

Dust Reduction in Bauxite Red Mud Waste using Carbonation, Gypsum & Flocculation

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Abstract Producing alumina by the Bayer Process creates fine air borne red dust in de-watered dumps which devalues property and causes irritation to the human respiratory system. Samples of red mud waste (1) treated 10 years before at the 0–15 cm depth zone with 40 t ha⁻¹ of gypsum (2) from the subjacent 15–30 cm zone, were collected, crushed and passed through a 0.5 mm diameter sieve. Leaves from *Acacia senensis* (a legume) were finely chopped to <1 mm and thoroughly mixed with the sieved bauxite waste at 25- and 50 %, and the samples incubated for 6 weeks at ambient room temperatures, at 60 % soil water-holding capacity. To determine the fraction of potential dust, the treated samples were submerged in de-ionized water for several days until there was no change in discoloration (due to clay dislocation) of the water. The samples were removed from the water and the water evaporated and the residues dried and weighed. This submergence process was repeated. The first submergence produced 30- and 20 % w/w dust respectively from the 25- and 50 % phytogenic treatments, and 0 % dust from the non-phytogenic treatments. Submergence #2 released no clay (wet dust) particles from any sample. Finally, the same samples were air-dried, re-crushed and dry-sieved through a 100 µm sieve, because dust-size particles are <100 µm in diameter. Dry-sieving produced dust as follows: non-phytogenic-treated subjacent red-mud zone = 50 % w/w, non-phytogenic—0–15 cm depth = 30 % w/w, phytogenic—at 25 % = 15 % w/w, phytogenic at 50 % = 7 % w/w. In total, the dust-reducing capabilities of the treatments were: 50 % phytogenic >25 % phytogenic >0–15 cm depth non-phytogenic >15–30 cm-depth non-phytogenic. The 50 % phytogenic-treatment reduced potential particles of fugitive dust by 70 % over the untreated controls and 95 % over the crushed-only (subjacent red mud; no organics added) samples. The binding of clay particles into larger entities by organic gums produced agglomerates which (1) reduced the number of <100 µm particles and (2) hence, particles which would have resisted air movements. The initial increases in fine clay dislocation amongst phytogenic treatments was attributed to the increase of small negatively charged organic colloids from the decomposition process, which repelled similar-sized negatively charged clay particles. All in all, phyto-organics increased average particle size >100 µm by flocculation, thereby

creating stable agglomerates which resisted disintegration and breakdown under simulated rain. This treatment promises the use of gypsum + phyto-organics for reducing the emanation of surface dust from red mud waste sites onto surrounding areas.

Keywords Guyana bauxites • Gypsum-organic amendments • Jamaica WI • Organic remediation • Virgin islands

Highlights

- A phyto-organic treatment decreased dust generation from dried bauxite waste red muds.
- Crushing and incubating lithified impermeable red mud into sub 2-mm particles failed to increase permeability in the crushed beds, but increased dust generation.

1 Introduction

1.1 Red Dust: Origin and Damages

Red mud waste (RMW) surfaces (crusts) of bauxite mine spoils are potential sources of dust emission. During storage, the surface gets dried, even though the consistency may be still liquid at a few millimeters below (Graham and Fawkes 1992). A strong wind can then blow a red dust cloud over the surroundings at a considerable financial and environmental cost. Buildings have been defaced and vegetation damaged by dust accumulation on leaves.

Of four categories, it was the high porosity un-compacted bauxites that stained the strongest (Bardossy 1982), and this strongest-staining group includes Jamaican bauxite, where the RMW particles are <2 microns in diameter (Ly 2001) due to the Bayer process of extraction. In a table indicating the textural analysis for several bauxite wastes, Wehr et al. (2006) reported bauxite residues (sand (%) 2–0.02 mm, silt (%) 0.02–0.002 mm clay (%) <0.002 mm) respectively, from various locations as follows: Australia—Gove 13, 40, 47; Australia—Kwinana 30, 30, 40; Canada 0, 47, 36; Jamaica 6–10–75; Spain-12, 50, 38; USA-Texas 8, 66, 26. It can be seen that Jamaica bauxite waste contains, on average, at 75 %, i.e., at least twice as much clay as any of the other bauxites wastes. This suggests the highest concentration of potential dust.

One successful approach in some countries has been the covering of aged red mud with 200-mm of top-soil followed by revegetation (Graham and Fawkes 1992). Another approach uses fresh or salt water irrigation sprays (Graham and Fawkes 1992), but generally, these are economically impractical. Potential topsoil sources in Jamaica are either already under plantation crops such as sugar cane

and bananas or protecting other subsoils. Indeed, in any country, removing and transferring topsoil to cover red-muds is destructive to the area from which the topsoil has been removed, and hence is counterproductive.

Already inadequate water resources in the karst bauxite areas are also unavailable for such purposes; large quantities of water diverted to the amelioration of bauxite waste may be viewed by local communities as an “unfair” usage of a scarce resource. Therefore, due to a shortage of topsoil and water, alternative strategies for the reduction of wind-blown dust have to be envisioned for, not only Jamaica, but wherever the Bayer process extracts alumina from bauxite.

1.2 Drawbacks of Gypsum Treatment

As a treatment for decreasing the alkalinity of red muds, gypsum has long been applied, but only after red muds had congealed and dried to a depth of at least 10–20 cm (Harris 2009) in the form of a thick crust, a process often requiring years of atmospheric exposure. Harris (2009) postulated that gypsum-treatment reduces dust by indurating the dried red muds, because gypsum-treatment after several years produces a thick crust throughout the layer so treated, due to sub-aerial carbonation from the air (Harris and Megahraj 2001). This facilitates the movement of heavy machinery on the surface to subsequently spread more of the gypsum. The solidifying process also permits mechanical comminution by tractors, which is an advantage if the gypsum is to be mixed in with the red mud waste. But such mixing was difficult to accomplish, and was not thorough when done by O’Callaghan et al. (1998). Difficulties of ploughing were attributed to the semi-viscous nature of the red mud at that stage. Such methods reduce dust created by red mud waste (RMW) after they have dried out by atmospheric exposure, and do so only after considerable damage has been done by dust to the surrounding areas. Nevertheless, the strength of this indurated layer exceeds the maximum for penetration by plant roots (Harris 2009). Plant growth is therefore difficult on gypsum-indurated red muds. In an effort to decrease the production of fine wind-blown dust while concurrently enhancing plant root growth conditions, a study using decomposable phyto-organics to bind finely crushed particles (<1 mm diameter) of gypsum-treated red muds is hereby proposed. The objective of this study was therefore to bind dispersible clay particles into larger quasi soil aggregates to resist wind-blown dust.

1.3 Dust Definitions

According to the International Standardization Organization (ISO 4225—ISO 1994a, b), “Dust: small solid particles, conventionally taken as those particles below 75 μm in diameter, which settle out under their own weight but which may

remain suspended for some time". The Glossary of Atmospheric Chemistry Terms (IUPAC 1990), characterizes dust as: "Small, dry, solid particles projected into the air by natural forces, such as wind, volcanic eruption, and by mechanical or man-made processes such as crushing, grinding, milling, drilling, demolition, shovelling, conveying, screening, bagging, and sweeping. Dust particles are usually in the size range from about 1–100 μm in diameter, and they settle slowly under the influence of gravity." Based on these definitions, decreasing air-borne dust entails the decrease of sub-100 μm particle sizes. It is at the micro-aggregate size level that excess sodium from the Bayer process produces separation of clay particles. Since micro-aggregates bind $<5 \mu\text{m}$ particles into larger entities at the $<250 \mu\text{m}$ level, and wind-blown dust particles do not exceed 100 μm in diameter, it follows that production of stable micro-aggregates from $<5 \mu\text{m}$ particles should reduce the rate of wind-blown dust.

1.4 Chemistry of Red Mud Dust

Bauxite red mud consists primarily of the insoluble fraction of the bauxite ore that remains after extraction of the aluminium-containing components. Iron oxides (10–30 %), titanium dioxide (2–15 %), silicon oxide (5–20 %) and undissolved alumina (0–20 %) make up the residue, together with a wide range of other oxides which will vary according to the initial bauxite source (Jones and Haynes 2011). The high concentration of iron compounds in the bauxite gives the by-product its characteristic red colour (Fig. 1), and hence its common name "Red Mud" (AAC 2012).

