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Natural evolution of alkaline characteristics in bauxite residue

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Abstract: Bauxite residue, a highly alkaline solid waste, is extremely hazardous to the surrounding environment and current research approaches have largely focused on the removal and separation of alkaline substances. Natural weathering processes may be a step forward in terms of their regeneration. In this study, natural evolution of basic alkalinity, electrical conductivity, exchangeable ions and acid neutralizing capacity of residue in the disposal areas is discussed. Minerals, exchangeable cations and alkaline anions were analyzed by X-ray powder diffraction (XRD), inductively coupled plasma atomic emission spectroscopy (ICP-AES) and titration, respectively. Acid neutralizing capacity was carried out by batch neutralization experiments. Basic alkalinity, electrical conductivity, cation exchange capacity and exchangeable sodium percentage decreased with increasing disposal duration. Sodium was the predominant exchangeable cation in fresh residue but its concentration significantly decreased with increasing time from initial disposal. The acid neutralizing capacity of bauxite residue was investigated by incubation with hydrochloric acid. Acid neutralizing capacity curves changed with disposal duration and each revealed a characteristic buffering behavior that could be controlled by its alkaline components.

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1. Introduction

As a result of the high demand for aluminum, the global alumina industry has developed rapidly. However, these rapid developments have triggered numerous environmental issues (Gelencser et al., 2011; Mayes et al., 2016; Ruyters et al., 2011) that severely restrict the sustainable development of the alumina industry. Bauxite residue (red mud) is an alkaline solid waste generated by extraction of alumina from bauxite in refineries. The volume of bauxite residue generated while producing one ton of alumina is typically about 0.5-2 tons. With increasing demand for alumina worldwide, the global inventory of bauxite residue has reached an estimated 4 billion tons based on its current rate of production, and is still rapidly increasing (Kinnarinen et al., 2015; Liu and Naidu, 2014; Power et al., 2011). China is the largest producer of alumina in the world (Liu et al., 2014; Si et al., 2013). Its accumulative inventory of bauxite residue has reached over an estimated 0.6 billion tons with an annual increase of more than 70 million tons (Xue et al., 2016). Currently, almost all bauxite residue is stored indefinitely in land-based bauxite residue disposal areas (BRDAs) (Burke et al., 2013; Santini et al., 2015; Zhu et al., 2016a), which require continuous resources to manage and transform the waste and reduce its potential to contaminate water and land, as well as the surrounding ecology (Banning et al., 2014; Lockwood et al., 2015; Santini and Fey, 2015). Leaching of alkaline waste is a further potential problem (Buckley et al., 2016; Pulford et al., 2012; Samal et al., 2015). The adverse alkalinity means that bauxite residue is listed as a contaminated waste, which limits its disposal, applications and options for its sustainable reuse.

Many amelioration techniques have been developed in an attempt to reduce the alkalinity of bauxite residue. For example, seawater neutralization is used by some coastal refineries (e.g. Shandong Aluminium Industry Co., Ltd; Queensland Alumina), which involves the addition of excess seawater to convert soluble hydroxides, aluminates and carbonates into insoluble solids as calcite (CaCO$_3$), hydrocalumite
(Ca₄Al₂(OH)₁₂·CO₃), aluminohydrocalcite (CaAl₂(CO₃)₂(OH)₄·3H₂O), brucite (Mg₃(OH)₆) and hydrotalcite (Mg₆Al₂(CO₃)(OH)₁₆·4H₂O) (Clark et al., 2015; Johnston et al., 2010; Menzies et al., 2004). Seawater neutralization lowers pH and alkalinity, but the generated colloidal particles are difficult to deal with. Carbon dioxide (CO₂) sequestration utilizes the reaction of CO₂ with OH⁻ to form HCO₃⁻, and the reversibility of key alkalinity reactions between OH⁻, CO₃²⁻ and HCO₃⁻ (Renforth et al., 2012; Wang et al., 2009; Yadav et al., 2010). The innovative nature of this technique is the consumption of CO₂ to reduce atmospheric and industrial carbon dioxide emissions via sequestration (Cooling et al., 2002; Guilfoyle et al., 2005; Rai et al., 2013; Sahu et al., 2010). Interaction of waste acid can react with and transform hydroxides, oxides and sodalite (Freire et al., 2012; Lu et al., 2010), but the leached liquor and residue becomes a complex problem to manage, generating additional pollution issues (Burke et al., 2013; Goloran et al., 2015; Zhu et al., 2015a). Furthermore, the physical properties of bauxite residue present a problem, being a hostile environment for plant establishment (Borra et al., 2015; Kopittke, 2004; Zhu et al., 2015b). Gypsum transformation of bauxite residue lowers the pH by precipitating OH⁻, Al(OH)₄⁻, and CO₃²⁻ as calcium hydroxide (Ca(OH)₂), tri-calcium aluminate (TCA, Ca₃Al₂(OH)₁₂), hydrocalumite (Ca₄Al₂(OH)₁₂·CO₃) and calcite (CaCO₃) (Babu and Reddy, 2011; Courtney and Kirwan, 2012). The efficacy of gypsum in transforming the alkalinity is limited to gypsum’s ability to readily dissolve (Courtney et al., 2009; Courtney and Harrington, 2012).

