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Modelling and optimization of digestion efficiency of bauxite in Bayer process: Iran Alumina company

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Abstract

In the present work, we investigated and optimized the digestion efficiency, A/S (Al_2O_3/SiO_2 in red mud), and N/S (Na_2O/SiO_2 in red mud) of mixed bauxite in Iran Alumina Company using the Bayer process. Digestion experiments were carried out in an induction rotary autoclave on a mix of Jajarm, Yazd, Tash, and Shirin Cheshmeh bauxites. A 4-factor 3-level response surface methodology was applied for the design and analysis of the experiment with the optimization of Na_2O concentration, digestion temperature, residence time, and amount of lime addition. Towquadratics and one linear model were derived for the prediction of digestion efficiency, and A/S and N/S responses. The results obtained showed that the optimum amounts for Na_2O concentration, temperature, amount of lime addition and residence time were 180 g/L, 275°C, 7.73%, and 50 minutes, respectively, in which the digestion efficiency, A/S, and N/S reached 72.05%, 1.169, and 0.27, respectively. Validation experiment showed that the digestion efficiency, A/S, and N/S were 72.24%, 1.162, and 0.28% respectively, which meant a 2% increase in digestion efficiency and a 0.09 and 0.02 decrease in A/S and N/S, respectively, compared to the current operating condition.

1. Introduction

The Bayer process is the most common and economical method used in the processing of alumina from bauxite, especially high-grade bauxite [1]. The use of low-grade bauxites in the Bayer process is not economical due to the presence of active silica, which results in Na_2O loss in red mud and low digestion efficiency [1]. Low-grade bauxites, when required, are used in the Bayer process by simple and inexpensive pre-processing to remove or reduce aluminosilicate mineral content [1, 2]. Pre-processing studies have been conducted on low-grade and shale bauxite using a pilot Heavy Media Separation (HMS) [3] and laboratory thermochemical method in Iran Alumina Company [4]. One of the advantages of using concentrated bauxite in the Bayer process is the low waste of Na_2O due to the low content of active silica in bauxite.The studies of bauxite digestion with low content of iron (after separating it using a magnetic method) and its effect on reducing the temperature required for digestion and increasing the digestion efficiency have been investigated [5]. Typically, pyro-metallurgical methods are used for the production of alumina from low-grade bauxites [6, 7]. In the Bayer process, bauxite is dissolved in a high pressure and temperature reactor by sodium hydroxide [8]. Diaspore, boehmite, and gibbsite are the main three aluminum-containing bauxite minerals. Most of the bauxite deposits in Iran are diasporic. The digestion of diasporic and Boehmite bauxites is in accordance with the chemical Equation (1):

$$AlO(OH)_{(s)} + NaOH_{(aq)} + H_2O \rightarrow NaAl(OH)_{4\ (aq)} \quad (1)$$

Digestion is one of the most important stages in the production of alumina from bauxite in the

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Bayer process. The parameters affecting digestion should be optimized to increase the digestion efficiency [9]. The aluminosilicate minerals and their content in bauxite are effective in the digestion efficiency [10, 11]. Lime, temperature, residence time, and concentration of Na_2O are the most important parameters affecting the digestion efficiency and A/S (which is related to digestion efficiency) of the Bayer process [12]. As the temperature increases, the viscosity of sodium aluminate solutions decreases, dissolution kinetics of Al_2O_3 increases, and therefore the required residence time for the digestion decreases. With increasing the digestion residence time, the amount of alumina dissolved in sodium hydroxide solution increases. By modifying the amount of lime addition, the digestion efficiency can be improved, and the N/S of red mud or the loss of Na_2O can be minimized [13, 14]. The existing titan in diasporic ore forms a membrane with Na_2O, which prevents alumina dissolving. Sodium titanium membrane changes to calcium titanium by the addition of lime. Thus alumina can be freely dissolved in Na_2O [15]. By increasing the concentration of Na_2O, dissolution kinetics increases and energy consumption reduces [16]. Increasing Na_2O concentration has a significant effect on the increasing production efficiency, and reducing energy and operational costs [17]. Digestion temperature is one of the most important factors involved in increasing the reaction rate between aluminum hydroxide and Na_2O. The amount of lime addition, digestion residence time, and temperature also have significant effects on the digestion efficiency and N/S of red mud [18]. In addition to the modification of Na_2O concentration, digestion temperature, digestion residence time, and amount of lime addition, the use of additives such as calcium ferrite can help to increase the digestion efficiency and to reduce alumina losses [19]. The effect of solution alkaline modulus (α) after digestion on the Bauxite charge, and, consequently, the Bauxite digestion efficiency has been investigated [20]. Mathematical modeling has been used to predict bauxite digestion efficiency in the Bayer process using statistical data [21]. Although several studies have been carried out on the parameters affecting the Bayer digestion efficiency, the simultaneous effects of these parameters on the bauxite digestion efficiency have not been reported. In addition, due to the reduced reserves of bauxite and the nessesity to supply the feed of Iran Alumina Company Plant from different sources, optimization of the parameters affecting the bauxite digestion is necessary considering the variation in the mineralogical and chemical characteristics of these resources. In this research work, the CCD (central composie design) model in RSM (response surface method) was used at three levels to simultaneously investigate the digestion residence time, digestion temperature, Na_2O concentrationt and amount of lime addition on the digestion efficiency, N/S, and A/S of Iran Alumina Plant with the aim of increasing digestion efficiency and reducing losses of Na_2O and Alumina.

