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1 **Recovery of Chromium from Residue of Sulfuric Acid**

2 **Leaching of Chromite**

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1 **Abstract:** The sulfuric acid leaching process is widely considered to be a cleaner technology to prepare
2 chromium salt from natural chromite as no Cr(VI)-bearing wastes are generated or discharged. However,
3 some insoluble anhydrous chromium sulfate could precipitate causing a serious chromium resource loss and
4 potential pollution problems. For the purpose of recovery of chromium from leaching residue, a Box-
5 Behnken design (BBD) based ammonium leaching treatment is investigated and optimized. A second-order
6 polynomial regression model that reveals the functional relationship between processing parameters and
7 recovery time is established and verified by the analysis of variance (ANOVA). Predicted results show a good
8 agreement with the experimental data. The main and interactive effects of the processing parameters on the
9 recovery time are illustrated by three-dimensional (3D) response surfaces. On the basis of the findings in this
10 study, an advanced sulfuric acid leaching process of chromite is proposed. All of the chromium resources can
11 be utilized in the novel process, and no hazardous wastes or potential pollutants are discharged to the
12 environment.

13

14 **Keyword:** Anhydrous chromium sulfate; Chromium recovery; Box-Behnken design; Remediation; Cleaner
15 production

1 **1. Introduction**

2 Cr(III) salts are important chemical feedstocks that serve as tanning agent, pigments, catalyst etc. in various
3 applications. Alkaline roast processes including calcium-roasting and low- or non-calcium-roasting are
4 principal technologies for preparing Cr(III) salts from natural chromite. In the strong oxidizing environment
5 at high temperature, chromite decomposes due to the transformation from Cr(III) into Cr(VI) and chromium
6 concentrates, and subsequently Cr(III) salt products are prepared after a reduction treatment for Cr(VI)-
7 bearing substances (Yarkadaş and Yildiz, 2013). In these processes, significant amounts of Cr(VI)-bearing
8 chromite ore processing residue (COPR) are generated and discharged to the environment (Freese et al., 2014;
9 Wang et al., 2017). It is known that Cr(VI) is a carcinogen and a dermatological and pulmonary sensitizer
10 that is 500 times more toxic than Cr(III) (Kowalski, 1994; Chrysochoou et al., 2009), but the remediation
11 and comprehensive utilization of COPR are still thorny problems (Sheng et al., 2006). Millions of tons of
12 COPR have been deposited in residential and industrial areas causing grave pollution problems in many
13 countries around the globe (Burke et al., 1991; Lioy et al., 1992; Farmer et al., 1999; Darrie, 2001; Matern
14 et al., 2016).

15 To avoid the formation of Cr(VI) from the source, a sulfuric acid leaching process was proposed and
16 extensively studied (Zhao et al., 2015, 2017; Zhang et al., 2016). Literature indicates that in this process, with
17 a suitable oxidant, chromium can be extracted from chromite in trivalent state using a heated sulfuric acid
18 solution (Geveci et al., 2002; Liu et al., 2011). A lot of effort is being made to improve this cleaner process
19 for manufacturing Cr(III) salts, but the extraction yield of chromium is still unsatisfactory.

20 Biermann et al. (1960) suggested the main reason of the incomplete recovery of chromium to be the
21 precipitation of a Cr(III)-rich multicomponent sulfates, which was reported to be grey-green in color and
22 acid-insoluble. Vardar et al. (1994) found similar phases in the residue after sulfuric acid leaching treatment

1 applied to UG-2 chromite, and speculated that the precipitation of the sulfates may be a function of processing
2 conditions. Experimental results indicated that when the leaching tests were conducted using 75 wt.% sulfuric
3 acid at 210 °C, sulfates in the residue add up to 80 wt.%. Geveci et al. (2002) detected $\text{Cr}_2(\text{SO}_4)_3$ in leaching
4 residue using X-ray diffraction (XRD) analysis, and attributed the incomplete extraction of chromium to the
5 sulfate precipitation.

