

Mine Drainage Management – Replicating Dump Physiogeochemical Conditions in Laboratory Columns

K.R. Malloch¹, P. Petrov² and P.A. Weber³

¹ O’Kane Consultants (NZ) Ltd, Christchurch, kmalloch@okc-sk.com

² O’Kane Consultants Pty Ltd, Perth, Australia, ppetrov@okc-sk.com

³ O’Kane Consultants (NZ) Ltd, Christchurch, pweber@okc-sk.com

Abstract

A number of key issues have been identified when using standardised kinetic tests to predict the physiogeochemical evolution of waste rock dumps (WRDs) due to the uncertainty of how to apply scaling factors to laboratory data. O’Kane Consultants has devised the advanced customisable leach column (ALC) to better replicate actual field conditions while an automated monitoring system provides flexibility in controlling key geochemical variables. The ALC method allows control of air flow rates, ambient temperatures, water application and drying with the ability to customise each column.

Economic coal seams within the Buller coalfield are associated with the Brunner Coal Measures (BCM). The coal measure sequences contain carbonaceous mudstone and siltstone with elevated pyrite indicative of estuarine conditions. Exposure of these pyritic materials during mining on the West Coast leads to significant acid and metalliferous drainage (AMD) management issues. Consequences of inadequate water quality management can be seen at historic mines where downstream contaminant loads are high.

The ALC method has been used to evaluate the intrinsic oxidation rate (IOR) of BCM by directly measuring oxygen consumption, to understand the geochemical differences that result from a WRD built to minimise oxygen ingress. Management of AMD by prevention of oxygen ingress, through improved construction methods of WRDs using shorter lift heights, compaction between lifts and the placement of cover systems, reduces oxygen ingress. Two ALCs have been set up using field parameters to model: 1) a poorly constructed waste rock dump with free exchange of atmospheric gases, and; 2) a well-constructed dump where, at the centre of the dump, oxygen content and flux is limited. Initial results from the ALCs will be presented and compared with a concurrently running AMIRA column, that uses the sulfate release rates, and the stoichiometric relationship between sulfate release to the quantity of pyrite oxidised, to calculate an IOR. Improved data provides better estimates of potential contaminant loads, essential for AMD management, and an improved understanding of risk.

Keywords: acid and metalliferous drainage, kinetic tests, advanced customisable leach column, waste rock dump, oxygen ingress, Brunner Coal Measures, Kaiata Formation, Buller coalfield, scaling factor.

Introduction

Economic coal seams in the Buller coalfield occur within the Eocene Brunner Coal Measures (BCM) on the West Coast of New Zealand. Coal mines within the Buller coalfield have to manage waste overburden from the BCM and the overlying Kaiata Formation (Flores and Sykes, 1996). Both units have been shown to have acid producing capacities from the oxidation of framboidal and euhedral pyrite in siltstones and mudstones when these units are exposed during mining (Weisener and Weber, 2010). For coal mines, acid and metalliferous drainage (AMD) resulting from pyrite oxidation is an environmental issue that requires active management through prevention, minimisation and treatment strategies. BT Mining Limited owns and operates the opencast Stockton coal mine in the Buller coalfield and actively manages AMD through waste rock management practices and treatment of waters impacted by AMD. Waste rock from the Stockton mine has been used in this study to replicate field

conditions in the laboratory to understand the effects preventative waste handling measures can have on mine drainage.

Waste Rock Dumps

Based on extensive field data, the method of WRD construction has been shown to have a direct impact on AMD risk (Harries and Ritchie, 1985; Wels et al., 2003; Weber et al., 2013; Pearce et al., 2016a). Lower lift heights produce WRDs that have lower oxygen ingress rates, resulting in lower pyrite oxidation rates. Oxygen probes installed into WRDs indicate that internal oxygen concentrations can be as low as 1% within 5m of the WRD surface (Figure 1; Harries and Ritchie, 1985; Pearce et al., 2016b; Pope et al., 2016). At the Stockton Mine, the Cypress Northern Engineered Landform (ELF) has oxygen contents of less than 5% within 5m of the surface. Although a component of oxygen ingress reduction, lift height has less of an impact at this site. This is a function of the friable nature of the Kaiata Formation, which weathers rapidly to produce significant fines minimising pore space and thereby limiting oxygen ingress. Where oxygen ingress is limited to diffusion, and oxygen concentrations are less than 1%, the rate of pyrite (sulfide) oxidation will decrease.

