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The Separation and Recovery of Barium from Barium Slag by Using Shaking Table Gravity Concentration Method

Yang Wan [1], Bo Zhang [1], Xing Yang [1], Xin Song [2,3,*], Guocui Li [3], Siqi Zhang [3,*] and Wen Ni [3]

[1] Guizhou Redstar Developing Co., Ltd., Anshun 561206, China; wanyang@hxfz.com.cn (Y.W.); zhangbo@hxfz.com.cn (B.Z.); star5252004@163.com (X.Y.)
[2] Solid Waste and Chemicals Management Center, Ministry of Ecology and Environment, Beijing 100029, China
[3] School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing 100083, China; m202210007@xs.ustb.edu.cn (G.L.); niwen@ces.ustb.edu.cn (W.N.)
* Correspondence: d202220006@xs.ustb.edu.cn (X.S.); zsq2017@ustb.edu.cn (S.Z.)

Abstract: Barium slag, classified as HW47 hazardous waste, is produced in large quantities and has a high accumulation with heavy metal Ba ions that are significantly above the standard levels, posing a serious threat to the ecological environment and the growth of flora and fauna. Before barium slag can be stored, it must undergo harmless treatment, which is costly, and with the current large volume of accumulated barium slag, storage facilities are strained. There is an urgent need for new technologies to extract barium elements from barium slag while achieving reduction in volume. This study first treats the barium slag to reduce its oxidation state and then utilizes the density differences to separate barium-rich compounds through shaking table concentration. Macro and microanalytical methods such as XRD (X-ray diffraction), XRF (X-ray fluorescence), and SEM&EDS (Scanning Electron Microscopy & Energy-dispersive X-ray Spectroscopy) were employed. The results show that barium in the slag is evenly distributed, and after sufficient crushing, it can be separated by gravity concentration. The barium content can be enriched from 20% to over 80%. This research provides theoretical support for the separation of barium compounds from barium slag.

Keywords: barium slag; minimization; shaking table; separation

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Academic Editor: Antoni Sanchez

Received: 17 February 2025
Revised: 13 March 2025
Accepted: 24 March 2025
Published: 28 March 2025

Citation: Wan, Y.; Zhang, B.; Yang, X.; Song, X.; Li, G.; Zhang, S.; Ni, W. The Separation and Recovery of Barium from Barium Slag by Using Shaking Table Gravity Concentration Method. *Processes* **2025**, *13*, 1012. https://doi.org/10.3390/pr13041012

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1. Introduction

Barium slag is a byproduct from the production of barium carbonate from barite, and its toxicity mainly originates from soluble barium ions, making it a hazardous waste [1]. The main production flow is shown in Figure 1. In China's "National Catalogue of Hazardous Wastes" (2021 Edition), barium slag is designated with the code HW47. The long-term storage of barium slag not only occupies a large amount of land resources, but also, the leaching of Ba^{2+} ions in the barium slag commonly exceeds national standards by more than 10 times [2]. Due to the erosion by rainwater, soluble barium salts such as barium sulfide can be leached from the stored barium slag, entering the soil and posing serious hazards to the environment and human health [3,4].

It is estimated that China emits about 1 million tons of Ba annually, and this amount is still accumulating [5]. Barium metal is primarily used in industries such as electronics and electrical engineering, oil and gas, glass and ceramics, metallurgy, chemical engineering, and new energy. For example, barium slag can be used in the production of ceramic capacitors, piezoelectric materials, ceramic glazes, and television screens. Currently, the accumulated stock of barium slag in our country has exceeded tens of millions of tons [2].

The industrial technologies for the disposal of barium slag mainly include comprehensive utilization, resource recovery, and safe landfilling, etc. The harmless treatment of barium slag is a prerequisite for its emission, storage, and comprehensive utilization. The main resourceful methods for barium slag include the preparation of building materials [6–8], and the extraction of high-purity barium salts in the chemical industry [9–11], etc. The main harmless disposal methods include reducing toxicity through incineration, barium ion extraction, and stabilization of barium ions [12–16], etc. Industrially, sodium sulfate and ferrous sulfate are mainly used for the harmless treatment of barium slag. The treated harmless barium slag can be used for the production of building materials [17–19], cement additives [2], road base, and building material bricks [8,20,21], etc. Additionally, hydrometallurgy represents a technology that transfers metal ions into the liquid phase, followed by their recovery in elemental form or as other compounds. Wu et al. [22] used hydrometallurgical methods to solve the scientific problems of flocculation and precipitation of soluble barium in the leach solution of acid treatment of barium slag. The experimental results showed that more than 98.5% of the barium-containing compounds were successfully converted into $BaCO_3$ and $BaSO_4$, achieving high purities of 98.7% and 79.4%, respectively. Furthermore, the use of flocculants significantly improved the flocculation efficiency and rate of the $BaCO_3$ turbid fluid.