6 These findings were verified by the authors of this paper. Scanning electron microscopy (SEM) images of
7 the sulfates generated in the leaching process of South African chromite have been presented in our earlier
8 reporting. Factors were proposed that could result in an ionic supersaturation in the solid-liquid reaction
9 boundary layer, which would cause the precipitation of Cr-rich sulfates (Zhao et al., 2014). Furthermore, the
10 precipitated sulfates were found to cover the unreacted chromite powder, limiting the chromite dissolution.
11 Therefore the extraction yield of chromium has a significant negative correlation with the precipitation
12 quantity (Jiang et al., 2014). It was noted that Cr(III) is not stable in the form of sulfate in the residue. It may
13 be oxidized to the toxic Cr(VI), especially in alkaline oxidizing conditions (Eary and Davis, 2007), making
14 the slag field an potential source of chromium contamination of nearby soils and waters (Elzinga and Ashley,
15 2010). Even if the chromium is not oxidized, the pollution risks still remain. Accumulation of Cr(III) in soils
16 can inhibit various enzyme systems of living organisms, and the influence of Cr(III) on the surrounding
17 environment could be more serious with the presence of organic ligands and/or under acidic conditions
18 (Ghaedi et al., 2006; Anirudhan and Radhakrishnan, 2007). Despite this, the stabilization or recycling of the
19 Cr-bearing residue generated in sulfuric acid leaching process of chromite has not been described in the open
20 literature.

21 Our earlier studies showed that the generation of Cr-rich sulfates could be restricted or even avoided by
22 optimizing leaching process parameters for South African chromite in the laboratory (Jiang et al., 2014). For

1 industrial production or for other kinds of chromites, however, the risk of chromium loss and pollution cannot
2 only rely on the process control. Therefore, specific treatments for chromium recovery and remediation of
3 residue need to be implemented.

4 It has been confirmed that the precipitated sulfates contain both water-soluble hydrous chromium sulfate
5 and water-insoluble anhydrous chromium sulfate. The former substance can be easily recovered by washing
6 treatment, and the Cr(III) extraction from aqueous phase is well studied (Aravindhana et al., 2004; Fahim et
7 al., 2006; Dettmer et al., 2010). However, little research addressed the recovery of anhydrous chromium
8 sulfate from solid wastes. One concept for separating this phase from unreacted chromite powder is to
9 transform it into water-soluble phases, by which chromium recovery and unreacted chromite enrichment
10 could be both achieved. Wenzel et al. (2010) added ammonium sulfate in the sulfuric acid leaching process
11 of high carbon ferrochromium alloy at 170 °C to inhibit the formation of anhydrous chromium sulfate.
12 Experimental results indicated that in the presence of ammonium sulfate almost all chromium was extracted
13 in a soluble form while no remarkable effect on the Fe(II)-bearing substance was found. Acid-soluble
14 ammonium chromium sulfate was claimed to be generated. However, whether the goal that transforming the
15 anhydrous chromium sulfate into ammonium chromium sulfate in sulfuric acid leaching process can be
16 achieved remains unknown.

17 Response surface methodology (RSM) is a group of mathematical and statistical techniques for analyzing
18 the relationships between controllable input parameters and one or more measured responses with a limited
19 set of experiments (Kwak, 2005; Ravikumar et al., 2007). Box-Behnken design (BBD) is widely adopted by
20 scientists in various research fields to provide experimental data for response surface modeling (Ferreira et
21 al., 2007; Kiran and Thanasekaran, 2012; Das, 2014; Jeganathan, 2014). With the aim of extracting anhydrate
22 chromium sulfate, an ammonium treatment was carried out in this work, and the combined effects of pH

1 value of solution (pH), processing temperature (T), and ammonium dosage (R) on the chromium recovery
2 behavior (i.e. time needed and efficiency) were studied by BBD and black-box modeling. .

3 **2. Thermodynamic analysis**

4 The formation of anhydrous chromium sulfate can be attributed to the dehydration effect of concentrated
5 sulfuric acid at high temperature, which was proven by the evidence that more anhydrous chromium sulfate
6 precipitated from aqueous solution when the temperature and/or concentration of sulfuric acid were high
7 in the leaching process (Jiang et al., 2014; Zhao et al., 2014).