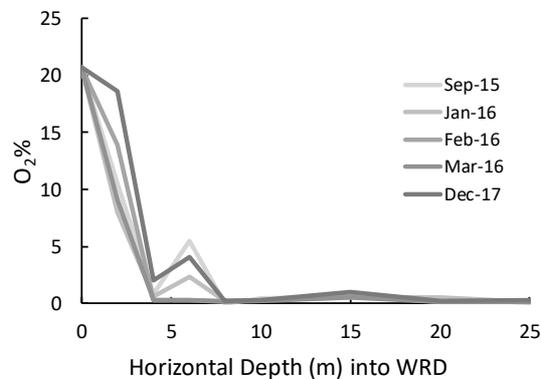


Figure 1. Oxygen concentrations from horizontal probes in the Cypress Northern ELF, Stockton

This paper looks at the effect of oxygen concentrations and flux rates can have on pyrite oxidation and the resulting risks of AMD for BCM waste rock. Through laboratory testwork, the experiment models a well-constructed WRD, where oxygen and gas flux is limited and the IOR is expected to be depressed by an order of magnitude (Lottermoser, 2010; Pearce et al., 2016a), and a poorly constructed WRD where oxygen supply is not a limiting factor to IOR (Harries and Ritchie, 1985).

Standard Kinetic Testing and AMD Prediction

Kinetic leach tests are used to aid in the prediction of long-term water quality trends and in the assessment of acid and metalliferous drainage (AMD). But these standardised tests have numerous factors that vary between the laboratory and the WRD, including but not limited to particle size distribution (PSD), liquid to solid (L:S) ratio, temperature and gas concentration and flux (Morin and Hutt 2007; Morin, 2013; Kirchner and Mattson 2015; Pearce et al., 2015). The difference in laboratory test conditions and field site conditions has resulted in the use of scaling factors in order to predict mine site drainage.

Humidity cell testing (Price, 2009) along with AMIRA (2002) columns both generate leachate through wet/dry cycles that accelerate the weathering process and are designed to mimic intermittent wetting up of the WRD after a rainfall event. The high liquid to solid (L:S) ratio of these tests (e.g. AMIRA columns operate at 8:1) are much higher than actual field conditions resulting in high leachate rates (Pearce et al., 2015) and hence lower solution concentrations. Heat lamps used for the dry cycles in the AMIRA column, result in fluctuating temperatures

that do not reflect WRD internal temperatures. Temperatures for WRDs may be higher or lower than these test conditions which will influence the rate of reactions, speeding up (high temperatures) or slowing down (low temperatures) reactions (Langman et al., 2014; Pearce et al., 2015). Furthermore, pyrite oxidation is an exothermic reaction and can result in internal WRD temperatures that are higher than external ambient air temperatures.

Sulfate release rates from kinetic tests are used as an indicator of the pyrite oxidation rate (POR) through the stoichiometric relationship between the mass of sulfate released to the quantity of pyrite oxidised (Tremblay and Hogan, 2000). Because of the formation of secondary sulfate minerals within the cells, the sulfate release rate and calculated POR can be underestimated (Pearce and Pearce, 2016; Maest and Nordstrom, 2017). The later dissolution of these secondary sulfate minerals during extended testing can lead to an over-estimation of long-term sulfate production and calculated PORs. Secondary sulfate salt formation in a WRD, such as gypsum, jarosite and melanterite, are common and can have a significant effect on water quality, stored acidity and sulfate release into the receiving environment (Jambor et al., 2000; Hammarstrom et al., 2005; Maest and Nordstrom, 2017).

Advanced Customisable Leach Columns

The development of the O’Kane Consultants (OKC’s) ACLCs addresses some of the test parameters mentioned in the previous section. With larger samples sizes and variable representative PSDs to better represent WRD field conditions, columns are housed in an automated laboratory where gas flux rates, ambient temperature, water application and drying can be controlled and monitored (Table 1; Pearce and Pearce 2016). This reduces the number of parameters to consider when scaling from small scale laboratory to large field scale.

Table 1. Comparison of standard kinetic tests to ACLC columns.

