Bauxite Residue Disposal Area Rehabilitation

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Abstract

The Rusal Aughinish Alumina (AAL) refinery is located on Aughinish Island, on the southern shore of the Shannon Estuary 33 kilometres west of Limerick city in the South West of Ireland. The plant, which commenced operation in 1983, is currently producing 1.965Mt/yr. It sources bauxite predominantly from Guinea, Brazil and Guyana and uses the Bayer process to produce Alumina. The refinery functions with an accredited Safety Management System (ISRS), Environmental Management system (ISO14001), Quality Management System (ISO9001) and Energy Management system (ISO50001). The bauxite residues generated from the Bayer process are deposited in an engineered facility called the Bauxite Residue Disposal Area (BRDA). The operation of the BRDA is one of the key enablers to execute the BRDA closure plan. Partial neutralisation of the mud by atmospheric carbonation through mud farming produces a mud with pH<11.5 which is suitable for remediation and revegetation. The preferred land-use option post closure, based on current knowledge of the chemistry and biology of the sown grassland cover, is to develop the area for nature conservation. This paper outlines the field studies, which have demonstrated that bauxite residue can be successfully rehabilitated.

Keywords: Alumina refinery, BRDA, bauxite residue, rehabilitation.

1. Introduction

Rusal Aughinish Alumina (AAL) refinery is located on Aughinish Island, on the southern shore of the Shannon Estuary 33 kilometres west of Limerick city in the South West of Ireland. The plant, which commenced operation in 1983, has a current production capability of 1.965Mt/yr. It sources bauxite predominantly from Guinea, Brazil and Guyana and uses the Bayer process to produce Alumina.

Green alumina has a key role to play in creating green aluminium. The production of green alumina at AAL is key to the environmental sustainability of the refinery. This sustainability is multi-faceted and includes bauxite residue disposal management, continuous monitoring to ensure there is no impact on the local environment and minimisation of CO_2 emissions [3].

This paper outlines the approaches taken by Aughinish to achieve revegetation and support ecosystem development on bauxite residue. The refinery at Askeaton, Co. Limerick currently produces approximately 1.37 Mt of bauxite residue per annum, which is stored in a Bauxite Residue Disposal area (BRDA) of 183 ha.

Rehabilitation involves amendment with a carbonation process to neutralise the pH, following this, gypsum and residue sand is effective in improving physico-chemical properties and promoting seedling establishment and growth. Application of compost is used to overcome the nutrient deficiencies of the residue [1]. Years of research in conjunction with the University of Limerick have established with this combined approach, several grassland species have successfully grown on the residue enabling the primary restoration goal to be achieved [1]

Conditions issued by the Environmental Protection Agency (EPA) outlined in the Industrial Emissions License (IE) stipulate that a closure scenario be enacted on a dedicated section of the BRDA to demonstrate that developed methodologies are adequate to successfully achieve closure. For the past 20 years AAL have a successful monitoring programme in place to demonstrate the success of the vegetation cover system. The establishment of a sustaining vegetation cover is the preferred method for post-closure management of the residue storage area to rehabilitate the residue, improve its aesthetic impact and develop an area for nature conservation

Since 1996 in conjunction with the University of Limerick, AAL have conducted a series of revegetation trials on the residue both at laboratory and field level to develop a revegetation programme and a revegetation recipe for the management of residue in the BRDA.

2. Residue Processing at AAL

The residue is dewatered by vacuum filtration to a solids concentration of 58 % before being slightly diluted and transported, by a 2km pipeline, to the BRDA where it is discharged, spread and allowed to consolidate and dry in layers. Two-metre high rockfill embankments form a stable boundary to stack the layers and increase the BRDA in height.

2.1. Atmospheric Carbonation

There are several stages to post deposition treatment. As mentioned after vacuum filtration, the residue is diluted with water, sheared, thinned in an agitated tank and then pumped as a 58 % solids paste to the BRDA. In this state, the deposited residue cannot yet be traversed by conventional machinery and first must be dewatered and compacted. An amphibious vehicle called an Amphirol is employed to carry out this de-watering and compaction process known as farming.

