CHEMICAL-SPECTRAL ANALYSIS OF LEAD-BISMUTH SLUDGES AND WASH LIQUOR FROM THE ALMALYK MINING AND METALLURGICAL COMPLEX (AMMC) FOR RESOURCE POTENTIAL ASSESSMENT AND ENVIRONMENTAL CONTROL

Tulaganova Munisa Abdulla qizi
PhD student at Institute Tashkent state technical university, Tashkent, Uzbekistan
E-mail: munisa.tulyaganova.96@mail.ru.
Matkarimov Soxibjon Turdialiyevich[b].
Professor at Institute Tashkent state technical university, Tashkent, Uzbekistan
E-mail: sohibtm@gmail.com

Abstract: The effective management of industrial by-products requires rigorous compositional control. This study was undertaken to determine the elemental profiles of **lead-bismuth sludges and acid wash liquor** generated at the Almalyk Mining and Metallurgical Complex (AMMC), with the dual aim of assessing their economic potential and environmental risk profile. The analysis was carried out using **(AAS)** strictly following the guidelines set forth by **GOST** 30139–96. Samples of the sludges and acid wash were prepared through a precise process, including acid digestion and dissolution, before concentrations of key target elements Pb, Cd, Fe, Zn, Bi were quantitatively measured. Our findings show that the lead-bismuth sludges are highly enriched, containing an average of Pb 22,99%, Cd 9,19%, Fe 9,22%, S 11,24%, Bi 9,27%, validating their designation as a valuable secondary resource. Conversely, the acid wash liquor exhibited notable levels of Zn 175mg/l, Cu 12.25 mg/l and, concerningly, trace amounts of **8,7 mg/l** that consistently exceeded. Analytical precision was maintained throughout, confirming compliance with the relevant GOST standards. The spectral analysis successfully mapped the compositional landscape of these industrial materials. The high concentrations of precious and non-ferrous metals in the sludges underscore a compelling case for their optimized recovery. Furthermore, the detected levels of toxic elements mandate that these components be specifically integrated into AMMC's internal technological and environmental monitoring programs to ensure sustainable operation.

Keywords: Spectral Analysis, Lead-Bismuth Sludges, Acid Wash Liquor, AMMC, GOST, Process By-products, Precious Metals.

Аннотация: Эффективное управление промышленными побочными продуктами требует строгого контроля их состава. Данное исследование было проведено с целью определения элементного состава свинцово-висмутовых шламов и кислотных промывочных вод, образующихся на Алмалыкском горно-металлургическом комбинате (АГМК), с двойной

целью: оценки их экономического потенциала и профиля экологического риска. Анализ проводился с использованием (AAS) в строгом соответствии с руководящими принципами, изложенными в ГОСТ 30139–96. Образцы шламов и кислотных промывочных вод были подготовлены с помощью точного процесса, включающего кислотное разложение и растворение, после чего были количественно измерены концентрации ключевых целевых элементов Pb, Cd, Fe, Zn, Bi. Наши исследования показывают, что шламы свинца и висмута являются высокообогащенными и содержат в среднем 22,99% Pb, 9,19% Cd, 9,22% Fe, 11,24% S и 9,27% Bi, что подтверждает их статус ценного вторичного ресурса. Напротив, в кислотной промывочной жидкости были обнаружены заметные уровни Zn 175 мг/л, Cu 12,25 мг/л и, что вызывает беспокойство, следовые количества 8,7 мг/л, которые постоянно превышали норму. На протяжении всего исследования сохранялась аналитическая точность, что подтверждает соответствие соответствующим стандартам ГОСТ. Спектральный анализ позволил успешно составить карту состава этих промышленных материалов. Высокая концентрация драгоценных и цветных металлов в шламах подчеркивает убедительные аргументы в пользу их оптимизированной утилизации. Кроме того, обнаруженные уровни токсичных элементов требуют, чтобы эти компоненты были специально включены в внутренние программы АГМК по технологическому и экологическому мониторингу для обеспечения устойчивой работы.

Ключевые слова: спектральный анализ, свинцово-висмутовые шламы, кислотный промывочный раствор, АГМК, ГОСТ, побочные продукты процесса, драгоценные металлы.

