

Article

# Beneficiation and Purification of Tungsten and Cassiterite Minerals Using Pb–BHA Complexes Flotation and Centrifugal Separation

Tong Yue, Haisheng Han \*, Yuehua Hu, Zhao Wei, Jianjun Wang, Li Wang, Wei Sun \*, Yue Yang , Lei Sun, Ruohua Liu and Khoso Sultan Ahmed

School of Mineral Processing and Bioengineering, Key Laboratory of Hunan Province for Clean and Efficient Utilization of Strategic Calcium-Containing Mineral Resources, Central South University, Changsha 410083, China; yuetong@csu.edu.cn (T.Y.); hyh@csu.edu.cn (Y.H.); weizhao@csu.edu.cn (Z.W.); wangjianjuncsu@126.com (J.W.); li\_wang@csu.edu.cn (L.W.); eric1911@126.com (Y.Y.); sunlei@csu.edu.cn (L.S.); ruohualiu@csu.edu.cn (R.L.); sultan.khoso@faculty.muett.edu.pk (K.S.A.)

\* Correspondence: hanhai5086@csu.edu.cn (H.H.); sunmenghu@csu.edu.cn (W.S.);  
Tel: +86-0731-8883-0482 (H.H. & W.S.)

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**Abstract:** Pb–BHA complexes have been shown to be selective for the separation of tungsten and cassiterite minerals from calcium minerals. These minerals could be enriched synchronously to some extent using Pb–BHA complexes flotation. However, it is difficult to further improve the quality and recovery of the scheelite, wolframite, and cassiterite concentrate due to their different behavior in flotation, such as flotation rate and sensitivities to depressants. Moreover, the super fine particles create some challenges for the cleaning flotation process. In this study, advanced gravity separators for super fine particles were introduced for the cleaning process based on the slight difference in the specific gravity of scheelite, wolframite, and cassiterite. The new process featured pre-enrichment using Pb–BHA flotation, and upgrading using gravity separation, taking into account both the similarities and differences in floatability and density of the different minerals. The grades of  $WO_3$  and Sn in the concentrate of the new process reached to 61% and 2.89%, respectively, and the recovery of Sn was significantly improved. In addition, gravity separation is highly efficient, cost effective, and chemical-free, which is environmentally friendly. This study has proven that physical separation can be used for the purification of flotation products and provide some solutions for separation problems of complex refractory ores, which has, up until now, been rarely reported in the literature and/or applied in mineral processing.

**Keywords:** tungsten minerals; cassiterite; flotation; gravity separation; Pb–BHA complexes

## 1. Introduction

Tungsten, which is a hard, refractory, and rare metal, is important in many commercial and industrial applications. For example, key alloys of tungsten are widely used in the production of incandescent light bulb filaments, X-ray tubes, electrodes in welding, radiation shielding, and superalloys. Tungsten's high strength, hardness, and density make it ideal for military applications in penetrating projectiles. Tungsten compounds are also often used as catalysts in many industrial processes, including dehydrogenation, isomerization, polymerization hydrocracking in the chemical industry, hydrodesulfuration and hydrodenitrification of mineral oil products, and removal of nitrogen oxides from combustion power plant stack gases by selective catalytic reduction with ammonia. Tungsten naturally occurs in the earth crust exclusively combined with other elements in chemical compounds as minerals, and is usually extracted from those minerals. Wolframite ((Fe,Mn)WO<sub>4</sub>)

and scheelite ( $\text{CaWO}_4$ ) are the main ore minerals of tungsten deposits that occur in sufficient abundance to be of economic significance. Those tungsten ores are generally subjected to physical beneficiation techniques such as gravity, flotation, magnetic and electrostatic separation. In particular, to extract tungsten from fine mineral particles, especially for mineral particles with a size of less than 10 to 20 microns, flotation methods using fine air bubbles are often adopted, as flotation is a surface-chemistry based process that takes advantage of the different wettability on mineral particle surfaces [1–4]. Research regarding floatability and reagents has gained great progress over the past 20 years.