The Amphirol travels using scrolls, to allow the vehicle to move through the residue. As the Amphirol travels, it compresses the residue and creates tracks or furrows. These furrows allow the water, which has been "squeezed" from the residue to drain along the sloping stack towards the perimeter wall of the cell and into the perimeter channel.

Once the residue has compacted to > 70 % solids by multiple passes of the amphirol, the surface is then graded by a bulldozer to level the surface and generate a constant gradient from the discharge (high point) to the perimeter wall (low point). This makes the residue suitable for conventional agricultural machinery to travel and operate on its surface. Atmospheric carbonation of the residue by the amphirol and agricultural machinery allows for exposure of the residue to CO_2 in the air. Sufficient exposure and carbonation reduces the causticity below 30% and reduces the residue pH below 11.5. This is the mechanism by which the residue is exposed to atmospheric CO_2. Once carbonation is completed as evidenced by pH measurements of samples from the cell, the area is then re-graded using a bulldozer to remove any depressions. The cell is then ready for the subsequent layer of bauxite residue.

3. Legislation

Although earlier planning permissions granted to the refinery contain requirements with respect to landscaping and restoration of the BRDA, the Integrated Pollution Prevention Control Licence (IPPCL) introduced in 2008 issued by the EPA contained many stringent conditions for BRDA restoration and aftercare. Since its issue in 2008, the licence has been updated in 2012 and most recently in 2014 to the Industrial Emissions License (IE P0035-06). Over the years, the major change has been the introduction of partial neutralisation of the residue surface by farming which is a well-established practice at AAL.

Conditions stipulated in the IE issued to Aughinish state that revegetation work be continued on the BRDA and findings reported in the Annual Environmental Report (AER) and sustainability issues of the revegetation system be determined (Condition 8.4.20). Provision of a dedicated research trial cell for demonstration of the proposed closure technique for the residue is a licence condition (Condition 8.4.22).

Figure 1. Farming with Amphirol.

4. Rehabilitation History at AAL

Rusal Aughinish in collaboration with the University of Limerick in 1996 implemented a series of revegetation trials on the BRDA to develop a restoration technique that can be established on the residue and to demonstrate the effectiveness and sustainability of the closure technique. The sequence of trials will now be discussed; an overview of the trial locations is shown in Figure 2.

Figure 2. Overview of BRDA and Area where trials have been carried out.

Table 1. Legend.

Reference in Paper	Description
Section 4.1	Early trail plots 1996 - 2007
Section 4.2	Larger trails 2007 - 2011
Section 4.3	First cell trial plot 2008/2009
Section 4.4	Terraced area rehab and grassing 2015
Section 4.5	New demonstration cell
Section 6	Side slope rehabilitation 2013

4.1. Early Revegetation Trials 1996 - 2007

The BRDA is designed using an upstream system using 2m high rock embankments. The rock lifts are terraced in an upstream fashion to increase the height of the BRDA and manage the disposal of residue. Consequently, available space for the initial revegetation work was restricted to terraced areas between the raises (see Figure 2). The restoration strategy adopted on the BRDA was to seed temperate grassland species on amended residue with a view to establishing amenity type grassland that is sustainable. A series of revegetated areas were implemented on these terraced areas during 1996-2007 as outlined below.

Table 2. Experiment History.

Year	1996 - 1999	1997-1999	2000-2005	2006	2007
Experiment type	Laboratory characterisation and Greenhouse trials on bauxite residue and amended bauxite residue.	Field experiment testing effect of amendments on residue properties and Plant uptake in revegetated residue	Continued field experiments testing efficiency of revegetation methods employed in 1997 - 1999.	Field experiments investigating variations of the procedure to optimise conditions for preparing residue prior to seeding	Larger scale field experiments on a 0.6 ha site demonstrating revegetation prescription is effective on residue typical of a closure scenario

Different scenarios were experimented with during the early trials. Plots were fully treated amended with gypsum, process sand, spent mushroom compost and seeded with a grassland mix. Partially treated plots were amended only with process sand, spent mushroom compost and then seeded. Other plots were left untreated [3].

