# *DEMONSTRATION OF THE APPLICATION OF UNSATURATED ZONE HYDROLOGY FOR HEAP LEACH OPTIMIZATION*

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## SUMMARY

Heap leaching has become a widely used method of mining low-grade gold, silver, copper, and uranium ores. One of the key components to success in heap leaching is favorable heap hydrology. Heap leach piles are unsaturated systems and therefore must be addressed as such, by applying the knowledge and tools of unsaturated soil science to design and optimize operation. This report presents the results of a laboratory column study completed to further characterize the nature of preferential flow within heap leach piles and its impact on mineral leaching. Numerical modelling of the column tests was completed to demonstrate the potential of developing a successful model for the prediction of heap leach performance using an unsaturated hydrology model as a basis. The objective was to demonstrate the application of unsaturated zone hydrology to aspects of heap and dump leach hydraulic dynamics.

Layers of coarse and fine textured ore inevitably develop within heap and dump leach piles as natural processes segregate coarse and fine material during material placement. Segregation of heap leach material will occur regardless of whether the material is agglomerated or non-agglomerated. Clearly, segregation is significantly reduced for agglomerated heap leach materials. However, due to the methodologies employed to place the material, segregation of agglomerated heap leach material will occur. Run-of-mine (ROM) material (i.e. dump leaching) will definitely segregate. Under such conditions leaching solution flows preferentially in the more conductive layer, potentially leaving areas within the heap unleached. The preferred flow path is not dependent entirely on the physical properties of each layer, but also on the stress state and resulting degree of saturation, and therefore the solution application rate. For this reason either the coarse or the finer material can be the preferred flow path. Research completed as part of this study investigated flow rates required to create both preferential flow conditions, and the impact that extreme cases of preferential flow have on the leaching of adjacent layers. This complicated flow and transport problem was then modelled to demonstrate the effectiveness of existing unsaturated zone hydrology numerical models. The objective was to illustrate tools exist for understanding key processes and characteristics that control performance and can improve design and operation.

Column testing revealed that solution application rates greater than the saturated hydraulic conductivity of the finer material resulted in preferential flow in the coarser

layer. The preferred flow path became the finer textured material when application rates were less than the saturated hydraulic conductivity of the fine material.

The coarse and fine textured layers of material in the columns were also “spiked” with salt prior to placement in the column and subsequent leaching. Under preferential flow conditions it was found that 30% of the salt within the less conductive material could be leached from that material by the horizontal movement of water into the more conductive material. This result was dependent on the amount of infiltration into the less permeable layer at the top of the column. An ineffectual volume flowed preferentially if little water originally entered the less conductive material.

Noteworthy is that for the segregated components investigated, the preferred flow path was the finer textured material for application rates common to heap leaching. The implication is that a typical operational response to poor recovery is to increase the solution application rate. However, the effect of this response will potentially decrease recovery because it enhances the potential of the solution to flow in the coarse textured material. It is also a common occurrence for flow to be transported laterally and exit from the sides of the pile under the higher solution application rates, as a result of internal segregation, compaction, consolidation, and generally differences with *in situ* density. The worst-case scenario is a massive slope failure and significant reduction in recovery. The answer for balancing the solution application rate and recovery is rooted in the hydraulic dynamics of the heap or dump leach, which by definition is an unsaturated zone hydrology problem.

The numerical modelling effort successfully reproduced both preferential flow patterns. The preferential leaching which resulted was also successfully modelled. In this way existing unsaturated soil science modelling tools proved to be valuable in predicting the performance of heap leach piles. The study clearly demonstrated that unsaturated zone hydrology should be used as a basis for heap and dump leach performance.

This project was initiated by O’Kane Consultants Inc. and was completed in partnership with the Unsaturated Soils Group, University of Saskatchewan, and M.D. Haug and Associates Ltd. The project was funded in part by O’Kane Consultants Inc., as well as through a grant from the Industrial Research Assistance Program under Contract # 332407.

## 1.0 INTRODUCTION

Heap leaching is a simple, low-cost method of recovering metals from low grade ores, which has come into widespread application in the mining industry. The heap leach process involves percolating a leaching agent solution through broken or crushed ore. A heap under leach is therefore an unsaturated system, because air exists in the pore spaces along with solution. Despite this fact, unsaturated soil science concepts, principles, and tools have yet to be widely applied for the optimization of leaching efficiency. For this reason research was done to demonstrate the usefulness of applying unsaturated zone hydrology to this unsaturated system.

Steeply dipping layers of fine, coarse and well-graded material commonly exist in leaching heaps as a result of segregation that occurs during heap construction. These layers can become preferred flow paths that channel the leaching solution through the heap. Solution channeling causes some regions within the heap to be poorly leached resulting in reduced metal recovery. To gain a better understanding of the nature and impact of this preferential flow condition column tests were conducted.

Column testing was followed by two-dimensional numerical modelling where each of the parameters column tested were simulated using available unsaturated flow modelling software. This was done to demonstrate the potential and value of developing a model for predicting heap leach performance that has heap hydrology as its core.

This report first introduces unsaturated zone hydrology and then discusses the key hydrological aspects of heap leaching. The column testing and numerical modelling methods are then presented and results and conclusions are provided.

# 2.0 BACKGROUND AND THEORY

## 2.1 Unsaturated Zone Hydrology Theory

Unsaturated zone hydrology describes the flow and storage of moisture in a porous media under conditions where an air phase, in addition to the water phase and solid material phase, is present. Alternately, the unsaturated condition can be defined as a situation where soil pore-water pressure is less than atmospheric pressure. This condition is the result of capillary and adsorptive forces that attract and bind water in the soil matrix, and is termed 'capillary potential' or 'matric suction'. This is illustrated in Figure 1, where water raised in a capillary tube, like water in an unsaturated soil matrix, possesses a negative pressure potential.

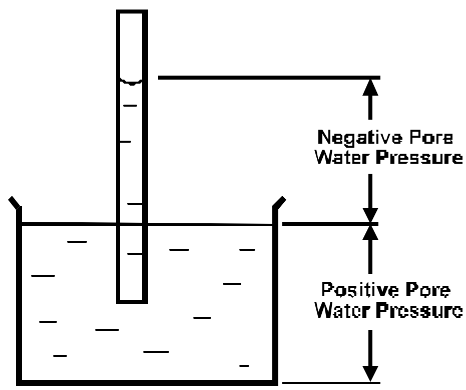


**Figure 1** Sub-atmospheric pressure within a capillary tube.

The key relationship for characterizing an unsaturated material is its soil water characteristic curve (SWCC), which is the relationship between the soil water content and total suction. Total suction has two components, matric suction and osmotic suction. Matric suction is defined as the negative pore-water pressure referenced to the pore-air pressure (i.e. $u_a - u_w$). It is a stress state variable, which is independent of material properties. For example, a sensor installed to measure *in situ* suction can be thought of as a piezometer of the unsaturated zone. In comparison, a piezometer completed below a water table can provide a measure of the positive pore-water pressure. Measurement of the SWCC is central to the design of any unsaturated system, such as a heap leach pile, because it describes the fundamental relationship between the energy state of the pore water, and the volume of water stored within the soil pores. Figure 2 presents typical SWCCs for fine and coarse textured materials.

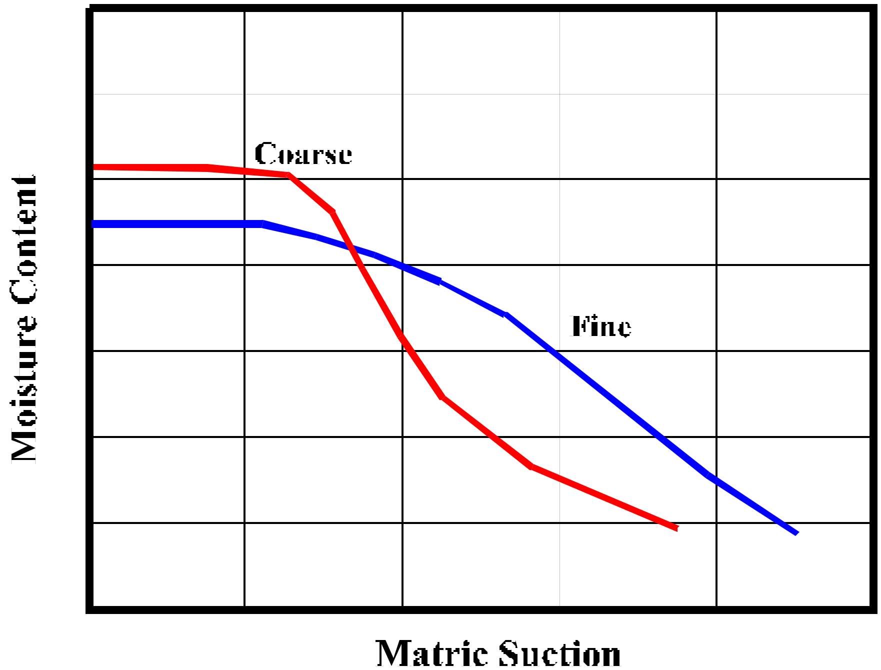


**Figure 2** Conceptual soil water characteristic curves for fine and coarse textured materials.

The finer textured material has the ability to retain moisture under higher suction values as compared to the coarse material because of the formers smaller pore sizes. Hence, the coarser textured material starts to "drain" first as suction is increased from saturated conditions, and loses moisture as suction continues to increase. In contrast, the finer textured material remains at the saturated volumetric water content (i.e. porosity) for the same suction condition. This phenomenon is referred to as "tension saturated" conditions. Ultimately the finer textured material will also begin to drain as the suction is increased. The rate at which the water content decreases with increasing suction is a function of the particle size distribution of the material. A uniform material will tend to drain "rapidly" over a small range of suction values because the pore sizes are generally the same size. Well graded materials will have a gentler slope to the SWCC once drainage conditions are initiated because they possess a wide range of pore sizes. A well graded material will drain under higher and higher suction values starting with the larger pore sizes first as the negative pore-water pressures overcome the water tension conditions within the pores.

The rate at which water flows through a saturated soil is described by Darcy's law and is proportional to the hydraulic head gradient as follows:

$$q_{sat} = -k_{sat}\, dh/dl$$

where,

$q_{sat}$ = flow rate of water,

$k_{sat}$ = hydraulic conductivity,

$dh/dl$ = hydraulic head gradient.