However, with the exploitation and consumption of tungsten deposits of high quality, the need of low-grade complex ores is increased. Those low-grade tungsten deposits are usually in finely disseminated form with a complicated composition, containing high calcium gangue minerals and multi valuable minerals, which create many challenges for tungsten extraction. Firstly, separation of scheelite from other calcium-bearing minerals by flotation is challenging due to their very similar surface properties [5–8]. Most attempts have only achieved limited success or specific application (related to the type or the location of the ore). In addition, some fine cassiterite minerals occur in nature in association with tungsten minerals, while neither recovering cassiterite from the flotation tailings of tungsten minerals, nor the synchronous extraction of them, are practicable because of the great differences between tungsten minerals and cassiterite. Our previous studies [9,10] indicated that Pb–BHA complexes had good selectivity for the separation of scheelite from calcium minerals by regulating the Pb/BHA ratio and pH value with the recovery of tungsten minerals being significantly improved. Tian et al. [11] proved that cassiterite can be separated efficiently from cassiterite–calcite binary mixed minerals by using Pb–BHA complexes as the collector, and carboxymethyl cellulose as the depressant. Therefore, it can be speculated that tungsten minerals and cassiterite minerals could be enriched together by Pb–BHA complexes, which will significantly improve the recovery of fine tungsten and cassiterite minerals. However, problems appear when it comes to the purification of tungsten and cassiterite minerals, as they possess different surface wettability and flotation rates. Also, the depressants used for gangue minerals depression, such as organic colloids (dextrine, starch), quebracho tannin, sodium phosphates, sodium silicate solutions containing polyvalent cations (hydrosols), etc. [7,12–14], depress tungsten minerals and cassiterite recovery to some extent. However, it is hard to gain good further separation of the tungsten and cassiterite minerals by flotation with multiple attempts. Therefore, new cleaning processes to further improve the concentrate grade and recovery of the tungsten minerals is needed.

Gravity separation [15,16] has been proven to have several advantages over the other mineral processing techniques due to its excellent properties such as high efficiency, low capital and operating costs, no additional chemicals, and consequently no environmental concerns. The extensive use of gravity circuits, and the need to recover super fine particles, have led to the development of specific devices to recover particles which are too fine to be recovered efficiently using conventional spirals etc. Some enhanced gravity concentrators are designed for gravity separation at fine particle size ranges, such as the hang and vibrate of cone concentrator (a Multi-Gravity Separator) [17] and Falcon concentrator [18]. They are very selective for separation of fine-sized particles (typically  $-75$  to  $10\ \mu\text{m}$ ) and have very high upgrading ratios (typically 20 to 1  $\mu\text{m}$ ). These gravity separators introduce centrifugal force, fluid force, shear force, and so on, except for the gravity, which provide possibilities for improving the cleaning process of the fine rougher concentrates.

In this study, floatability of scheelite, wolframite, and cassiterite using Pb–BHA complexes and Al– $\text{SiO}_3$  complexes were well studied. The mineral composition and size distribution of the raw ore and rougher concentrates were analyzed to account for the low indexes of the twice cleaning flotation. Both Falcon Concentrator and the hang and vibrate of cone concentrator were used for the upgrading of the rougher concentrate to evaluate the feasibility of the cleaning process using gravity separation. A novel process was developed to further improve the recovery and quality of the concentrate.

## 2. Materials and Methods

### 2.1. Materials

High-purity wolframite, and scheelite samples were obtained from Shizhuyuan Mine, Hunan, China. Pure cassiterite samples were obtained from Yunnan Province in China. X-ray diffraction (XRD) and X-ray fluorescence (XRF) data confirmed that the purity of the samples was higher than 97%. The fine size fraction of the samples (less than 74  $\mu\text{m}$ ) was used for the flotation experiments. Analytical grade BHA, lead nitrate, and terpineol (frother) were purchased from Guangfu, Tianjin, China. Deionized water was used throughout the flotation experiment.

Table 1 is the particle analysis of the raw ore, showing that most of the tungsten and cassiterite mineral particles fell into the fine particle size range. Specially, most of the valuable minerals distribute in  $-0.074$  mm fraction, and super fine particles ( $-0.019$  mm) account for more than 30%.

**Table 1.** Particle analysis of the raw ores.

Particle Size/mm	Yield (%)	Grade (%)			Distribution (%)		
	Individual	WO <sub>3</sub>	Sn	CaCO <sub>3</sub>	WO <sub>3</sub>	Sn	CaCO <sub>3</sub>
+0.074	23.68	0.27	0.08	12.80	17.98	12.90	25.82
$-0.074\sim+0.037$	18.54	0.31	0.11	13.41	16.17	13.89	21.18
$-0.037\sim+0.019$	27.76	0.40	0.16	11.58	31.23	30.26	27.38
$-0.019$	30.02	0.41	0.21	10.11	34.62	42.94	25.85
Total	100	0.36	0.15	11.74	100.00	100.00	100.00

### 2.2. Flotation Tests of Pure Minerals

Pure minerals flotation tests were carried out in an XFG flotation machine with a 40 mL plexiglass cell. The procedure of the flotation experiments has been described in our previous work [10]. In brief, 2.0 g of pure minerals, including scheelite, wolframite, cassiterite, fluorite, and calcite, was dispersed into 30 mL DI water at an impeller speed of 1900 rpm. This was followed by the adjustment of the pH of the suspensions in the range of 3 to 12 using 0.1 mol/L HCl or NaOH solutions. After adding the Pb–BHA complexes, which was prepared by mixing the PbNO<sub>3</sub> and BHA solutions with the molar ratio 5:3 (the concentration of Pb<sup>2+</sup> was  $2.5 \times 10^{-4}$  mol/L and the concentration of BHA was  $1.5 \times 10^{-4}$  mol/L), as the collector and 12.5  $\mu\text{L/L}$  of terpineol as the frother, the suspensions were homogenized for 3 min. The foams were collected for 3 min and then filtered and dried at 60 °C for 12 h. In the kinetic flotation, the collected time ranged from 0 to 300 s and the pH of the suspension was maintained at 9.5.