The revegetation recipe now used at AAL is based on the success of these trials. Residue that was treated and revegetated between 1996 and 1999 was surveyed in 2005. Species diversity was recorded and compared to the initial seed mixture of 6 species [1].

- There were 50 species belonging to 40 genera and 16 families.
- Asteraceae and Poaceae were the dominant families.
- Seven leguminous species were recorded growing.
- Dominant grass species were Holcus lanatus with Festuca rubra and Agrostis stolonifera.
- Woody species Betula, Salix and Alnus established on the revegetated areas.
- Patches of hay, spread on residue surface acted as a seed source [1].

The trials also have demonstrated that addition of process sand and gypsum is effective in lowering uptake of Na, Al and Fe in plants [1].

A detailed investigation of the trial area was also carried out in 2015 in collaboration with the University of Hull and Leeds, the findings of these tests are discussed in section 5 below.

Figure 3. Early small plot trials experimenting different amendments.

4.2. Large Scale Field Trial Implementation 2007 -2011

Previous field trial work conducted on the bauxite residue at Aughinish focused on small level ($2m^2$) plots. A series of large-scale trials were implemented in 2007 to develop practices for residue amendment and seedbed preparation at large-scale level. Findings from this work shows that the key stages in the revegetation programme can be achieved at a large-scale level. These include the ability for the residue to support movement of traffic [2].

A range of grassland species can be used in the seeding once the inhibitory properties of the residue are overcome and a seedbed with adequate nutrients and organic matter is established [2].

Due to the success of the trials and experiments onsite methodologies for optimising plant establishment on the bauxite residue are now well developed:

- Addition of process sand to improve texture and structure of the residue substrate, gypsum for reducing pH and exchangeable sodium (ESP) and organic matter for nutrients are essential components of the revegetation prescription.
- Several indigenous species are capable of growing in amended bauxite residue.
- Effective amendment of the residue results in lower plant content of Na, Fe and Al
- Nutrient cycling in the residue is seen a critical parameter to demonstrate that the vegetation cover is self-sustaining cover. [2]

Lack of organic matter and nutrient deficiency is recognised as a limiting factor in establishing vegetation on any soil including residue. Incorporation of organic matter into the rooting medium is a critical component of the revegetation prescription [2].

Figure 4. Selection of species growing on revegetated residue.

4.3. First Cell Trial Revegetation of Residue

A large-scale (0.6 ha) dedicated research trial cell was constructed in 2008 to test rehabilitating unfarmed residue. The lined cell was filled with fresh bauxite residue and underwent amendment as per the developed restoration technique (i.e. process sand, gypsum, organic matter, and organic matter). Revegetation was undertaken in September 2009, the amended area was seeded with species that had previously been trialled at small plot and large plot scale.

Key research areas within this trial area were:

- Vegetation establishment, survival and succession.
- Vegetation productivity, sustained growth and structure development.
- Fauna colonisation and habitat development.
- Ecosystem processes such as soil development and nutrient cycling.
- Colonisation of specific fauna groups that are involved in these processes.
- Microbiological studies e.g. colonisation by mycorrhizal fungi and microbial biomass [1].

The cell area is sampled bi-annually to monitor the emerging plant/residue soil system and assess functioning ability of the system. It is proposed that this system can be proven sustainable / self-regulating [1].

