GEOCHEMICAL AND GEOTECHNICAL INVESTIGATIONS AT THE REDDALE COAL MINE, REEFTON, NEW ZEALAND

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ABSTRACT

The Reddale Coal Mine, operated by Solid Energy (NZ) Ltd, commenced operations in early 2012. Acid-base accounting (ABA) techniques indicated the site would produce acid mine drainage (AMD) immediately after mining commenced and a treatment plant was constructed to manage the forecast acid loads. AMD had not occurred even after the removal of 494,000 tonnes of overburden. However, there is evidence to suggest that significant pyrite oxidation is occurring, and that it is possible with time that the site may generate low pH drainage waters. If this occurs it is likely that passive treatment technologies could be employed to treat the low flows derived from the engineered landform (ELF) basal landform.

ABA techniques indicated there will be a time lag to the onset of acid mine drainage, in line with other sites having a small, yet significant, amount of CaCO\textsubscript{3}. In addition to the inherent acid neutralisation capacity (ANC) present in the overburden, 15 mm (19 kg CaCO\textsubscript{3}/m\textsuperscript{2}) of aglime (AP < 2.5 mm CaCO\textsubscript{3}) was applied to each 4 m lift of the Ferndale ELF. The benefits of this layering approach were tested using trial pads at site. Results demonstrated a significant reduction in acid load when a limestone layer was present (43.5 g CaCO\textsubscript{3} eq. /m\textsuperscript{2}) compared to the control that was 539 g CaCO\textsubscript{3} eq. /m\textsuperscript{2}), however preferential flow was evident and highest flow rates yielded the highest acid loads.

The permeability of the uncompacted tipheads was 1 x 10^{-6.6} m/s, whilst on the traffic-compacted lifts it was 1 x 10^{-7.7} to 1 x 10^{-8.0} m/s, sufficient to retard significant oxygen ingress into the dump core and thus limit pyrite oxidation and AMD generation rates. Oxygen probes confirmed that only the outer 4-8m of the ELF is oxidising. Paste pH testing of the outer ELF surface confirmed a decreasing pH trend with time. Lysimeter results within the core of the dump, where oxygen is excluded, confirmed circum-neutral conditions, and validated the model.

Although the geochemistry of the ELF will provide a time lag to acid onset, it is likely that the geotechnical properties of the ELF will extend this time lag significantly.

1.0 INTRODUCTION

Acid mine drainage (AMD) is the result of sulfide mineral oxidation, typically pyrite in coal measures, where the pyrite reacts with oxygen and water to produce acidity and metal precipitates such as Fe oxyhydroxides (Eqn. [1]). The acidity generated by pyrite oxidation can be neutralised by materials such as limestone (CaCO\textsubscript{3}) as shown in Eqn. [2]. Rocks can contain both pyrite and carbonate, which means that although pyrite may be present, if the carbonate content is sufficient, depressed pH (< 3) may not occur.

\[
\begin{align*}
\text{FeS}_2(s) + \frac{7}{2}H_2O + \frac{15}{4}O_2 & \Rightarrow \text{Fe(OH)}_3 + 2H_2SO_4 \quad [1] \\
2\text{CaCO}_3(s) + 2H_2SO_4 & \Rightarrow 2\text{Ca}^{2+} + 2H_2O + 2\text{CO}_2(g) + 2\text{SO}_4^{2-} \quad [2]
\end{align*}
\]
Geochemical characterisation of overburden involves a variety of acid-base accounting (ABA) techniques to determine the proportions of pyrite (sulphides) and carbonate within a sample, e.g., the net acid production potential (NAPP) of the sample. This is the difference between the acid neutralisation capacity (ANC), which typically represents carbonates (Eqn [2]), and can be determined by titration methods (expressed in kg H$_2$SO$_4$/t equivalent), and the maximum potential acidity (MPA) where MPA = wt.% total S x 30.6 (in kg H$_2$SO$_4$/t equivalent): note this is a conservative approach as it assumes that the total sulphur determination is present as pyrite. A negative NAPP indicates that the sample has a net neutralising capacity and a positive NAPP indicates the sample has a net acid-generating capacity:

$$\text{NAPP} = \text{MPA} - \text{ANC} \quad [3]$$

One approach to managing incorrect geochemical classification of mine waste rock is to use comparative testing of samples to determine both the NAPP acidity and the net acid generation (NAG) acidity of the sample (e.g., IWRI and EGi, 2002) to provide two methods to assess whether the sample is PAF (potentially acid forming) or NAF (non-acid forming). The NAG analysis method also provides a robust basis for data interrogation and validation, as well as a schematic classification which makes it simple to identify anomalous samples and potential errors.

