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An innovative approach to bauxite residue site remediation: a case study reviewing the dewatering, reprofiling and revegetation of a closed bauxite residue site in Jamaica

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Abstract

Following the divestment of its alumina refineries in Jamaica, Rio Tinto agreed to close and revegetate some closed bauxite residue storage sites prior to returning the land ownership to the Government of Jamaica. The most challenging area to be restored was a dammed valley which contained approximately 2 million m^3 of high pH water (pH 12) over a 60 m deep deposit of bauxite residue tailings from the nearby Ewarton alumina refinery. The site was approximately 40 ha in size and located in an area with no mains power and subject to severe cyclonic rainfall events.

This paper describes the option analysis review, the trials undertaken and work at Kirkvine, the water treatment approach and disposal, reprofiling to allow suitable drainage, and the revegetation stages. The hilly nature of the terrain meant that there was no readily available topsoil to use as a covering over bauxite residue for revegetation. Instead, the high pH, highly sodic bauxite residue material was converted into a material that provided a sustainable plant growth medium. The soil conditioning to achieve a suitable medium was especially challenging. The project started in 2006 and the revegetation phase started in 2016. The paper describes in detail the current status of the vegetative species that are now growing and also reviews the diversity of fauna that have already colonised the site.

A major aspect of the work was close cooperation at all stages with the key regulators in Jamaica, especially the Jamaica Bauxite Institute, and the local community.

Keywords: *bauxite residue, red mud, dewatering, remediation, closure, Jamaica*

1 Introduction and historical background

The existence of bauxite in Jamaica dates back to 1860s when red earth, terra rossa, rich in alumina and iron, was found in St Ann and St Elizabeth. The quality of the Jamaican bauxite deposits was found to be excellent and the growth in aluminium demand and the resultant need for alumina in the 1940s encouraged Alcan to build its first alumina refinery in Jamaica near Mandeville, known as Kirkvine, in 1952. A second alumina refinery was constructed in 1959 at a site at the foot of Mount Diablo near Ewarton. Both plants were progressively expanded and ultimately had capacities of approximately 550,000 tonnes per annum of alumina. In 2001, Alcan sold its bauxite mining and alumina plants in Jamaica to the Glencore group (Glencore Alumina Jamaica Limited – operating locally as Windalco (now owned by UC RUSAL)) but agreed to keep responsibility for many of the bauxite residue sites with the intention of safely remediating them and returning ownership to the Government of Jamaica (GoJ). In 2007 Rio Tinto plc/Rio Tinto Limited acquired Alcan Inc. and responsibilities for the remediation were passed to Rio Tinto plc.

The alumina refineries at Kirkvine and Ewarton manufacture aluminium oxide (alumina) using the Bayer process starting from bauxite. Bauxites typically contain 42% to 60% aluminium compounds and in the Bayer process, these aluminium compounds are extracted under conditions of high temperature, high pressure and strongly alkaline conditions. A necessary byproduct of the manufacturing process is a significant fraction of residual material, bauxite residue (sometimes called red mud). Until the mid-1980s, the practice was to discharge a slurry containing typically 20% solids into lagoons ('ponds') or dammed areas (Evans 2016). This was the practice in both Ewarton and Kirkvine. Ewarton was the first plant in the world to adopt an improvement of this system, called dry mud stacking, which produced a high solids residue and enabled the residue to be stored in a semi-dry state with a solids content of up to 35% (Evans 2016). This practice has subsequently been adopted globally and remains the primary method for disposal, although the use of press filters is increasingly adopted (Avery et al. 2022). As a result of these operations, there were some 13 bauxite residue areas at Kirkvine and a large deposit adjacent to Ewarton at Mount Rosser which needed to be remediated and closed.

2 Remediation project

Following the sale of the operating assets, in 2004, Alcan initiated a review of possible remediation strategies for abandoned bauxite residue areas at the Kirkvine and Ewarton. A key area of concern to Alcan, and subsequently Rio Tinto, was adherence to all Jamaican national standards and Rio Tinto's internal standards. Rio Tinto always seeks to utilise best practice in undertaking closure operations to the benefit of all stakeholders. In addition, it seeks to operate with the best HSE practices and systems at both a management and practical level.

As well as desk reviews of the historical geological and hydrogeological information, analytical work, tracer studies, dam assessments, drilling trials and water/soil assessments studies were made. Following initial internal option reviews, extensive discussions were held with the key regulators in Jamaica principally via the Jamaica Bauxite Institute (JBI). The other parties involved were Water Resources Authority (WRA); National Water Commission (NWC); National Environmental and Planning Agency (NEPA – NRCA); Commissioner of Mines (CoM); Commissioner of Land (CoL) and the Environmental Health Unit of the Ministry of Health (EHU-MoH). There were many iterations of a suitable closure plan and when one had been provisionally agreed, there was an extensive exercise to review the plan with the local stakeholders. Following these reviews, the final closure plan was signed off in 2006 by all regulators listed above before commencement of the work.

2.1 Kirkvine

Phase 1 of the remediation programme following the sale of the Alcan assets was the closure of the bauxite residue ponds adjacent to the Kirkvine refinery near Manchester (coordinates 18.07979, -77.47805). At Kirkvine, there were some 13 areas to be remediated, some of which were permanently ponded, some had seasonal ponds and others and were the result of bauxite residue being deposited in former depressions left after bauxite mining.

