Comprehensive Utilization of Red Mud: Current Research Status and a Possible Way Forward for Non-hazardous Treatment

Ting-an Zhang, Yanxiu Wang, Guozhi Lu, Yan Liu, Weiguang Zhang, and Qiuyue Zhao

Abstract

Red mud is an alkaline solid waste produced in the process of alumina extraction from bauxite. Presently, more than 3.0 billion tonnes of red mud are estimated to be stockpiled on land with an annual growth rate of approximately 120 million tonnes. The large amount of red mud has become a very real threat to the environment and human health because its high alkalinity presents a potential pollution to water, land and air. This article provides an overview of current research status for the options of comprehensive utilization of red mud and attempts to review their strengths and weaknesses. Ideally red mud is encouraged to be utilized as an industrial by-product for other applications, leading to a zero-discharge situation. On this basis the review recommends the Calcification-Carbonization Method, a promising technology for non-hazardous treatment, to recover the alkali and alumina and meanwhile transform the red mud into a non-hazardous material available for subsequent use.

Keywords

Red mud • Non-hazardous treatment • Calcification-carbonization method • Recovery of alkali and alumina

Introduction

Red mud is a alkaline solid waste produced from bauxite as raw material to produce alumina or aluminium hydroxide. At present, the global red mud reserves have been estimated more than 3 billion tonnes with about 0.12 billion tonnes of annual growth rate [1]. The average utilization rate of red mud in the world is 15%. In China, the accumulated red mud pile has increased to 0.4 billion tonnes with the annual growth rate of about 50 million tonnes, but China's red mud utilization rate is only 4%. Most of the currently produced red mud is still dealt with by storage on land. The stockpiling of red mud not only causes a waste of resources and occupies a lot of land, but also destroys the surrounding environment red mud dam, which brings serious environmental problems to the alumina industry. In 2010, the Hungarian Ajka red mud dam collapsed, causing 4 deaths and 3 people missing. The alkaline red mud caused a serious impact on the European countries along the Danube and this event sounded the alarm for the global alumina workers. The environmental risk of red mud stockpiling has already drawn the attention of governments and enterprises in the field of alumina production, and the key to solve the problem of red mud is to develop new technologies of comprehensive utilization of red mud.

In this paper, the current status of the research on technologies of the comprehensive utilization of red mud is summarized and discussed. The disposal of red mud is described and evaluated from three aspects: the storage of red mud, integral utilization as raw material and extracting valuable metals from red mud. Advantages and disadvantages of different processing methods are discussed in this paper, including their rationale. The Chinese version of this article will be released informally at the Eleventh Annual Academic Conference of China Nonferrous Metals Society.

The Processing Method of Red Mud

The Storage of Red Mud

Storage of red mud is divided into deep discharge, wet stockpiling and dry stockpiling. In the past, some coastal alumina producers used their geographical advantages to discharge red mud into the deep sea. However, with the

T. Zhang (✉) · Y. Wang · G. Lu · Y. Liu · W. Zhang · Q. Zhao
Key Laboratory of Ecological Metallurgy of Multi-metal Intergrown Ores of Education Ministry, Special Metallurgy and Process Engineering Institute, School of Metallurgy of Northeastern University, Shenyang, 110819, China
e-mail: zta2000@163.net

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increasing awareness of global environmental protection recently, the sea-fill discharge of red mud has been prohibited by official order. Most of the alumina production enterprises discharge red mud into a red mud dam. Therefore, land stockpiling has been and will remain to be the main method of processing large amounts of discarded red mud [2]. Wet stockpiling is the traditional stockpiling method of red mud, including the wet storage method of storage in a lake formed in a natural gully, building a dam, underground drainage and abandoned mine filling method [3]. The dry stockpiling technology is a significant progress in the red mud treatment process which reduces the amount of liquid, reduces the pollution of red mud to the environment and reduces the alkali consumption by means of a dry slurry or cake filtration process.

