Available online at www.sciencedirect.com
ScienceDirect
Trans. Nonferrous Met. Soc. China 29(2019) 821−830
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Treatment of backwater in bauxite flotation plant and optimization by using Box-Behnken design

Qiang HUO[1,2], Xi LIU[3], Li-jun CHEN[1], Yong-hong WU[1,2], Hai-yan WU[1,2],
Jian-ping XIE[1,2], Xin-xing LIU[1,2], Guan-zhou QIU[1,2]

1. School of Minerals Processing and Bioengineering, Central South University, Changsha 410083, China;
2. Key Laboratory of Biohydrometallurgy, Ministry of Education, Central South University, Changsha 410083, China;
3. Zhengzhou Non-ferrous Metals Research Institute Co. Ltd. of CHALCO, Zhengzhou 450041, China

Received 7 May 2018; accepted 15 January 2019

Abstract: Flotation indexes gradually decrease with the increase of cycle time of the backwater in bauxite floatation, and discharge of backwater brings environmental risk. In this study, methods such as Fenton-oxidation, adsorption and coagulation were used in the treatment of backwater, the flotation indexes were checked after backwater treatments, and Box-Behnken design (BBD) was used in the optimization of the main operating parameters. The results reveal that flotation indexes are effectively improved after coagulation treatment by polyaluminum ferric chloride (PAFC). The optimum parameters predicted by BBD are pH 7.55, 1.09 g/L PAFC dosage and temperature of 25 °C. Under these optimum conditions, a maximum recovery of Al_2O_3 of 82.83% and a minimum A/S of 1.30 of tailings are gained, while the deviations are less than 3% from the predicted values. These findings encourage the application of BBD for the optimization of critical parameters in backwater treatment.

Key words: backwater treatment; bauxite flotation; polyaluminum ferric chloride; Box-Behnken design

1 Introduction

Ore grade decreases because of the sharp and increasing demand of bauxite [1]. More than 98% of the bauxite ores in China are of the diasporic type, having characteristics of complex mineral composition, low A/S (mass ratio of Al_2O_3 to SiO_2) and difficulty to be processed. The flotation method has been successfully industrialized for obtaining concentrates with an increased A/S that could be processed directly by the Bayer process, and this has made a great contribution to the sustainable development of China’s aluminum industry [2,3]. A large amount of water was saved by recycling through the flocculation and sedimentation of the ore pulp [4]. In industrial production, flotation indexes gradually decreased with the increase of cycle time of the backwater in bauxite floatation [5,6]. The bauxite flotation plants in China, most of which were built and put into production after 2009, retained good flotation indexes by discharging the backwater out of the recycling system and replacing it with fresh water. There are no reports on research and industrial applications of backwater treatment of bauxite flotation.

There were some organic pesticide residues in backwater, such as hydrolyzed polyacrylamide (HPAM). HPAM itself had no toxicity; however, it had been reported to be easily broken down by physical−chemical factors, and its intermediate products were hazardous because their monomer was highly toxic [7]. Therefore, the discharge of backwater brought potential environmental risk [8], but no studies have focused on that problem yet.

Treatment of backwater would improve the flotation

Foundation item: Project (1053320170205) supported by the Research and Innovation Project of Graduate Students of Central South University, China; Project (502211704) supported by the Fundamental Research Funds for the Central Universities, China; Project (SKL-SPM-201809) supported by the State Key Laboratory of Advanced Technologies for Comprehensive Utilization of Platinum Metals, China; Project (SKLAM005-2016) supported by the State Key Laboratory of Applied Microbiology Southern China; Projects (51320105006, 51504106, 51871250) supported by the National Natural Science Foundation of China; Project (2015FB204) supported by the Science and Technology Project of Yunnan Province, China
Corresponding author: Guan-zhou QIU; Tel: +86-731-88716592; E-mail: qgzcsu@126.com
DOI: 10.1016/S1003-6326(19)64992-7

indexes, increase the utilization rate of water resources and contribute much to the aluminum industry, while the environmental risk brought by the discharge of backwater was eliminated. In this study, in order to investigate an effective method for backwater treatment, a series of methods were used to treat the backwater, which had poor flotation indexes, and the Box-Behnken design (BBD) for experiments was adapted from the response surface methodology (RSM) to optimize the relevant operating parameters in order to reduce the researcher's experimental workload and high cost of chemical usage and to avoid uncertainty in industrial application [9,10].

2 Experimental

2.1 Materials

2.1.1 Water in tests

Fresh water was used in the control group. Backwater for tests was collected from the backwater basins at a bauxite flotation plant in Henan Province, China. The pH value of the backwater was 8.81, and the major chemical element analysis results are listed in Table 1.

Table 1 Major chemical element analysis results of backwater (mg/L)

Fe^{2+}	Zn^{2+}	Na^{+}	Mg^{2+}	Al^{3+}
1.46	1.87	1410.96	1.96	6.27
K^{+}	Ca^{2+}	SO_4^{2-}	Cl^{-}	F^{-}
13.89	54.88	93.21	121.89	6.84

2.1.2 Ore for tests

Bauxite ore for tests was collected from the homogenization yard in the bauxite flotation plant. The results from the chemical element analysis and mineral phase analysis of the ore are shown in Tables 2 and 3, respectively.