Darcy's law also applies for unsaturated soils; however, in an unsaturated soil the hydraulic conductivity (k) is not constant but is a function of matric suction or degree of saturation. For this reason the flow rate of water through an unsaturated soil, under a hydraulic gradient of one, is equal to the hydraulic conductivity.

The relationship between hydraulic conductivity and matric suction, commonly referred to as the soil's K function, is the second key relationship for the characterization of unsaturated soils. Figure 3 presents typical K functions for fine and coarse grained materials. At saturation and at low suctions hydraulic conductivity is at it's maximum and is referred to as the saturated hydraulic conductivity ($k_{sat}$).

Figure 3 shows that under saturated conditions the coarse material has a greater ability to conduct water than the fine material ($k_{sat}$ coarse > $k_{sat}$ fine). As suction increases however, the hydraulic conductivity of the coarse material decreases more rapidly than the hydraulic conductivity of the fine material, and eventually the fine material becomes a better conductor of water. This occurs because at higher suctions the larger pores of the coarse material drain rapidly and no longer have the ability to conduct water, while the smaller pores of the fine material have not yet drained at these suction conditions and continue to conduct water. For this reason in soil profiles containing layers of coarse and fine textured material the preferred flow path may be the fine textured material layer. This is counter-intuitive to flow in a saturated groundwater system and is discussed in detail in section 2.3.2.1.

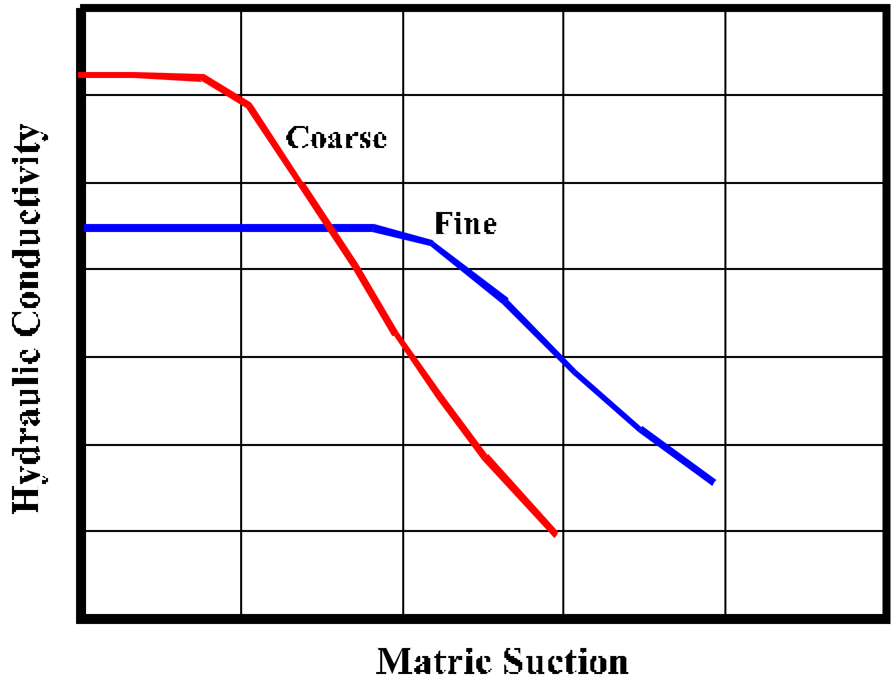


**Figure 3** Conceptual hydraulic conductivity functions for fine and coarse textured materials.

## 2.2 Heap Leaching

Heap leaching is a technology that is simple in principle. Crushed or run-of-mine ore (ROM) is piled on an impermeable pad and a leach solution is applied to the surface. The desired mineral is absorbed and the solution becomes "pregnant" as the solution percolates through the pile. The pregnant leach solution (PLS) is collected by a drainage system at the base of the pile and channeled to the pregnant solution pond. The PLS is then pumped to the processing facility where the value is recovered. The "barren" leach solution is pumped to the barren solution pond from where it is reapplied to the surface of the heap. Over the past three decades heap leaching of low grade ores has become wide spread. The rapid adaptation and maturation of this technology is primarily due to its low capital investment and production costs which make the processing of low grade ores profitable when conventional methods prove too expensive. Heap leaching has other advantages as well; such as a comparatively shorter start up time and the ability to economically mine deposits too small for conventional processing methods.

A large percentage of the available metal must be recovered over a limited time period for a heap leaching operation to be economically successful. Factors that play key roles in this are ore mineralogy, heap geochemistry, heap hydrology, and solution processing efficiency. The following discussion addresses the aspects of heap hydrology that impact leaching efficiency.

## 2.3 Heap Hydrology

Heap and dump leach piles are unsaturated environments and therefore heap leach management requires addressing all the complex flow conditions inherent to unsaturated zone hydrology. The two key hydrological concerns are adequate flow and even or uniform flow of solution through the heap. Adequate flow is necessary for the heap to be leached in an economical time, while uniform flow is needed to allow all the ore to be thoroughly leached.

The process requires a relatively permeable and a uniformly structured material that will not promote solution channeling or short-circuiting. Portions of the heap do not receive sufficient contact with the solution and remain unleached if solution does not flow evenly throughout the heap and instead flows preferentially through distinct paths.

### *2.3.1 Permeability*

Insufficient heap permeability is one of the most common causes of failure of heap leaching projects. Poor permeability means slow solution flow and results in uneconomic leach cycle times. In addition to this, recovery is reduced due to incomplete wetting of the heap. Low permeability also limits air ingress, a necessity for bacterial leaching operations. If heaps are too permeable the solution-ore contact time will be insufficient also resulting in reduced or slow recovery.

One of the major contributors to low conductivity is fine particles and clays within the ore. Fines in the ore block the inter-particle pore spaces, reducing the overall void spaces and thus the permeability of the ore. In extreme cases heaps can ‘plug’ when fines are transported by the solution and packed into an impervious layer deeper in the heap.

Heap permeability problems also arise in heaps where the ore has been compacted due to careless or inadequate material placement practices. Consolidation of the heap material during the life of a pile will also lead to permeability issues. The internal precipitation of species like calcium and iron, if allowed to occur, can also significantly reduce permeability. In copper heap leaching a considerable proportion of the ore is dissolved during leaching. This degradation will also result in reduced permeability.

### *2.3.2 Preferential Flow*

In unsaturated porous media, unlike in saturated conditions, solution flow is greatly influenced by variations within the profile. The general term "preferential flow" is used to describe flow non-uniformity due to profile heterogeneity. In such cases the flow is channeled through the more conductive regions, or 'preferred' flow paths. Structural non-uniformity within leaching heaps occurs commonly due to variability in the nature of the ore feed and as a result of segregation of ore during mining, stockpiling, crushing and placement activities. When leaching solution flows preferentially through a heap, metal recovery is reduced because of limited solution-ore contact in regions of reduced flow. Preferential flow can exists in a number of forms, three of which are described below.

2.3.2.1 Funnel flow

Water preferentially flows through the more permeable layers in soil profiles that contain distinct layers of different textured material. This form of preferential flow is referred to as funnel flow. Layers of steeply dipping coarse grained, fine grained and well graded layers form naturally in leaching heaps during heap construction making heaps particularly susceptible to funnel flow conditions. In cases of funnel flow the preferred flow path is typically thought of as being the coarser textured material. However, due to its larger and more continuous pores this is not always the case. Under certain unsaturated conditions it is possible for the finer textured layer to be more conductive and thus be the preferred flow path. This counter-intuitive flow pattern occurs because the coarse grained material is incapable of retaining water under higher values of matric suction. As water rapidly drains from the coarser material, the inter-particle spaces become air filled greatly reducing the crossectional area open to flow resulting in low unsaturated hydraulic conductivity. Under the same level of applied matric suction the finer-grained material is capable of retaining water and therefore maintains a higher unsaturated hydraulic conductivity. This results in preferential flow occurring through the fine-grained layers rather than through the coarse layers.

The matric suction conditions present in a leaching heap are a function of the rate of solution application to the top of the heap. Newman *et al*. (1997), experimented with segregated waste rock material. The study found through column tests that an applied surface flux greater than the saturated hydraulic conductivity ($k_{sat}$) of the fine material resulted in preferential flow through the coarse material, while fluxes less than the $k_{sat}$ of the fine material resulted in flow through the fine material.

2.3.2.2 Macro-pore flow

"Macro-pore flow" or "short-circuiting" are the names given to preferential flow through the larger pores of a given media. As flow rate increases, higher fractions of the total flow are shunted to ever larger channels. At high saturation almost all the flow (above 96%) is within 'macro-pores' - pores larger than 0.2 mm in diameter (Scooter, 1978). Even modest increases in the rate of surface application can lead to significant short-circuiting.

2.3.2.3 Fingering

An unstable front or interface may develop when one fluid displaces another fluid of different density and/or viscosity, which leads to propagation of discrete fingers rather than a uniform surface. This form of preferential flow referred to as 'fingering' can occur as leach solution infiltrates into the heap. Generally speaking, gravitational forces, heterogeneity, and low-conductivity layers promote fingering, while capillary forces have a stabilizing effect. Fingering most commonly develops beneath the interface of a coarse material overlain by a fine layer when ponding occurs above the fine layer. Heterogeneous soils under relatively high application rates are also prone to unstable wetting. Of significance to note regarding fingering flow is the fact that after infiltration ceases and the profile drains, subsequent infiltration follows the same finger-like pathways which where developed in the initial infiltration (Stephens, 1995; Glass, 1991).

## 2.4 Practical Applications in Heap Leach Operations

### *2.4.1 Agglomeration*

Agglomeration is the practice given to any process whereby the fine-grained particles and clays within the ore are attached to larger particles to form agglomerates. Agglomeration methods vary depending on the particle size distribution of the ore. In general agglomeration techniques increase in complexity and expense as the amount of fines present increases. In cases where the fine fraction is low the ore is simply wetted with water or leach solution and the agglomerates are formed as the ore is agitated during handling and heap construction. A binder is added in addition to the water or leach solution. Agglomeration equipment (usually in the form of a rotating drum agglomerator) is used for ore possessing a high fines content.

