Advanced Customisable Leach Columns (ACLC) – A New Kinetic Testing Method to Predict AMD risks by Simulating Site-specific Conditions

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Abstract

One of the most significant issues in the prediction of how waste materials will evolve geochemically within waste storage facilities is the applicability of scaling laboratory test results to field conditions. This is an important aspect laboratory data is primarily used for predictive calculations to determine geochemical evolution of waste materials in the field. This issue has arisen predominantly as a result of the relative paucity of field monitoring data from waste rock storage facilities (WRSFs) and the fact that laboratory test methods are not typically linked to specific field conditions rather are based on generic standardised methods. This issue is compounded by the fact that the majority of the test methods used are based on technology now over ten years old.

To address the limitations of current laboratory kinetic testing methods a new method has been developed by OKC that can accommodate and replicate site specific conditions. This method is termed the advanced customisable leach column (ACLC). The highly engineered columns have allowed for field conditions to be simulated in a laboratory setting.

OKC has utilised site data from instrumentation placed in multiple waste rock dumps as the basis of design and field calibration of the method. Key features of the columns include both their capacity, size and technical specification. The inclusion of fully programmable solenoid controlled air supply, ability to operate under very low liquid solid ratios, and in line heating options allow for variable water flux, airflow and pressure as well as temperature control. Columns can therefore be adapted for different conditions depending on site specific conditions and variability. Ongoing monitoring of the column conditions by automated temperature control and monitoring, automated oxygen consumption and carbon dioxide production monitoring, and soil moisture/matric suction monitoring enable rapid and reliable data collection for interpretation.

Key words: Pyrite oxidation rate, kinetic testing, liquid solid ratio

Introduction

The prediction of how waste materials will evolve geochemically within waste rock storage facilities (WRSFs) has been the subject of many hundreds of thousands of hours of research by geoscientists globally. Despite the quantity of research there are two significant areas of uncertainty that remain as partially resolved issues: (a) the majority of the research carried out has been at the laboratory not site scale leading to uncertainty over the applicability of scaling laboratory test results to field conditions (b) many predictions made using computer modelling have not, or are not normally able to be, validated from site data.

These areas of uncertainty have arisen predominantly as a result of the relative paucity of relevant field monitoring data from WRSFs and the fact that laboratory test methods are not typically linked to specific field conditions. They are more commonly based on generic standardised methods and are designed primarily to simulate accelerated weathering conditions that do not relate to field conditions in a linear manner.

To address these specific issues the authors have over the last three years made significant progress in the gathering of field data to determine internal WRSF geochemical and hydrological conditions. This

has been achieved as a result of the development and deployment of advanced field monitoring equipment within numerous WRSFs. The findings from data collected from these monitoring installations have previously been reported in a number of papers presented through 2013-2014 (Pearce and Barteaux, 2014a; Pearce and Barteaux, 2014b). A range of WRSFs were investigated to include both active facilities and historical closed facilities of around 10-30 years in age. These investigations included approximately 2,000 m of sonic drilling, the recovery and detailed analysis of over 2,000 samples of core material and the installation of over 200 sensors at depths between 5 and 140 m within the waste which have provided over 5 million points of monitoring data to date and are still actively generating data.

The quantity and quality of materials testing and in situ monitoring data collected has provided OKC the opportunity to assess and evaluate the comparability of laboratory testing methods to the macro scale. In addition these data have allowed OKC to determine the specific factors related to in situ field conditions that act as the main controls on geochemical evolution of waste materials in field conditions

OKC has used this data to develop a new test method termed the advanced customisable leach column (ACLC).

Methods

Scalability of testing methods

Laboratory testing methods have been developed and refined over many years for geochemistry assessment and acid and metalliferous drainage (AMD) predictions, which has resulted in a broad set of standardised testing methods being generally accepted internationally by the mine-geochemistry industry. This has been possible by and large because laboratory experiments are completed in a controlled environment with high degree of precision and accuracy. However common factors, and consequently the limitations, to all laboratory assessments is the scale at which these experiments are carried out, and the conditions under which they are carried out.