The site had been used for investigations and vegetation trials for several decades with the initial studies in 1972 (Adams & Lawrence 1972) followed by studies by Adams & Ramjus (1975) and Edwards (1991). The early trials were based on various studies undertaken in the 1970s and 1980s using gypsum to treat bauxite residue by various groups to create a material that would support growth of vegetation (Barrow 1982; Bennett 1974, Bucher 1985; Marschner 1983; Meecham & Bell 1977; Nelson 1981; Wong & Ho 1991, 1992, 1993). In 1991 on a 4 ha abandoned pond at Kirkvine, four large plots, (30 m × 18 m), and 16 small plots (2 m × 2 m), were treated with different levels of gypsum and fertiliser. The area was ploughed twice to a depth of about 15 cm to break up the surface and then traversed with a D-6 caterpillar to further breakup the large lumps. Gypsum loadings of between 10, 20, 40, 60, 80 and 100 t/ha were added at different times and the 'soil' characteristics assessed. Following the initial success of the soil free remediation of the northern part of the site, during the mid and late 1990s, the entire 4 ha site was remediated, and progress monitored by Alcan in conjunction with the University of the West Indies. Additional data was generated on how the electrical conductivity and pH changed with increasing levels of gypsum addition (O'Callaghan et al. 1998).

Following the sale of the Bayer operation, Alcan undertook further work at Kirkvine in 2004 which assessed manure additions and the optimum plant species to use. Trials used waste organic wastes from various sources including rum production (dunder), beer brewing, and akee fruit canning were evaluated with varying degrees of success. Cooperation with the JBI, the University of the West Indies (UWI) and the Jamaican Science and Research Council was sought in these projects. Plants species found to thrive in the trials were: Brachiaria, Leucaena, Bean Species (Bonavista and Castor Beans), Bermuda Grass and Guinea Grass and these were used for subsequent work at Kirkvine and formed the basis of the work at Mount Rosser.

Remediation of the ponds started in early 2007 and involved dewatering, mud conditioning, gypsum addition, manure addition followed by seeding. Aided by the benign climate, by 2011 growth was found to be extremely good and work is described in the paper by Lyew-Ayee et al. (2011). Subsequently extensive soil and plant (leaf, stem and root) analyses were carried out, vegetative assessments carried out by teams from the Life Sciences Department, UWI, (Webber et al. 2011), avian studies and all the data was submitted to the Jamaican authorities. Ownership of the land has now passed to the GoJ.

2.2 Ewarton/Mount Rosser

2.2.1 Background, initial assessments undertaken and end use options

The remediation of the bauxite residue pond at Mount Rosser (coordinates: 18.20956, -77.09094) was a much more challenging problem than the various ponds at Kirkvine because of: the much shorter time between residue deposition cessation and remediation work starting, the very large volume of overlying ponded water, the chemical characteristics of the overlying water, the topography, the volume of mud that needed to be moved, and the absence of mains power needed for many activities.

The Mount Rosser Pond is located approximately 5.6 km from the Ewarton alumina refinery and at an elevation 300 m higher than the plant. The tailings pond was constructed in 1959 when the refinery was built to act as the sole pond to hold the bauxite residue. It was formed by damming a portion of a valley by progressively increasing the height of the embankments such that they finally reached a height of 53 m. The bauxite residue was pumped as a slurry comprising 20% solids to the pond which was used until 1991. When the alumina facility was sold in 2001, the pond covered an area of approximately 37 ha. It contained approximately 11 million m^3 of bauxite residue up to 90 m deep, with nearly 9 m of water on the surface with a pH of 10.5 and a sodium content of approximately 2,000 mg/L. This area, like most of Jamaica, is subject to frequent hurricanes and very high rainfall events; therefore, the pond was continuously recharged with stormwater runoff from the surrounding hillsides, a catchment area of approximately 100 ha. The annual rainfall at the site exceeds 1,200 mm/year, and the annual recharge to the pond is approximately 1.5 million m^3/year; whilst this partly reduces the pH and sodium level, it adds considerably to the volume of water that has needed to be treated (see Figure 1).

Figure 1 Mount Rosser Pond 1996

The investigation included a bathymetric survey of the pond, an analysis of the pH changes with depth, detailed chemical analyses of the water, experimental work on neutralisation to determine acid requirements and the effect this would have on the concentrations of the various chemical species present. Drilling was also carried out on the site and detailed chemical composition and particle size distributions of the residue were analysed. The discharge procedure was to allow the pumped slurry to flow from outlet pipes around the perimeter of the site, so the residue deposited was much coarser near the outlet of the pipes and much finer towards the middle of the site. Therefore, the chemical characteristics of the residue varied across the site. The underlying geology was thoroughly reviewed together with the hydrogeological studies which had been undertaken at various times. Tracer test studies using Fluorescein were carried out to investigate and confirm the pathways of the water that was planned to be discharged after treatment.

Extensive reviews were undertaken to review strategies for rendering the site safe. The key objective was to ensure the site was safe for future generations and various end uses; end uses were reviewed with this in mind. Other objectives foremost under consideration were maximising employment and implementing training/capacity building within the local community, ensuring compliance with nationally and internationally recognised bodies of expertise to guarantee technical excellence, and creation of a legacy of best practice.