Part of the management plan for AMD minimisation at Reddale Coal Mine was the construction of the Ferndale ELF by 4m lifts. ELF construction using short lifts reduces chimney effects, which are prevalent in overburden disposal areas that utilise end tipping (where the end tip > 4-6 metres). Significant chimney effects develop in tipheads (> 4-6m) when the coarse and fine materials separate producing coarse grained layers (chimneys) for oxygen ingress and fine grained layers for water ingress with a high permeability rubble layer at the dump base (e.g., Fala et al., 2003; Wilson, 2008). Furthermore, to provide initial acid buffering capacity, and mitigate the initial effects of AMD every 4 m lift had 15 mm (19 kg/m$^2$) of aglime (AP < 2.5mm limestone) applied to prevent the onset of acid mine drainage. An application rate of 19kg/m$^2$ equates to 2.5 kg of aglime per tonne (or ~ 2.5 kg CaCO$_3$/tonne) (based on a cubic metre density of 1.9).

The time lag to acid onset in full scale dumps is dependent on complex scale-up factors that include dump construction (e.g., end tipping, end tip height, paddock dumping), hydrologic processes (e.g., unsaturated dumps and the effects of unsaturated flow), oxygen diffusion into the dump (influenced by waste rock dump permeability, geometry, and thermal regime), temperature (e.g., climate), mineral weathering rates (which are a function of the above and grain size of the waste rock), and microbial activity. Most of these factors are not considered in laboratory based trials and researchers are looking at scale-up of lab results to large scale field trials to evaluate the expected diminishment in acid loads at site.

A number of monitoring systems are used to understand the physical factors affecting the geochemical processes in the field, including lysimeters and leachate monitoring of field trials; monitoring of oxygen concentrations and temperature; and permeability testing using falling head methods. Our paper uses this data to understand the physical factors that are contributing to much slower geochemical reactions in the field.
2.0 MATERIALS AND METHODS

2.1 Site Description

The Reddale Coal Mine is located approximately 1.5 km north east of Reefton within the Brunner Coal Measures (BCM) that is associated with the Reefton Coalfield and is overlain in the area by recent alluvial gravels. The mine commenced operations in early January 2012. Current plans are that 1.3 million bank cubic metres of overburden (920,000 m$^3$ of BCM; 364,000 m$^3$ of alluvial gravels) will be excavated over the current planned mine life (3 years) within a total disturbance area of 29.1 ha.

2.2 Sampling

Two drillholes were used to assess the acid generating potential of rock from the Reddale Coal Mine (Drillholes 662 and 663) and were drilled in April 2005 prior to mining. A total of 36 samples were gathered from these drillholes for ABA testing. These samples were used to characterise the site and develop the AMD management strategy. Another 6 samples were obtained from drillholes DH697, DH699, and DH703, ~325 – 800 m from the Reddale Coal Mine and are considered representative of the area and were obtained in early 2012 after mining at Reddale Coal Mine had started. Two alluvial gravel samples were also tested.

2.3 Acid Base Accounting Techniques

Paste pH testing (e.g., IWRI and EGi, 2002) was conducted to determine the pH of the samples after the addition of water. The method adopted for paste pH involved mixing the sample with water at a solid to water ratio of 1:2 (50g : 100ml) with the pH measured on the slurry after 5 minutes.

ANC (IWRI and EGi, 2002) was not conducted as part of the pre-mining investigations for samples obtained from Drillholes 662 and 663, although this was done for later samples. Total sulfur was determined by LECO analysis. Forms of sulfur were determined by method AS 1038.11-1993. Sulfate sulfur was determined directly as a sulfate in a hydrochloric acid extract of the sample; pyritic sulfur is calculated from the determination of iron soluble in nitric acid following removal of non-pyritic iron by hydrochloric acid; and organic S is determined by difference. MPA was determined by calculation as discussed based on either total S or pyritic S (which is discussed).