Indeed, it is the rational for the design of these laboratory tests that presents possibly the most significant challenge. The primary rationale for these tests has been, in general to create a low cost, bench top scale test, using existing technology, to simulate an environment of 'accelerated weathering' so that oxidation rates can be studied in short timeframes of 6 to 12 months, at the bench top scale, at a cost that is scalable at the commercial level, and using existing technology. A key assumption behind these accelerated weathering tests therefore is that the results provide useful data that can be extrapolated to field scale to make predictions about field conditions and to make planning decisions. It should be noted that this assumption is not based on proven field calibration exercises and conclusive research, but is rather an artifact of 'reverse' engineering. In other words, the tests were created to provide a solution to a time, cost and technology constraint, not designed to provide an answer to the question about predicting field geochemical conditions.

Commonly used kinetic testing methods offer a good example of the challenges when attempting to determine how laboratory data should be used to extrapolate from the laboratory (micro) to site (macro) scale. Tests such as humidity cells (ASTM, 2012) and leach columns (AMIRA 2002) utilise a few kilograms of material that has been crushed to a few millimetres in size and then exposed to wetting and drying cycles with very high leaching rates. The concept of these kinetic tests is that by using small grain sizes and high leaching ratios the weathering processes (sulfide oxidation rates and carbonate dissolution) can be accelerated allowing the assessment of sulfide oxidation rates, acidity generation, neutralisation reactions, and leachate geochemistry within a reasonable and practicable timeframe in regards to mine planning.

Because of the large amount of published data from these tests it can be stated with reasonable confidence that it is beyond doubt that these tests achieve the aim of simulating accelerated weathering. However, the precise method, and value of how to apply these results in a scaled up situation, for example in the extrapolation of data to predictions of field conditions, such as oxidation rates or seepage quality, has not yet been conclusively determined.

Table 1 outlines some scale factors that require consideration when using kinetic test data for 'predictions' of field conditions, which will have a significant influence on the ability to predict field geochemical conditions and processes from laboratory data.

***Table 1** Laboratory to field scale factors*

Scale parameter	Industry standard Laboratory test conditions	Typical field conditions	Challenges extrapolating from lab to field
Grain size	<6mm	60% >6mm	Oxidation rates faster and dissolution of silicates/carbonates higher for smaller grain sizes. Lab tests may over estimate both sulfide oxidation rates and acidity buffering processes
Geochemical system	Open	Variable from open to closed	Open systems discharge acidity closed systems store acidity, lab tests are not reflective of field drainage geochemistry
Mass of material	1-2 kg	>1 Mt	Heterogeneity effects not accounted for in lab tests, bulk geochemistry of material in the field may not be well represented by material tested in the lab
Airflow (Oxygen supply)	Diffusion dominated potentially restricted	Advection dominated potentially restricted	Lab tests assumed unlimited oxygen supply, field conditions may vary, generally significantly lower than lab conditions
Temperature	20-30 degrees	0-100+ degrees	Due to effect of thermal properties by total mass of material, field temperatures may be significantly higher than lab, this can effect geochemical reaction rates
Liquid : solid ratio	8:1 per year	0.001: 1 per year	Lab leachate is order of magnitude dilute then field conditions due to high L:S ratio. No restriction on sulfide oxidation rates based on H2O supply in lab, field reaction rates may be H2O supply limited.

Because of the significant differences between laboratory and field conditions the relative effects of the listed scale parameters (Table 1) are inherently site specific. Therefore to scale up results from the laboratory to the field initially requires the generation of a detailed set of calibration functions to derive a scale up factor. It is outside the scope of this paper to provide detail on all of these factors, however one of these factors, the L:S ratio, is described in more detail as this is probably the most significant factor that is overlooked when laboratory results are interpreted and applied to field conditions.

Liquid Solid (L:S) ratio

Since it is the relative rate of supply of oxygen and/or water to a system that will be the primary control on the intrinsic oxidation rate (IOR), and seepage quality (due to solubility controls) it is necessary to establish what field and laboratory conditions and how they are inter related (or not).

