“THE EFFECTIVE PARTICLE SIZE IN HEAP LEACHING”

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Presented by

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ABSTRACT
Analysis of commercial and laboratory column leach data has shown that the system is diffusion controlled on a macro scale. The diffusion domains are the volumes of retained moisture of the ore and agglomerates. The domain size is directly related to the saturation of the ore within the heap. As a result the leaching is not controlled directly by the ore particle size distribution.
Within the domain the finer material has higher saturation with their smaller size. As a result the fines leach at a slower rate than would be expected from their size alone. The relative leach rates of the fines and the coarse, provides an estimate of the effective size of the fines. The effective size to actual size ratio increases with finer sizes.
A model has been developed from domain voidage and alternatively from saturation arguments to describe the phenomenon. Both approaches give the same form and relationships although from different logical bases. The model fits all the data with high degrees of correlation.
Some limitations in the model use are evident when the leach rate determinant changes from the saturated domain to a local particle domain such as chrysocolla silica matrix or intra-particle diffusion.
Any model of leaching that aspires to practical use, must take into account the effect of inverse relative leach rate with decreasing particle size.
Some further work is needed to allow normalization of the results between data sets with alternate particle top sizes.

INTRODUCTION
The AJ Parker Centre is sponsoring a PhD thesis by the author on acid copper heap leaching. This is part of a larger AMIRA project on heap leaching that aims to improve the understanding and practice of the technique. The aim of the investigation has been to develop an understanding of the leaching process and to use this to develop a model that is sufficiently robust; but also simple enough; for operators to use with confidence. The present work has been almost completed; with commercial heap leaching data used to verify and validate the model developments.
The shrinking core diffusion model has been taken as the basis for the development work. It has been shown that this model accurately tracks the progress of commercial leach heaps and also accounts for changes in acid concentration and irrigation rate (Miller 2003a, 2003b, 2003c). Over a hundred sets of commercial data have been analysed and all shown to behave in a manner that is consistent with the use of the model. The range of data includes alternate heap heights, oxide and sulphide minerals and column tests and pilot heaps. (Miller 2003a)
There are a number of parameters in the shrinking core diffusion model that have generally been ignored in the use of the model. These relate to the rock mass characteristics that define:
  o  the tortuosity,
  o  the void fraction of the leached domain and
  o  the ‘particle’ size that is being leached.
All of these parameters are affected by the local stresses in the heap so that they generally change with heap height. As a result the diffusion leaching rate is determined not so much by the inherent chemistry of the chemical reactions but the geo-technical characteristics of the ore mass itself. (Miller 2003b, 2003c)
Commercial data analysis has shown that the diffusion leach rate is constant through the leach cycle once leaching has begun. This implies that a single effective particle size is being leached. Figure 1 shows the typical consistent diffusion controlled leach rate.
Figure 1. Diffusion Leach Rate Model with constant Leach Rate

In general this is related to agglomerated heaps where the ‘particle’ can be considered to be the agglomerate itself. However for non-agglomerated material the same argument is also true but with larger effective sizes observed due to the uncontrolled saturated domain regions.

The tortuosity of heaps has been compared with other rock and soil data with interesting parallels emerging. The effect of clay is to add considerably to the tortuosity due to both the platy particle shape, the increased packing density and the increased sensitivity to imposed stress. As a result a small increase in clay can have a major (and generally unpredictable) effect on the heap tortuosity.

The void space in a heap has been shown to be a critical parameter in the leach rate determination. It is a determinant of both tortuosity and the voidage of the leaching domain itself. There are currently no models of leaching that include changes to the void space. Similarly there are no current models for the changes in void space with heap height (stress).

New correlations and models have been developed for the effect of clay on tortuosity and void space (Miller 2003b). Further models have been developed for tracking the void space and stress relationships for individual rock masses (Miller 2003c). These models are useful in general trend prediction with changes in geo-technical characteristics of the rocks.

In the current work it has been shown that the effective particle size of leaching is an inverse relationship with the actual particle size. Smaller particles leach at relatively slower rates than larger particles. For very small particles the ratio of effective leached size and actual size approaches infinity as the size tends to zero. This is a result of the saturation of the finer particles with capillary held moisture. The leach rate is determined not by the particle size but by the size of the capillary held moisture domain. These phenomena can be used to explain the often observed higher tails concentration in the very fine materials.