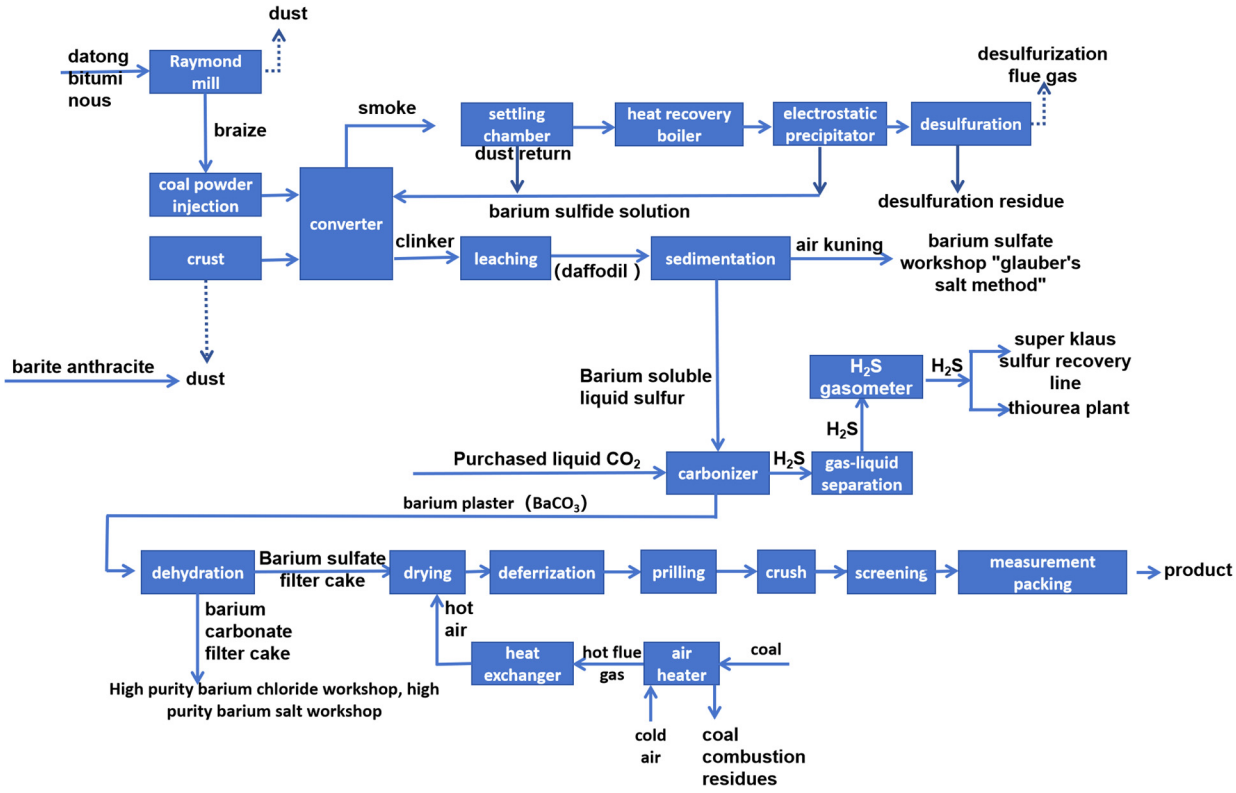


Figure 1. Process flow of barium slag generation.

Currently, the main application of barium slag has enabled these research efforts to achieve value-added utilization of barium. However, the introduction of these technologies also brings certain challenges. These factors include the gradual increase in barium slag stockpiles, the growing complexity of its composition, the low recovery rate of valuable components, high energy consumption, and non-compliance with sustainable development standards, particularly regarding the use of organic reagents [23]. Therefore, there is an urgent need to develop and implement innovative technologies for the effective removal of Ba to mitigate the resulting environmental pollution.

Studies have indicated that mining methods can be employed to comprehensively recover barium resources from barium slag, addressing the environmental pollution caused by barium slag and simultaneously recovering the barium contained within. Research into the properties of barium slag allows for the investigation of barium slag shaking table gravity concentration tests, barium slag flotation tests, barium slag acid leaching—preparation of barium sulfate from leachate tests, barium slag acid leaching residue flotation tests, and the study of flotation mechanisms of barium slag, among others. However, research on barium slag shaking table gravity concentration tests has shown that barium content in finer particle sizes of barium slag is higher than in coarser particle sizes. Through shaking table separation, it is difficult to effectively recover barium from barium slag, and multiple rounds of concentration cannot significantly improve the grade of the concentrate. Studies on the screening of barium slag flotation tailings have indicated that flotation has only a slight enriching effect on fine particle barium-containing minerals [24]. Flotation reagents and inevitable ions have a significant impact on the flotation of barite and quartz, with high concentrations of barium ions consuming a large amount of oleate, inhibiting barite [25]. Calcium and magnesium ions have a strong inhibitory effect on barite but can effectively activate quartz, making the floatability of the two very close, which makes flotation separation difficult. There is now an urgent need for more detailed mineral processing work to enhance the utilization of barium in barium slag.

In this study, a method was proposed to first reduce the state of barium slag and then separate and recover barium salts (barium sulfate, barium oxide) from barium slag through shaking table gravity concentration. The study primarily focused on the barium compounds in barium slag, with an emphasis on how to revert the agglomerated barium slag raw material back to its original state and separate the barium compounds, among other related issues.

2. Materials and Methods

2.1. Raw Material

The raw material used in this study is barium slag produced from the production of barium carbonate from barite, sourced from a company in Guizhou that manufactures barium carbonate. The raw material was dried and prepared for analysis.

2.2. Methods

In order to analyze the composition of the samples after the heavy media separation of barium slag, this study first pretreats the barium slag to a prereduced state and then uses the density difference to separate it into samples 1–16 using a shaking table, separating and selecting the compounds with high barium content. The model of the shaker table was LY-1100 × 500 (Shaker Manufacturing Co., Shaoxing, China). Macroscopic and microscopic analytical methods such as XRD (X-ray Diffraction), XRF (X-ray Fluorescence), FTIR (Fourier Transform Infrared Spectroscopy), SEM (Scanning Electron Microscopy), and EDS (Energy-dispersive X-ray Spectroscopy) are employed to analyze the barium compounds separated from the barium slag. The XRD analysis was conducted using a Japanese Rigaku SmartLab SE X-ray diffractometer (An Electronic Technology Co., Shenzhen, China), employing copper potassium radiation, with a voltage of 40 kV and a current of 40 mA. The scanning range was from 5° to 90°, at a scanning speed of 5° per minute, with a step size of 0.02, to perform X-ray dual-component (XRD) measurements on the powder samples and to observe and analyze the phases present in the samples. The XRF spectrometer used was the Japanese Rigaku ZSX Primus III+ (Rigaku Ltd., Tokyo, Japan), which uses high-energy X-rays or gamma rays to bombard materials, exciting secondary X-rays that are used to determine the types and amounts of elements in the materials. FTIR analysis was performed

