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Gravity-based pre-concentration strategies for complex rare earth ore containing niobium and zirconium

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Abstract: The Balzhe rare earth mine, renowned for its rich reservoirs of niobium, zirconium, and rare earth elements, poses a unique challenge due to its diverse and interbedded mineral composition. Despite the abundance of these elements, their valuable grade remains notably low, falling short of economic thresholds. To this end, pre-concentration of valuable minerals to discard gangue minerals before flotation would be an economical option. In response, this study delves into the feasibility of gravity-induced pre-concentration, aiming to segregate valuable minerals from gangue for subsequent flotation processes. Conducting float-and-sink tests on varied particle sizes (-2+0.5 mm, -0.5+0.074 mm, and -0.074+0.02 mm) within heavy liquids of specific gravities (ranging from 2.55 to 2.85), the study reveals the effectiveness of gravity separation. Notably, particles sized -2+0.5 mm and -0.074+0.02 mm demonstrated superior separation performance over the -0.5+0.074 mm fraction. Comparative analysis of diverse gravity separation equipment unveiled compelling results. The dense medium cyclone separator showcased impressive recovery rates and high-grade concentrates of Nb_2O_5, ZrO_2, and total rare earth oxides (TREO) at 0.34%, 8.20%, and 0.41%, respectively, surpassing the sand table's performance for -2+0.5 mm particles. Conversely, for -0.5+0.074 mm particles, the shaking table exhibited optimal separation efficiency, yielding grades of Nb_2O_5, ZrO_2, and TREO at 0.37%, 4.08%, and 0.44%, with substantial recovery values. Ultimately, the Knelson centrifugal separator proved most effective for -0.074+0.02 mm particles, yielding notable grades and recoveries of Nb_2O_5, ZrO_2, and TREO. This study underscores the promising potential of gravity-induced pre-concentration techniques for enhancing the recovery of valuable elements from the complex Balzhe rare earth ore, offering critical insights into optimizing mineral extraction processes.

Keywords: gravity separation, dense medium separation, rare earth minerals, pre-concentration

1. Introduction

The rare earth elements include the lanthanide elements plus yttrium and scandium, which can be divided into light rare earth (La, Ce, Pr, Nd, Pm, Sm, and Eu) and heavy rare earth (Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, and Y) elements, based on their physical and chemical properties and distribution in minerals (Chen et al., 2022; Humphries, 2010; Jha et al., 2014; Chang et al., 2010; Opare et al., 2021; Uda et al., 2000). Rare earth ores, known for their complexity and valuable constituent elements such as niobium and zirconium, pose significant challenges in efficient extraction and beneficiation processes (Jordens et al., 2013; Zhang et al., 2016). The increasing global demand for rare earth elements, coupled with the intricate mineralogical composition of these ores, necessitates innovative approaches to their processing and extraction (Liu et al., 2021; Golev et al., 2014; Weng et al., 2015).

The main issues in current rare earth mineral processing include: rare earth ores typically comprise multiple minerals that may be intricately mixed, making it impractical to achieve a single concentrate

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(Jordens et al., 2014; Lan et al., 2018;); direct flotation and chemical leaching, although utilized to a certain extent in rare earth element extraction, incur high grinding and reagent costs due to low target mineral content (Mukaba et al., 2021; Abaka-Wood et al., 2019; Rozelle et al., 2019); additionally, the recovery rate of valuable elements in rare earth ores is often low, leading to resource waste (Traore et al., 2023); some traditional extraction methods for rare earth ores might have environmental implications, such as the use of hazardous chemicals, thus demanding more environmentally friendly approaches for rare earth element extraction (Talan et al., 2022; Haque et al., 2014; Dutta et al., 2016; Yang et al., 2013).

The pre-concentration of complex rare earth ores is a critical procedural step aimed at enhancing the concentration of valuable elements within the ore while removing a significant portion of waste material, ultimately boosting efficiency in subsequent extraction processes (Hu et al., 2016; Wang et al., 2021; Marion et al., 2018; Das et al., 2020). Therefore, it is necessary to combine the beneficiation process and metallurgy process, and the purpose of early beneficiation has changed from obtaining a single concentrate to obtaining a mixed concentrate and providing enriched products for subsequent metallurgy.

Gravity pre-concentration technology is undoubtedly a favorable choice, exhibiting significant effectiveness in handling coarse-grained ores and demonstrating satisfactory separation outcomes for certain fine particles. With various equipment options available for gravity pre-concentration tailored to different ores and particle sizes, such as spiral chutes, shaking tables, centrifugal concentrators, and dense medium cyclones, selecting appropriate separation equipment for specific ores will be the focal point of this study (Veasey et al., 1993; Ambrós et al., 2023; Jordens et al., 2014). The separation efficiency of each equipment is influenced by numerous factors (Nayak et al., 2021; Jiao et al., 2010; Carpenter et al., 2021; Wakeman et al., 1999; Jordens et al., 2016), including the ore's characteristics (such as shape, particle size, density), operational parameters of the equipment (such as wash water quantity, slurry density, angle, stroke, and frequency of the shaking table, feed pressure and heavy suspension density in the dense medium cyclone, rotational speed of the Knelson concentrator (KC), pitch of the spiral chute, the position of the discharge partition, etc.).