The particle dimension of red mud is usually less than 1 mm (Hai et al. 2014) (actually usually lesser by $<10^{-1}$ of 1 mm), and dust generated from the residue drying area mostly consists of fine clay particles and a small fraction of sodium carbonate crystals (Alcoa 2007). The sodium carbonate is precipitated on the surface of residue as entrained moisture evaporates (Alcoa 2007). Therefore, dry red mud easily spreads into the air and causes dust pollution (Hai et al. 2014).

1.5 Red Mud Dust Impacts

Wind speeds in excess of 6.5 m s^{-1} (23 km h^{-1}) can pick up and transport the fine particles of bauxite mine residue if the dry residue surfaces in toxic red muds are not carefully managed (Alcoa 2007). This was discovered in the Weipa Mines of Western Australia (Alcoa 2007). The distance over which these particles are transported depends on a variety of factors including atmospheric conditions, the size, shape and mass of the particles and the surrounding infrastructure such as roads, embankments and drains (Alcoa 2007). Rolling topography and irregular terrain can increase wind speeds (Jackson and Hunt 1975) and such terrain exists in close proximity to all Jamaica bauxite mine locations (Fig. 1), thereby exacerbating the

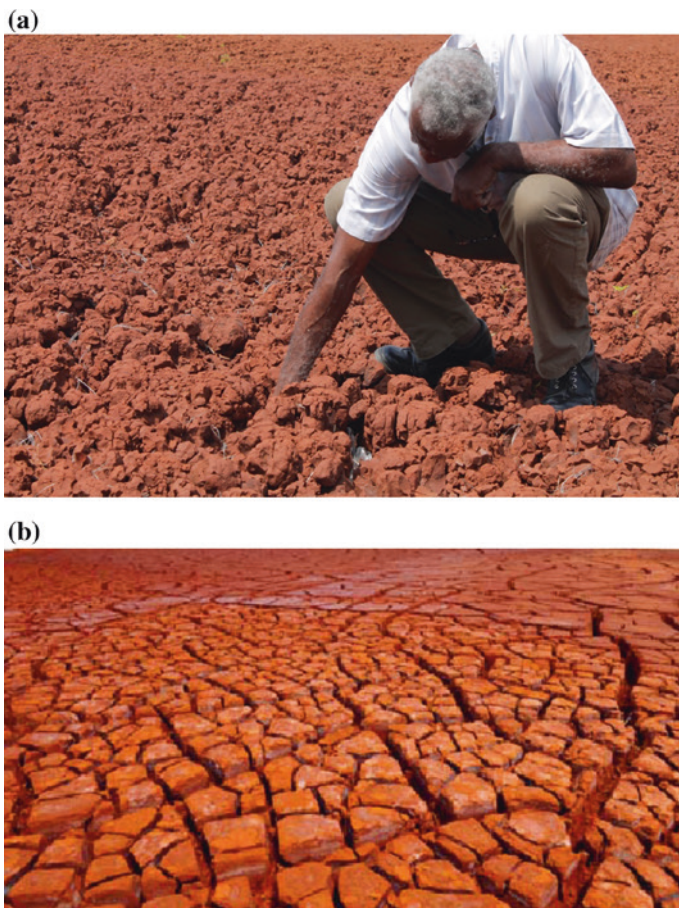


Fig. 1 **a** Surface crusts in dried red mud bauxite waste form after several years of atmospheric carbonation, producing dusts. Even after decades, vegetation is inhibited. Na^+ prevents particle agglomeration by occupying available attachment sites with its weak, hydrated, single charge. **b** Detailed view of carbonated, dried red mud waste. Note the whitish efflorescence of soluble salts close to, and on, the upper surfaces. Seemingly comminuted particles can be seen between the hardened masses (after Alcoa 2007)

volume and unpredictability of wind-blown dusts. Furthermore, as stated above, Jamaican bauxites contain a far larger clay fraction (75 %) than that of all other major bauxite locations (Wehr et al. 2006).

Though particle size analysis shows that Jamaican Terra Rossa bauxites contain 20 % sand (O’Callaghan et al. 1998), it is the secondary (clay) fraction which contains the bauxite. Similar processing techniques in Jamaica (Bayer process) to that of the Weipa (West Australia) kaolinities indicate similar post-beneficiation clay particle sizes. Above 11 m s^{-1} (40 km h^{-1}), such dust emissions from the residue area can increase rapidly and wind speeds above 14.5 m s^{-1} (50 km h^{-1}) are predicted

to be the largest source of dust. Attaining speeds often exceeding 13 m s^{-1} during winter months (Macpherson 1991), unobstructed trade winds in Jamaica and the northern Caribbean should, on the above basis, normally carry fugitive dust released from the dried surface of red mud dumps.

1.6 Effects on Health

Friesen et al. (2009) examined the associations between alumina and bauxite dust exposure and cancer incidence and circulatory and respiratory disease mortality among bauxite miners and alumina refinery workers. Their preliminary findings of the very few cases in the limited population study suggest that cumulative inhalable bauxite exposure may be associated with an excess risk of death from non-malignant respiratory disease and that cumulative inhalable alumina dust exposure may be associated with an excess risk of death from cerebrovascular disease. Nevertheless, neither exposure appeared to increase the risk of incident cancers. Further, there was no apparent danger and no association between every bauxite exposure and any of the outcomes (Friesen et al. 2009), though there was a borderline significant association between every alumina exposure and cerebrovascular disease mortality.

Friesen et al. (2009) also found that exposures to bauxite dust, alumina dust, and caustic mist in contemporary best-practice bauxite mining and alumina refining operations have not been demonstrated to be associated with clinically significant decrements in lung function. Exposures to bauxite dust and alumina dust at such operations were also not associated with the incidence of cancer (Friesen et al. 2009).

Despite these favourable findings, adverse health effects of bauxite dust are possible. This is because red mud residue and sand consist primarily of alumina, silica and iron oxides (USEPA 2004) and silicosis is an irreversible condition with no cure (Wagner 1997). Silicosis is the most common form of pneumoconiosis (lung-related diseases), which is caused by occupational exposure of free silica dust. Treatment options currently focus on alleviating the symptoms and preventing complications. According to Pattajoshi (2006), dust is inevitable in mineral industries, hence the risk factor leading to pneumoconiosis is assessed on the basis of equation:

$$R = f(d, f, s, i, t,)$$

where R = Health Risk, d = particle size, f = concentration of finer dust, s = specific noxiousness, i = individual factor (susceptibility) t = time of exposure. Also, Nough (1989) reports that a non-occupational form of silicosis has been described that is caused by long-term exposure to sand dust in desert areas, with cases reported from the Sahara, Libyan desert and the Negev, and that the disease is caused by deposition of this dust in the lung. It is thus suggested here, that long, non-occupational exposure to silicates in red mud dust could produce similar outcomes.

1.7 St. Croix—Virgin Islands Red Mud Dust Hazards

Located within the North East Trade Wind Belt, the major concern for northern Caribbean aluminium refining locations is the transportation and deposition of such caustic dust into residential and commercial areas. According to the USGS (2014), St. Croix has a total area of about 80 square miles and is dominated in the north-western (Northside Range) and eastern (East End Range) parts by highland areas that rise to altitudes of 1088 and 866 ft, respectively, and that are underlain chiefly by poorly permeable intrusive, volcanic, volcani-clastic, and sedimentary rocks. The Kingshill aquifer, which lies between these two ranges, is in a low-land that slopes from the south flank of the Northside Range southward to the sea (USGS 2014). The surface of the limestone and marl that compose the aquifer has been deeply eroded, but about one-fourth of it is covered by a blanket of alluvium, alluvial fan, debris flow, and slope wash deposits as much as 80 ft thick, which moderates the dissected topography and forms a broad rolling plain through which low, rounded limestone hills are exposed. St. Croix has four major streams that flow intermittently. All four rise in the Northside Range, and River Gut, the largest, flows southward across the Kingshill aquifer to the sea. The other three streams flow mostly across volcanic rocks to the west coast. The remainder of the streams on the island are very short and flow only after heavy rains (USGS 2014).

The following documentation from the USEPA Report (2012), in September 1998 depicts the Virgin Islands red mud dust problem: “Wind-blown fugitive dust, identified as bauxite by Virgin Islands Department of Planning and Natural Resources (VIDPNR), was deposited onto residential properties located 750 ft north of the red mud site as a result of Hurricane Georges. Observations by VIDPNR indicated that reddish material had been deposited onto the residential structures and their drinking water cisterns. EPA sampling confirmed that bauxite was in the cisterns. VIDPNR issued a Notice of Violation (NOV) to St. Croix Alumina (SCA) for the fugitive dust release, determining that there were no precautionary measures in place to secure the stockpiled bauxite from hurricane winds. Residents located north of the Site have reported red dust deposition on rooftops, inside cisterns, in outdoor gardens, and on indoor furniture associated with hurricanes and other high wind events.”

