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Experimental and simulative study on phase transformation in Bayer red mud soda-lime roasting system and recovery of Al, Na and Fe

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ABSTRACT

Red mud, or bauxite residue, is the largest environmental concern of alumina refineries, mainly because of the size of this waste stream and its caustic characteristics. This paper reports part of a research effort aimed at developing an economically feasible zero waste process for the treatment of red mud. Soda-lime roasting was carried out on fine red mud, which was separated from raw red mud physically with particle size below 75 μ m, under reductive atmosphere prior to leaching and magnetic separation. The aim was to recover valuable components such as Al, Na and Fe from the fine red mud. This study found that, the recovery of Al and Na after the water leaching was about 75.7% and 80.7%, respectively. The recovery of iron depended on the type of reduction products. Under the roasting conditions applied in this study, spinel, sodium aluminosilicate, and larnite are dominant mineral phases in the roasted samples, with calcium aluminoferrite, melilite and wustite being minor phases. The effect of Ca content and of reaction atmosphere on the equilibrium phases was studied by experiments and thermodynamic modeling, and the dependence of the recovery of Al and Na on these factors was demonstrated.

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1. Introduction

Each year more than 70 million tons of red mud is produced in the world (Red mud Project). This waste presents serious problems of storage and potential environmental pollution. In the red mud accident of October 4, 2010, in Ajka (Hungary), 10 persons lost their lives (Gelencsér et al., 2011); and 800 Ha of agricultural land were estimated to have been inundated (Mayes et al., 2011).

Red mud has been researched for use in remediation of sandy soils (Goen et al., 1989), neutralizing acidic mining wastes (Doye and Duchesne, 2003), and construction purposes (e.g. brick making (Yang and Xiao, 2008), and ceramics (Yang et al., 2008) and a range of other industrial uses. There are more than 15 mineral phases in red mud, with a significant quantity of valuable components such as iron, alumina, soda and titania, together with trace levels of valuable rare earth elements and some hazardous elements (Bruckard et al., 2010). The total content of Fe₂O₃, Al₂O₃ and Na₂O in Bayer red mud is over 60% wt/wt. The recovery of these three compounds from red mud is critical to realizing sustainable resource utilization (Liu et al., 2009a).

The recovery of a significant quantity of valuable components from the red mud is difficult, as they are locked up in complex mineral phases which are very fine grained and quite alkaline. Numerous attempts have been made to treat and to recover compounds

* Corresponding author. *E-mail address:* yjiakuan@hotmail.com (J. Yang). from red mud. Jamieson et al. (2006) documented investigations into processing red sand (red mud particle size >90 µm) through standard mineralogical processes to produce various fractions that have a higher potential value than the total sand fraction. Liu et al. (2009b) recovered iron from red mud by reductive roasting process and the residues were used for making building materials. Fursman et al. (1970) and Li et al. (2009) sintered the red mud with carbon, lime and sodium carbonate at around 1000 °C and leached the sinter to recover iron, alumina and soda. Some research work has also been carried out by reductive smelting at high temperatures to produce pig iron and a slag from which valuable materials were recovered (e.g. TiO₂ and Al₂O₃) (Ercağ and Apak, 1997). Bruckard et al. (2010) determined optimum fluxing, smelting and leaching practices for maximizing the recovery of alumina and soda, but not iron, from a slag produced by oxidative smelting of bauxite residues at 1400 °C.

This paper reports part of a research effort aimed at development of an economically feasible, zero waste process for the treatment of red mud. In the proposal, soda-lime roasting was carried out on fine red mud, which was separated from raw red mud physically with particle size below 75 μ m, under reductive atmosphere prior to leaching and magnetic separation. And the residue can be used in building materials production due to lower content of soda and fine hydraulicity. The proposed process is based on chemical and phase transformations through soda-lime roasting under reductive conditions to transform components in the red mud into desired mineral phases from which valuable constituents could be



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readily recovered. The present work was focused on determination of optimum conditions for roasting and leaching practices with respect to the recovery of alumina and soda, and the effect of Ca/Si ratio (mole ratio of Ca to Si) and of reductive atmosphere in the system. The roasting process was simulated using the Multi Phase Equilibrium (MPE) software developed by CSIRO (Bruckard et al., 2010; Zhang et al., 2002) which models and predicts the various phases and their output under equilibrium conditions.