At present, most alumina enterprises store red mud in the open air, and gradually transform from wet stockpiling to dry stockpiling. Compared with wet stockpiling, dry stockpiling has many advantages: smaller conveying capacity, larger effective inventory, less land occupation; lower moisture content, less attached alkali, higher alkali recovery, reducing pollution to ground water, easy storage, transportation and utilization. Dry storage is an effective method to reduce the environmental pollution of red mud, but the energy consumption and other cost is higher [3]. A lot of work was conducted on the disposal of red mud, but most of the red mud is still stockpiled on land which only temporarily slows down the damage to the environment. Stockpiling cannot fundamentally solve the environmental problems caused by red mud storage. As a large amount of red mud was not fully processed and reused, it takes up a lot of land resources, consuming huge yard construction and maintenance costs, increasing production costs. Beyond that, the strong alkaline and high salinity red mud liquid will lead to alkaline soil and groundwater pollution, resulting in a surge in environmental pressures. The red mud problem seriously restricts the sustainable development of the alumina industry, and the technical research and comprehensive utilization of red mud is an urgent problem for alumina industry.

Utilization of Red Mud as an Integral Unit

Application in Building Materials

Red mud itself contains a certain amount of β-Ca_2SiO_4 and amorphous aluminosilicate, which has the properties of hydraulicity and chemical curing so as to reach a certain mechanical performance. The application of red mud in building materials is a direct, simple, economical, effective way to consume a large quantity of residue and turn waste into treasure [4, 5]. Red mud is widely used in building materials, such as cement, brick, pavement base material, as well as PVC plastic, glass ceramics, pigments, high performance concrete admixtures, rubber filler, red mud ceramsite, mine filling cementitious materials, insulation materials, fluid self hardening sand hardening agent, impermeable material, radiopaque material.

Despite the application of red mud in building materials having made great progress after many years of research at home and abroad, the actual utilization percentage of red mud is still very low. The obstacles and barriers of red mud in the application of building materials mainly reflects the following three aspects:

(1) High alkali content.

The red mud output is very large. Considering consumption options, red mud is most suitable for producing cement, wall tiles, etc. However, cement has strict quality controls on composition. High alkali content will result in severe alkali aggregate reaction which leads to lower strength and inadequate durability of concrete, and induces serious engineering quality accidents. Sintered brick and other wall materials produced from red mud generate alkali efflorescence which results in the size expansion of the wall material, cracking and disintegration, thus decreasing the service life of the building if the alkali content is too high. Therefore, red mud usually needs dealkalization or stabilizing treatment when used to produce building materials [6].

(2) Less obvious economic benefits and lack of awareness.

Although red mud instead of traditional raw materials reduces the cost of building materials, the complex processing techniques often increase the expenses [6]. Budgeting for the total costs, the economic benefits of using red mud to produce building materials are not very obvious. The relevant departments of the state should strengthen the supervision of the surrounding environment of red mud storage yards, improve environmental monitoring indexes, and establish targeted supportive policies to improve the enthusiasm of enterprises for the use of red mud.

(3) Lack of relevant standards and product market approval.

In the minds of the public, red mud is a kind of industrial waste, which has some harmful effects on the human body and environment. Red mud product is difficult to popularize. Relevant standards are needed to promote the further application of red mud in building materials [7].

Reclamation

Some progress has been made in building materials, but in addition to the above restrictions, application in building materials is also limited by geographical transport radii. Reclamation is to recover the occupied land and reuse the red mud yard through engineering measures in agriculture, forestry, animal husbandry, civil sites, etc., that is land restoration and utilization in mines. Reclamation is an effective solution for low cost storage management [8, 9].

The red mud tailings dam is considered a waste dump site in the process of alumina production, which is a typical mining wasteland. It represents many problems, such as adverse physical structure, lack of organic matter and nutrients, strong alkalinity and high salinity, metal toxicity, unstable surface on which most plants have difficulty to grow [10]. Reviewing the research status of red mud yard reclamation at home and abroad, the main problems and the research emphasis of red mud reclamation can be summarized by the following two aspects:

(1) Strong alkalinity and high salinity.

One of the important factors of red mud's difficult reclamation is its strong alkalinity and high salinity. Soil salinization is not only manifested in chemical properties, but also causes surface soil hardening, structural deterioration, poor water conductivity and so on. It is necessary to explore a suitable, economical and effective way to remove salt and alkali from red mud.

