

Recovering rare earths from waste phosphors using froth flotation and selective flocculation

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Abstract

This study explores froth flotation and selective flocculation methods to recycle waste phosphors containing several rare earth elements, namely, yttrium (Y), europium (Eu), cerium (Ce) and terbium (Tb). The effects of the presence or absence of collector and of flocculant and their dosages, as well as the pH, were investigated. Reverse flotation resulted in concentrates with grade of 27.03 percent and recovery rate of 71.36 percent, while flocculation resulted in concentrates with grade of 31.43 percent and recovery rate of 91.28 percent. The flotation and flocculation behaviors were further analyzed by X-ray diffraction analysis, zeta potential measurements, particle size distribution and other methods. The successful separation of rare earth minerals by flotation was attributed to the selective adsorption of the collector onto quartz, making it particularly recoverable by reverse flotation so as to be separated from the valuable materials. The analysis of the particle aggregation process indicated that its better flocculation performance was due to the selective adsorption of flocculants onto the unwanted materials, enlarging the flocculant sizes by forming aggregations and facilitating the separation of rare earth minerals from waste materials based on different settling rates.

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Introduction

Because waste phosphors pose the problems of heavy environmental burden and high risk to human health (Hu and Cheng, 2012) as a result of containing heavy metals such as mercury and manganese (He et al., 2006; Lucas and Emery, 2006), they have received added attention as urban mining resources

for extracting rare earth elements (REEs) like yttrium (Y), europium (Eu), cerium (Ce) and terbium (Tb).

At present, chemical processes such as acid leaching, alkali fusion, roasting and extraction are the primary methods for recovering REEs from waste phosphors (De Michelis et al., 2011; Li et al., 2012; Li, 2010). With these strategies, phosphors can be effectively decomposed and their REEs extracted.

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After the removal of impurities, the REEs can be efficiently precipitated by adding an $H_2C_2O_4$ solution (Porob et al., 2012). Although relatively high recovery rates are achieved, those processes entail high energy consumption and can cause severe environmental pollution.

Studies have shown that the cost of these chemical processes can be reduced, and the recovery efficiency improved at the same time, by using a highly enriched product as the feed (Takahashi, Takano and Saitoh, 2001). Therefore, the preconcentration of rare earth materials from waste phosphors before chemical processes would be highly beneficial. However, investigations that address this have been scarce, although a few studies on separation techniques such as pneumatic separation (Takahashi, Takano and Saitoh, 2001) indicate that rare earth materials can be separated from waste phosphors. Using dense-medium centrifugation with methylene iodine as the dense medium and sodium oleate as the surfactant (Hirajima, Sasaki et al., 2005), a concentrate containing a high grade of rare earth materials was obtained. Following flotation (Hirajima, Bissombolo et al., 2005; Otsuki et al., 2008), rare earth phosphors were separated from calcium halophosphate phosphors using dodecyl ammonium acetate and sodium dodecyl sulfate or organic solvents as collectors. In Mei, Rao and Mitsuaki (2009), waste phosphors were separated into red, green and blue phosphors by liquid/liquid extraction using a heptane/dimethylformamide system. However, in view of the low separation efficiency, high cost and negative environmental effects of the organic reagents used in this process, an alternative energy-efficient and environmentally friendly method to recover rare earth minerals from waste phosphors is required.

As an important and inexpensive technology to concentrate minerals, froth flotation has been widely used for ore beneficia-

tion. Up to now, few studies had been conducted to recover rare earth materials from phosphors by froth flotation, even though this method may open a new door to recycling waste materials due to its particular capacity for separating fine particles during mineral processing (Gül et al., 2012).

Additionally, selective flocculation has been used successfully to separate fine, valuable minerals from ores during mineral processing. Panda et al. (2013) applied selective flocculation to separate ultrafine synthetic mixtures of haematite and kaolinite, using low-grade iron ore fines, slimes and existing tailings effectively. Yu, Che and Zheng (2014) showed that the recovery of ultrafine rare earth minerals can be enhanced through the use of the flocculant 1,4-benzoyl hydroxamic acid. Using two-stage shear flocculation (Ucbeyiyi and Ozkan, 2014), column flotation and flocculation-flotation techniques, fine boron minerals were recovered from colemanite mineral. Liu, Hu and Sun (2014) separated diasporite from bauxite by selective flocculation using hydrolyzed polyacrylamide.

The present study investigates the recovery of rare earths from waste phosphors by froth flotation and selective flocculation. Because quartz is the primary gangue mineral in waste phosphors, the cationic collector dodecyl ammonium acetate was used for the reverse flotation of quartz. In addition, cationic polyacrylamide was used as the flocculant in the selective flocculation process.

Materials and methods

Materials. The waste phosphors used were mercury-free and supplied by Peiyuan Lighting Materials Co. Ltd. (Jiangzhou, Zhejiang, China). Analysis of their compositions by X-ray fluorescence (XRF) (Table 1) indicated that their total content of rare earth oxides was 18.82 percent, including yttrium oxide (Y_2O_3), europium oxide (Eu_2O_3), cerium oxide (CeO_2) and terbium oxide (Tb_4O_7). The silica (SiO_2) content was 26.75 percent, which was much higher than expected for these phosphors as there was no silicon in the chemical formulas of the phosphors and was probably due to some silicon from the fluorescent tubes.

From the results of X-ray diffraction (XRD) analysis, presented in Fig. 1, the primary crystalline phases of this sample were $(Y_{0.95}Eu_{0.05})_2O_3$ (PDF card 25-1011), $(Ce_{0.67}Tb_{0.33})MgAl_{11}O_{19}$ (PDF card 36-0073), $(Ba_{0.9}Eu_{0.1})Mg_2Al_{16}O_{27}$ (PDF card 50-0512) and SiO_2 (PDF card 33-0271).