2. Materials and methods

2.1. Materials

Red mud samples were supplied by Shandong Aluminum Company, CHALCO. The red mud sample was obtained from the storage yards without any pretreatment. Then the sample was separated by wet screening at 75 μ m to remove coarser particles, and the slurry was evaporated to get the fine fraction of red mud for the present study. The Al/Si level (mass ratio of Al₂O₃ to SiO₂) in the fine particles is increased through the separation practice, which preferentially removes part of sand from red mud (Liu et al., 2010). The chemical composition of the fine red mud is shown in Table 1. Technical grade soda (Na₂CO₃) and limestone (CaCO₃) were used as sources of Na and Ca, respectively. Limestone was roasted at 1000 °C for 3 h before use. Low ash coal char was used as reductive agent, and its composition is shown in Table 2.

2.2. Methods

2.2.1. Roasting

About 120 g dry mixtures of the fine red mud, lime, soda and char were used in each reductive roasting experiment. The

Table 1

The chemical compositions of red mud expressed as elemental oxides (wt.%).

amounts of lime and soda added were to make the target mole ratio of CaO/SiO_2 and Na_2O/Al_2O_3 . The material was charged to a glass reactor, which was placed in a vertical tube furnace. Nitrogen or air was bubbled through the mixture at a flow rate of 0.5 L/min (STP) during each roasting test. At the end of each roasting test, the sample was cooled down to room temperature under N_2 atmosphere. The solid product was characterized through chemical and XRD analysis, and was used for separation and recovery tests.

Ten samples were prepared with different ratios of Ca/Si (molar ratio) while keeping the ratio of Na/Al (molar ratio) constant (around 1.0). The samples were roasted at 1000 °C for 3 h. Details of these conditions are listed in Table 3. The aim of these tests was to study the effect of CaO addition on the extractions of Al and Na.

In addition to those listed in Table 3, sample 11 (same starting materials as for sample 6) was roasted in air to demonstrate the effect of roasting atmosphere on product phase compositions.

2.2.2. Leaching

The leaching conditions were optimized by trials using the roasted products of sample 5. Leaching tests were carried out in a flat bottom flask fitted with a thermocouple and a condenser. Agitation was provided by an electric magnetic stirrer. A programmable temperature controller was used to gradually heat the solution from ambient to the set temperatures (18 °C, 60 °C, and 100 °C). The solid sample was then added to the water. After predetermined reaction times (varying from 15 min to 8 h) the slurries were filtered with an Ace Hirsch filter funnel, with porosity of 2 μ m. The filtrates were diluted by D-Mannitol solution (15 wt.%), and the resulting solutions were used for determination of Al, Na, Si, Ca and Fe. The filtered cakes were dried at 60 °C in an

	SiO ₂	Al_2O_3	Fe ₂ O ₃	CaO	Na ₂ O	K ₂ O	MgO	CuO	Mn_3O_4	Cr_2O_3
Red mud	19.7	21.0	31.4	3.08	8.58	0.253	0.24	<dl<sup>a</dl<sup>	0.047	0.036
	NiO	P_2O_5	SO ₃	TiO ₂	$V_{2}O_{5}$	ZnO	ZrO ₂	Cl	F	Co_3O_4
Red mud	<di< td=""><td>0.115</td><td>0.424</td><td>196</td><td>0.068</td><td>0.010</td><td>0 1 2 7</td><td>0.062</td><td></td><td><di< td=""></di<></td></di<>	0.115	0.424	196	0.068	0.010	0 1 2 7	0.062		<di< td=""></di<>
	VDL	0.115	0.424	1.50	0.008	0.010	0.127	0.002	NDL	NDL
	As ₂ O ₃	BaO	0.424 CdO	MoO ₃	РЬО	SnO ₂	0.127 WO ₃	SrO	Ga ₂ O ₃	Sum
Red mud	As ₂ O ₃	BaO 0.02	CdO <dl< td=""><td>MoO₃</td><td>PbO 0.011</td><td>SnO₂</td><td>0.127 WO₃ 0.005</td><td>SrO 0.009</td><td>Ga₂O₃</td><td>Sum 87.2</td></dl<>	MoO ₃	PbO 0.011	SnO ₂	0.127 WO ₃ 0.005	SrO 0.009	Ga ₂ O ₃	Sum 87.2