After extensive discussion with all the Jamaican regulators and other stakeholders, a plan was finally agreed and signed off by all the main regulators: the JBI, WRA, NWC, NEPA – NRCA, CoM, CoL and the EHU – MoH. The various stages of the remediation comprised: water treatment to standards agreed by the JBI, WRA, NWC, and NEPA and then discharges into agreed soakaways; after dewatering the body of water, reprofiling the exposed muds to provide a suitable site to allow runoff to flow into agreed pathway; lowering the dam wall; and vegetation of the reprofiled site to standards agreed by NEPA and the JBI.

2.2.2 Water treatment and water discharge options considered and implementation

A range of options were considered for treatment of the high pH water from returning the supernatant water to the Ewarton refinery, mass dosing with sulphuric acid, carbonation using flue gas or carbon dioxide, and inline neutralisation using acid prior to discharge. Returning the high pH supernatant to the refinery was rejected as in the intervening period between closing the residue disposal area and commencing work, much of the nearly 6 km pipeline had been stolen and the cost of reinstatement considered too high. Within Alcan, there was experience of both mass dosing of a residue disposal pond using sulphuric acid and inline dosing with sulphuric acid. Access to the Mount Rosser site is difficult and mass dosing with sulphuric acid was rejected because of health and safety concerns about bringing sulphuric acid tankers to the site. It was decided to construct an inline sulphuric acid neutralisation plant so that the pH of the discharge water could be carefully controlled immediately prior to discharge. Sulphuric acid was the only acid available in Jamaica in sufficient quantity.

Following treatment and neutralisation to the agreed pH, the water was discharged to various soakaways on the north and east edges of the pond. Hydrogeological and tracer studies had given an indication of the likely pathways of the water through the underlying karst limestone. Possible receptors and monitoring points were agreed with the JBI, WRA, NWC and NEPA and a comprehensive monitoring programme was agreed with the regulators on allowable levels for over 30 chemical species (including some 15 elements, seven anions and other parameters judged important by the regulators) twice per month and reported to all key regulators every quarter. Maximum daily discharge levels were also agreed upon. Discharge was carried out on a continuous basis commencing in early 2007. Up to May 2022, it is estimated that approximately 5.5 million m^3 of treated water has been discharged with no exceedances of any parameters at the agreed receptors and a few minor exceedances in some of the daily low limits under exceptional discharge conditions (very heavy rainfall events).

2.2.3 Reprofiling and mud moving options and implementation of mud moving

As the water was discharged from the pond, the bauxite residue shores were progressively exposed, and the pond's sunken middle was revealed, enabling reprofiling to commence. Various options were considered but as the work progressed the final plan was to introduce a 1 in 200 slope towards the dam at the site, initially collect the water and then allowed to discharge to the south when a quality acceptable to the regulators had been reached. Two main options were considered for mud profiling. Firstly, use of an Amphirol to help dewater the surface layer and consolidate the mud, followed by mud hauling in trucks to create surface contours. Secondly, use of a dredge mud pump was considered. It was estimated that over 300,000 m^3 of mud needed to be moved to achieve the required soil profile so that rainwater would runoff to the south toward the existing dam. Based on the high moisture content of the muds in the middle areas of the pond, the very poor load bearing characteristics of these muds, the large volume of mud that needed to be moved and hence the number of truck movements, and most importantly, the safety risks, a two-stage approach was adopted. For the initial phase of reprofiling when the muds had a solids content between 25–35%, a dredge pump was adopted; for the drier muds (>50% solids), a conventional cut-and-fill approach was used with trucks, excavators, and dozers.

The mud dredging system adopted utilised a Tornado floating dredge pump. A dredging system had not previously been used on bauxite residue areas but was ideal for Mount Rosser where there was a need to move mud which was still under water to obtain the required profile. Of the 300,000 m^3 of mud that was moved, approximately 70,000 m^3 was moved with the Tornado dredge.

2.2.4 Vegetation options considered and trials: initial small-scale, then pilot plant

2.2.4.1 Vegetation phase

The overall objective, as had been agreed with the regulators, was to establish 70% vegetative cover that was both sustainable and diverse. Challenges included: high pH, high sodium, high bulk density, low porosity, poor nutrient status, and low organic matter content of the residue. These factors, along with high moisture levels, minimal microorganisms, flora, and fauna, had to be overcome before any success could be realised. Traditional lining, then capping with topsoil would have been the most obvious choice. However, the volumes of topsoil required, combined with high cost and very limited availability, nullified this option.

After evaluating a range of options, and in view of the prior success at Kirkvine, it was decided to use a topsoil-free approach. This entailed conditioning existing bauxite residue into a medium like topsoil that can sustain plant growth. Unlike the older, well weathered Kirkvine site, Mount Rosser had a totally different starting point. After the dewatering and reprofiling stages, the bauxite residue was extremely wet, with high pH and sodium levels. An additional feature therefore adopted was the greater utilisation of mud conditioning by extensive mechanical working to accelerate neutralisation of the exposed muds (Clancy 2013). Figure 2 shows the site after dewatering, reprofiling and conditioning.

Figure 2 Mount Rosser prior to vegetation growth

2.2.4.2 Trials

Despite the success of the Kirkvine trials, the high pH and higher moisture levels at the Mount Rosser site meant than a substantial amount of trial work was required to establish a favourable growing environment. These trials involved greenhouse studies, small-scale pot trials onsite, small-scale field plots onsite, extending to trials onsite using large equipment. A baseline was set for the properties of the bauxite residue prior to planting which was progressive revised as new data was obtained. This included, pH, CEC values, EC values, soluble sodium levels, porosity, bulk density, and moisture content.