Figure 2 and Table 2 show the results of a scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDS) analysis of the original waste phosphors, in which the large granular particles are fragments of fluorescent tubes (point-1). The elements present in these particles were primarily silicon (Si) and oxygen (O) (Table 2), and the average particle size of the fragments was approximately 25 μm . The primary elements of the bright particles representing red phosphors (point-2) were Y and O, while the primary elements of point-3 (blue

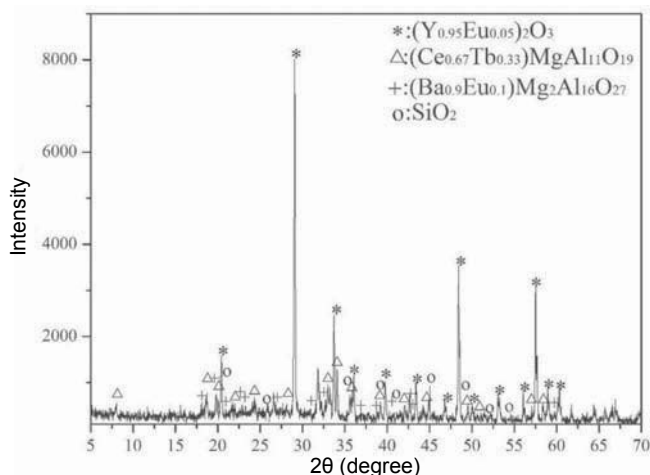


Figure 1 — XRD analysis of the waste phosphors.

Table 1 — Chemical composition of the waste phosphors.

Element	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	SO ₃	CaO	CuO	BaO	CeO ₂	WO ₃	Y ₂ O ₃
Content (weight %)	3.05	1.61	21.88	26.75	0.09	8.18	0.08	3.13	1.25	0.05	15.44
Element	Eu ₂ O ₃	MnO	Fe ₂ O ₃	ZnO	SrO	P ₂ O ₅	Sb ₂ O ₃	PbO	Tb ₄ O ₇	Cl	Loss
Content (weight %)	1.32	0.14	0.53	0.05	0.75	7.42	0.06	1.21	0.81	1.65	4.55

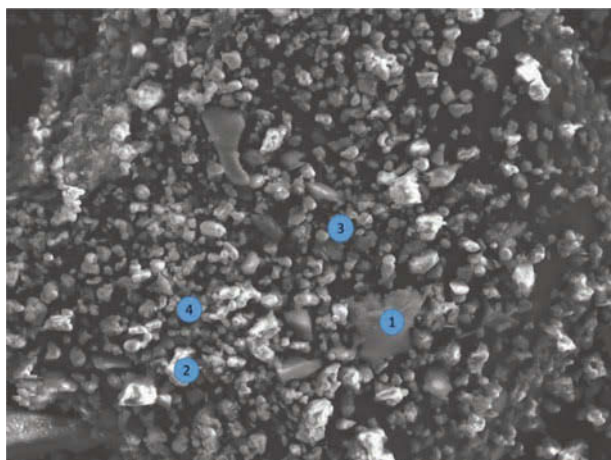


Figure 2 – SEM-EDS image of the waste phosphors.

Table 2 – SEM-EDS analysis of the waste phosphors.

Element	Content (weight %)			
	Point-1	Point-2	Point-3	Point-4
O	46.24	31.22	43.54	38.50
Mg	0.45	0.37	2.16	2.63
Al	2.91	5.09	37.21	35.05
Ca	1.03	0.74	–	0.29
Si	29.88	–	3.89	2.35
Y	–	57.22	8.15	3.42
Ba	1.48	1.38	5.46	12.41
Ce	–	0.38	4.46	–
Tb	–	–	2.65	–
Eu	–	2.79	2.62	2.66

Table 3 – Screening results for the waste phosphors.

Size (mm)	Yield (%)	Grade of rare earth mineral (%)	Distribution of rare earth oxide (%)
Larger than 0.109	11.7	9.57	5.66
Smaller than 0.109, larger than 0.074	15.3	13.67	10.56
Smaller than 0.074, larger than 0.053	19.0	15.27	14.65
Smaller than 0.053, larger than 0.045	19.9	26.20	26.33
Smaller than 0.045, larger than 0.025	11.8	25.16	14.99
Smaller than 0.025	22.3	24.68	27.81
Total	100	18.82	100

phosphors) and point-4 (green phosphors) included O and aluminum (Al). The size of the particles was approximately 10 μm. These characteristics made the separation and recovery of rare earth materials from the waste phosphors extremely difficult.

Further screening results for these waste phosphors, shown in Table 3, indicate that particles finer than 74 μm accounted for the majority of the rare earth minerals. In addition, the grades of the rare earth oxides increased as the particle sizes decreased.

