Characterization of Old Tailings Materials for Li-Sn Extraction and Sustainable Environmental Management: A Case Study of the Bielatal Tailings Dam, Altenberg, Eastern Ore Mountains, Saxony, Germany

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Abstract

Reprocessing potential and environmental risk of Bielatal tailings material, Altenberg, Germany, were assessed using percussion core samples (7 m depth), analyzed for geochemical, mineralogical composition, particle size, and milieu parameters (pH, Eh, EC). Tin (0.12 wt%) and lithium (0.10 wt%) were valuable elements, while arsenic (0.04 wt%) posed environmental concerns. Tin and lithium were associated with cassiterite and mica phases respectively. Samples were composed of 56% silt, 35% fine sand, and 9% clay, with enrichment of tin, lithium, and arsenic in fine fractions. Weak acidity (pH 6) and low oxidation (Eh 160 mV) suggest minimal acid mine drainage risk.

Keywords: Bielatal tailings dam, geochemical characterization, mineralogical characterization, lithium, tin

Introduction

Comprehensive characterization of historical tailings is essential for effective environmental management and resource recovery. Understanding their chemical, mineralogical, and physical properties helps mitigate environmental risks and identify opportunities for extracting valuable elements (e.g. Li, Sn) while assessing potential toxic metal (e.g. As, Pb) content (Jackson and Parbhakar-Fox 2016). Physical property analysis also ensures storage facility stability, preventing dam failures and promoting sustainable mining practices to protect ecosystems and communities (Anawar 2015). Each tailings storage facility (TSF) has a unique depositional history, structure, and composition influenced by processed ore characteristics, processing technology, and deposition methods (Büttner *et al.* 2018; Redwan *et al.* 2012). Exploration and feasibility studies, similar to those for primary ore deposits, rely on understanding material characteristics such as grade, particle size, mineral liberation, and metal deportment to minimize investment risks in tailings reclamation (Büttner *et al.* 2018).

To date, there has been no characterization studies of the Bielatal TSF, and that there is little or no literature been published about the reprocessing potential of this tailings body, hence its selection as a case study in this work. The interest in reprocessing the tailings coexists with the necessity to reduce harmful

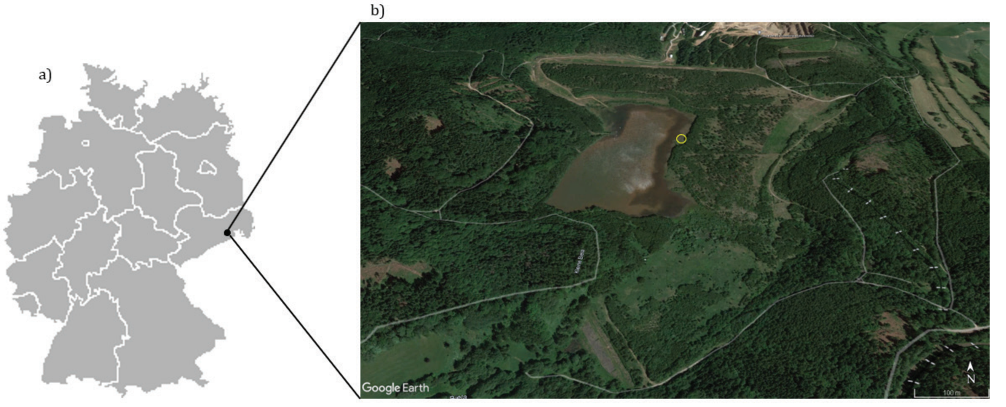

Figure 1 (a) Location of the Bielatal tailings dam in Germany, (b) oblique Google satellite image of the surface of the dam with marked (yellow) sampling area (modified after Google Inc. (2024)).

environmental impacts caused by the high arsenic contents which were completely discharged into the Bielatal tailings dam during the mining operation. Furthermore, it is important to investigate the current condition of the tailings material to ascertain its potential risk with respect to acid mine drainage. The findings from this preliminary study is compared to literature to check the correlations between survey data and site-specific materials examined. This would highlight the importance of combining historical data with detailed geochemical and mineralogical analyses to assess the potential for resource recovery and environmental risks in mine tailings.

Study area

The Bielatal TSF in Altenberg, Saxony (Fig. 1), was built by Volkseigener Betrieb (VEB) Zinnerz Altenberg and operated from 1967 until 1991. The dam stored processing wastes from the Altenberg Sn deposit, a world-class greisen deposit in the Eastern Erzgebirge, Saxony, Germany (Weinhold 2002). It measures around 73,000 m^2 by surface area, a height of 80 m, and an average width of 680 m. It holds about 10.5 Mio m3 of flushed-in tailings material. Located 1.5 km north of Altenberg, one-third of the TSF surface is covered by a residual lake (Fig. 1b) with a flushing beach as part of its reclamation strategy.