Based on results and observations from residue research field trials the surface residue (0-15 cm) pH and exchangeable sodium (ESP) indicates improvement in residue properties following amendment, seeding and subsequent soil development. [1]

As previously found, amendment procedures resulted in sufficient macro nutrient supply and there was no evidence of excessive uptake of elements associated with bauxite residue (e.g. aluminium or sodium). Courtney [1] states that:

"Decline is herbage N content observed in the third year is typical of restored sites receiving no further nutrient inputs and is sufficient for the grass sward cover. Other restored residue areas on the BRDA that are 18+ years old exhibit similar N content. Decline in herbage Na content in the third year has also been previously recorded on restored residue sites and is indicative of further improvement of the residue as a soil medium."

Figure 5. Cell five months after seeding.

Figure 6. Cell 10 months after seeding.

Figure 7. Soil Profile of amended and seeded residue after 3 years in trial cell.

4.4. Grassing of Terraced Area on BRDA

As part of a continuous improvement program a new area of the BRDA was rehabilitated in conjunction with Enrich Environmental Ltd. The area chosen was approximately 30m wide at an elevated location on the BRDA stack, in total 4 hectares of residue were seeded. Since its seeding, the area has been continually monitoring for grass growth (See Figure 3).

The aims of the work undertaken in 2015 were:

1. To establish grass on the wide terreaced area of the BRDA; and
2. Monitoring and maintaining the grass.

Analysis was undertaken in 2015 to characterise the bauxite residue. From the results of the characterisation, an inclusion rate of customised organic matter along with an incorporation depth and application method was devised. The organic matter provision was to provide the nutrients for grass establishment.

In 2015 the following was conducted:

- Addition of gypsum to the surface 3%
- Customised organic matter was incorporated at a rate of 30% and sown with the following nine salt tolerant grass species:
    - Creeping Bent
    - Common Bent
    - Crested Dog's Tail
    - Sheep's Fescue
    - Red Fescue
    - Perennial Rye grass
    - Salt Marsh Grass
    - Red Clover
    - White Clover [4]

A drainage plan was designed and a management plan for the established grass area was implemented. This involved mowing the grass 2-3 times during the year to return the nutrients to the ground. The ground was aerated as required.

Nine salt tolerant grass species were sown and grew well, the grass continues to thrive and currently presents a green belt along the north and west of the BRDA perimeter. This result shows that it is possible to establish grass on the BRDA. Aeration is required to ensure that the activate root zone remains aerated, due to compaction a hard pan can develop resulting in restricted movement of the roots limiting the plants access to vital nutrients [4].

Figure 8. Steps in rehabilitation and revegetation of deposited residue in terraced area.

Figure 9. Terraced area demonstrating healthy grass growth.

4.5. Rehabilitation of Farmed Residue

During 2017 AAL are constructing a new closure demonstration area which complies with condition 8.4.21 of the IE P0035-06 [8]. This condition states that;

"*The final lm of all exposed red muds deposited in the BRDA shall comprise 'amended mud'. This 'amended' layer shall include a proven composite of neutralized process residues, sand, gypsum and organic material. The amendment layer shall be underlain by a capillary break layer of process sands or equivalent approved. AAL shall continue to operate a dedicated trial research area for closure/revegetation research. Annual progress reports on research findings, and operational decisions flowing therefrom, shall be reported as part of the Annual Environmental Report*."

The cell is currently in the construction phase and when completed it will demonstrate the use of a capillary break and an amended layer for vegetation. The function of the capillary break is to prevent liquid or seepage from the residue making its way to the surface through capillary action. There will be two test areas formed within the cell to monitor the effectiveness of different types of capillary breaks (capillary break with crushed limestone material and neutralized process Sand).

The amended layer will be constructed from carbonated residue, neutralised process sand 25%, gypsum 3% and organic material 20%; the trial area will also be used to test the effectiveness of the amended layer without gypsum.

Once constructed this cell will reflect a typical closure scenario of the BRDA. To demonstrate its sustainability and comply with the license conditions it will be intensively monitored.

