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# A case study for rock clad non-topsoiled native woodland rehabilitation in Central Queensland

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## Abstract

*For many years, conventional rehabilitation of spoil on Central Queensland coal mines involved dozing slopes down to 10–15%, applying up to 300 mm of topsoil, fertilising, and sowing predominantly grass species for an eventual grazing post mining land use (PMLU). Monitoring indicates that this method is often not successful in achieving a grazing outcome, mainly due to erosional instability of the sandy loam topsoils in a climate dominated by summer storms.*

*Progressive rehabilitation and closure plans (PRCPs), recently introduced in Queensland, require mine operators to comply with a quantitative schedule for rehabilitation, based on measurable milestones. The transition to PRCPs has led to consideration of woodland habitat as an alternative PMLU. Woodland habitat has the potential advantage of not requiring the same level of inputs, including high-quality topsoil, as an agricultural PMLU. While rehabilitation to woodland habitat has been undertaken sporadically in the past, the details of design and performance were not captured in a way that enables accepted good practice to be established.*

*An area of native woodland was established on rock clad problematic bucket wheel excavator (BWE) spoil as part of set of trials in the early 1990s. The area has gradients ranging from 23% to 40% and was rehabilitated without constructed erosion controls, without topsoil, and with a single aerial application of seed. Monitoring has shown a sustainable mix of grasses, shrubs and trees for many years. This case study describes key elements about materials, construction techniques and seeding, gleaned from historical reports and from observations. These may provide a template for a rehabilitation methodology applicable to areas constrained by steeper slopes or limited topsoil.*

**Keywords:** *Coal mine rehabilitation, rock cladding, rock armouring, native woodland, post-mining land use*

## 1 Introduction

Mine sites are required to fully rehabilitate all areas of land disturbance caused by their activities. In Queensland, resource activities are licensed under the *Environmental Protection Act 1994* (EP Act) (Government of Queensland 1994) via an Environmental Authority (EA). Conditions prescribed in EAs require coal mine operators to complete progressive and final rehabilitation over the life of resource projects. The *Mineral and Energy Resources (Financial Provisioning) Act 2018* (MERFP Act) (Government of Queensland 2018) amended the EP Act, and the *Environmental Protection (Rehabilitation Reform) Amendment Regulation 2019* (Government of Queensland 2019) implements key elements of the Queensland Government's mined land rehabilitation policy. Specifically, mining proponents are required to prepare a progressive rehabilitation and closure plan (PRCP) for each mine site. The PRCP will:

- identify the post-mining land use (PMLU) and the non-use management areas (NUMA)
- identify the successive milestones to achieve the PMLU

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- identify when each milestone will be achieved
- identify the completion criteria for each milestone.

The predominant pre-mining land use in Central Queensland is cattle grazing and reinstating this land use is currently considered the highest practicable outcome for most rehabilitation. The technique to establish grazing on mine waste rock dumps is well established and usually involves dozing the waste down to 10–15% gradient, applying stockpiled topsoil to 150–300 mm depth, fertilising, amending (typically with gypsum), seeding and where possible applying organic material (Figure 1). The difficulties of this method are the general deficit of topsoil on mine sites, the Central Queensland summer storm rainfall cutting rill network in the freshly ripped surface, fertiliser (especially nitrogen) attracting weeds (note *Parthenium* in the lower right of Figure 1), longer-term nutrient and pasture decline, and the risk cattle pose in the longer term to erosional stability.

**Figure 1 Example of topsoil application on dozed spoil with a plot established the previous year evident in the foreground**

As a result there is increasing consideration given to the restoration of woodland habitat. Trying to establish native species into fertiliser topsoil has been difficult as the aggressive Buffel grass outcompetes the natives via self-seeding or the seed bank already contained in the topsoil stockpiles. This has led the interest in native woodland PMLU teamed with a rock clad cover. This combination has the following advantages:

- The rehabilitation design does not rely on scarce topsoil.
- The cover can potentially be constructed from site waste materials, specifically rock.
- The rock cover provides a competitive advantage for native species and is not infested with Buffel grass.
- The rocky cover is erosionally stable and provides landform design option advantages such as steeper batter gradients and avoiding the reliance on maintenance-dependent engineering structures such as cross banks and spine drains.
- It removes the long-term risk posed by cattle grazing.

This paper highlights an example of a native woodland on a rock clad cover derived from site waste materials. The area is over 20 years old, did not use topsoil, was self-sustaining, displayed no signs of erosion and did not use engineered structures. The information used is from internal archived company reports as well as more recent observations and is presented here to illustrate potential alternative design methods for mine site closure in Central Queensland.

# 2 Background

The study site is a metallurgical coal mine located in the Bowen Basin of Central Queensland, near the town of Moranbah (Figure 2).