Table 2 Chemical element analysis results of bauxite ore (wt.%)

Al_2O_3	SiO_2	Fe_2O_3	TiO_2	K_2O	Na_2O	CaO	MgO	A/S
56.99	19.13	4.57	2.21	0.43	0.08	0.67	0.32	2.98

Table 3 Mineral phase analysis results of bauxite ore (wt.%)

Diaspore	Boehmite	Kaolinite	Illite
50.69	2.54	27.84	3.55
Quartz	Hematite	Anatase	Rutile
4.7	4.6	2	0.2

2.2 Methods

2.2.1 Backwater treatment

(1) Control group: Flotation tests on fresh water were carried out as a blank control, and flotation tests on untreated backwater were carried out as a basic control.

(2) Ions influence group: Flotation tests on water to which was added analytic reagents such as $CaCl_2$, Fe_2SO_4, Na_2SO_4, KCl, NaF, and NaCl into distilled water were carried out to examine the influence of the ions in backwater. The ion concentrations of water added to ions were 1.62 mg/L Fe^{2+}, 54.05 mg/L Ca^{2+}, 2.00 mg/L Mg^{2+}, 13.60 mg/L K^{+}, 93.51 mg/L SO_4^{2-}, 121.69 mg/L Cl^{-} and 6.79 mg/L F^{-}.

(3) Backwater treatment group: Treatment methods, including natural placement, adsorption by zeolite and activated carbon, coagulation by 5 g/L polyaluminum ferric chloride (PAFC) and 5 g/L polysilicate aluminum ferric (PSAF), were carried out under three pH values (5, 7 and 9), while treatments by the Fenton-oxidation method were carried out under the other three pH values (3, 4 and 5). Flotation tests were carried out using the backwater after treatment.

2.2.2 Flotation test

Flotation tests [11] were performed in a flotation cell with a flotation volume of 1.5 L and were carried out under the industrial conditions of grinding fineness of 92.69% <0.074 mm, pulp density of 31%, pH value of 9.3, and temperature of 25 °C. A flowsheet of the flotation tests is shown in Fig. 1.

$NaCO_3$, NaOH and HCl were used as pH modifiers. The collector used in flotation tests was a mixture of saponified oleic acid and benzohydroxamic acid.

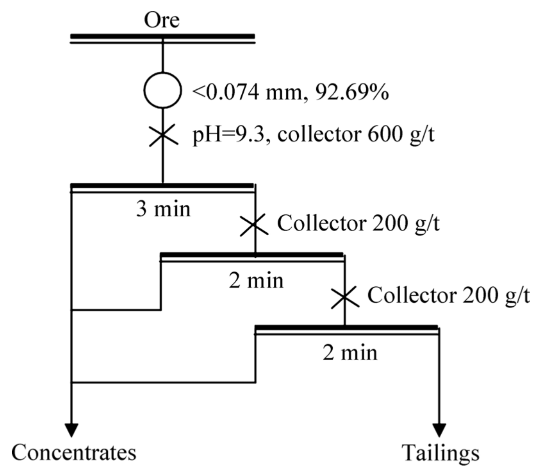

Fig. 1 Flowsheet of flotation tests

2.2.3 Measurements

Degree of dissociation of grinding products was determined using quantitative evaluation of minerals by scanning electron microscopy (QEMSCAN) [12]. The flotation indexes of the treated backwater, including recovery of Al_2O_3 and A/S of tailings, were used to characterize the effect of the backwater treatment.

2.2.4 Box-Behnken design

Backwater treatment was optimized by response surface methodology (RSM) using the BBD. The statistical software Minitab® 17.1.0 was used for the analysis. Three independent parameters: pH (X_1, 5−9); PAFC dosage (X_2, 0.6−1.4 mL/L), and temperature (X_3, 15−35 °C), were confirmed to optimize the backwater treatment, which was characterized by flotation indexes (Y_1 for recovery of Al_2O_3 and Y_2 for A/S of tailings). The coded and uncoded levels of these variables are presented in Table 4. The optimum response and the corresponding process parameters were also determined.

3 Results and discussion

3.1 Results of QEMSCAN

The distribution of main minerals of grinding products is indicated by area percent (AP, area ratio), which reveals the percentage of the particle area of diaspore to the total particle area. The results show that most diaspore particles with better dissociation were concentrated in fine-grained particles, whereas most diaspore particles with less than 50% dissociation were presented in coarse-grained particles. The percentage of coarse-grained particles should be reduced in the grinding process for the low dissociation and the complex association of minerals.

3.2 Flotation results

The reasons for the deterioration of the backwater flotation index, analyzed from the contact with the backwater, were mainly due to three aspects: the influence of the accumulation of ions brought into backwater by fresh water and ores, the influence of the accumulation of organics such as humus brought into backwater by ores, and the influence of the residual accumulation of HPAM added into the pulp of concentrates and tailings for the rapid settlement [13]. Therefore, three groups of experiments of backwater treatment, described in section 2.2.1, were carried out.

3.2.1 Flotation results for control group

As shown in Table 5, compared with the fresh water results, the backwater results had a decrease of 17.45% on recovery of Al_2O_3 and an increase of 0.98 on the A/S of tailings. In the backwater flotation system, the collection ability for diaspores was greatly reduced, resulting in the high A/S of the tailings and the low recovery of Al_2O_3.

