Processing of Zinc Production Wastes and Recycling Opportunities

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Abstract. The generation of large volumes of waste during zinc production presents both an environmental challenge and a potential secondary resource for valuable metal recovery. This study investigates the physicochemical characteristics of zinc-containing wastes and evaluates effective processing methods for improving metal extraction efficiency. Special attention is given to the decomposition of zinc ferrite through lime-assisted roasting followed by sulfuric acid leaching. Thermodynamic analysis and experimental data indicate that the proposed approach significantly enhances zinc recovery compared to conventional methods. The results demonstrate that waste recycling can contribute to sustainable metallurgy and resource conservation.

Keywords: zinc cake, zinc ferrite, waste recycling, hydrometallurgy, roasting, leaching, mineralogical analysis, zinc recovery.

Переработка Отходов Производства Цинка и Возможности Вторичной Переработки

Аннотация. Образование значительных объёмов отходов при производстве цинка представляет собой как серьёзную экологическую проблему, так и потенциальный источник вторичных ресурсов для извлечения ценных металлов. В данной работе исследованы физико-химические характеристики цинксодержащих отходов и оценены эффективные методы их переработки с целью повышения степени извлечения металлов. Особое внимание уделено разложению цинкового феррита с использованием обжига с добавлением извести с последующим сернокислотным выщелачиванием. Термодинамический анализ, подтверждённый экспериментальными данными, показал, что предложенный подход обеспечивает существенное повышение извлечения цинка по сравнению с традиционными методами. Полученные результаты демонстрируют, что переработка отходов цинкового производства является перспективным направлением для развития устойчивой металлургии и повышения эффективности использования ресурсов.

Ключевые слова: цинковый кек; цинковый феррит; переработка отходов; гидрометаллургия; обжиг; выщелачивание; минералогический анализ; извлечение цинка

Introduction. The sustainable management of industrial waste has become one of the most critical challenges in modern metallurgical industries, particularly in the production of non-ferrous metals such as zinc. Zinc plays a vital role in various sectors, including construction, galvanization, energy storage, and electronics. However, its production is inevitably associated with the generation of significant quantities of solid and liquid wastes, such as zinc cake, jarosite residues, goethite precipitates, and slag. These by-products not only represent a loss of valuable metals but also pose serious environmental risks if not properly managed [1].

In conventional zinc hydrometallurgical processes, especially those based on roasting–leaching–electrowinning (RLE) technology, a considerable portion of zinc remains locked in stable phases such as zinc ferrite ($ZnFe_2O_4$), which is difficult to dissolve under standard leaching conditions. As a result, large volumes of zinc-bearing residues accumulate over time [2-4]. These wastes often contain not only zinc, but also valuable associated elements such as lead, copper, cadmium, indium, and silver, making them a potentially important secondary resource.

Despite numerous studies on zinc extraction, the efficient processing of these residues remains a persistent technological problem. Traditional approaches, including direct acid leaching or pyrometallurgical treatment, often suffer from low metal recovery, high energy consumption, and environmental drawbacks. In particular, the refractory nature of zinc ferrite significantly limits zinc recovery efficiency, leading to incomplete resource utilization. Therefore, the development of effective and environmentally friendly technologies for processing zinc production wastes is still insufficiently addressed in current research [5].

Recent studies have demonstrated that advanced methods such as reductive roasting, alkaline treatment, and the use of additives (e.g., CaO, Na_2CO_3) can enhance the decomposition of zinc ferrite and improve subsequent leaching performance [6]. Thermodynamic analyses indicate that phase transformation reactions become favorable at elevated temperatures, while experimental evidence confirms that metal extraction efficiency can be significantly increased under optimized conditions. However, there is still a lack of comprehensive approaches that integrate thermodynamic justification, experimental validation, and industrial applicability [7].

This issue is particularly relevant in Central Asia, and especially in Uzbekistan, where large quantities of zinc production residues are generated at metallurgical enterprises such as the Almalyk Mining and Metallurgical Complex (AMMC). The accumulation of these wastes not only creates environmental concerns but also represents a missed opportunity for recovering valuable metals and improving resource efficiency. Given the country's strategic focus on developing a "green economy" and resource-saving technologies, the recycling of zinc-containing wastes has become an important scientific and industrial priority [8].