Parameter	Standard Kinetic Tests	OKC’s ACLC
Grain size	< 6 mm	Variable, can be > 6 mm
Sample size	1-2 kg	> 20 kg
Air flow	Unlimited supply at atmospheric conditions	Can be varied to WRD specifications
Temperature	20-30 °C	Temperature controlled room adjustable to internal WRD specifications and monitored
L:S ratio	8:1 per year	Site specific, typically 0.001:1 per year

Modified from Pearce et al. (2015) and Pearce and Pearce (2016).

Site-specific conditions can be simulated in the ACLC laboratory setting, using field data from instrumentation in WRDs to set test conditions (Pearce and Barteaux 2014). The columns are housed in a temperature-controlled room that can be set to simulate internal WRD temperatures that can vary from ambient air temperatures. The ACLC operate under low L:S ratios, similar to the low L:S conditions of WRDs resulting in leachate that is more of a comparison to field conditions than standard kinetic tests (Pearce and Pearce 2016).

Gas flux and oxygen concentrations can be adjusted to reflect internal site-specific conditions including low oxygen supply. The ACLCs can deliver a dynamic POR that is influenced by the rate of supply of water and air, as would be expected in the field. The intrinsic oxidation rate (IOR) is presented as an oxygen consumption rate representing the rate in which oxygen is consumed by rock materials (unit kg O₂/m³/sec), with typical IORs for WRDs ranging from 10-6 to 10-11 kg O₂/m³/sec (Ritchie et al. 1994; Lottermoser 2010; Pearce et al. 2016). The POR will be similar to the IOR if the organic carbon content within the WRD, and thus the carbon oxidation rate (COR), are negligible, where:

$$POR = IOR_{(measured)} - COR$$

As the IORs are monitored continuously through oxygen consumption and carbon dioxide production, over or under estimation of IORs using sulfate release rates, and first flush effects are avoided.

Interpretation of the ACLC column data is done in conjunction with static test results that include acid base accounting (ABA) data, PSDs and mineralogical information on the samples. Time series data can be produced for oxygen consumption, carbon dioxide production, IORs, CORs, temperature, rate of drying and loading rates of key contaminants can be produced (Pearce and Pearce 2016).

Methodology

A 90 kg bulk grab sample of freshly blasted waste rock from the Cypress pit at the Stockton Mine, was collected from the tip head of the Cypress Northern ELF. The sample comprises friable fine-grained mudstone from either the BCM or overlying Kaiata Formation. The sample was sealed in 20 L plastic containers and shipped to CRL Energy Ltd (CRL) laboratories in Christchurch for pre-characterisation testwork. The sample was wet sieved to 10 mm, with the 10 mm fraction crushed to 8 mm. The bulk sample was then riffle split to obtain identical sub-samples, which were then dried in a low temperature oven (~40 °C). Moisture contents of the samples averaged 7.5 wt%. Acid base accounting (ABA), which included Total S, acid neutralisation capacity (ANC), paste pH and NAG pH was done on multiple splits. A 50 kg split was sent to OKC's Perth Laboratory for two ACLC columns, to set up one column under atmospheric conditions (~21% O₂, ACLC 21%) and another column under low gas flux and low oxygen concentrations (1% O₂, ACLC 1%). Another split was used for an AMIRA leach column undertaken at the CRL laboratory.

Advanced Customisable Leach Columns

Columns were loaded with an Apogee S-100 O₂ sensor and a Kestrel temperature and barometric pressure sensor in the column immediately above the sample. Apogee sensors were calibrated according to the manufacturer's instructions. Column settings were automated by programmable dataloggers controlling and monitoring air flow, and monitoring sensor data every 5 minutes. The column room temperature was set at 10 °C to approximate the internal temperatures expected in WRD on the West Coast (mean annual temperature is c. 12 °C, NIWA 2017).

Columns were wetted up to ~16 wt% moisture content. The moisture content was derived from unpublished lysimeter data from the Barren Valley WRD at the Escarpment coal mine on the West Coast, that range from 9.3-14.2 wt%. Leachate was collected and then the columns were then flushed for 24 hours with their respective gases, 20.95% O₂ (atmospheric) for ACLC 21% and 1% O₂ (99% N₂ gas bottle) for ACLC 1%. The air flow was then turned off for a period of 4 weeks to ascertain the reactivity of the column materials. The initial wetting up followed preferential flow paths that were set up during column loading, so that the columns did not wet up evenly. The volume of leachate that was released after the initial wetting up was recycled to ensure that both columns were thoroughly wetted before beginning the air flow regime. This recycled leachate was then sent off for analysis.