8 Due to the high solubility in acid solution, ammonium chromium sulfate has been suggested to be a
9 promising reaction intermediate for recovering anhydrous chromium sulfate (Wenzel et al., 2010). An Eh-pH
10 diagram of the Cr-N-S-H₂O at 160 °C as shown in Fig. 1 was calculated by the FactSage software (7.0,
11 CRCT-ThermFact Inc., CAN; GTT-Technologies, GER). For negative ordinate ($E < 0$), the system is able
12 to supply the electrons to the species found in the solution. By contrast, the system tends to remove electrons
13 from the species if $E > 0$, which applies when oxidant is present. In the sulfuric acid leaching process for
14 chromite, a strong oxidizing environment is maintained by the presence of oxidant and the employment of
15 concentrated sulfuric acid. From Fig. 1 it can be confirmed that Cr₂(SO₄)₃ could precipitate from the solutions
16 and be stable under leaching conditions (area delimited by the dotted box), while NH₄⁺ can be oxidized into
17 a N₂ if the solution is in a strongly oxidizing state. Therefore, different from the study reported by Wenzel et
18 al. (2010), ammonium source materials cannot be directly added to the strong oxidizing acid solution that is
19 used for decomposing chromite, thus the ammonium treatment for leaching residue after leaching process
20 seems more reasonable.

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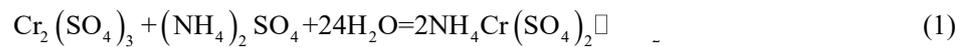
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Fig. 1 Eh-pH diagram of the Cr-N-S-H₂O system at 160 °C.

3. Experimental

3.1 Materials

Ammonium sulfate ((NH₄)₂SO₄ ≥ 99.0 wt.%) was employed as the ammonium source for recovering anhydrous chromium sulfate, giving the ion reaction



For the purpose of exclusively investigating the reaction behavior of the two substances, a pure anhydrous chromium sulfate was prepared from hydrous chromium sulfate (Cr₂SO₄•6H₂O ≥ 98 wt.%) by roasting in a muffle furnace at 350 °C for 4 h.

18.65 g of a typical leaching residue smaller than 10 μm obtained from a leaching test with a low leaching yield of chromium(37.5%) was also studied in this work. Processing details of the test and phase composition can be found in Jiang et al. (2014) and Zhao et al. (2014). The residue was collected after filtration and analyzed by inductively coupled plasma-optical emission spectrometry (ICP-OES), energy-dispersive X-ray spectroscopy (EDS), thermogravimetric and differential scanning calorimetry (TG-DSC), and chemical analysis according to the People's Republic of China national standards. Analysis results indicated that the residue contains 39.7 wt.% chromium sulfate, including hydrous chromium sulfate and anhydrous chromium sulfate, 26.9 wt.% of iron sulfate, 16.2 wt.% aluminum sulfate, 10.1 wt.% magnesium sulfate, 5.7 wt.%

1 amorphous silica, and 1.4 wt.% unreacted chromite. A Shimadzu SSX-550TM was employed for SEM-EDS
2 analysis, and the results are presented in Fig. 2. Many flaky particles smaller than 5 μm were observed in the
3 residue and were found to be Cr(III)-rich multicomponent sulfates, in line with the previous findings (Zhao
4 et al., 2014).

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8 Fig. 2 SEM images of residue obtained from leaching process of chromite using 80 wt.% sulfuric acid at 200 °C for 1 h.

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12 As reagents, sulfuric acid ($95.0 \text{ wt.}\% \leq \text{H}_2\text{SO}_4 \leq 98.0 \text{ wt.}\%$), sodium hydroxide ($\text{NaOH} \geq 96 \text{ wt.}\%$), sodium
13 carbonate anhydrous ($\text{Na}_2\text{CO}_3 \geq 99.8 \text{ wt.}\%$), sodium hydrogen carbonate ($\text{NaHCO}_3 \geq 99.8 \text{ wt.}\%$), scrap iron
14 ($\text{Fe} \geq 98 \text{ wt.}\%$), oxalic acid ($\text{C}_2\text{H}_2\text{O}_4 \cdot 2\text{H}_2\text{O} \geq 99.8 \text{ wt.}\%$), and ethanol ($73.0 \text{ wt.}\% \leq \text{C}_2\text{H}_6\text{O} \leq 75 \text{ wt.}\%$) were
15 used in this study, provided by Sinopharm Chemical Reagent Co., Ltd., China.

16 3.2 Methods

17 Sulfuric acid and deionized water were mixed in an Erlenmeyer flask on an automatic temperature-
18 controlled electric heater, after which the agitation and heating were started (cf. Fig. 3). Anhydrous chromium
19 sulfate (2 g) and some ammonium sulfate were poured into the solution and timing was started when the
20 temperature reached the set point. When all the particles dissolved into the solution, the experiments were
21 stopped and the time passed was reported as the recovery time. The effects of pH , T , and R , expressed as the
22 molar ratio of actual dosage of ammonium and theoretical (stoichiometric) dosage of ammonium with

1 reference to the Eq. (1), on the recovery behavior were investigated. Each experiment was repeated at least
 2 three times, and the mean value was reported as the experimental results.

