Ore permeability methods of evaluation and application to heap leach optimization

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Abstract

Efficient recovery of mineral resources from ore heap leaching requires good ore permeability to optimize metallurgical recovery. Solution and air (in the case of copper sulfide ores) need to move freely through the heap for adequate reagent-ore contact to occur. The primary factors that influence leach ore permeability include ore/rock behavior resulting from blasting and crushing processes, ore lift height and lixiviant irrigation rate. In the case of acid leaching, chemical decrepitation from agglomeration and raffinate contact (chemical crushing) are also factors. Whereas the generation of "fines" significantly affects ore permeability, the overall gradation of the material and how it consolidates (compacts) within the heap and over leaching time-frames also greatly influence permeability. Solution and air permeability typically decrease under increasing heap heights, and air permeability decreases under increasing irrigation rates. Depending on the ore type, ore consolidation may result in minor reductions in ore permeability, or may significantly decrease the permeability, thereby causing increased leach times, incomplete recovery and reduction of the economic value of the process.

A variety of physical and hydraulic laboratory property tests can be used to evaluate the solution and air permeability of leach ore material prior to placement on a pad. These tests are designed to emulate the effect of physical and chemical crushing on the physical and hydraulic properties of the ore, and the effect of construction methods (heap lift height) on the consolidation and permeability of the ore material. The primary physical and hydraulic parameters of concern are:

- the full particle size distribution resulting from ore processing and reaction with the lixiviant;
- consolidation of ore under different overburden pressures and changes in particle size distribution resulting from leaching; and

- the saturated permeability, soil water characteristic curves and air permeability under different irrigation rates.

These data are typically interrelated and can be reasonably related to ore specific physical properties. In addition, there is evidence that the bulk particle size distribution of post-leached ore samples and fully crushed (< #10 mesh) pre-leach ore samples can be related to the hydraulic characteristics of individual ore types.

Hydraulic property parameters developed from lab testing can then be used within a geometallurgical classification scheme to predict the hydraulic performance of different ore materials under different operational strategies. Typical geometallurgical classification schemes may incorporate factors such as rock type, degree of alteration, and resistance to physical and chemical crushing. A case study which compares different ore types based on geometallurgical classifications to laboratory derived hydraulic properties using the aforementioned test schema will be presented as an example of how quantifying the hydraulic properties of different ore types can be used to guide and optimize heap leaching operations.

Introduction

Ore permeability has long been recognized as a critical factor in heap leaching performance. Poor ore permeability results in decreased metal recovery and increased leach recovery time. Heap leaching practitioners generally attribute poor permeability to a variety of factors including a large proportion of fine particles (< #100 mesh) within the ore matrix, the migration of fine particles deeper into the heap and the loss of porosity and permeability due to ore consolidation, compaction or decrepitation. Finally, heterogeneous permeability is inherent in any porous media; ore blasting, processing, heap construction and irrigation practices affect the permeability distribution and can result in low or delayed metal recovery due to poor ore-solution contact and solution channeling through preferential flow paths.

Ore permeability can be improved by agglomeration to bind fine particles to coarser particles which provides a more uniform distribution of particle sizes (McClelland, 1986; Lastra and Chase, 1984). This in turn increases the amount of large pores to facilitate solution flow and also typically improves solution distribution within the ore. Whereas gold ore agglomerates are typically stable because of the use of cement, agglomeration of base metal ores with sulfuric acid or other binders is frequently unstable due to ongoing chemical decrepitation during the leaching process (Lewandowski and Kawatra, 2009).

In the case of bio-assisted leaching, both solution and air need to move freely through the heap for adequate reagent-ore contact to occur. High temperature bio-assisted heap leaching (Dew et al., 2011) has even greater needs for aeration efficiency. There are a number of factors that influence leach ore permeability, including: ore/rock behavior under physical crushing, chemical decrepitation from acid agglomeration and raffinate contact (chemical crushing), the nominal crush size, heap height and lixiviant irrigation rate. It is very challenging to accurately characterize the effect of these factors on permeability, and to identify spatial and temporal effects on permeability within large industrial heaps.