Air flows for both columns have been adjusted throughout the experiment to ensure sufficient oxygen supply so that there is no over or under supply. Air flow is delivered over 20-25 minute increments every day. At the current regime for ACLC 21% (gas flux = 5.2E-6 m³/m²/s), air within the pore spaces is flushed out within half an hour so that the lowest recorded oxygen concentration at the top of the column is after the daily air flow. Air flow within ACLC 1% is delivered at lower fluxes (6.3E-7 m³/m²/s). IORs for the ACLCs were calculated using oxygen consumption rates.



Figure 2. ACLC set up and leachate collection system.

AMIRA Columns

One AMIRA column was set up at the CRL laboratory in Christchurch on 16 March 2018 as a comparison to the ACLCs. The column followed standard methods (AMIRA, 2002) with the 2 kg sample watered weekly, flushed monthly for metals analysis and dried out in between with heat lamps. IORs were calculated from sulfate release rates using the stoichiometric relationship with sulfide oxidation.

Preliminary Results

ABA

All splits tested were similar with low paste pHs indicative of readily available acidity and low NAG pH and positive NAPP classifying the sample as PAF (AMIRA, 2002; Table 2.). The sample has no ANC to neutralise this acidity with negative numbers indicative of stored acidity.

Table 2. Acid Base Accounting results

Lab No.	NAG pH	Total Sulfur	Paste pH	ANC	MPA	NAPP
	<i>s.u.</i>	%	<i>s.u.</i>	<i>kg H₂SO₄/t</i>	<i>kg H₂SO₄/t</i>	<i>kg H₂SO₄/t</i>
111/305	2.5	1.57	3.9	-2	48	48
111/306	2.5	1.54	4.3	-4	47	47
111/307	2.5	1.53	3.7	-3	47	47
111/308	2.4	1.65	3.6	-5	50	50

ACLC

The first part of this experiment is concerned with oxygen consumption rates for the two columns operating at different gas flux and oxygen concentrations, with data reported for the first four months of the experiment. There have been continual adjustments to gas flux rates to provide the column running at atmospheric oxygen with enough air. As can be seen from Fig. 4, when the air was turned off in March after an initial gas flush and wetting up, oxygen consumption was rapid, with the oxygen dropping from near atmospheric to less than 10% over 10 days.

ACLC 1% had oxygen concentrations increasing for that same period in March, likely due to a combination of higher oxygen contents in the pore spaces forced out by the flush into the head space where the sensor is located, and it is also likely that the system was not completely air tight.