Small-scale trials using pots were undertaken at the JBI and onsite using a mixture of different amounts of gypsum and manure to determine the optimum loadings of these components when used with Ewarton residues (see Figure 3). In other trials dry bauxite residue was mixed with different amounts of gypsum and manure, placed at different depths over fresh bauxite residue. Various plant species were grown, and their growth rates and root development were investigated. These trials were undertaken to help assess the depth of tillage that needed to be done as it was accepted that the bauxite residue below a metre would always remain at a high pH, and a very high moisture level. These latter trials showed that irrespective of the species, all roots resisted growing into the wet bauxite residue below the conditioned layer. For the species which normally had tap roots (e.g. Leucaena (*Leucaena leucocephala*)), the roots grew out horizontally when they reached bauxite residue which had not been conditioned or amended.

Using the same plant species used at Kirkvine, a mixture of Leucaena (*Leucaena leucocephala*), castor bean (*Ricinus communis*), Bermuda grass (*Cynodon dactylon*), Guinea grass (*Megathyrsus maximus*) and brachiaria grass (*Brachiaria decumbens*) seeds was added. These treatments were observed weekly for germination and vegetative growth by measuring the number of leaves and height of plant. Leucaena, Bonavista and Bermuda grass exhibited the most vegetative growth. Other species showed less prolific germination and stunted growth.

Figure 3 Small pot trials

The information gathered from the pot trials was used as the starting point for the next phase of trials which involved small-scale plots onsite (Figure 4). These trials further investigated the levels of gypsum plus chicken manure and how the pH changed with time and depth. A small rotavator capable of turning over the soil like media to a depth of 15 cm was used in these trials. Various amendments were evaluated including beer waste, dunder from rum production, citrus waste, microbial bacteria additions. Some modest benefits were seen from these organic amendments evaluated but in view of the difficulty in obtaining large quantities at a reasonable cost of wastes such as dunder and beer waste, the idea of using them for the full-scale project was rejected. Root, leaf and stem specimens were collected from the different plant species planted and analysed for Al, As, Cd, Cr, Cu, Pb, Hg, Mo, Ni, Se, Na and Zn. The levels of the elements of concern were all very low.

(a) (b) (c)

Figure 4 Different experimental plots: (a) EXP4; (b) EXP2; (c) Island plot

In the next phase of trials, large plots were used at different locations onsite (Figure 5). The nature of bauxite residue was different at the different plots reflecting the origin of the mud and varied considerably in pH and texture. The objective of the trials was to determine if over time, pH could be decreased to a low enough level by encouraging atmospheric carbonation through mechanical working. The target we set was a pH < 9.5 prior to gypsum addition. The experimental work showed that the reduction in pH was extremely slow, and even after many months it was difficult get a pH of below 9.9; the initial values were in the range 10.2 to 11.5 in different areas of the site. Consequently, it was decided to move to full-scale conditioning trials using full sized agricultural equipment to obtain information more applicable to field conditions.