### 2.3. Gravity Separation

A Falcon centrifugal concentrator (Model SB40) and hang and vibrate of cone concentrator were used to upgrade the rougher concentrates of scheelite, wolframite, and cassiterite. The optimum parameters for the gravity separation are obtained by single factor experiments, which are listed in Table 2.

**Table 2.** The optimized parameters for the gravity separators.

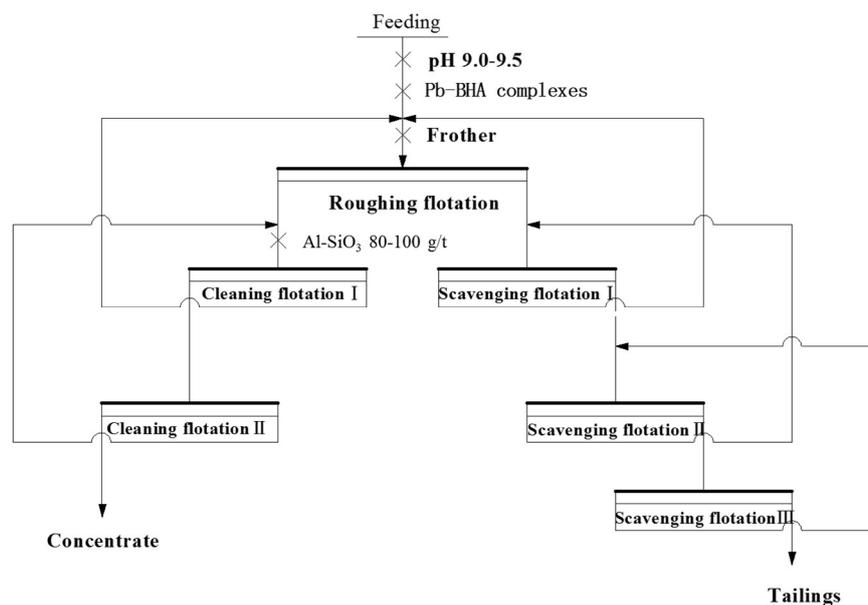
Gravity Separator	Parameters		
Falcon centrifugal concentrator	Feeding slurry concentration (%)	Rotation bowl speed (rpm)	Fluidized water flow rate (L/min)
	32	800	5.0
Hang-vibrate of cone concentrator	Feeding slurry concentration (%)	Rotation speed of drum (rpm)	Vibrational frequency (HZ)
	32	2.0	32

For Falcon centrifugal concentrator [15,18], fluidization water was introduced into the bowl (concentrate cone) through a series of fluidization holes at the top of its wall. The feed slurry was then introduced through the stationary feed tube at the bowl center and into the concentrate cone. When the slurry reached the bottom of the cone, it was forced outward and up the cone wall under the influence of the centrifugal force. During the separation process, tailings flowed out the top of the cone into the tailings launder. After the separation was finished, the concentrates were flushed from the cone into the concentrate launder. The tailing and concentrate were settled, collected, dried, weighed, and chemically analyzed.

Hang and vibrate of cone concentrator is a multi-gravity separator, which combines the centrifugal motion of an angled rotating drum (though not at such a high speed) of a Kelsey jig or Falcon Concentrator, with the oscillating motion of a shaking table, to provide an enhanced gravity separation, particularly suitable for fine particles separation. The principle of the separation is based upon the above-mentioned forces that act on the particles in a slurry stream being fed and are distributed onto the inside of the drum's surface. With the aid of the scrapers and wash water, the light fine particles migrated up the drum to discharge over the drum's top lip, while the heavy large particles flowed slowly and moved to the concentrate launder with the rotation of the drum.

#### 2.4. Pilot Scale Tests

The real ore flotation tests were performed in the dressing plant of Shizhuyuan Mine Group. During the pilot scale tests, 200 tons of real ore was treated per day. The mixed solution of BHA (400 g/t) and  $\text{PbNO}_3$  (500 g/t) was used as the collector, and terpeneol (10 g/t) was used as the frother. The flotation flowsheet was shown in Figure 1.