The objective of this study is to investigate the physicochemical characteristics of zinc production wastes and to evaluate effective methods for their processing and metal recovery. Special attention is given to the transformation of zinc ferrite and the enhancement of zinc extraction through innovative treatment techniques [9].

The aim of this paper is to develop and substantiate a technologically feasible and environmentally sustainable approach for recycling zinc production wastes, with a focus on improving metal recovery efficiency and reducing ecological impact [10].

Results. The following figure (Fig.1) illustrates the elemental distribution in the zinc cake sample:

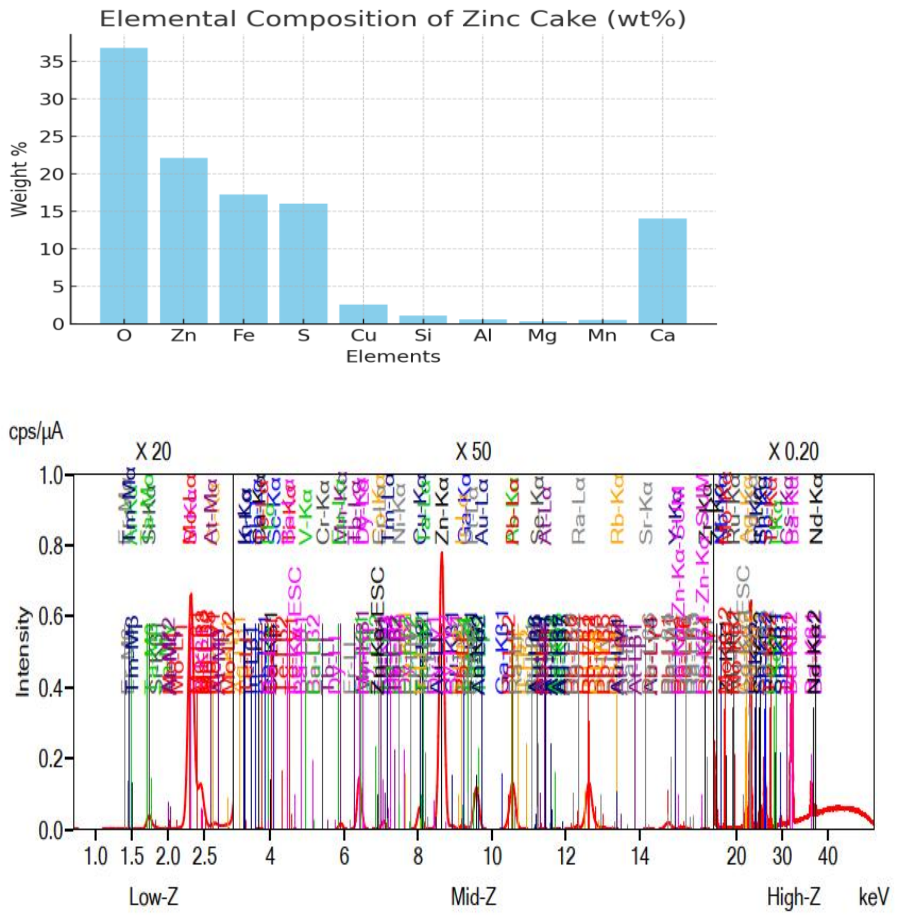

Fig.1. Results of Elemental Analysis in the 001-Spectrum Area of the Zinc Cake Sample

Figure 1 presents the energy-dispersive X-ray spectroscopy (EDS) spectrum obtained from the 001-analysis area of the zinc cake sample. The spectrum displays the distribution of detected elements across a wide energy range (keV), divided into low-Z, mid-Z, and high-Z regions, corresponding to light, medium, and heavy elements, respectively.

The analysis reveals that the sample contains a complex mixture of elements, with prominent peaks corresponding to zinc (Zn), iron (Fe), oxygen (O), and sulfur (S)**,** which are typical constituents of zinc processing residues. The strong presence of Zn and Fe confirms the dominance of zinc-bearing phases, particularly zinc ferrite ($ZnFe_2O_4$), which is known for its refractory nature in hydrometallurgical processes [11].

