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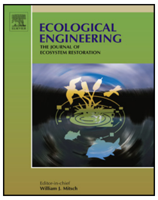

Aging of bauxite residue in association of regeneration: a comparison of methods to determine aggregate stability & erosion resistance

Feng Zhu[a], Jiayi Zhou[a], Shengguo Xue[a,*], William Hartley[b], Chuan Wu[a], Ying Guo[a]

[a] *School of Metallurgy and Environment, Central South University, Changsha 410083, PR China*
[b] *Crop and Environment Sciences Department, Harper Adams University, Newport, Shropshire TF10 8NB, UK*

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ABSTRACT

Aggregate stability is a significant factor governing soil erosion resistance. Bauxite residue has poor aggregate stability and is therefore a major consideration in terms of its regeneration. Residue samples collected from different stacking ages were assessed in order to quantify aggregate formation and stability and determine their resistance to erosion following the modified Yoder's method and the modified Le Bissonnais' method. It was demonstrated that natural plant colonization increased mean weight diameter (MWD) and improved water stable aggregate proportions in bauxite residues. With increasing stacking age, the erodibility factor (K) decreased indicating improved resistance to erosion following natural weathering processes. For unrestored residues, the fast wetting test (FW) was the most efficient for disrupting soil aggregates which indicated that slaking was the major disaggregation mechanism of residue aggregates. For residues which could support plant growth, the erodibility factor (K) had little obvious change under three disruptive tests including the fast wetting test (FW), the slow wetting test (SW) and the wetting stirring test (WS). It was demonstrated that slaking, differential clay swelling or mechanical breakdown had little effect on the residues which had a stable aggregate structure. The MWD of the modified Yoder's method was positively correlated to the MWD of the modified Le Bissonnais' method for FW, SW and WS (r = 0.984, 0.733 and 0.901 respectively, $P < 0.01$) which indicated that Yoder's and Le Bissonnais' methods could effectively determine aggregate stability. Compared to the modified Yoder's method, the modified Le Bissonnais' method was more appropriate to determine the susceptibility to disaggregation mechanisms.

1. Introduction

Structure is a fundamental property of productive soils due to its influence on the transport of nutrients, water and gases, as well as its provision of habitats for fauna and microorganisms. Aggregated soil structure can improve plant growth and increase resistance to soil erosion (Wang et al., 2015). Soil structure depends on the presence of aggregates and their stability, which is used as an indicator of soil structure (An et al., 2013). In fact, soil aggregate stability influences several soil physical processes including soil erosion, water infiltration, soil aeration and biological activity (Karami et al., 2012; Sheehy et al., 2015). Maintaining high soil aggregate stability is essential for preserving productivity and minimizing erosion and degradation (Liu et al., 2014).

Bauxite residue is an alkaline, saline-sodic byproduct, from the extraction of alumina from bauxite ore (Xue et al., 2016). The global inventory of stored bauxite residue in land-based impoundments is currently estimated to be over 3.4 billion tons, with an annual growth rate of approximately 120 million tons (Power et al., 2011). Little evidence exists to effectively exploit bauxite residue as an industrial by-product for other applications. As a consequence, large volumes of bauxite residue have been stacked in disposal areas causing potential environmental risk (Zhu et al., 2016a). Regeneration has been suggested as the main option for remediation of large scale stacks (Jones and Haynes, 2011). However, bauxite residues are often physically degraded, which impedes plant development. Several parameters for assessing soil physical quality such as bulk density, porosity, and aggregate stability are becoming more widespread in assessing restoration on mineral residues (Asensio et al., 2013). Courtney et al. (2013) used water stable aggregates as an indicator of soil formation in restored bauxite residues and found that they had greater aggregate stability which was significantly correlated with organic carbon content

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* Corresponding author.
E-mail addresses: sgxue70@hotmail.com, sgxue@csu.edu.cn (S. Xue).

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and exchangeable sodium percentage. Natural processes, without human intervention and amendment additions, may also improve the physical and chemical properties of bauxite residue to allow plants to establish. Santini and Fey (2013) found that natural weathering processes decreased pH, electrical conductivity, total Al and Na content, increased organic carbon content and changed the particle size distribution of bauxite residue. However, it did not discuss the physical structure and aggregate formation following natural regeneration.

Quantification and interpretation of aggregate stability is of great importance in determining the physical condition of soil. Direct measurements of soil susceptibility following detachment processes at the field level are often expensive and time-consuming (Barthès and Roose, 2002). Therefore, a more detailed understanding of the interactions between aggregate breakdown and soil susceptibility to erosion resistance is required. The wet sieving method has been routinely used in most studies to assess aggregate stability and disaggregation mechanisms. Of the wet sieving methods, Yoder's method (Zhu, 1982) separates aggregates by slaking and mechanical breakdown whereas "Le Bissonnais" method (Le Bissonnais, 1996) combines three disruptive tests that are characterized by different wetting conditions and energies which differentiate three disaggregation mechanisms: slaking, mechanical breakdown by raindrop impact and disaggregation induced by differential swelling (Table 1). The aim of this study was to quantify the effects of natural weathering processes on aggregate stability of bauxite residue within different stacking ages by comparing the mechanisms involved in the improvement of aggregate stability. This was assessed by comparing the modified Yoder's method and the modified Le Bissonnais' method to measure aggregate stability and to quantify the residues resistance to erosion.