The USEPA Report (2012) states that one of the side effects of gypsum applications is gradual lithifying through atmospheric carbonation. Thus, less than 10 years after treatment, such additives routinely transform red mud ponds into masses of hard, clinker-like cobble-stones of low individual permeability, low porosity and high strength with water movements unsuitable for plant growth. Such physical changes may have increased agglomeration of dust-sized particles, thereby increasing the mass and resistance to wind transport of each entity.

The Kingshill aquifer is located in the central to southwestern parts of the island of St. Croix in the Virgin Islands of the United States. The aquifer consists of limestone and marl that has a maximum saturated thickness of about 200 ft. Although the aquifer produces only small volumes of water of marginal chemical

Fig. 2 The typical rolling landscape of Jamaican mines. Such curved topographies increase the speed of air currents compared to flat terrain. Source: Jamaica Bauxite Institute



quality, it is the only significant aquifer in the U.S. Virgin Islands and supplies a large proportion of the water needed for public supply and industry on St. Croix. Water is scarce on St. Croix. Streamflow is meager and not reliable; aquifers are small and yield mineralized water, much of which is unfit for human use (USEPA 2012).

The USEPA (2012) reports that the contamination poses a potential threat to receptor areas including mangrove wetland areas, water-bird and endangered/threatened species habitats, fisheries, and fresh ground water in the Kingshill aquifer (Fig. 2). The “site conditions and analytical results provide evidence of hazardous substance migration in both the surface water and ground water pathways from on-site disposal areas.” (Fig. 3)

According to the USEPA (2012): “VIDPNR reviewed and approved a plan for the pre-design preparation work in October. It calls for St. Croix Alumina to conduct a series of studies, especially to find the boundaries of bauxite residue through test pits and shovel holes and to look into how the stuff behaves in the ground. A hydrology study is needed to evaluate storm water drainage requirements too. Then comes a greenhouse study looking at suitable plant species to cover the site. And SCA must acquire all the permits and approvals for drilling, test pits and the remediation work, according to VIDPNR.”

1.8 Particle Cementation

Cohesiveness between clay particles can be significantly increased by inorganic cementing agents such as CaCO_3 , and Fe and Al oxides (Zhang et al. 2015). In a study of African Ultisols and Oxisols, Ahn (1979) observed highly stable micro-aggregates not dependent upon organic matter. Therefore, binding agents need not be from organic sources. After adding gypsum to two different red-brown earths, Shanmuganathan and Oades (1984) noted a reduction in the amount of dispersible

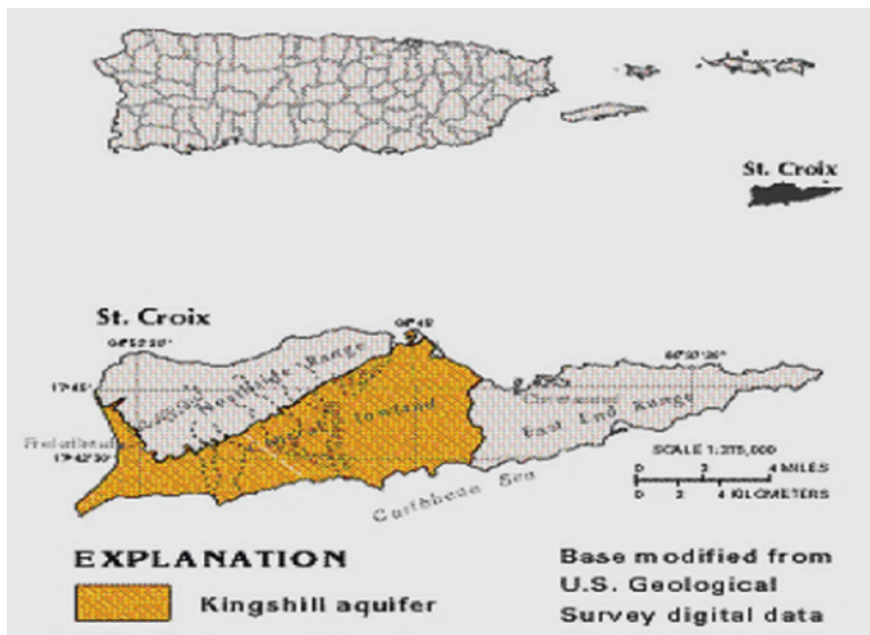


Fig. 3 The Kingshill aquifer is in central and southwestern parts of the island of St. Croix in the U.S. Virgin Islands. *Source* USGS

clay, an increase in the proportion of water-stable aggregates sized 50–250 μm diameter, and an increase in soil friability. Nevertheless, before carbonation occurred, mechanical strength was reduced by gypsum addition.

Due to its divalency, Ca^{2+} binds strongly to clay particles, therefore is not readily lost from the soil via leaching. Ca^{2+} therefore promotes aggregation and is non-toxic. Rengasamy et al. (1984) reported that dialyzed Ca-clays did not disperse in water even after a week, and it has been found that dry aggregates of montmorillonite or illite saturated with Ca^{2+} did not disperse when immersed in water (Rengasamy et al. 1984). Thus, replacement of the sodium on the clay colloids with a non-toxic cation which produces better structure is achieved, as the Ca^{2+} replaces the leached Na^{+} cations (Rengasamy et al. 1984). Applying the above principles, Harris (2009) infused finely grounded phytogenic materials into gypsum-treated remolded red mud aggregates during 6-month incubation. He then detected marginal to significant increases in aggregate stability under wet-sieving as compared to the controls. However, it is hereby postulated that his method would have achieved greater aggregation had he applied a smaller particle size than 2-mm to increase the surface area and the number of reactive surfaces during incubation.

1.9 Aim

Without dislocation there is no dust. The treatment of this study therefore aimed to “fix” the clay particles into soil aggregates. These were to bind the clay particles against dislocation by the wind. This procedure was also aimed at resisting natural field impacts such as rain and running water which dislocate fine clay particles prior to them becoming airborne dust.

2 Materials and Methods

Twenty kilogram of (1) gypsum-lithified red mud (2) red mud beneath the gypsum-treated layer were randomly collected from the Kirkvine Pond 6 Bauxite residue storage area in Jamaica. Whereas the gypsum-lithified red mud (G) exists in rock-hard form in the 0–30 cm zone, the non-gypsum fraction (R) exists adjacently below 30 cm as a semi-viscous constituent, having been seemingly unaffected by the gypsum which O’Callaghan et al. (1998) had ploughed into the zone (G) directly above, in 1996. Both materials are of the same age but very different physico-chemically. The top layer is non-dispersive while the 15–30 cm layer is highly dispersive (Fig. 4). Prior to air-dry, this 15–30 cm depth layer had the physical consistency of untreated red mud waste that supplies wind-blown dust. Samples were crushed at air-dry in a mortar and pestle and passed through a 1-mm aperture sieve. Decomposable organic material as finely chopped (<2 mm) leaves from *Acacia senensis* (“Kasha”, an invasive legume of southern Jamaica) was thoroughly mixed in with either above-mentioned bauxite waste in dry, grinded homogenous (<1 mm) form and incubated at room temperature for 42 days at a water content of 60 % of the field capacity of each soil. Of the two crushed red muds, field capacity (water-holding capacity) was substantially higher for the gypsum-treated samples (Table 1).

There were six treatments, each having three replicates: (1) G, (2) G25 (i.e., gypsum-treated red mud + 25 % phyto-organics), (3) G50 (i.e., gypsum-treated red mud + 50 % phyto-organics) (4) R (red mud), (5) R25 (red mud + 25 % phyto-organics), (6) R50 (red mud + 25 % phyto-organics). Phyto-organic treatments are referred to hereafter as GP or RP.