In addition to the major elements, several minor and trace elements such as lead (Pb), copper (Cu), cadmium (Cd), silicon (Si), calcium (Ca), and aluminum (Al) are also detected. These elements likely originate from the initial polymetallic concentrate and process additives. Their presence indicates that the zinc cake represents a valuable secondary resource containing recoverable metals.

The intensity peaks observed in the mid-energy range (approximately 6–10 keV) are mainly associated with transition metals such as Fe, Zn, and Cu, while higher energy peaks correspond to heavier elements such as Pb. The relatively broad and overlapping peaks suggest a heterogeneous and multi-phase structure of the sample [12].

Overall, the EDS results confirm that the zinc cake is a complex, multi-component material with significant metal content. This supports the necessity of applying advanced processing techniques, such as roasting or reductive treatment, to break down stable phases and enhance metal recovery efficiency [13].

Mineralogical analysis revealed the following phase composition (Table 1-2):

Table 1. Elemental Composition of Zinc Cake Sample (SEM-EDX)

Element	Weight %	Atomic %
S	7.24	14.94
O	36.80	56.82
Mg	0.32	0.31
Al	0.61	0.57
Si	1.08	0.97
Ca	14.04	1.04
Mn	0.53	0.25
Fe	17.29	7.64
Cu	2.57	1.02
Zn	22.14	8.19

Table 2. Mineralogical Composition of Zinc Cake

Mineral Name (Formula)	Content (%)
Zinc ferrite ($ZnFe_2O_4$)	41.28
Basic zinc sulfate ($3Zn(OH)_2 \cdot ZnSO_4 \cdot 4H_2O$)	31.0
Gypsum ($CaSO_4 \cdot 2H_2O$)	6.1
Calcium sulfate ($CaSO_4$)	6.4
Ktenasit ($(CuZn)_5(SO_4)_2(OH)_6 \cdot 6H_2O$)	4.82
Sphalerite ($(Zn,Fe)S$)	4.57
Zinc silicate (Zn_2SiO_4)	2.49

Discussion

Based on the obtained SEM-EDX results and mineralogical analysis, an effective processing strategy for the zinc cake can be proposed. The phase composition indicates that the sample is dominated by zinc ferrite ($ZnFe_2O_4$) (~41.28%), which is a refractory phase and represents the main limitation for zinc recovery. At the same time, the presence of more reactive phases such as basic zinc sulfate, sphalerite ((Zn,Fe)S), and zinc silicate (Zn_2SiO_4) suggests that a portion of zinc can be readily extracted under acidic conditions.

Considering these characteristics, a direct hydrometallurgical approach based on sulfuric acid leaching is recommended as the primary processing method. Zinc present in sulfate and sulfide phases can be effectively dissolved under moderate conditions, while the overall extraction efficiency can be improved by optimizing process parameters.

To enhance zinc recovery from the complex multi-phase material, it is proposed to apply intensified leaching conditions, including:

roasting,

elevated temperature (60–80 °C),

increased acid concentration (up to 150 g/L H_2SO_4),

sufficient agitation (300–600 rpm),

extended leaching duration.

In addition, the high content of iron-bearing phases suggests the possibility of selective separation of iron through controlled pH adjustment and precipitation during solution purification. The presence of copper and cadmium also indicates potential for sequential recovery of valuable by-products, improving the overall economic efficiency of the process.

Overall, the proposed method allows for the efficient utilization of zinc cake as a secondary raw material, reducing waste accumulation and contributing to sustainable and resource-efficient metallurgical processing.[5]

Conclusion

The present mineralogical analysis of the zinc cake confirms the presence of significant zinc-bearing phases, predominantly associated with refractory compounds such as zinc ferrite, along with various impurity elements. The complex and heterogeneous composition of the material highlights the challenges associated with its processing using conventional methods. A detailed understanding of the phase composition and elemental distribution is therefore crucial for the rational design and optimization of hydrometallurgical treatment routes. Such insights enable the development of more efficient processing strategies aimed at enhancing zinc recovery, improving resource utilization, and reducing environmental impact.

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