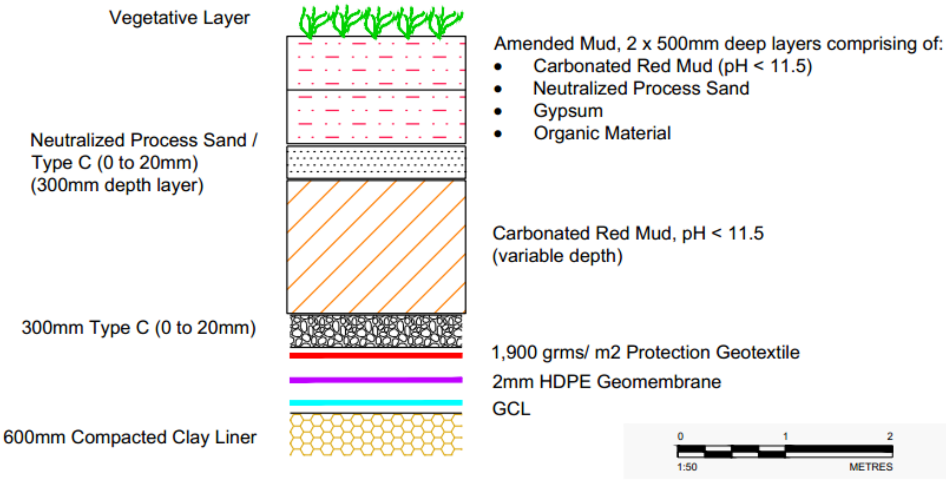

Figure 10. Section through new closure demonstration cell.

5. Sustainability of Remediated Bauxite Residue

In September 2015 in collaboration with the University of Hull and Leeds, trial pits were dug at 5cm intervals to a depth of 50 cm in the revegetated plots seeded in 1999 on the BRDA, sampling was undertaken 20 years after deposition and 16 years after treatment. Three plots within the BRDA were investigated. The fully treated plot which was amended with gypsum (3% w/w rotavated-in to a depth 30 cm), process sand (10% w/w rotavated-in to a depth of 30cm), spent mushroom compost (80t Ha^{-1} rotavated-in to a depth of 20cm), and seeded with a grassland mix (100 kg/ha) [3]. The partially treated plot which was amended only with process sand, spent mushroom compost, and then seeded. The third plot was left untreated. Samples of bauxite residue were collected to a depth of 50 cm from the trial pits in each of three different treatment zones [3].

5.1. Sampling Observations

Both the fully treated and partially treated sites were vegetated with a variety of perennial grasses (Holcus lanatus), trifoliate clovers (Trifolium pratense), and occasional small shrubs. The untreated plot was largely unvegetated with one or two areas of stunted grasses. The root zone of the fully treated and partially treated sites extended approximately 15 cm beneath the surface, and below 20cm the substrate had the appearance of dewatered bauxite residue with little change in appearance to 50 cm depth. The untreated profile had no root zone and at all depths had a very similar appearance to the residue in the other profiles at depths below 20 cm [3].

The pH of the treated plots was notably lower. The plots exhibited a decrease of 2.5 pH units at a given depth, compared to the untreated plot, giving the surface zone of the treated plots pH <8. The treated plots also displayed a 3 – 4 fold decrease in aqueous available sodium at all depths. Treatment also decreased the overall availability of trace metals Al, V, and Cr to 50 cm, compared to the untreated plot. These tests proved that the positive effects of treatment extend well beyond the 20 cm deep treatment zone, and are evident by the lush vegetation growing on the surface [3].