2. Introduction

2.1. Samples characterization

The representative samples were taken from deposits of Jajarm, Tash, Yazd, and Shirin Cheshmeh mines, and ground to 80% passing from 90 um screen using jaw crusher and ball mill to investigate the effective factors of the digestion efficiency. Diaspore, kaolinite, chamosite, hematite, and anatase were the most important minerals of 4 bauxite samples (Table 1). The chemical composition of Jajarm, Tash, Yazd, and Shirin Cheshmeh bauxite were analyzed by XRF, and the results obtained were tabulated in Table 2. Jajarm, Tash, Yazd, and Shirin Cheshmeh samples were combined with 35, 50, 10, and 5% ratios, respectively, to produce Al_2O_3 to SiO_2 ratio (modulus) in the digestion required range of 4.2. The lime samples were also prepared from furnaces of Iran Alumina Company with an active CaO content of 86%. Alkaline solution samples for digestion experiments were taken from circulating and enriched alkaline solution of the process. The Three samples shown in Table 3***Table*** were prepared according to the desired level of Na_2O concentration, discussed in the next section.

In Table 3, Na_2O_c refers to Na_2O of solution in the form of NaOH, which is effective in the digestion of bauxite, and Na_2O_t refers to the total Na_2O in solution (NaOH, Na_2CO_3, Na_2SO_4).

Table 1. Minerals of Jajarm, Tash, Yazd, and Shirin Cheshmeh bauxite (analyzed by XRD).

Sample	Diaspore (%)	Kaolinite (%)	Chamosite (%)	Hematite (%)	Anatase (%)
Jajarm	49.3	2.7	12.5	8.96	6.2
Tash	49.2	-	21.2	5.73	3.62
Yazd	47.95	0.5	24.4	15.69	5.81
Shirin Cheshmeh	49.1	22.9	-	16.34	6.37

Table 2. Minerals of Jajarm, Tash, Yazd, and Shirin Cheshmeh bauxite (analyzed by XRF).

Sample	Al_2O_3 (%)	SiO_2 (%)	Fe_2O_3 (%)	TiO_2 (%)	CaO (%)	MgO (%)	Module (Al_2O_3/SiO_2)
Jajarm	45.81	12.43	22.49	5.29	0.63	0.34	3.69
Tash	46.96	10.58	22.60	3.38	2.15	0.42	4.44
Yazd	45.86	9.71	24.45	5.11	0.34	0.37	4.72
Shirin Cheshmeh	52.7	9.82	16.84	5.69	0.4	0.21	5.37

Table 3. Chemical analysis of alkaline solution before digestion.

Sample	Na_2O_C(g/l)	Al_2O_3(g/l)	Na_2Ot(g/l)	α
L1 (170 g/L)	169.88	91.8	194.06	3.04
L2 (175 g/L)	174.84	94.35	198.71	3.05
L3 (180 g/L)	180.42	96.39	204.91	3.08

2.2. Design experiment

The operating parameters affecting the digestion of bauxite in Iran Alumina Plant is shown in Table 4. In this research work, the four factors residence time, temperature, Na_2O concentrationt and lime content in three levels were used to investigate their relationship with the digestion efficiency, A/S, and N/S using RSM in the Design-Expert 7 software (Table 5). RSM is a set of mathematical and statistical techniques used to optimize the processes that affect the response by a number of variables. There are many classes of response surface designs that are occasionally useful in practice such as central composite design, Box-Behnken design, hybrid design, and three-level factorial design. Among these methods, CCD is the most frequently used one under RSM [22]. This method gains the most information with the minimum tests; therefore, this method was used in this research work for optimizing the effective parameters in Bauxite digestion for the feed of Jajarm Alumina factory.

Studies have shown that the optimum range of temperature, residence time, Na_2O concentration, and lime addition for the digestion of diasporic bauxites are between 310-250 °C, 5-120, 140-100 g/L, and 4 to 30% of bauxite, respectively. The values of the operational parameters affecting the digestion of Jajarm alumina in the current conditions for Na_2O concentration, temperature, amount of lime, and time are 170 g /L, 270 °C, 9%, and 45 minutes, respectively. The levels of factors affecting the digestion efficiency of bauxite were determined by taking into account the operating limitations of the process and the previous studies. The maximum level of each one of the four factors will be selected according to the design criteria of process, bauxite characteristics, and maximum capacity of the equipment.

Table 4. Levels of parameters affecting the digestion of bauxite.

Parameters	**Temperature (Centigrade)**	**Na_2O (g/L)**	**Digestion residence time (min)**	**Lime (% of bauxite)**
Upper level	275	180	60	10
Intermediate level	270	175	45	8
Lowe level	265	170	30	6

A) Na_2O concentration: the concentration of Na_2O was 170-180 g/L. The concentrations above 180 g/L result in an increase in the amount of solids and a rise in the red mud level in settlement thickener. Moreover, due to the high temperature at the digestion unit, increased Na_2O concentrations increase the corrosion rate of pipes and equipment.