This study focuses on gravity-induced pre-concentration techniques as a pivotal step in the beneficiation of complex rare earth ores containing niobium and zirconium. To compare the separation efficiency of different equipment and determine the suitable devices, this study devised an innovative approach. Rather than relying on time-consuming and labor-intensive conventional condition tests, the study implemented a novel method. Initially, based on the particle size ranges of each separation device, the ore samples were divided into narrower size ranges. Through heavy liquid separation experiments, the theoretical separation efficiency for each particle size range was established as a reference. Using this as a guide, the corresponding discard tailings rates for each particle size were determined, and equipment parameters were adjusted to achieve the desired tailings effect for comparison purposes. The outcomes of this study are anticipated to contribute to the development of sustainable and economically viable techniques for processing complex rare earth ores, thereby addressing the growing global demand for these critical elements in various technological and industrial applications.

2. Materials and methods

2.1. Materials

Ore samples were collected from the underwent extraction from drilling cores inBalzhe deposit. These samples, taken from different depths of different boreholes and considered representative, were initially crushed to smaller than 30 mm (-30 mm) using a jaw crusher. Following thorough homogenization, representative samples were further crushed to -2 mm using a High-pressure Grinding Roll (HPGR) in a closed circuit. The particle size distribution is depicted in Fig. 1.

The raw ore was ground to analyze its chemical composition through X-ray fluorescence spectroscopy (XRF) and inductively coupled plasma mass spectrometry (ICP-MS). The equipment for both tests was supplied by the Testing Center of Northeastern University of China. A mineral liberation analysis (MLA) was performed to clarify the mineral associations and disseminated grain size of the raw ore. The MLA equipment was provided by the China Nuclear Mining Science and Technology Corporation.

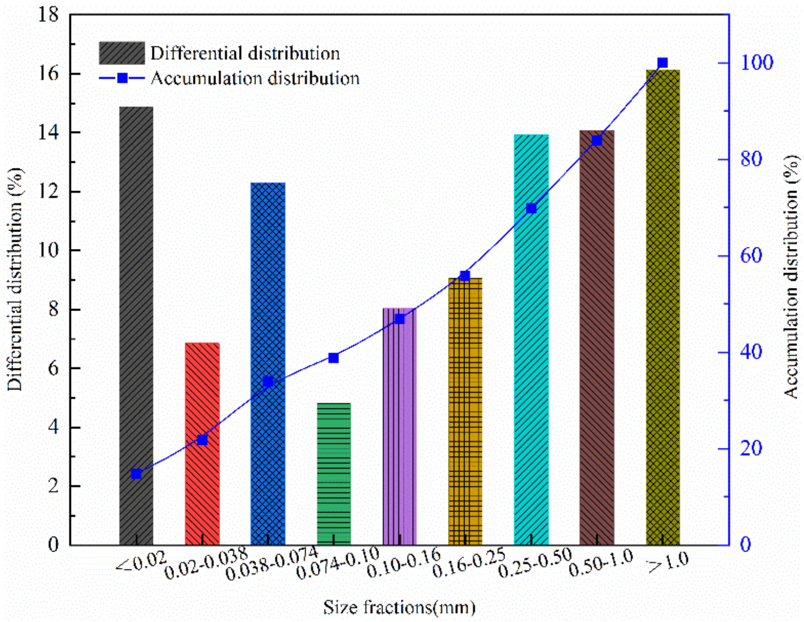


Fig. 1. Particle size distribution of -2 mm HPGR products

2.2. Heavy liquid tests

In dense medium separation (DMS), a liquid or an aqueous suspension of fine particles with a predetermined density is used to divide particles into heavy and light products. In this study, the heavy liquid was a mixture of tetrabromoethane and anhydrous ethanol, the heavy liquid was prepared as illustrated in Fig. 2. The balance was placed on an elevated surface, an iron rod was positioned above it, and a fine string was attached. After zeroing the balance, the other end of the string was attached to a weight. Following Newton's Third Law, $F_t + F_b = G$ was used to determine the specific gravity of the target heavy liquid, calculating F_t, and ascertaining the theoretical reading of the electronic balance. The amount of anhydrous ethanol and tetrabromoethane was adjusted gradually until the electronic balance displayed the theoretical value. To subject the gravity feed to DMS, ore samples were sieved into size fractions of -2+0.5 mm, -0.5+0.074 mm, and -0.074 +0.02 mm. One hundred grams of representative samples in each size category were added to a 500-mL beaker with about 400 mL of heavy liquid with an SG of 2.85. The solutions were stirred with a glass stick and then allowed to rest for adequate retention time to separate the heavy and light minerals. The float minerals were spooned onto filter paper, washed with anhydrous ethanol, and allowed to dry in a drying oven under the temperature of 80 centigrade. Subsequently, these minerals were added to heavy liquids with SGs of 2.75, 2.65, and 2.55 in the same manner. The float-and-sink fractions were respectively analyzed through ICP-MS.