(2) Difficulty in ecological restoration and reconstruction.

In addition to the strong alkalinity and high salt content, soil made from red mud is severely lacking in nutrients and aggregate particles with reasonable structure, resulting in poor capacity to retain water and fertilizer. When the aluminum content increases, the alkaline control probably raises the bioavailability of aluminum which will create toxicity to plants. The lack of effective ground buffer layer and great change of temperature in the storage yard makes it difficult for pioneer plants to invade and seriously endanger the growth of plants [10, 11]. Therefore, it is very difficult to balance the physical, chemical and biological indexes of soil at the same time and establish the ecological balance of soil, plant and microorganisms [12].

Application in Environmental Remediation

Red mud is the residue produced by bauxite leaching in alkaline solution in the process of alumina production. It has unique physical and chemical properties, such as fine particles, porous, large specific surface area. Based on these special features, red mud can purify the contaminants in water and air and remediate soils contaminated by heavy metals and acid. Red mud has been widely used in environmental governance. Unfortunately, this application contributes little to red mud reduction.

(1) Treating wastewater.

Red mud can be used as raw material for preparing adsorbent and water treatment flocculants. This application of the industrial residue has a low cost and it is a typical way of using waste to control another kind of waste. A considerable amount of work has been done to remove the heavy metal ions, inorganic anions, organic dyes and organic pollutants in water by using red mud adsorbent or flocculant and positive progress has been achieved in some research. If the original red mud is directly used as adsorbent, its adsorption capacity is limited. One of the important research directions in the future is how to find cheap and efficient modification methods. Meanwhile, further research is required to study the mechanism of dealing with various pollutants in water [13].

(2) Treating waste gas.

Alkaline red mud has a high absorption capacity for SO_2, SO_3, H_2S and other acid gas. It has many advantages, such as good chemical stability, low viscosity, and low corrosion after dilution. It can reduce equipment investment and maintenance costs and less secondary pollution will be generated in treating waste gas [14]. However, the red mud desulfurization agent used for a period of time will be prone to a hardening phenomenon and poor gas permeability. Because the active component in the desulfurizer will gradually be surrounded by sulfur, it ultimately results in the loss of activity and its failure to achieve the required standard of purification. At this time, this part of the desulfurizer will be scrapped [15]. Further treatment and reuse of waste desulfurizer still needs intensive research.

(3) Remediating soils.

Red mud particles have an effective adsorption effect on heavy metal ions, such as Cu^{2+}, Pb^{2+}, Zn^{2+}, Ni^{2+}, Cr^{6+}, Cd^{2+} which can be used to remediate soils contaminated by heavy metals and acid. As red mud contains many main components (Si, Ca, Mg, Fe, K, S, P) and trace elements (Mo, Zn, V, B, Cu) needed for the growth of crops, it can also be used to produce calcium silicon fertilizer and trace element compound fertilizer. But in the application of red mud, alkali in red mud must be paid attention to which directly leads to the pollution of water sources and does harm to human health. Therefore, when red mud is used to repair soil, the hazard of alkali should be avoided to achieve harmless treatment [16].

Extraction and Recovery of Valuable Metals

Red mud is a resource containing a lot of useful minerals. The main mineral composition includes SiO_2, CaO, Fe_2O_3, Al_2O_3, Na_2O, TiO_2, K_2O which account for more than 75%. In addition, red mud also contains a small amount of Zn, P, Ni, Ga, Ge, Sc, etc. [17]. Geological scientists estimate that the potential value of other metals in bauxite is far more than the value of producing Al_2O_3.

De-alkalization

Alkali removal is the key step for large-scale and harmless treatment of red mud. The discharge of red mud in China is very huge. Because of the current status of alumina industry in China, there are many related researches on de-alkalization methods domestically, including lime de-alkalization, salt leaching method, carbonization de-alkalization, acid neutralization, industrial waste neutralization, lime-sulfuric acid joint de-alkalization, ion-exchange membrane de-alkalization, and bacterial catalytic de-alkalization. Although some progress has been made in the removal of alkali from red mud, each method has its own problems.