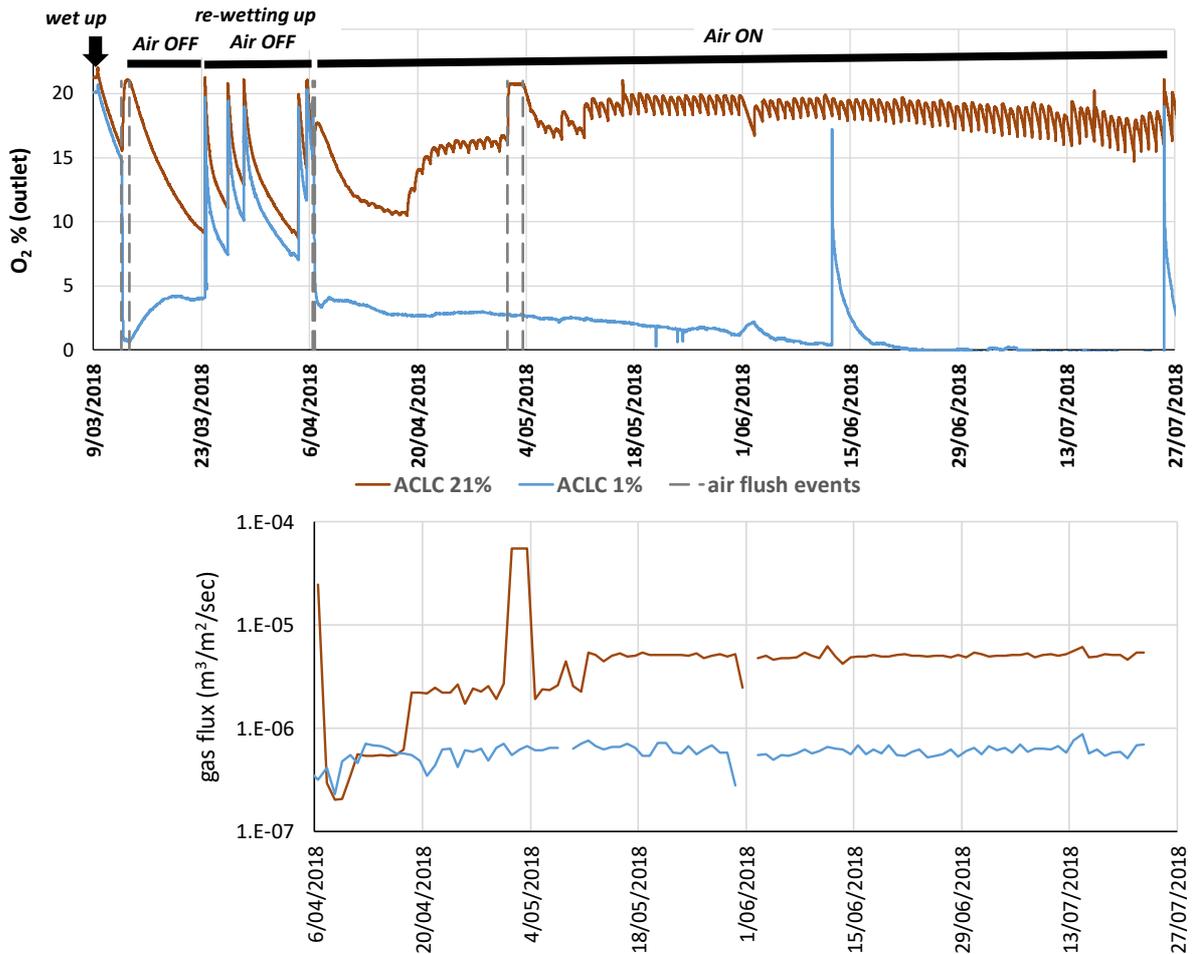


Figure 3. Oxygen concentrations for the two ACLCs (top) and air flow volumes supplied (bottom). Note that the spike in oxygen concentrations in ACLC 1% in June is due to a sensor change with a brief increase in head space oxygen concentrations around the apogee sensor.

Oxygen was re-introduced into the columns during the wetting cycles, with a second gas flush necessary to reduce oxygen concentrations in ACLC 1%. A further flush for ACLC 21% in early May was undertaken to increase oxygen concentrations in that column. Currently the oxygen concentration in ACLC 1% have reached the lower detection limits of the equipment, with the daily low oxygen supply exceeded by oxygen consumption of the material. Oxygen consumption rates in ACLC 21% have increased on the last couple of weeks despite air flow supply being constant over the last couple of months. The air flow will be adjusted so that the consumption rate is not oxygen limited. The gas flux for ACLC 21% may not be representative of field conditions as these haven't been measured at site, and are constantly being adjusted in this experiment to ensure oxygen concentrations remain above 15%. Pearce et al. (2016a) noted that gas flux is not directly related to AMD production, as there is a certain point where gas fluxes can exceed that needed for oxidation reactions.

IORs have been calculated from oxygen consumption rates using the Ideal Gas Law.

The wetting up phase at the beginning of the experiment produced leachate with low pH of 2, acidity of 9,000 mg CaCO₃/L and conductivity of 8,000 μS/cm. Recycling the leachate to ensure the entire column had wetted up resulted in a decrease of pH to 1.8 and much higher acidity and conductivity of 22,500 mg CaCO₃/L and 20,000 μS/cm respectively. Column flushing will occur at the conclusion of the experiment, with assessment of the leachate.

AMIRA

Sulfate release rates have been more or less consistent for the last couple of analyses, although the column has been in operation less than 6 months. The pH was acidic for the first analyse one month after loading (i.e. no acid lag) and has remained around pH 2 with acidities of 10,000 mg CaCO₃/L. Contaminant release rates are highest for sulfate averaging around 1,200 mg/kg/wk and Fe averaging around 350 mg/kg/wk (Figure 4).