B) Temperature: the digestion temperature range of 265-275 °C was considered in the experiments. The higher the temperature causes the temperature inside the furnaces to rise, which causes the pipe to be pierced. The high temperature also increases the volume of the slurry, in which case it will have to reduce the slurry volumetric rate, which will reduce production.

C) Lime: the amount of lime used is between 6% and 10% by weight of bauxite. The higher lime will increase the amount of solids, which will make it difficult to control the settlement and filtration of red mud. Also lower amounts of lime will also increase the loss of Na_2O in the red mud and increase the cost of consumed Na_2O.

D) Residence time: the range of time was between 30 and 60 minutes. It is not possible to increase the residence time furthermore considering the volume of reactors and tanks of the digestion unit.

All digestion experiments were performed by an induction rotary autoclave with a volume of 170 mL at Iran Alumina Research and Development Laboratory. After the preparation of bauxite, the weight required to conduct the digestion test was calculated from Eq. (2). The equation is an empirical formula that was derived from the results of a large numbers of technological tests, presented by the factory designer (Technoexport Czech), and used to calculate the amount of bauxite charge in the Jajarm Alumina process.

$$G = C_{Na_2O_C} \times (\alpha_0 - \alpha_C) / [0.608 \times (\alpha_0) \times (\alpha_C) \times (A_{Baux} - S_{Baux}) + 0.608 \times (\alpha_0) \times (S_{Baux}) \times V] \quad (2)$$

where:

G: Bauxite weight (g)

CNa_2O_c: Na_2O concentration (g/L)

α_0: Molar ratio of $Na_2O_c$to Al_2O_3 of the alkaline solution before digestion

α_c: Molar ratio of CNa_2O_c/CAl_2O_3 after digestion. In fact, α_c is usually considered to be about 1.5 to 1.4.

$$\alpha = \left(\frac{C_{Na_2O_C}}{C_{Al_2O_3}} \right) \times 1.645$$

A_{Baux}: Al_2O_3 content of bauxite (%)

S_{Baux}: SiO_2 content of bauxite (%)

V: Solution volume (mL)

The alkali modulus of the solution before digestion (α_0) is usually between 3 and 3.3, which depends on the precipitation efficiency of aluminum hydroxide and other process conditions and affects the amount of required bauxite. The alkali modulus of the solution after digestion (α_c) is one of the most important parameters for determining the desirability of the conditions of the digestion process. It is defined as the target point before conducting the digestion experiments, which also affect the amount of required bauxite and usually ranges from 1.45 to 1.48. Achieving the mentioned range after the digestion of bauxite indicates that the design of the experiment is proper and the bauxite quality is appropriate for use in the Bayer process. At the end of each experiment, the solid and liquid phase is separated by vacuum filter. The liquid phase is Al_2O_3 enriched solution, and the solid phase also contains the waste of the bauxite components. The concentrations of Na_2Oc, Na_2O_t, and Al_2O_3 in the liquid phase were determined by titration, and the amounts of Al_2O_3, SiO_2, and Na_2O solids were determined using XRF. Then the digestion efficiency was calculated in accordance with Eq (3).

$$\%\eta_{act} = \left[1 - \frac{\left(Al_2O_{3red\ mud\ (\%)} / SiO_{2red\ mud\ (\%)} \right)}{\left(Al_2O_{3Bauxite\ (\%)} / SiO_{2Bauxite\ (\%)} \right)} \right] \times 100 \quad (3)$$

Table 5. Experimental range and levels of the factors of the digestion test.

	Factors				Response		
# Run	A: Na_2O	B: Temp	C: Lime	D: Residence time	R1: A/S	R2: N/S	R3: Efficiency %
1	170.00	265.00	6.00	30.00	1.27	0.34	69.7
2	180.00	265.00	6.00	30.00	1.23	0.33	70.6
3	170.00	275.00	6.00	30.00	1.22	0.34	70.9
4	180.00	275.00	6.00	30.00	1.17	0.31	72
5	170.00	265.00	10.00	30.00	1.35	0.25	67.7
6	180.00	265.00	10.00	30.00	1.32	0.24	68.4
7	170.00	275.00	10.00	30.00	1.29	0.23	69.13
8	180.00	275.00	10.00	30.00	1.25	0.23	70.11
9	170.00	265.00	6.00	60.00	1.25	0.34	70.17
10	180.00	265.00	6.00	60.00	1.21	0.33	71.19
11	170.00	275.00	6.00	60.00	1.16	0.32	72.36
12	180.00	275.00	6.00	60.00	1.12	0.31	73.15
13	170.00	265.00	10.00	60.00	1.29	0.24	69.15
14	180.00	265.00	10.00	60.00	1.26	0.23	69.89
15	170.00	275.00	10.00	60.00	1.25	0.23	70.2
16	180.00	275.00	10.00	60.00	1.22	0.23	70.95
17	170.00	270.00	8.00	45.00	1.25	0.3	70.11
18	180.00	270.00	8.00	45.00	1.21	0.27	71.1
19	175.00	265.00	8.00	45.00	1.24	0.28	70.28
20	175.00	275.00	8.00	45.00	1.2	0.27	71.21
21	175.00	270.00	6.00	45.00	1.19	0.31	71.45
22	175.00	270.00	10.00	45.00	1.26	0.23	69.9
23	175.00	270.00	8.00	30.00	1.26	0.29	69.86
24	175.00	270.00	8.00	60.00	1.2	0.26	71.3
25	175.00	270.00	8.00	45.00	1.21	0.27	71.06
26	175.00	270.00	8.00	45.00	1.21	0.27	71.05
27	175.00	270.00	8.00	45.00	1.21	0.27	71.05
28	175.00	270.00	8.00	45.00	1.22	0.28	70.82
29	175.00	270.00	8.00	45.00	1.22	0.28	70.81
30	175.00	270.00	8.00	45.00	1.22	0.28	70.8

