are considered the most promising, as confirmed by experimental and analytical publications [[15],[16]].

In Kazakhstan, the production of ferrous [17] and non-ferrous metals is extensive. Along with the production of a large number of metals, both ferrous and non-ferrous, a huge amount of industrial waste is generated [[18],[19],[20]]. Among industrial wastes, aluminum slag is generated in small quantities compared to ferrous metal producers, whose waste amounts to hundreds of thousands of tons. However, the production of aluminum slag at aluminum alloy production plants amounts to approximately 5,000 tons per year.

Comprehensive processing of aluminum slag and waste allows for the recovery of several commercially significant fractions: pure metallic aluminum (for reuse in metallurgy), aluminum oxide (for the production of refractories, abrasives, and aluminum itself), as well as mineral residue suitable for construction materials, and metal fibers for improving the properties of concrete [21].

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Due to its properties, aluminum is widely used in key industries such as transportation, electrical engineering, packaging, construction, and the food industry [[22], [23], [24]].

The primary objective of recycling is to maximize the yield of aluminum metal, which reduces storage volumes and minimizes the negative environmental impact. Considering that aluminum is the second most used metal in the world, the current share of recycled materials accounts for approximately 33% of global production. This share is expected to reach 50% by 2050 [[25], [26]].

The development of technologies and the integration of industrial waste into metallurgical processing play an important role in Kazakhstan's economy, drawing on the experience of other countries. Hundreds of thousands of tons of waste end up in waste disposal sites annually, and the total volume of wasteful materials accumulated over the years by energy and metallurgical enterprises amounts to tens of millions of tons. This waste contains many useful components but is still considered unsuitable for use.

Nevertheless, there is still room for improvement. The development of rational technologies for the integration of industrial waste into metal production, for example, for the production of aluminum-silicon alloys and other metals, allows for significant conservation of natural resources. Unlike most known technologies, which focus on the use of aluminum slag in the construction industry, this study aims to directly integrate aluminum waste into the metallurgical cycle. This approach improves overall resource efficiency and significantly reduces the volume of waste requiring landfill.

Thus, the aim of the study is to investigate the physicochemical properties of aluminum slag and, based on the new data obtained, develop a rational technology for its integration into metallurgical processing.

MATERIAL AND METHODS

Aluminum dross is formed during the remelting of aluminum scrap and is a product of high-temperature reactions between aluminum, oxygen, non-metallic impurities, and flux additives. When aluminum is heated and melted, an Al_2O_3 oxide film initially forms on the surface of the bath. This film is continually broken down by turbulent processes and mechanical agitation, becoming entrained within the melt. These finely dispersed oxides accumulate at the top of the liquid metal and form the basis of the future slag. Simultaneously, coatings, oils, and other contaminants contained in the aluminum scrap decompose; organic components burn off, leaving carbonaceous residues, and inorganic impurities oxidize or solidify.

Recycled aluminum feedstock typically contains magnesium, silicon, and other elements. Magnesium oxidizes upon contact with oxygen, forming MgO, which then reacts with fresh Al_2O_3 to form high-temperature spinel $MgAl_2O_3$. Silicon also oxidizes to form SiO_2, which can react with aluminum and magnesium oxides to form aluminosilicate phases—enstatite, mullite, and sapphirine. This set of reactions determines the mineralogical basis of the future slag already at the melt stage.

During the study, samples were collected from primary aluminum slags of the metallurgical company JSC Aluminum of Kazakhstan and secondary slags generated at small enterprises. These slags contain high amounts of Al_2O_3 and have potential for the production of aluminum-silicon alloys.

The chemical composition of the materials studied is presented in **Table 1**. The data in Table 1 show that in aluminum slags (Sample No. 1) from primary aluminum processing, Al_2O_3 is 67.8% and SiO_2 is 12.4%. In aluminum slags (Sample No. 2) from secondary aluminum processing, Al_2O_3 is 34.9% and SiO_2 is 4.61%. However, in Sample No. 2, a high CaO content is observed.