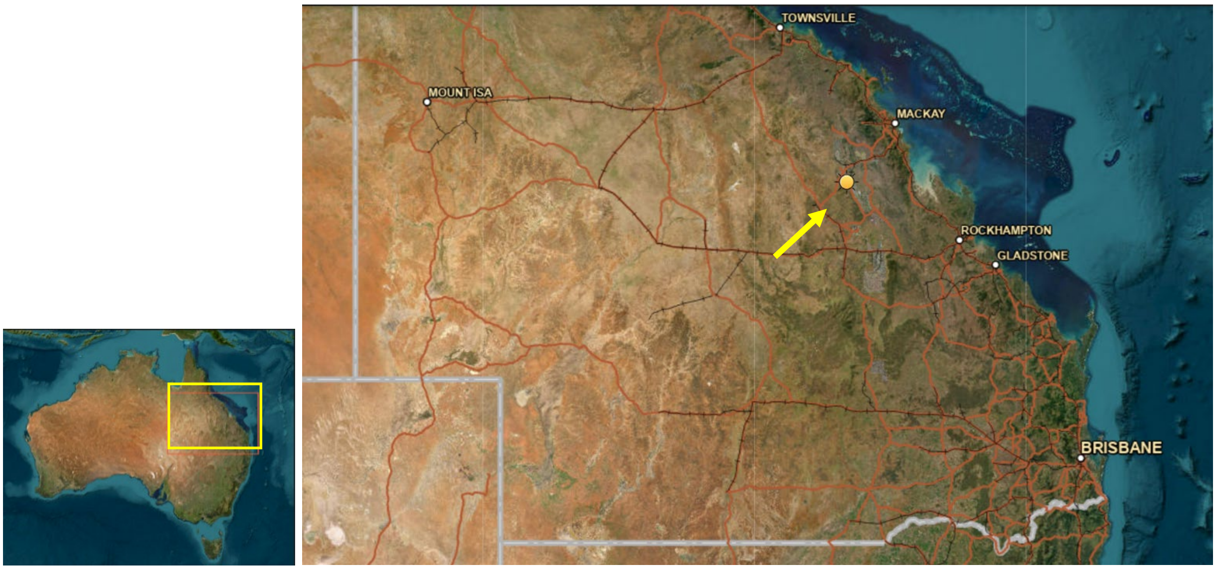



**Figure 2 Approximate location of the coking coal mine site in Central Queensland, Australia**

The site is typical of coking coal operations in Central Queensland; it has been in operation for several decades and is targeting coal seams within the terrestrial Moranbah Coal Measures. The coal measures consist of sandstones, siltstones, mudstones, claystones and coal, and extend to a depth of over 300 m beneath the surface. The mine site is situated on plains of flat land to gently undulating rises (typically <3% gradient). These flat areas are associated with areas of unconsolidated sediments of fine-grained texture, while the surrounding elevated landscapes are associated with more-resistant lithologies, such as volcanic rocks or coarse-grained sedimentary formations. The region experiences hot summers and cool winters, with rainfall dominated by summer storms. A distinct wet season occurs from November to April with an overall annual rainfall of approximately 600 mm. Storm intensities of 50 mm in 30 minutes are considered typical (Emmerton et al. 2017). The area's annual pan evaporation rate exceeds 2,000 mm (BOM 2003).

# 3 Bucket wheel excavator rehabilitation trial area

The area was initially a spoil dump created by a bucket wheel excavator (BWE) and formed from mixed Permian rocks and Tertiary spoils of unconsolidated clays and sands. Construction of this dump began in late 1982 and spoil was placed over unstripped ground. Unlike conventional truck and shovel construction, the BWE homogenises the spoil to a greater extent. The dumping conveyor belt moves in arcs, placing the spoil in lifts to the desired height, with the outer facing batter at the angle of repose. This construction technique created an area oriented in a north–south direction approximately 5.7 km long. Batter heights were between 50 and 100 m and the total area (including surface treatments) was approximately 330 ha. Placement of spoil in this area ceased around 1986. Before the end of construction in 1985, it was observed that large erosion gullies had initiated and there was ponding in many parts of the dump.

Consequently, a decision was made to conduct batter stabilisation trials using a range of techniques and landforms.

As best as can be ascertained, the treatments moving from north to south were as follows:

- rock clad† concave with no topsoil, sown with eucalypts and acacias
- rock clad concave with no topsoil, sown with *Leucaena* only
- single lineal slope with topsoil and jute netting, hand-sown with grasses
- single lineal slope with topsoil and (bizarrely) a fibreglass spray mesh, hand-sown with grasses
- batter/berm configuration of topsoil over Tertiary with a spine drain, sown with grasses
- batter/berm configuration of no topsoil with a spine drain, sown with grasses directly into the Tertiary waste
- batter/berm configuration of topsoil over Tertiary with no spine drain, sown with grasses.

Of interest was some trials of surface treatments of the plateau tops. One method was the bunding of a section of the dump top into 25 cells aimed at creating a water retention and evaporation area analogous to a gilgai landform (Figure 3). Some piping was reported from these pond areas.

As mentioned, the BWE mixed the waste but inspections show the material to generally not be rocky and resemble the finer Tertiary wastes. Sampling at the time showed the waste to be made up of 30–60% clay. It has very low to absent phosphorus, nitrogen, sulphur and potassium, with a high pH. The spoil had moderate cation exchange capacity (CEC) but this was dominated by sodium making it highly dispersive (Siebert et al. 1992). Another information source citing a drilling program for a geotechnical investigation for the planning of the rehabilitation trials reported mean values as 8.6 pH, electrical conductivity (EC) of 1.6 dS/m, CEC of 17.9 meq % and 30% exchangeable sodium percentage (ESP). The material was summed up as saline, strongly sodic and strongly alkaline (Henderson Geotech 1999). In short, the materials requiring rehabilitation were problematic, which is also the case today.