3. Results and discussion

3.1. Data Analysis

The data obtained from the Bayer digestion experiments were used to determine the main and significant effects of the effective factors with the ANOVA variance analysis at the 95% confidence level. Therefore, the significant and non-significant effects were determined to obtain the regression model, describing the digestion efficiency, A/S, and N/S.

3.2. Model fitting

It was observed that the quadratic reduced model was best fitted to the experimental results of digestion efficiency and A/S, while the linear model was best described by N/S. For the 95% confidence level, the coefficients with P-values greater than 0.05 were excluded from the model. The C.l range of the Box-Cox chart for the three response of digestion efficiency, N/S, and A/S are shown in Table 6.

Table 6. C.I range of Box-Cox.

Response	Low C.I	High C.I
Efficiency	-6.75	5.17
N/S	-1.55	0.88
A/S	-2.02	4.05

The transform of the models was selected in such a way that Lambada would be within the acceptable range of the Box-Cox chart. Thus for N/S, the inverse square root transformwith Lambda equal to -0.5 was selected. Eqs. (4)-(6) were obtained from 30 digestion trials using the Design-Expert 7 software.

$$\%Efficiency = 70.84 + 0.44 \times A + 0.72 \times B - 0.89 \times C + 0.55 \times D - 0.23 \times A^2 - 0.26 \times D^2 \quad (4)$$

$$\frac{A}{S} = 1.22 - 0.019 \times A - 0.030 \times B + 0.37 \times C - 0.022 \times D + 5.00E-003 \times B \times C + 0.012 \times A^2 + 0.012 \times D^2 \quad (5)$$

$$\frac{1}{\sqrt{\frac{N}{S}}} = 1.91 + 0.019 \times A + 0.021 \times B + 0.16 \times C + 0.013 \times D \quad (6)$$

in which, the coded factors A, B, C, and D are the Na_2O concentration, temperature, the amount of lime addition, and residence time, respectively. As it can be seen in Eq. (4), temperature and the amount of lime addition have the greatest impact on the digestion efficiency. Also the experimental model shows that the factors do not have an interaction effect on the digestion efficiency. The negative effect of the amount of lime addition on the digestion efficiency is evident. The results of the ANOVA variance analysis of the obtained model is shown in Tables 7 and 8. As it can be seen, the F-value of models are less than 0.05%. Also the P-value of Lack-of-Fit was greater than 0.05 and was non-significant, indicating the model's fitness.

Table 7. ANOVA for response surface models applied.

Response	Model	ANOVA				
		Source	Sum of squares	df	F-value	P-value Prob > F
Digestion efficiency (%)	Reduced quadratic model	Model	34.2168	6	109.774	< 0.0001
		A- Na_2O	3.5289	1	67.929	< 0.0001
		B- temp.	9.2880	1	178.788	< 0.0001
		C- lime	14.3827	1	276.855	< 0.0001
		D- residence time	5.5112	1	106.086	< 0.0001
		A^2	0.1884	1	3.626	0.0695
		D^2	0.2308	1	4.443	0.0461
		Residual	1.1949	23		
		Lack-of-Fit	1.1058	18	3.448	0.0877
		Pure error	0.0891	5		
		Cor total	35.4117	29		
A/S	Reduced quadratic model	Model	0.0602	7	100.336	< 0.0001
		A- Na_2O	0.0064	1	74.935	< 0.0001
		B- Temp.	0.0162	1	189.023	< 0.0001
		C- Lime	0.0249	1	290.989	< 0.0001
		D- residence time	0.0089	1	103.716	< 0.0001
		BC	0.0004	1	4.667	0.0419
		A^2	0.0005	1	5.420	0.0295
		D^2	0.0005	1	5.420	0.0295
		Residual	0.0019	22		
		Lack-of-Fit	0.0017	17	3.403	0.0903
		Pure error	0.0002	5		
		Cor total	0.0621	29		
N/S	Linear Model	Model	0.4565	4	183.234	< 0.0001
		A- Na_2O	0.0066	1	10.608	0.0032
		B- Temp.	0.0076	1	12.276	0.0017
		C- Lime	0.4390	1	704.821	< 0.0001
		D- Residence time	0.0033	1	5.230	0.0309
		Residual	0.0156	25		
		Lack-of-Fit	0.0138	20	1.908	0.2448
		Pure error	0.0018	5	183.234	
		Cor total	0.4720	29		

Table 8. Parameters for validation of model.

Response	R-Squared	Adj. R-Squared	Pred. R-Squared
Efficiency	0.9663	0.9575	0.9405
N/S	0.9696	0.9600	0.9380
A/S	0.9670	0.9617	0.9552

Note: In the efficiency model, the P-value of A^2 is 0.0695. Since this value is close to 0.05 and it is significant in the confidence limit of 90%, it is suggested to be used in the model. On the other hand, since A^2 is in the A/S model and these two are interrelated, it is better not to be omitted.