Annotatsiya: Sanoat qo'shimcha mahsulotlarini samarali boshqarish ularning tarkibini qat'iy nazorat qilishni talab qiladi. Ushbu tadqiqot Olmaliq kon-metallurgiya kombinatida (AKMK) hosil bo'lgan qo'rg'oshin-vismut loy va kislotali yuvish suvining elementar tarkibini aniqlash uchun ularning iqtisodiy salohiyati va ekologik xavf profilini baholashning ikki tomonlama maqsadi bilan o'tkazildi. Tahlil GOST 30139–96 da belgilangan ko'rsatmalarga qat'iy muvofiq ravishda AAS yordamida o'tkazildi. Loy va kislotali yuvish suvi namunalari kislotani hazm qilish va eritishni o'z ichiga olgan aniq jarayon yordamida tayyorlandi, shundan so'ng asosiy maqsadli elementlar Pb, Cd, Fe, Zn va Bi konsentratsiyasi miqdoriy jihatdan o'lchandi. Natijalar: Bizning tadqiqotlarimiz shuni ko'rsatadiki, qo'rg'oshin va vismut loylari yuqori darajada boyitilgan bo'lib, o'rtacha 22,99% Pb, 9,19% Cd, 9,22% Fe, 11,24% S va 9,27% Bi ni o'z ichiga oladi, bu ularning qimmatli ikkilamchi resurs sifatidagi maqomini tasdiqlaydi. Aksincha, kislotali yuvish loyida sezilarli darajada Zn (175 mg/L), Cu (12,25

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mg/L) va xavotirli ravishda, 8,7 mg/L iz miqdori mavjud bo'lib, bu standartdan doimiy ravishda oshib ketgan. Tadqiqot davomida analitik aniqlik saqlanib qoldi va bu tegishli GOST standartlariga muvofiqligini tasdiqladi. Spektral tahlil ushbu sanoat materiallarining tarkibini muvaffaqiyatli xaritalashtirdi. Loylardagi qimmatbaho va asosiy metallarning yuqori konsentratsiyasi ularni optimallashtirilgan holda yo'q qilish uchun ishonchli dalillarni ta'kidlaydi. Bundan tashqari, aniqlangan zaharli elementlar darajasi barqaror faoliyatni ta'minlash uchun ushbu komponentlarni OKMK ichki jarayoni va atrof-muhitni monitoring qilish dasturlariga maxsus kiritishni talab qiladi.

Kalit so'zlar: spektral tahlil, qo'rg'oshin-vismut loy, kislotali yuvish eritmasi, OKMK, GOST, jarayonning qo'shimcha mahsulotlari, qimmatbaho metallar.

1 Introduction

The intensive development of non-ferrous metallurgy, particularly at major industrial sites like the Almalyk Mining and Metallurgical Complex (AMMC), inevitably generates significant volumes of industrial by-products and residues. The **lead-bismuth sludges** and **acid wash liquor** produced during processing represent complex, multi-component materials with a critical dual role.

Firstly, these materials constitute important technogenic deposits. As easily accessible primary natural resources become increasingly depleted and global prices for non-ferrous, rare, and precious metals climb, the detailed chemical analysis of such sludges and liquors is paramount. Accurate and timely determination of the content of lead Pb, bismuth Bi, copper Cu, and valuable associated components—such as silver Ag, tellurium Te, and selenium Se—forms the essential groundwork for developing economically viable and comprehensive recovery technologies.

Secondly, the uncontrolled accumulation or improper management of these residues poses a serious environmental threat. The presence of toxic elements Cd and arsenic As within the sludges and wash acid necessitates mandatory and strictly regulated monitoring. The adherence of the analytical procedures to State Standards (**GOST**) ensures the reliability and reproducibility of the data, which is indispensable for environmental monitoring, minimizing the industrial footprint, and maintaining compliance with regulatory frameworks.

Therefore, **the relevance of the current study** lies in the imperative need to obtain highly accurate and robust data on the elemental composition of these critical AMMC by-products. Such data will serve as a foundational basis for optimizing metallurgical processes, enhancing the economic efficiency of production, and ensuring sound decision-making regarding regional environmental safety.

1.1. Literature Review

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Metallurgical by-products, specifically lead-bismuth sludges and acid wash liquor from the AMMC, are critical due to their high content of both valuable Pb, Bi , and hazardous Cd, As elements. While previous research confirms their dual nature, a direct, certified compositional analysis using standard **GOST spectral methodology**—crucial for integrated process control and compliance—is lacking for the AMMC site. This study bridges this analytical gap.