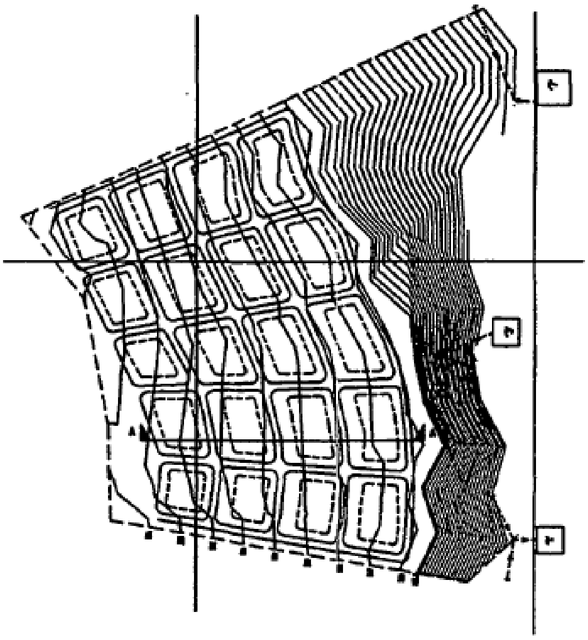


**Figure 3 Design of a section of dump top where bunding is used to create retention ponds to stop water flows over the batter. Note the toe of slope typical of conveyor belt swing placement (Siebert et al. 1992)**

† Rock cladding in this context is the same as rock armouring and consists of a cover at least 0.5 m deep. Rock mulching here means the spreading of rock, but the depth is only as deep as the largest rock clast.

# 4 Rock clad rehabilitation area

The focus of this paper is the northernmost rock clad rehabilitation area (RCRA). The batter section is approximately 350 m in horizontal length and 99 m in height. The overall batter gradient is 28%, but there is a slope break in the design. The lower slope segment is 23% from the toe to a height of approximately 57 m, whereas the upper slope segment becomes steeper to 40% and 42 m elevation (Figure 4).

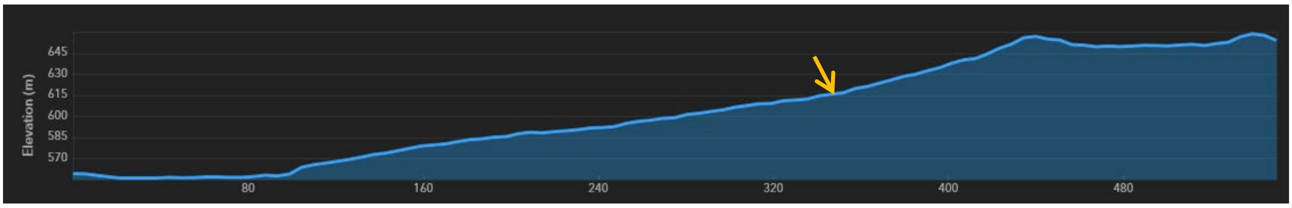



**Figure 4 Elevation profile of the rock clad rehabilitation area. Slope break indicated by arrow, and the dump top shows a cross-section of one of the retention ponds**

The cladding material was sourced from site and the best material from the Moranbah Coal Measures is a competent sandstone. It is reported that this area was sheeted in a blocky sandstone cover nominally 1 m deep. After sheeting, the material had a surface roughness (or microrelief) added. This consisted of a dozer blading the material to create something similar to a moonscaped surface. A moonscaped surface typically has a herringbone pattern where one peak is offset and downslope from the previous. Long-serving mine personnel familiar with the project refer to the pattern on the RCRA as 'backstacking'. The means that the dozer pushes the material down the slope perpendicular to the contour until a near-full blade is collected. The dozer then retreats up the hill and repeats the process. This creates a very rough surface as shown in Figure 5. Whether intentional or not, the pattern of the backstacking is closely aligned to the contour, creating a continuous series of contour banks down the slope.

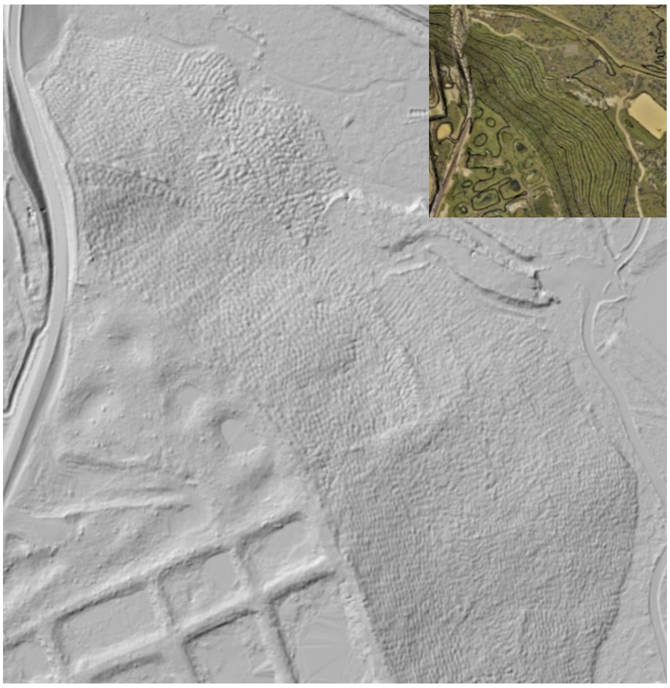


**Figure 5 Hillshade image of the northern rock clad rehabilitation area showing the backstacked surface microrelief and inset; aerial image with 2 m contour lines. Note the retention pond treatments on the dump top**

After sheeting and surface roughening, the RCRA was sown via a helicopter with a focus on eucalypt and acacia species, again noting no topsoil was used. In a 1997 vegetation survey, it was reported that *Acacia salicina, Acacia stenophylla, Atriplex nummularia* and *Atriplex vesicaria* were present but at the time no eucalypt species had emerged. These 1997 inspections also concluded that the vegetation establishment has been below average due to below average rainfall in the area since establishment and even analogue sites were also generally degraded. Despite this, the RCRA had the highest species diversity compared to all other treatments. Estimations of erosion rates stated the rock cladding had results of 44.5 t/ha/yr for the period 1993–1994, and 89 t/ha/yr for the 1995–1997 period (Henderson Geotech 1999).