3.3. Evaluation of model adequacy

The polynomial models provide an acceptable estimate in a relatively small range of independent variable space. Figure 1 shows the actual and measured values of digestion efficiency. The position of the points in the bisector represents the correlation between the measured and actual values. This indicates that the model is adequate in the condition of experiments.

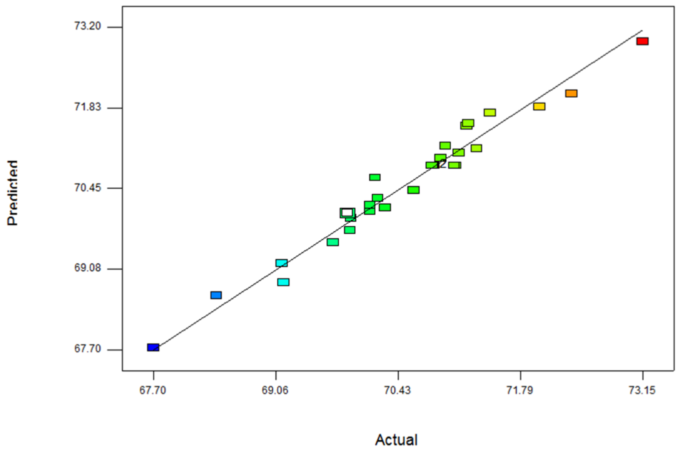


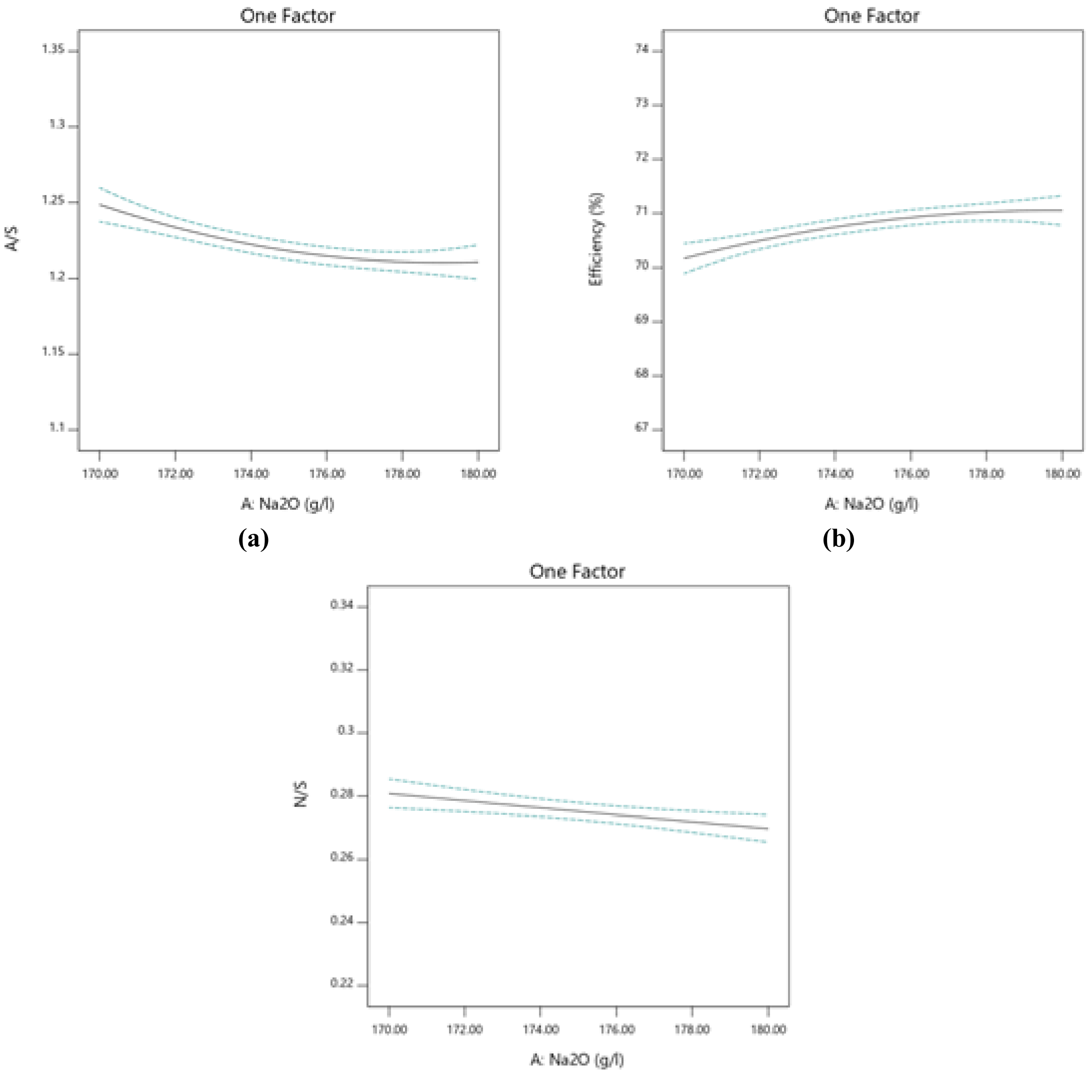
Figure 1. Predicted value *vs.* actual value of digestion efficiency.