**Figure 1.** Flotation flowsheet of tungsten minerals using Pb-BHA complexes in Shizhuyuan dressing plant.

#### 2.5. Analytical Techniques

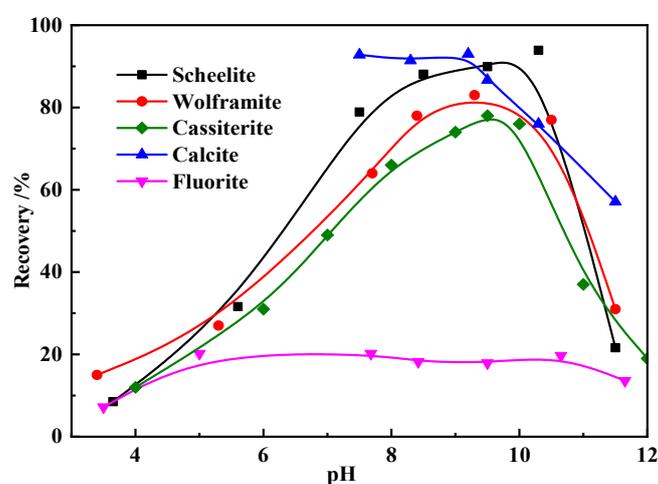
XRD (SIMENS D500, Bruker, Switzerland) analysis WAS used for semi-quantitative characterization of different crystalline phases. The composition of the samples was analyzed using XRF (AxiosmAX, Panalytical B.V., Almelo, The Netherlands) and AAS (ICE 3500, Thermo Fisher Scientific, Waltham, MA, USA). A laser particle size analyzer (Malvern Instruments Ltd., Malvern, UK) was used for particle size measurement of the raw ore and rougher concentrate.

### 3. Results and Discussions

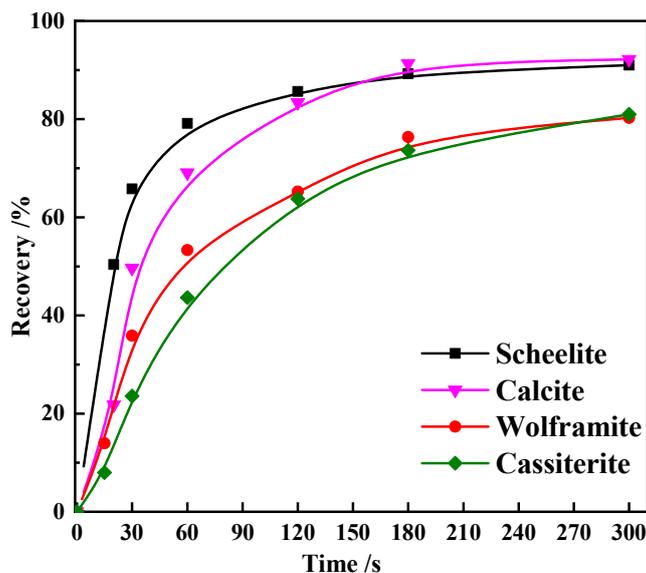
#### 3.1. Flotation Tests in Lab

Figure 2 shows the difference of floatability among scheelite, wolframite, cassiterite, calcite, and fluorite versus pH. The results indicate that scheelite, wolframite, cassiterite, and calcite could be well collected by Pb–BHA complexes and the former three minerals show a synchronous flotation behavior with pH change, while fluorite does not. Our previous work indicated that the colloidal Pb–BHA particles were positively charged in weakly alkaline conditions, while the surface potentials of scheelite, wolframite, and cassiterite were negative [18]. Therefore, the Pb–BHA complexes could be adsorbed on the mineral surfaces by electrostatic force, leading to the similar variation trend in the recovery of scheelite, wolframite, and cassiterite minerals with increasing the pH of the flotation system. In fact, the floatability of scheelite, wolframite, cassiterite, and calcite were different from each other. The recovery of scheelite was much higher than that of wolframite and cassiterite, and the effective pH range was also larger. Scheelite, wolframite, and cassiterite could be collected concurrently using Pb–BHA complexes at pH 9 to 10. The synchronous collecting of those minerals enhanced the recovery of tungsten minerals and cassiterite from a polymetallic deposit, such as the Shizhuyuan Mine. At this condition, the calcite was also, inevitably, collected to some extent, creating some difficulties for the upgrading of the concentrate. Figure 3 shows the difference in the flotation rate of scheelite, calcite, wolframite, and cassiterite using Pb–BHA complexes. The flotation rate of wolframite and cassiterite were lower than that of scheelite. It was difficult to get the maximum recovery and best grade of different minerals by flotation simultaneously.