These amelioration strategies may temporarily contribute to reduce the alkalinity of bauxite residue, but nevertheless there remains insufficient long-term success due to side effects and economic issues. Many of the current research techniques have focused on artificial amelioration of alkaline substances with less attention being paid to the natural evolution of alkalinity and its occurrence in bauxite residue.

There is limited mechanistic understanding of bauxite residue alkalinity characteristics following its long term disposal. Indeed, lack of understanding of evolution chemistry and alkalinity behavior has been highlighted as a significant knowledge gap in relation to the safe management and revegetation of bauxite residue.
in BRDAs. This study therefore had the following specific objectives: (1) Discuss the changes in overall alkalinity of bauxite residue during its disposal history. (2) Identify the quantitative relationships between EC, Na\(^+\) and OH\(^-\). (3) Investigate the transformations in exchangeable cation and sodium percentages. (4) Understand the neutralization behavior following long term natural evolution of the residue.

2. Materials and methods

2.1 Field sampling and sample handling

The raw bauxite residue sample used in this study was collected at the BRDA of the Zhongzhou refinery, Aluminum Corporation of China, Henan province, China. Samples were collected from 5 locations as follows; freshly deposited residue (0 years) (Lat 35°24′3.76″ N, Long 113°25′38.18″ E), 5 year old residue (5) (Lat 35°24′3.03″ N, Long 113°25′38.82″ E), 10 year old residue (10) (Lat 35°24′2.43″ N, Long 113°25′38.26″ E), 15 year old residue (15) (Lat 35°24′1.86″ N, Long 113°25′40.39″ E) and 20 year old residue (20) (Lat 35°24′28.11″ N, Long 113°25′47.33″ E). Residue age differences are approximate but were determined due to a change in zonation which was clearly visible within the stacks. At each location, three sub-samples were collected with a distance of 5 meters from each other to form a representative sample. Samples were stored in polyethylene bags, returned to the laboratory and subsequently air-dried for 1 week, disaggregated using a mortar and pestle, and sieved to retain the <2 mm fraction. Subsequently, X-ray powder diffraction (XRD) analysis was conducted on the samples using a Bruker D8 discover 2500 with a Cu \(K\alpha_1\) tube using a Sol-X detector. X-ray diffraction patterns were collected from 10 to 80° at a scan rate of 1° 2\(\theta\)/min and a step size of 0.04° 2\(\theta\). XRD data analysis used the PANalytical analysis package to identify and quantify phases.

2.2 Analytical methods

Bauxite residue : water (1:5) extracts were prepared to determine pH, electrical conductivity (EC), and alkaline anions, and a bauxite residue : 1mol/L ammonium acetate (1:5) extract was prepared to analyze exchangeable cations. Supernatant liquors
from the water extraction were mixed at 150 rpm (1 h) then centrifuged at 3000 rpm (10 min) and analyzed for pH and EC (Clark et al., 2015). Sodium, K, Ca and Mg in ammonium acetate (pH=7) extracts were analyzed by inductively coupled plasma atomic emission spectroscopy (ICP-AES). Since no exchangeable acidic cations are expected to exist in alkaline conditions, the sum of exchangeable Na, K, Ca and Mg can be used as an estimate of cation exchange capacity (CEC).