Table 4 Box-Behnken design matrix

Run No.	Code value			Actual value			Result	
	X_1	X_2	X_3	X_1	X_2/(mL·L^{-1})	X_3/°C	Y_1/%	Y_2
1	1	−1	0	9	0.6	25	74.94	1.72
2	0	1	1	7	1.4	35	80.47	1.43
3	0	0	0	7	1	25	82.50	1.30
4	1	0	1	9	1	35	77.89	1.43
5	0	−1	−1	7	0.6	15	78.62	1.52
6	0	1	−1	7	1.4	15	80.37	1.47
7	−1	−1	0	5	0.6	25	70.08	1.92
8	1	1	0	9	1.4	25	80.58	1.52
9	1	0	−1	9	1	15	80.17	1.49
10	−1	0	1	5	1	35	72.18	1.72
11	0	0	0	7	1	25	83.00	1.28
12	−1	1	0	5	1.4	25	74.53	1.82
13	−1	0	−1	5	1	15	73.78	1.74
14	0	0	0	7	1	25	81.93	1.31
15	0	−1	1	7	0.6	35	74.96	1.77

Table 5 Flotation results for control group

Sample	Product	Production/%	$w(Al_2O_3)$/%	$w(SiO_2)$/%	A/S	Recovery of Al_2O_3/%
Backwater	Concentrates	62.72	60.52	15.68	3.86	66.19
	Tailings	37.28	52.00	24.42	2.13	33.81
	Ore	100.00	57.35	18.94	3.03	100.00
Fresh water	Concentrates	76.89	62.47	13.85	4.51	83.64
	Tailings	23.11	40.65	35.35	1.15	16.36
	Ore	100.00	57.43	18.82	3.05	100.00

3.2.2 Results for ion influence group

Table 6 shows the flotation results of water added ions, which presented no obvious differences to those of fresh water.

Although studies suggested that Mg^{2+} advanced the dispersivity of bauxite, whereas Ca^{2+} and Fe^{2+} inhibited the dispersivity of bauxite [14], the results of this study indicated that the influence of ions in backwater was not the reason for the decrease in the flotation index because the concentrations of the ions hid not reached the upper limit.

3.2.3 Results for backwater treatment group

For the backwater treatment group, the results of the flotation tests, which were carried out after the backwater treatment, are shown in Fig. 2.

(1) Results for natural placement

As shown in Fig. 2(a), no improvements to the flotation indexes occurred in the natural placement group

Table 6 Flotation results for influence group

Sample	Product	Production/%	$w(Al_2O_3)$/%	$w(SiO_2)$/%	A/S	Recovery of Al_2O_3/%
Water added ions	Concentrates	76.66	62.21	13.92	4.47	83.40
	Tailings	23.34	40.66	35.67	1.14	16.60
	Ore	100.00	57.18	18.99	3.01	100.00