Pure specimens of phosphor materials. Because the waste phosphors consisted of several types of phosphors with quartz, three pure phosphors and quartz supplied by the same lighting company were used in these experiments. Figure 3 and Table 4 show the characterizations of the individual phosphors. For instance, the smallest median size of 5.94 μm was observed for red phosphors with a density of 5.17 g/cm³ while the largest median size of 24.5 μm was observed for quartz. However,

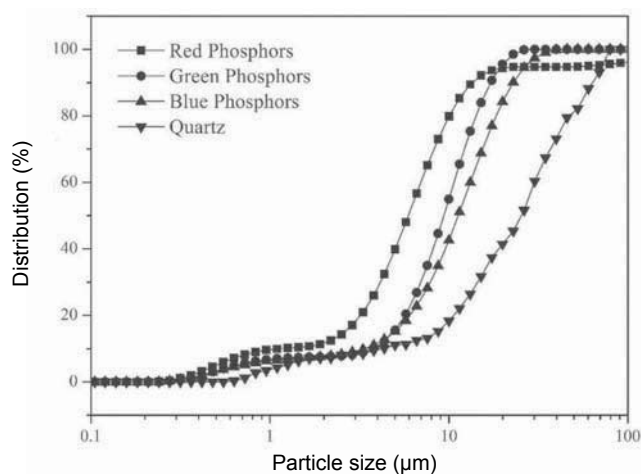


Figure 3 – Particle size distributions of the pure phosphors and quartz.

Table 4 – General characteristics of the phosphors and quartz.

Type	Simplified formula	Density (g/cm ³)	Median size, d ₅₀ (μm)
Red phosphors	(Y _{0.95} Eu _{0.05}) ₂ O ₃	5.17	5.94
Green phosphors	(Ce _{0.67} Tb _{0.33})MgAl ₁₁ O ₁₉	2.16	9.37
Blue phosphors	(Ba _{0.9} Eu _{0.1})Mg ₂ Al ₁₆ O ₂₇	2.81	11.28
Quartz	SiO ₂	2.65	24.5

Table 5 – Chemical compositions of phosphor materials (weight percent).

Sample	SiO ₂	Al ₂ O ₃	MgO	CaO	BaO	Y ₂ O ₃	Eu ₂ O ₃	CeO ₂	Tb ₄ O ₇
Red phosphors	0.22	0.08	0.07	0.14	–	91.17	8.32	–	–
Green phosphors	0.08	79.60	0.32	–	1.12	–	–	18.71	4.96
Blue phosphors	0.56	81.41	6.10	8.87	11.71	–	6.13	0.04	–

the density of the quartz was only 2.65 g/cm³, which was much lower than that of the red phosphors. According to the following equation, quartz has the fastest settling rates, blue phosphors have lower rates, and the settling rates of red and green phosphors are the lowest, so the materials will settle at different rates:

$$V = \frac{2(\rho - \rho_0) r^2 g}{9\eta} \quad (1)$$

where V is the terminal velocity of the particle, r is the radius of the particle, ρ is the density of the particle and ρ_0 is the density of the fluid, g is the gravitational acceleration and η is the viscosity of the fluid.

Table 5 shows the chemical compositions of three phosphor materials containing REEs, including Y, Eu, Ce and Tb, indicating that Y was predominantly found in the red phosphors while Ce and Tb were primarily from green phosphors, with Eu coming from both red and blue phosphors. Therefore, the recovery of each rare earth material was highly dependent on the recovery from the related red phosphors.

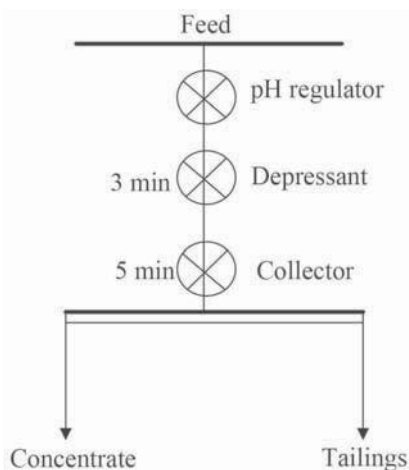
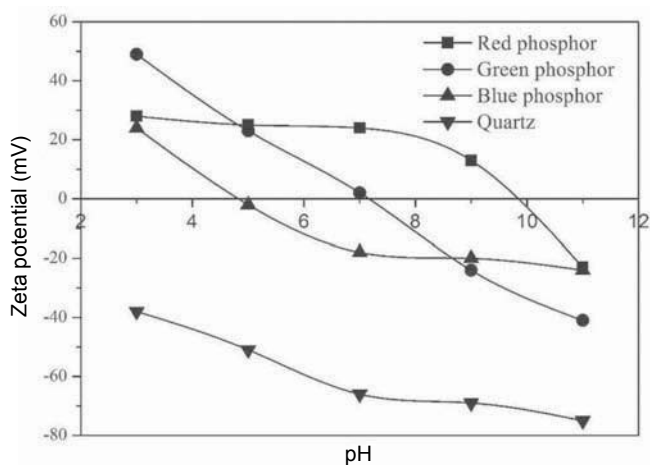
Reagents and equipment. The Ultra Pycnometer 1000 automatic pycnometer from Quantachrome Instruments (Boynton Beach, FL) was used to measure the densities. Zeta potential measurements were carried out with a ZetaPlus zeta potential analyzer (Brookhaven Instrument Corp., Holtsville, NY), and a Mastersizer 2000 laser particle size analyzer (Malvern Instruments Ltd., Worcestershire, UK) was used for the particle size distribution analysis. The XRF analysis was conducted using an Axios system (PANalytical B.V, Almelo, Netherlands), and the XRD analysis was performed with an RU-200B (Rigaku Corp., Tokyo, Japan). The pH meter used was an HM-40V (TOA Denpa Togyo Co. Ltd., Tokyo, Japan). The XFG 5~35g flotation machine was supplied by Wuhan

Exploring Machinery Factory, Wuhan, China.