Prepared supernatants from the water extraction were analyzed for alkaline anions (carbonate, bicarbonate and aluminate) by titration using a 0.02 mol/L H$_2$SO$_4$ standardized solution. The supernatant (5 mL) was diluted with Milli-Q water to 30 mL. For solutions that were initially at a pH above 10.5, the solution was titrated to pH 10.3 (first titration), and then a 250 g/L sodium gluconate solution was added until pH no longer increased. The solution was then titrated from pH 10.3 (second titration) to pH 4.5 (third titration) (Kirwan et al., 2013). For solutions that were initially at a pH between 8.3 and 10.3, the solution was directly titrated to pH 4.5 (third titration). From the first titration, the free hydroxide concentration (OH$^{-}$) was determined. From the second titration, the aluminate concentration (Al(OH$_4$)$^{3-}$) was determined, and from the third titration, the carbonate concentration (CO$_3^{2-}$) was measured.

2.3 Batch neutralization experiments

Acid neutralizing capacity (ANC) from each of the 5 locations was determined by repeatedly titrating the supernatants. Samples (10 g) were weighed into conical flasks (100 ml). Hydrochloric acid (HCl) (0.5 mol/L) was subsequently added at 0.8 ml increments, and made up to volume (50 ml) with Milli-Q water. The supernatant liquors were then shaken by hand and pH determined immediately. Samples were then placed on a shaker operating at 120 rpm (25°C). Supernatant pH was determined after 1 min, then on day 1, 5, 15, 30 and 60 of shaking. Measurements were conducted on supernatants in the conical flasks without removal of any sample. All samples (each in duplicate) from the different disposal dates were used for ANC determinations.
3. Result and discussion

3.1 Transformation of basic alkalinity

Basic alkalinity of the residue from the five locations are presented in Table 1. Following disposal, alkalinity decreased. For fresh residue, initial alkalinity was 28349.69 mg/L Na₂CO₃, compared to 21857.02 mg/L Na₂CO₃ from the 20 year old disposal area. Alkalinity is a result of the caustic solution from the Bayer process, and because of incomplete washing prior to disposal, alkaline substances (sodium hydroxide, NaOH; sodium carbonate, Na₂CO₃; sodium aluminate, NaAl(OH)₄) remain in the bauxite residue. During disposal, compounds such as OH⁻, CO₃²⁻, and Al(OH)₄⁻, will undergo a chemical transformation. These reactions are expressed as Eqs. (1), (2) and (3). Notably, the concentration of OH⁻ was greatly reduced after 15 years following disposal.

\[
\text{OH}^- + \text{H}^+ \rightarrow \text{H}_2\text{O} \tag{1}
\]
\[
\text{CO}_3^{2-} + \text{H}^+ \rightarrow \text{HCO}_3^- \tag{2}
\]
\[
\text{Al(OH)}_4^- + \text{H}^+ \rightarrow \text{Al(OH)}_3^- + \text{H}_2\text{O} \tag{3}
\]

Slaked lime (Ca(OH)₂) is commonly added within the Bayer process to improve digestion of alumina from the ore. This can lead to the formation of many solid phase calcium hydroxides, carbonates and aluminates, such as hydrogarnet (Ca₃Al₂(SiO₄)ₓ(OH)₁₂₋₄ₓ), calcite (CaCO₃) and tri-calcium aluminate (TCA, Ca₃Al₂(OH)₁₂) (Fig. 1). These insoluble solids act as an alkali store and their dissolution (hydrogarnet, Eq. (4); calcite, Eq. (5); tri-calcium aluminate, Eq. (6)) can provide a continuous source of alkaline compounds OH⁻, CO₃²⁻ and Al(OH)₄⁻ (Gomes et al., 2015).

These alkaline anions are continuously consumed (Fig. 1), but even after 20 years, the alkalinity of the residue remained at a relatively high level; this may be attributed to these insoluble solid substances.

\[
\text{Ca}_3\text{Al}_2(\text{SiO}_4)_{x}(\text{OH})_{12-4x} \rightarrow (6-4x)\text{OH}^- \tag{4}
\]
The de-silication products (DSPs) are a sub-set of more general Bayer process characteristic solids (BPCSs) generated by the reaction of reactive silica with sodium hydroxide and which impart significant alkalinity to the residues. The main DSPs formed are Bayer sodalite ([Na$_6$Al$_6$Si$_6$O$_{24}$][2NaOH or Na$_2$CO$_3$]) and cancrinite ([Na$_6$Al$_6$Si$_6$O$_{24}$]·2[CaCO$_3$]) (Fig. 1); they have a zeolite-type caged construction which can attach sodium. These anions tend to be dominated by OH$^-$, CO$_3^{2-}$, and Al(OH)$_4^-$.