Table 1 Chemical composition of aluminum slags

Name of material	Chemical composition, %				
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO
Sample No. 1	12.4	67.8	0.52	4,59	4,58
Sample No. 2	4,61	34,9	4,71	34,7	5,70

The physicochemical properties of the studied materials were determined by X-ray diffraction (XRD) and petrographic analysis, performed on an X'Pert PRO diffractometer using Cu Kα radiation (λ = 1.5418 Å) over the 2θ range of 10° to 80°. Surface morphology and microstructure were studied using a JEOL JSM-6390LV electron microscope.

RESULTS AND DISCUSSION

Subtitle of results and discussion

Studying the physicochemical properties of aluminum slags and aspiration dust is necessary to understand their actual chemical composition, phase structure, and reactivity. The materials being studied contain significant amounts of aluminum oxide and silicon, so it is important to determine their form—crystalline, amorphous, or bound into complex aluminosilicate compounds. This information allows for the selection of optimal processing methods, prediction of the behavior of slags and dust under thermal and chemical influences, and assessment of the possibility of recovering residual aluminum or producing valuable aluminosilicate products.

Physicochemical studies are also necessary to assess the particle size distribution, porosity, density, thermal effects, and the onset temperature of decomposition or melting. These parameters determine how the material will behave during sintering, melting, grinding, or alkaline treatment, and enable the correct selection of processing modes. An important aspect is identifying impurities that can form toxic or gas-forming products upon exposure to moisture or heat, a critical step in ensuring technological and environmental safety. Understanding the interactions between aluminum and silicon oxides and associated components helps predict the formation of new phases, for example, mullite, spinel, or silicates, which is important when using these wastes as raw materials for refractory, ceramic, or cementitious materials. Thus, studying the physicochemical properties of aluminum slags and aspiration dust forms the basis for developing effective and safe processing technologies and expanding their industrial applications.

Fig. 1 and **Table 2** show the X-ray diffraction pattern and X-ray phase analysis results for Sample No. 1 [27].

The X-ray phase analysis and microsection data for Sample No. 1 indicate that the main phases are Al_2MgO_4, $Al_{5.65}Mg_{2.39}O_{10}Si_{1.45}$, MgO_3Si, $Al_{2.4}O_{4.8}Si_{0.6}$, and Al_2O_3, which account for more than 75% of the mass.

Spinel is a magnesium-aluminum oxide (Al_2MgO_4) with a spinel-type structure. The mineral is stable at high temperatures, which explains its presence in aluminum slags formed under thermal conditions. It often forms as a primary high-temperature phase in aluminum processing.

Table 2 Mineral composition of sample No. 1

Name of mineral	Formula	Mass fraction, %
Spinel	Al_2MgO_4	25.4
Sapphirine	$Al_{5.65}Mg_{2.39}O_{10}Si_{1.45}$	26.0
Enstatite	$Mg\ SiO_3$	11.9
Mullite	$Al_{2.4}O_{4.8}Si_{0.6}$	11.7
Aluminum oxide (corundum)	Al_2O_3	25.0

In a microsection (**Fig. 2**), it appears as isometric, octahedral, and rounded grains. In reflected light, it is light gray or steel-gray, with moderate reflectivity.

Sapphirine ($Al_{5.65}Mg_{2.39}O_{10}Si_{1.45}$) is a rare aluminum-magnesium silicate of complex composition. It forms in high-temperature, high-alumina environments. The presence of sapphirine indicates intense reactions between MgO, Al_2O_3, and SiO_2 occurring in the melt. In aluminum slag, it is an important phase, characterized by high thermal and chemical stability. In a microsection (**Fig. 2**), it appears as irregular lamellar or granular-spotted aggregates.

Enstatite ($MgSiO_3$) is a magnesium pyroxene formed in environments with sufficient Mg and Si contents. Its presence is possible due to the interaction between magnesium-containing components and silica. Enstatite imparts increased hardness and resistance to thermal degradation to the slag. In a microsection (**Fig. 2**), it forms elongated prismatic or columnar crystals, sometimes thin plates.