Agglomeration improves the flow conditions within leach heaps in a number of ways. Of most importance is that agglomeration confines fines and clays within agglomerates eliminating their ability to restrict flow. In addition to this, overall heap homogeneity is improved because the mobility of the clays is reduced and their ability to migrate and form low permeability layers is decreased. The practice of agglomeration also reduces the potential for preferential flow to occur by producing a more homogeneous heap. This occurs because particles are of a more uniform size resulting in reduced material segregation. However, a review of the literature clearly shows that agglomerated heap leach material will still segregate. The material is initially wetted with agglomeration, which means a reduction in the likelihood of the development of fingering flow as discussed earlier. In addition, wetting during agglomeration, in advance of heap construction, prevents the reduction in permeability that can result when clay minerals expand upon wetting.

### *2.4.2 Heap construction*

Heap construction methods play a crucial role in insuring satisfactory heap hydrology and the overall success of heap leach projects. Every effort must be made in heap construction to produce heaps that are homogeneous and sufficiently permeable. That is, piles that are non-compacted and free of layers of segregated material or any other structural anomalies that would promote preferential flow. Problems with compaction normally result when heavy dump trucks and dozers are used for heap construction. In this case trucks driving on top of the pile causing the compaction. This problem can be mitigated somewhat by “ripping” the haul paths with a dozer.

Loaders and excavators can also be used to place the material. This method allows the material to be placed in a non-compacted condition, but is slower and heap height is limited by the loaders lift capability. Loaders have the potential to compact individual bucket loads during placement producing large consolidated blocks with low permeability within a heap of agglomerated ore.

A third method of heap construction uses conveyors and mobile stackers. These systems allow for “gentle” placement of the ore and can minimize both compaction and segregation. Consolidation at the base of heaps resulting from excessive dump heights is also an issue that can be addressed by minimizing the lift height. Leaving the stacker at the full height of the pile and allowing the agglomerates to cascade down the existing pile then produces the remainder of the heap.

In many cases a layer of coarse rock is placed directly over the liner for purpose of improving drainage from the heap. Some operations also construct layers of coarser ore (generally 1 meter thick) on the heap's surface to insure satisfactory infiltration into the heap.

### *2.4.3 Solution application*

The two common means used to apply heap leach solution are sprinklers and drip emitters. High droplet impact energies from the sprinklers dislodges the finer particles from the agglomerates and washes them into the heap or to a low spot on the heap surface. This process can produce barriers to flow within the heap or seal the heap surface. In either case, a significant reduction in metal recovery will result as portions of the heap remain unleached. This problem does not arise with the use of drip emitters.

It may be necessary to commence solution application shortly after placement of agglomerated ore (within 48 hours), in order to prevent agglomerates from drying. This is because upon re-wetting they may collapse leading to insufficient permeability, particularly at the surface where drying would be greatest. This would reduce infiltration into the heap and limit the maximum achievable solution application rate.

### *2.4.4 Solution application rate*

Selection of the optimum application rate requires knowledge of the range of permeability and moisture retention ability existing within the heap. The zone of minimum permeability (often the surface layer) determines the maximum effective application rate. Application rates in excess of this will introduce short-circuiting and channeling. Increasing the application rate once short-circuiting has lowered the wash efficiency can not increase the leaching rate in the longer term. In fact, a higher application rate will only dilute the PLS and make processing of the solution more difficult, as well as induce flow through the coarser textured segregated material. The use of low irrigation rates throughout the entire leach cycle will provide the best control of PLS grade for ores with low inherent permeability. In general the rate of solution application should be just enough to "wash" out the dissolved species of interest.

The economical recovery from older heaps can be protracted by the use of leach/rest cycles. This is due to the fact that after leaching ceases and the heap drains much of the smaller void spaces remain solution filled. Dissolution of values therefore continues during the rest cycle causing concentrations to build up in the water-filled voids. A relatively short period of solution application can then wash the solubilized values from the heap. In this way a limited flow of high grade pregnant liquor can be economically maintained.

### *2.4.5 Wetting agents*

Wetting agents are chemical agents that act to reduce the surface tension of the liquids. A reduction in surface tension can result in increased flow and a more thorough wetting of the heap when wetting agents are added to the leaching solution of heap leach operations. In this way wetting agents have the potential to produce the following benefits.

1. Increased recovery as a result of solution flow into regions of the heap that would otherwise be 'dry zones' or unleached regions.
2. Increased solution-metal contact as a result of improved penetration into voids and cracks in the ore particles resulting in increased metal dissolution and recovery.
3. Reduced leaching time which in turn reduces leaching agent and pumping costs.
4. Reduced need for agglomeration or special treatment of certain ores.

Wetting agents also have the potential disadvantage of reducing metal recovery. This can occur if wetting agents form a hydrophobic layer at the solution/air or solution/solid interface and retard diffusion of the reactants to the metal surface or products away from the surface.

A number of studies have been completed on the use of wetting agents to improve heap leaching efficiency, with mixed results. Browner and Strickland (1992) found that although a given surfactant increased the rate of solution percolation, metal dissolution was reduced, for the reason mentioned above. Arnold and Pennstrom (1988) found that the effect of wetting agents to be dependent on ore type. No increase in recovery was observed in one ore type while a small average increase (4.3%) was observed in another. Even small increases in recovery such as this result in a very favorable return on investment because the cost of the wetting agent addition is relatively low (only a few cents per tonne of ore treated).

## 3.0 COLUMN TESTING METHODOLOGY

The laboratory column testing program was completed in two steps. Preliminary column testing was completed to determine the conditions required to produce funnel flow (discussed in section 2.3.2.1) in segregated heap leach material. This was followed by the primary column testing, which was completed to investigate the effect of preferential flow on mineral leaching.

A schematic drawing of the laboratory column apparatus is shown in Figure 4. The column, constructed of eight clear plastic segments, was 160 cm in height. Its rectangular cross section measured 15 cm x 30 cm. A thin removable cutoff wall along the column's axis made it possible to place two different materials side by side. Once the column was assembled, the cutoff could be lowered to different elevations through the base, allowing the two materials to be in direct contact above the height of the cutoff. Water flowing above the cutoff was free to move between materials. Flow below the height of the cutoff was forced to report to the drainage port at the bottom of each half of the column enabling discrete collection. A peristaltic pump connected to a constant head reservoir made it possible to apply water to the top of the column at specific rates. Uniform distribution over the surface of the column was achieved using a "rain maker" – a plate covering the top of the column through which numerous small diameter tubes were inserted.

The materials used in the column tests were developed to be representative of an agglomerated heap leach material's segregated components. The material (Smithson, 1999) was segregated based on Yazdani, 1996, Herasymuik, 1995, and Kinard and Schweizer, 1987. Figure 5 shows the particle size distribution for an agglomerated heap leach material together with the particle size distributions of the fine and coarse textured materials used in the column tests.

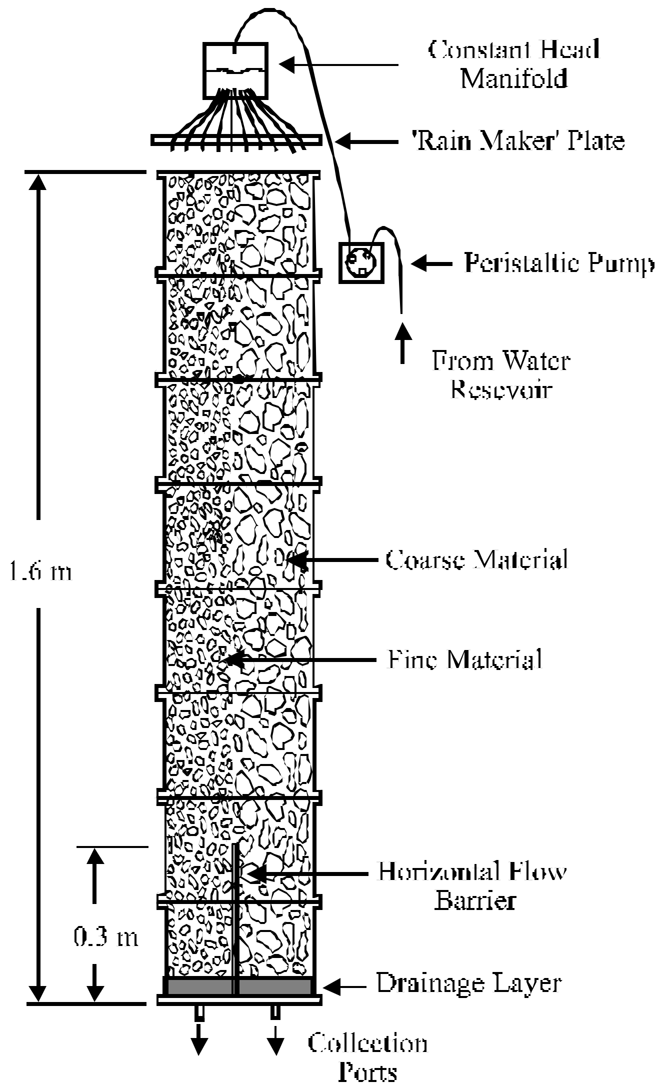


**Figure 4** Schematic of laboratory column.

The primary objective of column testing investigated the impact of funnel flow on mineral leaching. This required producing funnel flow conditions within the vertical layers of the test column. For this reason, precursory column tests were run to determine two fluxes, high and low, which would produce preferential flow through the coarse and fine textured material respectively. To this end four different fluxes were investigated. Two of the applied flow rates slightly exceeded the saturated hydraulic conductivity of the fine material, measured in advance to be $1.20 \times 10^{-4}$ m/s, and two were below this value. Measurements of the outflow from the coarse and fine textured sides of the column were recorded to determine the degree of flow partitioning. Tests were completed to determine the height of the dividing wall within the column that would allow for maximum horizontal flow between the two materials while preventing crossover at the base of the column. This work replicated the methods used by Newman et al 1997 that investigated funnel flow in waste rock. Preliminary tests also included measuring the soil-water characteristic curves of both materials.