The NAG test used and reported here was refined by IWRI and EGi (2002) and is based on earlier similar procedures. This test involves the addition of 250 ml 15 vol.% (unstabilised) hydrogen peroxide (with a measured pH of 4.5) to 2.5 g of pulv®erised sample (< 75 μm), to encourage the rapid oxidation of reactive sulfides.

2.4 Column Leach Testing

Two column leach tests were undertaken on drill core composites using the methodology developed by IWRI and EGi (2002). Testing commenced 6 months after drilling was completed and operated for 2 years starting in December 2005 and finishing in December 2007. 1.5 kg of BCM material (MPA = 32 kg H$_2$SO$_4$/t; ANC not determined) and 1.5 kg of alluvial gravels (ANC = 1 kg H$_2$SO$_4$/t; MPA = 12 kg H$_2$SO$_4$/t; NAPP = 11 kg H$_2$SO$_4$/t) were assessed.

Other columns were set up using the six samples that were obtained from the Burkes Creek Expansion project from drillholes DH697, DH699, and DH703, ~325 - 800 m from the
Reddale Coal Mine as the most suitable unweathered representative samples to rerun column leach tests. These columns started within 1 month of drilling and operated for three months.

2.5 Oxygen Probes and lysimeters

Oxygen probes were installed in the Ferndale ELF upon completion of every second 4 m lift of overburden. The 30 m long, 0.5 m wide trenches were constructed perpendicular from the ELF face. At intervals of 4, 8, 15, 20, and 30 m along the trench, a 0.5 m³ sample collection pit (~0.5 m x 1.6 m x 0.6 m deep) was excavated below the base of the trench. These sample pits were backfilled with large (> 40 mm) rounded gravels and the oxygen probe terminus was within this chamber. The trench was then backfilled and track rolled to recompact. A Teledyne Analytical Instruments portable oxygen analyser with built in vacuum pump was used to extract pore water samples from the five sample collection pits. The pump was run for up to two minutes to purge the conduit before a stable oxygen content was reported by the meter. Between measurements, the oxygen meter was re-calibrated to an atmospheric oxygen content of 20.6%.

Lysimeters were installed in trenches that ran parallel to the oxygen probes but were separated by 5m. Two lysimeters were installed in every second lift at a distance of 10 and 15 m into the ELF. Sample collection from lysimeters is gravity driven. The lysimeters consisted of three components; a leachate collection drum, a conduit and a sample collection bucket that was on the exterior ELF surface.

2.6 Falling Head Permeability

Four falling head permeability tests were carried out on the Ferndale ELF to determine the permeability of different materials under different compaction conditions. Two tests were completed on a machine compacted bench (dozer and dump truck). One test was done on uncompacted overburden which had been pushed up into a windrow. One test was done on compacted gravels. Permeability testing involved driving a 1.7 m long, 300 mm diameter cylinder made of 6 mm steel 300 mm into the material using a digger bucket. The columns were then completely filled with water (~ 1.4 m head) and left to saturate the underlying material overnight. The following day the columns were topped up and the permeability test was started, with daily water level recordings made over several days. The gravel columns drained almost immediately so water level recordings were made over a 90 second period to determine permeability.

2.7 Monitoring of the Ferndale ELF

Thirty random representative samples were collected from the Ferndale ELF on 4 separate occasions 1-4 months apart. Sufficient sample was obtained to undertake a paste pH test at a ratio of 1 part rock to 2 parts water. Paste pH can provide an indication of the amount of sulfide oxidation in a sample and the presence of any subsequent highly soluble stored acidic salts. The method adopted for paste pH involved mixing the sample with water at a solid to water ratio of 1:2 (50g : 100ml) with the pH measured on the slurry after 5 minutes.