*The combination of various parameters is synergistic and can affect the leach rate by one or two orders of magnitude with relatively small changes in the feed rock characteristics.*

Overall the investigation has been successful in combining the information that has been accumulated in a wide range of disciplines: soil science, environmental science, hydro-geology, heap leaching, nano-technology and bio-science. All of these disciplines have made steps forward in modeling the diffusion process and all have pertinent data for the mineral processing of copper heap leaching.
Previous papers have been published on the other aspects of the investigation [Miller 2002, 2003a, 2003b, 2003c, Miller and Newton 1999]. This paper covers the modeling undertaken on the relative leach rates as related to particle size.

EFFECTIVE SIZE MODEL

There is evidence in the literature that the diffusion zone extent is controlled by the ‘static’ moisture content of the soil or rock mass. The static moisture is held by capillary action and is limited only by the proportion of fines and clays present. The total voidage is also a function of the fines and clay content; as they can increase plasticity and decrease the voidage. A discussion of clay content effects is provided by Miller (2002a, 2002b, 2002c).

Some indication of these effects on leaching was noted by (Chae and Wadsworth, 1974) who reported an increase in effective leach particle size ($R_{eff}$) with a decrease in the actual particle size (R) as shown in Figure 2. Other than observing the phenomenon they did not discuss the implications nor to develop an explanation for its occurrence.

![Reff vs Size (Chao & Wadsworth)](image)

**Figure 2: Proportional Increase In Leach Particle Size With Decrease In Actual Particle Size. Data From Chae And Wadsworth.**

This is further supported from observations of column leach data; which can show significantly higher grades in the finer tails than in the coarser material. In the past this has been ascribed to:

- Higher head grade in the finer materials
- Greater proportion of refractory minerals (eg copper in mica’s, clays and wads) in the fines
- Difficulty in ‘wetting’ the fines.

It is likely that the ‘real’ reason for the slower than anticipated leach rate of the fines is their having a larger effective size from the greater capillary moisture that they retain. Some indicative data is provided in Figure 3 for a disseminated chalcocite ore.
Figure 3.0: Size By Size Large Column Tail Grade.

The effect is also seen in surface expressed oxide ores to the same sort of extent. This is further discussed in the following sections.

It is evident that the finer material (which should leach faster according to the conventional models) has leached relatively much more slowly than even the very coarse material +150mm. Material progressively finer than 9.5mm, leaches at progressively slower rates. This counter intuitive result needs explanation and elucidation.

Further support, for the concept that finer materials leach slower than coarser, is provided by (Wash et al, 1997) from the Girilambone operation. They have shown that coarser crush top size material leaches significantly faster than the same material crushed to a lesser top size. The crush size difference places more material in the larger size fractions and reduces the total fines that leach more slowly.

In attempting to assess the effective particle size being leached there are two limits that can be identified:

At infinite separation (ie very dilute slurry leaching) the leach particle dimension is the actual crushed particle size. This could be extended to some degree to assess the leaching of agglomerates in a heap, as rigid spheres of the agglomerate size distribution.

At heap voidage equal to the limit moisture capacity (plus the occluded and advection voids) the effective leached particle size is essentially infinite, or as set by the effective advection flow ‘finger’ spacing or other physical limits to the held moisture domain.

The resulting dependence of effective leached particle size on total heap void fraction is an inverse exponential of the form related to:

\[ \frac{R_{\text{eff}}}{R} = 1 + \frac{a}{(\varepsilon_t - \varepsilon_1 - \varepsilon_o - \varepsilon_a)^b} \]  

[1]

Where a and b are constants, that are related to the particle size distribution, ore plasticity and clay content.