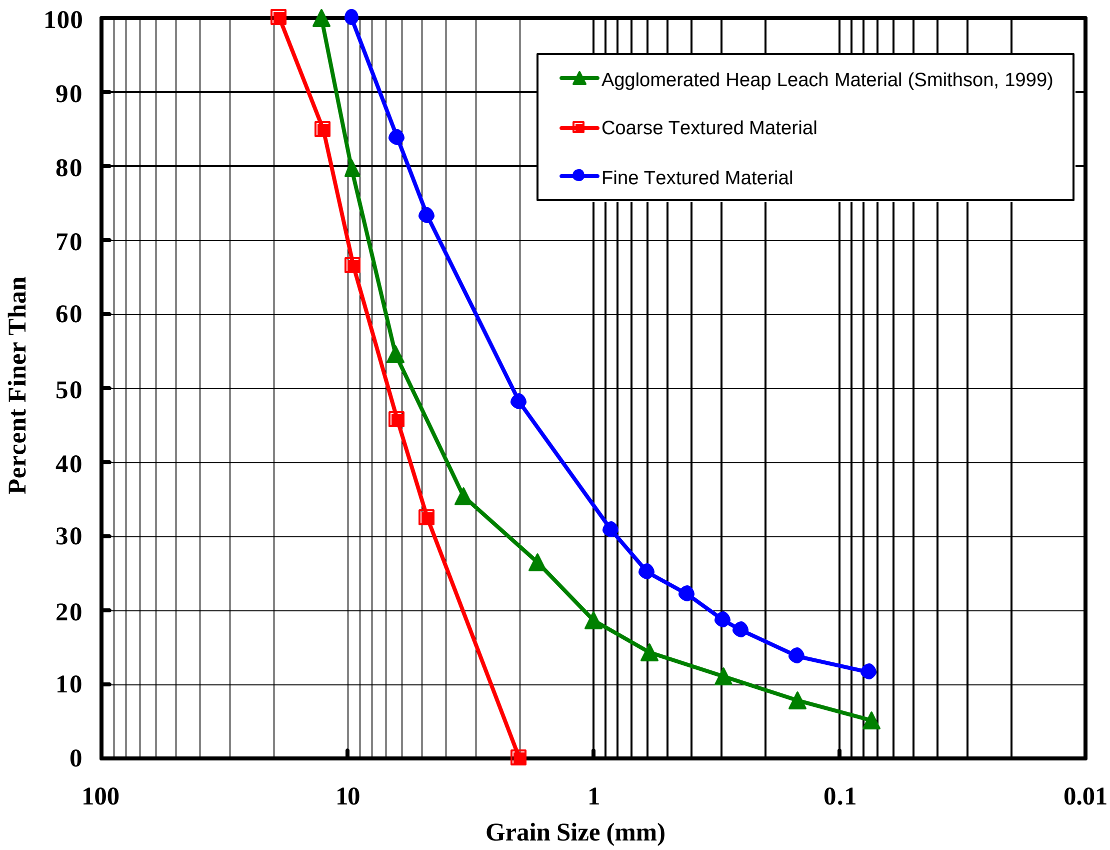


**Figure 5** Particle size distributions for the coarse and fine textured materials used in the column, as well as the agglomerated copper heap leach material.

The main body of column tests used a low flux of $2.8 \times 10^{-7}$ m/s and a high flux of $2.6 \times 10^{-4}$ m/s, based on the results of the preliminary testing, to produce the desired preferential flow conditions. A cutoff wall height of 30 cm was selected. Three different "ore types" were tested under both preferential flow patterns (i.e. at both high and low applied flux), for a total of six column tests. Adding salt to the material simulated mineral leaching from ore. The salt content of the salted 'ore' was approximately 23 g/kg, and 3g/kg for the unsalted material. The three different ore types were: 1) high grade fines with low grade coarse particles (simulated by salting the fine material only); 2) high grade coarse particles with low grade fines (simulated by salting the coarse material only); and 3) ore with both the fine and coarse material containing consequential quantities of metal (both materials salted). Each column was leached to completion with discreet samples obtained from beneath each side of the column. Volume outflow was measured to determine flow rate and degree of partitioning. The electric conductivity of the leachate was measured and from this the quantity of salt leached was determined. Figure 6 shows a schematic of the test columns.

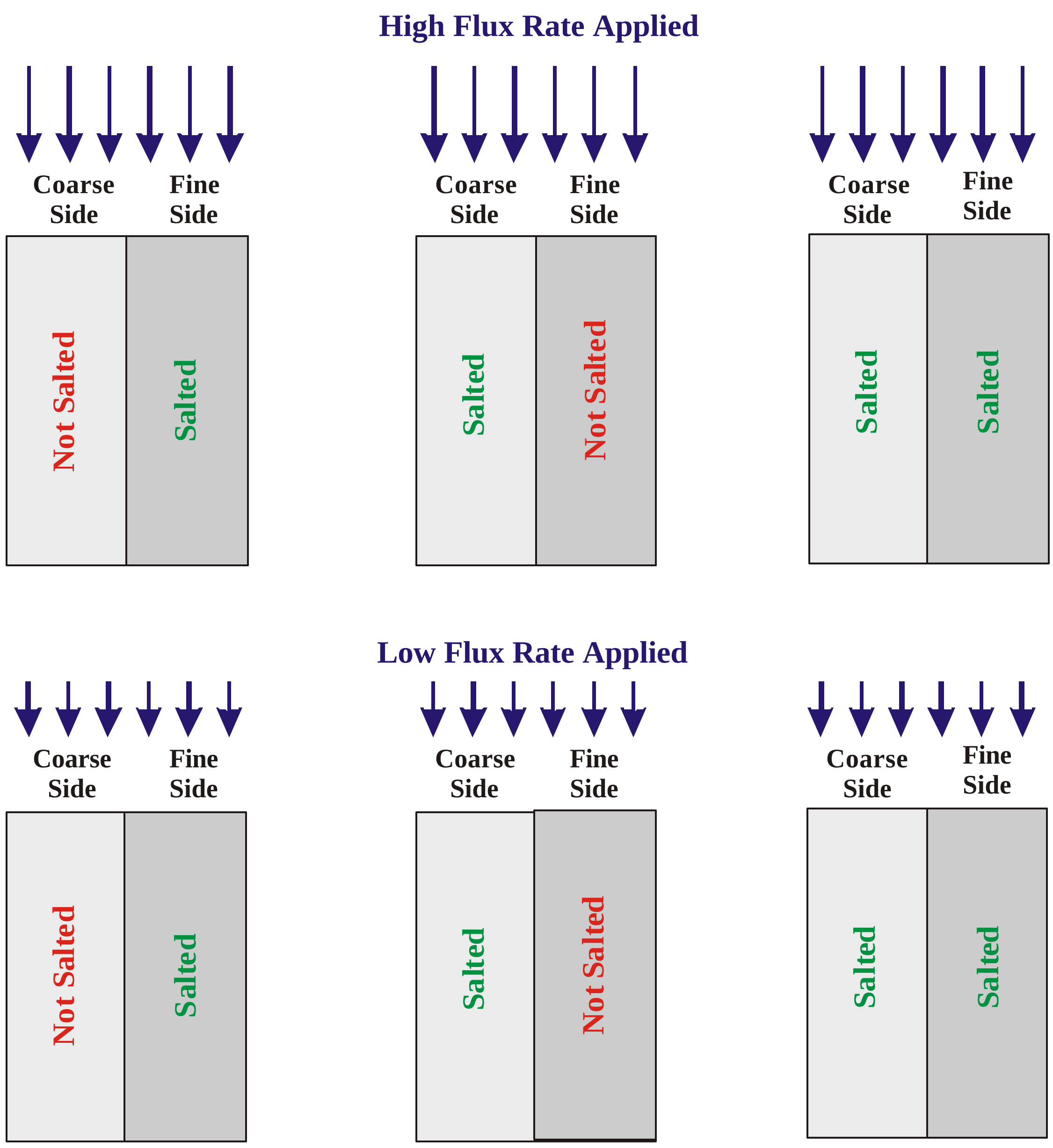


**Figure 6** Schematic of six test columns illustrating the coarse and fine side "salting", as well as the applied surface flux rates.

## 4.0 PRESENTATION AND DISCUSSION OF PRELIMINARY LABORATORY COLUMN DATA

The measured $k_{sat}$ values and SWCCs were used to determine the hydraulic conductivity as a function of suction for both materials using the Van Genuchten (1980) formulation. The hydraulic conductivity curves of the two materials cross at a matric suction of approximately 1 kPa, as shown in Figure 7. At suctions greater than the 1 kPa the fine material has a high permeability and becomes the preferred flow path.

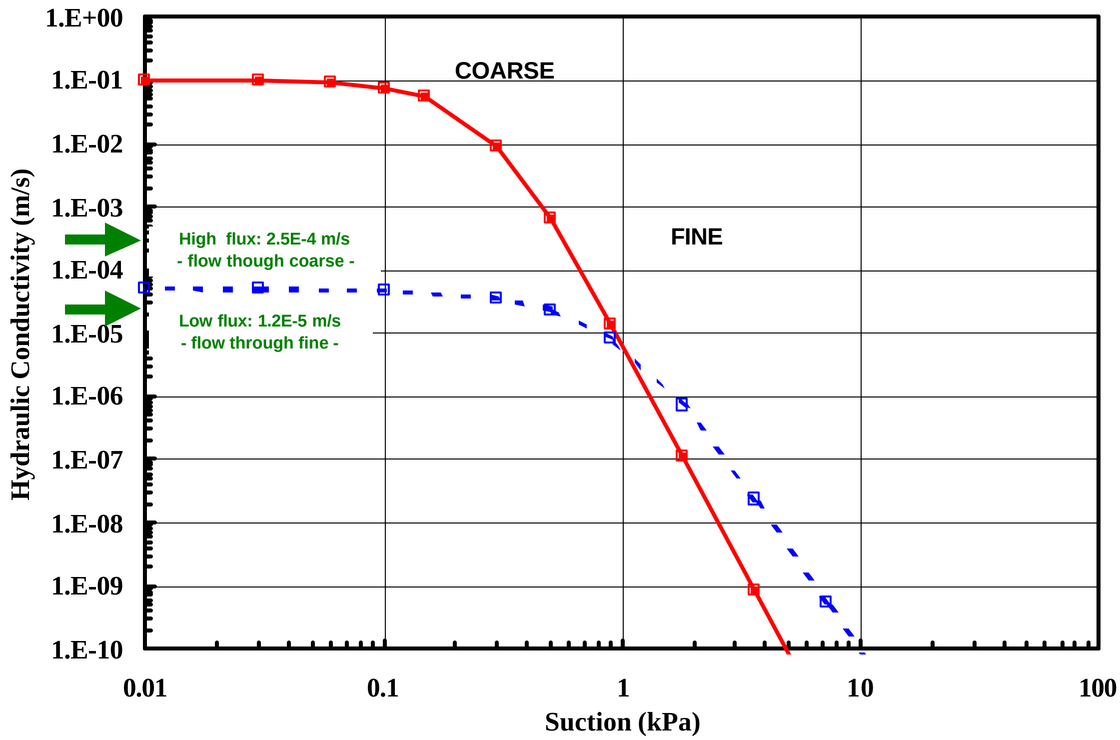


**Figure 7** Hydraulic conductivity functions for the fine and coarse textured materials.

Superimposed on Figure 7 are two of the applied fluxes, the lower value being below the saturated conductivity of the fine material while the higher flux is above. Approximately 95% and 5% of the water applied to the top of the column was collected from the coarse and fine textured material, respectively, when the flux rate applied at the top of the column was slightly greater than the saturated permeability of the fine textured material. Figure 8 illustrates the results of the column test results for top of column applied flux rates greater and less than the fine textured material. The latter condition resulted in 32% of the water applied to the top of the column reporting to the coarse textured collection port. Water collected from the fine textured port was 68% of the total volume of water applied over the entire surface area of the top of the column.