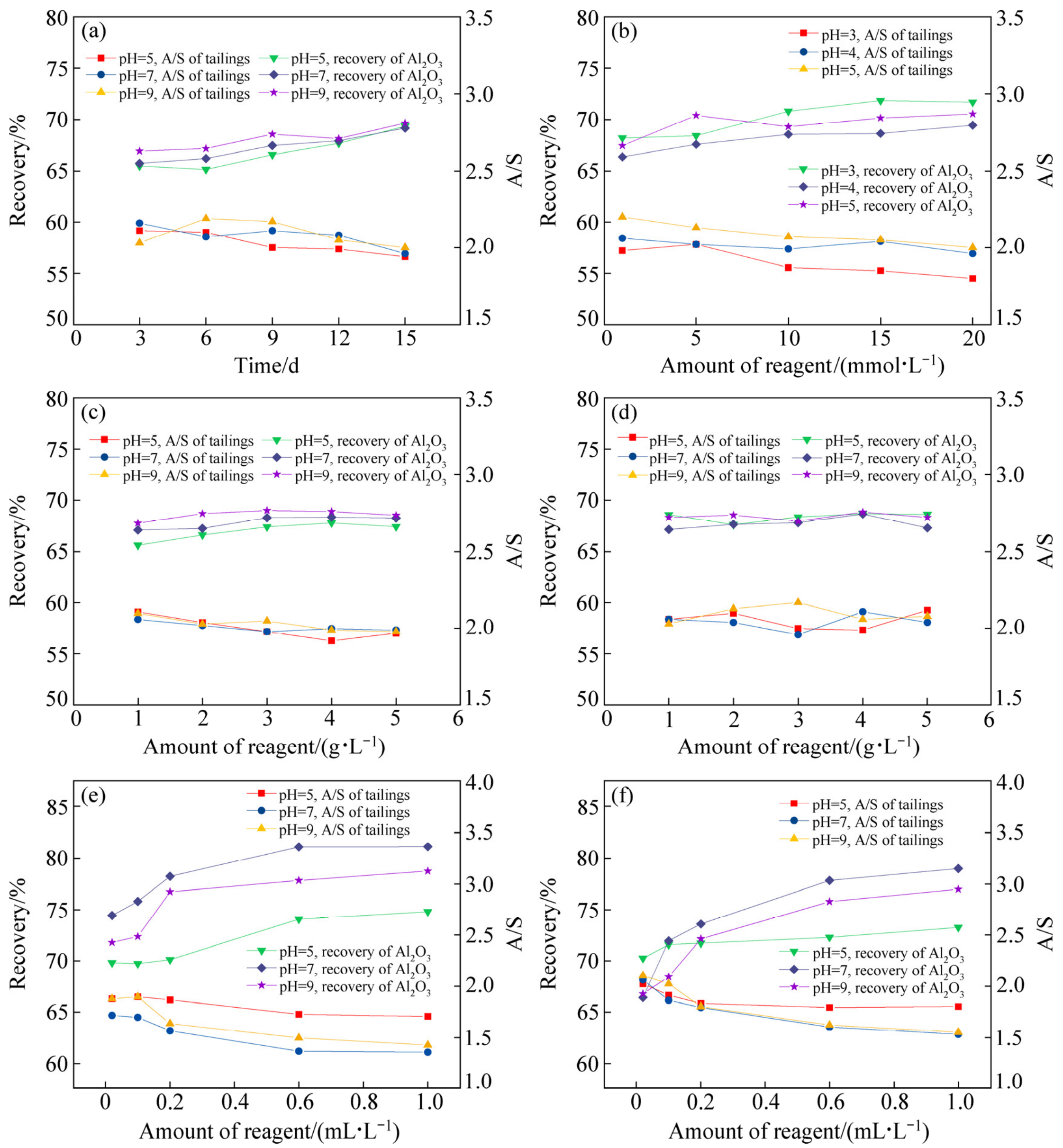

Fig. 2 Flotation results of backwater treatment group: (a) Natural placement; (b) Treated by Fenton reagent; (c) Treated by zeolite; (d) Treated by active carbon; (e) Treated by PAFC; (f) Treated by PSAF

under all three pH values within 9 d, whereas small and similar improvements to the flotation indexes occurred in the natural placement group under all three pH values after 15 d. This indicated substances that affected the flotation indexes in the backwater degraded naturally with the prolongation of natural placement time. These results also indicated that ions in backwater were not the main reason for the decrease in flotation indexes.

(2) Results for Fenton-oxidation method

As shown in Fig. 2(b), flotation indexes had a small increase after the Fenton-oxidation method, and the effect became obvious with the increase in the dosage of Fenton reagents under all three pH values, which were represented with the increase in recovery of Al_2O_3 and the decrease in A/S of the tailings.

Fenton-oxidation, as a powerful method for removing almost any organic contaminant [15], has become one of the promising and alternative wastewater treatment methods [16]. In this study, under the treatment conditions of a pH value of 3 and Fenton reagent dosage up to 20 mmol/L, the best flotation index was only gained with the increase in recovery of Al_2O_3 of 5.52% and the decrease in A/S of the tailings of 0.33, which also had a large gap in comparison with that of fresh water. The Fenton-oxidation process, combined with hydrogen peroxide and ferrous ions, generated oxidation potential species such as the hydroxyl radical, which exhibited strong oxidation and could efficiently degrade the refractory organics, whereas studies showed that the removal rate of HPAM could reach more than 90% by Fenton-oxidation in the treatment of oilfield sewage [17]. However, the HPAM concentration of the backwater was in a low range, which might be due to the inefficiency of the Fenton-oxidation method in this study.

(3) Results for adsorption method

Adsorption is a method used to purify waste water by adsorbing the pollutants by adsorbents such as activated carbon and zeolite. Activated carbon is recognized as an effective and reliable means of removing impurities due to its tremendous adsorptive capacity [18], whereas zeolite is a silicoaluminate mineral with good stability and becomes the focus of intense interest due to the potentiality of the zeolite-mediated heterogeneous processes, exclusively featured by the high reactivity for complete elimination of recalcitrant pollutants and environmental remediation [19]. However, the results of this study (Figs. 2(c) and (d)) showed the lower effectiveness of the adsorption method executed both by activated carbon and zeolite and revealed that the adsorption method executed by activated carbon and zeolite did not adapt to the treatment of backwater of bauxite flotation.

(4) Results for coagulation method

The results for the coagulation by PAFC (Fig. 2(e)) showed that the flotation indexes gradually became better with the addition of PAFC dosage under the condition of pH=7, which were better than the indexes under the conditions of pH=5 and pH=9. Charge neutralization and the adsorption bridging effect between PAFC and HPAM were the primary flocculation mechanisms when the pH was adjusted to 7. The flotation indexes became stable when the PAFC dosage exceeded 0.6 mL/L, and good results were achieved, with 81.12% recovery of Al_2O_3 and 1.37 of A/S of the tailings, representing a 14.93% increase in the recovery of Al_2O_3 and a decrease of A/S of the tailings of 0.76 in comparison to that of backwater.

Similarly, the results of the coagulation by PSAF (Fig. 2(f)) showed that the flotation indexes gradually became better with the addition of PAFC dosage. An optimum result was reached under the condition of pH of 7 and PAFC dosage of 1.0 mL/L, with an increase in the recovery of Al_2O_3 of 12.75% and a decrease in A/S of the tailings of 0.60 in comparison with that of backwater.

The coagulation/flocculation method was widely used in wastewater treatment due to its capability for destabilizing and aggregating colloids [20,21]. There were two main types of coagulants, inorganic flocculants (such as PAC) and organic flocculants (such as PAM), each of which had its advantages and disadvantages. The main coagulant used in bauxite flotation plants was HPAM, and studies showed that flotation indexes would be affected by HPAM [22]. Combined with the results of QEMSCAN, high performance of sodium polyacrylate on flocculation for diaspore was due to interaction of carboxyl of sodium polyacrylate with active Al sets of diaspores by chemical absorption or the formation of hydrogen bonds via the hydroxyl groups of macromolecules with surface Al—OH to enhance the sedimentation rate of diaspores and destroy the flotation of diaspores [23]. Treatments of backwater by inorganic flocculants (PAFC and PSAF) obtained good results, primarily due to the incompatibility between inorganic flocculants and HPAM and the removal of HPAM after the addition of inorganic flocculants by the formation of the flocs [24].