Alkali removal by water washing helps remove the free alkali effectively from red mud, but some structural alkali (especially existing in alumino-silicate) is difficult to remove because of its insolubility in water. The structural alkali will seriously affect the subsequent use of red mud. In terms of lime de-alkalization, the cost under atmospheric pressure conditions is generally low, but the alkali removal efficiency is poor. Although the operation under high pressure conditions is more efficient, the treatment cost is higher. Excessive addition of calcium oxide would be detrimental to further extraction of valuable metals. Magnesium chloride and ammonium chloride are both common salts for alkali removal. Although the removal efficiency is relatively high, the presence of chloride will cause serious corrosion of equipment and be negative for subsequent application of red mud. Although the removal efficiency is relatively high, the existence of chloride ion will cause corrosion to the equipment, and will bring some harm to the subsequent application of red mud.

Acid neutralization process can obviously improve alkali removal percentage of the Bayer red mud, but apart from free alkali and alkali structure, aluminum and iron, and a variety of rare-earth metal oxides will also consume large amounts of acid, resulting in an excessive consumption of acid in the process of de-alkalization. Other new methods of alkali removal also have many drawbacks. For ion-exchange membrane de-alkalization, it is difficult to achieve industrial expansion and control the process parameters. Although the effect of sodium removal is obvious, the requirement of bacterial culture for environmental temperature and humidity is quite strict, and there are still many difficulties in realizing industrialization [18, 19].

Alumina Recovery

The content of Al_2O_3 in red mud varies with the production process, which is generally 15–25%. The main methods to extract Al_2O_3 from red mud are sintering process, CaO method with high-pressure, sub-molten salt method, Na_2CO_3 decomposition, acid leaching, melting-acid leaching-extraction coupled method and bio-leaching. Sintering process can overcome the difficulties caused by carbonate and organic matter in ores. In addition, it has the advantages of high recovery ratio of alumina and low alkali consumption. The disadvantage of sintering production is the high energy consumption. Producing 1 tonne of alumina will consume 1 tonne of standard coal or more. When the Fe_2O_3 content is high in red mud, the sintering effect was significantly reduced. CaO method with high-pressure can simultaneously recover aluminum and alkali in red mud. But the treatment condition is rigorous with high temperature and high alkaline concentration which results in higher requirement for equipment. The costs for the evaporation to high concentrations are very high. The treatment effect of red mud is unstable, and the content of alkali in some tailings is 2%, which cannot be used in cement industry. Because of technical and economic reasons, the technology has not yet been used in industry. The method of sub molten salt has better effect on alumina extraction from Bayer red mud which can recover 80% of Al_2O_3 in Bayer red mud. However, due to strong alkaline, high temperature and pressure, the damage to the equipment is greater, and the operation and maintenance costs of equipment are higher [20]. The reaction conditions of acid leaching method are relatively mild and it can realize the preliminary separation of silica, titanium dioxide, ferric hydroxide and aluminum hydroxide. But throughout the processing, the pH value varies from high to low for several times which turns out to be a complex process with high equipment cost. This red mud treatment method has some limitations for the traditional calcium adding Bayer process. Biological leaching of red mud process is simple with low cost. But because of the barrier to cultivate efficient bacteria, long production cycle and strict operating environment, it still has many difficulties in industrialization [20].

Iron Recovery

Recovery of iron from red mud is an important item of comprehensive utilization of red mud. In the case of dwindling iron ore resources and environmental pollution, it is of strategic and practical significance to recycle iron from red mud to turn it into secondary resource [3]. The main methods of extracting iron from red mud are roasting-reduction-magnetic separation process, direct-reduction iron making, physical separation of iron, acid leaching.

