A Framework for improving the ability to understand and predict the performance of heap leach piles

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ABSTRACT

Operators and designers require a comprehensive model to predict performance of heap leach piles and provide input of reliable and defensible data for economic modelling. A conceptual, theoretical, or numerical predictive model addressing the required metallurgical, geological, biological, and operational considerations should be developed within the framework of the hydraulic performance of the heap leach pile. It is generally agreed that segregation, compaction, and consolidation are physical aspects which significantly affect recovery and in general hydraulic performance. Hydraulic performance of heap leach piles can be described through the application of unsaturated zone hydrology. Unsaturated zone hydrology describes the flow and storage of moisture and oxygen in a porous medium under conditions where the pore water pressure is less than atmospheric. The porous material is "unsaturated" if an air phase, in addition to the water phase and solid material phase, is present. These conditions describe the operation of a copper heap leach pile. This paper will focus on developing an understanding of hydraulic performance in segregated heap leach material and demonstrating that unsaturated zone hydrology can be used as the framework to improve understanding and prediction of heap leach performance.

INTRODUCTION

Heap leaching is an attractive alternative for extracting metals from ore for large heavily capitalized mining companies and in particular for comparatively smaller companies. The rationale is a function of capital and production costs. In general, heap leaching keeps capital investment low, construction of a heap leach operation is rapid, and production costs are low. Heap leaching can make mining low grade metal ores profitable, particularly as part of and open pit mine with low stripping ratios. The primary disadvantage of heap leaching is low recovery efficiencies. Mineralogical factors affecting recovery rates are: 1) the mineral bearing the metal; 2) grain size; 3) the host mineral of the ore; and 4) the distribution and location of the metal in the host mineral (Gasparrani, 1984). Key operational issues are segregation of ore, compaction, and solution application rates.

To date, the industry does not have access to the desired predictive modelling tool to develop reliable and defensible data for economic modelling. A discussion on segregation in heap leach piles is presented first. The paper then presents the theoretical background for unsaturated zone moisture storage and seepage. A laboratory study is presented to illustrate the impact of segregation on hydraulic performance. The results of the laboratory program are summarized to demonstrate the applicability of using unsaturated zone hydrology as the framework for the desired predictive modelling tool. Physical aspects (i.e. water storage and flow and gaseous oxygen transport) of heap leach performance are at a minimum equally significant as metallurgical, geological, geochemical, and microbial aspects.

Segregation

It is generally accepted that segregation, compaction, and consolidation have a significant impact on heap leach performance. The focus of this paper will be on addressing segregation although it should be clear the latter two issues can be equally if not more important. 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. For example, Kinard and Schweizer (1987) excavated 6 m test pits in a 9 m high operational heap leach pile and observed distinct zones of segregation resulting from deposition by a radial stacker. Alternating zones of coarse, fine, and well graded material were observed in all test pits ad throughout the depth of the test pit. Figure 1 shows a photograph of a test pit wall for an excavation in an agglomerated heap leach pile. The inevitable condition resulting from placing heap leach material is segregation. However, this condition does not need to be viewed as a negative aspect of heap leach performance if an understanding of unsaturated zone hydrology is developed, and more importantly applied, to the design and operation phases. Unsaturated zone hydrology provides a framework for addressing the condition of segregation.