Mullite ($Al_{2.4}O_{4.8}Si_{0.6}$) is an important high-temperature aluminosilicate phase. It forms upon heating mixtures of Al_2O_3 and SiO_2. The presence of mullite in the slag indicates thermal processing at temperatures above 1200–1400°C. It has high refractoriness and low thermal conductivity, improving the slag's performance properties as a heat-resistant material.

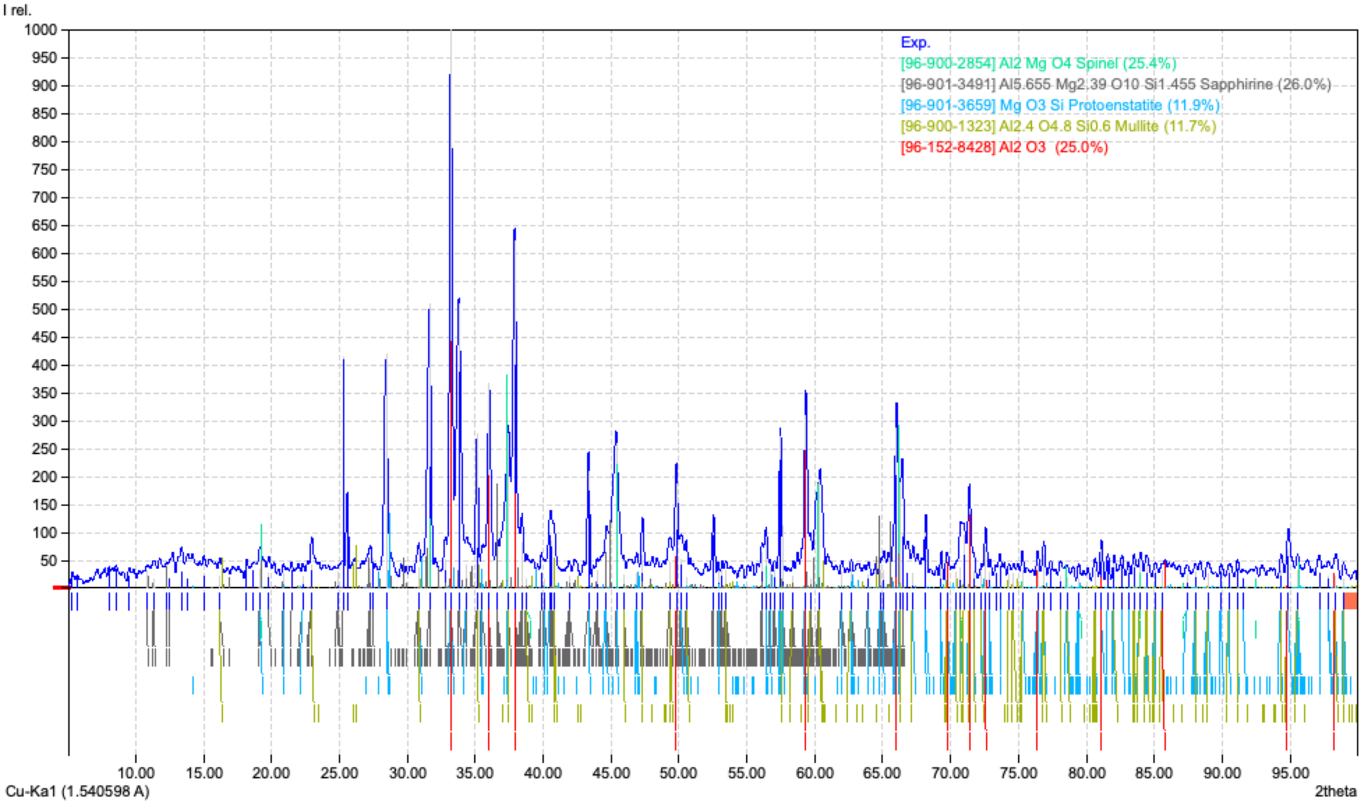
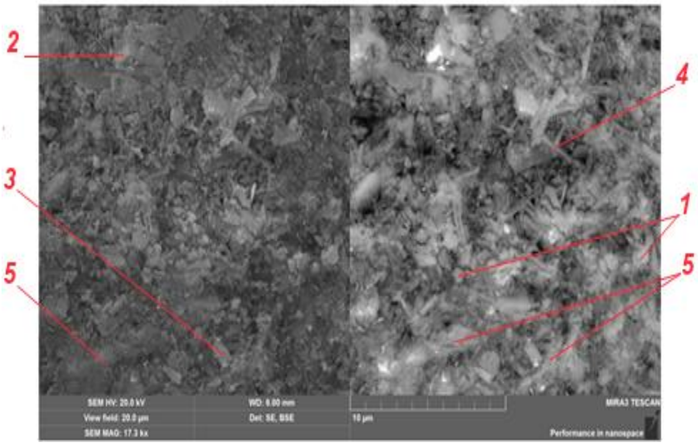