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6 Fig. 3 Experimental setup for the recovery of anhydrous chromium sulfate by ammonium leaching.

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10 Aiming at finding a suitable approximation for the true functional relationship between the three
 11 independent variables and the dependent variable, BBD was conducted and a quadratic response surface
 12 model with a consideration of parameter interactions was proposed as

$$13 \quad t_m = b_0 + b_1 pH_c + b_2 T_c + b_3 R_c + b_{12} pH_c T_c + b_{13} pH_c R_c + b_{23} T_c R_c + b_{11} pH_c^2 + b_{22} T_c^2 + b_{33} R_c^2 \quad (2)$$

14 where t_m is the predicted time (min) for anhydrous chromium sulfate recovery; b_0 is the model constant, b_i (i
 15 = 1, 2, 3) are the parameters of linear effect of the i^{th} factor, b_{ij} (i and $j = 1, 2, 3; i \neq j$) is the interaction effect
 16 parameter of the i^{th} and j^{th} factors, and b_{ii} is the quadratic effect parameter of the i^{th} factor. pH_c , T_c , and R_c
 17 are the normalized dimensionless factors (of pH , T , and R) in the model, represented as

$$18 \quad pH_c = \frac{pH - pH_0}{\Delta pH} \quad (3)$$

$$19 \quad T_c = \frac{T - T_0}{\Delta T} \quad (4)$$

$$20 \quad R_c = \frac{R - R_0}{\Delta R} \quad (5)$$

21 where pH_0 , T_0 , and R_0 are the central points of the experimental region of the variables, and ΔpH , ΔT , and
 22 ΔR are the intervals between the levels of the variables (Wenzel et al., 2010). Based on the thermodynamic

1 analysis, the central points of pH , T , and R were selected as -0.5 , 80 °C, and $2:1$, and the intervals were
2 defined as 0.5 , 10 °C, and $1:1$, respectively.

3 Multiple regression analysis and the analysis of variance (ANOVA) were performed to fit the model by
4 using Design Expert software (8.0.6, Stat-Ease Inc., USA). Three-dimensional (3D) response surface plots
5 were employed to study the interactive effect of processing parameters on the recovery time of anhydrous
6 chromium sulfate. The coefficient of determination (R^2), adjusted coefficient of determination (Adj. R^2) and
7 predicted coefficient of determination (Pred. R^2) were calculated to evaluate the goodness of fit and predictive
8 ability of the proposed model.

9 A significance level of $\alpha = 0.05$ was used to determine the statistical significance, and the F value was
10 employed for the evaluation of the significance of the mathematical model. The significance of each
11 coefficient was determined by p values: a low p value means a higher significance of the corresponding
12 parameter in the regression model (Yetilmezsoy and Saral, 2007).

13 The optimal conditions for anhydrous chromium sulfate recovery using ammonium leaching were obtained
14 by means of Derringer's desired function methodology (Derringer and Suich, 1980). Duplicate confirmatory
15 tests were conducted under the optimum conditions given by the model and the average value of the
16 experimental results was compared with the predicted value.

17 To recycle silica from residue and unreacted chromite, respectively, 5 wt.% sodium hydroxide treatment
18 was carried out after ammonium leaching. XRD and SEM-EDS analysis were employed to detect the phase
19 composition of the samples obtained after each treatment.

20 **4. Results and discussion**

21 *4.1 BBD based ammonium leaching*

1 4.1.1 Modeling

2 The result of the BBD design with actual and coded values for three variables at three levels are reported
3 in Table 1. The experimental recovery time, t_{exp} , and t_m are also listed in the table.

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Table 1 BBD with actual and normalized values for three variables and results of this study.