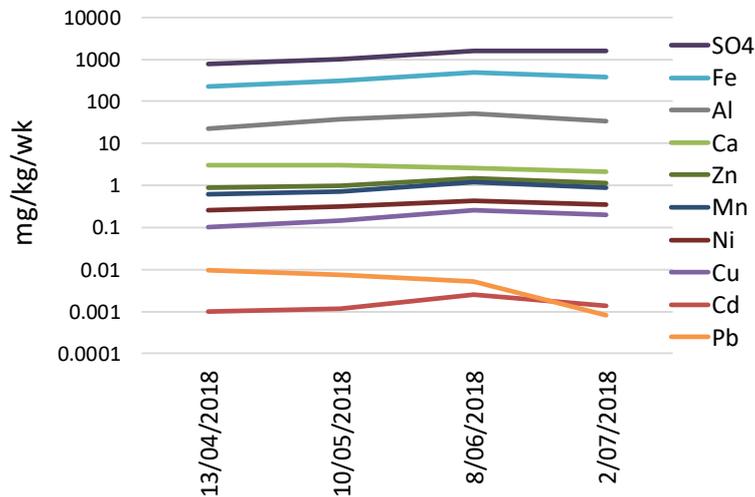


Figure 4. Contaminant release rates for the AMIRA column

IORs have been calculated using the stoichiometric relationship of sulfate release rates to pyrite oxidised and are compared to average monthly ACLC IORs.

Intrinsic Oxidation Rate (IOR)

IORs have been calculated for the two ACLCs and the AMIRA column for the four months that the columns have been operating (Fig. 6). Over the last month, oxygen concentrations in column ACLC 1% have stabilised to within 0-1% oxygen, with the latest IOR (July) most reflective of low oxygen conditions. IORs have increased in the ACLC 21% in the last month (Figure 3 and Fig. 6), so that oxygen concentrations within the column have been steadily decreasing despite constant supply. IORs calculated for the AMIRA column are an order of magnitude higher than ACLC 21%, both of which operate under freely oxidising conditions.

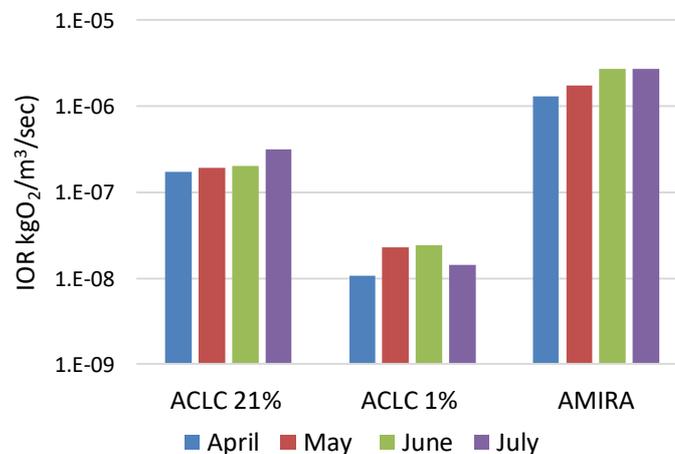


Figure 5. Average monthly IORs for the kinetic tests

Discussion

The advantage of the ACLC over other kinetic tests is that these columns take into account site-specific physical characteristics that are overlooked in other kinetic tests that are purely geochemically driven. Physical site conditions such as net percolation, temperature (especially internal temperatures of the WRD) and waste handling which includes WRD construction, will all influence POR/IOR (Harries and Ritchie, 1985). As the columns are not leached, secondary stored oxidation products can build up so that the effect of these products on mine drainage can be assessed when the columns are deconstructed. Previous studies have shown the leachate from ACLCs more closely resembles field conditions than that from AMIRA columns due to the low L:S ratios of the ACLCs (Pearce and Pearce, 2016). The effect on AMD drainage of a WRD built so that oxygen concentrations are minimal (Fig. 1), can be replicated in the laboratory using ACLCs operating under site conditions. This data can then be integrated into engineering planning decisions around waste management options.