Assuming that there is such an inverse relationship of the form:
\[ \frac{R}{R_{\text{eff}}} = Y = \frac{a}{X^b} \]  

with axes shifted to:

- Y asymptotic to 1.0
- X asymptotic to the Domain volume fraction \( \varepsilon_d = \text{limit moisture capacity} + \text{occluded voids} + \text{advection flow volume} \)

The net relationship will be:

\[ Y = 1 + \frac{a}{(X - X_d)^b} \]  

In this case \( X_d \) corresponds to the equivalent \( \varepsilon_d \)

For a relationship of this type to hold the X must take values from 0 to infinity for changes in void fraction from 0 to 1. This can be achieved with an X axis related to the ratio of the void volume to the particle volume (the void ratio beloved of the civil engineers):

\[ R_v = \frac{V_v}{V_p} \]  

And \( Y = 1 + \frac{a}{(R_v - R_d)^b} \)

From the definition of void fraction \( \varepsilon_t = \frac{V_v}{(V_v + V_p)} \) can be re-arranged to provide:

\[ \frac{V_v}{V_p} = R_p = \frac{\varepsilon_t}{(1 - \varepsilon_t)} \]  

And \( \frac{V_v}{V_d} = R_d = \frac{\varepsilon_d}{(1 - \varepsilon_d)} \)

\[ V_p = V_v[\varepsilon_t/(1 - \varepsilon_t)] = V_v(1 - \varepsilon_t)/\varepsilon_t \]  

The limit moisture capacity (\( m_l \)) is generally determined as % of the particle mass on a w/w basis. The limit moisture capacity on a v/v basis (\( v_l \)) is related to the particle and solution densities by:

\[ v_l = V_l/V_p = \frac{m_l \rho_p}{\rho_l} \]  

And

\[ v_l = V_p \frac{m_l \rho_p}{\rho_l} \]  

The volume of the occluded voids is given as a straight volume fraction of the particle volume \( V_o = kV_p \)

The advection flow hold up is generally given as a mass fraction of the particle mass and can be expressed similarly to the limit moisture capacity:

\[ V_a = V_p \frac{m_a \rho_p}{\rho_l} \]  

The total domain volume is:

\[ V_D = V_p + V_l + V_o + V_a = V_p(1 + m_l \rho_p/\rho_l + k_1 + m_a \rho_p/\rho_l) \]

\[ V_D = V_p + V_d \]  

Where \( V_d \) is the volume of the non particle void in the domain.

\[ V_d = kV_p \]

\[ V_D = (1+k)V_p \]  

The total domain voidage \( \varepsilon_d = V_d/(V_d + V_p) \)

\[ \varepsilon_d = V_d /(V_d + kV_p) \]
\[ \varepsilon_d = \frac{k}{(k+1)} \]  

\[ \frac{R}{R_{\text{eff}}} = 1 + \frac{a}{[\varepsilon_d/(1-\varepsilon_d) - \varepsilon_d/(1-\varepsilon_d)]^b} \]

ANALYSIS OF CHAE AND WADSWORTH’S DATA.

The data from (Chae and Wadsworth, 1974) for mono-sized granular materials, would suggest values of; \( a = 1.46 \) and \( b = 0.69 \) with larger values giving greater sensitivity. It is likely that values of both \( a \) and \( b \) will increase with wider size distributions and higher clay contents. In the sensitivity modeling shown in Figure 4, values of \( a = 1.0 \) and \( b = 0.69 \) have been used for illustration.

The ratio of effective leached particle size with various \( a \) and \( b \) parameters is shown in Figure 4.0.

![Figure 4.0: Effective Particle Size Ratio as a function of Heap Voidage](image)

The data from this investigation needs to be transformed into a form to enable it to be used to indicate the change of ‘effective’ particle size on the leach rate. It is most important to note that this data shows the smaller particles leaching at relatively slower rates than larger particles. This is postulated to be due to the increased retention of moisture with reduction in particle size; ie as the particle size reduces the moisture retention increases and the effective particle size ratio \( R_{\text{eff}}/R \) increases.

The method used to change the ratio \( R_{\text{eff}}/R \) to the particle size, is to use the moisture retention / size relationships developed by Schlitt, 1974. These are used to transform particle size into the saturation domain; which is then used to characterise the dependency. The Schlitt relationship is shown in Figure 5.
Saturation has been chosen, as the voidage relationship developed earlier can also be related to the saturation. In this way the two approaches can be aligned so that information from either method can be used in the modeling process.