(a) (b)

**Figure 6 Vegetation monitoring of the rock clad rehabilitation area from (a) 2005; (b) 2007. Note the rough, backstacked surface of the sandstone rock cover**

A 2007 vegetation survey of the area provides an update of the conditions of the RCRA. Ground vegetation cover was assessed at ~40% and this was dominated by Buffel grass. Other species observed were Annual Saltbush, Butterfly pea, Rhodes grass, Sabi grass, Seca stylo and Soft Roly Poly. No erosion was observed as the rock cover was providing the stability. The ecological function analysis scores were stable between 2005 to 2007, ants were observed and the area was judged to be meeting the standard for nutrient cycling with the presence of a litter layer, mycorrhizae and/or other microsymbionts (HGV 2007). Images from the report show the rough, backstacked surface of the sandstone rock cover (Figure 6).

# 5 Current observations

During inspections in 2023 it was observed that most of the area had a good coverage of vegetation (Figure 7); however, the ground cover was dominated by Buffel grass which is endemic to the region and is a widely acknowledged problem in the region. The entire slope was not exhibiting any visible signs of erosion and this was being achieved without the use of any formal engineering structures such as spine drains or contour banks. Figure 7a shows the slope break between the lower 23% gradient and the steeper (40%) upper section.

(a) (b)

**Figure 7 (a) Rock clad rehabilitation area looking up the slope with gradient change (arrow); (b) Profile view**

A more recent rehabilitation monitoring report assessed 2 established locations (Site 6 and Site 36) on the RCRA (Figure 8) against a cattle grazing end land use. The report stated that in fact there was a moderate amount of species diversity at Site 6 (11 total) and good amounts present at Site 36 (15 total), but again there was a dominance of Buffel grass that was retarding greater diversity. The vegetative ground cover percentage was higher at Site 6 (80%) and 47% at Site 36.

The spoil condition at Site 6 was rated a good as the surface pH, EC and sodicity were within limits. Site 36 reported strongly alkaline spoil, with EC and sodicity increasing with depth. Erosion at Site 6 was good, with minimal erosion evident due to the ground cover, while Site 36 had local erosion with soil loss from the mound tops and deposition into the furrows (Figure 8).

(a) (b)

**Figure 8 Rock clad rehabilitation area showing vegetation cover of Buffel grass and acacias and soil loss from mound tops. (a) Site 6; (b) Site 36**

A summary of the 2 monitoring sites of surface soil (0–10 cm) and subsoil (~30 cm) is shown in Table 1 (Eco Logical 2018). The results highlight the problematic nature of the spoil material being alkaline, saline and sodic, especially at Site 36. Site 36 was graded lower in the spoil category for this reason, and fair for vegetation and erosion as there is local spoil movement from the mound tops causing material movement and bare patches in the largely Buffel grass ground cover.

**Table 1 Rock clad rehabilitation area – physical and chemical results from rehabilitation monitoring**

| Property | Site 6 | | Site 36 | |
|---|---|---|---|---|
| | Surface soil | Subsoil | Surface soil | Subsoil |
| Soil and spoil | Good | | Poor | |
| Erosion | Good | | Fair | |
| Vegetation | Fair | | Fair | |
| pH | 8 | 8.7 | 8.8 | 9.6 |
| EC (µS/cm) | 101 | 88 | 253 | 967 |
| Emmerson class | 4 | 4 | 3 | 1 |
| Texture | Loamy sand | Sandy clay | Sandy clay | Sandy clay |
| Fines <75 µm (%) | 30 | 40 | 71 | 64 |
| Sand >75 µm (%) | 64 | 58 | 23 | 27 |
| Gravel>2 mm (%) | 6 | 2 | 6 | 9 |
| Organic C (%) | 0.8 | – | 0.73 | – |
| CEC | 7.4 | 7.3 | 8 | 15.6 |
| ESP | <0.2 | <0.2 | 10.9 | 49.2 |

# 6 Hypothesis for success of the rock clad rehabilitation area

When the RCRA is assessed in a conventional way for a cattle grazing end land use and the standard of Hazelton & Murphy (2007) is used for spoil quality, it generally does not achieve these completion criteria. The aim of a grazing end land use completion criteria is to have growth media with no rocks, neutral pH, low salinity, low sodicity, good levels of plant nutrients, organic matter and CEC, with a slope gradient no greater than 12% to control erosion with good surface cover (Grigg et al. 2001).

It is the authors' opinion that when viewed through another lens, the RCRA can be viewed as safe, stable, non-polluting and stable if the end goal is not for a grazing end land use but as a woodland favouring native species. Evaluating the success of such areas requires a move from a traditional agricultural/Hazelton and Murphy view to a silvicultural/ecological engineering perspective. Being able to construct the RCRA at gradients above 12% also offers many advantages to production in terms of increased waste storage, but this is not covered in this paper. The following will outline the reasons for the success of the RCRA and this is based on observations, inspections, previous reports and published literature.