The liquid to solid ratio (L:S) is a convenient way to express the relative supply of H_2O into the system, this simply reflects the weight for weight balance of water against the mass of the porous solid through which the liquid is passing. Free draining leach columns have very high L:S ratios in general, an AMIRA (IWRI and EGi, 2002) column has an annual L:S ratio of approximately 8:1 for example. In contrast

WRSFs typically have low L:S ratios and annual ratios in semi arid environments like the Pilbara of Western Australia are estimated to be around 0.001:1 (assuming a 40 m high WRSF has 400 mm of net percolation per annum). The difference between field and laboratory L:S ratios is therefore many orders of magnitude. Given the L:S ratio is 8:1 in free draining leach column tests then there is a significant excess of H_2O for pyrite oxidation not to be rate limited, based on stoichiometry there is approximately 300 times excess H_2O. As a result of this significant 'over supply' the conditions set up in the laboratory are not as controlled as would be envisaged as the effect of the supply rate of oxygen and water are not studied. That is, it is not an outcome of the testing to determine what effects the test conditions (over supply of oxygen and water) has on reaction rates, or leachate quality.

It should also be noted that the use of such excess H_2O in these tests will inevitably result in significant dilution of leachates. Therefore, leachate strengths are very unlikely to be representative of field conditions, and are in most cases likely to underestimate concentrations by a significant margin. For materials with low sulfide contents this is likely to be of particular concern as these tests will tend to significantly underestimate the concentration of contaminants of AMD leachates in the field as implied dilution factors are many times what may occur in the field.

Industry methods

Oxidation rates and long term predictions for mine drainage quality have typically been estimated through the application of humidity cell and leach column methodologies. The humidity cell (ASTM, 2012) and free draining leach columns (AMIRA, 2002) are two industry accepted kinetic testing methods that expose samples of mine waste rock and tailings materials to wetting and drying cycles to primarily accelerate the oxidation of sulfidic materials. The oxygen-gradient and oxygen consumption methods have been developed as alternatives to laboratory humidity cell and column leach tests and have also been applied in the field (Elberling, 1993; Kempton and Atkins, 2009).

A key feature of all of these tests is that they only allow estimation of the pyrite oxidation rate (POR) or the intrinsic oxidation rate (IOR). In reality oxygen consumption will be influenced by the pyrite oxidation rate (POR) and other oxygen consuming reactions such as carbon oxidation rate (COR).

Humidity cells and free draining leach columns

Samples are typically exposed to wetting and drying cycles to accelerate the oxidation of sulfidic materials. Although these cycles can be modified in an attempt to replicate climatic site conditions, they typically involve wetting cycles that result in significantly greater liquid to solid ratios than may actually be experienced within a waste rock storage facility. Oxidation rates are estimated by the sulfate release method through the stoichiometric relationship between the mass of sulfate released over time to the quantity of pyrite oxidized (AMIRA, 2002; ASTM, 2012; Elberling et al., 1994).

Using analytically determined sulfate concentrations in humidity cell or column leachates to estimate oxidation of sulfide can be difficult due to the tendency for secondary sulfate salts to precipitate before being released in the leachate (Hammarstrom et al.). This highlights an important distinction between the sulfate release rate and the sulfate production rate with the latter representing the weathering rate of pyrite (Sapsford et al., 2009). If all generated sulfate is not released the weathering rate will be underestimated assuming the release of sulfate is representative of pyrite oxidation. Conversely, the weathering rate may then be overestimated if at a later date, the stored secondary salts are dissolved and released into the leachate (Sapsford et al., 2009).

Oxygen-gradient and oxygen consumption methods

The oxygen-gradient method, otherwise known as the oxygen diffusion method, relates the flux of oxygen through a material to the rate of sulfide oxidation (Elberling et al., 1994). As oxygen is consumed by pyrite, a gradient forms in the profile which drives the diffusive transport of oxygen (Elberling et al., 1994). This method assumes that the main process controlling oxygen transport is diffusion and the amount of oxygen consumed by oxidative reactions is equal to the oxygen flux at steady-state conditions (Elberling et al., 1994).