Fig. 1 X-ray of sample No. 1



1 – Spinel; 2 – Sapphirine; 3 – Enstatite; 4 – Mullite; 5 – Corundum

Fig. 2 Microstructure of aluminum slag (Sample No. 1)

In microsection (**Fig. 2**), it has an acicular, fibrous, or tufted appearance, often with radial aggregates. In transmitted light, it is colorless or has a slight bluish tint.
The mineral composition of aluminum slag is characterized by a predominance of high-temperature oxides (spinel, sapphirine, and corundum), indicating that the material formed under intense thermal conditions. Mixed aluminosilicates (mullite and enstatite) are formed by the interaction of residual silica with aluminum and magnesium oxides. This composition provides the slag with high refractoriness, mechanical strength, and chemical resistance. Energy dispersive spectrum analysis (EDS analysis) of the sample spectrum from the surface of the aluminum slag section (sample No. 1) shown in Figure 3 showed that the main elements are Al, Si, Mg, Ca, Fe, O. According to the EDS analysis, the average elemental composition of the aluminum slag is given in **Table 3**.

Table 3 Energy dispersive quantitative analysis (EDS 500 mapB), %

Element	Quantity, %
O	27.0
Mg	19.4
Al	22.0
Si	21,0
Ca	3.70
Fe	6,90
Total	100,00

Fig. 4 and **Table 4** show the X-ray diffraction pattern and the results of X-ray phase analysis of secondary aluminum slag from aluminum processing (sample No. 2).

Table 4 Mineral composition of sample No. 2

Name of the mineral	Formula	Mass fraction, %
Spinel	$Al_{1.99}Mg_{0.998}O_4$	20.5
Quartz	SiO_2	10.5
Mullite	$Al_{2.4}O_{4.8}Si_{0.6}$	8.0
Aluminum oxide (corundum)	Al_2O_3	13.1
Calcite	$CaCO_3$	27.0
Breyit	$CaSiO_3$	20.9

X-ray diffraction analysis and a microsection of sample No. 2 reveal that the main phases are spinel ($Al_{1.99}Mg_{0.998}O_4$), quartz (SiO_2), mullite ($Al_{2.4}O_{4.8}Si_{0.6}$), corundum (Al_2O_3), calcite ($CaCO_3$), and breyite ($CaSiO_3$). The composition of the studied sample (sample No. 2) comprises oxide, silicate, and carbonate phases. The minerals exhibit a wide range of morphologies, from dense high-temperature oxides to reactive silicates and porous carbonate aggregates. **Fig. 5** shows the microstructure of the secondary aluminum slag (sample No. 2).
Quartz in the microsection shown in **Fig. 5** occurs as shapeless or poorly crystallized grains with irregular outlines. In transmitted light, it appears completely colorless, has a low relief, and is colorless. Cracking or traces of

mechanical failure due to temperature changes are characteristic. In reflected light, quartz appears dark gray, with very low reflectivity.