With natural disposal, it is difficult for these attached anions to be released and transformed. Hence in this way, DSPs can be a source of alkalinity. The natural transformation of these anions associated with the dissolution of DSP results in relatively stable alkalinity. However, with increasing duration following disposal, concentration of sodalite, hydrogarnet and calcite (Fig. 1) gradually reduced, whilst free hydroxides, carbonates and aluminates changed and the alkaline nature of the residue decreased.

3.2 Transformation of electrical conductivity

During disposal, EC decreased with increasing duration following disposal (Fig. 2). For fresh residue, the initial EC was 3.73 mS/cm, compared to 0.36 in the 20 year old residue. During disposal, electrical conductivity affected the evolution of the residues alkaline characteristics. To elucidate the relationships between EC and alkaline sodium ions (Na$^+$) and EC and hydroxide ions (OH$^-$) linear curves were plotted (Fig. 3 and Fig. 4). High EC values present high concentrations of alkaline Na$^+$ and is replenished from Na-bearing solids. With increasing time from initial disposal, Na-bearing solids decreased with a corresponding decrease in EC (Fig. 2).

Electrical conductivity is also related to hydroxide ions (OH$^-$), and it is important to note that the linear relationship is approximately a factor of 1/3. The linear curve was a good fit and showed EC (mS/cm) ~ 1/3 OH$^-$ (mmol/L) (Fig. 4). High EC values also
demonstrate high concentrations of \( \text{OH}^- \). The dissolution reactions are the main source of \( \text{OH}^- \), which result in bauxite residue becoming weakly alkaline with increasing duration following disposal.

In the absence of detailed supernatant compositional data, EC is the most feasible quantity to estimate ionic strength. In natural aqueous solutions, Griffin and Jurinak (1973) determined the equation of \( \text{EC} \sim 78 \text{ IS} \). The double-layer thickness of charged particles of bauxite residue becomes weak. Residue particles become dispersed, and the osmotic potential becomes more favorable. These transformed properties are beneficial to the disposal of bauxite residue and to stabilize the BRDA over the long term.

3.3 Transformation of exchangeable cations

The natural evolution of exchangeable cations (Na, K, Ca, Mg) are presented in Fig. 5. Exchangeable Na decreased with increasing disposal time whilst exchangeable K, Ca and Mg increased with increasing time following disposal. For fresh bauxite residue, the molar concentrations of various exchangeable cations were in the following decreasing order: \( \text{Na} > \text{Ca} > \text{Mg} > \text{K} \). Exchangeable Na accounted for approximately 72% of the total exchangeable cations (mean molar concentration). This revealed that exchangeable Na dominated the basic cations in fresh bauxite residue. However, the concentration of exchangeable Na decreased from 20.28 cmol./kg in fresh residue to 9.81 cmol./kg in 20 year old residue. The concentration of exchangeable Ca increased from 6.96 cmol./kg in fresh residue to 17.40 cmol./kg in 20 year old residue. The increase in K and Mg was however not obvious, indicating that a large concentration of exchangeable Na was replaced with exchangeable Ca during the disposal process.

It should also be noted that the cation exchange capacity (CEC) of the residue decreased with increasing duration following disposal (Fig. 6). This may be attributed to a reduction in pH over time (Eq.(7), resulting in precipitation of \( \text{Ca(OH)}_2 \) but also leaching of NaOH. The original negatively charged [\( \text{Al(OH)}_6 \)]\(^{\text{3-}} \) lost three \( \text{OH}^- \) which resulted in zero-charged [\( \text{Al(OH)}_3 \)]\(^{\text{0}} \) (Eq. (8)). Similar exchange reactions are available at edge sites of other alkaline compounds. The charged state of the colloids is therefore a significant regulator for cation exchange. During the time from disposal, with a
reduction in CEC, the negatively charged sites became increasingly positive.

\[
[\text{Al(OH)}_6]^{3-} \quad (7)
\]