using a Thermo Scientific Nicolet iS20 Fourier Transform Infrared Spectrometer (Thermo Fisher Scientific, Shanghai, China), which is a U.S. NICOLET 470 model. The analysis was conducted with a resolution of 4 cm^{-1}, 32 scans, and within the wavenumber range of 400 to 4000 cm^{-1}. The FTIR spectra of the samples were obtained and recorded, and the characteristic peaks of the hydrated products were determined by analyzing chemical bonds and functional groups. SEM-EDS was employed using a JSM-6701F field emission scanning electron microscope (JEOL Nippon Electronics Co., Akishima, Japan) to observe the microstructure of the samples. The operating voltage was set at 10 kV, with a beam (spot size 6) and an aperture of 3. The scanning electron microscope was used to observe the microstructure of the hydrated products in the samples.

3. Results and Discussion

3.1. Raw Material Composition, Heavy Metals Leaching Concentration and SEM Analysis

3.1.1. Raw Material Composition Analysis

The barium slag was analyzed by XRD and XRF testing. The XRD test results, as shown in Figure 2, indicate that the main phases are quartz and $BaSO_4$. The XRF test results, as presented in Table 1, show high contents of SiO_2, BaO, SO_3, Fe_2O_3, Na_2O, Al_2O_3, and CaO, with BaO content at 27.98%, which is consistent with the XRD results.

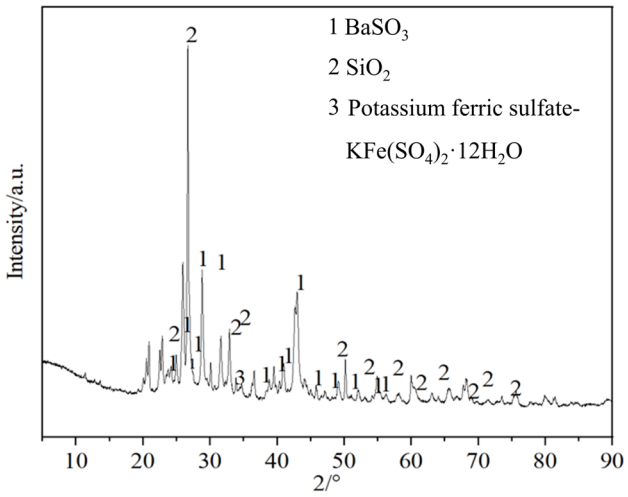


Figure 2. XRD analysis of the phase composition of barium slag raw material.

Table 1. The XRF Test Results.

BS	SiO_2	BaO	SO_3	Fe_2O_3	Na_2O	Al_2O_3	CaO	K_2O	MgO	MnO	TiO_2	P_2O_5
	Weight Ratio/%											
content	32.75	27.98	19.18	7.83	3.82	3.45	2.35	0.86	0.63	0.63	0.5	0.21

3.1.2. Raw Material Leaching Experiment Analysis

The barium slag raw material was subjected to heavy metal leaching tests, with the standard reference being the "Solid Waste—Extraction procedure for leaching toxicity Horizontal vibration method" HJ557-2010 [26]. The results are shown in Table 2. The leaching concentration of barium in the barium slag by the horizontal vibration method was 1,870,600 μg/L, which far exceeds the hazardous waste identification standard of 100,000 μg/L, and the pH of the leachate was 11.3. Therefore, there is a risk of heavy metal leaching from barium slag, whether it is stored or treated, and it is necessary to focus on the environmental pollution risk of heavy metal leaching of Ba and the high alkalinity.

Table 2. Heavy Metal Leaching Concentrations of Various Raw Materials (μg/L).

	Ba	Pb	Zn	Cr	Li
BS	1,870,600	ND	ND	ND	ND
Groundwater Class III	700	10	1000	50	-
Hazardous Waste Identification Standards	100,000	5000	100,000	1000	5000+

ND: Not detected.

3.1.3. Raw Material SEM Analysis

Figure 3 shows the scanning electron microscopy (SEM) results for the barium slag raw material, with panels a, b, c, and d. The surface of the barium slag is uneven, with small particles protruding, which preliminarily suggests that the barite has not reacted completely, retaining the general morphology of barite. This is not significantly different from the barite within the barium slag, further confirming the judgment that this is the product of incomplete reaction of barite. The surface of the barium slag is smooth and dense, without any obvious porous structures, leading to the conclusion that this area is the result of barite undergoing high-temperature calcination and melting. Naturally dried BS (barium slag) is an aggregate of gray/black fine particles. BS residue typically includes unreacted barite and byproducts such as coke, and accessory minerals associated with barite ore, such as clay minerals, calcium sulfate, etc.