Chemically pure dodecyl ammonium acetate (DDA), guaranteed-reagent-grade hydrochloric acid (HCl) and analytical-reagent sodium hydroxide (NaOH) and sodium carbonate (Na₂CO₃) were used as the collector, pH regulators and dispersant, respectively, with alkaline starch used as the depressant in the flotation test. In addition, cationic polyacrylamide, an analytical reagent with molecular weight of eight million, was used as the flocculant for the selective flocculation process. Deionized water obtained from a Milli-Q system (Millipore, Billerica, MA) was used in all of the tests. All of the reagents were supplied by Sinopharm Chemical Reagent Co. Ltd. (Shanghai, China).

Flotation tests. The flotation experiments were performed in a 20-mL flotation cell. Two grams of pure materials or waste phosphors were added to this cell after 3 mL of 0.1 mol/L Na₂CO₃ solution was added. Each flotation test was performed at an agitation speed of 1,600 rpm. At the desired pH value, the depressant and collector were added to the slurry and conditioned for three and five minutes, respectively, before aeration. After eight minutes of flotation, the flotation concentrate and tailings were filtered, dried at 60 °C for six hours, and weighed. The flotation tests were conducted in accordance with the flow sheet shown in Fig. 4.

Selective flocculation. Selective flocculation tests were conducted using a sedimentation method that was performed in a 100-mL glass cylinder with diameter of 35 mm and height of 200 mm, to which 3-g samples were added, followed by 5 mL of 0.1 mol/L Na₂CO₃ solution and deionized water to make a 3 percent (mass fraction) suspension. After pH adjustment, the cylinder was stoppered and inverted 10 times to mix the slurry adequately. The pulp was allowed to settle for one

**Figure 4** – Flow sheet of reverse flotation experiments.**Figure 5** – Zeta potentials of the pure materials.

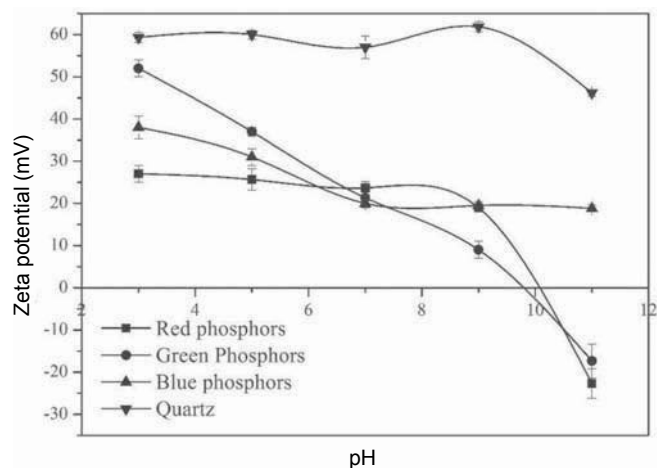


Figure 6 – Zeta potentials of the pure materials in the presence of the collector (DDA).

minute before 80 percent of the upper part was siphoned off. The sediment and the upper part were ultimately dried and weighed to calculate the sedimentation yield:

$$R = (w / W) \times 100\% \quad (2)$$

where R is the sedimentation yield of the particle, w is the weight of the sediment, and W is the weight of the samples used in the selective flocculation tests.

Zeta potential measurements. All of the zeta potential measurements were conducted in 50 mL of 10^{-3} mol/L NaCl solution at a fixed temperature of 25 °C and pH values that were adjusted using HCl and NaOH. After shaking for five minutes, a 5-mL sample of the well-mixed suspension was taken out and transferred to the measuring cell. The zeta potential distributions of the phosphors and quartz were then obtained in the absence and presence of the collector and flocculant at a concentration of 0.1 mmol/L. For each condition, three repeat tests were conducted, and the average value with a typical variation of ± 2 mV was calculated and used to plot the curve.

Results and discussion

Zeta potential measurements. *Zeta potential measurements of pure specimens of the materials.* Figure 5 shows the zeta potentials of pure red, green and blue phosphors and quartz, with quartz having a negative zeta potential across the entire tested pH range. The zeta potential values of the red, green and blue phosphors decreased gradually with increased pH, and the isoelectric points (IEP) occurred at pH 9.8, 6.9 and 5.0, respectively. The results show that from pH 6.9 to 9.8, the surfaces of the quartz, green and blue phosphors had negative zeta potentials while the surfaces of the red phosphor had positive zeta potentials. In other words, within this pH range, the cationic collector and flocculant can adsorb onto the surfaces of the quartz and blue and green phosphors. Therefore, the separation of red phosphors to raise the grades of rare earth oxides from the waste phosphors can be achieved using a cationic collector and flocculant during the reverse flotation and selective flocculation processes.

Zeta potential measurements in the presence of collector. Figure 6 shows the significant effect of DDA, the most

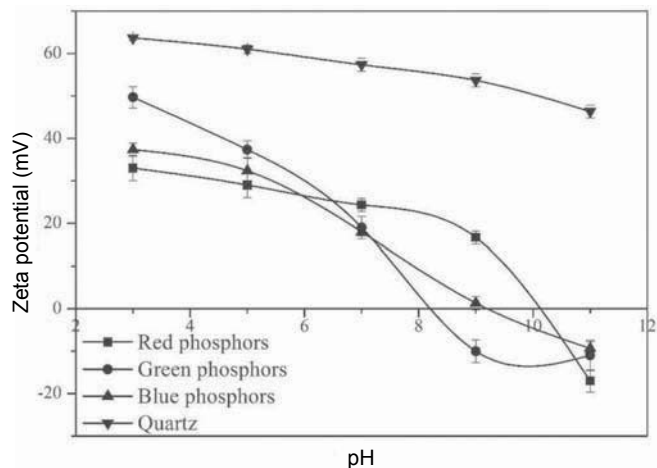


Figure 7 – Zeta potentials of the pure materials in the presence of the flocculant (cationic polyacrylamide).