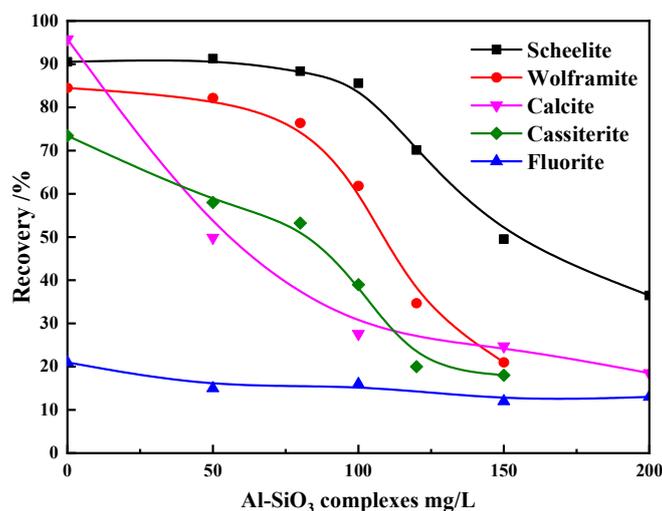
Depressants for calcite have been widely reported in previous studies [12,18–20], and aluminum silicate solutions ( $\text{Al-SiO}_3$ ) have been proven to be effective for scheelite flotation with Pb–BHA complexes as the collector [9,21,22].  $\text{Al-SiO}_3$  was used as the depressant for the upgrading of the rougher concentrate in this research. The effect of  $\text{Al-SiO}_3$  complexes on floatability of scheelite, wolframite, cassiterite, and calcite is shown in Figure 4. It can be seen that the recovery of all the minerals was depressed at different degrees, especially at high  $\text{Al-SiO}_3$  dosage. Obviously,  $\text{Al-SiO}_3$  was not suitable to improve the upgrading of the concentrate. The inhibition effect of the depressant on upgrading is a common issue in flotation. As is well known, floatability of the minerals greatly depends on the surface properties of the minerals, such as the crystal anisotropy, which can be greatly influenced by the depressant [23–26]. Take scheelite as an example; the wettability of the (001) plane of scheelite decreased slightly, whilst increasing the dosage of  $\text{Al-SiO}_3$ , while the wettability of the (112) plane decreased significantly. If the (112) plane are the main scheelite cleavage planes, the recovery of scheelite will be significantly affected by the use of  $\text{Al-SiO}_3$  in flotation [9].



**Figure 2.** The floatability of scheelite, wolframite, cassiterite, fluorite, and calcite minerals with Pb–BHA complexes as the collector ( $C_{\text{BHA}} = 1.5 \times 10^{-4}$  mol/L,  $C_{\text{Pb}} = 2.5 \times 10^{-4}$  mol/L,  $C_{\text{terpineol}} = 12.5$   $\mu\text{L/L}$ ).



**Figure 3.** Difference in the flotation rate of scheelite, calcite, wolframite, and cassiterite using Pb–BHA complexes ( $C_{\text{BHA}} = 1.5 \times 10^{-4}$  mol/L, and  $C_{\text{Pb}} = 2.5 \times 10^{-4}$  mol/L, pH = 9.5).



**Figure 4.** Effects of Al-SiO<sub>3</sub> complexes on the flotation of different minerals using Pb–BHA complexes as the collector ( $C_{\text{BHA}} = 1.5 \times 10^{-4}$  mol/L, and  $C_{\text{Pb}} = 2.5 \times 10^{-4}$  mol/L, pH = 9.5).

### 3.2. Flotation in Pilot Scale Tests

Table 3 shows the flotation process and the recovery of scheelite, wolframite, and cassiterite in different flotation units of the Figure 1, respectively. Scheelite, wolframite, and cassiterite can be well collected in the roughing flotation with the recovery rate at 81.81%, 78.48%, and 68.86%. The recovery rate decreased significantly in the cleaning flotation due to the use of depressants, especially for wolframite and cassiterite, which is consistent with the previous results. The cassiterite recovery of cleaning flotation I and II were only 71.34% and 58.82%. No improvement was found for the grade of the cassiterite, indicating that most of the cassiterite minerals were depressed in the cleaning process. Overall, synchronous flotation of tungsten minerals and cassiterite seems to be not efficient in the cleaning process.

**Table 3.** Grade and recovery of scheelite, wolframite, and cassiterite in different flotation units.

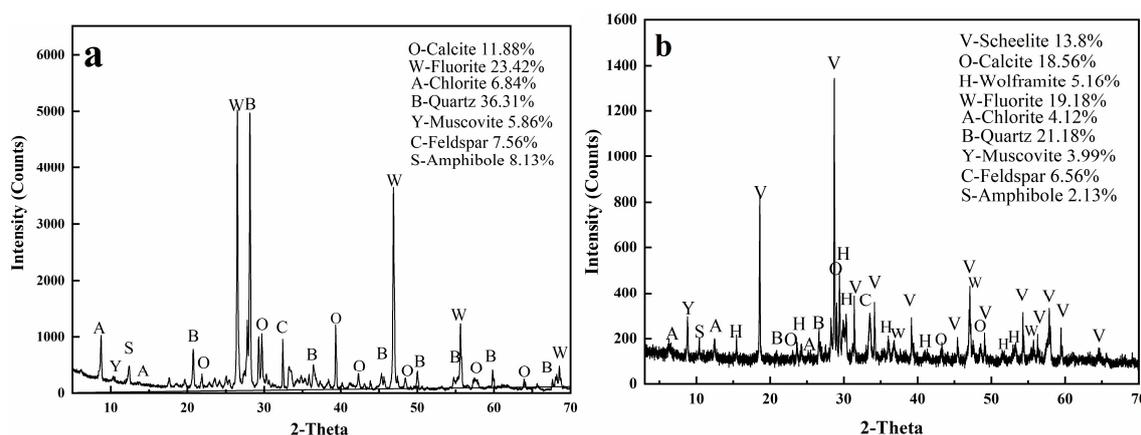
	Grade in each Flotation Unit/%			Recovery in Each Flotation Unit/%		
	Scheelite	Wolframite	Cassiterite	Scheelite	Wolframite	Cassiterite
Roughing flotation	12.12	6.18	0.56	81.81	78.48	68.86
Cleaning flotation I	32.86	13.83	1.24	91.23	86.38	71.34
Cleaning flotation II	41.20	16.86	1.02	88.69	81.76	58.82
Scavenging flotation I	0.43	0.31	0.27	37.66	41.38	45.22
Scavenging flotation II	0.11	0.12	0.19	27.72	32.16	39.34
Scavenging flotation III	0.08	0.10	0.11	12.5	16.44	18.98