The oxygen consumption method, which is becoming more prevalent in industry, measures oxygen consumption in a fixed chamber by monitoring changes in pressure or changes in oxygen concentration (Hollings et al., 2001). The consumption of oxygen is assumed to be proportional to pyrite oxidation enabling the calculation of a pyrite oxidation rate (kg pyrite/kg material/year) (Elberling et al., 1994; Schmieder et al., 2012).

One significant advantage of these two methods is the short testing period and therefore they are very useful in providing quick and inexpensive estimations of oxidation rates. However, these methods do not provide information on potential saline and metalliferous drainage quality with time as provided by humidity cell and column leach tests. Another uncertainty is how these methods account for pyrite oxidation by ferric iron or any other oxidation processes consuming oxygen in the subsurface. The oxidation of pyrite by ferric iron does not consume oxygen and therefore the oxidation rate estimated by the oxygen-gradient or oxygen consumption method may be underestimated if conditions conducive for ferric iron exist. Although the oxidation of ferrous to ferric iron does use oxygen, the stoichiometric relationship is different to that of pyrite oxidation.

Advanced customisable leach columns (ACLC)

Given the identified limitations associated with industry standard testing methods, and OKCs extensive database of in situ site monitoring data from WRSFs, OKC has sought to develop an alternative laboratory method to understand the kinetics of geochemical reactions. This method is termed advanced customisable leach column (ACLC). To date, laboratory methods have been designed on a reverse engineering principal as field conditions are not applicable to the design and conditions of the test. OKC has taken the opposite approach to design of ACLCs to enable field conditions to be replicated in the ACLC test or to be adjusted on a site specific and scaled basis. An important consideration of a site specific and scaled basis is the flexibility in design to allow the direct replication of field conditions and potential changes to conditions in future scenarios such as rehabilitation.

Establishing field conditions based on site data

Prior to designing the ACLC tests OKC completed a number of field investigations to determine in situ field conditions within a number of WRSFs. During 2013 and 2014 OKC completed drill programs that resulted in 2,000 m of sonic drilling, the recovery and detailed analysis of over 2,000 samples of core material and the installation of over 150 instruments within 12 WRSFs up to a depth of 100 m. The WRSF monitoring systems were equipped with instrumentation to measure in situ moisture, oxygen pore-gas concentrations, pore-water pressure and in situ temperature within the WRSFs. OKC has published a number of papers (Pearce, S. and Barteaux, M. 2014a, 2014b) describing the results of these large scale intrusive investigations of WRSFs in Western Australia. The principal finding from the study are that:

- L:S ratios are very low in the WRSFs due to the semi arid climate and the process of advective drying where by advective gas flux through the waste actively removes pore water. Geochemical analysis of drill core from this study indicates significant presence of secondary sulfate minerals which are indicative of precipitation of sulfate bearing minerals as a result of stationary pore fluids (and therefore a very low L:S ratios). The geochemical system can therefore be best thought of as semi closed in that oxygen and H_2O (possibly supplied from internal evaporation rather than matrix pore water flow) can enter the waste but very limited leachate leaves the system. This results in a buildup of secondary sulfate minerals.

- Data from oxygen and temperature probes installed within WRSFs along with analysis of sulfate:sulfide ratio of pyrite containing material were used to determine field gas flux rates within the WRSF using analytical calculations and field based IOR. This analysis indicates that gas flux may vary by an order of magnitude based on the internal structure of the waste and particle sizing. Oxygen ingress rates within the WRSF were found to range from locations with surplus to those with deficit required to support the theoretical POR derived from industry standard kinetic testing methods (AMIRA columns). It is noted that measured POR field rates range from 10% to approximately 80% of the laboratory rate. The supply of oxygen (gas flux)

is therefore likely an important control on field PORs, and importantly the data indicates that in some areas of the WRSF oxygen supply may not be a rate limiting factor to field POR.