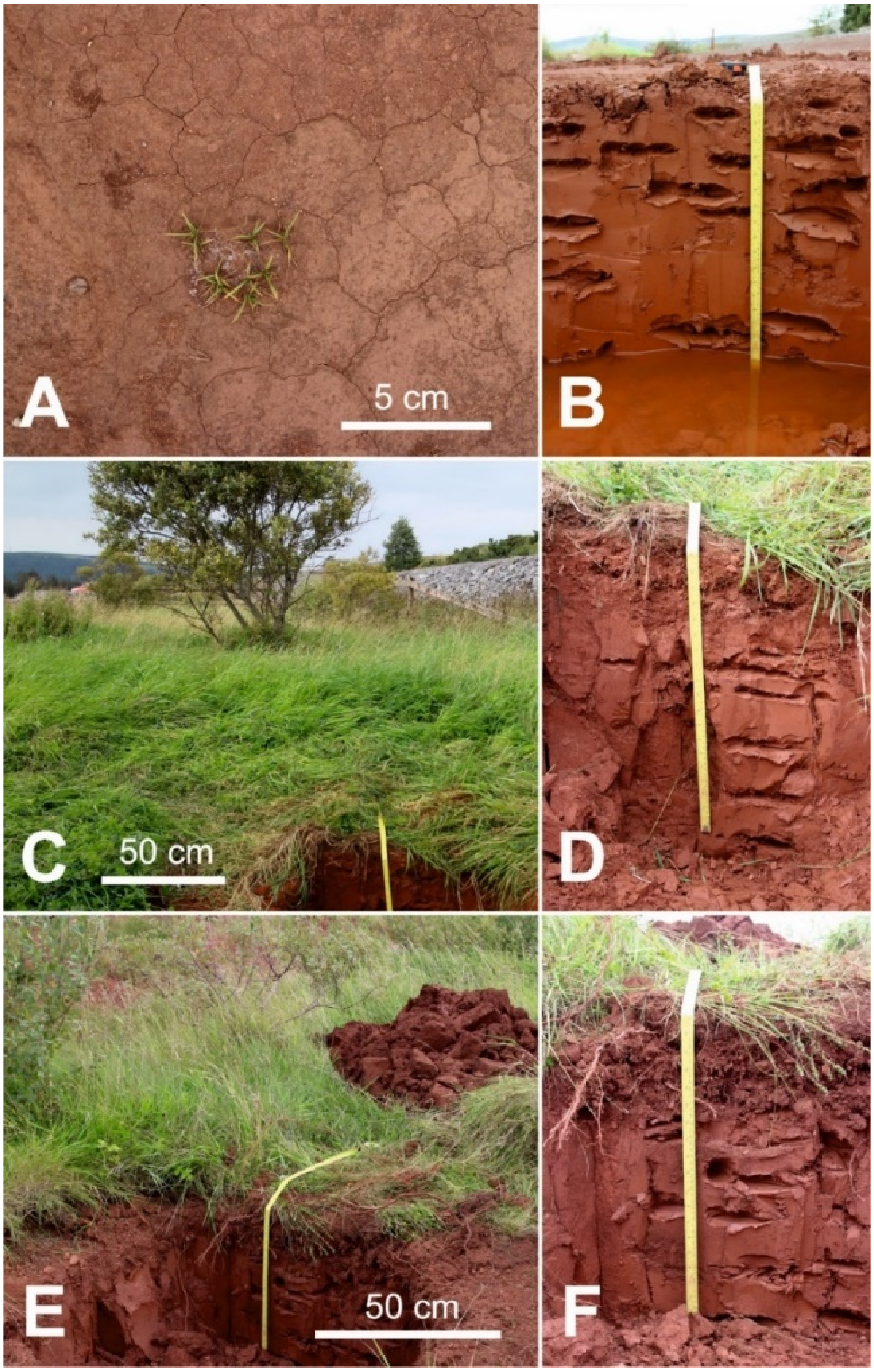

Figure 11. Slices taken through trial plots.

Untreated bauxite residue 20 years after deposition (A, B); bauxite residue 16 years after full treatment with gypsum, organic matter, and process sand (C, D); and bauxite residue 16 years after partial treatment with organic matter and process sand (E, F). The tape measure in B, D, and F measures 50 cm depth in each trial pit [3].