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11 It is found from the experimental results that the pH value of the solution, processing temperature, and
12 ammonium dosage have significant influence on the recovery behavior of anhydrous chromium sulfate. For
13 the purpose of describing the relationship between the recovery time and the three factors, the coefficients of
14 Eq. (2) were determined by applying multiple regression analysis on the experimental data shown in Table 1,
15 and a second-order polynomial was obtained

16
$$t_m = 100 + 41.63pH_c - 55.87T_c - 5R_c - 16pH_cT_c + 2.25pH_cR_c - 2.25T_cR_c + 34.5pH_c^2 + 35.5T_c^2 + 47.25R_c^2 \quad (6)$$

17 The positive coefficients of pH_c , pH_cR_c , pH_c^2 , T_c^2 , and R_c^2 indicate a favorable effect on the anhydrous
18 chromium sulfate recovery, while the negative coefficients of T_c , R_c , pH_cT_c , T_cR_c present an unfavorable effect.

19 4.1.2 ANOVA

20 The hypotheses in the parameters of the RSM quadratic model obtained in this study were tested by the
21 ANOVA (Mourabet et al., 2012), and the results are shown in Table 2. For the model, $F = 76.90$ which means
22 the model is significant: There is only a 0.01% chance that such a value would occur due to noise. In the

1 ANOVA, values of Prob. > F less than 0.05 suggest the model terms are significant, and values more than
2 0.1000 mean the model terms are not significant. On the basis of this, pH , T , pHT , pH^2 , T^2 , and R^2 are
3 significant model terms, while other model terms are not significant.

4 The criteria R^2 , Adj. R^2 , and Pred. R^2 were employed to check the goodness of fit and the predictive ability
5 of the model. The high value of the coefficient of determination ($R^2 = 0.9900$) implies that only about 1.00%
6 of the total variations is not explained by Eq. (6), demonstrating that the independent variables and dependent
7 variable have a high correlation. The Adj. R^2 that compares the explanatory power of regression models
8 which contain different numbers of predictors has a high value, Adj. $R^2 = 0.9771$. Pred. R^2 is a measure of
9 how well a regression model predicts a response value. The difference between Pred. $R^2 = 0.8568$ and Adj.
10 R^2 is less than 0.2 indicating the Pred. R^2 is in reasonable agreement with the Adj. R^2 (Mourabet et al., 2012).

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Table 2 ANOVA for RSM quadratic model obtained in this study.

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18 The experimental recovery time and the predicted values calculated using Eq. (6) are shown in Fig. 4. It
19 can be clearly seen that the experimental results and the predicted data fall close together, demonstrating that
20 the model is very useful to predict the recovery time of anhydrous chromium sulfate in the ammonium
21 leaching process operated under the conditions of this study (Marana et al., 2013).

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Fig. 4 Relationship between experimental and predicted recovery time of anhydrous chromium sulfate.

4.1.3 Optimization

3D response surface plots are very useful in understanding both the main and interaction effects of parameters. Moreover, 3D response surfaces and their contour plots can facilitate the examination of the effects of the experimental variables on the responses (Wu et al., 2009). In this study, plots of two processing parameters determining the recovery time of anhydrous chromium sulfate were prepared by keeping the other parameter at a certain level and are shown in Fig. 5, from which the optimum parameters for the ammonium leaching process can be easily identified. As seen in Fig. 5 (a) and (c), a temperature increase shows a positive effect on the leaching efficiency in the studied range. According to the thermodynamic analysis, a high temperature promotes the conversion of anhydrous chromium sulfate into ammonium chromium sulfate and improve the solubility of ammonium chromium sulfate in sulfuric acid. Recovery time decreased with increasing acidity of the leaching solution but did not show any notable changes as the pH value decreased below -0.5. A plot of recovery time versus ammonium dosage shows a parabola-shape, indicating that a reasonable dosage is around 2:1. Furthermore, the interaction effects of two processing parameters can also be determined from Fig. 5.

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Fig. 5 Recovery time 3D response surfaces as a function of (a) pH and temperature for ammonium dosage of 2:1; (b) pH and ammonium dosage for 80 °C; (c) temperature and ammonium dosage for pH = -0.5.

To optimize the ammonium leaching process on the recovery time of anhydrous chromium sulfate, Derringer's desirability function was applied within the experimental range of variables. Calculated results showed a the minimum value of $t_m = 71$ min if the process is conducted at 87 °C with the molar ratio of actual dosage of ammonium and theoretical dosage of ammonium of 2:1 and at pH = 0.7. Duplicate confirmatory tests were carried out under the obtained optimum conditions for confirmation, and the average recovery time was found to be about 72 min proving the good predictive ability of the established model.