The relationship between particle size, capillary diameter and moisture held in the particles has been developed by Schlitt for typical rock size distributions:
\( h_c = 32/d_p \)

\( h_c: \) capillary rise mm
\( d_p: \) particle diameter mm

The volume percent of solution retained is also directly related to the capillary rise through:

\[
S = h_c/200 \text{ giving}\nS = 0.16/d_p
\]

S: saturation = \( V_w/V_v \)

From this relationship it is possible to calculate the saturation that relates to individual particle sizes as shown in Table 1.

**Table 1: Particle Size, Capillary Rise, Saturation and Effective Size.**

<table>
<thead>
<tr>
<th>( d_p )</th>
<th>( h_c )</th>
<th>( S )</th>
<th>( R_{ef}/R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.1</td>
<td>1.679</td>
<td>0.008</td>
<td>1.3</td>
</tr>
<tr>
<td>8.0</td>
<td>3.992</td>
<td>0.020</td>
<td>1.55</td>
</tr>
<tr>
<td>4.0</td>
<td>8.002</td>
<td>0.040</td>
<td>1.9</td>
</tr>
<tr>
<td>2.8</td>
<td>11.364</td>
<td>0.057</td>
<td>2.2</td>
</tr>
<tr>
<td>2.0</td>
<td>15.976</td>
<td>0.080</td>
<td>2.4</td>
</tr>
</tbody>
</table>

In this instance the values of saturation are constrained by a minimum of 0.0 and a maximum of 1.0. As \( S \to 0 \) (\( dp \to \infty \)) the value of \( R_{ef}/R \to 1.0 \). As \( S \to 1.0 \), (\( dp \to 0 \)) the model postulates that the value of \( R_{ef}/R \to \infty \). The infinite value of \( R_{ef}/R \) can be inferred from the previous discussion relating the effective particle size as the total voidage approaches the field capacity. In this instance the field capacity for each size is calculated and then this is further transformed into the saturation ie percentage of the total voidage occupied by the moisture component. As the saturation approaches 1.0 the actual voidage approaches the field capacity voidage and the effective particle size approaches infinity.

The Schlitt correlation is a linear approximation to a non-linear relationship (as evidenced in Figure 5.0). The data in this figure has been re-plotted and modeled to determine if a more accurate representation can be obtained – Figure 6.0.
**Figure 6.0: Re-analysis of Schlitt Data**

It is evident that the actual capillary rise data is close to the Schlitt model but that there are increasing differences as the particle size reduces. The curve fit model is:

\[ h_c = 33.8/d_p^{1.26} \]

compared to the Schlitt model of:

\[ h_c = 32/d_p \]

Similarly the saturation model shows a divergence from the Schlitt model with:

\[ S = 0.16/d_p \]

Now better represented by:

\[ S = 0.15/d_p^{1.42} \]

The applicability of this data to other ore systems is likely to be limited as the dependence of saturation on ore type (size distribution and proportion of platy particles) is variable (Schlitt, 1974). However in the absence of further data to more closely relate the saturation with particle size distribution the new relationship has been used to help analyse the available data.

**SATURATION AS A FUNCTION OF THE OTHER PARAMETERS**

In this case we are looking for the relationship between “Saturation” and the other parameters of the porous medium. Saturation is the ratio of the water filled void volume to the total non solid volume.

\[ S = V_w/(V_w+V_v) \]  \hspace{1cm} [16]

\[ S = \varepsilon_w/\varepsilon_t \]  \hspace{1cm} [17]

From previous relationships

\[ \varepsilon_w = \rho_p/\rho_w(1-\varepsilon_t) \]  \hspace{1cm} [18]
\[ \varepsilon_w = \rho_b/\rho_w \] \hspace{1cm} [19]

and
\[ \varepsilon_t = (\rho_p - \rho_b)\rho_p \] \hspace{1cm} [20]

Combining and simplifying
\[ S = \frac{\rho_b}{(\rho_p - \rho_b) \rho_p} \times \rho_p/\rho_w \times m_i \] \hspace{1cm} [21]

or
\[ S = m_i \times \rho_p/\rho_w (1 - \varepsilon_t)/\varepsilon_t \] \hspace{1cm} [22]

This provides a relationship between the degree of saturation \( S \) and the total voidage (and dry bulk density through \( \rho_b = (1 - \varepsilon_t)\rho_p \))
\[ S = \rho_p\rho_b m_i/\left[ \rho_w(\rho_p - \rho_b) \right] \] \hspace{1cm} [23]
\[ \rho_b = S \rho_p/[S + m_i \rho_p/\rho_w] \] \hspace{1cm} [24]