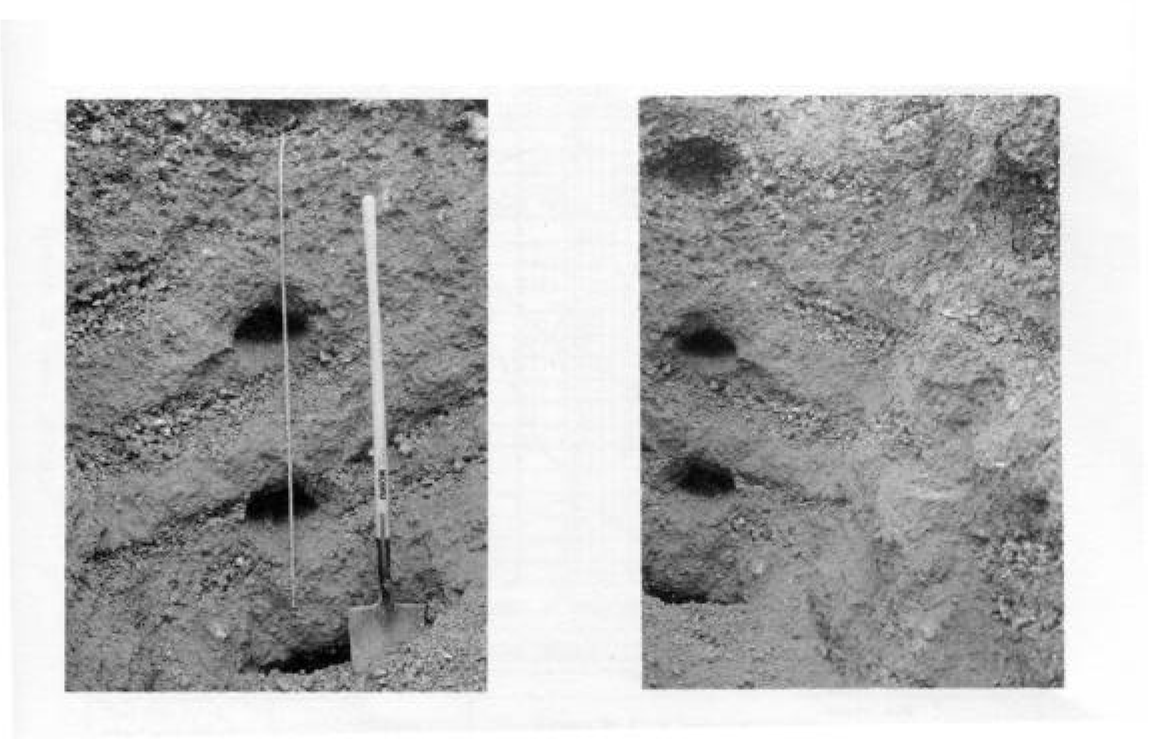


Figure 1 – Photograph Showing Segregation in an Agglomerated Heap Leach Pile (from Kinard and Schweizer, 1987)

UNSATURATED ZONE HYDROLOGY

Figure 2 shows a schematic column of fine (on the left side) and coarse (on the right side) textured material segregated down the axis of the column. The material is prepared and placed at moisture conditions similar to that experienced in the field for heap leach materials. There is no barrier to lateral flow across the interface of the fine and coarse textured materials. Water is applied to the top of the column as shown and the question arises: Will the water "prefer" to flow in the fine or coarse textured material? Clearly, for saturated conditions the preferred flow path will be the coarse material due to its higher permeability. However, the correct answer to the question for unsaturated conditions, such as that describing a heap leach pile, is: "It depends on the applied flux rate at the top of the column". In general, at low flux rates the "preferred" flow path will be the fine textured material. This counter-intuitive phenomenon of unsaturated zone hydrology has a significant impact on the hydraulic performance of segregated fine and coarse textured material, whether the material is separated as shown in Figure 2 or layered at an angle as would be found in a heap leach pile.

Unsaturated Zone Flow and Storage

In general, a mass of soil consists of a collection of solid particles with voids interconnected between the solid particles. Figure 3 shows a schematic representation of an elemental soil volume. The darker solid material, (S), can be viewed as the solid particles, whereas the voids are filled with either water, (W), air (A), or partly filled with water and air. Therefore, the total volume of water, V_t, is the sum of the volume of solids, V_s, and the volume of voids, V_v. The degree of saturation, S, is defined as:

$$S = {}^{V_w}\!/_{V_v} \times 100\% \tag{1}$$

and is a calculated percentage of the volume of voids which contain water. In general, if the soil is completely dry (i.e. the volume of water equals zero) then $S = 0\%$, and if the pores are filled with water (i.e. the volume of water is equal to the volume of voids) then the soil is saturated and $S = 100\%$. In reality, a small amount of water will always be present in the voids, and as the contractile skin, as represented schematically in Figure 3a) where $S <<<< 100\%$.