Calcite appears as large anedral or subedral grains, often with signs of recrystallization. In transmitted light, it appears colorless, low in relief, and may exhibit characteristic twinning or very slight turbidity. In reflected light, calcite has a darkish, grayish-brown hue, with virtually no luster. Porosity, voids, and traces of decomposition or reactions with silicates are often observed. This is one of the softest phases; traces of mechanical damage may be visible.

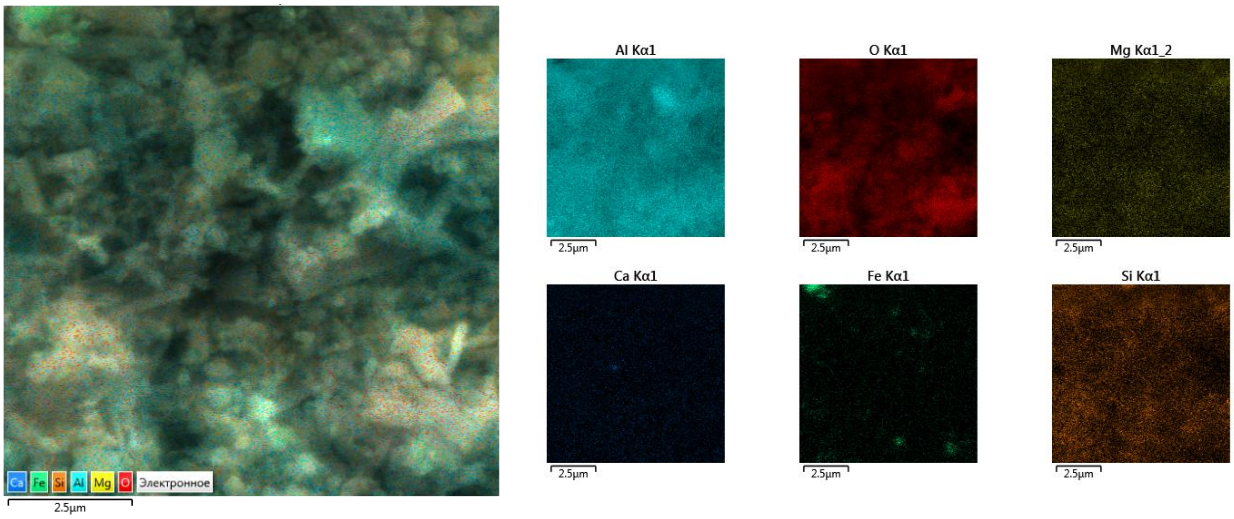


Fig. 3 Multilayer map of EDS analysis of aluminum slag (Sample No. 1)