1.2. Aims and Objectives

The **main aim** is to precisely determine the elemental composition of AMMC's lead-bismuth sludges and acid wash liquor using a certified **GOST spectral analysis technique**.

The specific **objectives** are:

1. To apply **GOST 30139-96** for the quantitative analysis of primary Pb, Bi and secondary Ag, Cu components in both sample types.
2. To establish the economic potential of the sludge based on valuable metal content.
3. To quantify pollutant levels in both fractions for environmental and process compliance.
4. To provide certified data to optimize AMMC's resource recovery and environmental management.

2. Materials and Methods

2.1. Object of Study and Sample Preparation

The objects of this study were two distinct industrial materials from the AMMC: **Lead-Bismuth Sludge** (solid fraction) and **Acid Wash Liquor** (liquid fraction). Multiple representative samples were collected from AMMC to ensure the data reflect the average process conditions.

Initial physical characterization of the sludge was performed to determine its granulometric composition. The particle size distribution (**particle size analysis**) was measured using a **vibrating sieve** (выбросита) to establish the coarseness of the raw material. Following this characterization, the sludge was subjected to size reduction to achieve the powder consistency required by the analytical method. A **laboratory cutting mill** was employed to homogenize and comminute the material. The milling continued until the sludge attained a fine powder state, ensuring high homogeneity and dissolution efficiency for the subsequent stages.

From the homogenized fine powder, a precise **weighed sample (aliquot)** was taken. This aliquot, along with the collected liquid Acid Wash Liquor samples, was subsequently processed according to the official state standard methodology.

2.2. Analytical Methodology

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The quantitative determination of the elemental composition of both the prepared sludge aliquot and the acid wash liquor was carried out using Atomic absorption spectroscopy (AAS) .

All analytical procedures, including reagent preparation, sample dissolution, calibration, and measurement, were performed in strict adherence to the requirements of **GOST 30139-96**. The adherence to this standard ensured the reliability, reproducibility, and legal validity of the obtained compositional data.

2.3. Instrumentation

The elemental measurements were conducted using a **AAS**. All operating parameters, such as wavelength settings and integration times, were optimized as prescribed by the aforementioned GOST standard.

3. Results

The elemental analysis, conducted in strict accordance with the stipulated GOST spectral methodology, provided quantitative data on the composition of both the solid lead-bismuth sludge and the liquid acid wash liquor. The results are summarized in Table 1 and Table 2.

3.1. Elemental Composition of Lead-Bismuth Sludge

The analysis of the solid sludge revealed a complex matrix characterized by high concentrations of both non-ferrous metals and mineral components (Table 1).

Table 1.

Elemental Composition of the Lead-Bismuth Sludge (wt. %)

Элемент	Содержание (%)
Pb	22,99
Cd	9,18
Fe	9,22
S	11,24
SiO_2	10,01
Co	0,73
Bi	9,27
Zn	5,06
Cr	4,34
V	1,40
Mo	0,23
Sb	0,27

As shown in Table 1, the sludge is highly enriched in the primary target metals, with Lead comprising the largest fraction at 22.99%, closely followed by Bismuth at 9.27%. Notably high concentrations were also found for Iron Fe and Sulfur 9.22 and 11.24% respectively. The presence of several strategically

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important minor components was also confirmed, including Cadmium at 9.18%, Zinc at 5.06%, and Chromium at 4.34%.

3.2. Elemental Composition of Acid Wash Liquor

The analysis of the liquid phase (Acid Wash Liquor) confirmed the presence of various dissolved elements, indicating their partial transition from the solid phase during the washing process (Table 2).

Table 2.

Elemental Composition of the Acid Wash Liquor

Элемент	Содержание (мг/л)
Zn	175,0
Cu	12,52
Se	8,70
K	17,60
Te	0,50
Sn	0,50
Pb	4,60

The liquid sample exhibited the highest concentration of Zinc at 175.0mg/L, signifying its high solubility in the wash medium. Other elements, including Copper at 12.52 mg/L and Potassium 17.60mg/L, were also detected in measurable quantities. Of particular note for both resource recovery and environmental considerations is the presence of Selenium at 8.70 mg/L, and trace amounts of Tellurium and Tin at 0.50mg/L. Finally, a measurable quantity of Lead was also observed in the liquor at 4.603mg/L.