<table>
<thead>
<tr>
<th>Moisture mass ratio</th>
<th>( M_w/M_s )</th>
<th>( m_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation</td>
<td>( \rho_w/\rho_t )</td>
<td>( S )</td>
</tr>
</tbody>
</table>

The mass of field capacity water is related to the mass of solids by the water mass fraction \( m_i \):
\[ M_w = M_s m_i \]

The volume of water is related to the volume of the solids by:
\[ V_w = V_s m_i (\rho_s/\rho_w) \]

The volume of the voids is related to the volume of the solids by:
\[ \varepsilon = V_v/(V_s + V_s) \]
\[ V_s = V_s (1 - \varepsilon)/\varepsilon \]
\[ V_v = V_s \varepsilon/(1 - \varepsilon) \]

**SATURATION MODEL OF EFFECTIVE SIZE**

The relationships between the parameters and their limits is shown in Table 2.

**Table 2: Relationship between the Saturation Model Parameters**

<table>
<thead>
<tr>
<th>Original</th>
<th>Transformed</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S )</td>
<td>( \text{Reff}/\text{R} )</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>infinite</td>
</tr>
</tbody>
</table>

The values of \( S \) calculated from the modified Schlitt correlation have been used to assess the \( \text{Reff}/\text{R} \) values as shown in Figure 7.
Figure 7.0: Values of the Chae and Wadsworth Data with Saturation from Schlitt.

The correlation is very high (although there are only four data points to use). Despite this it indicates that there is a validation of the modelling approach from the high correlation obtained. Figure 8 provides the same information but with the axes returned to show the model asymptotes of: \( R_{\text{eff}}/R = 1.0 \) and \( 1/S = 1.0 \).

Figure 8.0: Data from Chae and Wadsworth Including Model Asymptotes.

The equation for the model is:

\[
R_{\text{eff}}/R = 1 + 5.76 \left( 1/S - 1 \right)^{0.486}
\]

\[
y = 5.7584x^{-0.4846}
\]

\[
R^2 = 0.9973
\]

Limit testing the model shows that it reflects the real physical significance.

As \( S \to 1.0 \); \( R_{\text{eff}}/R \to \infty \)

As \( S \to 0.0 \); \( R_{\text{eff}}/R \to 1.0 \)
The values of a and b are significant (a = 5.76 and b = 0.485), in that there is a high level of dependence between \( \frac{R_{\text{eff}}}{R} \) and S.

The implications from this analysis are quite important:

- For any saturated domain the effective radius is ‘infinite’ ie it is limited only by the physical bounds of the domain.
- Unless the domain has physical boundaries (channels, large particles, agglomerate boundaries, drainage layers etc) there is no theoretical limit to the effective size of the “particles”. These domain boundaries are characterised by a step change in the local voidage, i.e. agglomerate inside to outside, etc.
- The sensitivity of the relationship is relatively high with \( \frac{R_{\text{eff}}}{R} \) up to values of 4.0 for saturation levels of only 20% as shown in Figure 9.

![Figure 9.0: Effective Particle Size Ratio and Saturation.](image)

- As overall saturation approaches 50% the effective size ratio becomes even greater
- For particle size less than 0.24 mm the whole of the (mono sized particle) mass is essentially saturated.
- For domains of fine particles the saturation is high and effective size ratios are high. This explains (at least) the greater part of the reason, for fines showing high tails grade from column leach tests.

**VOID MODEL RELATED TO SATURATION.**

A further extension of this analysis has been made to use the absolute saturation of the domain rather than the total non solid voidage. In this case it is required to transform the saturation relationship developed below into the void related parameters.