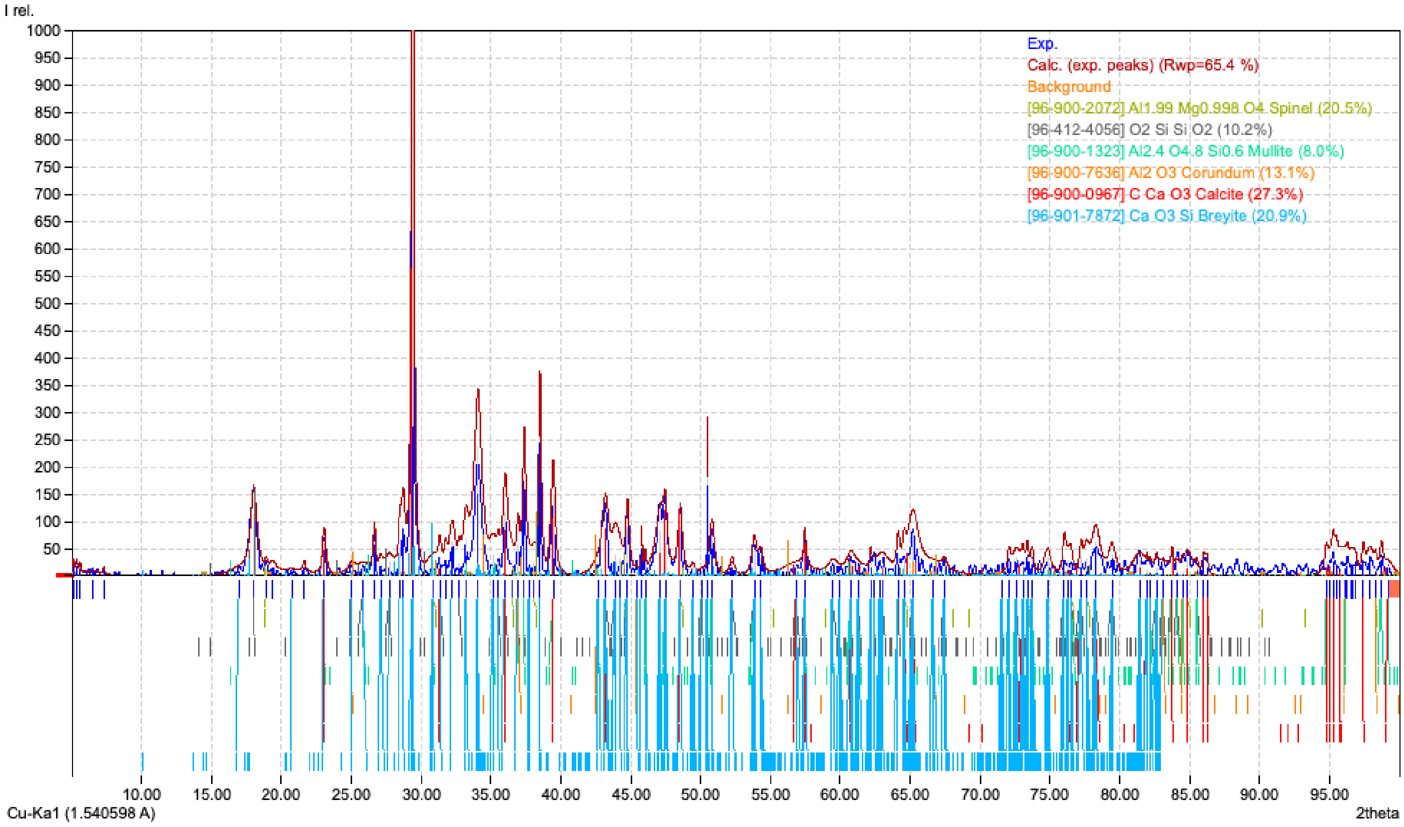
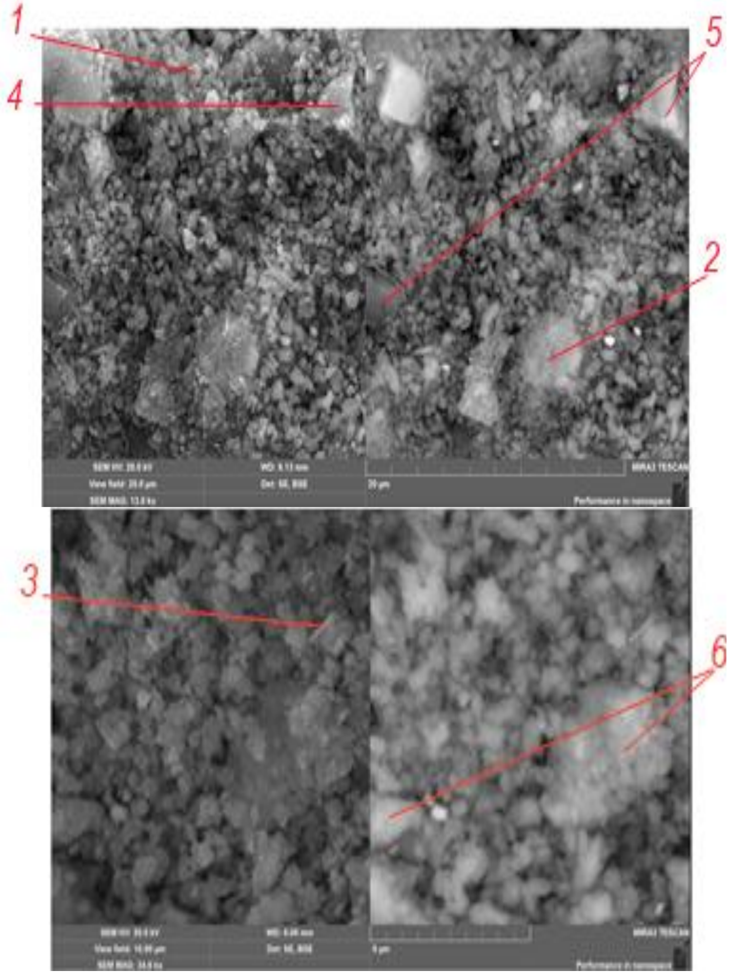