IORs from this experiment have been compared to those from a large leach column of Cypress Northern ELF waste rock collected in late 2017 (BT leach in Fig. 7), and with 1 kg sized leach columns operated in 2004 comprised of drill core from the then proposed Cypress pit (KF E and KF F in Fig. 7; Hughes, 2004). IORs were calculated from sulfate release rates. For the larger BT leach column, the column was wetted weekly according to annual site rainfall (~6,000 mm/yr), so that the L:S ratios were similar to expected site conditions. Particle size was reflective of recently dumped material, with the sample sieved on site using 50 mm sized sieve and the sample size was large at approximately ~90 kg. Hughes (2004) columns were wetted every 4 days at high L:S ratios similar to AMIRA columns.

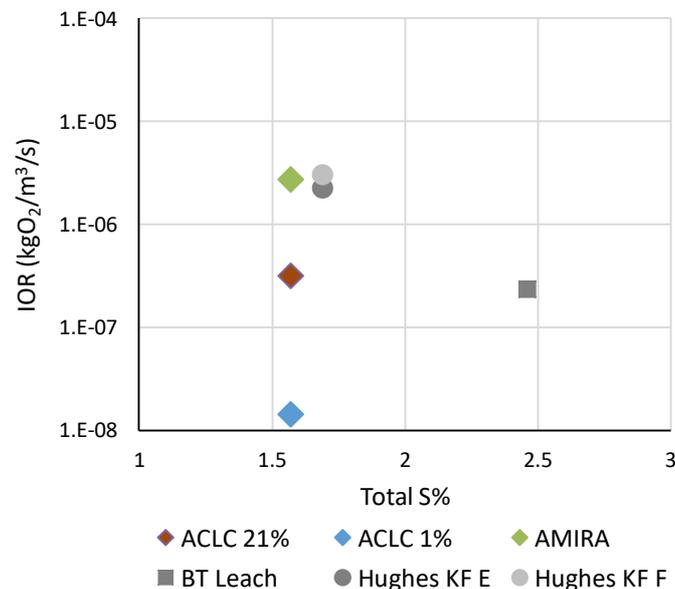


Figure 6. Average monthly IORs for the kinetic tests

Columns that operated at much higher L:S to site conditions (AMIRA this study, Hughes (2004) columns) had IORs an order of magnitude higher than the columns that were wetted up according to field data (Fig. 7). The higher IOR for the AMIRA may also be due to the faster oxidation of pyrite under higher temperatures, where the heat lamps produce surface temperatures of 20-30 °C (Lottermoser, 2010). The IOR of ACLIC 21% is similar to calculated IORs from leachate from the BT column. This IOR, ~3E-07, is thought to be representative of BCM under freely oxidising conditions at the edges of WRD or in a poorly constructed WRD.

Accelerating IORs in ACLC 21% over the last month may be due to a growth in the bacterial population, which oxidise sulphides and sulfur compounds and accelerate the conversion of Fe^{2+} to Fe^{3+} , with the Fe^{3+} remaining in solution due to the low pH also acting as a sulfide oxidiser and accelerating acid formation (Lottermoser, 2010).

ACLC 1%, modelling a well-constructed WRD where oxygen ingress is minimal, has an IOR an order of magnitude lower than the freely oxidising systems. Oxygen concentrations of 1% have been measured in the Cypress Northern ELF at Stockton although the effect low oxygen concentrations have on pyrite oxidation and the resulting WRD drainage has not previously been studied. The next stage of this experiment will look at the effect oxygen supply has had on the formation of secondary acid storage products and resulting water quality from the two ACLCs.

Conclusion

Kinetic laboratory tests are a useful tool in assessing AMD risk at a site, although traditional tests require the application of scaling factors to make the data site applicable. The advantage of the ACLC method is the replication of site specific factors such as L:S ratios, air flux, temperatures and particle size distribution in the laboratory, all are factors which will affect IORs and the water quality of WRD seepage.

Data from ACLCs can be integrated into engineering planning decisions around waste management options as these columns incorporate site conditions. The columns present a quantitative assessment to manage AMD risk that can be balanced against operational constraints.

Preliminary results from this ACLC testwork indicate that well-constructed WRDs, that limit oxygen ingress, will see a reduction in IORs by an order of magnitude. A deconstruction study will investigate sulfate oxidation products in the columns and assess the effect differing gas fluxes and oxygen concentrations have had on leachate and therefore mine drainage. The next step will be to compare geochemical information from the columns with that from WRDs where oxygen concentrations are actively monitored.

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