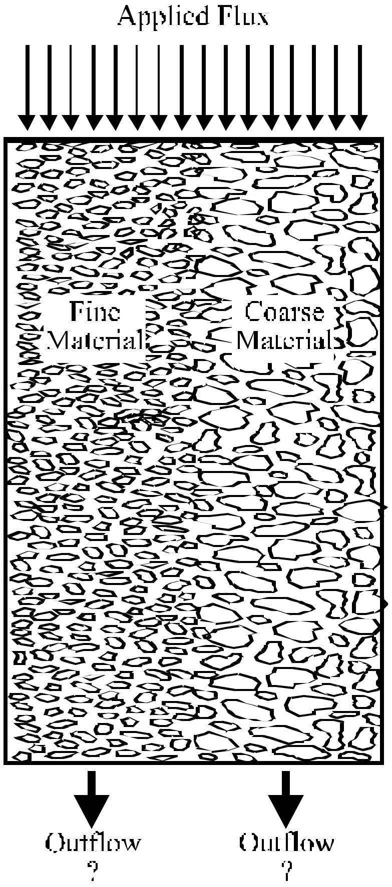
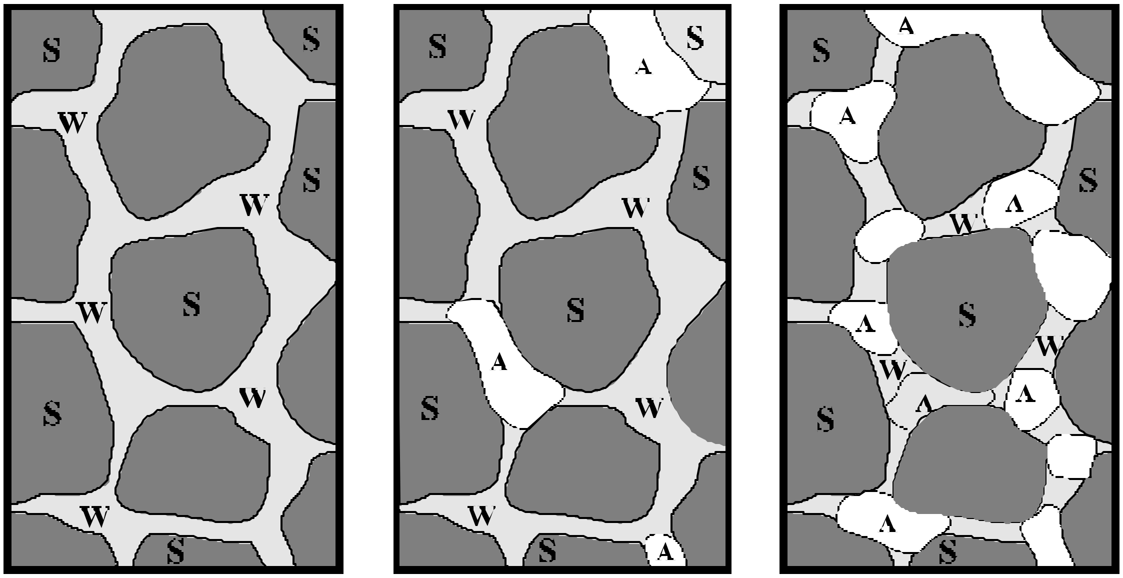


Figure 2 – Schematic of a Column with Segregated Coarse and Fine Textured Materials



a) S = 100%   b) S < 100%   c) S <<<< 100%

Figure 3 – Schematic Representation of Soil Mass Consisting of Solids (S) with Voids in Between Filled with Water (W) and Air (A)