6. Side Slope Rehabilitation

A side slope rehabilitation programme of the BRDA was undertaken in 2013 to improve drainage and visual impact of the area (see Figure 2 overview). The objective was to establish a relatively dense green vegative cover and to establish a dispersed and relatively low-level scrub style planting. The planting has a random and naturalistic appearance when viewed from areas surrounding the structure. The total area for revegetation was 36,870m² in which over 4,000 trees and scrubs of varying species were planted. Many plant species have also naturally developed on the side slopes of the BRDA improving the naturalistic appearance. Side slope rehabilitation differs from dome rehabilitation, as the residue is not directly amended. A layer of drainage stone is first placed on the residue surface followed by subsoil and top soil. Brady Shipman Martin Ltd in conjunction with Golder Associates Ltd designed the drainage and landscaping system. AAL have a proactive landscaping program that targets the appearance of the BRDA and each year invest heavily on planting to improve the visual impact.

Figure 12. Side slope rehabilitation.

7. Final Land Use

The long-term sustainable land-use of the BRDA is the goal for the rehabilitated facility. In deciding the most suitable end use for the BRDA, it has been determined that activities which may lead to over-grazing, poaching, cultivation, uprooting of trees by wind-blow and other surface disturbance will be avoided. The preferred land-use option, based on current knowledge of the chemistry and biology of the sown grassland cover, is to develop the area for nature conservation [5].

AAL operates in a rural, agricultural area bordering areas of special conservation. A section of AAL land to the north of the BRDA has already been developed as a Bird Sanctuary and there are also butterfly and dragonfly sanctuaries on site. Areas to the east of the BRDA are used as nature trails for walking and jogging. The relationship of Aughinish with the local community is paramount to having a Social License to Operate. The final development of a nature conservation area is in keeping with AAL's relationship with its local community [5].

Figure 13. Evidence of thriving ecosystem on revegetated residue (trial 2007 -2011).

8. Conclusion

The establishment of a sustained vegetation cover is the preferred method for post-closure management of the residue storage area to improve its aesthetic impact. Effective BRDA residue farming is the key enabler to achieve this.

Establishment of vegetation on the bauxite residue stored at the BRDA has been successfully demonstrated by laboratory, greenhouse and field trial studies undertaken by AAL, University of Limerick and the University of Hull and Leeds. To achieve this, amendment of the residue is required and an understanding of the basic physical and chemical principles for reclaiming alkaline residues has been established.

The underlying principles of remediation are:

- Creation of drainage channels to assist in drying of the residue
- Partial neutralisation by farming of the bauxite residue to reduce pH
- Application of process sand to improve texture and structure of the residue substrate
- Amendment with gypsum ($CaSO_4$) to replace entrained sodium with calcium
- Addition of nutrients (compost)
- Seeding with native grass and cultivar species.

Field trials have demonstrated that re-vegetation can be achieved through a process of physical and chemical amendment of the residue. A number of treatments were implemented to investigate performance levels of vegetation growing directly on the surface of the residue. Optimum performance was produced by physically amending the substrate with process sand and gypsum.

Previously revegetated residue areas were surveyed after 6 and 8 years. Species diversity was recorded and compared to the initial seed mixture of 6 species. The survey showed significant increase in biodiversity and that there were 50 species belonging to 40 genera and 16 families and indicates that colonisation by further species occurs on areas once vegetation is established [1].

The extracted DNA concentrations from treated bauxite residue are within the range of extracted DNA concentrations from natural soils, treated bauxite residue has been shown to contain diverse soil-like bacterial communities [3].

At a portion of the financial cost of a traditional cap and cover remediation, these treatments provide a cost effective and viable solution to BDRA closure and residue rehabilitation.

In conclusion, research has shown that vegetation can be successfully grown on bauxite residue, giving a sustainable vegetation cover come closure. AAL have been and continue to be proactive in researching suitable capping methods and demonstrating its success. Strict licensing conditions coupled with ongoing research will ensure an environmentally viable capping method at Aughinish. The overall environmental footprint at AAL ensures that there is no impact on the environment and the community.

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