2.1 Measuring Potential Wind-Blown Dust

Clay dislocation: 1st submergence

After incubation for six weeks, the samples at air dry were subjected to submergence in (1) de-ionized water which simulated rain water and (2) ionized water from a tap carrying ground water. Deionized water was included because Khattab

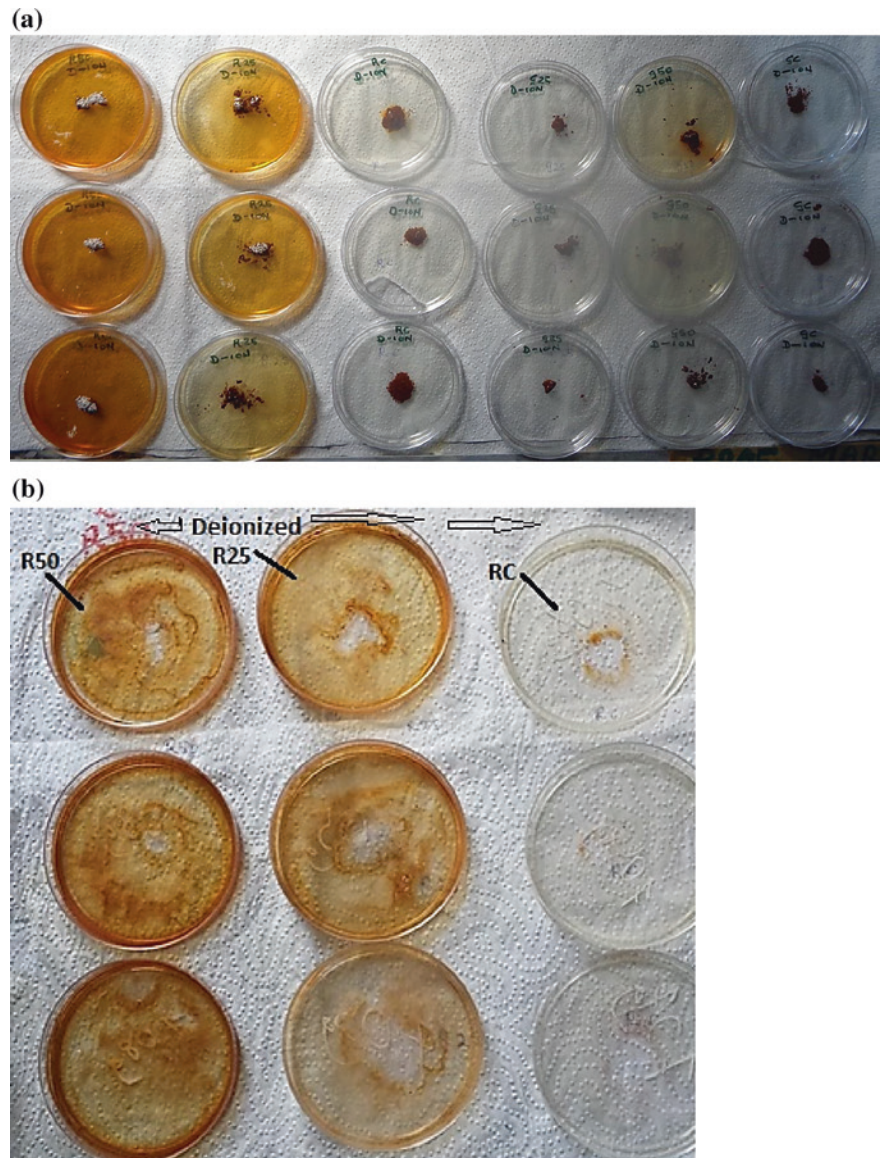


Fig. 4 **a** Before drying, clay dislocation in deionized water for remolded aggregate samples from the 15–30 cm depth in carbonated red mud. At extreme left are the R50 samples; second from left are the R25 samples with less clay dispersion depicted by the *lighter colour*. **b** Dried samples. Clay dislocation in deionized water for remolded aggregate samples from the 15–30 cm depth in carbonated red mud. Samples at left had 50 % decomposable phyto-organics (R50), centre had 25 % (R25), and the 3rd column had no phyto-organics (RC)

Table 1 Properties of red mud subjacent to 0–15 cm depth gypsum-treated red muds

Properties	Values
Red mud pH (saturated extract)	12
EC (saturated extract: dS. m ⁻¹)	0.25
Organic carbon (%)	0.3
CEC (c molc kg ⁻¹)	40
Al ₂ O ₃ (%)	16
CaO (% w/w)	7
Fe ₂ O ₃ (%)	47
Na ₂ O (%)	3
P ₂ O ₅ (%)	2
SiO ₂ (%)	3
TiO ₂ (%)	6
Bound H ₂ O (%)	14
Particle size	0.001-mm

and Othman (2013) noted a general reduction of strength of rocks with an increase the number of wet-dry cycles when using distilled water. Replicates of treated aggregates having a diameter of approximately one cm were each placed in a watch glass, after which water was slowly added because the weak structure of bauxite waste is subjected to breakdown by electrolytes. The relative rates of clay dislocation from the aggregates signified the amount of dust particles which would have emerged on drying. Without clay dislocating forces on the aggregates there would be no potential dust. The extent of clay particle dislocation from the aggregates was determined by using weight differences. The clay dislocation process was monitored for the ensuing days until no further change was observed. At air dry, aggregates were removed from the watch glasses and the masses of air-dry residues of fine dust weighed by difference between watch glasses before usage post-usage containing the samples.

Clay dislocation: 2nd submergence

After clay removal from watch glasses at air-dry, the clay dislocation procedure was repeated. Each aggregate was then mechanically agitated in an end-over-end shaker for a pre-determined time period. At air-dry, all particles were again weighed. The separated fractions were air-dried. They were weighed after sieving on a nest of three scales: 2 mm, 500, and 100 μ m.

2.2 Flocculation Measurements by Wet-Sieving

For the following reasons, some incubated aggregates were subjected to wet-sieving at air-dry: (1) Aggregate breakdown under rain water (and running water) destroys unstable soil aggregates (2) because wet sieving simulates the action of the electrical and mechanical disintegrating forces inflicted by the high di-electric

constant of rain water, (3) the energy inflicted on the red mud waste by wet-sieving, being greater than that imposed by expected daily winds, indirectly indicates resistance of the aggregates to the production of wind-blown dust at high wind velocities. Residues of aggregates disintegrated by wet-sieving were air dried until no further loss in weight. The ratio of $<100\ \mu\text{m}$: $>100\ \mu\text{m}$ sized floccules was used to determine the effectiveness of each treatment.

3 Results

3.1 Clay Dislocation: 1st Submergence

3.1.1 In De-ionized Water

While evaporating after submergence samples were observed daily until there was no further change (due clay dislocation) in appearance. After just the first day, and onwards, the inner surfaces of petri dishes containing the 15–30 cm sub-jacent depth R-phyto-samples became covered with what seemed like a layer of fine $<100\ \mu\text{m}$ sized dislocated particles (Fig. 4). On the assumption that this colouration was due to dislocated clay particles, Table 2 shows that after incubation plus air-dry and 5 days of submergence in deionized water, relatively little observable clay particle dislocation occurred from any of the non-phyto-organic treatments as compared to that of the phyto-organic treatments (Table 2; Fig. 4). The R50 dislocated 33 % of the mass of the sample as clay, and the R25 dislocated 29 % of the sample mass for an average of 29 % dislocation by the subjacent phyto-treated samples. The R50 dislocated more clay than did the R25. This was unexpected because these soil particles were considered bound by organic matter.

Further, it can be seen that the quantity of clay dislocated was much greater from the 15 to 25 cm depth compared with the 0–15 cm depth, i.e., in a ratio approximating 15:1 (Table 2). For the 0–15 cm depth the samples containing 25 % phyto-organics dislocated no clay, while the samples containing 50 % phyto-organics produced a 4 % w/w rate of clay dislocation. Thus for the 0–15 cm depth, rate of phyto-organics determined effectiveness to suppress clay dislocation in deionized water. The reverse is true at the 15–30 cm depth (Table 2), where the 25 % phyto-organics treatment dislocated approximately 25 % more clay than the 50 % phyto-organic treatment. This was surprising. Clearly, the factor which produced the initial dislocation in deionized water existed in the phyto-samples. Yet, the greater concentration of phyto-material the smaller was the clay dislocation. This anomaly is examined later.

Table 2 Clay (% of mass) dislocated after incubation treatments and submergence in de-ionized water for 8 days

Red mud (depth in cm)	0 % phyto-organics	25 % phyto-	50 % phyto-	Average
0–15	0	0	4	2
15–30	0.01	33	25	29

After 8 days of submergence in deionized water, non-phyto-organic treatments from all samples dislocated very little clay above the level of detection (Table 2; Fig. 5).