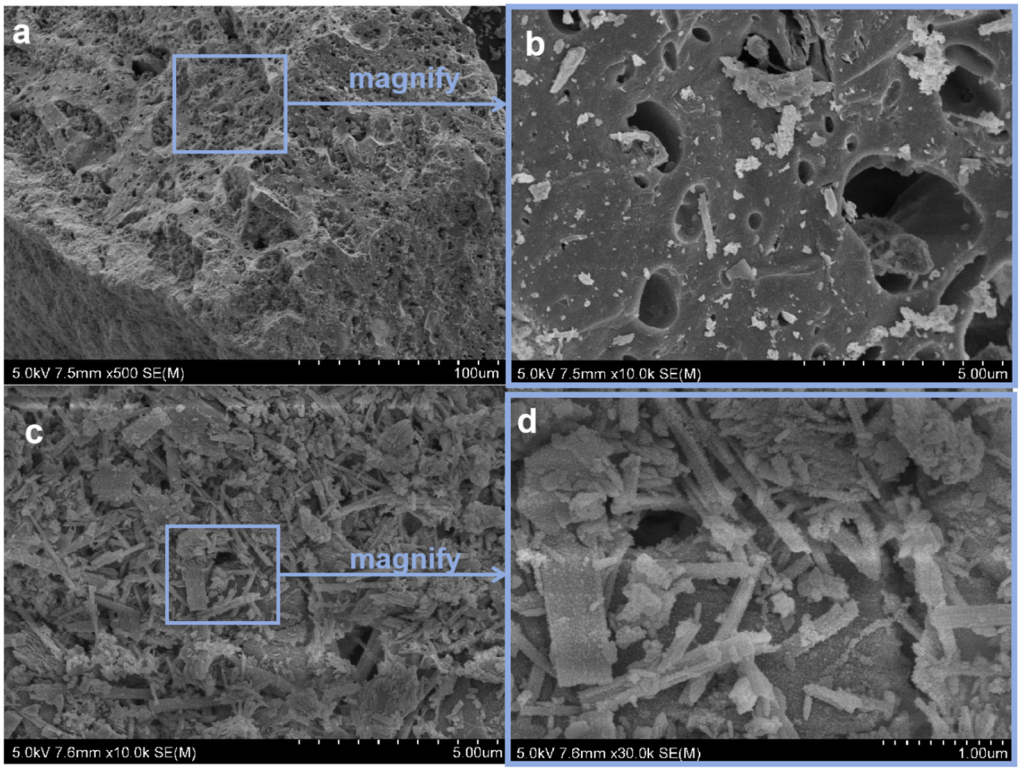


Figure 3. SEM results of the raw material: (**a**,**b**) are SEM images of barium slag, (**c**,**d**) are magnification of a and b, respectively.

3.2. Raw Material Particle Size Analysis

3.2.1. Simple Crushing and Reduction Treatment Analysis

The barium slag raw material was agglomerated, so a simple crushing and reduction treatment was performed on the raw material, followed by screening as shown in Figure 4. The results are shown in Table 3. It was later found that simple crushing treatment could

not fully restore the state of the barium slag, so the particle size analysis results are for reference only.



Figure 4. Sieve test of barium slag raw material.

Table 3. Sieve Test Results of Barium Slag Raw Materials.

Particle Size Grade	Yield/%
>4.75 mm	15.109
−2.36 mm + 4.75 mm	33.259
1.18 mm + 2.36 mm	18.904
−600 μm + 1.18 mm	18.193
−300 μm + 600 um	8.683
−150 mm + 300 um	3.86
−75 um + 150 um	1.562
<75 um	0

3.2.2. Wet Sieving Test Analysis

Take 1000 g of finely ground barium slag and select screens with mesh sizes of 45, 150, 200, 325, and 400 for wet sieving. The barium slag was ground using an SM-500 cement test mill (Experimental Instrument Co., Ltd., Dahong, China). Pour the finely ground barium slag into a bucket, thoroughly wet it in the bucket, mix evenly, and slowly pour it into the 45-mesh screen, allowing it to flow down with the water. Distribute the particles on the 45-mesh, 150-mesh, 200-mesh, 325-mesh, and 400-mesh screens, stirring until the water runs clear. Collect the material on each screen, drain, and dry it before weighing to calculate the yield and send samples for testing. The experiment is shown in Figures 5 and 6, and the yields and test results are shown in Table 4. The test results did not show a clear separation of barium, and the effect was not significant.

Table 4. Wet Sieving Test Results.

Particle Size Grade	Yield/%	BaO/%	Ba/%
−45 mesh	78.1	16.387	14.677
−150 mesh	11.25	31.808	28.489
200 mesh	2	24.223	21.695
325 mesh	1.73	29.979	26.851
400 mesh	0.49	33.533	30.034
400+ mesh	5.1	24.479	21.925
sum	98.67	-	-



Figure 5. Filtration by filter press.



Figure 6. Drying and preparation of test samples for submission.

3.2.3. Screening After Fully Restoring the Original State of Barium Slag

In order to fully restore the agglomerated barium slag raw material to its original state, the experiment first used a jaw crusher and a fine jaw crusher to crush the barium slag raw material, restoring its initial state. After crushing with a roller crusher, a sieve was used for screening, and sieve analysis was conducted on the ore sample. Standard sieves with mesh sizes of 0.05 mm and 1.18 mm were used. The fraction larger than 1.18 mm was subjected to cyclic crushing treatment until no more particles smaller than 1.18 mm could be produced. The fraction smaller than 1.18 mm was mixed evenly, and a portion was taken for further screening into fractions larger than 0.05 mm and smaller than 0.05 mm. The experimental preparation process is shown in Figures 7 and 8. The samples obtained from the sieve analysis at each particle size grade were assayed for barium grade, as shown in Table 5.



Figure 7. Crushing of barium slag.