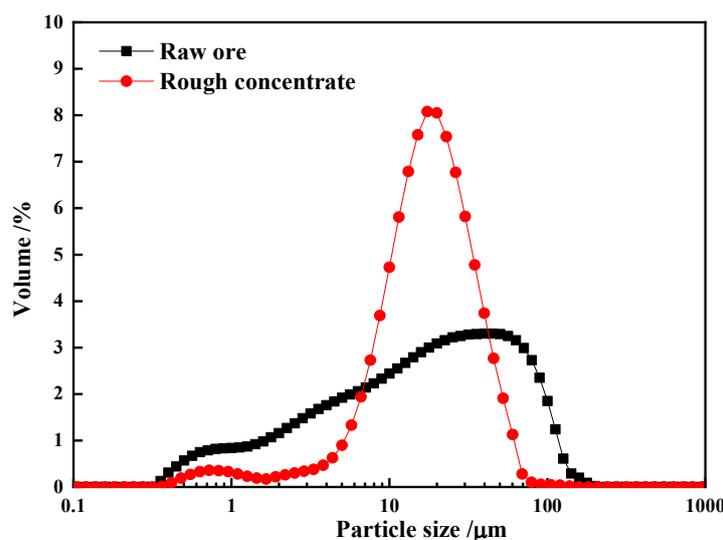
### 3.3. Mineral Composition and Characters of the Rougher Concentrate

Table 4 and Figure 5 show the mineral composition and phases of the rougher concentrate. Most of the scheelite, wolframite, and cassiterite minerals were recovered with a high enrichment ratio in the roughing flotation. The selectivity of Pb–BHA complexes on calcium minerals was confirmed by the lower enrichment efficiency of calcite and fluorite. Quartz, the main gangue mineral in the rougher concentrate, was not a concern here as it can be separated easily. XRD results show that quartz, chlorite, muscovite, feldspar, and amphibole also exist in the rougher concentrate, which could be due to the entrainment of super fine particles in the foam. The existence of those minerals made it easier for the grinding process to get muddy because of their lower hardness [27–29], posing great challenges for the separation of them from the valuable minerals by flotation. As shown in Figure 6,  $D_{50}$  of the rougher concentrate was 0.021 mm, which falls into the fine particle size range, causing problems for further improvement of the concentrate quality.

**Table 4.** Multi-elementary analysis results of the rougher concentrate/%.

Elements	WO <sub>3</sub>	Sn	Fe	Mn	Ti	Zn	Zr	Pb
Content (%)	10.58	0.54	7.94	0.99	0.39	0.18	0.02	0.17
Elements	Mo	Ca(CaF <sub>2</sub> )	Ca(CaCO <sub>3</sub> )	SiO <sub>2</sub>	Bi	As	Cr	Else
Content (%)	0.13	14.68	18.54	29.27	0.09	0.05	0.04	16.39

**Figure 5.** X-ray diffraction (XRD) analysis of the raw ores (a) and the rougher concentrate (b).



**Figure 6.** The particle size distribution of the raw ores and the rougher concentrate.

### 3.4. Flotation and Gravity Separation Combination in Pilot Scale Tests

Roughing flotation using Pb–BHA complexes has been proven to be effective in the recovery of scheelite, wolframite, and cassiterite minerals, which takes full advantage of their similar floatability. It should be noted that scheelite, wolframite, and cassiterite are heavy minerals with a density of 6.1, 7.2 to 7.5, and 6.8 to 7.1 g/cm<sup>3</sup>, respectively, which are much heavier than that of most gangue minerals, such as quartz, calcite, and fluorite. With great progress in new gravity separation equipment development over the last 20 years, gravity separation is always a preferred technique [15,30]. Some advanced gravity concentrators have been developed for the gravity separation of fine mineral particles. The combination of flotation and gravity separation, which depends on the surface chemical and physical properties of the minerals, is considered to be effective in further improving the recovery of the minerals.