The roasting-reduction-magnetic separation process usually uses reduction roasting to convert Fe_2O_3 to Fe_3O_4, and then extracts Fe_3O_4 by magnetic separation. The recovery ratio of iron in this process is high, but the magnetic separation efficiency of iron is low, the energy consumption is large, the process flow is complex, and the production cost is high. Physical iron separation avoids the large amount of energy needed for roasting and reducing in the high temperature. The minerals in red mud usually exist in the form of Fe, Al and Si cements. The particles are fine and the crystallization is very incomplete which causes great difficulty in iron separation and extraction. The grade of iron concentrates generated by physical separation is generally low. When using acid leaching method to recover iron, the oxide of Fe, Al, rare-earth metals, the free alkali and structural alkali in red mud all consumes a great deal of acid which leads to excessive acid consumption. Therefore, in the process of acid leaching, all the components in red mud should be considered to choose a feasible extraction process to recycle other valuable metals in red mud at the same time. Otherwise, it may cause secondary waste of resources and secondary pollution.

Many research data show that it is not too difficult to recover iron from high iron red mud. The main problem is how to optimize the process to reduce waste of resources and energy consumption, reduce recycling costs, and truly achieve sustainable economic development [21].

Recovery of Rare Metals

Some red mud is also rich in rare metal components, such as titanium, scandium, gallium. The alumina production process recycles most of the alumina in bauxite, which further enriches the rare metals dispersed in the natural ores. The recovery of rare metals from red mud is of great economic and social benefits.

The main method to extract rare metal from red mud is acid leaching-solvent extraction. In order to obtain higher metal leaching ratio, higher acid concentration and liquid solid ratio are needed. Thus, the production cost is high, and the impurities in the leaching solution are various and the content is high, so that the extraction and separation and purification of each metal are difficult. As the extraction of rare metals from red mud is still at the experimental stage, the extraction of trace elements mostly adopts extraction or ion exchange method, which will produce large amount of waste water, and increase the difficulty of environmental protection treatment. After enrichment, the content of rare metals is still low. Whether there is economic benefit after industrialization has yet to be proved [17].

Calcification-Carbonization Method: Extract Valuable Elements First and then Fully Use the Treated Residue in an Integral Unit

The analysis of the above red mud utilization methods shows that if you want to solve the problem of red mud stockpiling, the end of the comprehensive utilization process must fully consume the residue, e.g. for producing building materials and reclamation. The de-alkalization process is the key technology for the integral utilization of red mud. Therefore, for the large-scale solution of the problem of red mud, the idea of extracting valuable metals first, and then using the residue in an integral unit is encouraged to completely recover or reuse all valuable components in red mud.

Based on the above analysis, the calcification-carbonization process can effectively recover alkali and alumina from red mud, meanwhile, a new red mud with low alkali and low alumina content is obtained through the non-hazardous treatment which facilitates the subsequent use of cement and soil for production [22–29]. The experimental results show that more than 90% of the alkali and more than 50% of the alumina in the red mud can be recovered through the calcification-carbonization process, meanwhile obtaining a newly structured red mud with calcium silicate and calcium carbonate as the main components which may directly be used for producing cement or soil, so that all the valuable components in red mud can be completely recovered or utilized [30, 31].

The main process of treating red mud with calcification-carbonization method includes:

First, sodium alumino-silicate in red mud is transformed into hydrogarnet by calcification transformation in which most of the Na_2O in red mud can be removed. Second, high-pressure CO_2 is used to decompose calcified product (hydrogarnet) into calcium silicate, calcium carbonate and aluminium hydroxide (carbonized product) through carbonization transformation. Third, aluminium hydroxide in carbonized product is extracted by leaching of NaOH solution at lower temperature (60 °C). A residue in which calcium silicate and calcium carbonate are the main components is obtained which can be directly used in the cement industry or reclamation. This method not only ensures the recovery of valuable elements in the low-grade bauxite or red mud (such as alumina, red mud, etc.), but also realizes the direct bulk utilization of tailings (transformation of red mud) in the production process. In this way, the stockpiling problem of red mud is fundamentally solved and the situation that plenty of solid waste is ejected into the environment is improved. The main processes and conditions of calcification-carbonization method are as follows (Fig. 1 and Table 1):

(1) Calcification process:

$$Na_2O \cdot Al_2O_3 \cdot xSiO_2 \cdot (6-2x)H_2O + 3CaO + H_2O = 3CaO \cdot Al_2O_3 \cdot xSiO_2 \cdot (6-2x)H_2O + 2NaOH \quad (1)$$