Over the last decade, we have developed several laboratory and field methods to improve our understanding of solution and air flow behavior in heap leach materials. Laboratory methods, which are the focus of this paper, include:

- using large diameter cores;
- directly measuring the hydraulic conductivity function under irrigation with the lixiviant; and
- using flexible wall methods to determine solution and air permeability under variable bulk density and irrigation conditions to mimic the effect of overburden pressure and chemical decrepitation.

Leach ores have been tested from a number of sites in North and South America, with reasonable agreement between measured leach ore permeability and heap leach performance.

In this paper we provide an example of a laboratory permeability testing program that simulated effects of operational conditions on ore hydraulic properties and correlations of permeability and ore physical properties which allows for mapping of ore body permeability.

Methods

Eighteen samples with different mineral associations and alterations were selected for hydraulic property testing. The following briefly describes the leach ore material hydraulic testing procedures used in this study.

Anticipated ore permeability classification

The eighteen samples represent a variety of geologic facies and alteration from one mine pit. Prior to the hydraulic property testing, the ores were grouped into three expected permeability types: "Bad", "Regular" and "Good" based on known geometallurgical properties such as mineral type, particle distribution under crush, alteration, rock quality designation, rock strength and clay type and fraction.

Hydraulic and physical property test overview

The eighteen ore samples were processed as follows: 50 kg of drill core of each leach ore sample was crushed to 1.27 cm diameter (25 mm tertiary crusher setting). The <1.27 cm crush samples were screened and divided into 12 size fractions with screen sizes of >22.2 mm, >19 mm, >16 mm, >12.5 mm, >9.5 mm, >6.3 mm, >#4, >#14, >#35, >#65, >#100, and <#100. Based on the target sample weights needed for the various physical and hydraulic property tests, sample fractions were split using a universal type splitter (Versa-Splitter) and reconstituted to the target sample weights with identical particle size distributions. Each fraction was split a minimum of three times before reconstitution.

Each of the <1.27 cm diameter (whole) samples was thoroughly agglomerated in two batches in a mixer with 5% to 12% raffinate content by sample weight until all the fines agglomerated to the larger particle sizes. Then 19 or 7.5 kg of H_2SO_4 per ton of sample material, depending on the ore-type, was added to the batches; after thorough mixing, the samples were cured for at least three days.

Physical property screening tests were conducted on sample material to include:

- 1.27 cm crush sample particle size distribution (PSD) on before (pre-test) and after (post-test) hydraulic property testing to determine the gradation of the material size fractions and examine the effect of decrepitation.
- Specific gravity to determine the mineral density before hydraulic property testing.
- Atterberg limits to determine clay characteristics after hydraulic property testing.
- Specific surface area (SSA) was calculated from pre-test and post-test PSD data.

The following hydraulic property tests were conducted on the 1.27 cm crush samples over a range of bulk densities representative of conditions from the top to the bottom of 20 m ore lift height:

- Consolidation-permeability tests to estimate changes in saturated hydraulic conductivity (Ksat) at pressures mimicking various heap heights.
- Direct irrigation measurements (unsaturated hydraulic conductivity [Kunsat]) to determine solution content and air porosity at different irrigation rates and ore densities.
- Air permeability tests during the Kunsat measurements as a function of solution content, air porosity, and repacked ore sample density.

Hydraulic property testing methods

Consolidation-permeability tests were conducted in 15 cm diameter by 30 cm high, dual wall permeameters on the 1.27 cm crush samples. The dual wall permeameter provides a more even distribution of pressure to the ore compared to the vertical pressures applied in a rigid wall (uniaxial) consolidation permeability test. Dual wall permeameter procedures for flexible wall permeameters are specified in ASTM D5084-03 (American Society for Testing and Materials, 2003). The sample is packed to an initial relatively low bulk density and then saturated overnight with raffinate leach solution by upward infiltration. Subsequent hydraulic conductivity tests are performed over a range of sample consolidation created by increasing the flexible wall membrane pressure to mimic increasing lateral earth pressures within the heap.

Dual wall permeameters were packed to initial bulk densities between 1.53 and 1.64 g/cm^3. Sidewall stresses of 0 kilopascal (kPa) to 140 kPa were applied to simulate vertical pressures of up to 420 kPa depending on the sample. Ksat tests were run via upward infiltration for 8 hours using a constant head of approximately 3 cm.