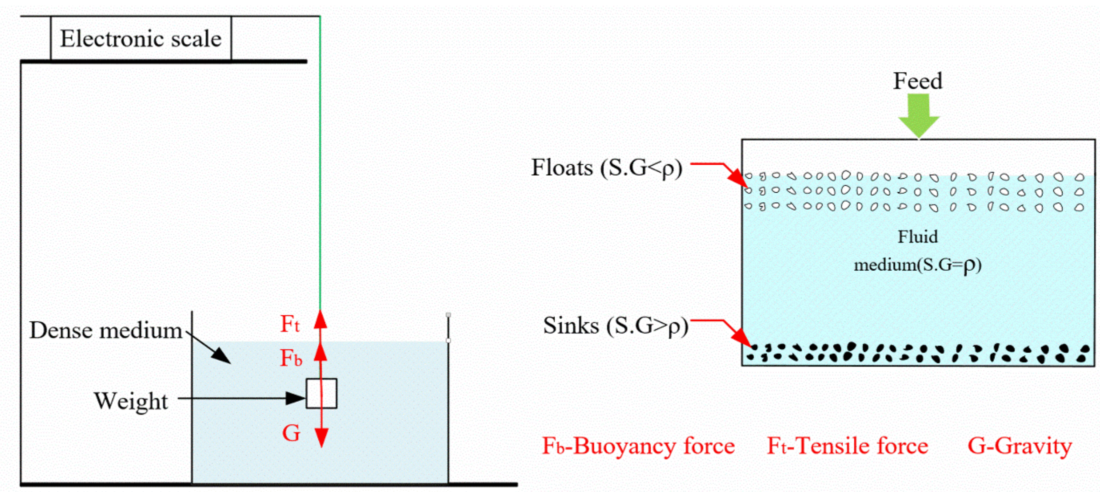


Fig. 2, Preparation of heavy liquid and experimental schematic diagram

2.3. Tests of dense medium cyclone and sand-shaking table

According to the DMS test results, the -2+0.5 mm size fraction could be subjected to gravity separation to reject gangue. Therefore, the suitable gravity separation equipment was dense medium cyclone or sand-shaking table. The dense medium cyclone used in this study was a laboratory cyclone supplied by Weihai Haiwang Hydrocyclone Co., Ltd. in China. The laboratory sand shaking table was manufactured by Wuhan Exploration Machinery Co., Ltd. In China. The highest gangue removal yield was determined based on the heavy liquid test, and at the same tailing yield the two equipment were compared in terms of gangue removal.

2.4. Tests of spiral separator, shaking table, and Knelson concentrator

The laboratory CL600-60 spiral separator was manufactured by Wuhan Exploration Machinery Co., Ltd. in China. The outer diameter of the spiral groove was 600 mm, and the feed particles were sized –0.5+0.01 mm.

The shaking table was a laboratory LYN-1100×500 shaking table manufactured by Wuhan Exploration Machinery Co., Ltd. (China), operated at a deck angle (5°), water flow rate of 2 L/min, and feed pulp density of 25 wt%.

A laboratory MD3 KC (FLSmidth Knelson, Canada) manufactured as a compact version of an industrial was utilized to recover fine-grained dense mineral particles. The KC was fed with a 25 wt% solid pulp density at a flow rate of 50 g/min. During testing, the pulp was diluted with fluidization water at a flow rate of 6 L/min, and the bowl rotation speed was 60 G.

The slurry with particles sized -0.5 mm and a mass percentage concentration of 20% was stirred and evenly fed to the three types of equipment. After tests, the concentrates and tailings were separately collected, sub-sampled, and analyzed by ICP-MS.

3. Results and discussion

3.1. Compositions of run-of-mine (ROM) ores

The chemical properties of the samples were analyzed using XRF and ICP-MS at Northeastern University. Table 1 summarises the ROM elemental compositions.

The primarily targeted element oxides (ZrO_2, Nb_2O_5, and total rare earth oxide (TREO)) in the ROM ore were assayed as 3.12%, 0.24%, and 0.33% respectively. TREO includes seven rare earth elemental oxides, La, Ce, Nd, Gd, Dy, Er, Yb, and Y. The associated useful compositions were graded as HfO_2, 0.051%; Ta_2O_5, 0.009%; BeO, 0.033%; ThO_2, 0.052%; U, 0.021%; FeO, 1.02%; and TiO_2, 0.55%.

The mineral associations and major mineral disseminated grain size were analyzed through MLA and exhibited in Table 2 and Table 3.

The valuable minerals in the ore were xinganite, zircon, niobite, ilmenorutile, pyrochlorite, aeschynite, monazite, and bastnaesite. The contents of xinganite, zircon, niobite, as the main valuable minerals, were 0.44%, 3.41%, and 2.16%. The main gangue minerals were quartz, albite, and potash feldspar, with contents accounting for 81.55% of the total mass.

Table 3 shows that zircon had coarse grains and could be enriched in coarse fractions. The disseminated particle sizes of the other valuable minerals were mostly 0.15+0.02 mm. Therefore, during crushing and grinding, the comminuted products were recommended to be controlled larger than 0.02 mm to prevent overgrinding.

Table 1. Elemental composition of ROM ore

Composition	ZrO_2	HfO_2	TREO①	Nb_2O_5	Ta_2O_5	BeO	ThO_2	U
Content/%	3.12	0.051	0.33	0.24	0.009	0.033	0.052	0.021
Composition	Fe_2O_3	FeO	MnO_2	SiO_2	TiO_2	Al_2O_3	CaO	MgO
Content/%	3.88	1.02	0.14	74.25	0.55	9.14	0.48	0.11
Composition	Na_2O	K_2O	P	S	F	—	—	—
Content/%	2.65	3.24	0.01	0.04	0.02	—	—	—

① TREO represents seven kinds of rare earth elemental oxides including La, Ce, Nd, Gd, Dy, Er, Yb, and Y

Table 2 Mineral compositions

Minerals	Content/%	Minerals	Content%
Xinganite	0.44	Ilmenite	0.64
Zircon	3.41	Quartz	38.17
Niobite	2.16	Albite	21.25
Ilmenorutile	0.18	Potash feldspar	22.13
Pyrochlorite	0.11	Aegirite	2.11
Aeschynite	0.18	Riebeckite	2.45
Monazite	0.09	Mica	0.12
Bastnaesite	0.08	Chlorite	3.13
Genthelvite	0.04	Allanite	0.06
Huttonite	0.04	Calcite	0.13
Hematite/magnetite	2.70	Other minerals	0.38