2.8 Field trials

Field trials were established in early 2012 on site to compare the benefits of the addition of limestone to the ELF. The trial pad was divided into two 3 m x 3 m sections. Two sets of nine 200mm diameter lysimeters were then arranged in a 3 x 3 grid on the left and right sections with the middle section left empty. The lysimeters drained individually to 20 L
buckets. Clean river rounded gravels were used to form up a 300 mm high flat pad, 3 m wide and 9 m long over the lysimeters; the lysimeters where thus filled with gravels as well. The surface of one of the pads was then dusted with aglime at a rate of 5.7 kg limestone per m², which is proportional to the application rate in the Ferndale ELF over 4 m lifts. Approximately 60 t of run of mine PAF mudstone (~0.4 wt.% sulfur) was then spread over the whole trial pad to a depth of 1.2 meters above the lysimeters using an excavator. The surface was flattened off at least 1 m wider than the footprint of the lysimeters to maintain one dimensional flow through the PAF layer above the lysimeters. The leachate collected in the buckets from the preferential flow trial was sampled approximately monthly. The sample bucket was weighed (to determine vol.) and the pH was measured. A samples was taken for acidity determination in the laboratory.

3.0 RESULTS AND DISCUSSION

3.1 Acid-base accounting

The ABA results presented (Figure 1) indicate that the majority of samples, are PAF as determined by NAG testing. For the samples obtained from Drillholes 662 and 663 no ANC was measured so NAPP data is biased towards PAF or Uncertain classification. Even a small amount of ANC can result in a time lag to onset of acidity for PAF samples and this can be predicted from NAG pH versus paste pH testing (e.g., Weber et al., 2006). Figure 2 indicates that the majority of samples obtained from early drillhole samples at Reddale Coal Mine will have a time lag to acid onset.

![Fig. 1. NAPP versus NAG pH Plot.](image)

NAPP in kg H₂SO₄/t equivalent. DH 662 and 663 ABA data obtained prior to mining and NAPP is based on the assumption that ANC = 0 kg H₂SO₄/t equivalent.
Fig. 2. **Paste pH versus NAG pH Plot.** DH 662 and 663 ABA data obtained prior to mining. Column data was obtained from nearby drillholes.

Column data samples (Figure 1) were obtained from nearby drill holes and NAPP includes ANC for these samples. There is a good correlation except for the three samples circled, due to there being no ANC data being considered for these samples. Similarly, these uncertain category samples may be due to organic S and thus overestimation of the MPA.

To confirm the new expected geochemical trend (Figure 2) a total of fifty representative grab samples were collected from the Ferndale ELF during the placement of the overburden and were assessed for paste pH, ANC, and total S. Results indicated that a small quantity of ANC was present in both overlying gravels that became the base of the Ferndale ELF (mean = 4.2 kg H$_2$SO$_4$/t equivalent) and for the BCM PAF rock (mean = 5.9 kg H$_2$SO$_4$/t equivalent), indicating there is more ANC available in the PAF BCM than the alluvial gravels.

Sulfur speciation work indicated that the majority of the S was present as pyrite in both the alluvial gravels and the PAF BCM overburden. However, the results indicated that the non-acid forming organic S fraction is significant, reducing the MPA determination for the BCM PAF overburden from a mean of 33.3 kg H$_2$SO$_4$/t equivalent (based on total S) to a mean of 27.8 kg H$_2$SO$_4$/t equivalent (based on pyritic S).

Neither ANC nor sulfur speciation was considered during the pre-mining ABA characterisation of the Reddale mine site. The mean ANC for the PAF BCM is 5.9 kg H$_2$SO$_4$/t equivalent and MPA calculated from total S is 5.5 kgH$_2$SO$_4$/t higher than the MPA calculated from pyritic S. If the NAPP was calculated for this tiphead dataset using only MPA based on total S (and assuming ANC = 0 kg H$_2$SO$_4$/t equivalent) then the NAPP would be 33.3 kg H$_2$SO$_4$/t equivalent for the BCM. Taking into account ANC and using MPA based on pyritic S indicates the more correct NAPP is 21.9 kg H$_2$SO$_4$/t equivalent. The conservatism associated with assuming ANC = 0 kg H$_2$SO$_4$/t equivalent for BCM and using total S rather than pyritic S at Reddale alters the acid base accounting balance by about a third and are therefore significant.
3.2 Column Leach Test Results

Two columns were established in December 2005 and were operated for 2 years finishing in December 2007, however the columns were not started until 6 months after drilling and the core was not stored appropriately enabling oxidation processes to occur prior to testing. Acidity and pH results indicated low pH and elevated acidity from the first month and no time lag to acid onset could be determined. In total, 8.8 kg H$_2$SO$_4$/tonne equivalent acidity was leached from the BCM column over the 2 years of operation. The column BCM rock sample had a measured MPA (based on total S) of 32 kg H$_2$SO$_4$/t acidity prior to starting, thus more than a third of the acid load had leached from the remaining sulfides after two years confirming the potential for significant acid mine drainage from the BCM at Reddale.