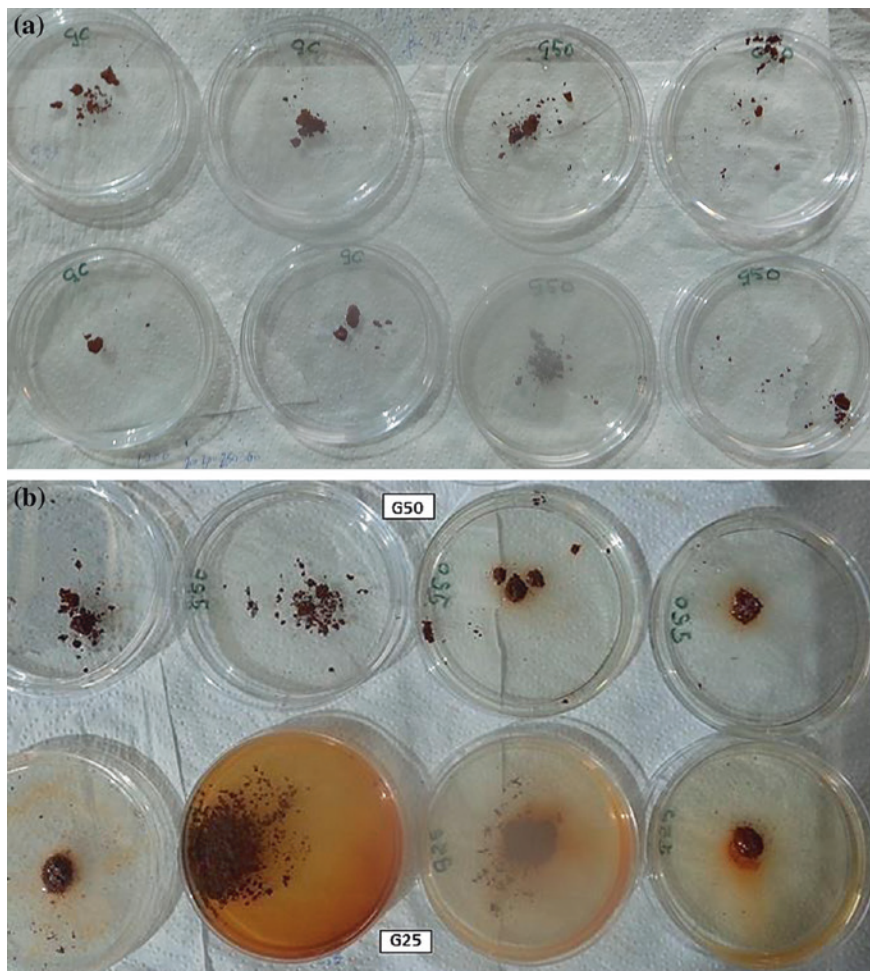


Fig. 5 **a** Post-incubation gypsum-treated samples in distilled water after 1st submergence. The colourless water indicates that even after 8 days of submergence, no dislocated clay particles were observed at the <50 µm diameter size. The four samples at right which were treated with 50 % w/w phyto-organics show only a slight discoloration. Effective flocculation of red mud individual particles therefore occurred in all the above samples. **b** Post-incubation gypsum-treated samples in non-deionized water after 1st submergence. In contrast to the reaction with deionized water (Fig. 5a) where the colourless water indicated no clay dislocation, here, samples from within the same treatment dislocate clay when added to non-deionized water, especially the samples with the lower rate (G25) of added phyto-organics. The possible explanation could lie in an increased number of negative charges in the system (see text)

3.1.2 Non-deionized Water

Non-de-ionized water also dislocated clay from the samples but there were minor but significant differences. Firstly, the total mass of clay dislocated was higher for the deionized water (Table 3), where the 15–30 cm level dislocated almost twice as much clay under the deionized water compared to the non-deionized water. On the other hand, for the 0–15 cm level, the non-deionized water caused a 4-fold increase in clay dislocation compared to the deionized water (Fig. 6). Again, only the phyto-treatments caused substantial clay dislocations.

For the G samples (no phyto-), submergence in non-deionized water produced small, barely visible levels of clay dislocation (Table 3). This nevertheless was greater than that for de-ionized water, where no dispersion appeared from any of the non-phyto samples. Similarly, from the 0 to 15 cm depth, only those GP samples treated with 25 % phyto-organics increased clay dislocation up to half the level of the phyto-organically treated R samples. Of all the phyto-organic treatments, GP samples treated with 50 % phyto-organics exhibited the lowest levels of clay dislocation from the aggregates (Table 3). The possible reasons are discussed later.

The clay dislocations in deionized water were less severe for the G samples. Only 2 % of the GP mine-waste dispersed, whereas 29 % of the R samples dislocated in the form of clay particles. This is almost a 15-fold difference. As electrical stresses on soil aggregates vary directly with purity of water, a high concentration of electrolytes (i.e., >EC) in a soil should increase clay dislocation in deionized water. Thus the R samples, with a higher electrical conductivity than the G samples, released more clay particles in deionized water than in non-deionized water.

The relative rates of clay dislocation from the aggregates signified the amount of dust particles which would have emerged on drying. After incubation for 6 weeks, the result for either the G or R samples was that little or no observable clay dislocation occurred in deionized or non-deionized water.

In deionized water, gypsum-treated bauxite waste without phyto-organics (GC) showed no dispersion of clay-particles at the microstructural level (<100 μm diameter) for the 0–15 cm-depth. For non-phyto samples taken from the subjacent level, a very slight clay dislocation effect was visible. This was below the detection level of the weighing equipment. However for the RP samples a large amount of dust averaging 25 % w/w would have been generated by phyto-organic treatments. This was unexpected, and possible reasons are explored later. Based on these results, the GP samples were overwhelmingly less dispersive than the RP samples.

Table 3 Clay (% of mass) dislocated by non-deionized water after incubation treatments

Red mud (depth in cm)	0 % phyto-organics (controls)	25 % phyto-organics	50 % phyto-organics	Average
0–15 (G)	0	8	8	8
15–30 (R)	0	16	16	16

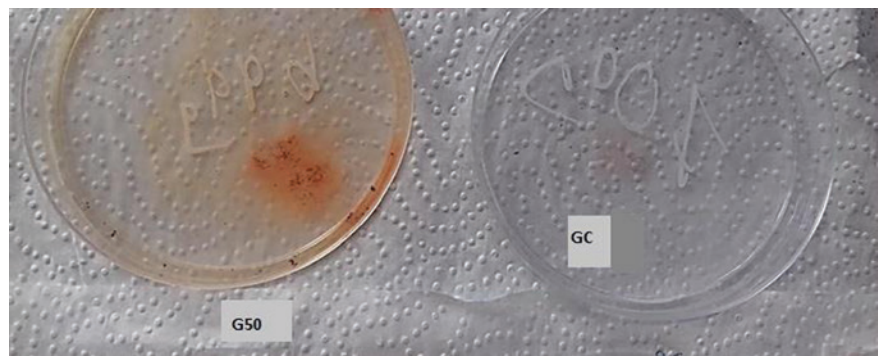


Fig. 6 Post-incubation gypsum-treated samples in non-distilled water after the 1st submergence. Though it can be seen that the non-phyto-treatment at right dislocated very little clay at this stage (hence almost colourless water), dislocated clay particles were observed from the 50 % phyto-treatment at *left* (G50). This strange reaction by the G50 (discussed later in the text) contrasts starkly with that which occurred in de-ionized water. Stippled background contains 1-mm diameter circles

3.1.3 Clay Dislocation: 2nd Submergence

After removal from Petri dishes at air-dry, and after the second episode of clay dislocation in water the remolded aggregate masses were weighed and measured. Even after the 2nd submergence, the phyto-organically treated samples in general retained stability in water to a far greater degree than that of the 1st submergence. Clay dislocation procedure was repeated on the aggregates and the results show that no dislocation occurred at all from any sample. It can be seen that the 2nd submergence produced no dislocation of clay particles (Table 4) as the total mass for each sample submerged was zero.