The maximum permeability of the soil mass depicted in Figure 3 is for a degree of saturation of 100%, as shown in Figure 3a (i.e. the saturated permeability). The conditions depicted in Figure 3a also represent the minimum gas diffusion condition, such as for oxygen required in bio-heap leaching. The degree of saturation decreases due to gravity drainage and evapotranspiration as the larger pores drain (Figure 3b). The result is an unsaturated material. In the case of the column shown in Figure 2, or a heap leach pile, the saturation level to which the material comes to "steady-state" will be a function of the applied flux rate, in addition to the material properties controlling moisture storage. The permeability of the soil mass shown in Figure 3b will be less than the saturated permeability because the voids filled with air cannot transport water. In short, the air voids act in a similar manner to the solids and the cross-sectional area available for water flow decreases. The permeability of the soil mass will continue to decrease, and eventually be dominated by water vapour flow at the low saturation levels shown in Figure 3c because the liquid water phase is discontinuous. The saturation levels shown in Figure 3c would also represent the maximum condition for gaseous oxygen diffusion. In summary, the permeability of a material decreases as the saturation level decreases while the effective diffusion for gaseous oxygen would increase for similar conditions.

Ideally, effective permeability should be plotted as a function of negative pressure head or suction. However, for simplicity the effective permeability is shown as a function of the degree of saturation in Figure 4 where typical relationships of permeability as a function of the degree of saturation for a coarse textured material and a fine textured material are shown. The permeability corresponding to a degree of saturation of 100% represents the saturated or maximum permeability. Initially, at saturated conditions, the coarse textured material has a higher permeability than the fine textured material, as shown in Figure 4. However, at the point when the larger pores drain the effective permeability of the coarse textured material decreases due to, among other factors, a decrease in the cross-sectional area available for flow.