3.3 Optimization by Box-Behnken design

3.3.1 Analysis of Box-Behnken design

In this study, the BBD was applied, and 15 experimental runs were conducted in random order to optimize backwater treatment by PAFC, which was characterized by recovery of Al_2O_3 (Y_1) and A/S of Tailings (Y_2) [25]. The effects of key parameters, pH (X_1), PAFC dosage (X_2) and temperature (X_3), on backwater treatment were evaluated. The analysis of variance results are listed in Tables 7 and 8. According to the

Table 7 Analysis of variance for recovery of Al_2O_3 (Y_1)

Source	Degree of freedom	Sum of squares	Mean square	F-value	p-value
Model	9	226.397	25.1552	71.29	0.000
Linear	3	110.730	36.9098	104.61	0.000
X_1, pH	1	66.183	66.1825	187.57	0.000
X_2, PAFC dosage	1	37.628	37.6278	106.64	0.000
X_3, temperature	1	6.919	6.9192	19.61	0.007
Square	3	111.663	37.2211	105.49	0.000
X_1^2	1	93.125	93.1249	263.93	0.000
X_2^2	1	21.661	21.6609	61.39	0.001
X_3^2	1	7.759	7.7586	21.99	0.005
2-way interaction	3	4.004	1.3347	3.78	0.093
X_1X_2	1	0.354	0.3540	1.00	0.362
X_1X_3	1	0.116	0.1156	0.33	0.592
X_2X_3	1	3.534	3.5344	10.02	0.025
Error	5	1.764	0.3528		
Lack-of-fit	3	1.191	0.3970	1.38	0.445
Pure error	2	0.573	0.2866		
Total	14	228.161			
Model summary	S=0.594	R^2=0.9923	R^2(Adj)=0.9783	R^2(Pred)=0.9108	

Table 8 Analysis of variance for A/S of tailings (Y_2)

Source	Degree of freedom	Sum of squares	Mean square	F-value	p-value
Model	9	0.5711	0.0635	26.02	0.001
Linear	3	0.1968	0.0656	26.91	0.002
X_1, pH	1	0.1352	0.1352	55.45	0.001
X_2, PAFC dosage	1	0.0595	0.0595	24.41	0.004
X_3, temperature	1	0.0021	0.0021	0.87	0.395
Square	3	0.3504	0.1168	47.89	0.000
X_1^2	1	0.2269	0.2269	93.07	0.000
X_2^2	1	0.1483	0.1483	60.82	0.001
X_3^2	1	0.0094	0.0094	3.85	0.107
2-way interaction	3	0.0239	0.0080	3.27	0.117
X_1X_2	1	0.0025	0.0025	1.03	0.358
X_1X_3	1	0.0004	0.0004	0.16	0.702
X_2X_3	1	0.0210	0.0210	8.62	0.032
Error	5	0.0122	0.0024		
Lack-of-Fit	3	0.0117	0.0039	16.75	0.057
Pure error	2	0.0005	0.0002		
Total	14	0.5833			
Model summary	S=0.04938	R^2=0.9791	R^2(Adj)=0.9415	R^2(Pred)=0.6766	

RSM results in regard to the response variables of the effect of backwater treatment, which were acquired from 15 groups of experiments with the help of Minitab 17 software, the regression analysis of data from Tables 7 and 8 resulted in the following quadratic expressions:

$$Y_1=-9.41+18.86X_1+27.22X_2+0.456X_3-1.2555X_1^2-15.14X_2^2-0.01450X_3^2+0.372X_1X_2-0.0085X_1X_3+0.2350X_2X_3 \quad (1)$$

$$Y_2=5.772-0.889X_1-2.049X_2-0.0020X_3+0.06198X_1^2+1.253X_2^2+0.000504X_3^2-0.0313X_1X_2-0.00050X_1X_3-0.01812X_2X_3 \quad (2)$$

Statistical testing was carried out by the calculated Fischer values (*F*-value) and probability values (*p*-value). The corresponding parameter is more significant if its *p*-value is smaller than 0.05 at a 95% confidence level [26]. Lack of fit was used to represent the degree of fit between the model and the actual experiment. The model was significant, and there was no missing factor when the *p*-value of lack of fit exceeded 0.05. A nonsignificant lack of fit was required to obtain an acceptable model.

As shown in Table 7, regarding the analysis of variance for recovery of Al_2O_3, the model had a higher *F*-value of 71.29, which implied that the model was significant, and the probability that the *F*-value would occur due to noise was less than 0.1%. The independent variables of the linear model, pH (X_1), PAFC dosage (X_2) and temperature (X_3), those of the quadratic model, pH (X_1^2), PAFC dosage (X_2^2) and temperature (X_3^2), and the interaction model between PAFC dosage and temperature (X_2X_3) were quite significant because the *p*-values were less than 0.05, whereas the interaction between pH and PAFC dosage (X_1X_2) and the interaction between pH and temperature (X_1X_3) were not significant because the *p*-values exceeded 0.05. Judging by the *F*-values of the items in the regression model, the pH (X_1) had the highest *F*-value (187.57), whereas the *p*-value was at a low level among other parameters, and, therefore, the degrees of importance of the three parameters on recovery of Al_2O_3 were ranked in the order pH (X_1) > PAFC dosage (X_2) > temperature (X_3). The lack of fit *F*-value of 0.445 implied that lack of fit was not significant relative to the pure error. The R^2 was 99.23%, and the adjusted R^2 (R^2(Adj)) was 97.83%, representing an excellent fit, and the predicted R^2 (R^2(Pred)) was 91.08%, which was in fair arrangement with the R^2(Adj).