## 6.1 Erosion-resistant rock cover

The relationship between increased proportion of rock fragments in the cover and the reduction in erosion rate is well established (e.g. Avala & Jordan 2010). Simply put, a 100 mm rock clast is more resistant to moving down the slope by fluvial processes than a 2 mm sand grain. This is exacerbated in the Bowen Basin as the topsoil that is stripped and preserved for application on the rehabilitation areas for seeding and grazing is derived from unconsolidated sediment of an alluvial/colluvial origin, making them susceptible to erosion when placed on slopes over 3–5% gradient (Emmerton et al. 2017).

The conventional view is that erosion can be controlled by establishing a vegetation cover and managing how water is moved off the slope. Even when these soils are used in conjunction with conventional engineering controls of cross banks reporting to rock lined spine drains, the result is still rill network development after the first wet season. This is mainly due to the planted seed requiring natural rainfall from February to April to grow, but this rainfall typically comes in the form of summer storms which cause erosion before the ground cover can develop (Emmerton 2018) as shown in Figure 9.

**Figure 9 Recent topsoiled grazing PMLU with cross banks and spine drains after a single wet season**

In comparison of multiple historical mine rehabilitation and analogue sites, the data showed that rock clad areas were virtually indistinguishable from undisturbed stable analogue sites in terms of gully erosion (Emmerton 2018) (Figure 10). An inspection report of all the different treatments of the BWE rehabilitation trial area noted that 'rock armouring on batters is the most effective measure for reducing erosion damage and providing sites for establishment of diverse vegetation species. Durability of the armour boulders is not critical, as along as the material remains coarse and granular' (Henderson Geotech 1999).

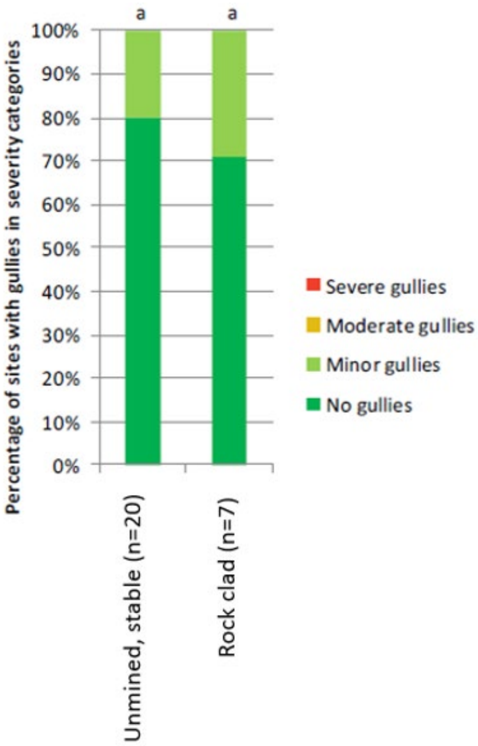



**Figure 10 Comparison of unmined/stable analogue sites in comparison to rock clad rehabilitation sites for gully erosion type and severity**

## 6.2 Water-concentrating versus water-dispersing design

The RCRA design does not direct water flows along cross banks or into drains and dams. The example in Figure 9 shows the failure of the fertilised, amended, and seeded topsoil areas between the cross banks. The RCRA erosional performance can be highlighted by a comparison with an inspection report to other trial areas that followed conventional design of cross banks and spine drains. The inspection was conducted due to storm damage to the rock lined drainage system. This east-facing rehabilitation area was a relatively new area that had been constructed in response to a previous 'catastrophic' failure of a similar cross bank and rock drain in the same area in 2007 (Restricted 2010). The drains were lined with high-quality quarried basalt estimated $D_{50}$ to be on average around 300 mm, underlined with a geotextile to protect the underlying spoil from water ingress. The most recent failure event caused the scour of the rock armouring material as well as the tearing of the geotextile (Figure 11). The duration of the rainfall event was approximately 3 hours, with peak intensities of 30–42 mm/h depending on the weather station (Restricted 2010). Note that the RCRA is approximately 1 km from this site and that a water-concentrating design brings other problems; a water-dispersing design like the RCRA therefore warrants further investigation. This is in line with previous observations that contour banks will concentrate flows and over time will overtop and lead to the formation of gullies (Hancock & Willgoose 2021).

(a)

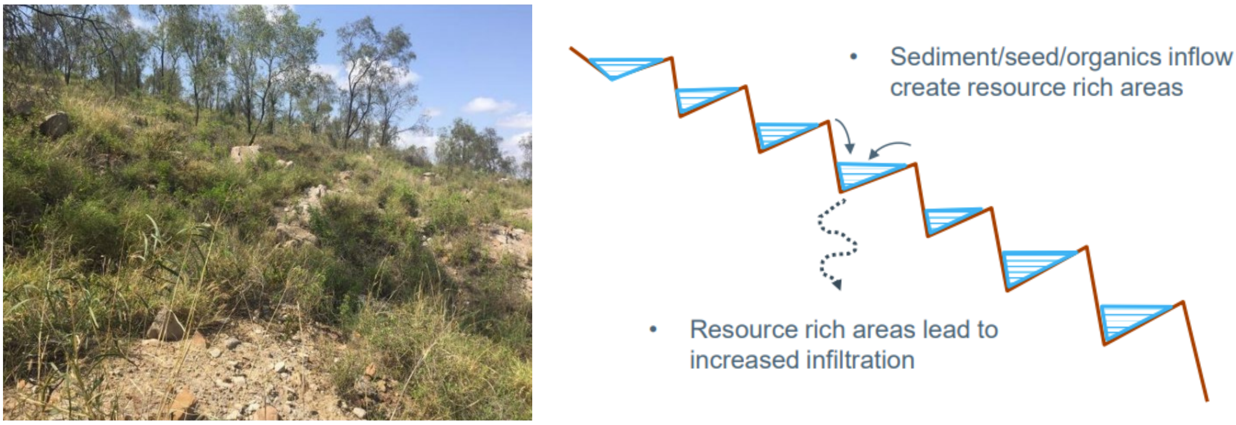
(b)