Materials and Methods

Sampling was conducted in Oct.–Nov. 2023 on the eastern side of the residual lake (Fig. 1b) at five points (RKS1–RKS5) using percussion coring to a depth of 7 m and about 5 m apart, yielding about 100 kg of material. Samples were dried at 105 °C, deagglomerated, and homogenized for analysis. Particle size distribution was determined using a laser particle size analyzer and pH, redox potential (Eh), and electrical conductivity (EC) were measured in a 1:2 solid-liquid ratio. Eh values were corrected to the standard hydrogen electrode (Blowes *et al.* 1998).

Bulk chemical composition was analyzed using a hXRF analyzer, while Li was measured by Na-peroxide fusion. Strong agreement was observed between Na-peroxide fusion and hXRF for Sn and major elements. Mineral phases were identified via Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray spectroscopy (EDX) analysis.

Results and discussion

Geochemical characterisation

A summary of the chemical composition of the tailing samples is presented in Tab. 1. The results indicate that, the main components of the tailing samples (RKS1-RKS5) are Si with average concentration of 33 wt%, Al 8 wt%, Fe 5 wt%, and K 2 wt%. The valuable elements in the tailing samples like Sn and Li have average concentrations of 0.12 wt% and 0.10 wt% respectively. All other elements have an average concentration < 0.1 wt%. The results show that, the major environmentally concerning element is the Arsenic (As) content present in the tailings with the average

Table 1 *Average metal concentration of tailing samples, (combined hXRF and Na-peroxide fusion (*) data from individual drill holes).*

Sample	Al %	As %	Bi %	Ca %	Fe %	K %	Li* %	Mn %	Mo %	Rb %	S %	Si %	Sn %	Ti %	W %
RKS1	7.57	0.04	0.02	0.78	4.45	1.90	0.10	0.09	0.02	0.06	0.06	32.32	0.09	0.04	0.02
RKS2	7.72	0.04	0.01	0.79	4.70	1.96	0.10	0.08	0.01	0.11	0.05	32.60	0.10	0.04	0.02
RKS3	7.49	0.04	0.01	0.77	4.63	1.94	0.10	0.08	0.01	0.11	0.05	33.25	0.10	0.04	0.02
RKS4	8.04	0.04	0.01	0.76	4.75	2.03	0.09	0.08	0.01	0.11	0.06	32.85	0.11	0.04	0.02
RKS5	7.83	0.04	0.02	0.77	4.90	2.02	0.10	0.08	0.01	0.11	0.06	31.91	0.19	0.04	0.02

concentration of 0.04 wt%. From the results it can be seen that, the element distribution values in all 5 drill core bulk samples are quite similar, indicating a relatively even element distribution in these sampling locations. A more deep and extensive drilling campaign is needed to further confirm this for the entire tailings body.

Correlation of Rb-Li in tailings material

Conventional lithogeochemical techniques often result in delays between sample collection and laboratory analysis, creating a gap between data acquisition and application (Kalnicky and Singhvi 2001). Since Li, a lighter element, is not directly measurable by XRF, its correlation with Rb (by hXRF) plays a crucial role. Weinhold (2002) reported strong Li-Rb correlations (R^2 = 0.95–0.99) in the Altenberg ore deposit, where Li is primarily associated with mica phases like zinnwaldite. Correlation between Rb and Li can be seen in Fig. 2. Similarly, a high correlation (R^2 = 0.95) in the investigated samples is confirmed, indicating that high Rb samples are also richer in Li. This validates the use of hXRF-measured Rb to predict Li content

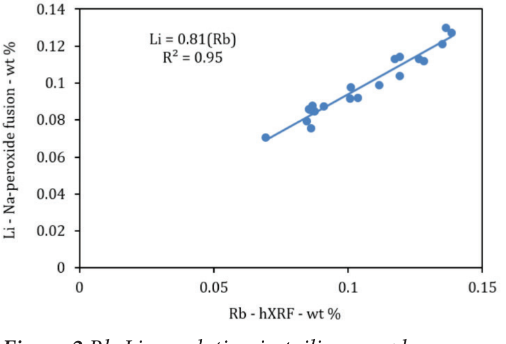

Figure 2 *Rb-Li correlation in tailing samples.*

using the correlation equation, particularly for rapid decision-making in process steps. Furthermore, the establishment of such a kind of correlation equation has not only the potential to reduce the time between sampling and result gathering but can also substantially reduce analytical costs in extensive sampling campaigns. It is worth noting that, the prediction is reliable within the range of 0.07–0.14 wt%, but new dataset is needed to validate the equation for values outside this range.