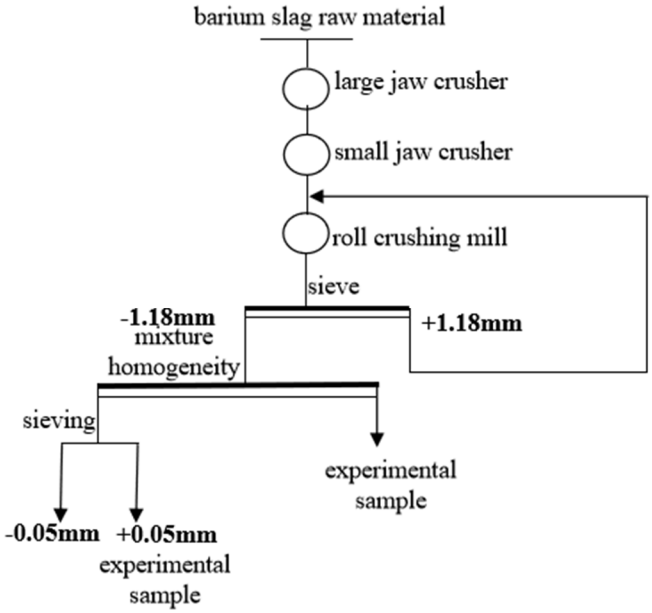


Figure 8. Preparation process of the ore sample used in the experiment.

Table 5. Yield and Barium Grade of Each Particle Size Fraction of the Ore Sample.

Particle Size Grade/mm	Yield/%	BaO%	Ba%
>1.18	1	8.83	7.91
−0.05 + 1.18	33	43.683	39.13
−0.05	66	44.64	39.98
sum	100	-	-

From Table 5, it can be observed that the barium grade of the +1.18 mm particle size fraction in the ore sample is relatively low, and it is possible to remove the fraction with a yield of 1% and a barium content of only 7.91% through screening.

3.3. Shaking Table Jigging Experiment and Analysis

The difficulty of mineral separation by gravity can be roughly assessed using the separation ratio, according to Equation (1):

$$\text{The separation ratio} = \frac{\delta_{1-\Delta}}{\delta_{2-\Delta}} \quad (1)$$

In Equation (1): δ_1 is the specific gravity of the lighter mineral; δ_2 is the specific gravity of the heavier mineral; Δ is the specific gravity of the separation medium. When e > 5, the ore is extremely easy to separate; when 5 > e > 2.5, the ore is easy to separate; when 2.5 > e > 1.75, the ore is relatively easy to separate; when 1.75 > e > 1.5, the ore is relatively difficult to separate; when 1.5 > e > 1.25, the ore is difficult to separate; when 1.25 > e, the ore is extremely difficult to separate. Since the density of barium salts in barium slag is much greater than that of other gangue minerals, with barium sulfate having a density of about 4.5 g/cm^3 and barium carbonate having a density of 4.43 g/cm^3, and the densities of quartz and dolomite being 2.65 g/cm^3 and 2.85 g/cm^3, respectively, the calculation using quartz and barium carbonate yields e = 1.81, which is considered easy to separate, so theoretically, gravity separation methods can be employed. Therefore, gravity separation is considered for the beneficiation of barium slag to recover barium resources.

Ming Jiangbo, in his study on the new process of comprehensive utilization of barium sulfate waste residue [27], proposed the use of jigging principles to recover un-reacted

barite and coal from barium slag. First, large chunks in the barium slag are screened out and mechanically crushed using mechanical devices such as ball mills and jaw crushers to grind or crush the under-burned large particles. This helps to destroy the structure of the particles, making further processing easier. Then, un-reacted barite and coal are separated out by jigging, and the remaining waste residue is treated with acid to recover high-purity barium sulfate. The main advantages of shaking table beneficiation are high-enrichment ratio, obtaining final concentrate and waste tailings after a single separation, sometimes obtaining multiple products simultaneously as needed, and clear mineral zoning on the table. Therefore, the shaking table is first used to explore the feasibility of heavy media separation for quartz purification. The particle size and density difference of the material are key factors affecting the shaking table separation. Exploration of different particle sizes on the shaking table is conducted, and the experimental process and results are shown in Figures 9 and 10.

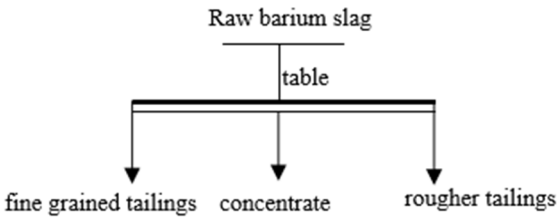


Figure 9. Flowchart and products of shaking table separation experiment.



Figure 10. Gravity separation experiment process.

Due to the agglomeration of the original ore, the experimental process as shown in Section 3.2.3 involves initially crushing the raw material into fractions of particle sizes less than 1.18 mm, less than 0.05 mm, and between 0.05 mm and 1.18 mm, which are then subjected to shaking table tests separately. During the preliminary processing stage, it is important not to grind the barium slag too finely; a certain particle size must be maintained.

3.3.1. Simple Crushing and Reduction Treatment Analysis Gravity Separation Experiment on Raw Materials Smaller than 0.05 mm

After the shaking table jigging experiment, the results are shown in Figure 11, which exhibits a clear band distribution. The detection results are shown in Table 6, with the highest barium content in the concentrate at 50.72%. The tailings are the next highest, and the middlings have the least content.



Figure 11. Results of the shaking table for materials smaller than 0.05 mm.

Table 6. Shaking Table Test Results for Materials Smaller Than 0.05 mm.