Design and Construction

The ACLCs are engineered to closely simulate in situ WRSF conditions in the field, thereby replicating them in a laboratory environment. Specific field conditions that were included in design considerations comprise airflow rates, ambient temperature, and water dynamics (water application rates and drying). Components of the ACLC that support the control of these field parameters in the laboratory include the large capacity (25kg) and diameter (100mm) of the columns, a dedicated temperature controlled room, variable air flow gauges for each ACLC, automated air flow solenoids, and automated sprinkler heads. A fully automated monitoring system provides the ability to customise each ACLC to a specific set of controls, i.e. reduced or increased air flow rates.

Each ACLC is fitted with a material supporting layer at the base consisting of nylon balls, and geofabric to allow for leachate collection and to maintain air flow from the base of the column. At the top of the column custom sprinkler heads for the even distribution of water to the material surface. Whilst not necessary to replicate field conditions, these features improve the overall functionality of the system. Leachate samples are collected at the base of the columns by gravity drainage into large glass flasks. An engineered exhaust and watering system allow for each ACLC to be isolated from external pressure and air influences, meanwhile allowing for potentially low oxygen and hazardous gas to be extracted from the laboratory safely and efficiently.

Installation of Monitoring Equipment

The ACLCs are equipped with a fully automated monitoring system designed to monitor temperature, matric potential (wetting and drying), and oxygen and carbon dioxide concentration of exhaust gas. The system is controlled by programmable dataloggers, which can be customised to dictate measurement frequency, control air flow and water into the system, and are expandable to accommodate various sensor types and sensor numbers depending on research objectives. Sensors currently employed in the ACLC monitoring system include Apogee galvanic oxygen probes, Decagon MPS2 matric potential sensors, and non-dispersive infrared Co_2 instruments.

The MPS2 is utilised to monitor the suction (negative pressure) of the column material, providing information on wetting and drying processes occurring within the material following wetting events and during drying phases. The MPS2 also measures temperature which allows for monitoring potential exothermic oxidation reactions occurring in the ACLCs. Oxygen and Co_2 is monitored at the exhaust, located at the top of the ACLCs allowing direct measurement of oxygen consumption and thus determination of IOR but also allows estimation of COR and POR as Co_2 is measured as well as oxygen. Sensors are installed in-line with the exhaust system so that gas exiting the column will pass over the sensors, providing readings of composition.

Summary of method

Table 4 presents the key parameters for the humidity cell and free draining leach columns methods. For comparison, Table 4 also presents the potential ranges for key parameters for the ACLCs.

Table 4 Laboratory to field scale factors

Method	Sample Mass (kg)	Grain Size (mm)	Air Temp (°C)	Air Flow (L/m)	Annual Liquid to Solid Ratio
ACLC	10–25	<50	20–45	<0.1–1	>0.1
Humidity Cell (ASTM, 2012)	1–2	<6.3	23–31	1–10	13-26
Free Draining Leach Columns (AMIRA 2002)	2–2.5	<4	30–35	-	10-13