**Figure 11 (a) Erosion failure of a rock lined drain; (b) Detail of the scour (hardhat shows rock scale)**

## 6.3 Surface roughness (microrelief)

Following on from the above point (Section 6.2), it is further speculated that erosion resistance is additionally increased with the very rough surface treatment (also known as microrelief). The backstacking construction method has created something similar to moonscaping but rather than a herringbone pattern the arrangement is mostly in rows along the contour. Recent rehabilitation work frequently shows that in the final step of cross ripping the slope, the rip lines quickly fill with water during a rainfall event and then overtop into the next rip line and begin to form rill networks down the slope (Figure 12). The current surface of the RCRA shows an approximately 500 mm difference between the mound peak and the adjacent furrow, typically more. This leads to a very large on-slope storage capacity for any rainfall event. Unlike moonscaping where flows can travel downslope in a zigzag pattern, backstacking retains this water in place. There was no evidence from this area of furrows filling and overtopping onto lower slope areas (Figure 13).

**Figure 12 Cross ripped rehabilitation slope where the rip lines have failed to stop erosion and rills formed down the slope after a single rainfall event**

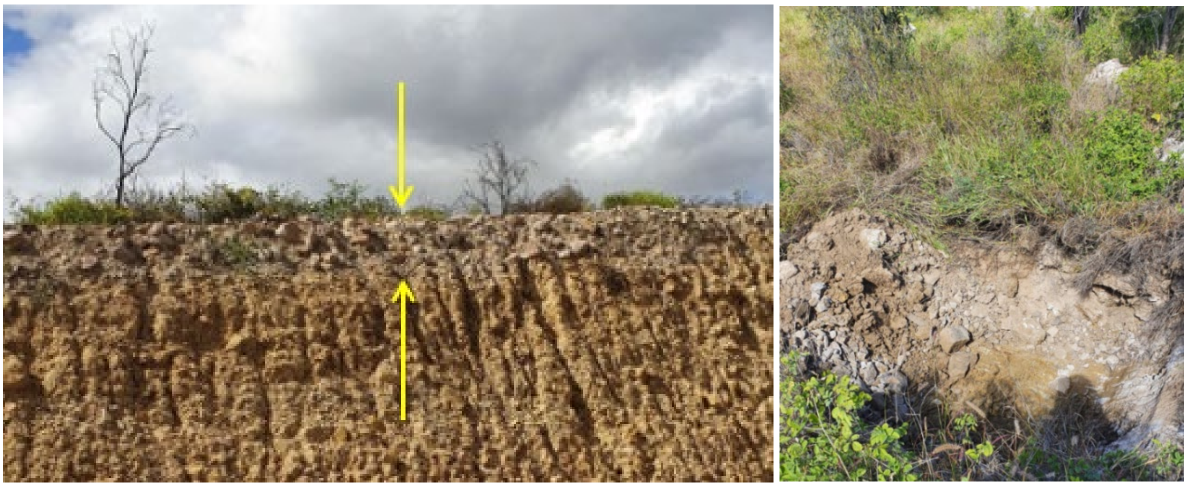



(a) (b)

**Figure 13 (a) Close-up of the 25% backstacked surface showing roughness; (b)Conceptual diagram of on-slope water storage**

## 6.4 Cover depth and infiltration characteristics

It is speculated above that the very rough surface of the RCRA stores rainfall on slope. As the underlying spoil is quite sodic, there is an absence of tunnel or piping failure in the area. It is further speculated that another reason for the area's success is the depth of the cover. That is to say, the infiltration characteristics of the cover (along with the water use by plant evapotranspiration) serve to keep the underlying spoil effectively dry. Parts of the RCRA will be mined through, and access tracks have exposed sections of the rock cladding over the spoil (Figure 14a). An opportunity arose to dig some test pits within the RCRA; an example is shown in Figure 14b. The depth of cover in this test pit was approximately 800 mm and the shallowest cover encountered was 400 mm in furrow areas. The combination of cover depth, size of rock, type of rock, grading of rock, and water use by the vegetation prevents the clay-rich, sodic spoil from subsurface drainage.



(a) (b)

**Figure 14 (a) Road cutting showing the rock clad surface (arrows) over spoil; (b) Close-up of a test pit showing the clay-rich underlying spoil on the test pit floor**

## 6.5 Particle size effect

The sodic nature of many of the Bowen Basin soils and spoils is typically addressed by the application of gypsum in the range of 5–20 t/ha. As the gypsum takes time to move into the surface material and displace the sodium cation, the problem of surface sealing occurs on recently topsoiled rehabilitation; this increases surface runoff, increasing erosion. The use of rock cladding from site waste material means the particle size distribution is typically fine sand and coarser. One <2 mm soil sample showed that sand made up 64% of the surface soil and 58% of the subsoil. Long-term rehabilitation monitoring has shown that even for sodic and saline rock clad material, over the long term (where leaching rates could be determined) these levels in the rooting zone reduced over time (Emmerton 2018). The effects of sodicity are confined to clay (hard setting) and silt (piping) so that even spoils with high levels of sodicity and/or salinity as measured on the <2 mm fraction can improve without intervention over time. This effect is shown in the rehabilitation results in Table 1.