In total 0.01 kg H$_2$SO$_4$/t equivalent acidity was leached from the alluvial gravels, which is negligible. However, leachate from the alluvial gravels column had near neutral pH and it is likely substantial alkalinity could have been leached from the gravels over the two years of testing, which would help offset any AMD formation. Unfortunately, the alkalinity was not quantified in these lab trials.

To understand whether any time lag to acid onset is possible for rocks obtained from the Reddale site, a number of fresh drill core samples (< 1 month old) from the nearby Burkes Creek site were tested by column leach testing. The samples tested have ANC from 3.7 to 13.7 kg H$_2$SO$_4$/tonne equivalent and have paste pH values greater than 6. This indicates that there would be a time lag to acid onset based on the NAG pH – paste pH classification process. In addition compared to earlier columns there is a time lag to acid onset in these column leach tests (not shown).

3.3 Oxygen Probe Monitoring

Oxygen probe monitoring was carried out monthly (Figure 3) and shows the oxygen content data collected from the two sets of oxygen probes. This data demonstrates that the oxygen content in pore space gas in the dump decreases rapidly from 20.6% (atmospheric) outside the dump to less than 5% at depths greater than 8 m into the dump. The oxygen content of the outer 8 m skin varies between 1 and 9%. The higher oxygen content readings were recorded in the initial monitoring periods, 3 to 44 days after oxygen probe installation. This suggests that initially atmospheric oxygen penetrates the dump to a depth of up to 8 m. After 44 days the oxygen content of the 4 m probes became similar to that of the deeper probes. Over the preceding 44 days, additional material was dumped over the oxygen probes and compacted by heavy vehicle traffic, resulting in a reduction in permeability of overlying material. Following this compaction and stabilisation period, the reactive skin of the dump thins to less than 4 m.
3.4 Lysimeters

Leachate water samples did not report through the lysimeters until the 24th January 2013. The low permeability of overlying material limits percolation through the dump, delaying capture of any drainage. Only a few samples were obtained. Results from 15m horizontally into the ELF indicated that pH remains near neutral (pH 6.3 - 6.6) and acidity (to pH 7.0) was low 5 mg/L CaCO₃. These results indicate that at depth within the ELF the majority of the material is beyond the limit of significant oxygen ingress and indicates the core of the ELF is not producing significant acidity.

3.5 Permeability

The four permeability tests were carried out from the 6th to the 14th November 2011. Results indicated the permeability of the heavy vehicle compacted PAF ($10^{-7.1} - 10^{-8.0} \text{ m.s}^{-1}$) was lower than the permeability of the un-compacted PAF rocks ($10^{-6.6} \text{ m.s}^{-1}$). Thus, vehicle compaction of the PAF materials decreases permeability by an order of magnitude.

3.6 Paste pH Monitoring

The outer surface of the ELF was sampled four times over a period of 9 months and tested for paste pH. A clear trend is identified of decreasing paste pH from 5.2 (6 months after mining started) to 3.0 demonstrating that the outer surface of the dump is becoming more acidic with time and producing acid runoff (Figure 4).
pH has been monitored on a daily basis at a monitoring location downstream of the Reddale Coal Mine site within Burkes Creek. Results indicate the pH has remained fairly consistent, and is comparable to pre-mining conditions of pH ~ 6-7. It may therefore be concluded the onset of depressed pH associated with significant AMD has not eventuated, as predicted by the pre-mining geochemistry analysis.