3.4. Effect of Na_2O

In alumina production, sodium hydroxide is the main agent (solvent). Based on the chemical Equation (1), sodium aluminate is produced but since Al_2O_3 digestion is in a high temperature, and silica and titanium react with sodium hydroxide in low temperatures, consequently, some amount of Na_2O is lost. Also with increasing the Na_2O concentration of the alkaline solution, the amount of bauxite charge increases, and as a result, the solid content in the slurry increases, which affects the reduction of efficiency, so the optimal Na_2O concentration of the solution must be determined.

Figure 2 shows the effect of Na_2O concentration on A/S, N/S, and digestion efficiency. With increasing Na_2O concentration from 170 to 180 g/L, the amount of A/S in red mud decreases. By increasing the concentration of Na_2O, the digestion rate increases. Thus the amount of Al_2O_3 dissolved in solution and red mud increases and decreases, respectively. At a concentration between 178 and 180 g/L, the A/S reduction trend is reduced, and higher concentrations do not significantly affect A/S. In general, with a increase in the Na_2O concentration, the N/S value in red mud decreases but at a concentration above 178 g/L, N/S increases slightly, so the optimum concentration value of the Na_2O is 178 g/L. By increasing the concentration of Na_2O from 170 to 180 g/L, the digestion efficiency increases. As Na_2O concentration increases, digestion rate also increases, and the amount of Al_2O_3 dissolved in solution also increases. Besides, in a concentration between 178 and 180 g/L, the increasing trend of efficiency is lower, and higher concentrations do not have a much effect on the efficiency.

also increases. Besides, in the concentration between 178 and 180 g/l, the increasing trend of efficiency is lower, and higher concentrations do not have much effect on efficiency.



(c)

Figure 2. Effect of Na_2O on a) A/S, b) N/S, and c) digestion efficiency at a constant temperature, lime, and residence time.

3.5. Effect of temperature

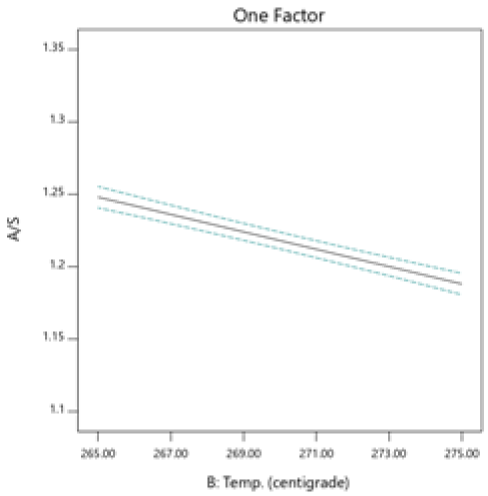
The effect of temperature on A/S, N/S, and digestion efficiency is shown in Figure 3. As the temperature increases, A/S declines. Temperature is one of the most important factors involved in accelerating the digestion reaction, increasing the dissolution of Al_2O_3, and thus decreasing A/S of the red mud. As the temperature increases, N/S decreases. Temperature also plays an important role in accelerating the reaction between the lime and the sodium hydro-aluminosilicate, and is effective in recycling the Na_2O or reducing N/S of the red mud during the digestion process. As the temperature increases, the digestion efficiency increases as well.

3.6. Effect of lime addition

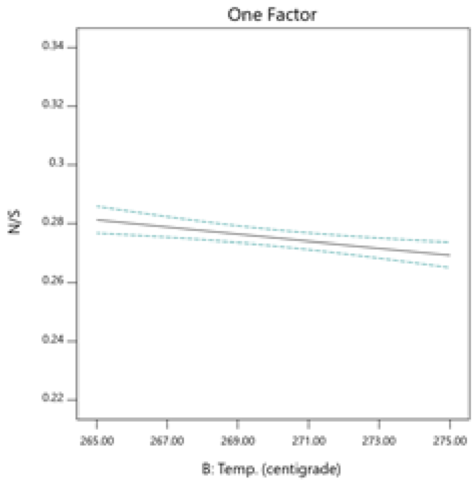
The effect of lime addition on A/S, N/S, and digestion efficiency is shown in Figure 4. With increase in lime addition, A/S of red mud increases. Lime, as in the digestion process, has a positive role in dissolving but its excess amount results in a reaction with aluminum hydroxide, causing alumina losses or an increased A/S of red mud. With increase in lime, N/S of red mud drops. Lime is an important factor involved in recovering the loss of Na_2O in sodium hydro-aluminosilicate composition, and by producing calcium hydro-aluminosilicate, recovers some Na_2O. Thus it results in the reduction of N/S in the red mud during the digestion process. With increasing lime, the digestion efficiency increases.