Particle size distribution related to geochemical composition

The geochemical composition of tailings samples is bound to minerals that passed the ore processing procedures. These multi-stage treatments result in different grain sizes.

Fig. 3a shows the relevant particle size data (d50) and element (Li, Sn, As) concentration against depth from drill core samples RKS5. For simplicity, only the data for d50 is shown. Basically, the results for the 5 different drill core samples show the same trend, therefore, only one drill hole (RKS5) is shown. The general tailings samples are very heterogeneous with regard to grain size ranging from 0.35 to 300 µm. The silt fraction (2 to 63 µm) represents the highest content (56–60%). The fine sand (63 to 300 µm) and clay (< 2 µm) content ranges from 30–35% and 6–9% respectively. Fig. 3b is a correlation between element concentration (Li, Sn, As) and particle size distribution (d50). Note that, Li data are predicted values from the Rb-Li correlation equation for reasons mentioned above. A vertical fractionation layered structure is clearly evident in the drill profile (Fig. 3a) with an alternating layer structure of coarse and fine-grained materials. This could be attributed to the tailings spilling (deposition) process.

From 3a, it is clear that, Li, Sn and As concentrations are higher in the finer particle size fractions. However, there exit a poor correlation between Sn-As and the entire size distribution (Fig. 3b). Li on the other hand shows a consistent correlation across all size fractions. This means that the processing technology (flotation) used for the extraction of Sn was very efficient for the coarser particles, resulting in a higher enrichment only in a specific fraction (fine particles). Li, which was not a target element at the time was not attacked by flotation, resulting in a uniform distribution of Li-bearing minerals within the sample and broke down proportionally during size reduction, hence, the consistent correlations across all size fractions. This implies that, the extraction of Sn from the tailing samples should be targeted in the fine fraction while Li should be targeted across all particle size streams. For environmental reasons, the fine particles should be of major concern as As is highly enriched in the fine fraction.

Determination of mineral content by SEM-EDX

According to Weinhold (2002), the Bielatal tailing materials consist mainly of quartz, mica, topaz and alkali feldspars with minor hematite, and clay minerals resulting from feldspar alterations (Redwan 2022). Of particular importance to this study are the minerals cassiterite, mica and some relevant arsenic bearing mineral phases. Therefore, SEM-EDX analysis was conducted to further confirm the presence of these mineral phases in the tailing samples. From Fig. 4, it can be seen that, silicates are homogeneously distributed in the sample and associated to most elements such as K, Al, Fe, F, Na, Ca, Mg and Ti. In this regard, the following mineral phases could be present; quartz, topaz, feldspar, mica, and kaolinite. Tin is bound to the cassiterite phase (SnO_2) represented as strongly bright, discrete particles in the Backscattered Electron (BSE) mode. Fe to some extent shows an association with sulfur and arsenic which could indicate the probable presence of pyrite and/or arsenopyrite. A homogeneous S and As distribution observed is likely due to the low content and peak overlap making it difficult to identify specific As-S rich phases in the sample. A more detailed analysis of these materials would be performed using XRD to further confirm the presence of these probable mineral phases.

Environmental (milieu) parameters

Fig. 5 shows the pH, Eh and EC measured values in the eluates against profile depth for one drill core sample. These parameters are key indicators of the geochemical

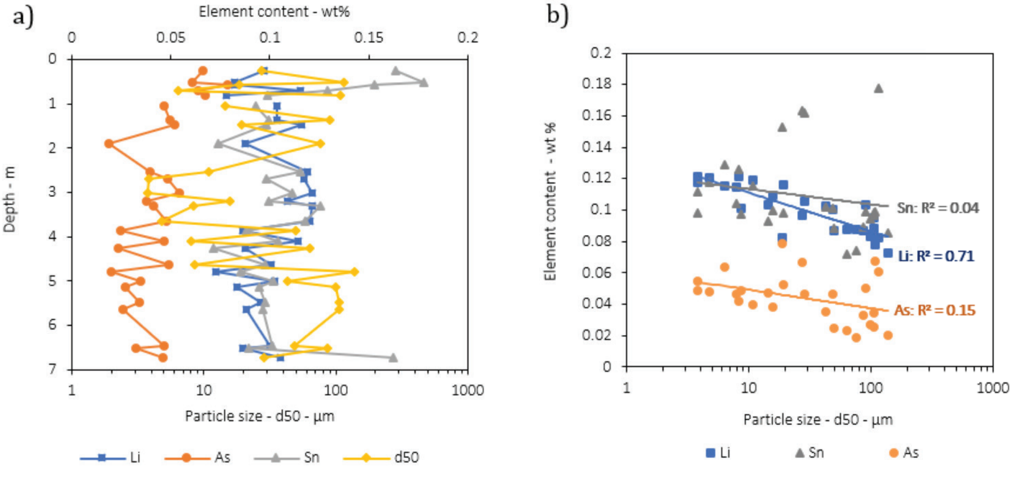

Figure 3 *(a) Particle size distribution and concentration of Li, Sn and As of drill core RKS5 by depth (b) correlation between particle size distribution and concentration of Li, Sn and As on a logarithmic scale.*