^a DL: Detection Limit.

Table 2 Analysis of coal char.

Proximate anal	Ultimate analysis (% db)						C.V. ^d (MJ/kg)			
Moisture ^b	Volatiles	Ash	F.C. ^c	С	S	Ν	Н	Cl	0	
7.9	2.1	2.6	95.3	92.9	0.22	0.64	1	0.03	2.6	33

^a db is dry base

^b Moisture content was determined as received.

^c F.C. is fixed carbon.

 $^{\rm d}\,$ C.V. is gross dry calorific value.

Table 3

Roasting conditions and Ca/Si and Na/Al ratio of the sample mixtures from XRF analysis.

Sample no.	1	2	3	4	5	6	7	8	9	10	11 ^a
Ca/Si	0.17*	1.31	1.48	1.72	1.88	1.98	2.05	2.08	2.12	2.38	1.98
Na/Al	1.03	1.03	1.01	0.96	1.00	0.99	0.99	0.99	1.01	0.97	1.01

Note: *The Ca/Si molar ratio of 0.17 was from CaO and SiO₂ in the red mud without addition of CaO.

^a For samples 1–10, 0.5 g char was mixed with 100 g red mud to form reductive atmosphere. These ten samples were roasted at 1000 °C for 3 h in N₂. Sample 11 was roasted in air without char.

oven and then weighed. Sub-samples were taken for chemical and phase analyses.

2.2.3. Magnetic separation

The magnetic separation was carried out with Davis magnetic tube tester (XCGS-99, 50 mm ID) to recover magnetic ferrous compounds from the leached residues.

2.2.4. Analytical methods

For X-ray fluorescence (XRF) analysis, a sub-sample was melted with 1222 flux to produce a flat 40 mm glass tablet for analysis. The tablet was analyzed with a Philips PW 2404 XRF spectrometer.

The mixed solutions of filtrate and mannitol solution were diluted in 5 vol.% nitric acid to match the standard calibration range and analyzed for Al and Na by an ICP-AES (inductively coupled plasma atomic emission spectroscopy) and also for Si, Fe, and Ca in one test, using an ICP-OES (inductively coupled plasma optical emission spectrometer).

The X-ray diffraction (XRD) analyses were made on powdered samples in a PANalytical multipurpose diffractometer using Co K α radiation. Phases were identified using XPLOT for Windows and the ICDD database.

For examination in an FEI Quanta 400F environmental scanning electron microscope (ESEM), sub-samples were mounted in epoxy resin that was ground and polished. The polished sections of the dip samples were coated with a carbon film and examined. Qualitative chemical analyses were performed using an EDAX energy dispersive X-ray spectrometer (EDS).

3. Results and discussion

3.1. Effect of leaching conditions on extraction

Roasted samples were ground and leached in water at different temperatures for varying periods. Details of the results obtained for sample no. 5 are listed and discussed in the following, as an example. The results showed that the leaching efficiencies of the elements depend on the temperature and the leaching period (Fig. 1). The concentrations of Na and Al in solutions are higher than that of Ca, Si and much higher than Fe (over 100 times). When the sample is leached at room temperature (Fig. 1A), the concentrations of Na and Al initially increase sharply with time. Beyond the first 2 h, Al and Na in solutions increase slowly. After leaching for 8 h, the concentrations of Al and Na in the solution level at 4.46 g/L and 4.56 g/L, respectively. Fig. 1A-C shows that higher temperatures result in higher extraction rate of Na and Al from the roasted samples. At 100 °C (Fig. 1C), 62.4% Al and 74.9% Na are dissolved from the solid sample in 15 min. However, the recovery falls with prolonged reaction time possibly due to secondary reactions of $Al(OH)_2^-$, Na^+ , Ca^{2+} , and SiO_4^{2-} , at high temperatures over time. As Yang has found (Yang, 1983), the reactions produce precipitates of calcium hydrate garnet (3CaO·Al₂O₃·xSiO₂·yH₂O) and hydrated sodium aluminosilicate (Na2O·Al2O3·xSiO2·yH2O), resulting in lowered levels of recoverable Al and Na from the filtrates. Similar behavior was observed for other samples tested.