Comparison of leachate quality from lab to field

Figure 1 shows the results from analysis of field seepage data, leachate from the ACLC column constructed for the site, and AMIRA column testing data used for previous predictions of seepage water quality. As is clear from the results the higher L:S ratio of the AMIRA column significantly impacts the ability to make informed use of this data to predict field seepage conditions as concentrations of key metals like aluminum are significantly underestimated. In comparison the low L:S ratio of the ACLC test produces seepage quality results that are much closer to field conditions and therefore offer a much more direct means to assess and predict field seepage quality.
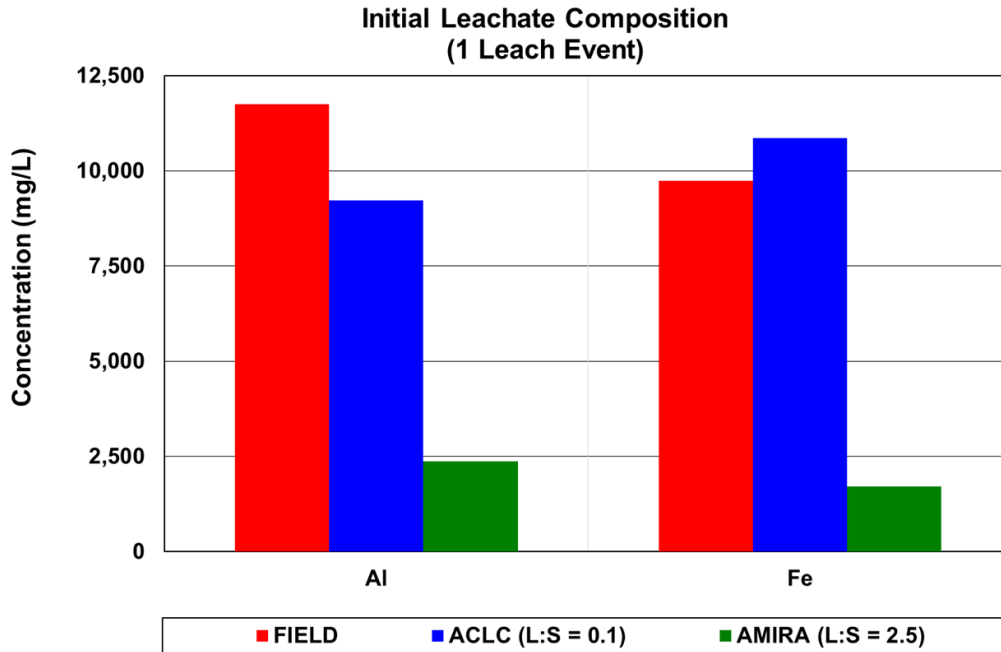
Figure 1 *Leachate quality based on field seepage, ACLC and AMIRA leach columns*

Conclusions

A number of key issues have been identified with using industry standard kinetic testing for predictions of geochemical evolution of waste materials containing sulfides in the field due to significant uncertainty with how to apply scale up factors for the extrapolation of laboratory data to the field. In an attempt to resolve this challenge of scaling up laboratory results, a new laboratory testing method has been derived that can accommodate and replicate site specific conditions. This method is termed the advanced customisable leach column (ACLC). The highly engineered columns have allowed for field conditions to be simulated in a laboratory setting while automated monitoring systems providing flexibility in controlling research variables.

Extensive field data collected as part of extensive intrusive WRSF drilling projects has been used as a basis for the design of the ACLC to allow laboratory conditions to closely replicate in situ field conditions thereby reducing the difficulty in scaling laboratory leach experiments to field scale. Reducing uncertainty about scaling factors will allow for more accurate estimates of field POR.

Key features of the columns include both their capacity, size and technical specification. Columns can be adapted for different conditions depending on site specific conditions and variability. Ongoing monitoring of the column conditions by automated temperature control and monitoring, automated oxygen consumption and carbon dioxide production monitoring, and soil moisture/matric suction monitoring enable rapid and reliable data collection for interpretation.

The flexibility of the design allows for more accurate field based assessment of POR, COR and IOR rates, through increased controls on temperature, water and oxygen availability. As such, by completing

concurrent assessments of the same material type under different conditions the ACLC system allows the assessment of the potential effectiveness of waste management options, such as deposition within a reduced oxygen environment, as simulations of reduced net percolation rates or oxygen ingress rates can be accommodated.

Low L:S ratios that are common to WRSF during the periods during and shortly after construction, and over longer time frames in semi arid environments have been identified as a particular challenge for industry standard methods to replicate. These conditions can be better represented by the ACLC as leaching is not required to generate a POR, COR or IOR as inline oxygen and carbon dioxide monitoring allows direct measurement of these rates. This means that leaching rates at L:S <0.5 can be simulated which allows more representative estimation of seepage quality as the effects of solubility controls are directly studied.

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