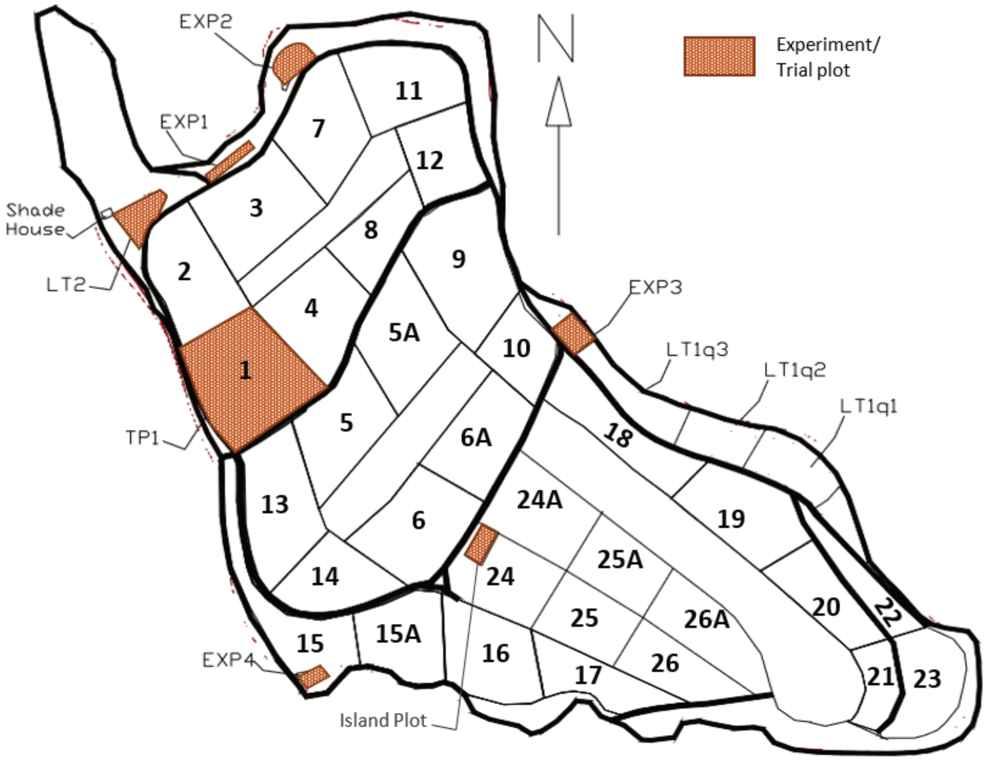

Figure 5 Map showing different plot locations onsite

2.2.4.3 Large-scale conditioning trials

The conditioning aspect of the project was divided into two distinct categories: physical conditioning that involves the use of specialised machinery and chemical conditioning, predominantly gypsum and manure application. Tractors were used to plough the areas to a depth of 40 cm, turning over wet material and exposing it to the elements, see Figure 6. After ploughing, fields were left uninterrupted for two to three days, and this process was repeated multiple times and the pH and CEC values at monthly intervals and at 10 cm increment of depths up to 50 cm measured. Whilst the values fell steadily in some locations, in others there was considerable fluctuation in pH; this was mainly due to rainfall.

Figure 6 Tractor with implement ploughing a field

The initial plan had been to mechanically work the bauxite residue until a pH < 9.5 had been achieved and then add gypsum and plough it in, allow to stabilise for a month, then add the manure and plough again. However, trials showed that earlier gypsum addition, for example when the bauxite residue had decreased to a pH of 10 to 10.5, meant that the target pH of < 9 could be achieved in a much shorter period of time. Using just mechanical working, 70 to 80 passes by a tractor on a 2 to 3 day cycle was needed to achieve a pH of < 9.5 whilst with the addition of gypsum at a rate of 120 t/ha, the number of mechanical workings was reduced to 25–35. A comparison of the cost of the higher amount of gypsum being used against the cost of mechanical working meant that it was more economic for the project to use higher levels of gypsum to achieve the target pH characteristics. This would obviously vary with the site and availability and cost of gypsum; in Jamaica, waste fine gypsum was available from Cemex in Kingston.

The final target values prior to planting were set at pH < 9 after gypsum addition, EC < 1 dS/m, CEC 2–9.5 meq/100 g; moisture 30–50%, bulk density < 1 g/cm^3, porosity 65–72%. As the project progressed, we found the main parameters of importance to be pH and soluble sodium, which were tracked and used to make critical decisions.

Constant mechanical working with heavy duty tractor with specialised implements (see Figure 6), exposed the wet residue to the elements causing moisture loss and carbonation processes to take place. In addition, mechanical activities lead to the breaking up of large chunks of bauxite residue over time and the rain encouraged leaching of sodium. Based on field observation onsite and the monitoring of mechanical activities, improvements in porosity, drainage and aeration were observed over time. The increase in porosity is believed to contribute to better drainage, that further facilitates the removal of soluble sodium from the profile during rain events. Additionally, better aeration also enhances the carbonation process, which can gradually reduce pH levels.

The bauxite residue found on the Mount Rosser site was high in soluble sodium, low in essential plant nutrients and organic matter. Applying chicken manure significantly enhanced the nutrient status of the residue, also microbes and organic acids in the manure were expected to reduce the pH further and improve the soil structure.

2.2.4.4 Weather impact

From the project conception, weather has proven to be one of the most important factors impacting the work. Jamaica has a tropical climate that fluctuates year-round between dry and rainy periods. Figure 7 shows the site after a particularly dry period and after a period of heavy rainfall. The first rainy season of the year could start as early as March and ends in May, whilst the second starts in September and ends in

November. The latter coincides with the peak of the hurricane season. During these periods, rainfall is either spread over the entire season or defined by high intensity periods in close intervals. These rain patterns vary in duration, intensity, and volume, making it very difficult to predict and plan contingency measures. High rainfall causes damage to road infrastructures, submerging, and in extreme cases, killing vegetation, stopping mechanical activities, waterlogging, requiring extra resources like pumps and drain infrastructure, eroding exposed bauxite residue, and resulting in seed loss and damage to irrigation infrastructure. However, heavy rainfall is not all negative as these weather patterns can be viewed as helpful and yield some positives such as washing of muds to remove soluble sodium, provide water for field establishment, triggers growth phase in established fields, and present opportunity to evaluate runoff water quality.

(a) (b)

Figure 7 Site during different climatic events: (a) after a severe period of drought; (b) after heavy rainfall

The season temperature fluctuations at Mount Rosser are relatively small compared to many other regions where alumina plants are located with the average minimum temperature in the cooler months being 28°C and the maximum being 33°C in the hotter months. The combination of sun, humidity and low rainfall presents a unique impact on the project. For example, the dry periods accelerate conditioning works because of less downtime from rain interruption and speeds up drying of bauxite residue thus accelerating the carbonation rate. Variability of rainfall between different years was a challenge as shown by the rainfall between March and May for successive years: in 2018: 455 mm; in 2019: 392 mm; in 2020: 104 mm; in 2021: 257 mm; in 2022: 366 mm (Figure 8). This rainfall data was measured on the site.