Flotation and gravity separation using falcon concentrator or hang and vibrate of cone concentrator were conducted for the cleaning process. It can be seen in Table 5 that cleaning process using flotation shows the highest recovery of tungsten minerals, while the grade of the concentrate was about 55%, which was lower than that of gravity separation. The recovery of cassiterite was only at 29.18% by flotation, indicating a great loss of cassiterite in the tailings. Gravity separation, especially when using hang and vibrate of cone concentrator, was found to be effective for the recovery of both tungsten minerals and cassiterite, with the quality of the concentrate significantly improved.

**Table 5.** Results of cleaning process using flotation and gravity separation by Falcon concentrator or hang and vibrate of cone concentrator.

	Product	Yield	WO <sub>3</sub>		CaCO <sub>3</sub>		CaF <sub>2</sub>		Sn	
			Grade	Recovery	Grade	Recovery	Grade	Recovery	Grade	Recovery
Flotation	Concentrate	16.18	55.64	87.83	1.98	1.79	6.99	8.63	1.01	29.18
	Tailing	83.82	1.49	12.17	20.99	98.21	14.28	91.37	0.47	70.82
		100.00	10.25	100.00	17.91	100.00	13.10	100.00	0.56	100.00
Falcon Concentrator	Concentrate	12.86	60.88	76.38	0.91	0.65	5.82	5.71	2.62	60.17
	Tailing	87.14	2.78	23.62	20.42	99.35	14.17	94.29	0.26	39.83
		100.00	10.25	100.00	17.91	100.00	13.10	100.00	0.56	100.00
Hang-vibrate of cone concentrator	Concentrate	13.92	61.35	83.15	0.87	0.68	4.81	5.13	2.89	74.50
	Tailing	86.08	2.01	16.85	20.70	99.32	14.38	94.87	0.16	25.50
		100.00	10.27	100.00	17.94	100.00	13.05	100.00	0.54	100.00

It should be noted that gravity separation was not shown to be efficient for the separation of ultrafine particles with a size of less than 10 μm. As shown in Table 5, the recovery of WO<sub>3</sub> in the gravity separations was lower than that of the cleaning flotation. As a result of that, the collecting ability of gravity separations for the ultrafine mineral particles (<10 μm) was worse than

that of flotation. Although, the optimum particle size in flotation ranges from 10 to 100  $\mu\text{m}$  [31,32]. Ultrafine particles tend to be caught in streamlines created by the rising bubbles instead of attachment with the bubbles. This problem would be solved if some coarse particles could serve as the carrier for the fine particles (defined as carrier flotation) or the fine particles could aggregate with each other to form a larger particle, (defined as flocculation flotation). It has been reported that hydrophobic fine particles could aggregate with each other or a large particle to form larger particles, thereby improving the flotation recovery [33]. The mechanisms of shear-flocculation and carrier flotation are governed by physical, chemical, and geometrical variables, which have been investigated comprehensively in Subrahmanyam's review paper [34]. After research for almost three decades, it has been widely accepted that carrier flotation and shear-flocculation can be used for pre-treatment of fine particles in flotation. Numerous studies have reported improvements in the recovery of fine particles by using this technique, with the recovery rate increased from 20% to 50% compared to the conventional flotation. Feeding the tailings of gravity separation and fine particles to the roughing flotation for a further recovery is thus proposed. The effect of the stirring rate on the shear flocculation was studied in the lab and the results are shown in Figure 7. Initially, the recovery of tungsten minerals increased significantly when increasing of the stirring rate. Where a downward trend, followed by optimum tungsten minerals recovery was observed, this was more noticeable for coarse particles. Aggregation of fine particles promotes the flotation of the gravity tailings, with the optimum recovery is said to be around 78%. When the gravity tailings were fed back to the raw ores containing coarse particles, the recovery was improved dramatically. Both carrier flotation and flocculation flotation contributed to the recovery of fine particles. Moreover, the increased tungsten recovery with the increased stirring may also result from increased probability of collision between fine particles and bubbles and the increased entrainment. As shown in Figure 7, the improved concentrate grade with the increasing of the stirring indicates that it is not due to the increased entrainment but from carrier flotation, flocculation flotation and increased ore collision between bubbles and particles. However, the decreasing of the grade may from an increasing entrainment.