Product Name	Yield/%	BaO/%	SO_3/%	Sum	Ba/%
1	13.5	56.63	25.83	82.46	50.72
2	33.5	28.47	11.35	39.82	25.50
3	38.5	31.63	15.16	46.79	28.33
4	8.5	40.88	14.66	55.54	36.62

3.3.2. Gravity Separation Experiment on Raw Materials Smaller than 1.18 mm

After the shaking table jigging experiment, the results are shown in Figure 12, which do not exhibit a clear band distribution. The detection results are shown in Table 7, with the highest barium content in the concentrate at 42.46%. The tailings are the next highest, and the middlings have the least content.

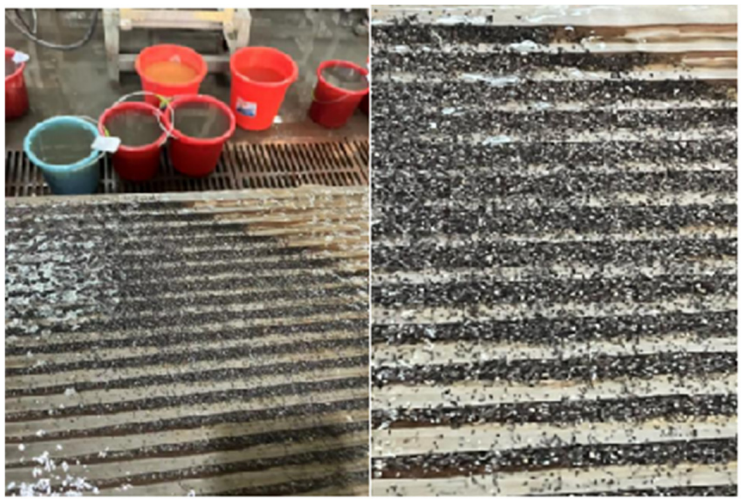


Figure 12. Results of the shaking table for materials smaller than 1.18 mm.

Table 7. Shaking Table Test Results for Materials Smaller Than 1.18 mm.

Product Name	Yield/%	BaO/%	SO_3/%	Sum	Ba/%
5	12	47.41	20.60	68.01	42.46
6	37.5	24.69	14.63	39.32	22.11
7	25	29.18	15.97	45.15	26.13
8	3	36.32	14.21	50.53	32.53
9	2	42.64	13.59	56.23	38.19

3.3.3. Gravity Separation Experiment on Raw Materials Larger Than 0.05 mm

After the shaking table jigging experiment, the results are shown in Figure 13, which do not show a clear band distribution. The detection results are presented in Table 8, with the highest barium content in the concentrate at 32.61%, the tailings being the next highest, and the middlings having the least content.



Figure 13. Shaking Table Results for Materials Larger Than 0.05 mm.

Table 8. Shaking Table Test Results for Materials Larger Than 0.05 mm.

Product Name	Yield/%	BaO/%	SO_3/%	Sum	Ba/%
10	29	36.61	3.28	39.89	32.61
11	33	20.30	7.91	28.21	18.18
12	39	13.67	13.78	27.45	12.24

3.3.4. Gravity Separation Experiment on Materials Ground from Larger Than 0.05 mm to Smaller Than 0.05 mm

The detection results indicate that the distribution of barium content in the concentrate, middle product, and tailings of materials larger than 0.05 mm is not significant, with the highest barium content in the concentrate being only 32.61%. The raw materials with particle sizes larger than 0.05 mm were ground using a planetary ball mill for 2 min and then sieved once, continuing this process until all particles were smaller than 0.05 mm in size, as shown in Figure 14. Compared with the materials that were not ground to less than 0.05 mm in size, as shown in Table 9, there was no overgrinding.



Figure 14. Grinding of barium slag with particle size larger than 0.05 mm using a planetary ball mill.

Table 9. Comparison of Particle Sizes Before and After Grinding to Less Than 0.05 mm.

Particle Size Range	Not Ground to Less than 0.05 mm/%	Ground to Less than 0.05 mm/%
<0.08 mm	32.17	17.35
>0.08 mm	67.68	82.92
sum	39	13.67

After the shaking table jigging experiment, the results are shown in Figure 15, which display a very clear band distribution. The detection results are presented in Table 10, with the highest barium content in the concentrate reaching 43.75%, the tailings being the next highest, and the middlings having the least content.



Figure 15. Shaking table results for materials ground to less than 0.05 mm.

Table 10. Shaking Table Test Results for Materials Ground to Less Than 0.05 mm.