Table 3. Major mineral disseminated grain size

Particle size/mm	Content analysis/%						
	Zircon	Niobite	Ilmenorutile	Aeschynite	Xinganite	Monazite	Bastnaesite
+0.5	5.38	—	—	—	—	—	—
-0.5+0.3	8.22	—	—	—	—	—	—
-0.3+0.21	18.23	9.25	—	—	7.23	—	—
-0.21+0.15	22.91	17.11	7.22	—	12.35	4.83	—
-0.15+0.1	16.12	18.32	12.11	14.21	19.05	9.23	8.66
-0.1+0.074	10.42	18.41	25.24	20.23	17.25	16.60	15.32
-0.074+0.053	8.05	12.52	22.65	21.88	14.38	22.35	25.23
-0.053+0.038	5.20	10.12	14.01	15.17	11.21	17.42	20.18
-0.038+0.020	3.84	8.71	11.42	13.25	9.88	13.00	14.32
-0.020+0.010	1.21	3.04	5.23	7.02	7.54	9.45	8.21
-0.010	0.42	2.52	2.12	8.24	1.11	7.12	8.08

3.2. Heavy liquid separation

By conducting heavy liquid separation experiments, the theoretically achievable reselection effect under a narrow particle size distribution can be obtained. Based on the tailings yield at this point, adjust the separation parameters to make the selected equipment reach or approach this yield. Compare the separation effects of each device at this point and determine the separation equipment for this particle size. Table 4 presents the float-and-sink test results with different feed sizes and heavy liquids with different SGs.

$$\gamma = \frac{m_i}{m_1 + m_2} (i = 1\ ,\ 2) \tag{1}$$

$$\varepsilon = \frac{\alpha_i \cdot \gamma}{\beta} (i = 1\ ,\ 2) \tag{2}$$

where m_1 is the mass of the float, m_2 is the mass of the sink, γ is the yield, ε is the recovery rate, a_1 is the float grade, a_2 is the sink grade, β is the feed grade.

It can be observed that for the same particle size sample, as the specific gravity of the heavy liquid increases, the yield of floaters gradually increases, and the rate of change in floater yield for samples of different particle sizes is essentially consistent. With the decrease in sample particle size, the tailings yield at the same specific gravity gradually increases, but the increasing trend gradually moderates. The difference in tailings yield between -0.5+0.074mm and -0.074+0.02mm at the same specific gravity is relatively small. This is because as the particle size decreases, the degree of particle dissociation increases, and the difference in specific gravity between particles increases.

All three particle sizes show a trend of increasing grade of useful minerals in the sink particles with the increase in heavy liquid specific gravity, and the grade significantly increases when the heavy liquid specific gravity reaches 2.75. In the heavy liquid tests for -2+0.5mm and -0.5+0.074mm particle sizes, when the heavy liquid specific gravity reaches 2.85, the grade increase rate of useful minerals, except for zirconium, tends to zero. However, for the -0.074+0.02mm particle size, there is still a significant upward trend in grade when the heavy liquid specific gravity reaches 2.85. This indicates that when the particle size is above 0.074mm, the dissociation degree of useful minerals is relatively low, and particles mostly exist in a coexisting form. When the particle size is smaller than 0.074mm, the dissociation degree of each useful mineral increases, leading to an increase in the grade of separated high-density particles.

Table 4. Float-and-sink test results

SG of Heavy-liquid	Feed size /mm	Products	Yield /%	Nb_2O_5		ZrO_2		TREO	
				Grade /%	Recovery /%	Grade /%	Recovery /%	Grade /%	Recovery /%
2.55	-2+0.5	float	7.08	0.12	2.17	0.19	0.33	0.06	0.84
		Sink	92.92	0.42	97.83	4.39	99.67	0.52	99.16
	-0.5+0.074	float	20.42	0.14	7.52	0.59	8.54	0.14	11.15
		Sink	79.58	0.44	92.48	1.62	91.46	0.29	88.85
	-0.074+0.02	float	22.34	0.08	4.08	0.17	2.08	0.05	1.75
		Sink	77.66	0.54	95.92	2.31	97.92	0.74	98.25
2.65	-2+0.5	float	46.01	0.13	14.78	0.29	3.28	0.12	11.20
		Sink	53.99	0.63	85.22	7.33	96.72	0.80	88.80
	-0.5+0.074	float	59.27	0.13	20.81	0.50	21.21	0.12	27.81
		Sink	40.73	0.74	79.19	2.73	78.79	0.45	72.19
	-0.074+0.02	float	59.99	0.07	10.09	0.10	4.34	0.03	3.36
		Sink	40.01	0.99	89.91	3.37	95.66	1.42	96.64
2.75	-2+0.5	float	71.12	0.17	29.99	0.52	8.99	0.15	22.51
		Sink	28.88	0.97	70.01	12.89	91.01	1.31	77.49
	-0.5+0.074	float	84.63	0.15	33.48	0.54	32.54	0.11	37.01
		Sink	15.37	1.65	66.52	6.19	67.46	1.05	62.99
	-0.074+0.02	float	82.23	0.13	23.79	0.29	13.21	0.08	11.70
		Sink	17.77	1.88	76.21	8.93	86.79	2.91	88.30
2.85	-2+0.5	float	78.91	0.22	43.59	0.87	16.73	0.22	34.79
		Sink	21.09	1.07	56.41	16.15	83.27	1.51	65.21
	-0.5+0.074	float	88.36	0.19	44.27	0.57	35.45	0.12	39.62
		Sink	11.64	1.82	55.73	7.82	64.55	1.33	60.38
	-0.074+0.02	float	90.14	0.21	42.21	0.58	28.61	0.21	32.90
		Sink	9.86	2.57	57.79	13.25	71.39	3.99	67.10