Sample 5 was leached for 8 h at 18, 60 and 100 °C and the leach residues were analyzed by XRD. The XRD results identified spinel, sodium aluminosilicate phase, larnite, calcium aluminoferrite, melilite and trace wustite as dominant phases in the roasted samples. Variation of sodium aluminosilicate phases in the samples during leaching is obvious (Fig. 2). Traces of sodium aluminosilicate phase in sample 5-A may be due to the residual solid as the lower reaction ratio. The sodium aluminosilicate phase in sample 5-C may be due to product of secondary reactions at high temperature as discussed above.



Fig. 1. Results of the concentration of Al, Na, Ca, Fe and Si in solution versus leaching time for filtrates produced from sample 5 at 18 °C, 60 °C and 100 °C.

3.2. Effect of Ca/Si ratios on recovery of Al and Na

The recoveries of Al and Na from samples 1 to 10 are shown in Fig. 3, the results indicating the dependence of the extraction of Al and Na on Ca/Si ratio. Sharp increases in the extraction of Al and Na with Ca/Si from 1.48 to 1.88 are obvious, followed by a moderate increase of Al and Na extraction with Ca/Si from 1.88 to 2.38. When the sample 6 (with a Ca/Si of 1.98) was leached at 60 °C, about 75.7 wt.% Al and 88.4 wt.% Na were dissolved within 15 min, and the Na₂O content in leached residue was low at 1.55%. Excluding the soda added into the mixture, 80.7% of Na in raw red mud



Fig. 2. XRD patterns of sample 5 before and after leaching. So: Sodium Aluminosilicate, Sp: Spinel ($Fe^{2+}(Al, Fe^{3+})_2O_4$), C: Calcium ferrite ($Ca_2(Al, Fe)_2O_5$), L: Larnite (Ca_2SiO_4). There are also trace amount of Melilite (($Ca, Na)_2(Al, Mg, Fe^{2+})$](Al, Si)SiO₇]) and Wustite (FeO) were identified in these four samples.



Fig. 3. Dependence of Al and Na extractions (60 $^\circ\text{C})$ on Ca/Si ratio in roasted samples.

was recovered. This result indicates that the potential hazard from caustic of red mud can be significantly reduced.

The compositions of the phases observed in the roasted samples were analyzed by ESEM/EDX. Phases were identified by comparing the EDX analysis to a list of expected phases from XRD and matching the elemental composition to the mineral phase that most closely matched the EDX composition. It was found that the compositions of the sodium aluminosilicate in samples change with the Ca/Si ratio (Table 4). The Si content of the sodium aluminosilicate phase decreases from 17.92 at.% (Ca/Si = 0.17) to 4.04 at.% (Ca/Si = 1.97). In sample 9, the content of Si in this phase is higher than that of sample 6. This may be caused by non-equilibrium experimental conditions and/or uncertainty in the analysis of the fine grains.