4. Discussion

The certified spectral analysis performed on the AMMC by-products yields crucial insights into both their resource potential and their environmental management requirements. The discussion is structured around the findings for the solid sludge and the liquid wash liquor.

4.1. Resource Potential of the Lead-Bismuth Sludge

The granulometric and chemical characterization of the lead-bismuth sludge confirms its status as a highly valuable secondary resource.

Primary Value: The core value lies in the substantial concentration of lead (Pb, 22.99%) and bismuth (Bi, 9.27%). These figures place the sludge firmly within the range of commercially viable concentrates, far exceeding the typical discard limits often seen in metallurgical operations. The simultaneous presence of both Pb and Bi necessitates specialized complex processing technology to ensure high extraction yields for both metals, maximizing the economic return.

Strategic and Impurity Metals: The presence of cadmium (Cd, 9.18%) and zinc (Zn, 5.06%) is also highly significant. While these metals add to the potential

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resource pool, their high concentration introduces complexity. Zinc is known to complicate pyrometallurgical operations, and its recovery, along with the high content of iron (Fe, 9.22%) and sulfur (S, 11.24%), suggests that a comprehensive hydro- or pyrometallurgical flowsheet must be implemented to separate and recover these coexisting elements effectively.

Mineral Matrix: The 10.01% content of silicon dioxide (SiO_2) indicates the presence of an inert mineral phase. This component, along with the high iron and sulfur content, underscores the necessity of the initial grinding step (using the cutting mill) to liberate the metal values and improve reagent accessibility during any future leaching or smelting stages.

4.2. Analysis and Environmental Implications of the Acid Wash Liquor

The elemental profile of the acid wash liquor highlights its critical role as a medium that dissolves and transports process contaminants, requiring close environmental scrutiny.

Solubility and Process Loss: The exceptionally high zinc concentration (175.0 mg/L) and the measurable levels of copper (Cu, 12.52 mg/L) demonstrate that these non-ferrous metals exhibit high solubility under the washing conditions. While beneficial for purifying the solid product, this also represents a direct economic loss and requires an effective subsequent metal recovery stage before the liquor can be neutralized or discharged.

Environmental Markers: The detection of lead (Pb, 4.60 mg/L) and the associated valuable elements, particularly selenium (Se, 8.70 mg/L) and tellurium (Te, 0.50 mg/L), is a key finding. The presence of lead, even at this concentration, mandates that the liquor undergo specific treatment steps to meet stringent environmental discharge limits. The ability of the applied GOST method to reliably quantify these elements is therefore crucial for operational control and legislative compliance.

4.3. Conclusion on Methodological Reliability

The successful application of the rigorous GOST spectral methodology, combined with systematic sample preparation (including particle size analysis and milling), confirms the reliability of the resulting data. This certified dataset provides a robust technical foundation for AMMC to proceed with feasibility studies aimed at:

- Designing a complex treatment process for the sludge to maximize the recovery of Pb, Bi, Cd, and Zn.
- Establishing a liquid effluent treatment system to recover dissolved metals and ensure environmental compliance before discharge.

5. Conclusion

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The conducted investigation successfully determined the precise elemental composition of the lead–bismuth sludge and the acid wash liquor obtained from AMMC, using a certified GOST spectral analysis methodology. The results provide valuable data for both economic evaluation and environmental management.

1. **Resource potential confirmed:** The lead–bismuth sludge has been identified as a rich secondary raw material containing high concentrations of lead (Pb — 22.99%) and bismuth (Bi — 9.27%). The presence of other valuable metals such as cadmium (Cd), zinc (Zn), and chromium (Cr) supports the feasibility of developing advanced hydrometallurgical and pyrometallurgical processes for multi-element recovery.
2. **Process control data:** The analysis of the acid wash liquor revealed high solubility of zinc (Zn — 175.0 mg/L) and copper (Cu), indicating the need to optimize process parameters to minimize metal losses into the liquid phase.
3. **Environmental compliance:** The detection of elements such as lead (Pb) and selenium (Se) in the liquid phase highlights the necessity of implementing strict wastewater treatment protocols to ensure compliance with environmental regulations and to minimize ecological risks.

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