(2) Carbonization process:

$$3CaO \cdot Al_2O_3 \cdot xSiO_2 \cdot (6-2x)H_2O + (3-2x)CO_2 = xCa_2SiO_4 + (3-2x)CaCO_3 + 2Al(OH)_3 + (3-2x)H_2O \quad (2)$$

(3) $Al\,(OH)_3$leaching : $Al(OH)_3 + NaOH = NaAl(OH)_4$ (3)

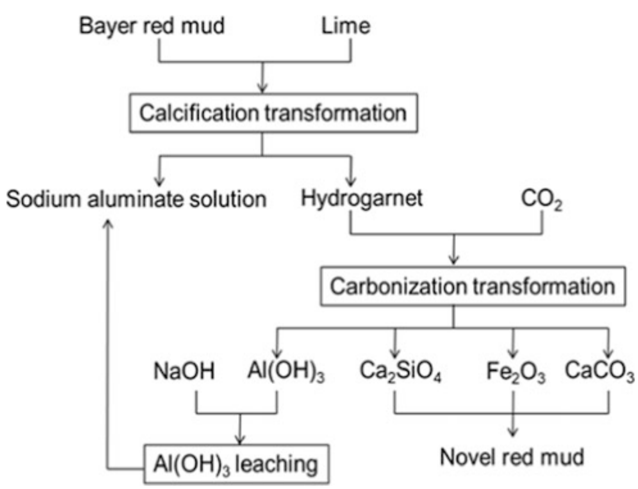

Fig. 1 The flow chart of calcification-carbonization process

Table 1 The main conditions for calcification-carbonization process

Process	Main conditions
Calcification	Temperature: 120–160 °C; Holding time: 1 h; Mass ratio CaO/SiO_2: 2.5; Stirring rate: 300 r/min
Carbonization	Temperature: 120 °C; Holding time: 1–2 h; CO_2 pressure: 1.2 MPa; Stirring rate: 300 r/min

Considering the production costs (including wages, depreciation, repair costs), the economic benefits for processing 1 ton of red mud can obtain 10–20 dollars. As red mud is not treated and just stockpiled on land in most alumina plant, this method can also save the red mud yard maintenance costs about 7 dollars per year for each ton of red mud. Compared with the existing red mud treatment process, the technical and economic advantage and innovation of the calcification-carbonation method is a low cost red mud technology, resulting in a large consumption of red mud through structural transformation. Through carbonization-carbonization transformation, the main component of red mud converts from sodium silicate hydrate to a novel red mud with calcium silicate and calcium carbonate as the main components. In the processing of diasporic red mud and gibbsite red mud, the recovery percentages of alkali and alumina are respectively more than 90% and 50%, and at the same time the non-hazardous treatment of red mud is achieved.

We should actively promote the existing comprehensive utilization of red mud, and at the same time, we should also actively explore new ideas for the use of red mud, so that the value of the comprehensive utilization of red mud can be fully exploited and maximized.

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References

1. Klauber C, Gräfe M, Power G. Bauxite residue issues: II. Options for residue utilization [J]. *Hydrometallurgy*, 2011,108: 11–32.
2. Power G, Gräfe M, Klauber C. Bauxite residue issues: I. Current management, disposal and storage practices [J]. *Hydrometallurgy*, 2011,108: 33–45.
3. Li W X, Theory and Technology of Alumina Production [M]. Changsha: Central South University Press, 2010.
4. He S Y, Jiang S X, Wang W L. Research progress of utilizing red mud as resource of building material in China [J]. Light, Metals, 2007 (12): 1–5.
5. Pappu A, Saxena M, Asolekar S. Solid wastes generation in India and their recycling potential in building materials[J]. *Building Environment* 2007, 42 (6): 2311–2320.
6. Zhuo R F. Research on the preparation of CBC road base material from red mud [D]. Kunming: Kunming University of Science and Technology, 2009.
7. Huang J, Lin L, Yu Y J, et al. Comprehensive Utilization Technology of Industrial Solid Waste and Product Evaluation [M]. Beijing: China Metrology Publishing House, 2014.
8. Liu X B. Development of the red mud ecological treatment technology [J]. Brick & Tile 2015 (12): 62–63.