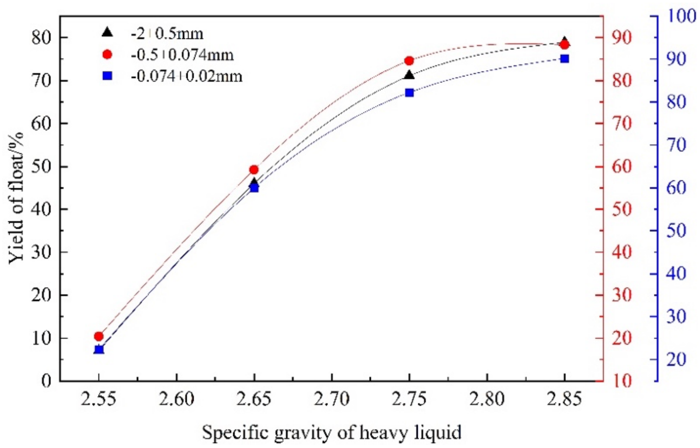
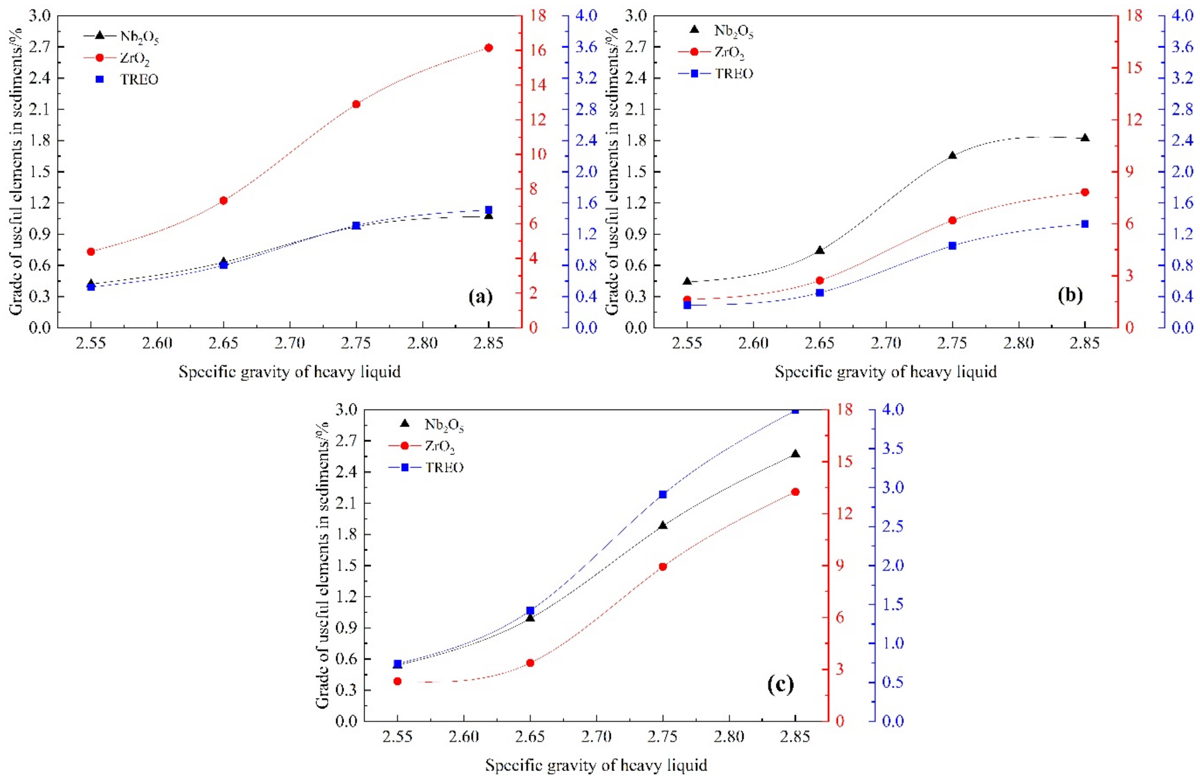


Fig. 3. The float yield of heavy liquid tests varies with specific gravity



(a) -2+0.5mm size fraction; (b) -0.5+0.074mm size fraction; (c) -0.074+0.02mm size fraction

Fig. 4. Grade of useful elements in heavy liquid test sediments of different particle sizes