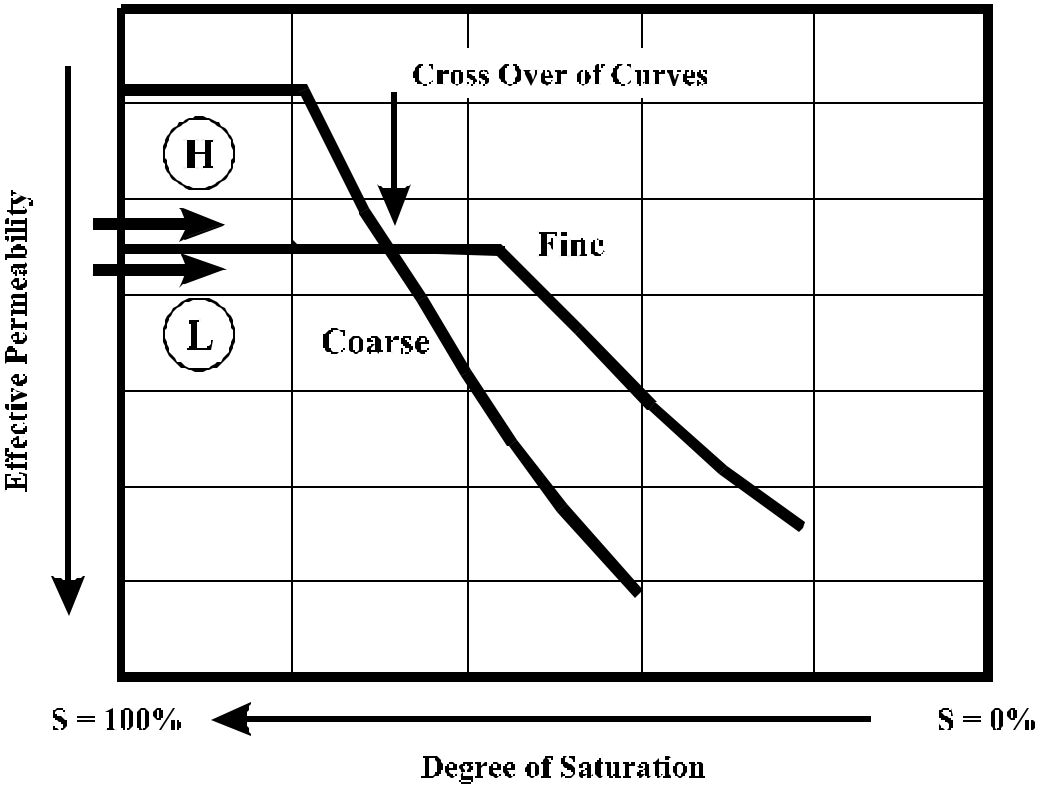


Figure 4 – Typical Relationship Between Permeability and Degree of Saturation for Fine Textured and a Coarse Textured Materials

The effective permeability of the fine textured material will continue to remain near the saturated permeability as the coarse material drains because the pores of the finer material are smaller, as compared to the coarse material. The fine textured material possesses a greater ability to retain moisture, as compared to the coarse textured material due to the smaller pore spaces. Hence, it will maintain tension saturated conditions even though the coarse material drains. Eventually, the pores of the fine textured material will also drain at lower saturation levels and its effective permeability will also decrease, as shown in Figure 4. The rate at which the effective permeability decreases will be a function of the gradation of the material. The effective permeability will decrease rapidly for uniform materials and less so for well graded materials.

The two permeability functions cross at a specific degree of saturation, as shown in Figure 4. The effective permeability of the coarse textured material will be greater than the fine textured material at saturation levels to the left of the cross over point (i.e. greater). The opposite is true for a degree of saturation less than the cross over point (i.e. to the right) when the fine material will posses a higher effective permeability than the coarse textured material. This is counter-intuitive to saturated groundwater flow hydrogeology and a key component for understanding hydraulic performance of an unsaturated system, such as a heap leach pile.

The answer to the question of the preferred flow path for the water applied to the top of the column shown in Figure 2 can now be answered with some understanding. A flux rate applied to the top of the column that is greater than the saturated permeability of the fine textured material (see "H" in Figure 4) will lead to preferential flow in the coarse material. The higher applied flux rate will create a pressure profile leading to saturation conditions where the effective permeability of the coarse material is greater than the fine material. An applied flux rate less than the saturated permeability of the fine textured material (see "L" in Figure 4) will lead to preferential flow in the fine textured material. The lower applied flux rate creates a pressure profile where the coarse material drains while the fine material retains moisture and its effective permeability is higher than the coarse material. The key issue is that determining the predominant flow path is not completely intuitive.

LABORATORY DEMONSTRATION OF PREFERENTIAL FLOW

A laboratory column was prepared as shown in Figure 2. The applied flux rate, q, was varied between 1 x 10^{-5} m/s (≈ .014 gal/min/ft^2) and 1 x 10^{-6} m/s (≈ .0014 gal/min/ft^2). Discreet samples from the base of the column were obtained to measure the outflow from the coarse and fine textured materials. Inert material was used for the fine and coarse textured material to focus on demonstrating the physical aspects of the segregated heap leach material. A laboratory demonstration not discussed in this paper is in progress and addresses leaching aspects of the coarse and fine textured materials. The gradation of each material was based on assuming segregation of an agglomerated heap leach material during construction of a pile. The material was segregated based on Yazdani, 1996, Herasymuik, 1995, and Kinard and Schweizer, 1987. Figure 5 shows the particle size distributions for the agglomerated heap leach material together with the assumed segregated components resulting from placement of the material.

Water was applied to the surface of the entire column using a peristaltic pump, a reservoir of water, and numerous small diameter tubes. A uniform drip from each tube was maintained and the column was allowed to reach a steady state condition. Discreet samples were periodically collected from ports installed below each of the coarse and fine textured materials. The sum of the volume of water collected from each of the two collection ports was compared to the volume of water applied to the surface over a specified time frame to determine if steady state conditions were achieved.