The dependence of Al solubility and Si content in sodium aluminosilicate phase on the value of Ca/Si in roasted samples is shown in Fig. 4. Quantitative analyses generally indicated a similar trend that



Fig. 4. Correlation between Al extraction and Si in the sodium aluminosilicate.

both Al and Si become less soluble at lower Ca/Si ratios in the roasted sample. Broadly speaking, the trend indicates a negative impact of Si on the leachability of the sodium aluminosilicate phase. The chemical reaction can be expressed as the equation following:

$$\begin{split} \mathsf{Na}_2\mathsf{O} \cdot m\mathsf{Al}_2\mathsf{O}_3 \cdot n\mathsf{SiO}_2 \cdot x\mathsf{H}_2\mathsf{O} + 2n\mathsf{CaO} + (m-1)\mathsf{Na}_2\mathsf{CO}_3 \\ \to m\mathsf{Na}_2\mathsf{O} \cdot \mathsf{Al}_2\mathsf{O}_3 + n2\mathsf{CaO} \cdot \mathsf{SiO}_2 + x\mathsf{H}_2\mathsf{O} + (m-1)\mathsf{CO}_2 \uparrow \end{split} \tag{1}$$

As the concentration of CaO increases in the roast, the thermodynamic activity of silica is decreased, and less SiO_2 is available to form the sodium aluminosilicate phase at high temperature (Bruckard et al., 2010). However, the Si reversal in sample 9 accompanies a sharp increase of CaO in the phase perhaps as a result of the CaO excess in the sample.

3.3. Effect of roasting atmosphere on products

Sample 11 (chemically identical to sample 6) was roasted in air, while sample 6 was roasted in the reductive atmosphere formed by the char and protected with N₂. When these two samples were leached under the same conditions to recovery Al and Na, the extractions of Al and Na from sample 11 were 13% and 17% respectively, which are much lower than that from sample 6 (75.7% and 88.4%). The XRD patterns for two roasted samples are shown in Fig. 5. The phase composition of two samples is quite different. In particular, spinel was more dominant in sample 6 and in sample 11, melilite ((Ca, Na)₂(Al, Fe)[(Al, Si)SiO₇]) and calcium ferrite (CaFe₂O₅) were more abundant (in the oxidizing atmosphere).

The effect of reaction atmosphere was also modeled by using the MPE software. The product phases and their amount of the roasting process can be calculated under equilibrium conditions. As shown in Table 5, the iron-containing phases change with varying P_{02} . A previous study found that more reductive condition was required to keep spinel stable in the soda-lime roasting system than in the raw red mud at the same roasting temperature (Liu, 2010). The yields of phases and Si contents in sodium aluminosilicate phase at given P_{02} are shown in Fig. 6. Table 5 and Fig. 6 indicate that, when the P_{02} is above 1×10^{-9} atm, there is more

Table 4

Compositions of the sodium aluminosilicate phase in different samples with varying Ca/Si ratios.

No.	Ca/Si ^a	Average C	Average Compositions of sodium aluminosilicate phases (at.%)								
		Na	Mg	Al	Si	К	Ca	Ti	Fe	0	
1	0.17	10.19		16.67	17.92	0.06	0.72		0.59	53.76	4
2	1.31	11.10		17.57	13.83	3.28	1.89	0.25	1.64	50.44	5
6	1.98	16.77		17.81	4.04		1.50			59.88	3
9	2.12	13.32	0.41	17.45	7.14		5.91		0.82	54.95	2

^a The molar ratio of Ca/Si from XRF analysis.



Fig. 5. XRD patterns of samples roasted in different atmospheres. S: Spinel, So: Sodium aluminosilicate, Ca: Calcium Ferrite, M: Melilite, L: Larnite.

Fe in calcium aluminosilicate and slag. When the P_{O2} is in the range from 1×10^{-9} atm to 1×10^{-13} atm, spinel is a stable phase, and more calcium is released to react with Si in sodium aluminosilicate. Simply, the reaction atmosphere can affect the stability of ferrous compounds and further affect reactivity of Ca and Si in the system. Li et al. (2009) and Kizhakke et al. (1977) also found the effect of carbon addition and of sintering temperature on Al extraction.