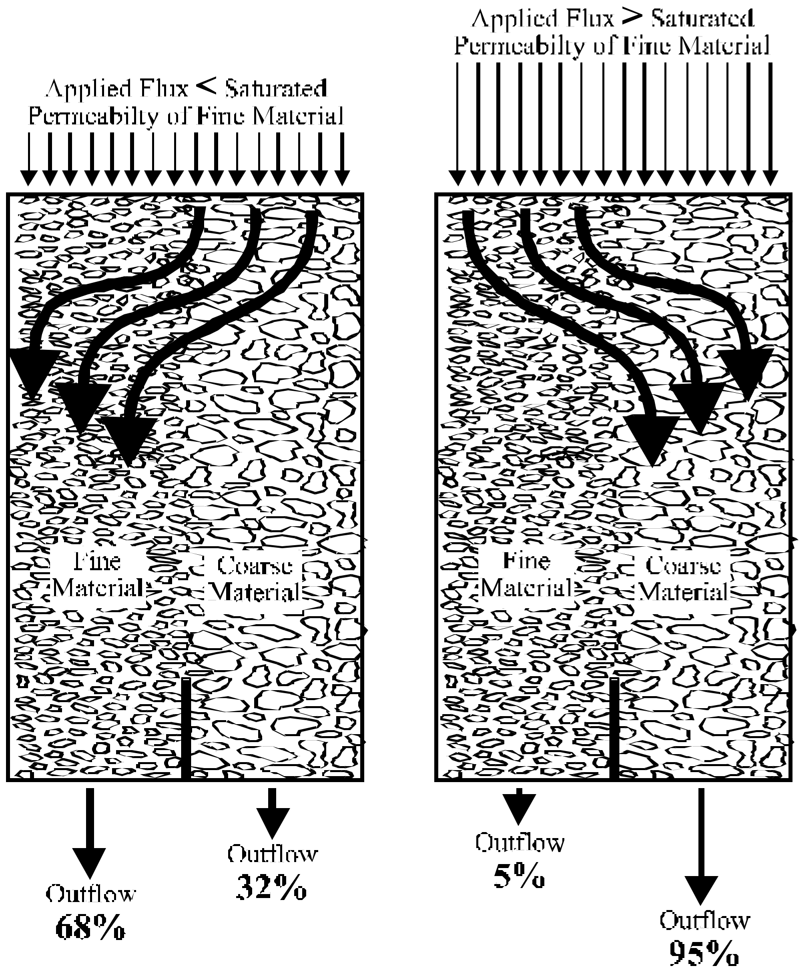


**Figure 8** Illustration of the preliminary segregated column test results.

The pore air and water pressure conditions created in the column are a function of the flux applied to the top of the column. The coarse textured material is somewhat drained if the flux rate applied at the top of the column is less than the saturated permeability of the fine textured material. The effective permeability of the coarse textured material decreases to less than that of the fine textured material. Water entering the top of the coarse material side of the column crosses the vertical interface and preferentially flows in the fine textured material. The opposite occurred when a flux rate greater than the saturated permeability of the fine textured material was applied to the top of the column. Water entering the top of the fine material side crossed the interface and was transported preferentially in the coarse textured material.

Table 1 summarizes the results for the additional flux rate applications and corresponding degree of flow partitioning.

**Table 1**

Flow partitioning over the 11range of applied fluxes

| **Applied Flux (m/s)** | **Volume Reporting from Fine Material (%)** | **Volume Reporting from Coarse Material (%)** |
|---|---|---|
| $2.48x10^{-4}$ | 4.7 | 95.3 |
| $1.75x10^{-4}$ | 5.0 | 95.0 |
| $1.19x10^{-5}$ | 63.9 | 36.1 |
| $8.38x10^{-6}$ | 67.7 | 32.3 |

## 5.0 PRESENTATION AND DISCUSSION OF LEACHING COLUMN DATA

Table 2 presents the flow rates applied for each of the six column tests as well as the degree of flow partitioning produced within each column. Between 93.9-99.0% of the flow exited the column from the coarse side under high applied fluxes. Under low fluxes from 87.1- 89.4% of the applied water exited the column from the fine side.

**Table 2**

Applied fluxes and resultant flow partitioning

| Column Test Parameter | | Applied Flux (m/s) | Volume Reporting from Fine Material (%) | Volume Reporting from Coarse Material (%) |
|---|---|---|---|---|
| **Applied Flux** | **Salting** | | | |
| High | Coarse Side | $1.57x10^{-4}$ | 6.1 | 93.9 |
| High | Fine Side | $2.81x10^{-4}$ | 1.3 | 98.7 |
| High | Both Sides | $1.73x10^{-4}$ | 1.0 | 99.0 |
| Low | Coarse Side | $2.59x10^{-7}$ | 100.0 * | 0.0 * |
| Low | Fine Side | $3.17x10^{-7}$ | 89.4 | 10.6 |
| Low | Both Sides | $2.88x10^{-7}$ | 87.1 | 12.9 |

* The collection port beneath the coarse material became plugged.

Figure 9 shows the information listed in Table 2, together with the flow partitioning observed in the preliminary column tests. A trend is evident where the percentage of the total water flowing through the fine material drops as the application rate increases, even though a limited number of column tests were conducted. As the application rate approaches the saturated hydraulic conductivity of the fine material, flow through that media drops rapidly. Essentially all flow is through the coarser material at fluxes above this value.

Superimposed on Figure 7 is the range of solution application rates commonly used in heap leaching. From this it can be deduced, that for the segregated material tested, approximately 75% of the flow would be through the finer material under normal heap leach operating conditions. Note that this flow pattern is contrary to common thought that would say the majority of solution flow would be through the coarser material.

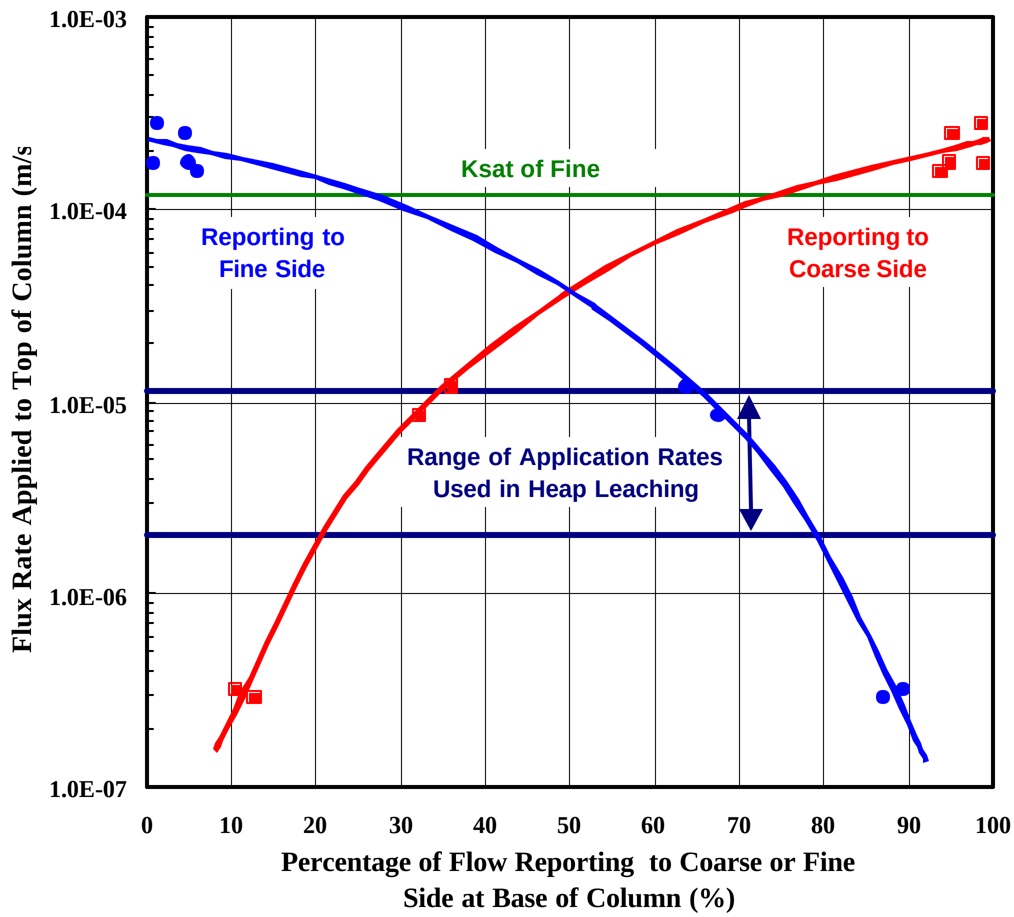


**Figure 9** Percent of total applied water exiting column from both fine and coarse materials over the range of applied surface fluxes.

The funnel flow conditions within the columns had an impact on "mineral" leaching. The results of leaching when both materials were salted are shown in Figures 10 and 11, where the percent recovery of the total salt within each material is plotted against leach time. Under low flux conditions approximately 30% of the salt within the coarse material side of the column was removed from the coarse material by the water crossing over into the more conductive fine material. This is shown in Figure 10 where a recovery of approximately 130% from the fine material indicates that all the salt initially present within the fine material was returned as well as 30% originally within the coarse material. Approximately 5% of the salt initially in the fine material exited from the coarse side collection port under high flux conditions, as evidenced by the 105% recovery from the coarse material recovery curve shown in Figure 11. The reduced degree of preferential leaching observed under high flux conditions is believed to be a function of ponded water on the surface of the column. This allowed most of the water to infiltrate the more conductive coarse material. A small amount of the water originally entered the fine material and little water was available to flow preferentially from the fine material into the coarse and transport the salt horizontally.