The saturation S is the proportion of the total volume this is occupied by the “solution”.

\[
S = \frac{V_w}{V_v}
\]

The solution volume in terms of the solid volume is:

\[
V_w = V_s m_d \rho_s / \rho_w
\]

The total void volume \( V_v \) is:

\[
V_v = V_s \epsilon / (1-\epsilon)
\]

Substituting and simplifying:
\[ S = \frac{m_{sl}\rho_s}{\varepsilon [(1-\varepsilon)\rho_w]} \]  \[ 25 \]

Rearranging:

\[ \varepsilon = \frac{m_{sl}\rho_s}{m_{sl}\rho_s + S\rho_w} \]  \[ 26 \]

When \( S = 1.0 \) the domain voidage equals the moisture voidage:

\[ \varepsilon_d = \frac{m_{sl}\rho_s}{m_{sl}\rho_s + \rho_w} \]  \[ 27 \]

From the definition of the moisture voidage:

\[ \varepsilon_d = \frac{m_{sl}\rho_s}{\varepsilon_d / \rho_w} \]  \[ 28 \]

\[ 1 = \frac{m_{sl}\rho_s (1 - \varepsilon_d)}{(\rho_w \varepsilon_d) = \frac{\rho_w}{m_{sl}\rho_s \varepsilon_d} / (1 - \varepsilon_d)} \]  \[ 29 \]

\[ \frac{1}{S} = \frac{\rho_w}{[(1-\varepsilon) m_{sl}\rho_s]} \]  \[ 30 \]

\[ \frac{1}{S} - 1 = \frac{\rho_w}{m_{sl}\rho_s} x \varepsilon /[(1-\varepsilon) - 1] \]  \[ 31 \]

\[ \frac{1}{S} - 1 = \frac{\rho_w}{m_{sl}\rho_s} x \varepsilon /[(1-\varepsilon) - \rho_w / m_{sl}\rho_s \varepsilon_d / (1 - \varepsilon_d)] \]  \[ 32 \]

\[ \frac{1}{S} - 1 = \frac{\rho_w}{m_{sl}\rho_s} \varepsilon /[(1-\varepsilon) - \varepsilon_d / (1 - \varepsilon_d)] \]  \[ 33 \]

The full expression for effective size as a function of Saturation now becomes:

\[ \{1/S-1\}^b = \{ \frac{\rho_w}{m_{sl}\rho_s} \varepsilon /[(1-\varepsilon) - \varepsilon_d / (1 - \varepsilon_d)] \}^b \]  \[ 34 \]

\[ \text{Reff}/R = 1 + a / \{ \frac{\rho_w}{m_{sl}\rho_s} \varepsilon /[(1-\varepsilon) - \varepsilon_d / (1 - \varepsilon_d)] \}^b \]  \[ 35 \]

This is exactly the same form of the relationship as developed via the discussion on voidage alone. It is a strong validation that the two approaches are equivalent and that results from either can be transformed into the other with confidence.
The only difference is the scaling using $\rho_w / m_s \rho_s$. This resolves the voidage ratios into the saturation ratios.

The exponent is the same in both cases and the constant ‘$a$’ is modified by the factor:

$$\frac{1}{[\rho_w / m_s \rho_s]^b}$$

The overall effect of the absolute values of the parameters is to suggest that there are modest changes in particle size for voidages more than three times the moisture voidage. However below three times the moisture voidage the change in effective particle size is very significant and increasing exponentially as the voidage decreases.

**ANALYSIS OF FIELD AND LABORATORY DATA.**

A significant number of data sets have been made available for analysis for the present work. These consist in the main of accurate head and tail assays of leached material on a size by size basis. In determining the ‘effective size’ dependency from this sort of data, it is necessary to make some significant simplifying assumptions:

1) The leaching of the coarsest particle interval is *particle* diffusion controlled

2) The effective relative leach rates can be determined as linear approximations based on the head and tail recovery end points (ie the assumption that the acid concentration has the same affect for all particle sizes).

3) The other factors in the diffusion control model are constant across the various size fractions
   - Diffusivity
   - Tortuosity of the diffusion domain
   - Diffusion domain voidage.

Under these conditions the diffusion leach model for the $i_{th}$ size interval is:

$$\text{Tr}(R)_i = K/(%Cu_i Re_i^2)$$ \[36\]

Rearranging and solving for $K$ for the first interval:

$$K = \text{Tr}(R)_1 %Cu_1 Re_1^2$$ \[37\]

Substituting into the equation for the $i_{th}$ interval and solving for $Re_i$ gives:

$$Re_i = R_i ([Tr(R)_1 %Cu_1]/[Tr(R)_1 %Cu_i])^{0.5}$$ \[38\]

One issue with this style of analysis is that the relative leach rates are related to the maximum top size. As a result the interpretation between data sets with different top sizes is difficult due to this ‘scaling’ factor. Some account of the scaling is required if the $Re/R$ effect is be utilized fully.