Fig. 4 X-ray of sample No. 2



1 - Spinel ($Al_{1.99}Mg_{0.998}O_4$); 2 - Quartz (SiO_2); 3 - Mullite ($Al_{2.4}O_{4.8}Si_{0.6}$); 4 - Corundum (Al_2O_3); 5 - Calcite ($CaCO_3$); 6 - Breyite ($CaSiO_3$)

Fig. 5 Microstructure of aluminum slag (Sample No. 2)

Breyite (wollastonite) is observed in a microsection (**Fig. 5**) as a fibrous form. It is colourless in transmitted light and has a fine, fibrous structure. In reflected light, breyite has a medium-grey hue with moderate reflectivity, making it noticeably lighter than quartz but darker than aluminium oxides.

Energy dispersive spectrum analysis (EDS) of the aluminum slag surface (sample no. 1) shown in **Fig. 6** revealed that the main elements are Ca, O, Al, Mg, and Na. Based on EDS analysis, the average elemental composition of the aluminum slag is given in **Table 5**.

Table 5 Energy Dispersive Quantitative Analysis (EDS 500 mapB),%

Element	Quantity, %
Ca	23,0
O	29.0
Al	14.0
Mg	25.4
Na	9.0
Total	100,00

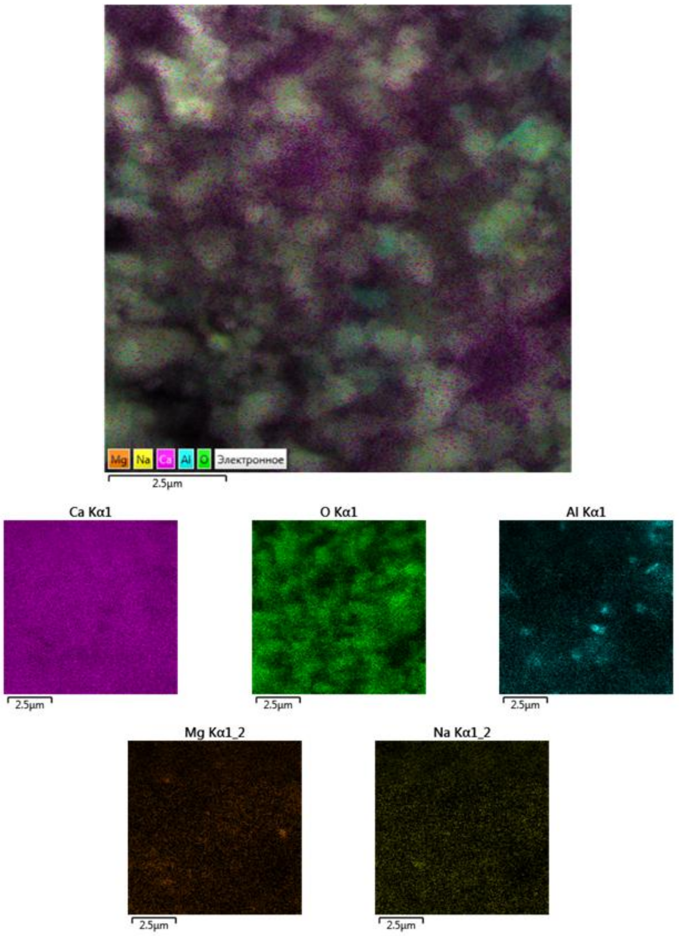


Fig. 6 Multilayer map of EDS analysis of aluminum slag (Sample No. 2)