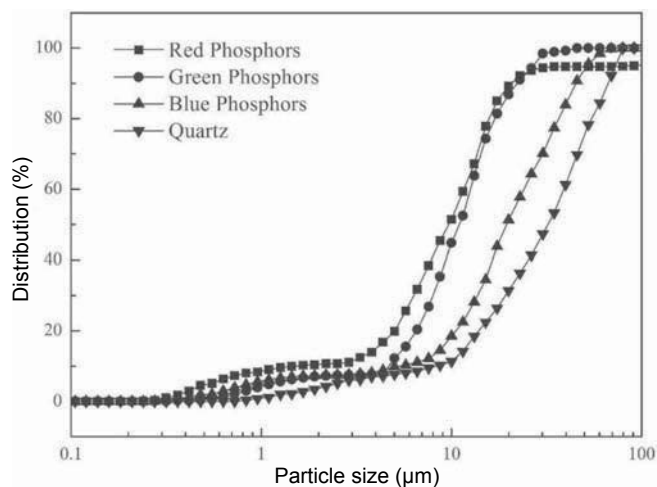


Figure 8 – Particle size analysis of the pure materials with 2 mg/L cationic polyacrylamide and 75 mg/L Na_2CO_3 .

commonly used cationic collector, on the zeta potentials. The zeta potentials of quartz and blue phosphors shift to positive values while a slight change was observed for the green phosphors. However, no apparent change was observed for the red phosphors. This finding indicates that DDA can be preferably adsorbed onto the surfaces of quartz and blue phosphors, further indicating that a successful flotation separation of red phosphors from waste phosphors is possible.

Zeta potential measurements in the presence of flocculant. Figure 7 shows the effect of cationic polyacrylamide on the zeta potentials of the pure materials. The zeta potentials of quartz and blue phosphors were found to shift positively, with the IEP increasing to 9.0 for the blue phosphors, indicating that the cationic polyacrylamide can be adsorbed onto the surfaces of quartz and blue phosphors, leading the particles to have positive surfaces. However, the presence of flocculant had no significant effect on the zeta potentials of red and green phosphors, indicating that this cationic polyacrylamide primarily adsorbed onto the surfaces of quartz and blue phosphors

rather than red and green phosphors. Therefore, the addition of flocculant can result in a greater settling rate for quartz and blue phosphors due to aggregation.

Particle size distribution analysis. Figure 8 and Fig. 3 indicate that with the addition of 75 mg/L Na_2CO_3 and 2 mg/L cationic polyacrylamide, the median particle sizes, d_{50} , of blue phosphors and quartz increased significantly. The particle sizes increased to 19.46 and 31.26 μm from 10.82 and 24.5 μm , respectively, resulting in the generation of dense blue phosphors and quartz flocs, but the particle sizes of red and green phosphors increased by an insignificant degree. This trend accelerates the sedimentation speed of blue phosphor particles, leading to different phosphor sedimentation speeds. These results show that the flocculants of cationic polyacrylamide have a selective flocculation effect on the mixture dispersion system of quartz and phosphors.

Tests on pure specimens. Flotation tests on pure specimens. The results of the flotation tests on pure specimens in

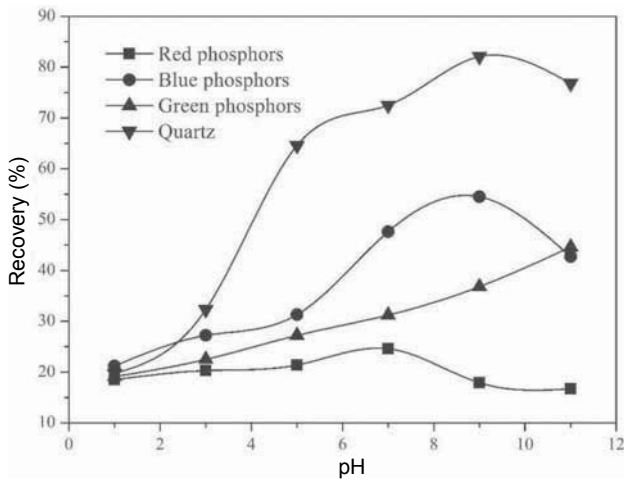
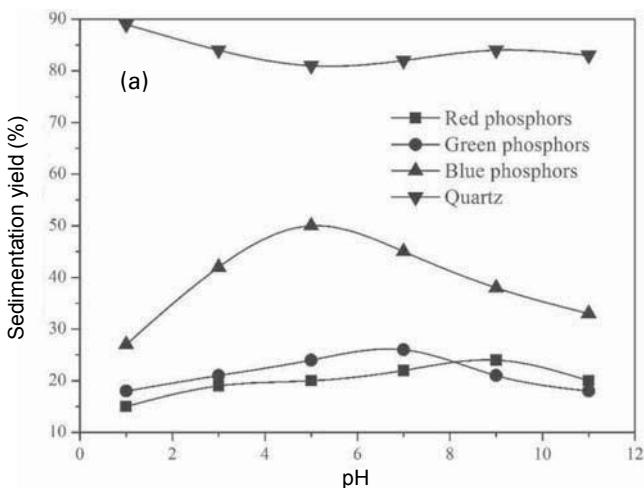


Figure 9 – Flotation results for the pure materials in the presence of the collector (DDA).



the presence of DDA are shown in Fig. 9, in which the four materials demonstrated quite different flotation behaviors under alkaline conditions. It is noted that the floatability of quartz was quite high under alkaline conditions, with the maximum recovery rate of quartz being achieved at approximately pH 9. By contrast, less than 25 percent of the red phosphors floated at the test pH. The flotation results were consistent with the zeta potential measurements, that is, DDA can be adsorbed onto the surfaces of quartz and blue phosphors, resulting in the separation of red phosphors from the waste phosphors.