The simulated heap height is calculated from an assumed relationship between lateral earth pressures applied to the side-walls and the overburden pressure (and heap height). The "at rest lateral earth pressure ratio" or "coefficient of earth pressure at rest" (K_0) is the ratio of horizontal pressure (or stress) to vertical pressure. K_0 is a function of the ore's angle of shear resistance (or effective angle of internal friction) φ' and in its simplest form can be calculated as (Bishop, 1959):

$$K0 = 1\text{-}\sin(\varphi') \quad (1)$$

For sandy gravel material such as leach ores, φ' is expected to range from 35 to 50 degrees, such that K_0 may range from 0.23 to 0.42 (Bowles, 1988); thus K_0 is assumed to average 0.33 for the tests. Consequently, overburden pressures within the heap can be simulated up to approximately 20 m.

Direct irrigation (Kunsat) tests were performed using the dual wall permeameter and a range of bulk density values representing different heap heights as determined from the dual wall consolidation permeability Ksat results. Raffinate solution was applied to the surface of the ore through an evenly distributed network of irrigation points at two different rates, a low rate (≈ 1 to 2 $l/m^2/hr$) and a high rate (≈ 6 to 13 $l/m^2/hr$). A constant suction of approximately 30 cm was applied to the bottom of the core by a wick. Water content and tensiometer sensors were also buried within the leach ore to continuously measure water content and matric potential (capillary pressure) at two depths in the ore column.

Air permeability was determined during periods of irrigation and solution drainage (i.e. no raffinate irrigation) by injecting air into the bottom of the dual wall cell during the direct irrigation experiments. Air permeability is determined by measuring the pressure drop across the bottom to top of the cell with several air flux rates (9.4×10^{-3} to 0.45 cm/sec) used to confirm the consistency of measurements.

Specific surface area calculations

Specific surface area (SSA) is defined as the total surface area of the particles per unit mass. The clay fraction largely determines the SSA of a material because the SSA of a clay particle is upwards of 100 times greater than that for a sand particle. Specific surface area for each ore sample was estimated based on the relative mass of the different particle size diameter groups. For the estimation, all particles were assumed to be spherical, allowing the SSA to be calculated from the particle size distribution using the summation equation:

$$SSA = \frac{6}{\rho_s}\sum\frac{c_i}{d_i} \quad (2)$$

Where ρ_s is particle density and c_i is the mass fraction of particles of average diameter d_i. This estimation method likely underestimates SSA because particles have irregularities and are not smooth spheres. For example, clay may be platy in shape which would produce a larger surface area than a sphere, and the estimation does not consider expanding type clays. Nonetheless, errors associated with the estimation method are likely to be relatively consistent for all samples, allowing comparative analysis of SSA to be valid.

Correlation analyses

Correlation analyses were conducted by fitting power functions to the relationships between the 1.27 cm crush Ksat values at estimated heap heights of 3 m, 6 m, and 10 m compared to:

- estimated post-test 1.27 cm crush sample SSA;
- estimated pre- and post-test 1.27 cm percent passing #100 mesh; and
- PSD indicator which is calculated as the percent retained by the #4 mesh/percent passing the #100 mesh (> #4 mesh/< #100 mesh).

Results

Particle size distribution

All of the ore samples tested showed some signs of decrepitation (chemical crushing) during the hydraulic property testing. Table 1 compares the observed change in the percent of material passing the 1.27 cm, #4 mesh (4.75 mm), and #100 mesh (0.15 mm) before and after the hydraulic property testing. The anticipated "Bad" ore types showed the lowest PSD indicator values and with the exception of M9, the anticipated "Good" ores showed the greatest values. Two anticipated "Regular" ores also showed low PSD indicator values. Of note, the initial PSD was a poor predictor of the final PSD after agglomeration and leaching; this is due to variable resistance to decrepitation from acid between the different ores.

Table 1 also presents PSD indicator values for pre- and post-test material. The PSD indicator relates the proportion of large particles (> #4 mesh), which increase permeability by creating large, clast supported pore sizes, to small particles (<#100 mesh) which decrease permeability by reducing the average pore size diameter. Previous test work by the authors (data not published) indicates the post-test PSD indicator is well correlated to ore permeability since it is representative of the material gradation, which is not reflected in the percent passing the #100 mesh. Previous work also shows that post-test ore samples with PSD indicator values lower than 2.0 show unacceptable permeability and values greater than 3.0 show acceptable permeability for heap leaching; ore samples values between 2 and 3 can show either poor or good permeability. Comparison with Ksat testing shows that for this group of 18 samples, all of the samples with post-test PSD indicator values greater than 3.0 showed acceptable permeability.