3.7 Field Trials

The results for the field trial are provided in Table 1. For a well-controlled uniform system it is interesting to note the variation in flow rates, demonstrating preferential flow paths. If such variable flow occurs in a trial, then its occurrence within the Ferndale ELF is almost certain. Results also demonstrate that with increasing flow there is an increase in acid load, which indicates that more secondary acidic oxidation products are being flushed out with higher flow rates. The use of limestone, although not preventing AMD from developing significantly reduced the amount of acid departing the system. The average acid load for the limestone trial was 43.5 g CaCO$_3$ eq./m$^2$ whereas the control was 539 g CaCO$_3$ eq./m$^2$. Over the course of the 6 month trial the average acid load neutralised by the addition of the limestone was ~500 g CaCO$_3$ eq./m$^2$. When compared to the starting application rate of 5.7 kg limestone per m$^2$ this indicates an efficiency of 9%.

After 6 months the measured acidity of the limestone amended pad had increased significantly (not shown) indicating exhaustion of the limestone neutralisation capacity. This suggests the time lag to acid onset created by the addition of neutralent was within 6 months following trial pad construction. By inference there is potential that this time lag to acid onset would be occurring in the ELF where oxygen is freely available (e.g., the outer oxidising zone where oxygen > 10%). Where oxygen ingress is limited in the core of the ELF the time lag to acid onset is expected to be greater.
Table 1. Combined total flow rate, acidity, and acid load for the field trial pads. Data presented on a per m² basis. Monitoring period was from June 2012 to Jan 2103.

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4.0 CONCLUSIONS

At this site, the assumption that the Brunner Coal Measures do not have significant ANC is incorrect. As shown here at Reddale there may be sufficient ANC (~5.9 kg H₂SO₄/t equivalent) to provide a time lag to acid onset. Omission of this ANC is conservative and conservatism can lead to over-engineering and greater project costs. Similarly, use of total S for MPA determinations of the Brunner Coal Measures is conservative and MPA can be lower if pyritic S is used. At Reddale the use of pyritic S reduces MPA by ~5.5 kg H₂SO₄/t equivalent compared to using total S content for the MPA calculation. Thus, original ABA data suggested that acid potential could be ~ 33.3 kg H₂SO₄/t equivalent, whereas the inclusion of ANC and MPA based on pyritic S results in a NAPP of 21.9 kg H₂SO₄/t equivalent; close to a 30% decrease in acid potential.

Approximately 2.5 kg CaCO₃/tonne has been added to each 4m lift within the Ferndale ELF thereby increasing the total ANC within the dump to ~8.4 kg CaCO₃/tonne. This will further contribute to acid neutralisation within the dump and again extend the time lag to acid onset.

The oxygen gradient to < 5wt% oxygen within the first 4-8m indicates that diffusion is the dominant gas transport mechanism. Paste pH results of the ELF surface indicate that acid generation is occurring on the surface of the ELF where oxygen is freely available; yet at depth, 10m into the ELF, near neutral drainage is still being observed.

The work presented here indicates that the Ferndale ELF can be divided into two geochemical zones, an outer oxidising skin where oxygen is freely available (>5%) and where the dominant sulfide oxidation reactions are occurring, producing acidity; and an inner core that has reduced oxygen content (< 5%) and sulfide oxidation rates are much lower and percolation remains near neutral. It should be noted that the oxidising skin model proposed here is specific to the site. In some waste rock dumps this oxidising skin may encompass the whole dump (Ritchie, 1994).

The field trials demonstrated that preferential flow occurs and that the highest flow rates also delivered the highest acid load. This indicates increased flush rates of acidic salts with increasing flow. Limestone application reduced acid loads and was 9% efficient in this instance. Results indicate that where oxygen is freely available, the addition of the prescribed
quantity of aglime used in the trial will provide about 6 months time lag to acid onset and the trial is probably a reasonable analogue for the outer oxidising zone of the ELF.

The ABA testing indicated that there is likely to be a general delay to AMD onset due to inherent ANC of the PAF overburden, combined with the application of aglime to the ELF. In conjunction with reduced oxygen ingress there is likely to be a greater delay to significant AMD generation. In retrospect, the upfront installation of a Ca(OH)$_2$ water treatment plant was thus unnecessary and a better option could have been the design of a low cost passive treatment system.

5.0 ACKNOWLEDGMENTS

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6.0 REFERENCES