Selective flocculation of pure specimens. Figure 10a shows the flocculation-dispersion behaviors of the four pure materials as a function of pH in the presence of 0.1 mol/L Na_2CO_3 . At all of the pH values, quartz had the highest sedimentation according to Eq. (1), while the red and green phosphors were well dispersed and the pH had less of an effect on their dispersion behaviors. The maximum aggregation was detected at pH 5 for blue phosphors, with a sedimentation yield of approximately 50 percent. These results further indicate that it is highly possible to recover rare earth material from waste phosphors by sedimentation.

Figure 10b presents the flocculation-dispersion behaviors of the pure materials in the presence of the flocculant, cationic polyacrylamide, at a concentration of 2 mg/L at different pH values. The sedimentation yield of blue phosphors in the presence of cationic polyacrylamide increased gradually from pH 1 to pH 9, with a maximum yield of approximately 80 percent, followed by a decline to pH 11. By contrast, the red and green phosphors were almost dispersed at all of the pH values, even when cationic polyacrylamide was added. It should be noted that there was a great sedimentation yield difference among the red and green phosphors and quartz or blue phosphors at pH 9. Therefore, it is possible to separate quartz and blue phosphors from waste phosphors at pH 9 to achieve a high grade of REEs by selective flocculation.

Tests on real waste phosphors. Flotation tests on real waste phosphors. Figure 11 shows the effect of pH on the reverse flotation of the waste phosphors. As the pH increased to 9, the grade of rare earth oxides increased while the recovery decreased, with the highest grade of 26.01 percent and a

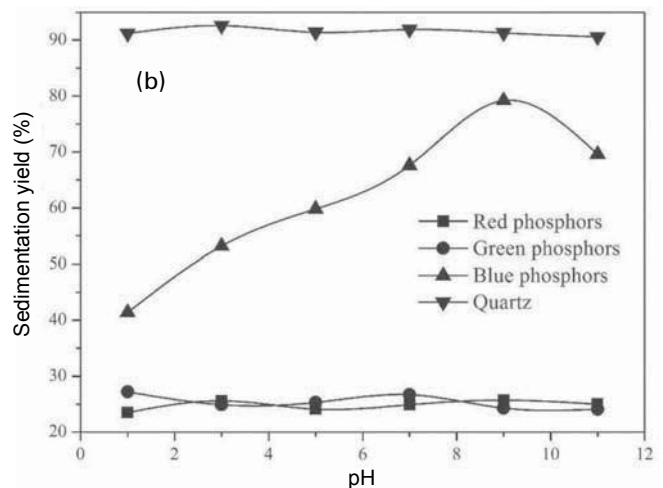


Figure 10 – Effect of pH on the dispersion of pure materials under different conditions: (a) with Na_2CO_3 and (b) with Na_2CO_3 and cationic polyacrylamide.

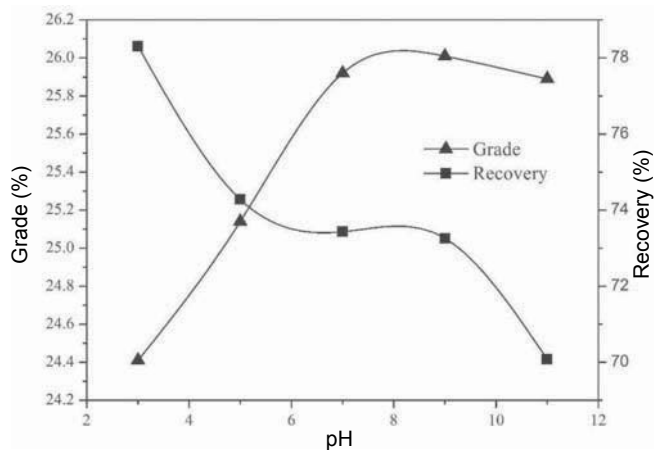


Figure 11 — Influence of pH on flotation.

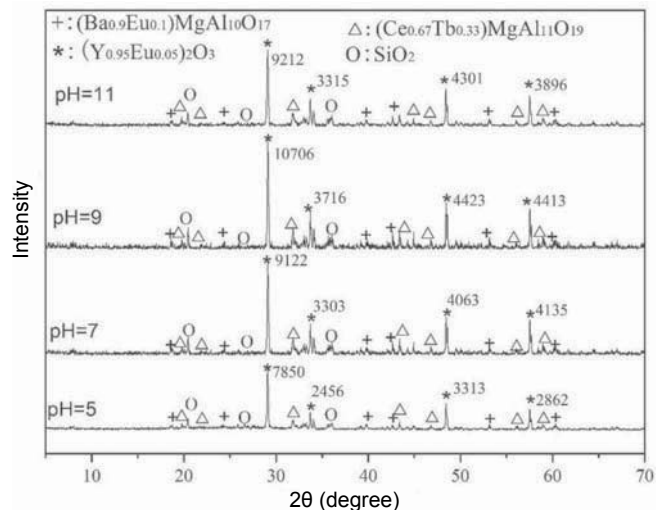


Figure 12 — XRD analysis of the flotation concentrates.