Table 1: Change in percentages of material passing the 1.27 cm sieve, # 4 mesh, and #100 mesh and pre- and post-test PSD indicator values

Sample	Expected ore permeability group	Change in percent material passing (Post-test – Pre-test)			Pre-test PSD indicator	Post-test PSD indicator
		12.7 mm	4.75 mm	0.15 mm		
		1.27 cm	#4 mesh	#100 mesh		
M16	Bad	27	28	23	5.35	0.85
M17	Bad	18	27	29	10.95	1.11
M22	Bad	5	8	20	1.65	0.70
M7	Bad	−2	−5	14	4.65	2.21
M4	Regular	8	11	11	8.67	2.56
M5	Regular	6	3	8	9.34	3.93
M8	Regular	4	8	10	7.01	2.79
M10	Regular	5	3	8	16.09	5.17
M14	Regular	2	1	10	9.01	3.31
M18	Regular	−1	2	7	16.42	6.27
M2	Regular/Good	1	3	9	6.21	3.11
M13	Regular/Good	2	2	6	7.88	4.14
M1	Good	−4	−1	10	16.82	4.38
M3	Good	2	10	7	11.68	4.31
M6	Good	2	2	8	13.05	4.77
M9	Good	0	4	11	4.54	2.22
M15	Good	−2	−3	1	7.40	7.00
M20	Good	−7	−2	7	10.41	5.08

Saturated hydraulic conductivity testing results

Ksat was measured as a function of estimated heap height (applied equivalent pressure) and ore consolidation (expressed as bulk density) with the dual wall consolidation-permeameters. Ore consolidation was variable as observed by the ore bulk densities. Figure 1 shows the ore sample consolidation under various equivalent heap heights; under 10 m of equivalent heap height bulk densities ranged from 1.72 to 2.05 g/cm^3.

For the purposes of analysis, we have defined acceptable permeability as 100 times greater than the nominal irrigation rate of 6 l/m^2/hr. The 100× permeability safety factor allows for sufficient air permeability and also spatial variability in permeability under field conditions. Figure 2 shows that the permeability criteria of Ksat values of at least 100 times greater than the target irrigation rate is met by eleven samples, at all of the simulated estimated heap heights (from 0 m to about 18 m). Anticipated

"Bad" samples M7, M16, M17, and M22 showed the least favorable performance with acceptable Ksat values at estimated heap heights less than 4 m. Anticipated "Regular" sample M4 and "Good" sample M9 only showed acceptable Ksat values at estimated heap heights less than about 8 m and 6 m, respectively.