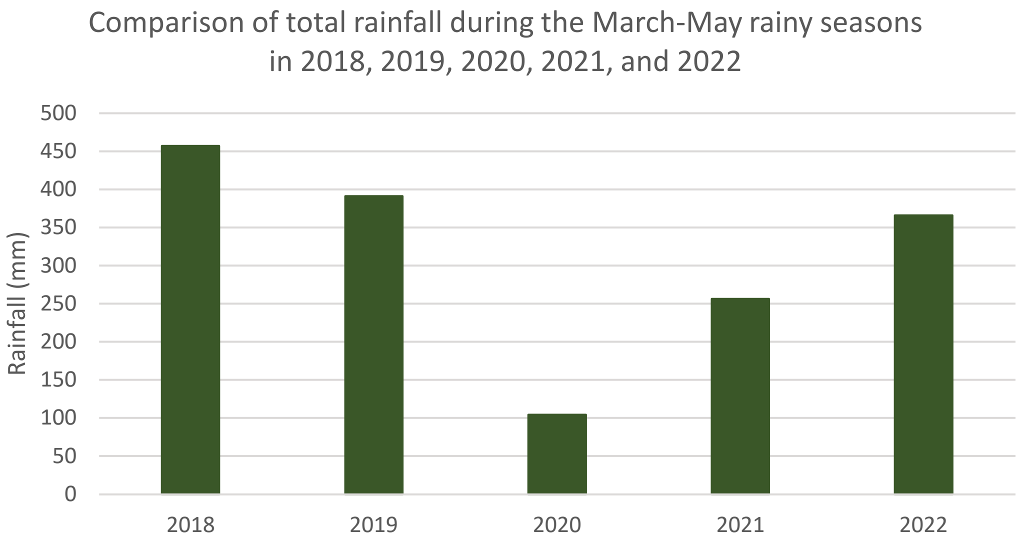

Figure 8 Comparison of rainfall for March to May period for 2018, 2019, 2020, 2021, and 2022

The impact of these dry periods was substantial and resulted in: vegetation dying in older fields, fire hazards, halting planting programmes, difficulty in acquiring sufficient irrigation water, challenges to keep young fields alive and avoiding dust generation. The adoption of drip irrigation was therefore critical, and water was sourced from a well at a nearby factory and transported to site with the aid of water trucks. This water was applied at a rate of about 9,000 L/ha twice weekly.

2.2.4.5 Large-scale planting

Originally the bauxite residue was to be conditioned and seeded using the broadcasting method as had been done at Kirkvine. However, after compiling data from various trials and taking into consideration the unique environment and starting point of the Mount Rosser site, the approach was revised. The target plan based on Kirkvine and Mount Rosser trials was to start planting when the soil characteristics were: pH < 9 after gypsum addition, EC < 1 dS/m, CEC 2–9.5 meq/100 g; moisture 30–50%, bulk density < 1 g/cm^3, porosity 65–72%). A higher amount of gypsum, 120 t/ha, was used than found to be necessary from the small-scale trials at Kirkvine and onsite. A 'generous' amount of chicken manure was also used, 120 t/ha. The gypsum/manure were ploughed into a depth of 40 cm, planting was done on furrows, and combined seeds, nursery plants and vegetative material were used for rapid establishment. Tree species had a 1.2 m × 1.8 m spacing (4,500 plants/ha), while grass was planted at 0.9 m × 1.8 m spacing (6,100 grass roots/ha). The seeding formula used was as following: Leucaena at 15 kg/ha, brachiaria at 31 kg/ha, Guinea grass at 21 kg/ha, castor bean at 4.5 kg/ha, bona vista at 4.5 kg/ha), Bermuda grass at 21 kg/ha. In addition, supplemental irrigation was applied, where necessary during dry periods. The baseline plan proved to be a successful formula, so large-scale plating commenced in 2017 and all major fields completed by 2021. Figure 9 shows part of the site in 2017 and Figures 10 and 11 show the site in 2021.

Figure 9 Trial plot 1 and ponds void of vegetation in 2017

Figure 10 View of pond from the north in 2021

Figure 11 View of pond from the southeast in 2021

Before planting, fields were void of vegetation and four years after planting started, all the major areas were fully vegetated and visually meeting and, in some cases, exceeding the vegetative coverage required. The first attempts at large-scale planting was in TP1, 2 and 3; these were the most crucial areas, as they would indicate if the strategy for revegetation could work on a large-scale.

The strategy worked very effectively, and the site is now covered with lush vegetation that has survived several floods and drought events. In addition, most species have begun flowering and seeding, a good indicator for species continuation.

2.2.4.6 Flood and water logging issues

At an early stage of the planting project, it became apparent that several areas on the site would prove to be difficult to vegetate due to seasonal rainfall and localised water accumulation. Extensive mechanical and chemical soil conditioning in these areas were also expected to be challenging due to prolonged periods of wet soil and loss of nutrients and organic matter. A project was initiated to develop a different planting strategy with species that can survive a combination of poor soil conditions, short periods (less than two weeks) of flooding, and periods of drought during the dry season.

Over 30 species from various wetland areas were carefully selected for trials in flood-prone areas and monitored for survivability and growth. Based on their performance, only five of those species were selected for the final wetland planting strategy including whistling pine (*Casuarina equisetifolia*), seaside mahoe (*Thespesia populnea*), giant reed (*Arundo donax*), para-grass (*Brachiaria mutica*), and saltwater couch (*Paspalum vaginatum*) (see Figure 12).

(a) (b) (c)

Figure 12 Successful flood tolerant plant species: (a) Seaside mahoe; (b) Giant reed; (c) Root development in saltwater couch

During the trials it was found that well established wetland plants were better able to cope with periods of flooding and waterlogging compared to newly planted vegetation. With limited time in between rainy seasons, it became apparent that rapid growth and establishment would give the wetland plants a better chance of survival when exposed to extreme wet conditions. As such, a specific compost was generated to encourage rapid growth, which consisted of grass cuttings, horse manure, goat manure and chicken manure. The compost was applied directly in the hole before transplanting the seedlings; this strategy turned out to be a success: vegetation survived many flood events (see Figure 13) and most areas prone to waterlogging have also successfully been vegetated with mainly with wetland species (see Figure 14).