## 6.6 Vegetation interactions

Primarily, the rock clad cover provides an erosion-resistant surface over very problematic waste. This is in direct comparison with nearby areas that used conventional high-quality rock lined drains with geotextile and cross banks that failed on multiple occasions. The rock cladding also provides other advantages in terms of supporting native plant communities sustainably.

### *6.6.1 Competitive advantage for native species*

The conventional approach to topsoiled grazing PMLU areas is to fertilise – typically with nitrogen and phosphorus. While this might result in a good seed strike in the first year, longer-term observations of these areas shows that this creates favourable conditions for the highly aggressive Buffel grass and then weeds. This has been observed elsewhere in Central Queensland (Erskine & Fletcher 2013; Emmerton 2018).

The RCRA was sown with native species (by helicopter) into the rocky surface without topsoil. There is some dispute regarding whether the seed mix included Buffel grass. The low fertility status of the rock cover would favour better-adapted native species and potentially teamed with an autumn planting instead of spring, this would provide better conditions for native species establishment. This concept was demonstrated at the University of Queensland in a hothouse trial over 3 months where site waste rock and other waste materials were used as growth media. The plants were cultured in these 3 media blends for 30 days without the use of fertiliser or other soil amendments and watered every 1–3 days depending on weather conditions. Salt and drought-tolerant Rhodes grass (*Chloris gayana*) was chosen as a test species. The best result was Mix 2, which consisted of 30% sandstone waste, 40% coal rejects, 20% coal tailings and 10% hay mulch (Figure 15). Viewed from an agricultural perspective, these would normally be regarded as very hostile materials for use as growth media (Roddy et al. 2024). This suggests improved techniques for native species establishment using pioneer species and/or other waste types to create a novel native ecosystem to outcompete Buffel grass.

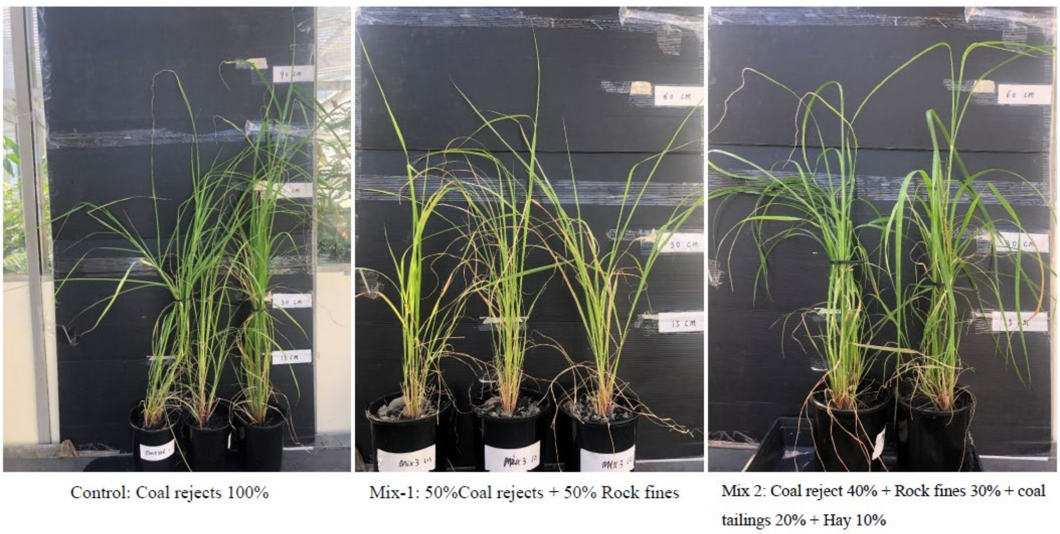



**Figure 15 Preliminary test of Rhodes grass growth in growth media engineered from coal rejects and fines and fragments of sedimentary rocks**

### *6.6.2 Weeds*

It has been observed that the first seed strike on fertilised topsoil promotes the invasion of Buffel grass and weeds in subsequent years. Buffel grass is currently declared a weed of national significance in South Australia and the Northern Territory (Landscape Board of South Australia 2025). Other weeds observed to quickly establish in fertilised topsoil grazing rehabilitation are *Parthenium* and *Leucaena* (Figure 16). In contrast, the neighbouring councils list both weeds in their biosecurity plans (CHRC 2022). The unintentional consequence of standard rehabilitation practices is to encourage weeds within the mine lease that are banned outside the lease. It is also worth noting that in Figure 16a, the *Leucaena* areas show up as dark green. The *Leucaena* is rapidly colonising pasture grass areas (indicated by arrows) but not areas of established woodland (orange line).

(a) (b)

**Figure 16 (a) Example of *Parthenium* infestation on 2-year-old topsoil/fertilised rehabilitation; (b) *Leucaena* colonisation of grassland (arrows). Established woodland area indicated with orange line**

### *6.6.3 Heterogeneity of rock clad surface*

As shown in Figures 5–8 and Figure 13, the RCRA has a high degree of surface roughness consisting of a mound and furrow arrangement due the backstacking construction technique. This has inadvertently created zones of resource loss and gain. The furrow tops are areas of sediment loss and some of these areas are active today. This was one of the reasons the RCRA was given an overall lower score during the rehabilitation monitoring inspection (Table 1). As a consequence the surface roughness also creates areas of resource gain where finer material accumulates along with other windblown sediment, seed and water flows. This has been observed by other authors as shown in Figure 17 where for uniform waste material there is no self-seeded vegetation on the flat-dozed area, but grass has begun to colonise the furrow areas of the paddock-dumped spoil areas (Salfate et al. 2024). The civil engineering approach to mine site rehabilitation tends to create homogenous surfaces as opposed to the usual variability seen in nature. This variability can then be exploited by native species that have adapted to surviving in tough substrates through mechanisms such as root zone weathering for mineral alteration to unlock nutrients (e.g. Wu et al. 2021).