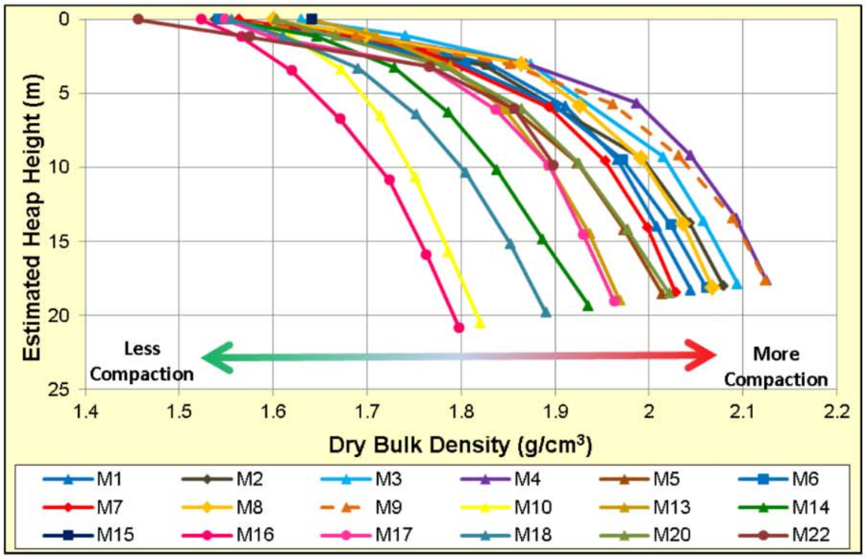

Figure 9: Changes in ore bulk density over estimated equivalent heap heights

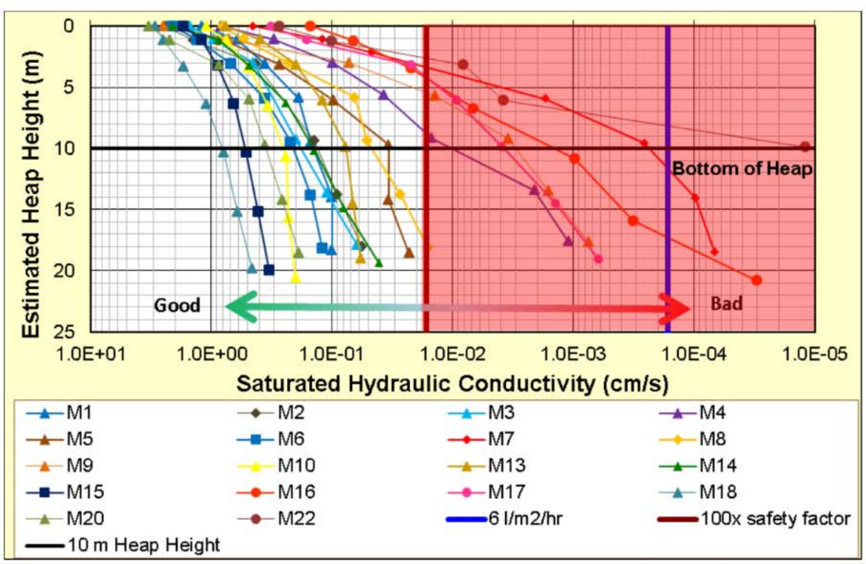

Figure 10: Changes in Ksat over estimated equivalent heap heights

The consolidation-permeability results are consistent with a greater percent of post-test fines in samples M7, M17, M16, and M22 and higher plasticity and slightly greater percent of post-test fines in M4 compared to the remaining samples. However, the maximum bulk density did not correlate highly to

Ksat, because pore size distribution also contributes significantly to permeability. For example, sample M4 had the highest maximum bulk density and intermediate performance; M16 had the lowest maximum bulk density and the third worst performance. Relative changes in bulk densities were most pronounced in samples that were well graded, poorly graded samples (samples with a high percent of large or small particles) showed the least consolidation.

Unsaturated hydraulic conductivity and air permeability testing results

Under direct irrigation testing in the dual wall consolidation-permeameters the volumetric solution contents were observed to increase by 1% to 6%, resulting from an increase from low irrigation rates (1 to 2 $l/m^2/hr$) to high irrigation rates (6 to 13 $l/m^2/hr$). The "Good" ore samples generally showed greater air porosity and small changes in air porosity with increasing heap height conditions, which indicates that the pore size distribution for these samples does not change significantly under consolidation pressures. Higher initial volumetric solution contents and larger increases in solution content were observed in the remaining samples under increasing irrigation rates. Of note, the anticipated "Bad" samples M7, M16, M17, and M22 all showed ponding (and zero air permeability) under high irrigation rates at estimated heap heights of 6 m or less. M4 showed ponding under high irrigation rates at estimated heap heights above 9 m. These results are consistent with the saturated hydraulic conductivity test results.

For the purposes of analysis, we have defined acceptable air permeability as 100 Darcies at the target irrigation rate. 100 Darcies is believed to allow sufficient air permeability and interconnectivity of air pore space for efficient aeration. Figure 3 through Figure 5 show the measured air permeability plotted versus the estimated equivalent heap height for the anticipated "Bad", "Regular", and "Good" ores, respectively. Significant changes in air permeability (from around 600 to 0 Darcies) were observed under low and high irrigation rates and variable estimated heap heights for anticipated "Bad" samples M7, M16, M17, M22, "Regular" sample M4, and "Good" sample M9. These samples also failed the Ksat permeability criteria of greater than 100× the nominal irrigation rate. Samples M1, M6, M10, M13, M14, M15, M18, and M20 showed air permeability greater than 100 Darcies at estimated heap height greater than 10 m under both high and low irrigation rates.