As shown in Table 8 for the analysis of variance for A/S of tailings, the model had a higher *F*-value of 26.02, which implied that the model was significant, and the chance for the *F*-value to occur due to noise was less than 0.1%. The independent variables of the linear model, pH (X_1) and PAFC dosage (X_2), the quadratic model, pH (X_1^2), PAFC dosage (X_2^2) and temperature (X_3^2), and the interaction model between PAFC dosage and temperature (X_2X_3) were quite significant because the *p*-values were less than 0.05, whereas the linear model temperature (X_3), the interaction between pH and PAFC dosage (X_1X_2) and the interaction between pH and temperature (X_1X_3) were not significant because the *p*-values exceeded 0.05. Judging by the *F*-values of the items in the regression model, the pH (X_1) had the highest *F*-value (55.45), whereas the *p*-value was at a low level among other parameters, and, therefore, the degrees of importance of the three parameters on A/S of tailings were ranked in the order pH (X_1) > PAFC dosage (X_2) > temperature (X_3). The lack of fit *F*-value of 0.445 implied that lack of fit is not significant relative to the pure error. The R^2 was 0.9791, and the R^2(Adj) was 0.9415, which represented a good fit, but the R^2(Pred) was 0.6766, which meant some deviations with the R^2(Adj).

3.3.2 Analysis by RSM

The significance of each of the three independent factors (pH, PAFC dosage and temperature) on recovery of Al_2O_3 (Y_1) and A/S of Tailings (Y_2) was revealed by illustrating the response surfaces as three dimensional (3D) plots (Fig. 3). The temperature was fixed at 25 °C (Figs. 3(a) and (d)), whereas the PAFC dosage and pH were kept constant at 1.09 mL/L (Figs. 3(b) and (e)) and 7.55 (Figs. 3(c) and (f)), respectively.

The variation in pH led to the steep climb and drop as shown in Figs. 3(a), (b), (d) and (e), whereas the gentle climb and drop appeared during the variations in PAFC dosage and temperature. Meanwhile, in Figs. 3(c) and (f), the variation in PAFC dosage dramatically affected recovery of Al_2O_3 and A/S of tailings, whereas the variation in temperature was less important. It can be seen that the variation in pH was more important than the other two factors for recovery of Al_2O_3 and A/S of tailings, whereas the variation in temperature gained the least contribution among the three factors.

3.3.3 Results of verification tests

The response optimization technique helped to identify a production of a combination of input variables that collectively optimized a single response or a set of responses [27]. By using response optimizer to identify the combination of predictor values that jointly optimize the recovery of Al_2O_3 (maximum) and the A/S of tailings (minimum), which were a pH of 7.55, PAFC dosage of 1.09 mL/L and temperature of 25 °C, with maximal recovery of Al_2O_3 of 83.28% and minimal A/S of tailings of 1.27.

As shown in Table 9, under optimal conditions proposed by response optimizer, 82.83% of the recovery of Al_2O_3 and 1.30 of the A/S of tailings were achieved