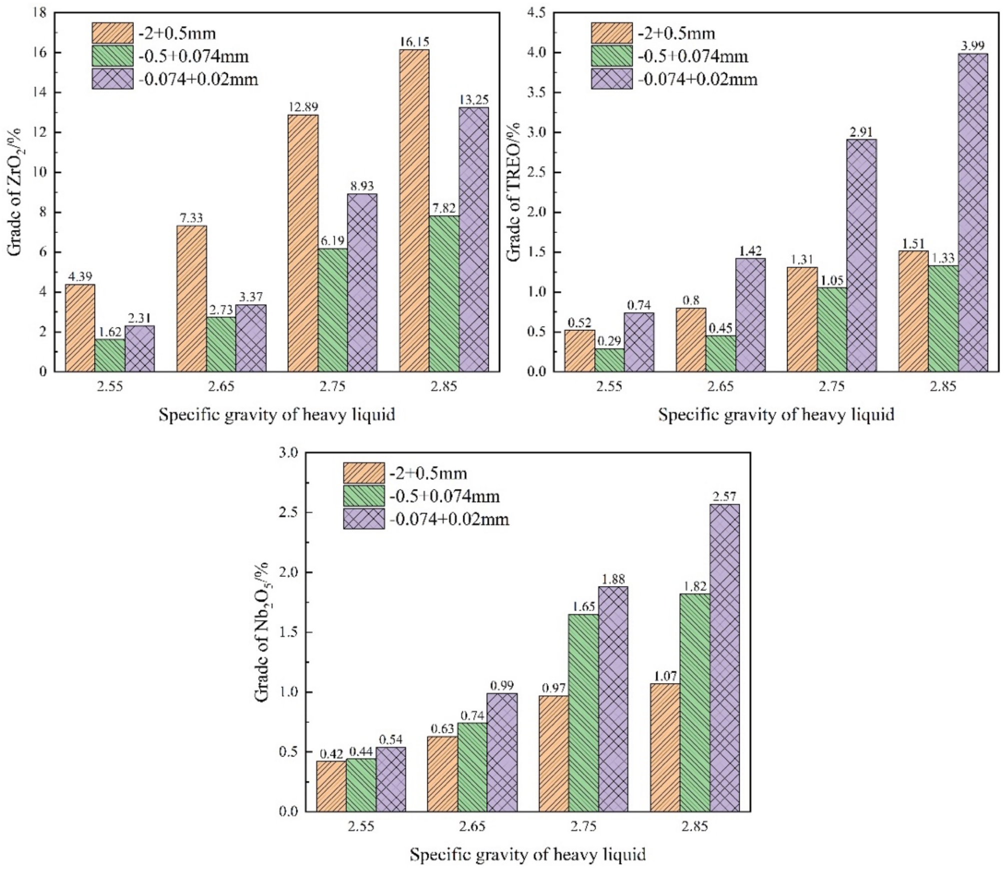


Fig. 5. Comparison of useful element grades in sinking materials at different particle sizes in the same heavy liquid

In heavy liquid experiments, particle size and density are crucial factors influencing the settling terminal velocity. For zirconium, as shown in Fig.5, -2+0.5mm is more conducive to the pre-enrichment of zirconium, as the zircon grains are coarser in this size range, leading to partial dissociation at coarser sizes. This portion has a higher density compared to gangue and coexisting minerals, making it easier to enrich. The next favorable size is -0.074+0.02mm because the dissociation of zircon grains increases, aiding in the separation from gangue. However, due to the smaller size, the settling terminal velocity difference between useful minerals and gangue is smaller compared to -2+0.5mm, resulting in a slightly lower enrichment effect for this size. For -0.5+0.074mm, the individual dissociation degree is lower than -0.074+0.02mm, and the settling terminal velocity difference decreases due to the smaller particle size, leading to a poorer separation effect for this size.

For niobium, in the selected experimental particle sizes, the grade of niobium in heavy liquid sediments increases with decreasing particle size. This indicates that the embedding granularity of niobium minerals is finer, and as the particle size decreases, the dissociation degree of useful minerals increases, enhancing the separation effect.

For rare earth minerals, the pre-enrichment effect of -2+0.5mm is slightly better than -0.5+0.074mm, both of which are far less than the -0.074+0.02mm size. This suggests that a small portion of rare earth minerals is embedded coarsely, while the majority is embedded finely. In the -2+0.5mm size range, although the dissociation degree is lower, the advantage in particle size results in a larger settling terminal velocity difference between useful minerals coexisting with gangue and gangue minerals compared to -0.5+0.074mm. As the size decreases to -0.074+0.02mm, the dissociation of wanted minerals significantly increases, and the density difference increases, leading to a larger settling terminal velocity difference, making it easier to separate wanted minerals from gangue.

Heavy liquid separation experiments can not only explore information such as the density distribution of useful minerals and the suitable reselection particle size of wanted minerals but can also determine the tailings rate for narrow particle sizes based on the relationship between the tailings rate