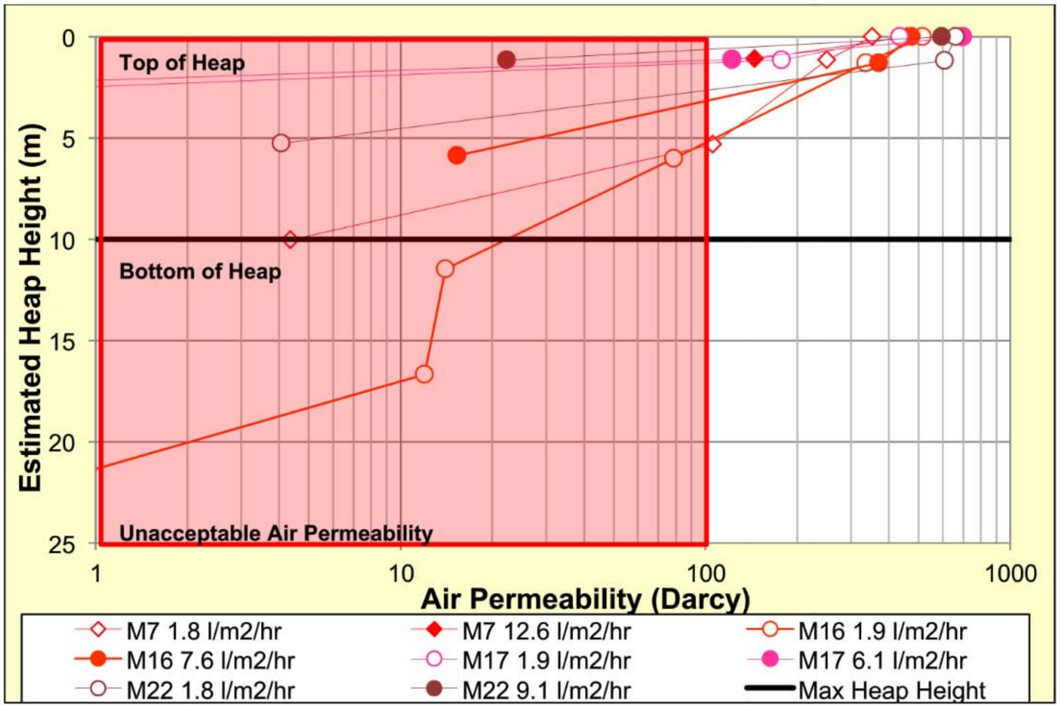

Figure 11: Air permeability versus estimated heap height for "Bad" samples

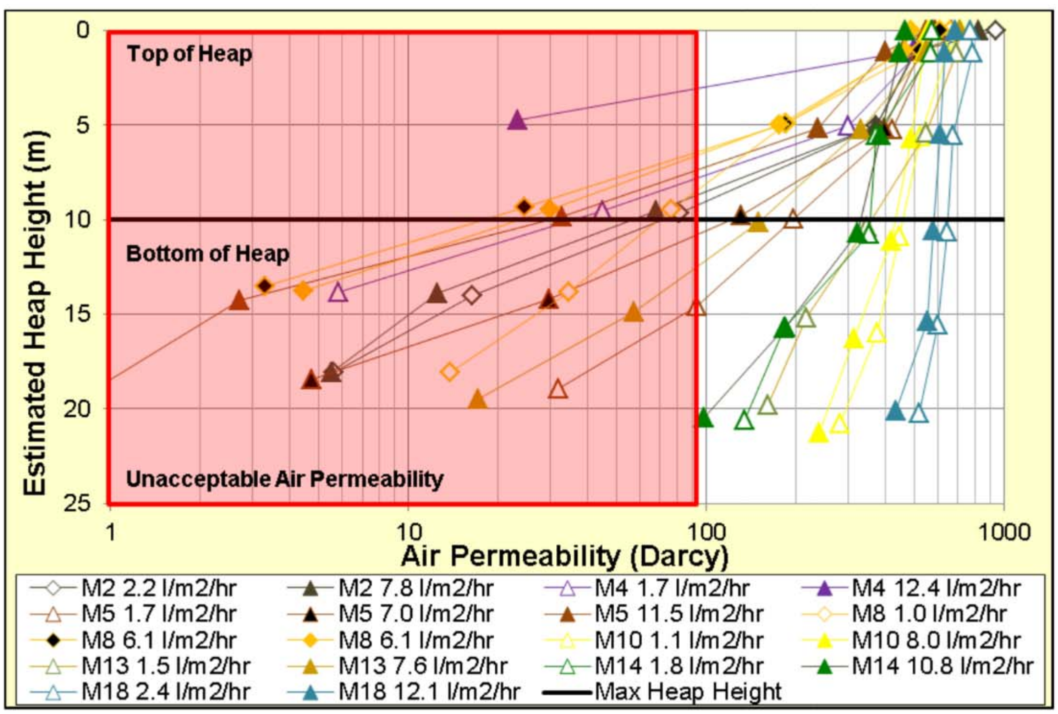

Figure 12: Air permeability versus estimated heap height for "Regular" samples

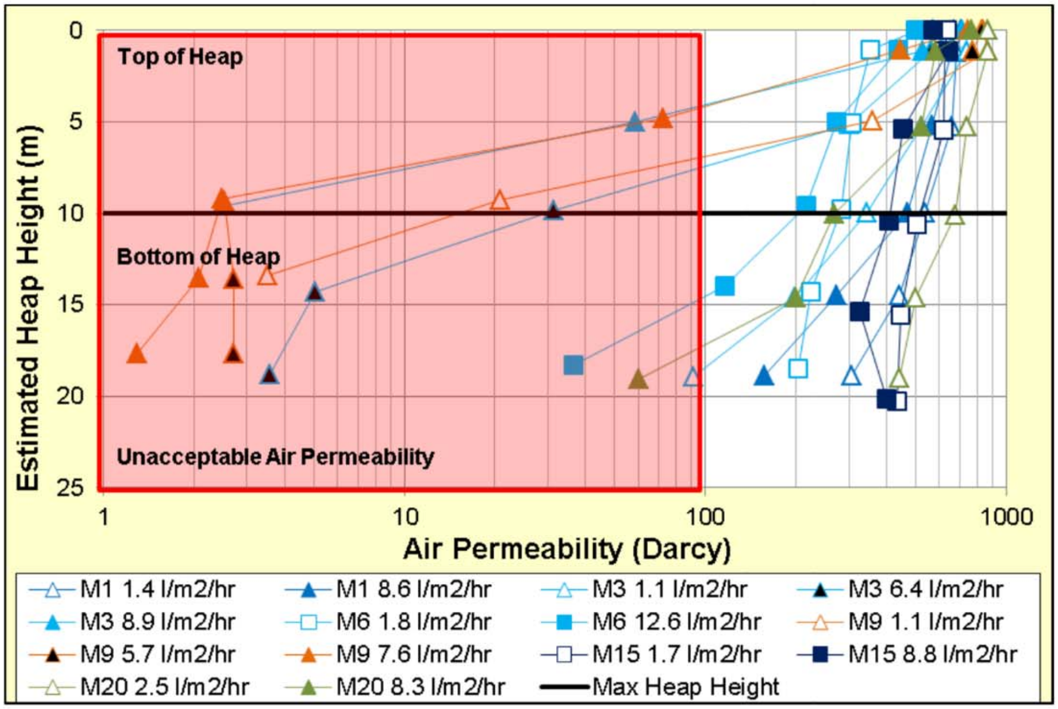

Figure 13: Air permeability versus estimated heap height for "Good" samples

Of note, the air permeability of samples M2, M3, M4, M5, M7, M8, M16, M17, and M22 typically decreased by 50% or more at the high irrigation rates compared to the low irrigation rates. This indicates that the pores contributing to air permeability (active air porosity) in these samples consist of relatively small pore diameters that become filled with solution at higher irrigation rates with a concomitant reduction in air permeability.

Correlation analyses

Correlation analyses were performed to evaluate potential relationships between Ksat values for the ore samples under different heap heights and estimated SSA, the PSD indicator, and the percent passing the #100 for the pre-test and post-test < 1.27 cm crush samples. Table 2 summarizes the results of the correlation analyses of Ksat values at estimated heap heights of 3 m, 6 m, and 10 m.