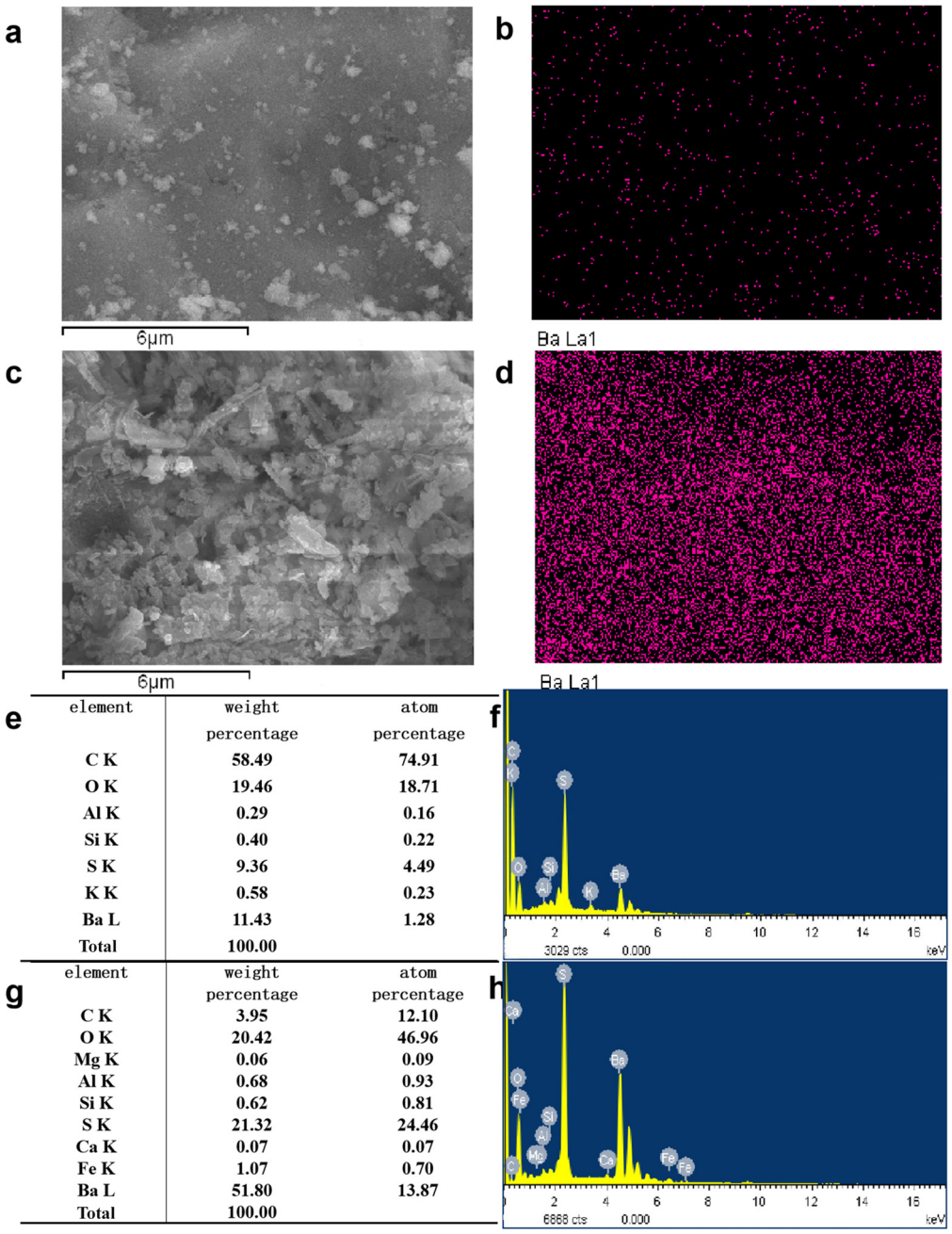
Product Name	Yield/%	BaO/%	SO_3/%	Sum	Ba/%
13	17.4	48.85	18.93	67.78	43.75
14	50.76	12.55	7.09	19.64	11.24
15	27.28	15.05	11.97	27.02	13.48
16	4.54	23.00	11.18	34.18	20.61

3.4. Mechanism Analysis

3.4.1. SEM&EDS Analysis

Figure 16a,b,e,f are the scanning electron microscope (SEM) surface scans of Ba distribution and elemental content ratio of the raw material, while Figure 16c,d,g,h are the

SEM surface scans of Ba distribution and elemental content ratio of sample 1, which has the highest Ba content after beneficiation. The distribution of Ba in the raw material is uniform but with a relatively low content (as shown in Figure 16a,b), and the surface scanning results e and f also confirm this. The distribution of Ba in sample 1 is more uniform with a significantly increased content (as shown in Figure 16c,d), and the surface scanning results are consistent with Figure 16g,h. Therefore, the shaking table jigging has a significant effect on the separation of Ba.



element	weight percentage	atom percentage
C K	58.49	74.91
O K	19.46	18.71
Al K	0.29	0.16
Si K	0.40	0.22
S K	9.36	4.49
K K	0.58	0.23
Ba L	11.43	1.28
Total	100.00	

element	weight percentage	atom percentage
C K	3.95	12.10
O K	20.42	46.96
Mg K	0.06	0.09
Al K	0.68	0.93
Si K	0.62	0.81
S K	21.32	24.46
Ca K	0.07	0.07
Fe K	1.07	0.70
Ba L	51.80	13.87
Total	100.00	

Figure 16. SEM and EDS results of raw material (**a**,**b**,**e**,**f**) and sample 1 (**c**,**d**,**g**,**h**).

3.4.2. Infrared Analysis

Figure 17 presents the infrared results for the barium slag raw material and samples 1, 5, and 10, which have barium content exceeding 40%. The absorption peak near 3400 cm^{-1} corresponds to the stretching vibration of O-H [26]; the absorption peak near 1100 cm^{-1} is associated with the stretching vibration of S-O in ettringite [26], with sample 1 showing the

highest peak and the greatest content, indicating the highest barium sulfate content; the absorption band near 1400 cm^{-1} may be a characteristic peak of CO_3^{2-} [28]; the absorption peak near 460 cm^{-1} corresponds to the bending vibration of Si-O, with the smallest peak in sample 1, which correlates with the lowest content of quartz.

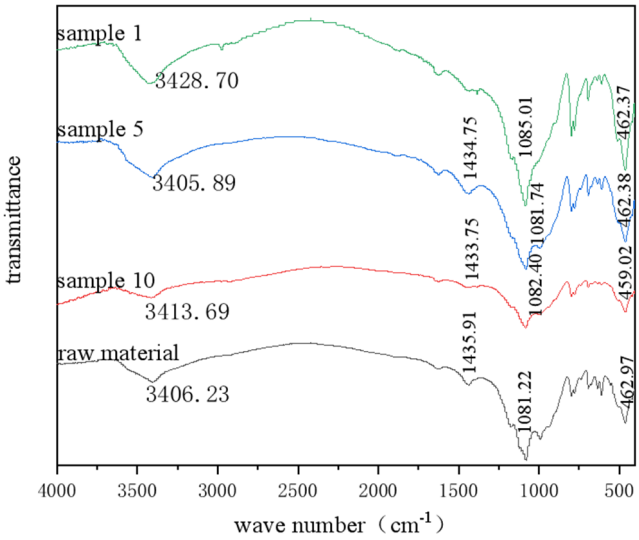


Figure 17. Infrared results of raw material and samples 1, 5, and 10.