**Figure 17 Western Australian waste dump with no vegetation development in the flat-dozed background, but grass recruitment in the heterogenous paddock-dumped foreground area**

#### *6.6.4 Long-term sustainability/low maintenance*

The engineering approach to mine site rehabilitation tends to focus on the construction phase being achieved typically within one financial year for the nominated hectare targets in the design plans. It is unusual to see immediate follow-up activities such as weed control or top dressing with fertiliser. Most maintenance tends to be erosion repair within the first 5 years post construction.

The RCRA is a good case study as it was constructed and seeded over 25 years ago and is a non-eroding surface not reliant on engineering structures with a self-sustaining vegetated surface of native species (albeit with a ground cover of exotic Buffel grass). Further research is planned to learn the lessons of the self-sustaining element of the vegetation to better understand and design a native novel ecosystem on new rock clad rehabilitation areas.

Some of the factors that contribute to the sustainability of the RCRA are best illustrated by contrast with fertilised topsoil grazing rehabilitation:

- Pasture decline – there has been some focus on a number of commonly sown grass species in Central Queensland cattle grazing pastures (and mine site rehabilitation) that are at risk of dieback. Some of these species are Buffel grass, Sabi grass, Rhodes grass, Panic and Creeping blue grass (Applied Horticultural Research 2019). The RCRA does not depend on these exotic grasses.
- Nutrient decline – it is acknowledged that a grazing PMLU will require supplemental nutrient additions either through fertiliser top dressing or the sowing and maintenance of legume species in the pasture, which is typical of Central Queensland cattle grazing. Either way, previous monitoring has shown that grazing pasture is more fragile than rock clad native woodland areas due to this nutrient decline and these areas will take longer to recover from perturbation such as drought, fire, over-grazing (Emmerton 2018).
- Fire – a study by McKenna et al. (2017) compared mine site rehabilitation with undisturbed native woodland. In terms of fuel loads, rehabilitation dominated by Buffel grass was 9.3 t/ha compared to 5.3 t/ha for woodland and 2.25–3.63 t/ha for native Mitchell grassland. This led to a fire intensity of 1,977 ± 804 kW/m$^2$ for woodland compared to 4,612 ± 502 kW/m$^2$ for mine site Buffel grass. The authors acknowledged that Buffel grass mine site rehabilitation represented a substantial fire risk to both site and the surrounding areas.

# 7 Conclusion

Observation, previous reporting and other published sources identify that the RCRA is performing well to achieve safe, stable, non-polluting and sustainable goals based on a rock clad cover supporting native woodland. While this is the conclusion of this paper, other authors have also come to this conclusion. Emmerton's (2018) thesis based on decades of mine site rehabilitation monitoring concluded that 'extended slope lengths and steeper slopes than those which naturally occur on those material types (i.e. 3–5%) will need… rock cover to maintain an acceptable level of surface stability'. A paper for Mine Closure Conference by Williams (2022) identified that dozing spoil down to 10–15% to control erosion was a flawed rationale.

He concluded that:

- Natural slopes are concave and do not have contour banks or downslope drains.
- Dozing down spoil (or 'mine slope flattening') to control erosion actually increases the catchment and smooths the surface and increases runoff.
- Topsoil placement significantly increases erosion.
- Vegetation alone will be insufficient to control erosion in a dry climate.
- A rocky surface is required on mine slopes for erosion control.

The current rehabilitation practice of 15% gradient fertilised topsoil for cattle grazing pasture seems to focus on the PMLU as the ultimate goal rather than first assessing the limiting conditions of available materials, climate, etc. Some previous mine site rehabilitation researchers took an alternative view that the initial objective should be to create a landscape that is stable against erosive forces and remains stable regardless of the PMLU. Most of the erosion failure of topsoil pasture is before the additional stress of cattle is applied. The creation of this stable landscape (and the plants that will grow in it) can be achieved by selective material handling (Hannan & Bell 1986).

# 8 Further work

The RCRA and other rehabilitation trial areas on the BWE spoil will be mined through in approximately 5 years' time. To capture the many valuable learnings from the RCRA, the following areas of further work are proposed:

- Identify the site-won rock used in the cover, including a robust testing method of identification of other useful site rock types for use in a cover system.
- Assess the rock size, grading, particle size distribution, cover depth and any other elements contributing to the erosional stability of the cover.
- Identify the native species growing in the RCRA leading to a consideration of other species and techniques that could be used for better novel ecosystem outcomes, especially ground cover to outcompete Buffel grass (e.g. pioneer species, organic additions, root depth, planting schedules, sequencing, etc.).
- Synthesise the above points for the understanding of the infiltration characteristics of the cover (including plant water use) to ensure the underlying spoil remains dry in a summer storm dominated 600 mm rainfall pattern and a ~1.5 m pan evaporation regime.
- Identify all aspects of erosional stability, including surface microrelief, infiltration and overland flows, with the potential to model these elements to support future rehabilitation planning and design.

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