Under high flux conditions, with only the fine side salted, approximately 8% of the salt originally within the fine material was removed by the water crossing preferential into the coarser material. No preferential leaching was observed under the high flux-coarse side salted condition and low flux-fine side salted condition because the salted material was the preferred flow path. This provided a useful control. Data collected under the low flux-coarse material salted condition is inconclusive because the outlet plugged preventing flow from the coarse material side.

The salted columns are conceptually representative of an oxide copper deposit, where oxidation of the ore is not required. It is important to note though that the rapid and complete recovery observed in the columns is the result of using salt to simulate metal recovery. In reality, the dissolution rate of those minerals normally heap leached is in the range of days, weeks or even months.

It is fundamental to realize that an understanding of unsaturated zone hydrology will be that much more important for sulphide deposits where oxidation of the heap material (chemical and/or biologically enhanced) is required. Optimizing the balance between sufficient oxygen concentrations within the heap or dump leach pile, and adequate permeability conditions is a function of the unsaturated conditions. Transport of oxygen within the heap or dump heap, whether by diffusion, advection, or convection (a likely small component of the transport process) significantly increases as the degree of saturation decreases (i.e. suction decreases). In contrast, Figure 3 showed that permeability decreased with an increase in suction (i.e. decrease in saturation conditions). Determining the optimum balance between these two objectives is thus rooted within unsaturated zone hydrology.

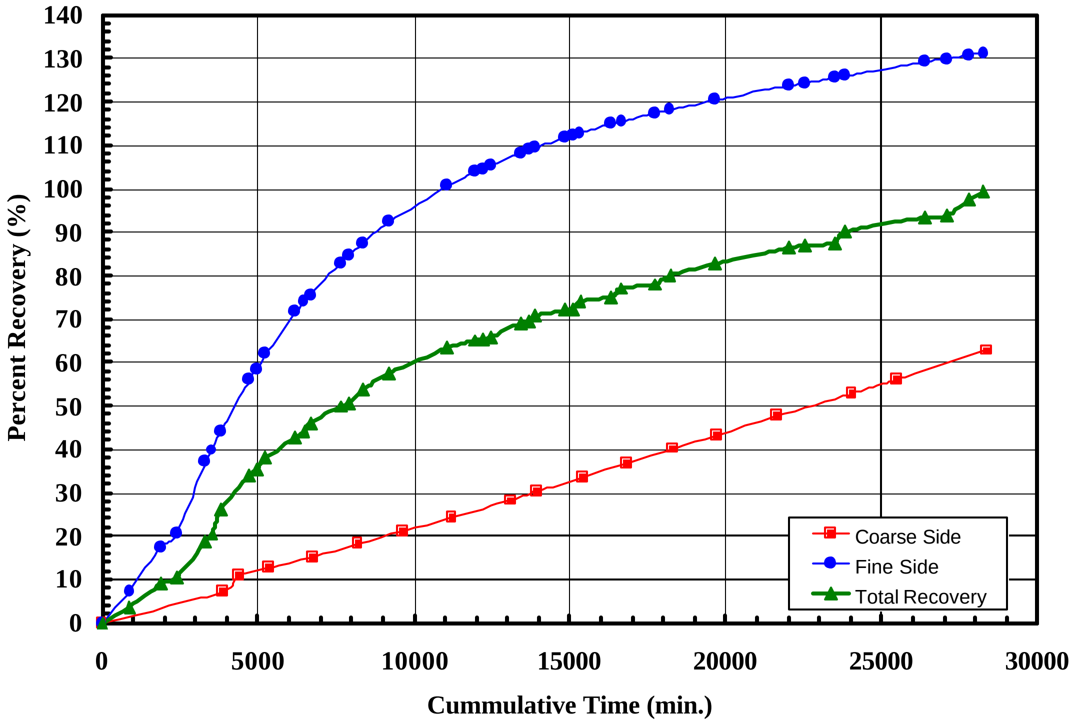


**Figure 10** Percent recovery from each material for the low flux-both materials salted condition.

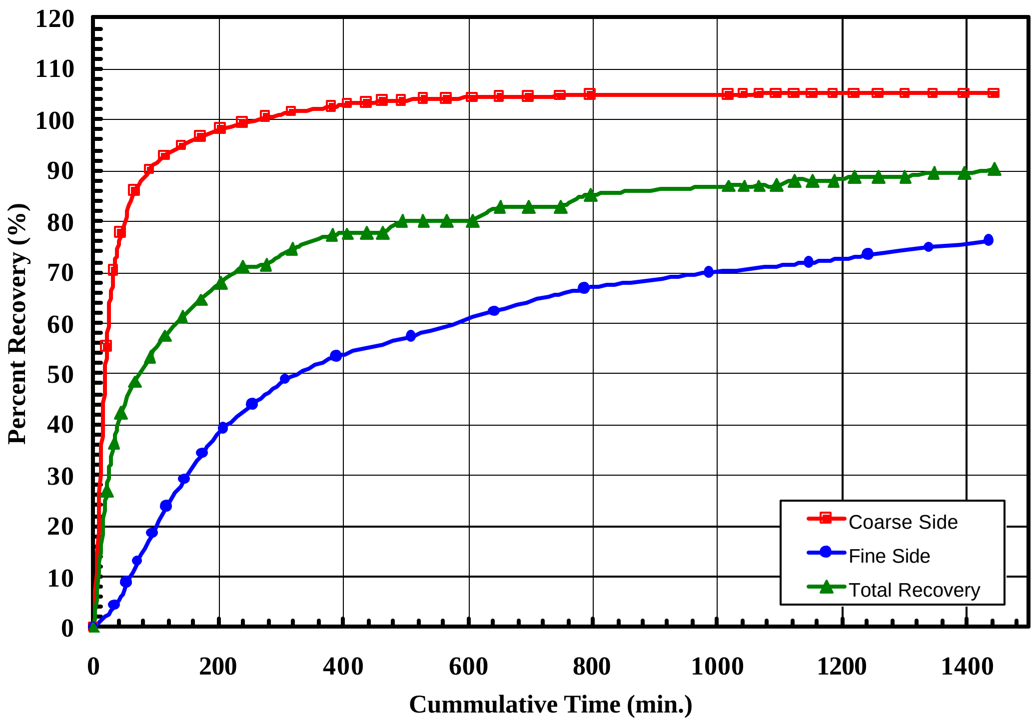


**Figure 11** Percent recovery from each material for the high flux-both materials salted condition.

## 6.0 DESCRIPTION OF THE NUMERICAL MODELLING

Numerical modelling of the columns was conducted once the laboratory experiments were completed to demonstrate the ability of existing software to effectively model both preferential flow and leaching. The modelling consisted of two main steps. First, SEEP/W (Geo-Slope, 1999a) was used to obtain flow partitioning representative to that observed in the laboratory columns. Next, these simulations were used as input for CTRAN/W (Geo-Slope, 1999b) simulations that modelled mineral leaching.

Several steps were taken in order to determine models that would accurately, replicate the heap leach results of the six laboratory columns. The SWCCs, $k_{sat}$s, and K functions derived by the numerical models were adjusted slightly during the modelling process in order to create more representative functions of the fine and coarse materials used in the laboratory column. The coarse and fine SWCCs used in modelling, as compared to those originally measured in the laboratory are shown in Figure 12. The final $k_{sat}$ values chosen were $1x10^{-1}$ m/s for the coarse textured material and $5x10^{-5}$ m/s for the fine textured material. The high and low fluxes used in the modelling were chosen as an average of those applied in the physical columns, they were: $q_{high}$ = 1.7 x $10^{-4}$ m/s, and $q_{low}$ = $2.9x10^{-7}$ m/s. The dimensions of the modelled column were identical to that of the laboratory column.

Diffusion modelled by CTRAN/W was assumed to be constant with volumetric water content, and no adsorption or decay was used. Central difference time integration was used and the time steps were made small enough such that the peclet and courant numbers were within the recommended guidelines for stability. The models were also run for a sufficient time frame to allow for the simulated salt levels in the columns to be completely leached out.

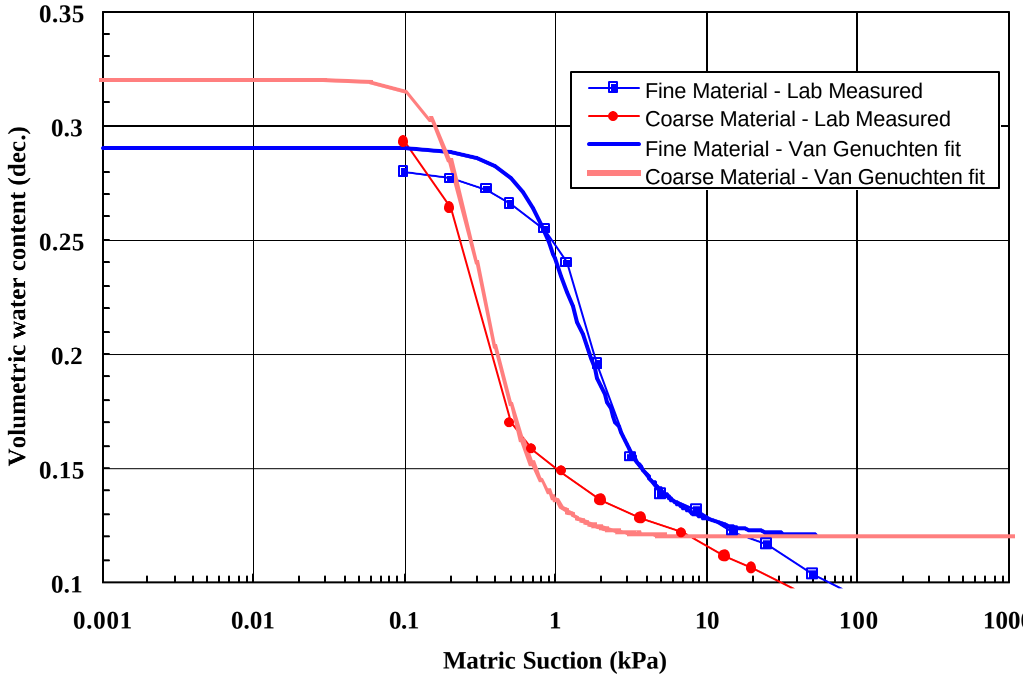


**Figure 12** Laboratory measured SWCCs plotted with the SWCCs used for modelling.

# 7.0 PRESENTATION OF THE NUMERICAL MODELLING RESULTS

## 7.1 Preferential Flow Modelling (SEEP/W)

The SEEP/W simulations closely replicated the partitioning that was obtained in the laboratory columns. Table 3 shows the partitioning from the columns, as well as the partitioning predicted by the SEEP/W model. The partitioning was reasonable for all cases but clearly more accurate for some cases than others.