[Na\(^+\)+Ca\(^{2+}\)]\(^+\)→[Al(OH)\(_3\)]\(^0\)+NaOH(leaching)+Ca(OH)\(_2\)(precipitation)

\[
[\text{Al(OH)}_6]^{3-}-3\text{OH} \rightarrow \text{zero-charged} \ [\text{Al(OH)}_3]^0 \quad (8)
\]

The exchangeable sodium percentage (ESP) (Fig. 7) decreased with increasing duration following disposal. The ESP approximates to the composition of cation exchange sites on the residue surface as a result of the composition of exchangeable Na, Ca and Mg (Gräfe and Klauber, 2011). Sodium ions can’t be dehydrated as readily as Ca and Mg, which is indicative of stable hydration layers in bauxite residue particles. Additionally, Na ions can’t be coordinated with negatively charged surfaces. The effect is that particles of fresh bauxite residue do not aggregate well and usually tend to be crusted and eroded in the dry state as Na eventually precipitates out as soda ash (trona and nahcolite), which simultaneously leads to the formation of alkaline dust and efflorescence at the surface of BRDAs (Klauber et al., 2008). The poor structural conditions at the surface of BRDAs are ultimately dependent on revegetation. With increasing time following disposal, the poor structural conditions may gradually be ameliorated (Zhu et al., 2016b).

3.4 Transformation of Acid neutralizing capacity

Acid neutralization of fresh residue shows changes in pH created by addition of hydrochloric acid (Fig. 8). Acid neutralizing capacity (ANC, final pH 7) of 1 min, 1, 5, 15, 30 and 60 days were 0.091 mol H\(^+\)/kg, 0.27 H\(^+\)/kg, 0.36 H\(^+\)/kg, 0.57 H\(^+\)/kg, 0.68 H\(^+\)/kg and 0.78 H\(^+\)/kg solids, respectively. Fig. 8 shows that the moles of H\(^+\) taken to reach pH 7 increase as neutralizing time elapses, and most of the increase occurs at day 1 and 5. The curve at day 60 reveals an extensive horizontal section. Some of this neutralizing behavior can be attributed to soluble free Na\(_2\)CO\(_3\) and NaOH (Eqs. (9) and (10)) occurring at the region of pH>8. Much of this neutralizing behavior is associated with hydroxyls on the surfaces of iron oxides (FeO, Fe\(_2\)O\(_3\)-OH, its reaction (Eq. (11)) occurs at the region of pH<6) in the bauxite residue and dissolution of sodalite, tricalcium aluminate and calcite ([Na\(_6\)Al\(_6\)Si\(_6\)O\(_{24}\)]·[2NaOH], Ca\(_3\)Al\(_2\)(OH)\(_{12}\) and CaCO\(_3\).
(Eqs. (12), (13) and (14) (Snars and Gilkes, 2009; Wissmeier et al., 2011; Xue et al., 2016). The length of the neutralizing region reflects the contents of these components in the bauxite residue.

\[
\text{Na}_2\text{CO}_3 + \text{H}^+ \rightarrow 2\text{Na}^+ + \text{H}_2\text{O} + \text{CO}_2 \quad \text{The pH region: } > 8 \quad (9)
\]

\[
\text{NaOH} + \text{H}^+ \rightarrow \text{Na}^+ + \text{H}_2\text{O} \quad \text{The pH region: } > 8 \quad (10)
\]

\[
\text{FeO}, \text{Fe}_2\text{O}_3\cdot\text{OH} + \text{H}^+ \rightarrow \text{FeO}, \text{Fe}_2\text{O}_3 + \text{H}_2\text{O} \quad \text{The pH region: } < 6 \quad (11)
\]

\[
[\text{Na}_6\text{Al}_6\text{Si}_6\text{O}_{24}]\cdot[2\text{NaOH}] + 8\text{H}^+ + 10\text{H}_2\text{O} \rightarrow 8\text{Na}^+ + 6\text{H}_2\text{SiO}_3 + 6\text{Al(OH)}_3 \quad (12)
\]

\[
\text{Ca}_3\text{Al}_2(\text{OH})_12 + 6\text{H}^+ \rightarrow 3\text{Ca}^{2+} + 2\text{Al(OH)}_3 + 6\text{H}_2\text{O}; \quad \text{The pH region: } 6-8 \quad (13)
\]

\[
\text{CaCO}_3 + 2\text{H}^+ \rightarrow \text{Ca}^{2+} + \text{H}_2\text{O} + \text{CO}_2 \quad \text{The pH region: } < 6 \quad (14)
\]