3.7. Effect of residence time

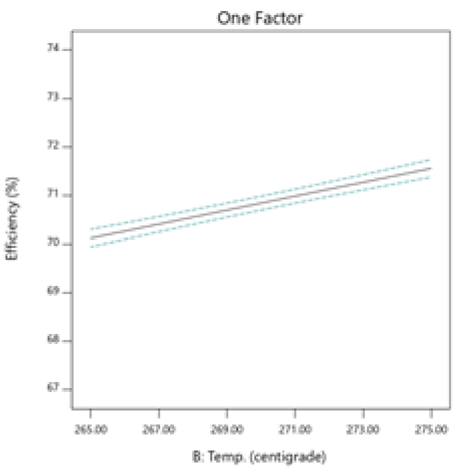
The effect of residence time on A/S, N/S, and digestion efficiency is shown in Figure 5. As time increases, the A/S rate decreases, although the reduction rate is reduced in a time above 50 minutes and has no significant effect on reducing A/S. Increasing the residence time results in a complete reaction between Na_2O and aluminum oxideو and thus the dissolution of alumina in sodium hydroxide solution increases and alumina loss in red mud or A/S decreases. As time increases, N/S decreases and, as shown in Figure 5, there is no significant reduction in N/S from 30 minutes to 60 minutes. Considering the proper conditions for Na_2O concentration, temperature, and amount of lime in the digestion process, some of the consumed Na_2O is recovered, and increasing the time from 30 to 60 minutes does not have a significant effect on the reduction of N/S. As the residence time increases, the digestion efficiency is increased. As it is evident in Figure 5, in times above 50 minutes, it does not have a significant effect on the increase in the digestion efficiency. Increasing the residence time causes the complete reaction between Na_2O and aluminum oxide, resulting in a higher level of alumina dissolution in the sodium hydroxide solution.



(a)

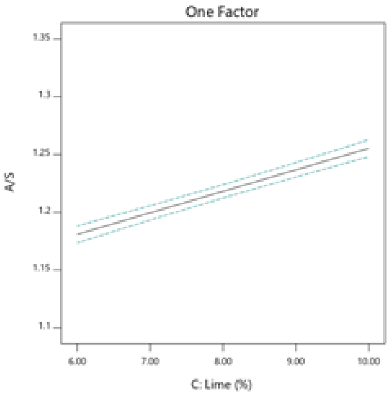


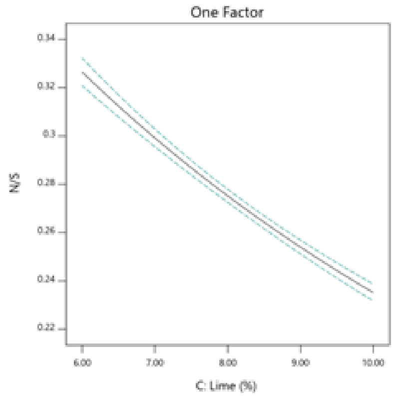
(b)



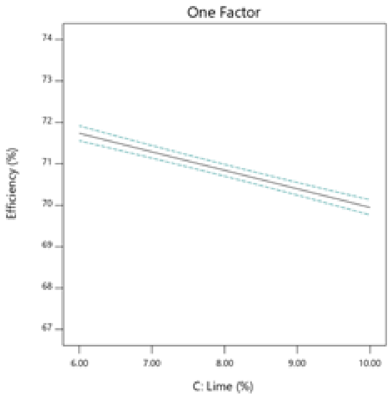
(c)

Figure 3. Effect of temperature on a) A/S, b) N/S, and c) digestion efficiency at constant Na_2O, lime, and residence time.



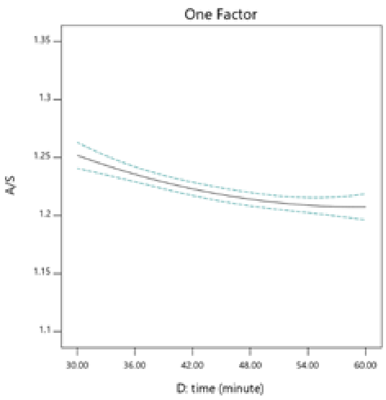


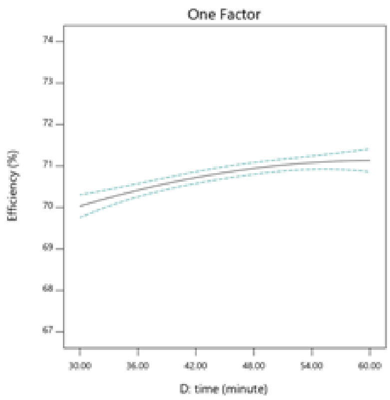
(a) **(b)**



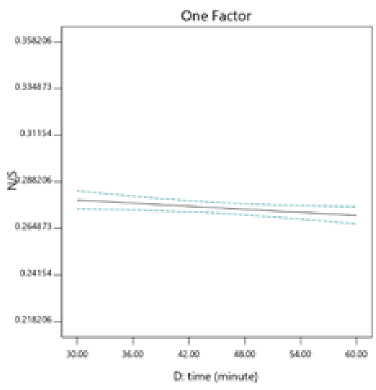
(c)

Figure 4. Effect of lime on a) A/S, b) N/S, and c) digestion efficiency at constant Na_2O, temperature, and residence time.





(a) **(b)**



(c)

Figure 5. Effect of lime on a) A/S, b) N/S, and c) digestion efficiency at constant Na_2O, temperature, and residence time.