**Table 3**

Comparison of predicted and laboratory measured partitioning of flow within the test columns

| Column Test Parameters | Laboratory Measured Flow Partitioning (%) | | Partitioning Obtained from SEEP/W Models (%) | |
|---|---|---|---|---|
| | Fine Side | Coarse Side | Fine Side | Coarse Side |
| High Flux-Coarse Salted | 6.1 % | 93.9 % | 6.1 % | 93.9 % |
| High Flux-Fine Salted | 1.3 % | 98.7 % | | |
| High Flux-Both Salted | 1.0 % | 99.0 % | | |
| Low Flux-Coarse Salted | 100.0 %* | 0.0 %* | 86.9 % | 13.1 % |
| Low Flux-Fine Salted | 89.4 % | 10.6 % | | |
| Low Flux-Both Salted | 87.1 % | 12.9 % | | |

* The collection port beneath the coarse material became plugged.

## 7.2 Preferential Leach Modelling (CTRAN/W)

The results of the CTRAN/W models illustrate that the process of preferential leaching can be successfully modelled. The modelling did however predict greater degrees of preferential leaching than were observed in the laboratory columns. This is illustrated in Figure 13 which compares the predicted model results with the laboratory measured results for the low flux-both materials salted condition. In this case the modelled curves follow the same pattern as the measured values, but the model predicts that approximately 60% of the salt will be preferentially leached from the less conductive material, when in reality only 33.5% was.

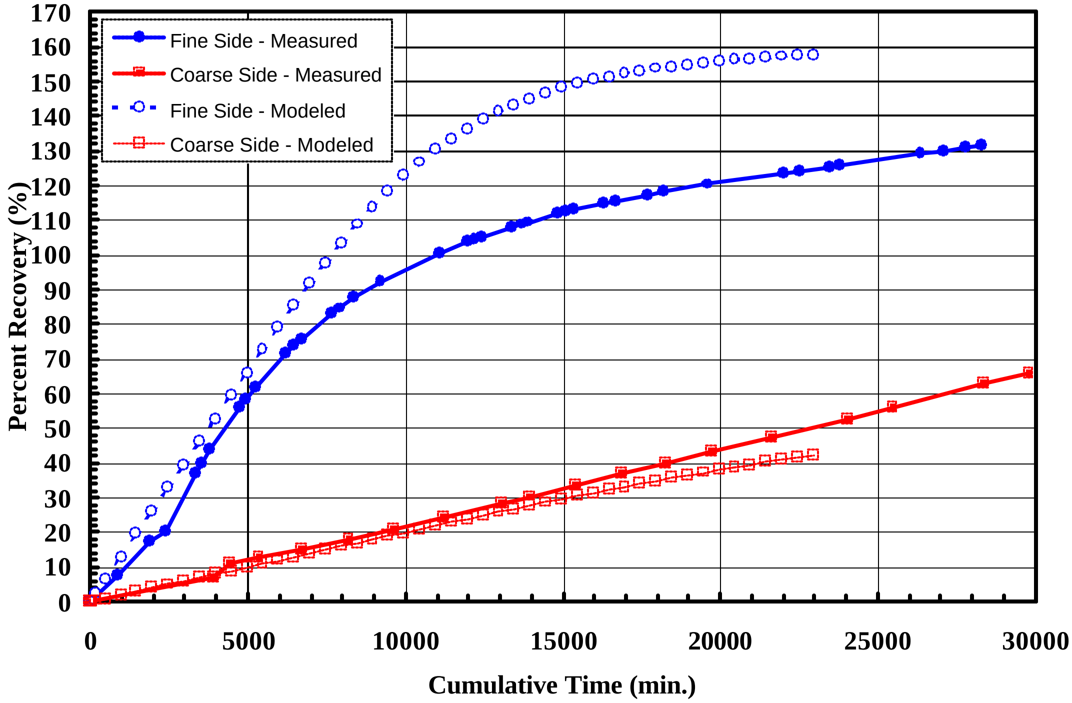


**Figure 13** CTRAN/W modelled preferential leaching compared with measured values for the column with a low applied flux and both materials salted.

The numerical model predicted that approximately 37.5 % of the salt initially within the fine material would exit from the coarse side for the high flux-both materials salted condition. In reality, only 5% of the salt was transported in this manner, as shown in Figure 14. This difference is due to the ponding at the top of the column that occurred, as described previously, under high surface application rates. The result was that only a small amount of infiltration occurred into the fine material, and thus little preferential leaching. Appendix A contains figures comparing measured values with modelled results for the remaining test columns not presented and discussed in this section.

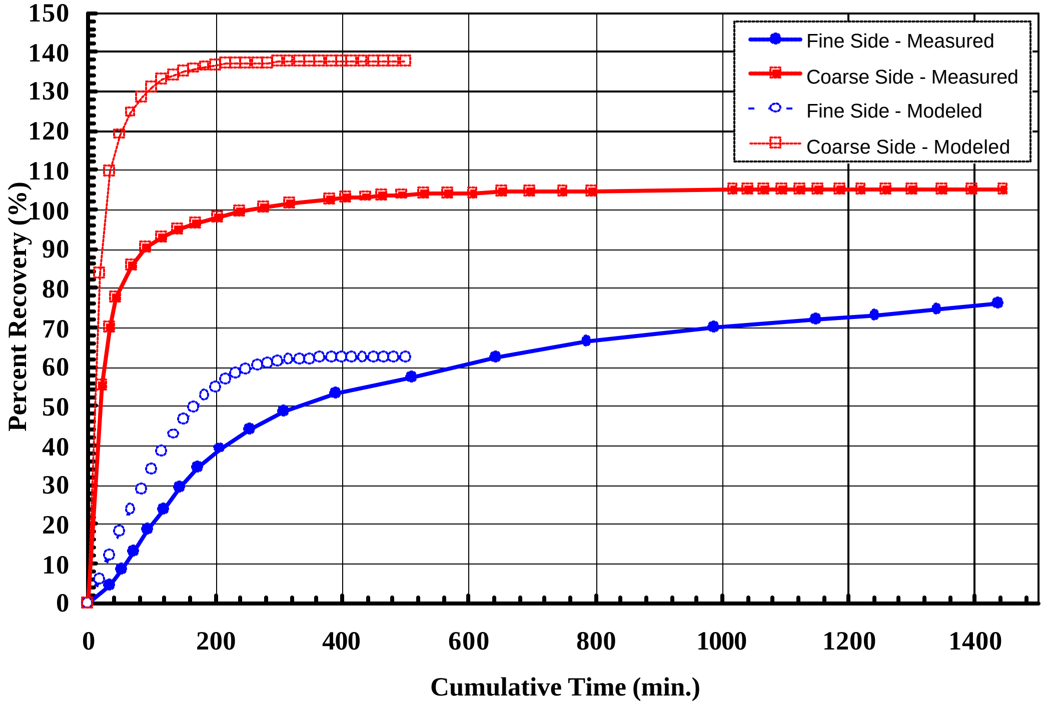


**Figure 14** CTRAN/W modelled preferential leaching compared with measured values for the high flux-both materials salted column.

# 8.0 DISCUSSION AND IMPLICATIONS FOR HEAP LEACH DESIGN AND OPERATION

A review of the literature illustrates that there are very few operators and designers of heap leach piles utilizing the conceptual, theoretical, and numerical tools available for evaluating performance in unsaturated systems. A significant number of unsaturated "tools" are available to improve heap leach performance. In addition, it is generally just starting to become accepted among heap leach "experts", that the hydraulic dynamics of a heap leach pile are as important, if not more important, to metal recovery, as metallurgical, geological, biological, and operational considerations. The current tendency by practitioners is to employ an empirical approach to the hydraulic performance aspect. The eventual acceptance that hydraulic performance is a key factor controlling performance, must be followed by the realization that a heap or dump leach pile is an unsaturated system, and that theoretical and numerical tools are available to help with understanding and improving design.

The scope of this study was to primarily address one component of heap leach operation (i.e. segregation), as a tool to demonstrate the application of unsaturated zone hydrology to heap leaching. There are numerous additional factors influencing performance that could also be addressed from an unsaturated materials perspective to improve performance, as described previously. The physical (i.e. laboratory) and numerical modelling completed as part if this study has shown that the preferential flow path in segregated heap leach material with sharply contrasting layers is dependent on the solution application rate. In such cases the pivotal solution application rate, with respect to determining whether flow occurs preferentially in the finer or coarser textured material, is the saturated hydraulic conductivity of the finer textured material. Heap leach operations will benefit from quantifying the inevitable segregation that occurs and measuring the saturated hydraulic conductivity of finer textured layers within the heap. Cycling solution application rates below this value would ensure acceptable flow and leaching of fine textured material. Column tests on layers of representative fine and course material using a method similar to the one used as part of this study could be undertaken to characterize the impact of solution application rate for the specific material properties of a given heap.

An improved understanding of the fundamental hydraulic regime within the pile (i.e. particles size distributions, density conditions, moisture conditions, soil water characteristics, permeability) will provide a basis for evaluating heap leach performance, and developing methodologies to improve recovery for a particular site.

The limited scope of this study did not provide the opportunity to develop definitive conclusions regarding the effect preferential flow has on mineral leaching. The study does, however, clearly demonstrate the potential benefit of varying the application rate so that both layers can be fully leached.

Preferential flow in segregated heap leach material was successfully modelled as well as preferential mineral leaching resulting from preferential flow. The study has demonstrated that existing unsaturated zone hydrology tools can be used to understand the performance of heap leach piles, and ultimately improve long-term performance.

## 9.0 RECOMMENDATIONS FOR FURTHER STUDY

A number of areas require further study.