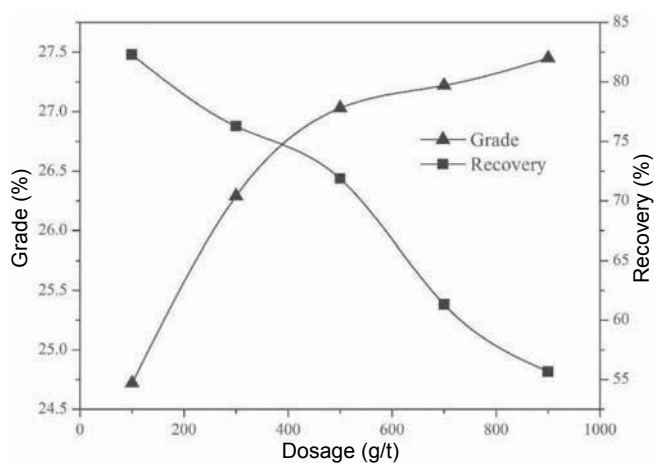


Figure 13 — Influence of collector (DDA) dose on flotation.

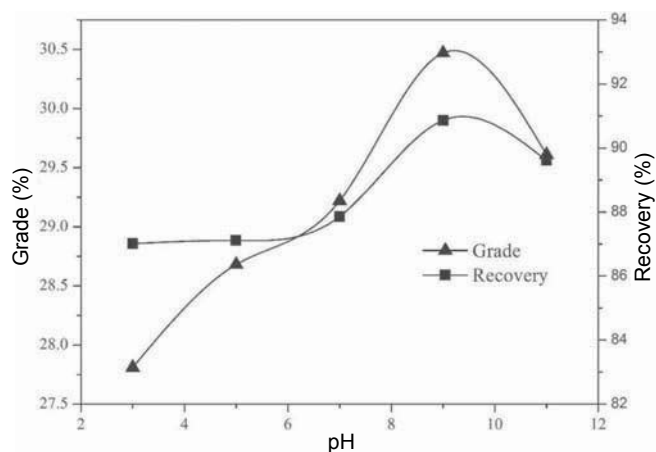


Figure 14 — Influence of pH on flocculation.

recovery rate of 73.28 percent occurring at pH 9.

The XRD analysis of the reverse flotation concentrates at different pH values is shown in Fig. 12. As the pH increased to 9, the intensity of the red phosphor peaks increased. The XRD results confirmed that red phosphors accounted for the majority of the reverse flotation concentrate, probably due to the high floatability of quartz and the low floatability of red phosphors. Therefore, a high grade of rare earth oxides can be achieved through the reverse flotation of waste phosphors at alkaline conditions.

Figure 13 presents the effect of the collector dose on the flotation of the waste phosphors. As the amount of added DDA increased, the grade of rare earth oxides increased but the recovery decreased. At 500 g/t, the grades and recovery rates were all at relatively high levels. Therefore, a dose of 500 g/t was selected as the optimum condition with a grade of 27.03 percent and a recovery rate of 71.36 percent.

Selective flocculation of real waste phosphors. In addition to flotation, selective flocculation was applied to recover rare earth materials from waste phosphors. The effect of pH on the selective flocculation of the waste phosphors is shown in Fig. 14.

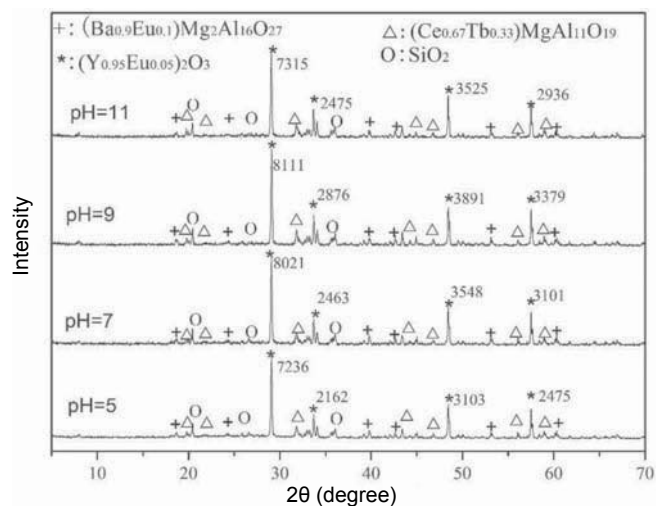


Figure 15 — XRD analysis of the flocculation concentrates.

As the pH increased to 9, the rare earth grade increased, with the highest grade of 30.47 percent and the highest recovery rate of 90.86 percent achieved at pH 9. Therefore, selective flocculation can be used to recover the rare earth materials with high recovery at alkaline conditions, especially at pH 9.

Figure 15 presents the XRD analysis of selective flocculation at different pH values. The intensity of the red phosphor peaks increased as the pH increased from 5 to 9. The XRD analysis confirmed that red phosphors were the majority phase in the final concentrate due to selective flocculation. As a result, red phosphors can be separated from waste phosphors by selective flocculation using cationic polyacrylamide.

Figure 16 illustrates the effect of flocculant dosage on the flocculation behaviors of the waste phosphors. The optimal grade of 31.43 percent and recovery rate of 91.28 percent were obtained when the flocculant dosage was 50 g/t. As the flocculant dosage increased, the grade and recovery of rare earth decreased gradually. By comparing with the flotation results shown in Fig. 11, it can be concluded that selective flocculation can achieve better recovery of rare earth materials from waste phosphors than flotation.