4.2 Recycling of leaching residue

Based on the phase composition of the leaching residue and the experimental findings from ammonium treatment of anhydrous chromium sulfate, an investigation on recovery of chromium from actual leaching residue was conducted as follows: the residue was firstly washed by deionized water to recover the water-soluble phases, after which ammonium leaching was conducted for anhydrous chromium sulfate recovery, and then a 5 wt.% sodium hydroxide treatment was applied to separate the silica that formed during sulfuric acid leaching process of silicate. Morphology and phase variation were determined by SEM-EDS, XRD and TG-DSC analysis, and the total extraction yield of chromium after each treatment was calculated, with results given in Fig. 6.

Water-soluble Cr(III)-rich multicomponent sulfates were extracted by the washing treatment, and, as a

1 consequence, the total extraction yield of chromium increased from 37.5% to 55.6% while the weight reduced
2 by about 36%. Ammonium leaching recovered about 29% of the chromium and caused a 35 % weight loss.
3 No Cr-bearing sulfate was found in the residue implying that all the anhydrous chromium sulfate had
4 transformed into acid-soluble ammonium chromium sulfate. After the 5 wt.% sodium hydroxide treatment,
5 only Cr-rich spinel and silicate remained in the residue, showing phase and chemical compositions similar to
6 those of the chromite raw material. Because of the precipitation and the deposition of the sulfates, chromite
7 was bound in these insoluble phases inhibiting diffusion of the materials, and as a result some chromite still
8 remained at the bottom of the reactor after the leaching process.

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12 Fig. 6 Morphology and phase variation of residue and total extraction yield of chromium after each treatment.

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16 For the sulfuric acid leaching process of chromite, the produced Cr-rich leachate has usually $\text{pH} \approx -1.5$,
17 which needs to be adjusted $\text{pH} > 2$ for subsequent treatments. On the basis of this and the experimental
18 findings from this work, the Cr-rich solution obtained from chromium recovery can be used for the pH
19 adjustment, and the unreacted chromite could be utilized as a raw material in the following leaching process.
20 The sulfuric acid leaching process of chromite was improved for recycling of leaching residue, and a flow
21 sheet of the process route proposed here is given in Fig. 7.

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Fig. 7 Flow sheet of the process route proposed on the basis of the findings of this study.

A series of tests was conducted under the conditions optimized by the model established in the current work to verify the feasibility of the new process. The results showed that hydrous and anhydrous chromium sulfate were completely recovered from the leaching residue after the secondary extraction for chromium, and the average difference between the predicted and actual recovery times was less than 4%. Only unreacted chromite remained in the final residue, which could be collected and fed back to the sulfuric acid leaching process. Moreover, sodium silicate generated from silica separation is a valuable material for manufacturing of industrial water glass. In this novel method, almost all of the chromium resource is utilized, and no hazardous wastes or potential pollutants are discharged to the environment. These promising features justify further analysis of the process and its scale-up.

5. Conclusions

For the purpose of recovering anhydrous chromium sulfate from leaching residue, an ammonium leaching treatment was developed and conducted, and the effects of pH of the solution (pH), processing temperature (T), and ammonium dosage (R) were investigated using Box-Behnken design (BBD). A black box model was developed, and analysis of variance (ANOVA) was employed for model validation.

In this study, a second-order polynomial regression model that captures the functional relationship between the processing parameters and the recovery time was developed and verified. The significance of model terms

1 were tested, indicating that pH , T , pHT , pH^2 , T^2 , and R^2 were significant model terms, while other terms were
2 not significant. The independent variables and dependent variable were found to show a strong correlation,
3 and the regression model exhibited excellent prediction accuracy. Three-dimensional (3D) response surfaces
4 were plotted to investigate the main and interactive effects of ammonium leaching parameters on the recovery
5 time of anhydrous chromium sulfate, and optimum process conditions were found to be a processing
6 temperature of 87 °C, a molar ratio of actual dosage of ammonium and theoretical dosage of ammonium of
7 2:1, and $pH = 0.7$ for the solution. According to the findings of the study, slightly above 2.5 kg ammonium
8 sulfate is needed for recovering 1 kg chromium from residue.

9 An advanced sulfuric acid leaching process of chromite was finally proposed. Experimental results showed
10 that the chromium sulfates were completely recovered from the leaching residue, and the unreacted chromite
11 can be recycled to the process. No hazardous wastes or potential pollutants are discharged to the environment
12 from this novel process route, which holds promise for industrial application. However, work is still needed
13 on an efficient scale-up of the processing steps.

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