The data available covers a significant range of ore types with:

- Coarse ore with oxide copper
- Chrysocolla dominant oxides
- Ore with little fines and clays
- Ores with significant fines and clays
- Chalcocite dominant
- Mixed chalcocite and oxide copper minerals
- Chrysocolla dominant
- Disseminated chalcocite
- Fracture controlled (surface expressed) copper minerals.

The chrysocolla dominant minerals are treated as a separate category as the mineral matrix does not disappear as with leaching of the other oxide and sulphide ores. The silica that is left after copper leaching has a low porosity (compared with the general domain porosity) and a resultant low effective diffusion (and leach) rate. As such chrysocolla exhibits a further physically smaller controlling domain and should thus have different effective size characteristics.

**EFFECT OF FINES CONTENT**

The Project A data is from three column test with the same head material with varying amounts of the finer (- 200 mesh) material added back into the column feed. As shown in Figure 10 the addition of extra fine material to the leach feed does not effect the relationship of Re/R with either the particle size nor the level of saturation calculated from the particle size.

![Plant A Fines Test Columns](image)

**Figure 10.0: Effect of Fines on Effective Particle Size**

This result confirms the premise that the level of saturation (as determined by the absolute particle size) is the controlling mechanism for determining Re/R. The particle size distribution has little discernible effect on the Re/R dependency.

**EFFECT OF CRUSH SIZE.**

The Data from Plant B Sample No 4 was tested at three different crushed top sizes as shown on Figure 11.
In this case the sensitivity of Re/R to top size would appear to be of importance. However it needs to be recognised that the analysis assumes that the top size is particle diffusion controlled. There has been a shift in the curves to the left with decreasing top size from this effect alone.

The ore is a breccia (fracture controlled) chrysocolla dominated copper mineralization. It would seem from this analysis that there is some small gain to be made for crushing the ore to 25 mm but no further decrease in Re/R dependency for smaller top sizes.

It would appear this analysis technique can provide further input into the crush size optimisation process.

Further crush size dependency information is obtained from the Plant A trial heaps on ROM and primary crushed ores shown in Figure 12. This ore is a coarse, disseminated chalcocite dominated material with significant amounts of the copper contained within the rock particles.

Figure 11.0: Effect of Top Size on Effective Particle Size

Plant A Equiv Size

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Further crush size dependency information is obtained from the Plant A trial heaps on ROM and primary crushed ores shown in Figure 12. This ore is a coarse, disseminated chalcocite dominated material with significant amounts of the copper contained within the rock particles.
In this instance it is evident that the Primary Crushed material has a higher apparent degree of dependence than the ROM ore.

A method of normalisation of the results needs to be developed. The particle size normalisation is accomplished with the shift to $1/S – 1$ but there needs to be a method to normalise the $Re/R – 1$ as well!!

**EFFECT OF CLAYS**

The effect of increasing clay content can be gauged by consideration of the results from the Project C column tests. These were conducted on similar rock types with a higher proportion of clays in the AD-AD1 and AD-AD2 types. The ore is a fracture controlled mixture of oxides and chalcocite.

The effect of clay is to decrease the dependency of $Re/R$ on the particle size. This is almost counter intuitive but really relates to the effect of the clays within the agglomerate. They cause the diffusion path length closer to the agglomerate size; and thus subject most of the finer sizes to a totally saturated environment. Under these circumstances the particles are acting much more like individual particles and their relative leach rates are very much closer to 1.0 for finer and finer particles.

However the effect of the clayey ore types is to increase the overall dependency of $Re/R$ as compared to coarse ore. Comparison of the Project B (very coarse) and Project C (AD series) show that the $Re/R$ for 2.5 mm particles are:

Project B: 1.8

Project C: 4.5

As can be seen there is a substantial increase in the absolute values of the $Re/R$ ratio with the clayey ore type.