1. Additional column tests are required using a similar column apparatus to investigate surface fluxes within the range normally used in heap leaching. The objective would be to draw specific conclusions about the nature of preferential flow and leaching within leaching heaps.

2. Field evaluation of an existing heap leach pile is required to evaluate internal heap leach structure. The opportunity would then exist to collect samples for fundamental characterization and develop an understanding for the particular heap leach pile using existing theoretical and numerical unsaturated zone hydrology tools. The result would be a practical evaluation of field conditions, as compared to a laboratory study which attempts to represent field conditions. The key development would be a better understanding for the hydraulic conditions that exist under full scale field conditions, as compared to column test studies, which are used to predict metal recovery and form the basis for obtaining funding for heap leach projects.

3. The development of a comprehensive robust model is required using existing unsaturated hydrology tools as a framework, which are coupled to fundamental tools capable of describing biological, metallurgical, geochemical, and operation conditions. It is important to note that the theoretical tools required to develop the different modules of the model are likely available in the literature. It would be a matter of coalescing the existing information, as well properly configuring and "building" the model. A team of experts in each area could assist with reviewing each module, while the work was conducted by a small project group over a relatively short time frame.

   The model would provide the opportunity to "scale-up" column test results to full scale field conditions and improve the ability to predict performance. The model should not be thought of as a definitive measure of performance, but rather as a tool to illustrate the most promising leaching conditions. Column tests and pilot scale studies could then be used to verify the most promising alternatives. The key is to use the physical test in the correct manner. That is, as a verification of a numerical model, rather than as an empirical design tool. These column test results would then form the basis for developing a financial model for the project, and ultimately securing funding for the project. The result would be a significant decrease in the costs associated with developing a heap leach pile design due to the significant decrease in the number of column tests.

**ACKNOWLEDGEMENTS**

O'Kane Consultants Inc. acknowledge that this project would not be possible without the financial assistance provided by the Industrial Research Assistance Program. The contributions of Dr. Lee Barbour, P.Eng. and Ms. Brenda Bews of the Unsaturated Soils Research Group at the University of Saskatchewan, and Dr. Moir Haug, P.Eng., Mr. Jeff Stone, P.Eng., Mr. Julian Gan, and Mr. Jim Stone of M.D. Haug and Associates Ltd. to the completion of the project is greatly appreciated. Finally, the encouragement, support, enthusiasm and patience of Mr. Dennis Belliveau, P.Eng of the Industrial Research Assistance Program is greatly appreciated.

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# APPENDIX A:

Additional figures comparing measured and modelled results

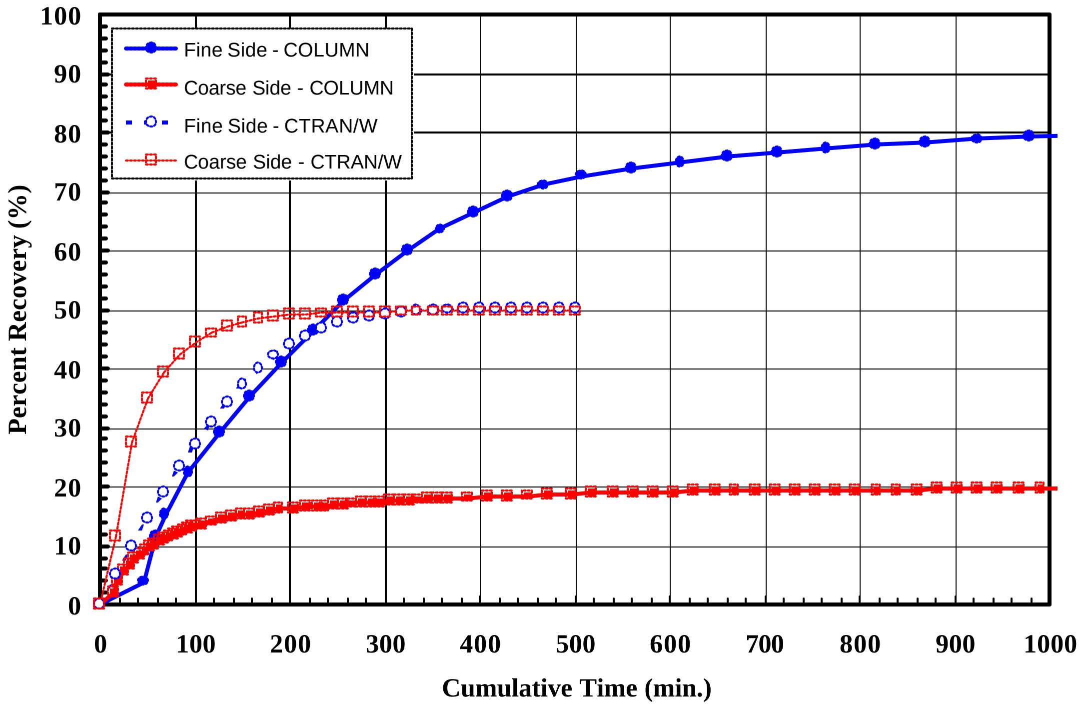


**Figure A.1** CTRAN/W modelled preferential leaching compared with measured values for the high flux-fine material salted column.

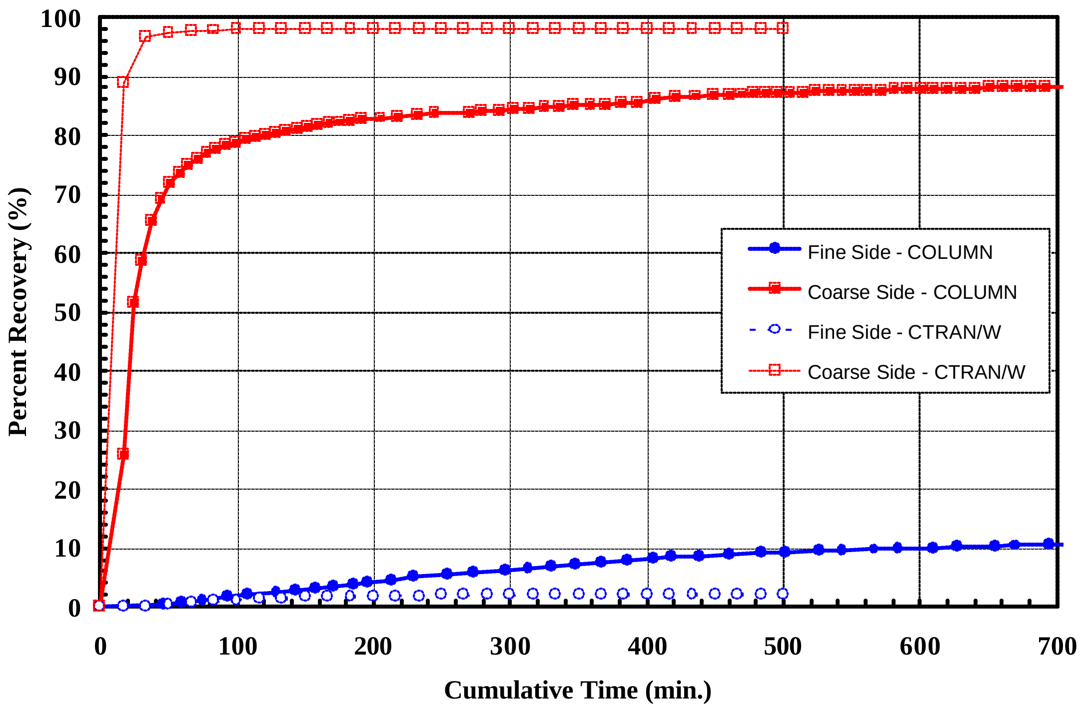


**Figure A.2** CTRAN/W modelled preferential leaching compared with measured values for the high flux-coarse material salted column.

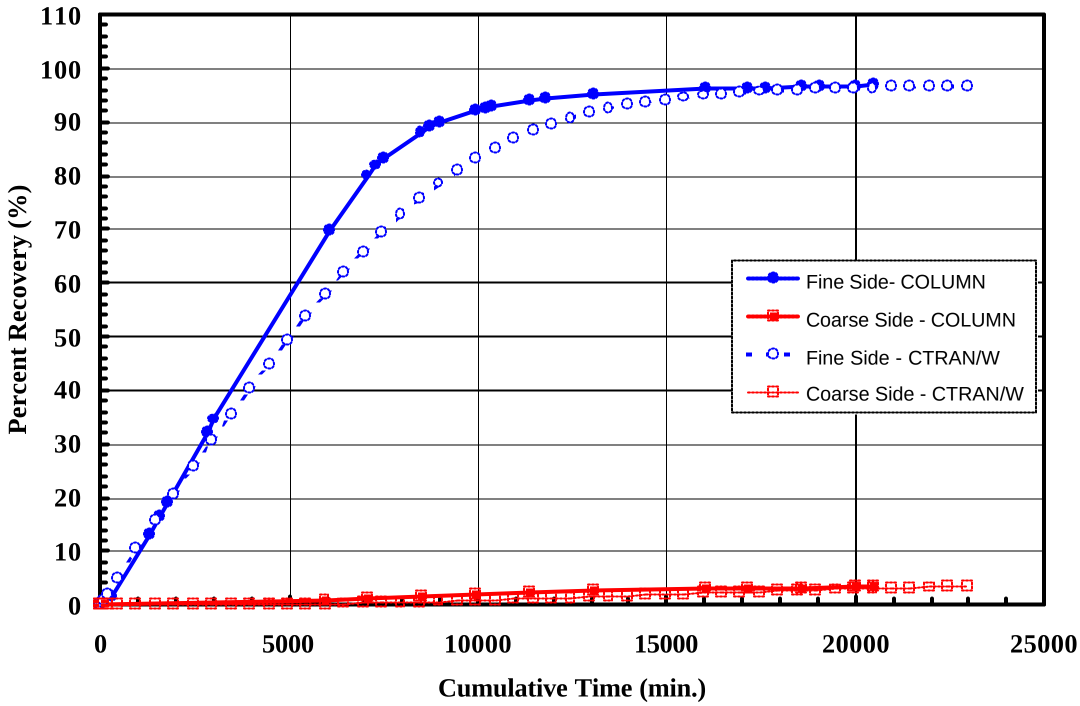


**Figure A.3** CTRAN/W modelled preferential leaching compared with measured values for the low flux-fine material salted column.