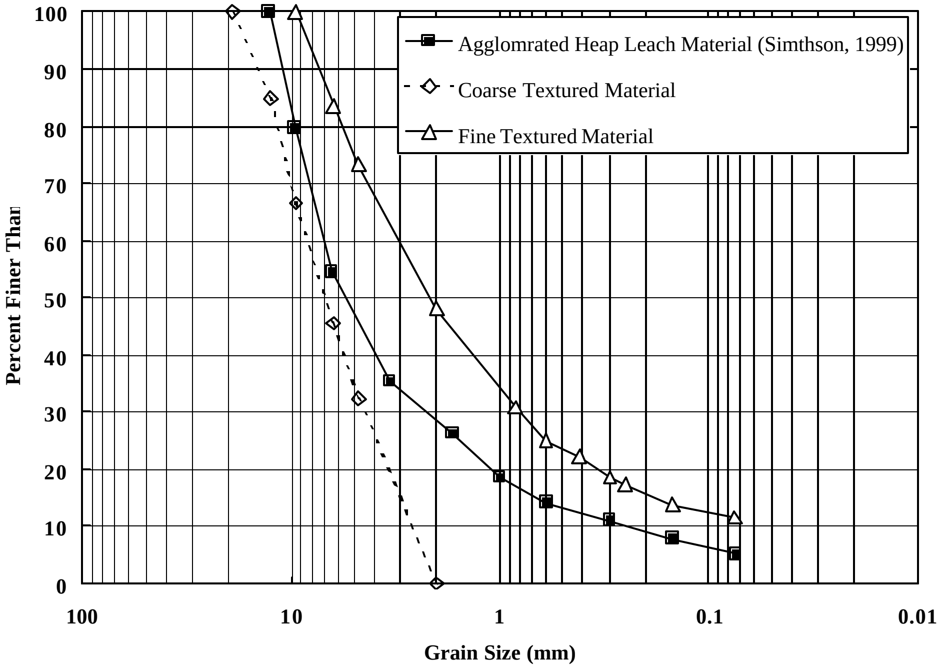


Figure 5 – Particle Size Distributions for the Coarse and Fine Textured Column Materials.

Laboratory Column Results

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 6 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.

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.