(a) (b)

Figure 13 Flood-prone area in TP21: (a) Area planted with 'regular' species after a flood event in March 2019; (b) Same area in 2021 showing well established wetland species

(a) (b)

Figure 14 Area prone to waterlogging in NTPX: (a) The area after heavy rainfall event in 2019; (b) Same area in 2020 approximately six weeks after planting

2.2.4.7 Preliminary fauna assessment

The process of extensive soil conditioning and the wide variety of plant species growing on the conditioned bauxite residue has created suitable habitats for many different species of fauna. At this point, limited data is available on species richness on the site though signs indicate rapid colonisation of fauna once areas have been conditioned and vegetated. An interesting observation is the early presence of macro-organisms in the topsoil layer. During a species inventory in one of the small-scale trial plots (Island plot) in 2018, a total of nine ant species with various diet preferences were found just 18 months after planting. Other soil organisms observed at the time include millipedes, woodlice, earwigs, spiders, mites, true bugs, and wasps (genus *Sphex*).

The expansion of vegetated areas over time resulted in a rapid growth in number of animal species. A group of animals that stands out due to their ecological importance are the insect pollinators. Early colonisers on the site include bees, wasps, moths, and butterflies with four species of butterflies observed in the Island plot in 2018. At the end of 2019, when 66% of the site was vegetated, a total of 16 species of butterflies (including two endemics) were observed in vegetated areas.

Another significant ecological development on the site includes the rapid growth of bird diversity. Frequent field observations have resulted in a list of birds that have been spotted in various vegetated fields on the site so far. The list now comprises of 36 different bird species of which seven are endemic, 19 are residents and 10 are migrants. The large variety of bird species can be attributed to the diversity in plant species and habitat types (e.g. forest, grassland, wetland), which create an abundance of food sources, shelter, nest sites, and nest material all year round.

2.2.4.8 Soil and vegetation assessment

As discussed earlier, the site will need to meet certain requirements with regards to potentially harmful concentrations of elements in the soil and established vegetation before it can be handed over to the government. Work is in progress to acquire the necessary data and from the currently available results, looks very promising.

From the small-scale trials, it was apparent that the selected plant species could perform well on the conditioned bauxite waste, however, long-term success was uncertain. In 2018 it was found that many volunteer plant species settled in that area in some of the experimental plots. A total of nine plant species were used for that experiment, but during a species inventory 18 months after planting, a total of 33 species were identified. A plant database is being established with recordings of all plant species observed throughout the vegetation process.

Long-term survival and growth is particularly important when assessing the introduced species, in particularly the tree species as they are planted for the long-term. Limited data is available at this point as this is an ongoing project, however, measurements taken of trees in field TP1 in 2018 reveal a massive growth within a span of one and a half years. This field was the first large field (>0.4 ha) that was planted on the site (in 2017) with the main introduced tree species being Leucaena and calliandra (seedlings with a height of <50 cm at time of planting). Approximately 18 months after planting, the average height measured 2 m (±0.7) and 3.1 m (±1.1) respectively (see Figure 15). This data is based on measurements of 78 leuceana trees and 16 calliandra trees.

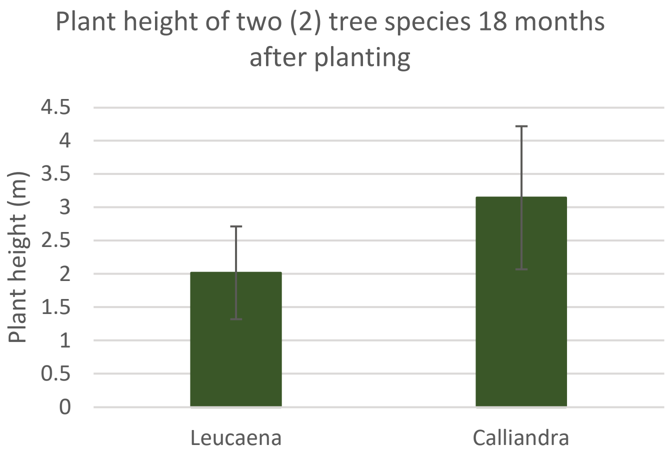

Figure 15 Plant height of Leucaena and calliandra trees in TP1 approximately 18 months after planting ±SD

Root development also gives an insight into long-term survival and growth. Observations from uprooted trees reveal that the root system develops quickly, however it seems that the roots stay within the conditioned soil layer (<40 cm). Roots in most cases will start to grow down from the base and after 10–15 cm they make a 90° turn and start grow horizontally, even though there have been exceptions (e.g. poinciana and seaside mahoe) where roots have been found to grow beyond the 40 cm layer. In the long-term, the horizontal growth of the root system could result into compromised tree height and increased chances of falling over at an early stage due to inadequate anchoring (Figure 16). Conditioning at a deeper level could improve this and various agricultural equipment was tried, including a spader which was capable of achieving a depth of 60 cm, but the amount of work to achieve a 60 cm layer of soil media at the required targets was deemed to be very high. It is, however, expected that leaf litter and fallen trees will increase the biomass over time and expand the fertile soil layer.