3.8. Determining optimal conditions and validating model

The statistical and qualitative analysis of results showed that increasing the Na_2O concentration, temperature andresidence time, and reducing the amount of added lime would increase the digestion efficiency. On the other hand, reducing the amount of lime increases the digestion efficiency but also increases N/S, which means loss of Na_2O. The results of the experiments showed that the digestion efficiency at a Na_2O concentration of 180 g/L, a temperature of 275 °C, a lime addition of 6%, and a 60-minute residence time maximizes to 73.15%. In the mentioned condition, the N/S and A/S values were, respectively, 0.31 and 1.12, indicating an increase in Na_2O and alumina loss. For this purpose, the optimal parameters were determined using the Design-Expert 7 software to achieve the maximum amount of digestion efficiency and the minimum amount of loss of Na_2O and alumina in the process. The results obtained showed that at a Na_2O concentration of 180 g/L, a temperature of 275 °C, a lime addition of 7.73%, and a residence time of 50-minute digestion efficiency would reach 72.0455%. The N/S and A/S values are 0.27 and 1.17, respectively, which are acceptable.

To validate the model, a digestion test was conducted at the proposed levels of the optimal point. The results obtained showed that the experimental values were close to the predicted values and that the model responses were appropriate. In this test, the digestion efficiency, N/S, and A/S were 72.24%, 0.28, and 1.162, respectively. Thus in comparison with the current operating parameters (Run #17), the digestion efficiency, N/S, and A/S were improved by 2%, 0.02, and 0.09, respectively.

It should be noted the alkaline modulus of the solution after digestion ranged from 1.47 to 1.50, which in the experiments with a high digestion efficiency, was lower than that of the low digestion efficiency experiments, which showed the accuracy of analyzes and confirmation of experiments. The alkaline modulus of solutions in the test with maximum digestion efficiency (L12) and the optimum test predicted by the model (LO) are shown in Table 9.

Table 9. Chemical analysis of alkaline solution after digestion.

Sample	Na_2Oc (g/l)	Al_2O_3 (g/l)	Na_2Ot (g/l)	α
L12	158.1	176.7	184.0	1.47
LO	158.7	176.5	184.1	1.48

4. Conclusions

Bauxite feed of Iran Alumina Company Plant is composed of different sources, namely Tash, Jajarm, Yazd, and Shirin Cheshmeh. Jajarm, Tash, Yazd, and Shirin Chesmeh samples were combined with 35, 50, 10, and 5% ratios, respectively, to produce Al_2O_3 to SiO_2 ratio (modulus) in the digestion required range of 4.2. The mixed bauxite digestion efficiency was optimized by changing the effective parameters and using the Design-Expert 7 software and response surface method. The results obtained show that increasing the Na_2O concentration, temperature, and residence time, and reducing the amount of lime in comparison with the current operating conditions is effective in improving the digestion efficiency. The optimal conditions for the digestion of the mixed bauxite are 180 g/L of Na_2O at 275 °C with the lime addition of 7.73% and the residence time of 50 minutes. According to the model prediction at the mentioned optimum condition, the digestion efficiency is 72.0455%, and N/S and A/S are 0.27 and 1.17, respectively. The validation test was carried out at the Iran Alumina R&D laboratory under the proposed optimal conditions. The digestion efficiency was 72.24, and A/S and N/S were 1.16 and 0.28, respectively. Thus in comparison with the current operating parameters (Run #17), the digestion efficiency, N/S, and A/S have improved by 2%, 0.02, and 0.09 respectively.

Acknowledgments

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مدل‌سازی و بهینه‌سازی راندمان انحلال بوکسیت در فرآیند بایر: شرکت آلومینای ایران

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چکیده:

در این پژوهش بهینه‌سازی راندمان انحلال، A/S (Al_2O_3/SiO_2) و N/S (Na_2O/SiO_2) گل قرمز بوکسیت خوراک کارخانه آلومینای ایران با استفاده از فرآیند بایر بررسی شده است. آزمایش‌های انحلال در یک اتوکلاو القایی چرخشی، روی مخلوط بوکسیت‌های جاجرم، تاش، یزد و شیرین چشمه انجام شد. روش سطح پاسخ با ۴ فاکتور و ۳ سطح برای انجام آزمایش‌ها و بهینه کردن غلظت Na_2O، دمای انحلال، زمان‌ماند و مقدار آهک اضافه‌شده به کاربرده شد. برای پیش‌بینی پاسخ‌های راندمان انحلال، A/S و N/S دو مدل درجه ۲ و یک مدل خطی به دست آمد. نتایج نشان داد که مقادیر بهینه غلظت Na_2O، دما، مقدار آهک اضافه‌شده و زمان به ترتیب ۱۸۰ گرم بر لیتر، ۲۷۵ درجه سانتی‌گراد، ۷/۷۳٪ و ۵۰ دقیقه است که راندمان انحلال، A/S و N/S به ترتیب به ۷۲/۰۵٪، ۱/۱۶۹ و ۰/۲۷ رسید. آزمایش اعتبارسنجی نشان داد که مقادیر راندمان انحلال، A/S و N/S به ترتیب برابر ۷۲/۲۴٪، ۰/۱۶۲ و ۰/۲۸ بوده که در مقایسه با شرایط فعلی عملیاتی، راندمان انحلال بیش از ۲٪ افزایش و A/S و N/S به ترتیب ۰/۰۹ و ۰/۰۲ کاهش یافته است.

کلمات کلیدی: فرآیند بایر، بوکسیت، بهینه‌سازی، راندمان انحلال، مدل‌سازی، روش سطح پاسخ.