Discussion

The compositions of waste phosphors, concentrates and tailings following reverse flotation and selective flocculation were analyzed by XRF and XRD (Table 6, Figs. 17 and 18). Compared with the untreated waste phosphors, the overall grade of the rare earth oxides, Y_2O_3 , Eu_2O_3 , CeO_2 and Tb_4O_7 , increased from 18.82 percent to 27.03 percent after flotation and 31.43 percent after selective flocculation. The XRD results

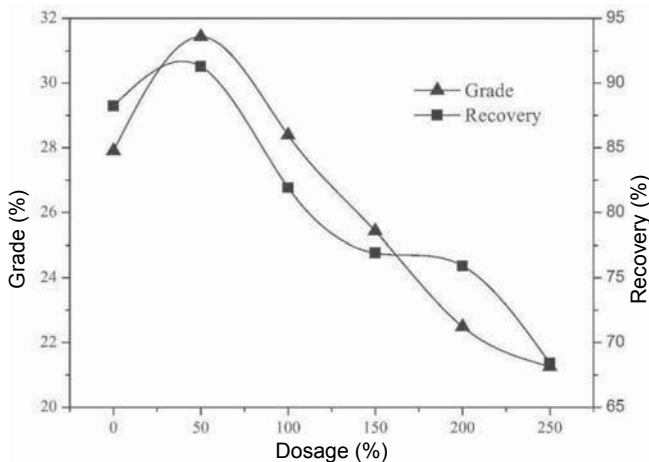


Figure 16 — Influence of flocculant (cationic polyacrylamide) dosage on selective flocculation.

Table 6 — XRF analysis of the concentrates.

Elements	Y_2O_3	Eu_2O_3	CeO_2	Tb_4O_7	Al_2O_3	SiO_2	MgO	BaO	CaO
Flotation	24.75	1.11	0.96	0.21	23.56	20.01	9.09	2.52	8.43
Selective flocculation	24.38	2.97	2.41	1.67	24.20	16.08	1.87	2.30	9.49

also indicated that the majority of the flotation product was red phosphors while the majority of the selective flocculation product was red phosphors and green phosphors. In addition, the intensity of the red phosphor peaks decreased while the intensities of the quartz and blue phosphor peaks increased for the tailing samples, both indicating a significant decrease of red phosphors in the tailings.

Conclusions

Froth flotation and selective flocculation were investigated to recover rare earth materials from waste phosphors. Red phosphors were successfully separated and recovered from real waste phosphors by flotation, with grade of 27.03 percent and recovery rate of 71.36 percent. Froth flotation of the pure materials and zeta potential measurements revealed that the successful separation of red phosphors was due to the preferential adsorption of the collector, DDA, onto the surfaces of the quartz and blue phosphors, improving the recovery of those materials by reverse flotation and the separation of red phosphors from the waste phosphors at pH 9.

Using selective flocculation, a high recovery rate of 91.28 percent with a grade of 31.43 percent was achieved. The flocculation of pure materials and zeta potential measurements showed that the high performance of selective flocculation in recovering the rare earth materials was due to the selective flocculation of blue phosphors and quartz by cationic polyacrylamide, leading to the formation of large, dense aggregations and a faster sedimentation speed. As a result, red phosphors were successfully separated from the waste phosphors by selective flocculation.

Resource recycling and the assuring of REE supply from waste phosphors is important. Selective flocculation can provide better results for REE extraction using chemical processes, as the obtained concentrate can be used as the feed for the chemical processes, reducing their cost and improving their recovery efficiency.

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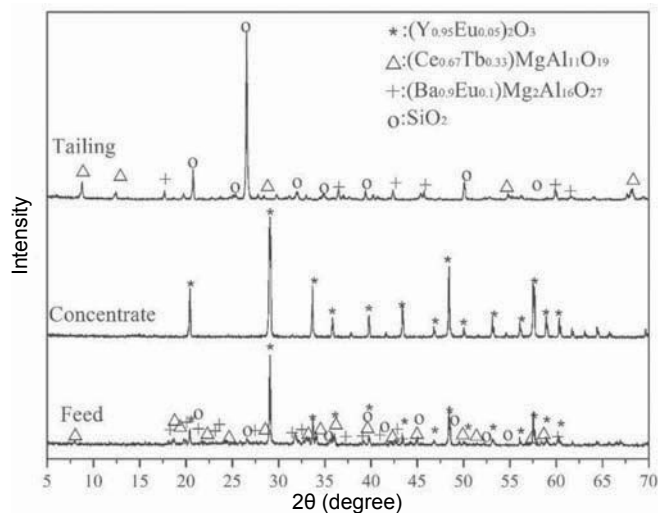


Figure 17 — XRD analysis of reverse flotation products.

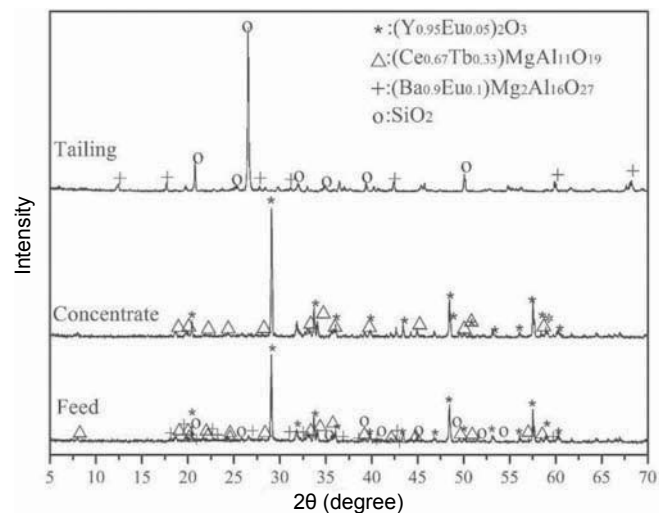


Figure 18 — XRD analysis of selective flocculation products.

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