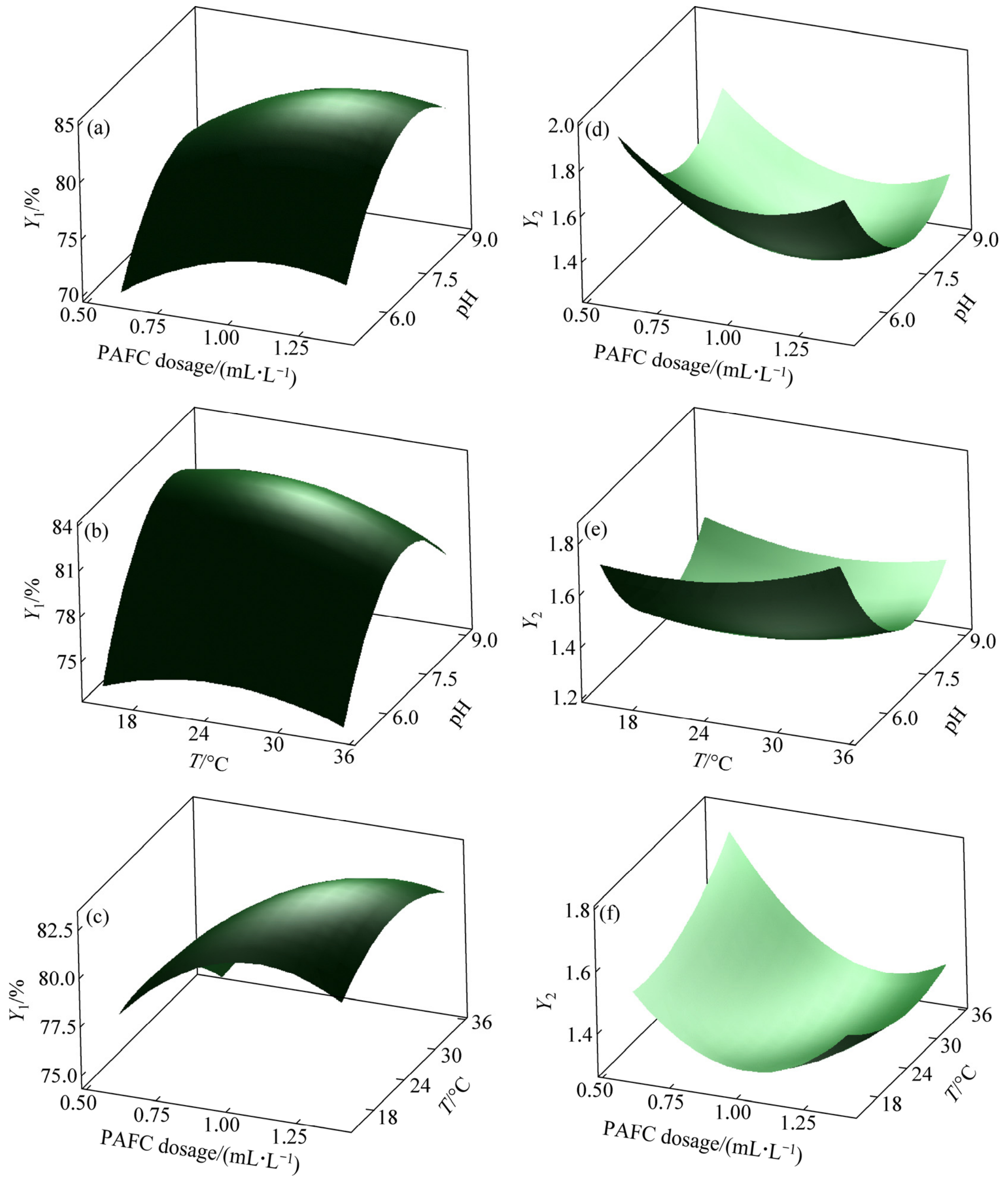

Fig. 3 3D surface plots of recovery of Al_2O_3 (Y_1) as functions of pH and PAFC dosage (a), pH and temperature (b) and PAFC dosage and temperature (c); 3D surface plots of A/S of tailings (Y_2) as functions of pH and PAFC dosage (d), pH and temperature (e) and PAFC dosage and temperature (f)

Table 9 Flotation results of backwater treated under predicted conditions

Product	Production/%	$w(Al_2O_3)$/%	$w(SiO_2)$/%	A/S	Recovery of Al_2O_3/%
Concentrate	77.12	61.66	14.64	4.21	82.83
Tailing	22.88	43.07	33.13	1.30	17.17
Ore	100.00	57.40	18.87	3.04	100.00

(the average of three replicates), while the deviations between the actual and predicted values were both less than 3%. The predicted values were basically consistent with the measured values, indicating that the mathematical model established by RSM of BBD was powerful in prediction.

4 Conclusions

(1) Flotation indexes gradually decreased with the increase in cycle time of the backwater in bauxite floatation. Accumulation of the residual HPAM in

backwater was the main reason for the decrease in flotation indexes.

(2) After the backwater was treated by PAFC, good flotation indexes were gained; this result was due to the reduction in the concentration of HPAM in the backwater for the incompatibility between PAFC and HPAM.

(3) The optimum parameter values were predicted to be a pH of 7.55, PAFC dosage of 1.09 mL/L and temperature of 25 °C by BBD. Under these optimum conditions, a maximum recovery 82.83% of Al_2O_3 and a minimum A/S 1.30 of tailings were gained. Both of the deviations were less than 3% with respect to the predicted values; these finding thus encourage the application of BBD for the optimization of critical parameters in backwater treatment.

References

[1] WANG Bo, CHU Wei-qin, HAO Yuan-liang, RONG Shuo, SUN Hui-lan. Synthesis and alumina leaching mechanism of calcium sulphoaluminate [J]. Transactions of Nonferrous Metals Society of China, 2017, 27(9): 2090−2095.

[2] XIA Liu-yin, ZHONG Hong, LIU Guang-yi. Flotation techniques for separation of diaspore from bauxite using Gemini collector and starch depressant [J]. Transactions of Nonferrous Metals Society of China, 2010, 20(3): 495−501.

[3] CHEN Xiao-jing. The influence of mineral processing technology of low grade bauxite on the efficiency of Bayer process [J]. World Nonferrous Metal, 2017(7): 37−38. (in Chinese)

[4] CHEN Xiang-qing, YAO Guo-xin, XIONG Dao-ling, ZHENG Hui-hui, CHEN Jin-zhou, YANG Jin-xing, LI Su-min. Application research on flocculant for Dressing-Bayer process of alumina production [J]. Light Metals, 2014(10): 21−26. (in Chinese)

[5] CHANG Zi-yong, FENG Qi-ming, OU Le-ming. Study on the impact of flocculants in backwater on bauxite flotation [J]. Nonferrous Metals (Mineral Processing Section), 2014 (6): 88−91. (in Chinese)

[6] LIU Han. Study on utilization of tailings backwater from bauxite flotation [D]. Changsha: Central South University, 2011. (in Chinese)

[7] LOPACHIN J R M, LEHNING E J. Acrylamide-induced distal axon degeneration: A proposed mechanism of action [J]. Neurotoxicology, 1994, 15(2): 247−259.

[8] LUO Yuan-ling, YANG Zhao-hui, XU Zheng-yong, ZHOU Ling-jun, ZENG Guang-ming, HUANG Jing, XIAO Yong, WANG Li-ke. Effect of trace amounts of polyacrylamide (PAM) on long-term performance of activated sludge [J]. Journal of Hazardous Materials, 2011, 189(1−2): 69−75.

[9] GOLPAYEGANI M H, ABDOLLAHZADEH A A. Optimization of operating parameters and kinetics for chloride leaching of lead from melting furnace [J]. Transactions of Nonferrous Metals Society of China, 2017, 27(12): 2704−2714.

[10] TETTEH E K, RATHILAL S. Effects of a polymeric organic coagulant for industrial mineral oil wastewater treatment using response surface methodology (RSM) [J]. Water SA, 2018, 44(2): 155−161.

[11] YU Xin-yang, WAN Hao-lin, WANG Qiang-qiang, FENG Bo, ZHONG Hong. Flotation of low-grade bauxite using organosilicon cationic collector and starch depressant [J]. Transactions of Nonferrous Metals Society of China, 2016, 26(4): 1112−1117.