9. Brunori C, Cremisini C, Massanisso P, et al. Reuse of a treated red mud bauxite waste: studies on environmental compatibility [J]. Journal of hazardous materials, 2005, 117 (1): 55–63.
10. Xue S G,Wu X E,Huang L, et al. Progress in the Research on Ecological Treatment of Bauxite Residues [J]. Mine Engineering 2015 3: 13–18.
11. Zhou L B. Investigation and Practice on Mining Land Rehabilitation and Ecological Reconstruction in China [J]. Nonferrous Metals 2015 59(2): 90–94.
12. Hamdy M K, Williams F S. Bacterial amelioration of bauxite residue waste of industrial alumina plants [J]. Journal of Industrial Microbiology & Biotechnology, 2001, 27: 228–233.
13. Zhu X F,Yang S J,Jiao G Z. Progress in research and application of red mud in water treatment [J]. Inorganic Chemicals Industry 2010 42(2): 5–8.
14. Lv C S,Wang J W,Lu C Y, et al. The summary of the desulfurization process with Bayer red mud [J]. Guangzhou Chemical Industry 2012 40(18): 20–22.
15. Gu T Y, Wang R Y, Run G F. Confection and application of the red mud desulphuration dosage [J]. Tong Mei Technology 2002 (2): 17–18.
16. Fan M R, Luo L, Liao Y L, et al. Application of Red Mud in the Remediation of Heavy Metal Pollution and Agricultural Production [J]. Chinese Journal of Soil Science 2010 41(6): 1531–1536.
17. Li D, Pan L X, Zhao L Q, et al. Advance research of utilization technology of red mud [J]. Environmental Engineering 2014 32 supplement: 616–618.
18. Zhu X B, Li W, Guan X M, et al. Research status on dealkalization of the red mud by Bayer process [J]. Bulletin of the Chinese Ceramic Society 2002 (2): 2254–2257.
19. Zhang C L, Wang J W, Liu H L, et al. Research advance and status quo of dealkalization of red mud [J]. Multipurpose Utilization of Mineral Resources 2014 (2): 11–14.
20. Ma S H, Zheng S L, Zhang Y. Recovery of soda and alumina from red mud [J]. Multipurpose Utilization of Mineral Resources 2008 (1): 27–30.
21. Lu J Z, Yu X J, Zhang L P. Development condition of recovering iron from red mud [J]. Shandong Metallurgy 2007 29(4): 10–12.
22. Zhang T A, Lv G Z, Liu Y, et al. A method of consuming Bayer red mud [P]. China, CN201110275030.X.
23. Zhang T A, Lv G Z, Liu Y, et al. Calcification-carbonization one-step method for treating Bayer red mud [P]. China, CN201610333963.2.
24. Zhang T A, Lv G Z, Liu Y, et al. Calcification-carbonization method for the recovery of alkali and alumina in treating Bayer red mud [P]. China, CN201410182568.X.
25. Zhang T A, Lv G Z, Zhang Z M, et al. A method for treating low grade aluminium-containing raw material and aluminium circulation by calcification-carbonization process [P]. China, CN201410181684.X.
26. Zhang T A, Lv G Z, Liu Y, et al. A method for reducing aluminium-silicon ratio of red mud by multi-stage carbonization [P]. China, CN201410179294.9.
27. Zhang T A, Lv G Z, Zhang Z M, et al. A Method for producing alumina without evaporation by calcification-carbonization process [P]. China, CN201410182601.9.
28. Zhang T A, Lv G Z, Liu Y, et al. A method for calcification transition by adding calcium mineralization in alumina production process [P]. China, CN201410183034.9.
29. Zhang T A, Lv G Z, Liu Y, et al. A comprehensive utilization method of valuable metal elements in iron aluminum intergrowth ore [P]. China, CN201410179437.6.
30. A new technology for large-scale and low-cost harmless treatment of Bayer red mud. Chinese certificate of scientific and technological achievements, [2015] No.051.
31. Clean production of alumina by efficient utilization of medium-low grade bauxite by calcification carbonization process, Chinese certificate of scientific and technological achievements, [2015] No. 052.