Low correlations were observed between the Ksat values and estimated SSA at all estimated heap heights (Table 2). Low correlations were also observed with the pre-test percent passing the #100 mesh. R^2 values for Ksat and the post-test percent passing the #100 mesh greatly improved to 0.88, 0.80, and 0.81 at estimated heap heights of 3 m, 6 m and 10 m, respectively. This result is expected since decrepitation causes large changes in PSD before and after hydraulic property testing.

Table 2: Ksat correlation analysis (R^2) results[1]

Test parameter[2]	K_{sat} < at 3 m	K_{sat} < at 6 m	K_{sat} < at 10 m
Estimated SSA (post-test)	0.41	0.50	0.49
Passing #100 mesh (pre-test)	0.50	0.49	0.63
Passing #100 mesh (post-test)	0.88	0.80	0.81
PSD indicator (post-test)	0.89	0.75	0.78

[1] R^2-values from fitting a power function relationship

[2] Passing #100 mesh, PSD indicator values and SSAs were calculated from the PSD of the respective sample

The post-test PSD indicator value was also highly correlated to Ksat, but correlation values were slightly lower at the 6 and 10 m estimated heap heights than correlation values with the percent material passing the #100 mesh. Overall, the post-leach values for percent passing #100 mesh and the PSD indicator can reasonably predict the measured Ksat for the ore samples.

Correlation analyses were also performed on the measured air permeability of the 1.27 cm crush ore samples at estimated heap heights of 6 m and 10 m under both low and high irrigation rates. Correlation was moderate to strong (R^2 = 0.74 and 0.86) for air permeability under low irrigation rates. Correlation with air permeability was poor at high irrigation rates (R^2 = 0.54 and 0.42). Under low irrigation rates the correlation increased with heap height, whereas under high irrigation rates the correlation decreased with heap height. These results indicate that the measured Ksat values can reasonably predict air permeability under low irrigation rates, but that additional data (i.e. moisture retention characteristics) are needed to predict air permeability at high irrigation rates.

Conclusions

Eighteen ore samples were tested for saturated and unsaturated hydraulic conductivity and air permeability characteristics under a range of estimated heap height conditions. The laboratory testing program was used to validate and improve the geometallurgical classification scheme used to predict the ore permeability and thereby optimize heap leach operations. Acceptable permeability is defined as Ksat being greater than 100 times the nominal irrigation rate (6 $l/m^2/hr$) and air permeability greater than 100 Darcies.

All of the samples showed some decrepitation during testing. Decrepitation significantly affected the permeability of some of the samples, whereby they had a low percent passing the #100 mesh before hydraulic property testing, but produced “Bad” permeability performance. Measured Ksat values met the acceptable permeability criteria at 10 m equivalent heap heights for all of the samples except anticipated

"Good" sample M9 (< 6 m heap height), "Regular" sample M4 (< 8 m heap height) and "Bad" samples M7, M16, M17, and M22 (< 5 m heap height). These samples showed similar poor air permeability behavior. Air permeability for all "Bad" samples and some "Regular" and "Good" samples decreased by 50% or more at the high irrigation rate (12 $l/m^2/hr$) compared to the low irrigation rate (2 $l/m^2/hr$).

Post-test PSD indicators ranged from 0.70 to 7.0. Samples with PSD indicators less than 3 did not meet the acceptable solution or air permeability criteria under high irrigation rates at estimated heap heights up to 10 m. The post-leach percent passing the #100 mesh and the PSD indicator values showed the strongest correlations to the measured Ksat values for 1.27 cm crush samples. The poor correlation of solution and air permeability with pre-test percent passing #100 mesh and PSD indicator values is consistent with results from a large number of ore samples from other properties we have tested (data not-published), and serve as a caution to heap leach operations that rely on pre-test < #100 mesh values to predict permeability.

Acknowledgements

This work would not have been possible without project support and collaboration over many years from BHP Billiton Base Metals, Barrick Gold, Freeport McMoran Copper and Gold, Newmont Gold and Dirk van Zyl of the University of British Columbia, from which our methods have been developed and tested. Many thanks also to all the workers in the GeoSystems Analysis, Inc. laboratory for their diligence and commitment to excellence.

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