3.4.3. The Chemical Composition of Barite Concentrate and Tailings

Table 11 indicated that the BaO content in the barium concentrate was relatively high, reaching 56.63%, and it also contained certain amounts of SO_3 and SiO_2, with proportions of 25.83% and 10.84%, respectively. In addition, the tailings mainly consisted of SiO_2, with a content of 49.34%, while BaO only accounted for 24.69%. This demonstrated that the barium slag could be purified through sorting, removing the impurity components, and isolating the barium concentrate.

Table 11. The XRF Test Results of Barite Concentrate and Tailings.

Types	BaO	SO_3	SiO_2	Fe_2O_3	Al_2O_3	CaO	TiO_2	Na_2O	SrO	MgO	P_2O_5	K_2O
	Weight Ratio/%											
Barite concentrate	56.63	25.83	10.84	2.45	1.87	0.79	0.60	0.46	0.14	0.13	0.10	0.08
Tailings	24.69	14.63	49.34	2.96	3.95	1.90	0.83	0.35	0.10	0.34	0.23	0.58

3.5. Significance and Limitations of the Study

The storage of barium slag occupies land resources and pollutes the surrounding environment, making its harmless disposal a current research hotspot. Barium slag contains a high content of soluble or insoluble barium compounds; therefore, existing studies have mainly focused on methods such as acid leaching, complexation dissolution, hydrometallurgy, ammonium chloride leaching, and chlorination roasting–water leaching. For example, studies have shown [12] that leaching barium slag with hydrochloric acid can dissolve more than 70% of the barium. However, acid leaching also leads to the dissolution of silicon, calcium, aluminum, and iron in the barium slag, which is unfavorable for subsequent solid–liquid separation. Relevant researchers [5] also used the organic chelating agent diethylenetriaminepentaacetic acid (DTPA) to enhance the solubility of barium slag and promote the synthesis of $BaSO_4$. This method effectively reduces acid

consumption; however, the use of organic reagents may pose environmental pollution concerns. Additionally, relevant studies have revealed that barium can be recovered through the chlorination roasting–water leaching method [29] and the ammonium chloride leaching method [30]. Although existing studies have made some progress in barium recovery, challenges such as the difficulty of impurity removal in barium slag, high cost and energy consumption, and environmental pollution still persist. This study is the first to recover barite from barium slag using the jigging process, obtaining a barite concentrate with a grade of 82.46%. The recovered barite concentrate contains over 50% barium sulfate. This concentrate is used to produce barium carbonate, thereby achieving resource recycling and reuse. It is worth noting that after sorting, the content of toxic substances such as soluble barium in the tailings is significantly reduced, making them more suitable for use as building materials and road construction materials. This method not only improves the utilization rate of barium slag and the recovery rate of barium elements but also reduces the environmental impact of barium slag. It provides theoretical support for the resource utilization of barium slag.

However, further research on the resource utilization of the subsequent tailings is needed, with a focus on clarifying the performance and mechanisms of the final products, in order to align with the principles of green and circular development.

4. Conclusions

The content of barite in barium slag is mostly around 20%, especially for the partially unreacted and larger particles of barite, as well as the partially sintered symbiotic bodies, where the content can reach over 30%. By employing a jigging process to reuse the incompletely reacted barite, the recovery rate of the barite component, barium sulfate, in sample 1 can reach up to 82.46% or higher.

The process pioneers the delamination of sintered ore and symbiotic bodies from waste slag generated in the production of barium sulfate. It utilizes the differences in densities of various components to sort the waste slag and employs a jigging process, a physical method, to recover the incompletely reacted barite for reuse. The recovered barite component, barium sulfate, can have a content of over 50%. The residual slag undergoes harmless treatment, and high-purity barium sulfate is chemically recovered. The method for processing the unburnt large particles or incompletely reacted sintered symbiotic bodies in the remaining waste slag may depend on specific experimental conditions and sample properties. This approach not only enhances the utilization rate of resources but also contributes to environmental protection by reducing the environmental impact of waste slag.

Therefore, the pretreatment of barium slag by shaking table beneficiation experiments can separate and sort out barium compounds, obtaining a barite concentrate with a grade of 82.46%, which is a significant improvement in the index. This concentrate can be used locally for the production of barium carbonate, allowing for the recycling and reuse of resources. At the same time, the soluble barium and other toxic substances in the tailings after beneficiation are essentially removed, making the tailings more suitable for use as building materials and road construction materials.

Author Contributions: Conceptualization, Y.W. and B.Z.; Methodology, S.Z.; Software, G.L.; Validation, W.N., S.Z., and Y.W.; Formal analysis, X.Y.; Investigation, S.Z.; Resources, W.N.; Data curation, X.Y.; Writing—original draft preparation, Y.W.; Writing—review and editing, X.S.; Visualization, S.Z.; Supervision, G.L.; Project administration, X.S.; Funding acquisition, S.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Guizhou Provincal Science and Technology Project (Qianke Hezhong Yindi (2025) 011).

Data Availability Statement: Data available on request due to restrictions privacy. The data presented in this study are derived from a confidential project and can be obtained at the request of the corresponding author.

Conflicts of Interest: Authors Yang Wan, Bo Zhang and Xing Yang were employed by the company Guizhou Redstar Developing Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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