Thus, the conducted studies of the physicochemical properties have shown that aluminosilicates contained in primary aluminum slags are characterized by high structural, phase, and chemical complexity [[28], [29]], which significantly complicates their extraction and requires the use of special separation techniques. During high-temperature aluminum production, a wide range of aluminosilicate phases is formed, including mullite, sapphirine, spinels of aluminum-magnesium and aluminum-iron composition, as well as complex solid solutions based on the Al_2O_3-SiO_2-MgO-CaO-FeO systems. These phases are characterized by high thermodynamic stability, a dense crystal lattice, and low chemical activity, which makes them low-reactive under standard conditions of acid or alkaline leaching [30]. An additional complication is created by the finely dispersed and often amorphous-crystalline state of aluminosilicates, their close fusion with metallic aluminum, aluminum in the form of intermetallic compounds, and other oxide phases, which complicates their physical separation by mechanical methods.

Polymorphism and isomorphic substitutions in the crystal lattices of aluminosilicates also have a significant impact, in which aluminum, silicon, magnesium, calcium, and iron mutually replace each other, forming stable solid solutions with variable composition. This leads to a blurring of phase boundaries, changes in their solubility, and unpredictable behavior under chemical influences. Furthermore, aluminosilicates in slags are often present as a glassy phase, which is highly chemically inert and requires either preliminary activation (thermal or mechanochemical) or concentrated reagents and elevated temperatures. However, secondary aluminum slags are characterized by a significant difference in phase composition: as can be seen from the data in Figures 4 and 5, aluminosilicate compounds are not observed in them. The main components of such slags are aluminum oxide, spinel, quartz, calcite, breyite, and a small amount of mullite.

Due to the absence of stable aluminosilicate phases, secondary aluminum slags exhibit higher reactivity and can be effectively used in metallurgical processes without complex preactivation. In particular, they are well-suited for use in ferrosilicon production as pellets, when combined with ferrosilicon fines, thereby ensuring the rational reuse of waste materials and reducing the consumption of natural silica [32].

CONCLUSION

Physicochemical and mineralogical-analytical studies have revealed that primary and secondary aluminum slags differ significantly in phase and chemical composition, necessitating fundamentally different approaches to their subsequent processing and use. Primary aluminum slags are characterized by a predominance of high-temperature aluminosilicate and oxide phases—spinel, sapphirine, mullite, enstatite, and corundum—the formation of which is due to intense thermal-oxidative and silicate-forming processes in the melt. These compounds possess high thermodynamic stability, a dense crystalline structure, and low chemical reactivity, which significantly complicates their processing and requires the use of specialized combined activation and extraction methods. It was established that secondary aluminum slags have a fundamentally different mineral composition and are represented predominantly by oxide, silicate, and carbonate phases—corundum, spinel, quartz, calcite, and breiite—with a minor mullite content and the absence of complex aluminosilicates. This phase structure ensures higher reactivity of secondary slags and expands the possibilities for their direct use in metallurgical processes without complex preliminary thermochemical preparation. X-ray phase, petrographic, and energy-dispersive analysis confirmed that the studied slags contain significant amounts of aluminum, silicon, magnesium, and calcium, making them a promising technogenic raw material for the production of aluminum-silicon alloys. It was demonstrated that secondary aluminum slags can be effectively used in the production of ferrosilicon in the form of pellets in combination with the addition of ferrosilicon metal fines, reducing the consumption of natural silica materials and increasing the overall resource efficiency of production.

Thus, the study results confirm the feasibility of a differentiated approach to the processing of primary and secondary aluminum slags, taking into account their actual phase composition. The comprehensive integration of aluminum waste into metallurgical processing not only expands the raw material base but also significantly reduces the volume of man-made waste, lowers the environmental impact, and ensures the rational use of mineral resources.

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