3.4. Optimization of other roasting and leaching conditions

A series of experiments were carried out to optimize the roasting and leaching conditions. Within the range covered, the best roasting conditions were: the molar ratio of Ca/Si around 2.0, Na/Al around 1.0, 0.5 g coal char per 100 g red mud, roasting temperature of 1000 °C, roasting time of 3 h. The leaching conditions were optimized as the following: 50 g solid sample (with particle size below 0.125 mm) for 100 mL water, leaching temperature of 60 °C for 15 min. Under optimized conditions, the lixivium was obtained after leaching twice, and the concentrations of Na and Al in the solution were 61 and 63 g/L respectively. The solution can be recycled into the Bayer process for refining alumina from bauxite, or for diluting the digested solution.

3.5. Magnetic separation of ferrous compounds

From XRD and SEM results, there are spinel phases in samples which are solid solution of magnetite (Fe_3O_4), hercynite ($Fe(Fe,AI)_2O_4$) and ulvospinel ($TiFe_2O_4$). It is possible to recover some of the ferrous compounds from the leached residue. Experiments indicated that 51.2% of Fe was recovered in a magnetic concentrate and the total Fe content in the concentrate was 52.8% by weight in magnetic separations with magnetizing current of 1.0 A (the magnetic field intensity about 110 mT). The Fe



Fig. 6. Yields of slag and contents of Si in sodium aluminosilicate phase in system under different P_{Ω^2} .

recovery and Fe content in the concentrate are lower than that obtained from reductive sintering process (Fursman et al., 1970). The reason for the lower recovery ratios and lower Fe levels in concentration lies in the fact that, the magnetic ferrous phases usually bond together with other phases, such as larnite and sodium aluminosilicate phase. As shown in Fig. 7a, in the roasted sample spinel agglomerates as large particles with other impurities at the edge of the particle. The impurity adherence together with the



Fig. 7. Electron micrograph of sample 5 before and after leaching.

Table 5

Predicted equilibrium phases at different P_{O2} at 1000 °C by the MPE software in the reductive soda-lime roasting process.

<i>P</i> _{O2} (atm)	Larnite Ca ₂ SiO ₄	Sodium Aluminosilicate Na ₂ Al(Al, Si)O ₄	Calcium aluminoferrite $Ca_2(Fe, Al)O_5$	Slag	Spinel Fe(Fe,Al) ₂ O ₄	Fe
0.21	Υ	Υ	Υ	Y		
$0.1 - 1 \times 10^{-8}$	Y	Y	Y	Y		
$1 imes 10^{-9}$ – $1 imes 10^{-12}$	Y	Y	Y	Y	Y	
$1 imes 10^{-13}$	Y	Y		Y	Y	
$1 imes 10^{-14}$	Y	Y		Y		
1×10^{-15} - 1×10^{-16}	Y	Y	Y			Y
1×10^{-18}	Y	Y				Y

Note: Y indicates the existence of the phase in the equilibrium system.

presence of other weak magnetic or non-magnetic ferrous compounds, such as calcium aluminoferrite and hercynite, decrease the mass ratio of Fe in the magnetic concentrate and the recovery ratio. After grinding and leaching (Fig. 7b), the phases were more separated. However, experimental results did not show any benefit in recovering the much finer particles.

4. Conclusions

High degree of recovery of Al (75.7%) and Na (80.7%) from red mud was obtained through soda-lime roasting followed by leaching of the roasted material. Spinel, sodium aluminosilicate, larnite, calcium aluminoferrite, melilite and wustite were observed in the roasted samples at 1000 $^{\circ}$ C.

The dissolution of the Al and Na from the roasted samples was shown to be mainly due to the leaching of a sodium aluminosilicate phase. The addition of CaO within a certain limit promotes the degree of leaching percentages of Al and Na from the roasted solids by reducing the Si content of sodium aluminosilicate phase. The reaction atmosphere can affect the ferrous phases in equilibrium system, and further affect the activity of Si in the system. The work may be used in designing strategies to achieve zero waste from the Bayer red mud.

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References

Bruckard, W.J., Calle, C.M., Davidson, R.H., Glenn, A.M., Jahanshahi, S., Somerville, M.A., Sparrow, G.J., Zhang, L., 2010. Smelting of red mud to form a soluble sodium aluminium silicate phase to recover alumina and soda. Min. Process Extractive Metall. (Trans. Inst. Min. Metall. C) 119, 18–26.