The length of the neutralizing region reflects the contents of these components in the bauxite residue. The natural evolution of acid neutralizing capacity (ANC) (Fig. 9) was examined due to the characteristics of the fresh bauxite residue (Fig. 8). During disposal, ANC demonstrated some inconsistencies with increasing duration following disposal. For fresh residue, the initial ANC recorded (at pH 7) was 0.78 mol H⁺/kg solid, which presents a strong ANC compared to 0.25 mol H⁺/kg solid from the 20 year old residue. The ANC of fresh residue was higher than that of the residue disposed over the long term, which may be attributed to partial removal of NaOH and Na₂CO₃ by leaching during rainfall and alkali compound transformations. Furthermore, the curves for fresh and 5 year old residue (Fig. 9) present a broad horizontal section; the curves for 10, 15 and 20 year old residue (Fig. 9) only exhibit a narrow section. This neutralizing behavior is associated with the dissolution of sodalite, tricalcium aluminate, calcite and other alkaline compounds (Snars and Gilkes, 2009; Wissmeier et al., 2011). This tendency may demonstrate that fresh bauxite residue contains a larger concentration of sodalite, tricalcium aluminate and calcite, compared to aged residues (consistent with Fig.1 results). Further, the acid neutralizing behavior may enhance the natural evolution
of alkaline substances in bauxite residue following disposal.

3.5 Environmental management for long-term disposal

Historically, the management practices of BRDAs have focused on containment, with little attention given to long term changes in the chemical and physical properties of the residues. Currently, management plans are moving towards remediation and revegetation and/or further soil-formation of BRDAs to reduce environmental risks associated with long term disposal. Subsequently this will establish a stable ecosystem in the residue disposal areas, finally returning occupied land areas to an alternative option. In this work, alkalinity of bauxite residue was reduced with increasing duration following disposal. In addition, aged residue particles (10 to 20 years) had favorable osmotic potential that can’t be considered dangerous to the surrounding environment and may be safely disposed. Furthermore, the long-term disposal of bauxite residue allows a significant decrease in exchangeable Na, EC, and pH values, which can increase the rate of revegetation. The ecological restoration of bauxite residue has many challenges due to its high alkalinity, salinity and sodium content, deficiencies in organic matter and nutrient concentrations. Recent research has indicated the possibility for surface revegetation by Bermuda grass (Cynodon dactylon) together with arbuscular mycorrhizal fungi (Babu and Reddy, 2011) and giant reed (Arundo donax L.) (Alshaal et al., 2013). Revegetation of bauxite residue following disposal in combination with phytoremediation may be a feasible option in the future.

Recently disposed bauxite residue presents potential threats to the environment such as leakage of alkaline compounds into groundwater, risk of caustic exposure to organisms, overflow of alkaline substances during storm events and the loss of alkaline dust and efflorescence forming at the surface of BRDAs, which require sustained and intensive resources to manage and transform their alkalinity. Several methods have been considered for safe disposal, including washing, dewatering, covering with vegetation, neutralization and wetland construction (Burke et al., 2013; Liu et al., 2014; Santini and Banning, 2016). It is critical that residues are washed and dewatered for separation of caustic liquors prior to disposal into BRDAs. Following this, the residue
particles may aggregate well and be stable rather than crusted and become eroded. Furthermore, the formation of alkaline dust and efflorescence at the residue surface may be ameliorated and the residue may be safely stored for long-term natural regeneration.

4. Conclusion

This work provides evidence for the natural evolution of alkaline characteristics of bauxite residue in BRDAs following long term disposal. Bauxite residue has highly alkaline characteristics which decrease with increasing duration following disposal. High EC is related to Na\(^+\) and OH\(^-\) which appear to decrease with increasing disposal time. Cation exchange capacity and exchangeable sodium percentage decrease with increasing duration following disposal. Furthermore, Na was the predominant exchangeable cation in fresh residue but decreased over the long term being replaced with Ca. Acid neutralizing capacity curves changed with disposal history and bauxite residue demonstrated a characteristic buffering behavior that further confirms the natural evolution of alkalinity. More importantly, these findings are applicable to surface revegetation and improved soil-formation because they demonstrate that decreasing alkalinity and increasing structural formation have a positive influence on the residues physical and chemical properties.

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Reference