**Figure 13.0: Effect of Clays on Re/R Dependency.**

**EFFECT OF ANALYSIS TECHNIQUE.**

One data set has been analysed by both wet and dry sizing techniques. The ore is a clayey type with significant quantities of both swelling and non-swelling materials. The copper mineral is a mixed fracture and disseminated chalcocite dominant. Accurate head and tail wet and dry sizing and assays were conducted. The results are shown in Figure 14.
It is evident that the method of determining the size analysis has little effect on the calculated Re/R for the various size fractions.

**COMPARATIVE ANALYSIS**

The total data suite has been combined to provide the comparisons available in Figure 15.

**Figure 14.0: Project D Column Data**

Most of the of the data are clustered fairly tightly other than the coarse samples. An average curve for the clustered data has been developed that describes the behavior of the bulk of the materials tested. It is interesting to note that it is significantly more sensitive than the original data from Chae and Wadsworth would suggest. Comparative values for the these two are given in Table 2.
Table 2: Comparative Re/R for Ave Data and Chae and Wadsworth

<table>
<thead>
<tr>
<th>mm</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ave C &amp; W</td>
<td>19.9</td>
<td>7.8</td>
<td>4.9</td>
<td>3.6</td>
<td>2.9</td>
<td>1.8</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>4.8</td>
<td>3.4</td>
<td>2.8</td>
<td>2.5</td>
<td>2.2</td>
<td>1.8</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The inclusion of finer material in the sample space has the effect of increasing the sensitivity of the model at the finer sizes. The Chae and Wadsworth data did not include any material finer than 1.7 mm. As such it has no possibility of showing the fines type sensitivity and the effect of these fines on the coarser particles. The fines have higher capillary moisture and when attached to a larger particle increases the effective saturation associated with that particle as well. By this mechanism the presence of fines will by themselves increase the Re/R sensitivity. But also note that once present, increases in the fines content do not of themselves increase the Re/R sensitivity.

NORMALISING Re/R

A significant draw back to the use of this technique is the need to account for the effect of the selection of the top size as the basis for analysis of the data set. A method of normalization of the Re/R is required to enable comparisons to be made between data sets; and to draw more general conclusions.

One method that has been developed is to use the average diffusion path length as the characteristic length of the data set. As determined by previous work for this study and confirmed by (Bouffard and Dixon, 2001) the leaching rate is characterised by a single dominant diffusion path length that predominates for greater than 95% of the recovery. By using this ‘definitive’ length parameter, the relative leach rates of the physical particles can be related to the dominant ‘size’ ie the domain size including tortuosity.

This work has yet to be done to confirm the applicability of the approach.

LIMITATIONS OF THE MODEL

The model breaks down whenever the leaching of the material is no longer diffusion controlled within the leaching of a saturated domain. This can occur (generally at high recoveries >90% total) when some other diffusion controlled domain becomes dominant. Some of these situations have been described by Miller 2002. In this instance the leach control changes from a saturated domain to the large particles within the agglomerate.

Similar changes in leach diffusion control can occur when there is a significant proportion of the copper mineral as chrysocolla. Here the low porosity silica matrix becomes the diffusion rate control step in the latter parts of the leach. Figure 16 shows a typical change in diffusion rate control from a saturated domain to large particles.
Figure 16.0: Change of Diffusion Rate Control from Saturated Domain to Large Particles.

Under these circumstances the fines continue to leach to a stage where their recovery is still determined by the domain diffusion; but the relative recovery ratio (that determines the Re/R) is now set by the summed recovery of the faster domain diffusion and the slower particle diffusion rates. The assumption of straight line leaching through the whole of the leach time for all the particle sizes falls down in these circumstances. The Re/R calculated to the leach curve in Figure 16 is shown in figure 17.

Figure 17.0: Re/R for Leaching with Two Sequential Diffusion Control Systems.

As the reference large particle leaching slows the relative leach rate of the still saturation, domain controlled fines continues at the same rate. The resultant relative rate (Re/R) approaches 1.0 and even goes below 1.0 for the finer materials.

Thus the model needs to be applied circumspectly only when the underlying leach diffusion control can be determined. It is likely to be only partially applicable in those cases where there is both a high recovery and a change in the leach rate determinant. To date the only indicators that have been shown have all been from column tests. No commercial field data has shown a similar change in leach rate determinant (Miller 2003a).
ACKNOWLEDGEMENTS

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REFERENCES