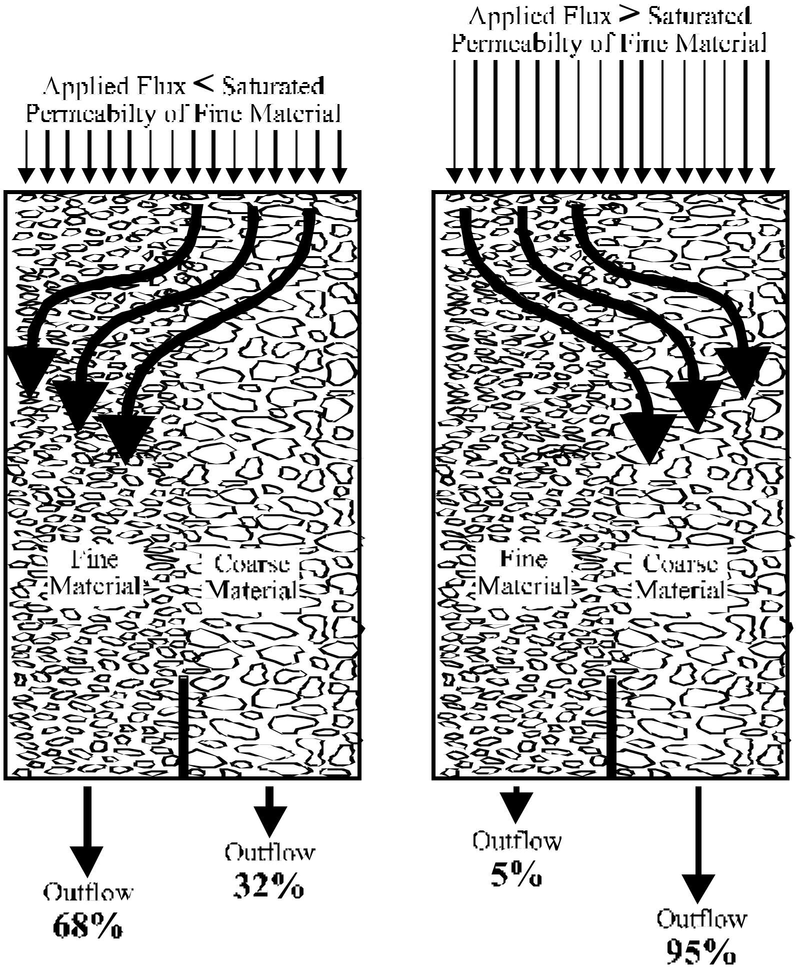


Figure 6 – Illustration of the Segregated Column Test Results

IMPLICATIONS FOR HEAP LEACH OPERATION

The laboratory column test results coupled with an understanding of unsaturated zone hydrology illustrate that preferential flow will occur in a heap leach pile containing lenses of segregated material. Segregation is inevitable and the impact of preferential flow resulting from unsaturated zone hydrology should be addressed properly. For example, increasing the solution application rate on an operating heap leach pile to achieve higher recoveries may in fact lead to reduced recovery rates if the desired mineral is primarily located in the fine textured component of the ore. Flow may tend to preferentially occur in the coarse material at the higher solution application rate and in effect the operator will have created "blind" zones in the heap leach pile simply by increasing the solution application rate. In reality, a single optimum solution application rate may not exist. Higher and lower solution application rates, applied for different lengths of time during the heap cycle may lead to more uniform leaching of the entire heap leach pile, significantly improve contact and residence time, and ultimately increase recovery.

The latter solution application methodology may be a practical and economic alternative to employing costly measures which attempt to minimize segregation. Clearly the methodology attempts to employ a more theoretical approach to heap leach design and operation. However, conceptual and numerical tools are available, or can be developed, to move the design and operation of heap leach piles from a largely empirical approach to a theoretical basis. Improvements in heap leaching performance can be achieved as the theoretical base for design is improved and a better understanding for key design components is developed. It is not unreasonable to postulate that operations may find production costs reduced and recovery increased if segregation is encouraged, as a better understanding for hydraulic performance of heap leach piles is developed.

Degradation of the Heap Leach Material

Keane (1998) is one of numerous authors that provide examples illustrating the shift of the particle size distribution to a finer texture as a result of leaching ore. The degradation of the ore occurs during the heap cycle and will impact flow and storage within the heap leach pile. The saturated permeability and more importantly the shape of the effective permeability versus degree of saturation curve for the heap leach material will change as a result of degradation during the heap cycle. In addition, as the material degrades and becomes finer in texture it will develop a greater ability to retain, or store, moisture. Hence, a single optimum solution application rate may not exist for the heap leach pile for the entire heap cycle because unsaturated flow and storage material properties change during the cycle due to degradation.

SUMMARY

Heap leach piles are by definition unsaturated systems. The flow and storage of moisture will be a function of the unsaturated material properties. Segregation of material into interbedded fine and coarse textured layers will occur in agglomerated and non-agglomerated heap leach piles. The laboratory column test results demonstrated that the preferred flow path in segregated material is a function of the applied flux rate. The preferred flow path will be the fine textured material for an applied flux rate lower than the saturated permeability of the fine textured material. This is counter-intuitive and a key component for understanding and properly applying unsaturated zone hydrology. The implication for heap leach performance is a function of the nature of the ore with respect to which particle sizes the leachable mineral is primarily located. A lower, rather than higher, solution application rate would increase recovery if a heap leach pile is segregated and the mineral primarily occurs in the finer particle sizes. In summary, proper application of unsaturated zone hydrology provides a framework for improving the ability to understand and predict heap leach performance.

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