- Doye, I., Duchesne, J., 2003. Neutralisation of acid mine drainage with alkaline industrial residues: laboratory investigation using batch-leaching tests. Appl. Geochem. 18, 1197–1213.
- Erçağ, E., Apak, R., 1997. Furnace smelting and extractive metallurgy of red mud: recovery of TiO₂, Al₂O₃ and pig iron. J. Chem. Technol. Biotechnol. 70, 241–246.
- Fursman, OC., Mauser, JE, Butler, MO., Stickney, W.A., 1970. Utilization of Red Mud Residues from Alumina Production. Report of Investigations 7454, United States Department of the Interior, Bureau of Mines, Washington, DC, USA.
- Gelencsér, A., Kováts, N., Turóoczi, B., Rostási, Á., Hoffer, A., Imre, K., Nyirő-Kósa, I., Csákberényi-Malasics, D., Tóth, Á., Czitrovsky, A., Nagy, A., Nagy, S., Ács, A., Kovács, A., Ferincz, Á., Hartyáni, Z., Pósfai, M., 2011. The red mud accident in Ajka (Hungary): characterization and potential health effects of fugitive dust. Environ. Sci. Technol. 45, 1608–1615.
- Goen, E.H., Kuruvilla, M., Peter, W.G.N., 1989. Leachate quality from gypsum neutralized red mud applied to sandy soils. Water Air Soil Pollut. 47, 1–18.
- Jamieson, E., Jones, A., Cooling, D., Stockton, N., 2006. Magnetic separation of Red Sand to produce value. Miner. Eng. 19 (15), 1603–1605.
- Kizhakke, G.H., Little, R., Ark, 1977. Process for Recovering Soda and Alumina Values from Red Mud. United States Patent, 4045537.
- Li, X., Xiao, W., Liu, W., Liu, G., Peng, Z., Zhou, Q., Qi, T., 2009. Recovery of alumina and ferric oxide from Bayer red mud rich in iron by reduction sintering. Trans. Nonferr. Metals Soc. China 19, 1342–1347.
- Liu, W., 2010. Study on the Multiphase Transformation of Bayer Red Mud in the High Temperature Roasting Reaction and Recovery of Iron, Aluminum, and Sodium. Ph.D. Dissertation, Huazhong University of Science and Technology, Wuhan, China.
- Liu, W., Yang, J., Xiao, B., 2009a. Review on treatment and utilization of bauxite residues in China. Int. J. Miner. Process. 93, 220–231.
- Liu, W., Yang, J., Xiao, B., 2009b. Application of Bayer red mud for iron recovery and building material production from aluminosilicate residues. J. Hazard. Mater. 161, 474–478.
- Liu, W., Zhu, X., Zhang, X., Yang, J., 2010. Size separation pre-treatment and alumina recovery from Bayer red mud. In: XXV International Mineral Processing Congress (IMPC) 2010 Proceedings, Brisbane, Australia.
- Mayes, W.M., Jarvis, A.P., Burke, I.T., Walton, M., Feigl, V., Klebercz, O., Gruiz, K., 2011. Dispersal and attenuation of trace contaminants downstream of the Ajka bauxite residue (red mud) depository failure, Hungary. Environ. Sci. Technol. 45, 5147–5155.
- Red mud Project. <http://www.redmud.org/>.
- Yang, Z., 1983. The Technology of Alumina Production. Metallurgical Industry Press, Beijing, pp. 226–245.
- Yang, J., Xiao, B., 2008. Development of unsintered construction materials from red mud wastes produced in the sintering alumina process. Const. Build. Mater. 22, 2299–2307.
- Yang, J., Zhang, D., Hou, J., He, B., Xiao, B., 2008. Preparation of glass-ceramics from red mud in the aluminium industries. Ceram. Int. 34, 125–130.
- Zhang, L., Jahanshahi, S., Sun, S., 2002. CSIRO's multiphase reaction models and their industrial applications. JOM November, 51–56.