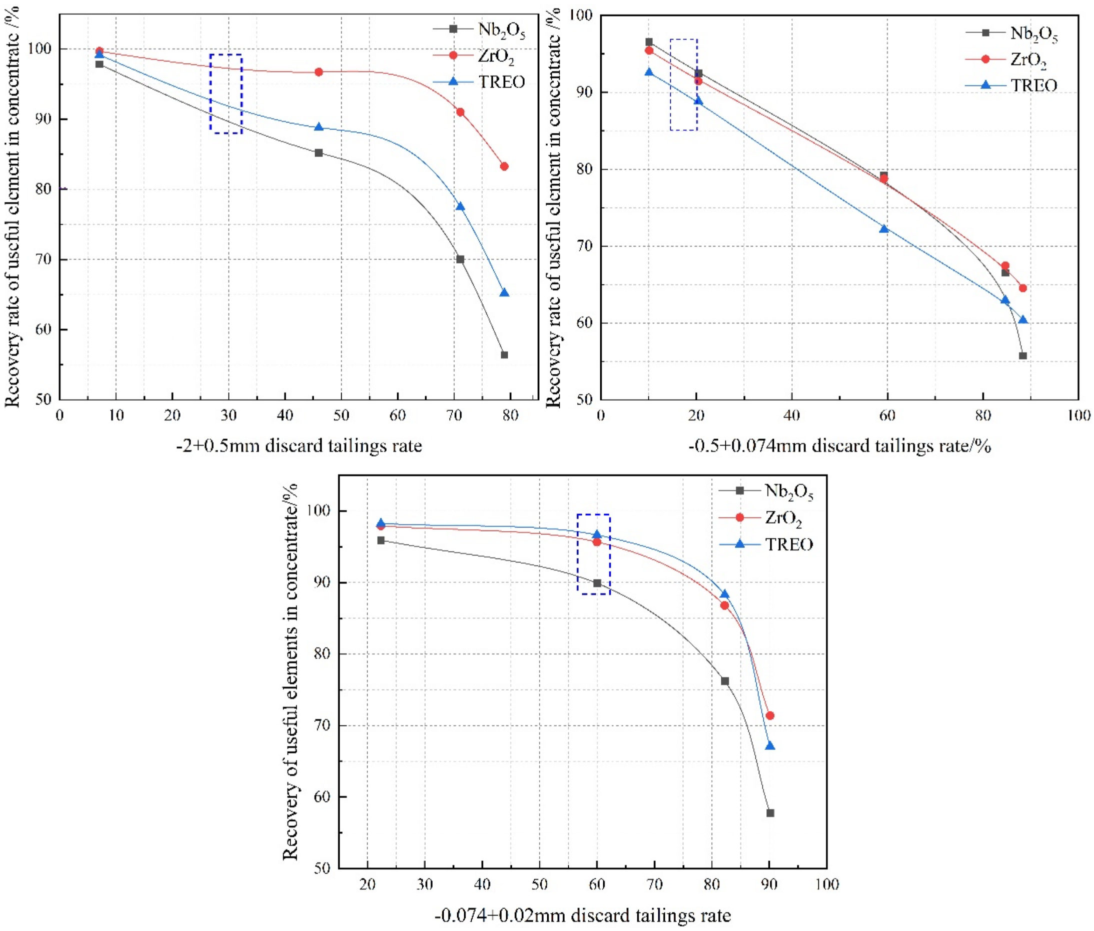


Fig. 6. Determination of tailings rates for each particle size fraction

and the recovery rate of useful elements in the concentrate. For the -2+0.5mm particle size, ensuring that the recovery rates of all useful elements in the sink particles are above 90%, a recommended tailings rate of around 28% is suggested. For the -0.5+0.074mm particle size, ensuring that the recovery rates of all useful elements in the sink particles are above 90%, a recommended tailings rate of around 15% is suggested. Similarly, for the -0.074+0.02mm particle size, ensuring that the recovery rates of all useful elements in the sink particles are above 90%, a recommended tailings rate of around 60% is suggested. Fig. 6 also shows that the -2+0.5mm and -0.074+0.02mm particle sizes have better separation effects compared to the -0.5+0.074mm particle size. It is worth noting that the recommended tailings rates mentioned above are results from heavy liquid separation, which can be referred to by the selection of gravity-based devices. The operational parameters for the involved gravity-based devices in this work were optimized for narrow-size fractions before the comparison among them. Table5 presents the devices' models and their optimized operational parameters.

Table 5. Gravity-based devices and their optimized operational parameters for narrow-size fractions

-2+0.5mm			
Dense medium cyclone		Shaking table	
Conditions	Parameters	Conditions	Parameter
Diameter (mm)	710/500	Stoke (mm)	20
Feeding pressure (MPa)	0.15	Frequence (n/min)	230
Medium density (g/cm^3)	1.91	Angle of inclination/°	3.5
		Flow velocity L/min	10

-0.5+0.074mm					
Spiral		Shaking table		KC	
Conditions	Parameters	Conditions	Parameter	Conditions	Parameters
External diameter(mm)	600	Stoke (mm)	15	Washing water velocity (L/min)	10
Concentration (wt.%)	30	Frequency (n/min)	287	Rotational speed (rev/min)	1196
Flow velocity (L/min)	8	Inclination angle (°)	2.5	Feed rate（g/s）	3
		Flow velocity (L/min)	7.5		

-0.074+0.02mm					
Spiral		Shaking table		**KC**	
Conditions	Parameters	Conditions	Parameters	Conditions	Parameters
External diameter(mm)	600	Stoke (mm)	9	Washing water velocity (L/min)	6
Concentration (wt.%)	30	Frequency (n/min)	410	Rotational speed (rev/min)	1465
Flow velocity (L/min)	4	Inclination angle (°)	1	Feed rate（g/s）	3
		Flow velocity (L/min)	5		

3.3. Dense medium cyclone and shaking table

Results in Table 6 indicate that the dense medium cyclone and sand shaking table had similar gangue yields (26.16% and 23.92%, respectively). The grades of Nb_2O_5, ZrO_2, and TREO in the concentrate from the dense medium cyclone separation were 0.34%, 8.20%, and 0.41%, with recovery of 88.62%, 98.30%, and 90.61%, respectively. The corresponding grades for sand shaking table separation were only 0.32%, 7.65%, and 0.36%, with recovery of 82.23%, 94.63%, and 86.42%, respectively. Therefore, the separation performance of the dense medium cyclone was superior to that of the shaking table for -2+0.5 mm.

Table 6. Results of gravity separation tests for -2+0.5 mm

Equipment	Products	Yield/%	Nb_2O_5 Grade /%	Nb_2O_5 Recovery /%	ZrO_2 Grade /%	ZrO_2 Recovery /%	TREO Grade /%	TREO Recovery /%
Dense medium cyclone	Concentrate	73.84	0.34	88.62	8.20	98.30	0.41	90.61
	Tailings	26.16	0.12	11.38	0.40	1.70	0.12	9.39
	Feed	100.00	0.29	100.00	6.16	100.00	0.33	100.00
Sand shaking table	Concentrate	76.08	0.32	82.23	7.65	94.63	0.36	86.42
	Tailings	23.92	0.22	17.77	1.38	5.37	0.18	13.58
	Feed	100.00	0.30	100.00	6.15	100.00	0.32	100.00

3.4. Spiral separator, shaking table, and KC

Table7 displays the separation performances of shaking table, spiral separator, and KC for 0.5+0.074 mm. At the same rate of discarded tailings, the shaking table yielded the best sorting effect at this particle size. The concentrate yield for the shaking table was 68.82%, and the grades of Nb_2O_5, ZrO_2, and TREO were 0.37%, 4.08%, and 0.44%, with recovery of 85.36%, 92.88%, and 89.00%, respectively.