In comparison to the low levels of dislocation observed from the G, R, and G50 treatments, the level of clay dislocation exhibited by all RP treatments was more than 10 times as high. However, for all phyto-organic treatments, especially in the case of the RP, the second submergence produced far less clay dislocation (>10-fold decrease) than the first submergence (Table 4). On the established fact that totally untreated Bayer red muds are (1) totally dispersive (AAC 2012) and (2) hence totally disaggregated (Bardossy 1982), clay dispersion would therefore have been far greater in such totally untreated red muds than had occurred with the

Table 4 Mass of clay (grams) dislocated from aggregates after shaking in water (wet-sieving) and 2nd submergence for 8 days

Red mud (depth in cm)	0 % phyto-organics (controls)	All phyto-organics	Total mass	Difference
0–15	0	0	0	0
15–30	0	0	0	0

treatments of this study. Overall, greater clay dislocation was more evident from the de-ionized samples, especially the R and RP samples.

The lack of dislodged clay particles from the 2nd submergence could have meant that all the dispersible clay had been released at the first submergence (Table 4). To test this assumption, the aggregates were again air-dried and subjected to dry sieving in a shaker where the aggregates were rolled and bounce on a sieve having a 100 μm aperture. Each aggregate was then mechanically agitated in an end-over-end shaker for a pre-determined time period. At air-dry, all particles were again weighed. The separated fractions were viewed and measured under magnification using a microscope with a graticuled lens. In the rating scheme for this study, the clay dislocation ratio for the RP as compared with the GP samples was $>10:2.6$.

Therefore, as (1) the 2nd submergence of this study caused no observable clay dislocation, the maximum total potential dust for any treatment remained at 29 % w/w. After the 2nd submergence, samples were air-dried and shaken in a sieve having apertures 100 μm in diameter. Results are shown in Table 5. It can be seen that, whereas the phyto-treatments continued to dislocate very little clay even during dry sieving, the non-phyto-treatments dislocated at least twice as much clay as the least efficient phyto-treatment during this procedure. In fact, R samples (non-phytogenic-) dropped 60 % of their mass from the dry-sieve as dislocated $<100 \mu\text{m}$ clay particles (Table 5). As noted in Sect. 1.0 above, among the world's bauxite ores Jamaican bauxite texturally contains by far the largest clay fraction at 75 % (Alcoa 2007). Therefore, had this been a field study, it is reasonable to assume that the R (non-phyto-organic) samples would have potentially released 42 % of its mass as wind-blown clay. Again, as stated above, several variables determine the actual concentration of wind-blown dust at any given location. Therefore no attempt is made here to quantify the potential rate of wind-blown dust. Nevertheless, it can be seen that despite being by far the least effective treatment of this study, the R (non-phyto-) samples reduced potential wind-blown dust by 33 % (i.e., $75 - 42 = 33$). Using Tables 2, 3, 4 and 5, similar calculations estimate the potential dust reduction by other treatments as follows:

Table 5 Proportion of $<125 \mu\text{m}$ particles after dry-sieving of aggregates following two submergences in water for a total of 15 days after incubation

Red mud (depth in cm)	0 % phyto-organics (controls)	25 % phyto-organics	50 % phyto-organics	Total
0–15 (G)	4	2	1	7
15–30 (R)	60	2	0	62

Table 6 Impact of large falling water drops on remolded aggregates (days) after incubation and submergence in water for 15 days as depicted by the counted number of drops (CND) before shattering

Red mud (depth in cm)	0 % phyto-organics	25 % phyto-organics	50 % phyto-organics	Total
0–15	150	30	430	670
15–30	50	70	330	450

$$G50 = 75 - (4 + 8 + 0 + 1) = 67 \%$$

$$G25 = 75 - (8 + 0 + 2 + 3) = 67 \%$$

$$R50 = 75 - (16 + 0 + 0 + 13) = 56 \%$$

$$R25 = 75 - (16 + 0 + 2 + 3) = 54 \%$$

$$G = 75 - (0 + 0 + 0 + 4) = 71 \%$$

$$R = 75 - (.01 + 0 + 0 + 60) = 14.99 \%$$

Prior to the test of aggregate stability, the leading treatment for dust reduction here is still gypsum (71 %), with gypsum + phytogenic being second at 67 %. Predictably, without gypsum, incubation yielded only 15 % dust reduction for non-gypsum treatments.

3.1.4 Aggregate Stability

In a physical sense, resistance to shattering impacts reduces dust production. After 15 days, the samples were subjected to falling drops of water which simulated raindrops from a pre-determined height. The results showed that the phyto-organically treated samples at 50 % from either the 0–15 cm depth or the subjacent red mud withstood more than twice as many impacts before shattering, as each of the non-phyto-organically treated samples (Table 6). Additionally, the G50-proved substantially more resilient in this respect than the R50 samples (Table 6). Without organics, the G aggregates withstood three times as many raindrop impacts as the R aggregates. The overall G treatment produced 50 % greater resiliency under simulated raindrop impacts than the R treatments (Table 6). However, the counted number of drops (CND) resistance of the R25 exceeded that of the G25 samples by 50 %. This apparent anomaly is discussed later.

3.1.5 Stability in Stagnant Water

See Table 7.

Table 7 Longevity of remolded aggregates (days) after incubation and submergence in water for 15 days

Red mud (depth in cm)	0 % phyto-organics (controls)	25 % phyto-organics	50 % phyto-organics	Total
0–15	2	3	13	21
15–30	12	3	13	28

Table 8 Aggregate longevity in minutes of stability during wet-sieving after incubation treatments

Red mud (depth in cm)	0 % phyto-organics	25 % phyto-organics	50 % phyto-organics	Total
0–15	11	2	2	15
15–30	12	3	13	28

3.1.6 Stability in Moving Water

A vast difference of water-stable longevity amongst treated samples can be seen, because samples from the 15–30 cm depth with either 50 % phyto-organics (R50) or without phyto-organics (R only) are by at least a 5-fold margin the most resilient under wet sieving (Tables 7 and 8). Aggregates subjected to wet-sieving maintained their integrity in the following order of decreasing longevity: R50 = G50 > R = G25 = R25 = G25 (Tables 7 and 8).

4 Discussion

4.1 Fine-Particle Dislocation

As dust results from dislocated clay, and contact with water weakens soil aggregates and dislocates clay (Rengasamy et al. 1984), the most resilient aggregates are the lowest potential producers of dust. It can be seen that despite being submerged in still water for 15 days, the phyto-organic (P) samples outlasted all others. In fact, before the end of day 1, several non-P samples had already disintegrated (Table 6), some having done so within a few minutes of submergence.

For aggregates without phyto-organics from the 0–15 cm previously gypsum-treated layer, relatively few measurable clay particles (potential dust) were dislocated during submergence in water for several days. At the end of day 2 of submergence, those samples incubated from the 15–30 cm layer (i.e., under the gypsum-treated layer, without phyto-organics) released no visible clay particles. Wind power increases exponentially with wind speed such that the power of the wind varies as the cube of its speed (Kovarik et al. 1979). Thus an increase of even 2 or 3 km h⁻¹ is a significant increase in terms of energy expended and hence the amount of dust removable from a surface. As Na⁺ causes mutual repulsion among clay particles, and

the 15–30 cm depth contained Na^+ far in excess of the surface layer, the low level of clay dislocation from that depth was unexpected. This is further discussed later.

In the first submergence, the gypsum plus phyto-organics treatment dislocated >5-times the amount of fine clay particles (potential dust) compared to the amount from the gypsum-only treatments. This also was against expectations because applying similar treatments to sodic (Na^+ -rich or high ESP) subsoils, Harris and Rengasamy (2004) used sub-micron particle analysis to show that phyto-organics with gypsum substantially flocculated (agglutinated) clay particles. Thus by increasing the mass sizes, they decreased the release of individual clay particles. Further, for submergence #1, the greatest reduction of potential dust in this study occurred as follows in descending order of efficiency:

$$\text{G} > \text{R} > \text{G50} > \text{G25} > \text{R50} = \text{R25}.$$

Decomposable phyto-organics have been shown to bind sodic clay particles (Harris and Rengasamy 2004) and inorganic particles in bauxite waste (Harris 2009), and as discussed later, wet-sieving results showed that strong binding of inorganic particles also occurred in this study. Yet, for the ultra-fine (highest dust-potential) inorganic colloids, such a binding force from phyto-organics proved, particularly at the lower phyto-organic rates, ineffective initially in this study. Isomorphic atomic substitution causes the negative charge exhibited by all clay particles. Muneer and Oades (1989) noted an increased number of negatively charged particles formed as decomposition and breakdown of phyto-organics advances in remolded aggregates. They concluded that small negative charges from organic colloids which were the same approximate length as clay particles, were dispersing the clay particles. In this study, it can be seen that, compared with non-phyto-organic-treatments, it was the phyto-organic samples that produced more clay dislocation in the 1st submergence, especially the phyto-organics at the lower rate (R25, and to a lesser extent, the G25). On the other hand, though they readily broke down even in still water, non-phyto-treated macro-aggregate samples from the 0–15 cm depth (G) did not dislocate ultra-fine clay particles when those macro-aggregates were submerged in water (Table 1). Furthermore, the following observations were made:

- No clay dislocation from the G50 or G25 samples occurred in deionized water
- Between G50 and G25 samples, clay dislocation in non-deionized water was greater from G25

Clay dislocation by the G25 and G50 in the non-deionized water could have been due to a greater number of negatively charged colloids (organic and/or inorganic) intrinsic to that water as compared to the deionized (less contaminated) type. On this assumption, the total mass of negative colloids would be greater in the non-deionized system. The G25, with less microbial substrates than the G50 and hence with more competition among microbial decomposers, would have been expected to have undergone more advanced breakdown of organic matter, thereby presenting smaller colloids to the system. As noted earlier, highly comminuted negative colloids of similar sizes mutually repel. It is thus more likely that of the two treatments, the G25

would have been more likely to contain organic colloids fine enough to repel clay particles of similar sizes. Such electronic forces could have dislocated the clay particles at a higher rate from the G25 than from the G50 aggregates.

For similar reasons, in a study incubating gypsum with sodic sub-soils, Harris and Rengasamy (2004) observed no stable macro-aggregates (i.e., $>250\text{ }\mu\text{m}$) at any stage of incubation. They concluded that gypsum alone cannot produce stable macro-aggregates, though stabilization occurred at the $<250\text{ }\mu\text{m}$ size level. They also reported that phyto-organic additions caused a slight increasing trend.

The ability of negatively charged clay colloids to disperse clay particles is illustrated by the immediate settling out by flocculation of clay colloids or organic colloids whenever small amounts of multivalent cations from $\text{Al}_2(\text{SO}_4)_3$ (alum) are added to such suspensions. It is very likely that after the first submergence, most or all of the organic colloids became trapped in the dried residue. This may explain why, after dislocating such high levels of clay in the first submergence, at submergence #2, the phyto treatments failed to dislocate any clay at all.

4.2 Natural Flushing

The natural flushing by rainfall for more than a decade (Harris 2009) would have removed much sodium sulphate in the 0–15 cm layer. This relative increase in the ratio of Ca^{2+} to Na^+ ions promoted the binding action among clay particles. However, annual rainfall also subsequently depleted the unprotected Ca^{2+} ions in the upper (0–15 cm) layer. It was expected that phyto-organic gums from the decomposing phyto-organics, would have induced stable aggregation among the G25 and G50 samples. This did not occur. On the other hand, with the same levels of gypsum in the same bauxite waste, Harris (2009) observed stabilization of macro-aggregates. The explanation may be that Harris (2009) incubated the samples for a much longer period of time (more than 24 weeks) compared to the 6-week incubation of the present study. With more advanced levels of decomposition, stronger binding between inorganic particles may have occurred in that earlier study.

Aggregate stability

Yet, paradoxically, in this same study of just six weeks, underneath the surface, the 15–30 cm layer, despite having massively accumulated Na^+ ions from the prolonged elluviation from the 0–15 cm layer plus residual Na^+ from the Bayer Process, produced stable macro-aggregates of 6-fold the longevity under wet-sieving than those produced by the N^+ -deficient 0–15 (surface) layer. Moreover, as stated above, Harris and Rengasamy (2004) concluded that with or without gypsum applications, phyto-organics cannot macro-aggregate sodic clays to a level of water-stability, though stable micro-aggregation ($<250\text{ }\mu\text{m}$) can be achieved. The object of flushing is to remove the Na^+ in the form of Na_2SO_4 from the exchange reaction with CaSO_4 to provide greater opportunities for the adsorption of Ca^{2+} onto clay particles. Yet despite the obvious absence of flushing at the 15–30 cm

level (indicated by high Na^+ levels), strong Ca^{2+} adsorption as proven by high aggregate stability, had clearly occurred subsequently (i.e., after gypsum addition to the superjacent layer). The only samples to exhibit efflorescence were the phyto-treated R samples (R25 & R50). Therefore, this white efflorescence on the outside of the aggregates (Fig 4a: the six samples on the left) may more clearly explain the substantial resilience of the R50 aggregates during wet-sieving. In this particular system, the white efflorescence could be drawn only from the following major group of substances— Na_2SO_4 , NaCl , Na_2CO_3 , CaSO_4 , $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, CaCO_3 , $\text{Ca}(\text{OH})_2$. All forms of sodium sulphate, sodium chloride, and sodium carbonate are white solids that are highly soluble in pure water. The efflorescence exhibited relatively low solubility in water at $<0.0030 \text{ kg L}^{-1}$ in deionized water at 20°C . As this is substantially lower than that of all the above substances except gypsum and calcium carbonate, the efflorescence is comprised of either calcium carbonate or gypsum, or a combination of both. The explanation may be that with such unusually high levels of Ca^{2+} in the 15–30 cm level, exchange sites became dominated by the more strongly bound Ca^{2+} . Purely from the standpoint of stability, this nullified the need for Na_2SO_4 flushing. Interestingly, as stated above, the R25 samples dislocated more clay than all other treatments. It is therefore surprising that the R25, despite the above-mentioned statements, exhibited the least resistance to wet sieving. However the relatively low level of phyto-organics, compared to the R50, may explain this condition (Tables 7 and 8).

On the other hand, the lower resistance to wet-sieving of the 0–15-cm gypsum-treated phytogenic macro-aggregates suggests an inactivation by carbonation to CaCO_3 of a substantial quantity of the Ca^{2+} released in the early stages of the gypsum treatment applied several years before this study. Being exposed sub-aerially, greater atmospheric CO_2 would have been available in the 0–15 cm depth compared to the subjacent layer.

Another possible explanation for the longevity of the R samples to wet sieving entails thixotropically affected entities, referred to by Coughlan et al. (1973) as “fortuitous agglomerates.” These fortuitous agglomerates survive wet-sieving but are not true aggregates, being case-hardened during storage possibly in this case by oxidation of iron oxides.

As stated above (Sect. 1.2), based on Wehr et al. (2006), the total clay fraction for the Jamaica bauxite waste is 75 %. On the assumption that all clay particles are $<100 \mu\text{m}$ in diameter, potential dust in Jamaica bauxite waste, according to his table, is at least 84 % w/w. As the best treatments of this study increased more than 95 % of the particle size of the bauxite waste to well over the $<100 \mu\text{m}$ -diameter threshold after submergence in de-ionized water, it is concluded that the phyto-organic treatments substantially decreased potential dust not just from Jamaica bauxite wastes, but potentially for all other wastes listed above. This includes red muds from St. Croix (Virgin Islands), Guyana, and Haiti.

The relatively high level of aggregate stability under wet-sieving observed for the crushed G (no phyto-organics) samples in this study was not expected because an opposing result occurred in a study of the same lithified red mud waste by Harris (2009). In yet another study, Harris and Rengasamy (2004) also found that no macro-aggregate stability in a sodic sub-soil when treated with gypsum.

However, in both of those studies, they used <2 mm particle sizes, whereas in the current study the particle size used was <1 mm. Particles must be fine enough to provide a sufficient reactive surface area for the solid-state chemical reactions (Mehta and Monteiro 1993). It is thus postulated that the larger surface area (more than twice as large) of the smaller particles of this study afforded far greater opportunities for cohesive forces of the Ca^{2+} ions among inorganic particles.

It is the binding action of organic cements and electronic attraction of cations that produce aggregation and, by extension, can reduce dust formation in sodic soils and spoil heaps. It is interesting that both the mine tailings of the present study and the soil studied by Harris and Rengasamy (2004) reacted similarly to phyto-organic additives. Neither sodic entity was influenced by phyto-organics acting alone. In other words, without gypsum, sodic clays do not react significantly with phyto-organics to form stable macro-aggregates. This is primarily because organic colloids and sodic clays are mutually repulsive, being both negatively charged. Without multi-valent cations there are few positive charges to link the clay particles. Harris and Rengasamy (2004) found that the role of gypsum is to flocculate the clay particles, as has been found by Baldock et al. (1994); and Muneer and Oades (1989), where Ca^{2+} in soil solution did not improve macro-aggregation. In this study, however, gypsum acting alone stabilized macro-aggregates from finer inorganic particles.