2. Materials and methods

2.1. Site description and residue sampling

The study site is located in the bauxite residue disposal area of the Zhongzhou Branch, Aluminum Corporation of China Limited, Jiaozuo city, Henan province, China (35° 24′N, 113° 25′E). The climate is warm temperate continental monsoon, characterized by significant winds, four seasons, with a mean annual daily temperature of 12.8 °C-14.8 °C and an average precipitation ranging from 600 mm to 1200 mm per year. The rainy season starts in June and continues until September. The July rainfall accounts for 20% of the annual precipitation.

Bauxite residue samples from 5 different locations related to stacking age were studied. These included (a) 1-year-old bauxite residue (B1), (b) 4-year-old bauxite residue (B2), (c) 6-year-old bauxite residue (B3), (d) 10-year-old bauxite residue (B4), and (e) 20-year-old bauxite residue with spontaneous native grass growing on it (B5). Sparse vegetation, mainly dominated by Couch grass (*Cynodon dactylon*) and Black Nightshade (*Solanum nigrum*), have established on residues which have been stacked for almost 20 years (B5). All locations were sampled during August 2014. The residues were sampled to a depth of 20 cm at ten randomly chosen points at each location (a-e). Bulk samples were stored in polyethylene bags, returned to the laboratory, air dried for one week and subsequently passed through a 2 mm sieve prior to analysis.

2.2. Physical and chemical analysis

Bulk density was determined on naturally compacted samples using the cutting ring method (Haynes and Goh, 1977), particle density was determined by the pycnometer method (Bork, 1988) and total porosity was calculated using the following equation (Jones et al., 2011):

$$\text{Total porosity}\,(\%) = \frac{\text{Particle density-Bulk density}}{\text{Particle density}} \times 100 \quad (1)$$

All residues were ground to a fine homogenous powder and analysed for total organic carbon by the low-temperature external-heat potassium dichromate oxidation colorimetric method (Zhu et al., 2016b). Total carbon and nitrogen were determined by dry combustion using a Vario MAX C, N analyser. Available phosphorus was extracted with 0.5 M $NaHCO_3$ (pH = 8.5) and phosphorus was analysed by the molybdenum blue method. Extractable mineral N was extracted by 2 M KCl followed by colorimetric analysis of $NH_4{}^+$ and $NO_3{}^-$-N using a Seal automated discrete analyser (Jones et al., 2011). Exchangeable bases were extracted with 1 M ammonium acetate (pH = 7) and exchangeable Ca, Mg, K and Na contents in the extracts were analysed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) (Jones et al., 2011). ESP (exchangeable sodium percentages) was calculated using the following equation:

$$ESP\,(\%) = \frac{100 \times Exchangeable Na}{\sum (Exchangeable\text{Ca+Mg+K+Na})} \quad (2)$$

2.3. Methods of aggregate stability

Aggregate stability was firstly determined using the modified Yoder's method. A set of 1, 0.2, and 0.05 mm sieves were suspended in a can of distilled water (Kemper et al., 1986). Initially a 20 g sample was placed on filter paper and distilled water applied along the edge of filter paper until the sample was saturated. Subsequently the sample was placed into the top sieve of each set and rapidly immersed in distilled water whilst being oscillated for 3 min at a displacement of approximately 4 cm at 37 rounds per minute. All fractions were dried at 40 °C for 48 h prior to weighing. The mean weight diameter (MWD) and geometric mean diameter (GWD) of the residues were calculated using the following equations:

$$MWD = \sum_{i=1}^{n} \overline{X_i} \times W_i \quad (3)$$

$$GMD = \exp\left(\sum_{i}^{n} W_i \ln X_i / \sum_{i}^{n} W_i\right) \quad (4)$$

Where $\overline{X_i}$ is the mean diameter over each portion (mm), W_i is the percentage of aggregates in that size range and n is the number of sieves. For a given sample, three replicates were used at each location. As for Yoder's method, the MWD was used as a structural stability index. A larger MWD indicated greater structural stability (Le Bissonnais, 1996). The geometry size model was used to calculate the erodibility factor (K) by the equation as follows:

$$K = 7.954 \times \left\{0.0017 + 0.0494 \times \exp\left[-0.5 \times \left(\frac{lgGMD + 1.675}{0.6986}\right)^2\right]\right\} \quad (5)$$

Subsequent to the above, stability tests were performed using the modified Le Bissonnais method (Deviren Sayg et al., 2012). This method combined three disruptive tests that correspond to various wetting conditions and energies: fast wetting (FW), slow wetting (SW) and wet stirring (WS). A 6 g sample containing aggregates of 1–2 mm was air-dried at 40 °C for 24 h prior to the tests. For the FW test, aggregates were gently immersed in deionized water for 10 min; the FW test is sensitive to the slaking process. For the SW test a sample was placed on filter paper on a humid sponge for 30 min in order to reach saturation; the SW test determines