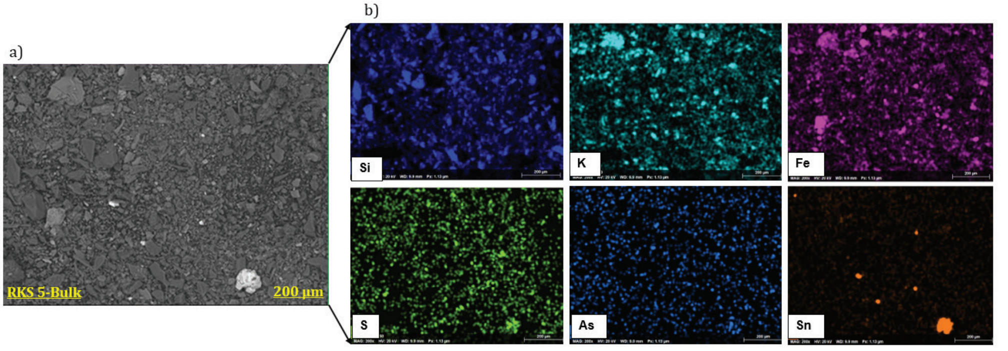

Figure 4 *Mapping of tailing sample (RKS5 bulk sample) at x100 magnification (a) SEM image (BSE) (b) EDX.*

environment in the tailings. The pH increases gradually from 5.5 at the top to 6.8 at depth, indicating a weak acidic to neutral conditions in the tailings body. This can be attributed to the buffering effect of the primary ore processed at the time (Modabberi 2018), the processing technology used and or only to the infiltration of meteoric waters (pH 5.6). The Eh to some extent decreases with increasing depth from 486 mV to less than 200 mV, indicating a highly oxidized condition at the upper part of the tailings body. This could lead to certain weathering effects at the upper part of the tailings body. The lower part of the tailings body is less oxidized. The electrical conductivity fluctuates in a range of 38–68 µS/cm suggesting relatively low levels of dissolved ions in the tailings body. An average moisture content of 35% was recorded for the drill core samples which indicates that the tailings are relatively moist,

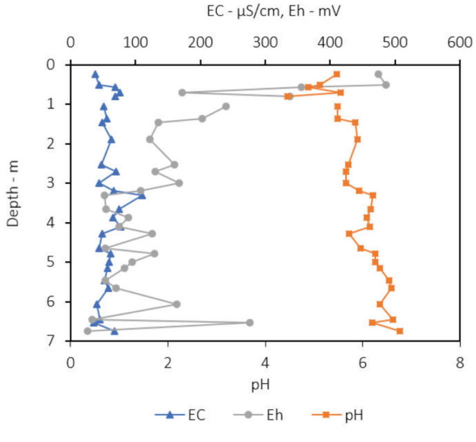

Figure 5 *Milieu parameters (EC, pH and Eh) measured with depth – RKS5.*

but not in a fully saturated state. Under these above described conditions, the tendency for acid mine drainage and metal mobility is minimal. However continuous monitoring and management is paramount to minimize environmental risks.

Conclusion

This study evaluated the Bielatal tailings dam material to assess its potential for valuable metal recovery and environmental management. The material consists mainly of quartz, mica, topaz, feldspars, hematite, and clay minerals, reflecting its greisen origin, with economically relevant concentrations of Li and Sn enriched in finer grain fractions. A Rb-Li correlation equation was developed to address challenges in direct Li measurement, aiding rapid decision making in process control and analytical cost reductions. The material is predominantly fine-grained, with silt and fine sand dominating. Based on the findings, it is recommended that Sn extraction from the tailing samples should be focused on the fine fraction, while Li extraction should be considered across all particle sizes.

Environmental assessment revealed weak acidity, moderate oxidation, and minimal acid mine drainage risk, with arsenic being the primary element of environmental concern. The fine particles of the tailings require special attention, as As is notably enriched in this fraction. Low metal mobility is expected under the current tailing's conditions. These findings align with historical data, confirming the resource potential of the tailings and emphasizing the need for further studies and ongoing monitoring to guide sustainable reclamation strategies and minimize environmental risks.

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