Applying similar treatments to sodic subsoils, Harris and Rengasamy (2004) found that clay particles had been aggregated by decomposing phyto-organics into a size range not exceeding $30\text{ }\mu\text{m}$. In this study, agglomerates from the RM + phyto-organics treatment remained stable under physical pressure, and did not release dust particles. Yet, these agglomerates of varying sizes up to 4 mm from the RM + phyto-organics treatments were readily unstable under wet-sieving (Table 2), as was the case for those produced in an experiment conducted by Harris and Rengasamy (2004). The implications here are that under field conditions, such stability would be destroyed during the first rain shower, and that dust would be produced on drying of the crumbled masses. However, destruction of unstable macro-aggregates produce progressively smaller aggregates with an inverse change in soil strength (Dexter 1988) caused by stronger inter-particle binding mechanisms (Seguel and Horne 2006). Thus, below a particular wind speed, micro-aggregates above dust-size produce less dust per volume than macro-aggregates. As reported above, dust particles of up to $100\text{ }\mu\text{m}$ can be airborne. As soil micro-aggregates range up to $250\text{ }\mu\text{m}$ (diameter), an appreciable proportion can be airborne. Though micro-aggregate size was not measured in this study, Harris and Rengasamy (2004) found that micro-aggregates which formed under similar conditions had an average size of $30\text{ }\mu\text{m}$ (diameter). It is therefore reasonable to conclude that a large proportion of micro-aggregates in this study would be below $100\text{ }\mu\text{m}$, and hence susceptible to creating dust hazards.

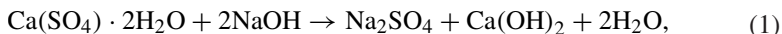
Based on the above, it is clear that (1) the water-stability of red mud waste with or without added phyto-organics varies directly with addition of gypsum (2) water-stability of red mud waste determines dust production levels. Under specific conditions of this study, water-stability was achieved not only during wet-sieving trials, but prior to that, during two episodes of several days of submergence.

5 Conclusions

The potential effect of gypsum treatments and phyto-organics on quantities of wind-blown dust from red mud wastes was examined. Gypsum treatment decreased dust-sized clay particles by >80 %. Average dust particle sizes of <100 μm in original samples were transformed in the gypsum-treated samples in soil crumbs. The average dust particle size showed a >4-fold increase over that of the controls. The size of dislocated particles was <100 μm . Under the influence of simulated de-ionized water, decomposable phyto-organic additives initially increased small quantities of the finest clay particles. It is likely that this minor dislocation was due to an increase in negatively charged organic colloids formed by phyto-organic decomposition during incubation. Nevertheless, increasing the size of particle clusters in this study potentially produced greater resistance against wind saltation and airborne movements.

6 Geotechnical Applications

- 6.1. One successful approach to dust reduction is to spray bitumen emulsions onto red mud embankment walls.
- 6.2. Unfortunately, the waste oil used has a short life-span in the environment due to its chemical reaction with caustic (NaOH and its derivatives), and natural biodegradation (Alcoa 2007). Studies have shown that the oil is undetectable below 2 m (Alcoa 2007). However the protection of the ground water below and around the tailings dump can be guaranteed only with an effective waste dump seal. Since such protective seals were never installed at the base of Caribbean red mud waste ponds, the bitumen emulsion could seep into those underlying aquifers. Moreover, as added gypsum removes the caustic in the following reaction:



The bitumen emulsion would not degrade as easily wherever gypsum had been previously applied. In Jamaica, gypsum had been applied at over 10 t/ha, as has been the case for Kirkvine Pond 6 (O'Callaghan et al. 1998). Potentially, therefore, excess hydrocarbon oils could remain in gypsum-treated red muds after application of bitumen emulsions. Such excess oils in the environment create non-wetting soils (Ward et al. 2015). Non-wetting soils are often prone to dispersion and structural breakdown (Ward et al. 2015).

- 6.3. A non-toxic regime is preferred as follows:
Cover dry solid red mud waste with approximately 30 cm of incubated dried red mud mixed with grinded phytogenic material. Roughen the material before adding grass seeds.

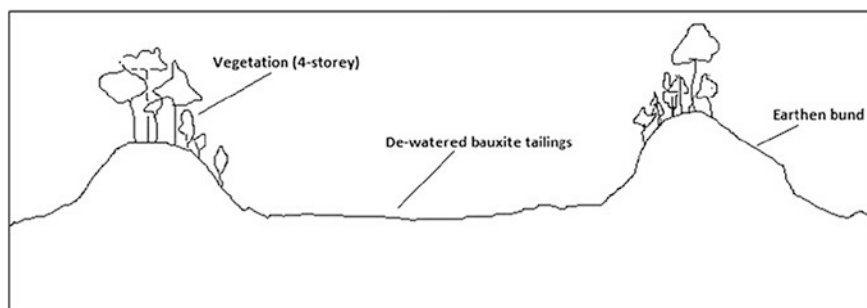


Fig. 7 Earthen bunds planted with native vegetation comprised of several storeys for trapping wind-blown dust

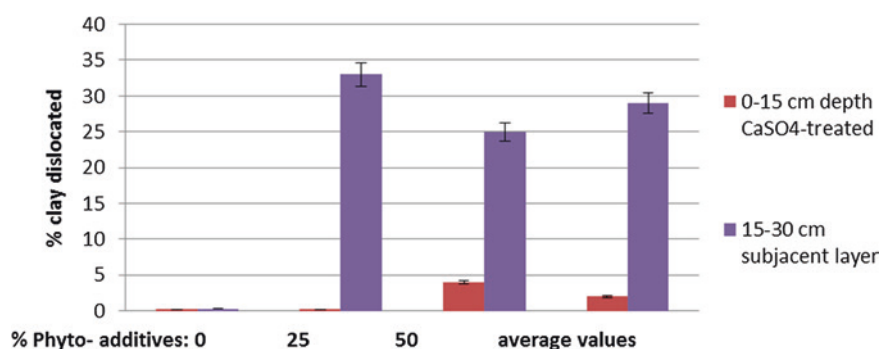


Fig. 8 Mass of clay dislocated after incubation and soaking in deionized water for 8 days

To conserve water, cover with thin polythene to simulate a horizontally extended glass house. After several weeks, add grass seeds.

6.4. Other field methods:

Raised banks (bunds) can be planted with wind-breaking vegetation to trap dust (Figs. 7, 8), being non-toxic compared to bitumen emulsions (Fig. 9).

6.5. Phosphorus depletion

P-fixing in such acidic soils prevents the successful growth of most plants except *Cajanus cajan*, which has the ability to extract P from P-fixing soils. *C. cajan* exudes piscidic acid which enhances the availability of phosphate from iron-phosphate and rock-phosphate (Ae et al. 1990). Thus, unlike other legumes, pigeon pea is one of the few crop species that can utilize iron bound P efficiently making it capable of binding clay particles under P-limiting conditions.

6.6. On the other hand, growth media, by producing aggregation of individual soil particles, can minimize dust from bauxite mine tailings (residues).



Fig. 9 Bitumen emulsion being sprayed to reduce dust from embankment walls. Adapted from Alcoa World Alumina Australia, March 07.

- 6.7. As bauxite is a residual product containing extremely fine particles, suspensions of red mud are ubiquitous wherever bauxite is mined. Hence mud reduction strategies are trans-continentially applicable. In Queensland, Australia (Alcoa 2007), specific dust controls employed by Alcoa to minimize dust generation include:
 - 6.8. Turning over the mud in the residue area;
 - The use of sprinklers and water carts;
 - Spraying exposed banks with bitumen;
 - Applying rock aggregate to large areas that are not required in the short term;
 - Road management through application of emulsified waste oil as a dust suppressant and
 - Restricting access and; planting grasses or native vegetation.
 - 6.9. However, most of the above efforts each have major drawbacks ranging from high cost (sprinklers and water carts, applying aggregate) to environmental unsustainability (waste oil, bitumen). Hence, for the developing Caribbean region, the most sustainable from the standpoint of cost and environmental damage are turning over the mud in the residue area (a short-term corrective) and planting grasses or native vegetation (a long-term strategy). For the latter strategy, the major problem is the edaphically hostile growth media of red muds including $\text{pH} > 11$, and lack of aeration.

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