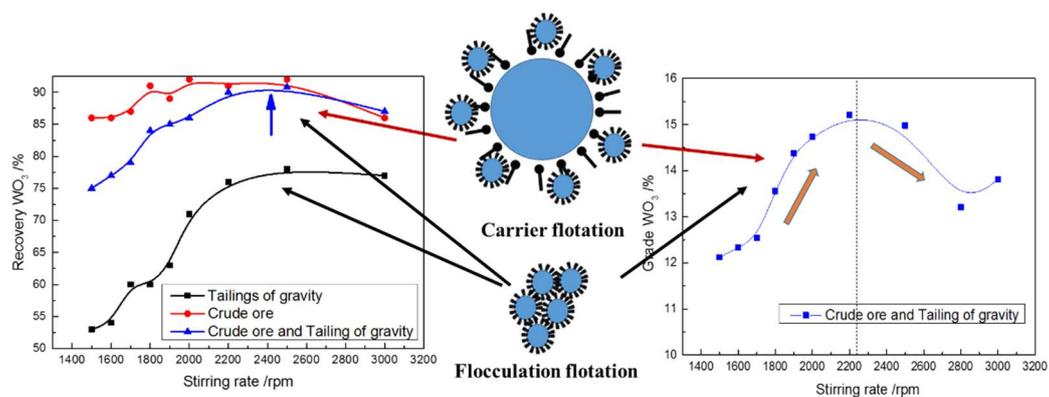
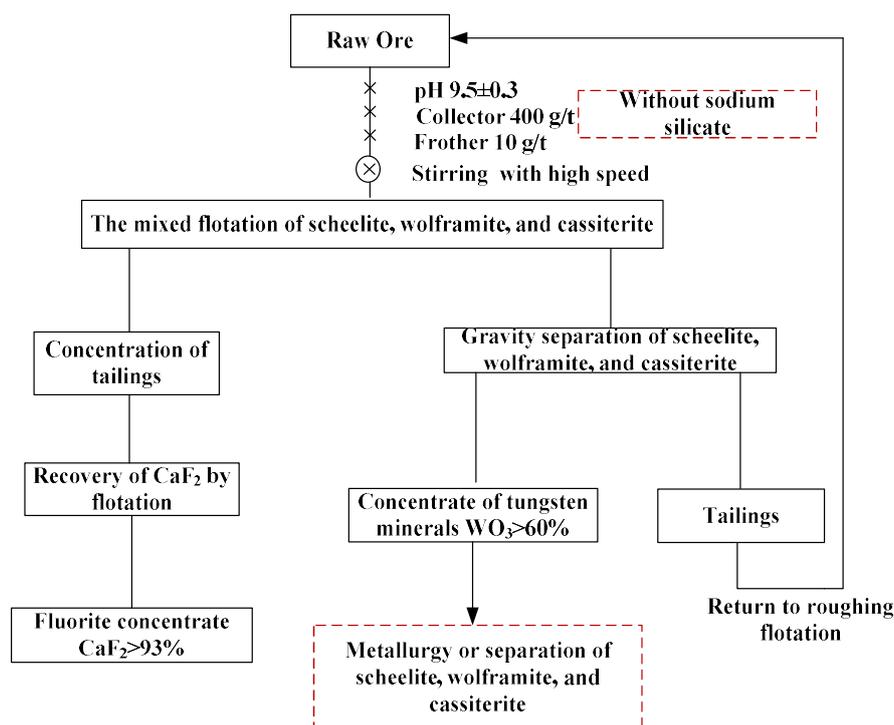


Figure 7. Flocculation and carrier flotation of fine particles.

A new closed-circuit process, pre-enrichment using flotation with Pb-BHA complexes, upgrading using gravity separation and feeding the tailing of gravity separation back to rougher flotation, was developed to further improve the recovery and grade of tungsten minerals and cassiterite. A pilot-scale experiment was conducted with Figure 8 illustrating the flotation process. Table 5 shows that a concentrate with 61%  $\text{WO}_3$  and 2.89% Sn can be obtained, and the recovery of cassiterite was significantly improved. This concentrate meets the requirements for the following metallurgy process. Cassiterite in the concentrate could be further enriched and recovered either by mineral processing or metallurgy process. Moreover, gravity separation is highly efficient, cost effective, and chemical-free.



**Figure 8.** New flotation flowsheet of tungsten minerals in Shizhuyuan dressing plant.

#### 4. Conclusions

For the flotation of the polymetallic minerals in the Shizhuyuan Mine Group, Pb–BHA complexes can effectively collect scheelite, wolframite, and cassiterite in the rougher flotation synchronously. But it was hard to increase the grade of these minerals in the concentrate to the expectations following twice-cleaning flotation. The XRD and size distribution results revealed that the rougher concentration included the fine gangue particles, which was easier to be entrained into the concentrates in the cleaning flotation. The advanced gravity separation equipment was applied to deal with the rougher concentrates. Comparing with the grade and recovery of  $WO_3$  (55.63% and 87.83%) and Sn (1.01% and 29.18%) in the cleaning flotation, the grade and recovery were 60.88% and 76.38% for  $WO_3$  and 2.62% and 60.17% for Sn using the falcon concentrator, while the results were 61.35% and 83.15% for  $WO_3$  and 2.89% and 74.50% for Sn using the hang and vibrate of cone concentrator. These process indexes indicated that the advanced gravity separation dealing with the rougher concentrate could effectively enhance the grade of  $WO_3$  and Sn and the recovery of Sn, with a slight decrease in the recovery of  $WO_3$ . In addition, the results of hang and vibrate of cone concentrator are comprehensively superior to that of Falcon concentrator. Therefore, the advanced gravity separation is a high-efficiency and low-cost method to displace the traditional cleaning flotation to deal with the complexed polymetallic rougher concentrates.

#### Reference

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