[12] RAO D S, DAS B. Characterization and beneficiation studies of a low grade bauxite ore [J]. Journal of The Institution of Engineers (India): Series D, 2014, 95(2): 81−93.

[13] LI Su-min, GUO Xin, TIAN Ying-zhong. Study of settleability of bauxite flotation concentrates and tailings [J]. Light Metals, 2017(2): 7−12. (in Chinese)

[14] LIU Xiao-kai. Study on strengthening dispersion and flotation test of low grade bauxite [D]. Xuzhou: China University of Mining and Technology, 2015. (in Chinese)

[15] CETINKAYA S G, MORCALI M H, AKARSU S, AKARSU S, ZIBA C A, DOLAZ M. Comparison of classic Fenton with ultrasound Fenton processes on industrial textile wastewater [J]. Sustainable Environment Research, 2018, 28(4): 165−170.

[16] WU Dong-lei, WANG wei, GUO Qing-wen, SHEN Yan-hong. Combined Fenton-SBR process for bamboo industry wastewater treatment [J]. Chemical Engineering Journal, 2013, 214: 278−284.

[17] PI Yong-rui, ZHENG Zhong-huan, BAO Mu-tai, LI Yi-ming, ZHOU Ying-ying, SANG Guo-liang. Treatment of partially hydrolyzed polyacrylamide wastewater by combined Fenton oxidation and anaerobic biological processes [J]. Chemical Engineering Journal, 2015, 273: 1−6.

[18] ELTOM A E, LESSA M P F, DA SILVA M J, DA ROCHA J C. Production & characterization of activated carbon membranes [J]. Journal of Materials Research and Technology, 2012, 1(2): 80−83.

[19] FOO K Y, HAMEED B H. The environmental applications of activated carbon/zeolite composite materials [J]. Advances in Colloid and Interface Science, 2011, 162(1−2): 22−28.

[20] MENEZES F M, AMAL R, LUKETINA D. Removal of particles using coagulation and flocculation in a dynamic separator [J]. Powder Technology, 1996, 88(1): 27−31.

[21] ZHANG J C, WANG Y H, SONG L F, HU J Y, ONG S L, NG W J, LEE L Y. Feasibility investigation of refinery wastewater treatment by combination of PACs and coagulant with ultrafiltration [J]. Desalination, 2005, 174(3): 247−256.

[22] HUO Qiang, CHEN Zhi-you, CHEN Shun-jiao, XIE Jian-ping, LIU Xin-xing, QIU Guan-zhou. Experimental study on backwater treatment by polyaluminum chloride in bauxite flotation [J]. Non-Metallic Mines, 2018, 41(4): 80−82. (in Chinese)

[23] HUANG Chuan-bing, WANG Yu-hua. Removal of aluminosilicates from diasporic-bauxite by selective flocculation using sodium polyacrylate [J]. Separation and Purification Technology, 2008, 59(3): 299−303.

[24] WU De-na. Study on interaction between HPAM and water treatment agents [D]. Xi'an: Northeast Petroleum University, 2012. (in Chinese)

[25] TETTEH E K, RATHILAL S. Application of response surface methodology (RSM)-reduction of industrial wastewater chemical oxygen demand [C]//CBU International Conference Proceedings. Bohemia: Central Bohemia University, 2017: 1226−1232.

[26] PENG Zhi-xiong, HE Hui-jun, YANG Chun-ping, ZENG Guang-ming, WEN Shan, YAN Zhou, XIANG Hai-hong, CHENG Yan, TARRE S, GREEN M. Biological treatment of wastewater with high concentrations of zinc and sulfate ions from zinc pyrithione synthesis [J]. Transactions of Nonferrous Metals Society of China, 2017, 27(11): 2481−2491.

[27] YANG Chun-ping, ZHAO Kun, CHENG Yan, ZENG Guang-ming, ZHANG Ming-ming, SHAO Jing-jing, LU Li. Catalytic oxidative desulfurization of BT and DBT from n-octane using cyclohexanone peroxide and catalyst of molybdenum supported on 4A molecular sieve [J]. Separation and Purification Technology, 2016, 163: 153−161.

基于 Box-Behnken 设计优化铝土矿选矿回水处理工艺参数

霍 强[1,2]，刘 晰[3]，陈黎军[1]，吴永宏[1,2]，武海艳[1,2]，谢建平[1,2]，刘新星[1,2]，邱冠周[1,2]

1. 中南大学 资源加工与生物工程学院，长沙 410083；
2. 中南大学 生物冶金教育部重点实验室，长沙 410083；
3. 中国铝业郑州有色金属研究院有限公司，郑州 450041

摘 要：随着铝土矿浮选回水循环时间的增加，铝土矿浮选指标逐渐降低，而浮选回水的外排会带来一定的环境风险。采用 Fenton 氧化、吸附、混凝等方法处理浮选回水，测定处理后浮选回水的浮选指标，并采用 Box-Behnken 设计(BBD)对主要试验参数进行优化。结果表明，聚合氯化铝铁对混凝处理后的浮选指标有明显的改善作用。BBD 预测的最佳参数值为 pH 7.55、聚合氯化铝铁用量 1.09 g/L、温度 25 °C。在预测的最佳工艺参数下，精矿氧化铝回收率 82.83%、尾矿铝硅比为 1.30，结果与预测值的偏差均小于 3%，这表明 BBD 适用于选矿回水处理中关键参数的优化预测。

关键词：回水处理；铝土矿浮选；聚合氯化铝铁；Box-Behnken 设计

(Edited by Xiang-qun LI)