Table 7. Gravity separation results for-0.5+0.074 mm

Equipment	Products	Yield/%	Nb_2O_5 Grade /%	Nb_2O_5 Recovery /%	ZrO_2 Grade /%	ZrO_2 Recovery /%	TREO Grade /%	TREO Recovery /%
Shaking table	Concentrate	68.82	0.37	85.36	4.08	92.88	0.44	89.00
	Tailings	31.18	0.14	14.64	0.69	7.12	0.12	11.00
	Feed	100.00	0.30	100.00	3.02	100.00	0.34	100.00
Spiral	Concentrate	65.41	0.31	71.82	3.87	85.61	0.40	84.38
	Tailings	34.59	0.23	28.18	1.23	14.39	0.14	15.62
	Feed	100.00	0.28	100.00	2.96	100.00	0.31	100.00
Knelson	Concentrate	66.53	0.36	82.67	3.92	87.73	0.45	86.47
	Tailings	33.47	0.15	17.33	1.09	12.27	0.14	13.53
	Feed	100.00	0.29	100.00	2.97	100.00	0.35	100.00

Table 8. Gravity separation results for 0.074+0.02 mm

Equipment	Products	Yield/%	Nb_2O_5 Grade /%	Nb_2O_5 Recovery /%	ZrO_2 Grade /%	ZrO_2 Recovery /%	TREO Grade /%	TREO Recovery /%
Shaking table	Concentrate	49.32	0.48	74.49	4.99	93.28	0.74	80.01
	Tailings	50.68	0.16	25.51	0.35	6.72	0.18	19.99
	Feed	100.00	0.32	100.00	2.64	100.00	0.46	100.00
Spiral	Concentrate	50.35	0.44	74.84	3.55	68.84	0.65	73.31
	Tailings	49.65	0.15	25.16	1.63	31.16	0.24	26.69
	Feed	100.00	0.30	100.00	2.60	100.00	0.45	100.00
Knelson	Concentrate	48.52	0.56	84.07	5.12	94.52	0.82	90.62
	Tailings	51.48	0.10	15.93	0.28	5.48	0.08	9.38
	Feed	100.00	0.32	100.00	2.63	100.00	0.44	100.00

In contrast, for the results of -0.074+0.02 mm in Table8 the KC was the most suitable pre-concentration method, as it discarded 51.48% of the tailings. The grades of Nb_2O_5, ZrO_2, and TREO were 0.56%, 5.12%, and 0.82%, with recovery of 84.07%, 94.52%, and 90.62%, respectively.

The diverse mineral composition and intricate interbedding of these ores from the Balzhe deposit posed significant challenges to achieving economically viable grade concentrations. However, the implementation of gravity-based pre-concentration methods demonstrated promising results in segregating valuable minerals from gangue for subsequent extraction processes. The present study focused on gravity-induced pre-concentration methods for Balzhe complex rare earth ores with notable concentrations of niobium and zirconium.

The float-and-sink tests revealed the efficacy of gravity separation, particularly highlighting the -2+0.5 mm and -0.074+0.02 mm particle fractions as exhibiting superior separation performance over the -0.5+0.074 mm fraction. These findings underscored the potential of gravity-induced pre-concentration in efficiently segregating valuable elements from complex ore matrices.

The comparative analysis of diverse gravity separation equipment provided critical insights. The dense medium cyclone separator exhibited commendable recovery rates and high-grade concentrates for -2+0.5 mm particles, surpassing the sand table's performance. Conversely, for -0.5+0.074 mm particles, the shaking table demonstrated optimal separation efficiency, while the Knelson centrifugal separator proved most effective for the -0.074+0.02 mm particles, yielding notable grades and recoveries of target elements.

The study highlighted the significance of tailings handling in the separation process. Tailings rates below certain thresholds were identified as more suitable, influencing the recovery rates for valuable elements. These findings provide crucial guidance for optimizing separation equipment and tailings handling in subsequent processing stages.

4. Conclusions

In conclusion, the study testifies the promising potential of gravity-induced pre-concentration techniques in enhancing the recovery of valuable elements from complex rare earth ores containing niobium and zirconium. Ahead of the flotation and metallurgy process, the utilization of diverse gravity separation equipment and the tailored approach for particle size fractions underscored the feasibility of achieving improved grade concentrations while discarding significant gangue material.

In the pre-concentration stage, ensuring a higher recovery rate is the primary objective. With an appropriate amount of tailings, higher recovery rates lead to greater resource utilization and improved separation efficiency; the higher the grade of the obtained concentrate, the better the quality of the final products in subsequent operations, resulting in greater profits. Additionally, a higher grade in the pre-concentration stage results in reduced usage of reagents in subsequent flotation and metallurgical processes, not only saving costs but also minimizing the environmental impact of tailings generated during the flotation and metallurgical stages.

The findings suggest a shift towards environmentally conscious and economically feasible beneficiation approaches for this type of complex ores. This study lays the groundwork for further optimization of pre-concentration techniques, offering critical insights into efficient mineral extraction processes for meeting the escalating global demand for rare earth elements.

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