Figure 16 Person inspecting root development

An interesting observation within various plant on the site, is the natural occurrence symbiotic relationships between plant roots and fungi (mycorrhizae) and nitrogen-fixing bacteria (root nodules). Without manual inoculation, many species show signs of such relationships to increase their chance of success in the conditioned fields (Figure 17).

Figure 17 Root nodules observed on roots

Plant survival and growth form two critical components that are required to be successful on the conditioned bauxite residue. However, for long-term sustainable vegetation, the ability to reproduce becomes another important factor where older vegetation can be replaced by young ones over time.

The most obvious signs that have been observed on the site with regards to this, are indications of sexual reproduction. The majority of plant species that have been recorded on the site have been observed to produce flowers and seeds (Figure 18).

(a) (b) (c)

Figure 18 Various flowers and seeds from vegetation onsite: (a) Leucaena (*Leucaena leucocephala*); (b) Whistling pine (*Casuarina equisetifolia*); (c) Brachiaria grass (*Brachiaria decumbens*)

Viability of seeds produced by plants on the site remains to be investigated, however recent observations of newly emerged tree seedlings in older fields confirm that certain species do produce viable seeds after which germination occurs. Various successful plant species on the site also show signs of asexual reproduction, such as saltwater couch, giant reed, para-grass, and African star grass.

Each field on the site has unique characteristics, which influences the performance of the vegetation. This has resulted in a very diverse environment where different species thrive in different locations on the site. There is a long list of very successful species, both introduced and volunteer species, however a few stand out based on their growth performance and adaptability. Poinciana (*Delonix regia*), seaside mahoe (*Thespesia populnea*), and African star grass (*Cynodon plectostachyus*) are three plant species that have demonstrated rapid growth, extraordinary resilience to high soil pH and sodium levels, are very drought tolerant, flood tolerant (poinciana to a lesser extend), and show early signs of reproduction.

3 Discussion

The traditional approach for closure and remediation of closed bauxite residue areas has been capping, either with a membrane to prevent water ingress, an engineered cap sometimes with drainage system incorporated into the upper most layers, or a combination of the above (Avery et al. 2022; Evans 2016). The challenge in the Jamaican situations at Kirkvine and Mount Rosser was paucity of topsoil or indeed any soil that could be used to sustain a vegetative cap. High quality agricultural land is at a premium in Jamaica and using topsoil for capping landfills was regarded as an unacceptable approach. The experimental trials, and then work at Kirkvine, have shown that given the right climatic conditions, conditioning of the dried bauxite residue with intensive mechanical working to encourage carbonation, the use of adequate addition levels of gypsum, the incorporation of chicken manure, and careful selection of plants for the conditions can give an excellent vegetative cover in reasonable time. The use of hardened off seedlings under nursery conditions and planting of fields during rainy periods or under supplemental irrigation proved to be key to ensuring success. These simple steps along with good conditioning approach, methods of lowering pH, and sodium, combined with nutrient and enrichment process condition result in a best practice for vegetating bauxite residue sites The vegetative cover at Kirkvine has now flourished for over ten years and needs no intervention; the early indications at Mount Rosser are that a similar sustainable vegetative cover will be achieved. To the authors' knowledge, this is believed to be the first time that large areas of bauxite residue have been remediated in this manner.

The key lessons from the work have been: establishing a partnership between the company and the regulators so that each understands the others' objectives and challenges; early engagement with all stakeholders to understand their expectations and concerns and, critically, to listen with an open mind to others ideas; agreeing to target objectives and required standards as early as possible in the process even if these may need some modifications as time progresses; the importance of learning from trials; holding regular discussions with all stakeholders to ensure that emerging issues are identified and remedial steps can be taken; the importance of doing what you say you're going to do, on time reports; the value of workshops to resolve critical decisions; the use of Value Risk Management tool to review possible ongoing issues; and despite all the planning and risk assessments – expect the unexpected.

4 Conclusion

The work undertaken at Mount Rosser and Kirkvine in Jamaica demonstrates how abandoned, ponded bauxite residue areas can be safely and effectively closed and remediated. The phases were: dewatering, reprofiling, soil conditioning and vegetation. In the case of Mount Rosser, some 5.5 million m^3 of overlying high pH water was discharged, approximately 300,000 m^3 of high moisture mud was moved, and the 37 ha site is being vegetated without the use of topsoil to a state which it is believed will be diverse and sustainable prior to return to government ownership at agreed conditions.

Key aspects to success were:

- Establishing a partnership between the company and the regulators so that each understands the others' objectives and challenges.
- Early engagement with all stakeholders to understand their expectations and concerns and, critically, to listen with an open mind to all ideas.
- Agreeing to target objectives and required standards as early as possible in the process even if these may need some modifications as time progresses.
- Extensive vegetation trials were undertaken onsite and demonstrated the importance of learning from experimental work under the specific field conditions found.
- Extensive soil working to encourage carbonation and improvement in highly alkaline bauxite residue were essential in order to establish a medium with the characteristics that with suitable amendments could sustain vegetation. Flexibility in amending initial soil characteristics targets in order to meet the desired results were essential.
- Soil amendment levels and addition times were determined from onsite trials to provide a growing medium that would enable the identified plants to thrive without the need for a topsoil capping.
- Plant species were identified that would survive in the climatic conditions onsite, including droughts, exposure to highly intensive rainfall events and short-term flooding.

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