ORE GEO-MECHANICAL PROPERTIES AND EFFECTS ON COPPER HEAP LEACH KINETICS

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1. ABSTRACT

The geo-mechanical and geo-technical characteristics of the ore are important aspects of understanding the potential extraction kinetics of a copper heap leach operation. These characteristics are not simply an indicator of potential problems but can be used to determine the semi-quantitative reduction (or increase) in field kinetics as compared with column kinetics. The application of this approach allows a more rigorously based determination of ‘scale up factors’ than has been the case to date.

The shrinking core model has been shown to be a poor predictor of leach kinetics based on the crushed ore size distribution. This problem has been variously ascribed to poor wetting efficiency, poor solution distribution, presence of preferred solution channels etc. However the model itself is a very useful tool to analyse commercial heap data and provide an understanding of the leach kinetics and the effects of field variables.

The easiest geotechnical parameter to measure is bulk density (and it reciprocal voidage). This is determined as a function of both applied stress and consolidation over time. The response curve indicates if the ore has a high plastic deformation characteristic or reacts with a sandy in-elastic deformation style. The more plastic character is an effect of the clay and ultra fines content and is an indication of the ease with which the material can accrete (grow in size and reduce in voidage) under consolidation and stress from the ore mass above.

The other easy measurements are the moisture holding capacity ($m_\ell$) of the ore and the agglomerated ore size distribution. The $m_\ell$ corresponds to the voidage at which the ‘local’ global ore mass acts as a single large particle with all chemical movement restricted to diffusion within the retained moisture domain. The $m_\ell$ will generally be higher with higher clay/ultra fines content.

From these measures it is possible to determine the maximum lift height that can be used before the total voidage is at or less than $m_\ell$, and the lower parts of the lift act as a single almost infinite size particle. The voidage is also an indirect measure of the level of particle (agglomerate) accretion within the heap with the subsequent reduction in leach kinetics.

Leach kinetics (from the shrinking core model) are related to the ratio: \[ \frac{\varepsilon}{\tau(r_0)^2} \]

The combination of voidage reduction, tortuosity increase and in situ particle size increase by accretion and agglomeration provides an interactive non linear decrease in the leach kinetics particularly with higher clay content ores. By consideration of the geo-technical reaction of the ore mass it is reasonable to adjust the leach kinetics by the voidage ratios and the anticipated fraction of the ore that will show accretion and consolidation; to give a better estimate of the effective particle size. Some early work is presented on consideration of the plastic deformation characteristics and estimates of the resultant particle size increase. The other aspect of tortuosity increase is addressed by relating the overall tortuosity to the proportion of clays present and the bulk voidage of the heap.
2. INTRODUCTION

The heap and dump leaching of copper has been studied for decades by many academics and practitioners of the process. The aim of the long period of work has been the attempt to develop sufficient basic knowledge to enable prediction of leaching rates from fundamental aspects of the ore. The most fundamental tool developed has been the shrinking core model Chae and Wadsworth [1]. This is based on the analysis of diffusion control in extraction of a disseminated leachable material from a porous particle. This has been extended to include the slow reaction rates in a mixed diffusion model Bartlett [2], where the leach interface within the particle is a band rather than a sharp transition. Further refinements of this model have been made by Dixon and Hendrix [3] with analysis of the system in great depth and complexity.

Analysis of a large volume of commercial and column leach data Miller [4] has shown that copper heap leaching (other than for chalcopyrite) is always under diffusion control. This is contrary to the assumption of sulphide leaching where the reaction control plus diffusion has been made in all previous analysis. It has also been shown by a large number of workers Schlitt [5] Cathles and Murr [7] that neither model can accurately predict the leach rate from fundamental size distributions for anything other than larger (+1.0mm) nearly mono sized particle systems. Once leaching of finer materials is tested the ability of the models to predict the leach rate falls off. The discrepancy between the prediction and the practice increases non linearly with increasing fines and clay contents.

In an effort to provide a 'rational' model of the heap and dump leaching process an alternate view has been put forward to help explain the phenomenon of leach rate reduction with increasing fines. Finer material should leach faster according to the particle shrinking core model. However this is not the case in practice where in many cases it has been found that the coarse crush material has a faster leach rate James and Lancaster [8]. The underlying reasons for this are two fold:

- The shrinking core model assumes a rigid particle that does not interact with its neighbours and is surrounded by the leaching solution
- The size distribution of the particles is the determinant size distribution for the leach rate.

If on the other hand we assume that the global leach rate is set by diffusion and then try to look for the 'effective particle' that is determining the leach rate, then we can understand what is happening. The rock mass can agglomerate giving an agglomerate size distribution which will in most cases be coarser than the 'natural' sizing. These agglomerates will not be rigid but will have some deformability (= plasticity in soils engineering) and create insitu mega agglomerates with even coarser sizes.

The presence of clays will increase the plasticity and promote the creating of larger effective particles. The clays will also have a number of effects (as outlined in this paper) on other parameters that also adversely effect the leach rate: increase the effective path length for diffusion, increase the sensitivity to compaction or increase the moisture holding capacity of the ore mass.

Many of these effects have been studied in the soil sciences and chemical engineering but have not yet been brought to bear on the question of analysis of heap and dump leaching data. There is a large body of work on leaching of species from soils Marshall and Holms [9], Bouma [10] using similar techniques. Much of this work is relevant to the copper industry. Some further leach modelling is required to include the hydraulic soil parameters and the other aspects described later in this paper.
3. LEACH KINETICS

The overall leach kinetics for commercial copper heap leaching are generally driven by a diffusion process with the effective diffusion rate ($D_{\text{eff}}$) being the rate controlling parameter. The actual rate controlling step can be a number of parameters eg oxygen supply, acid supply, copper removal from particles. The effective diffusion rate for an individual ‘particle’ is modified by the local physical parameters according to:

$$D_{\text{eff}} = D_{\text{int}} \frac{\varepsilon}{\tau}$$  \hspace{1cm} (1)

and the diffusion controlled recovery is calculated from [1]:

$$Tr(R) = \text{time} \times K D_{\text{eff}} / r_{0}^2$$  \hspace{1cm} (2)

There are three significant variables in this relationship all of which are affected by the ore geo-mechanical and geo-technical characteristics. The void fraction for a porous domain is a relationship controlled by the interaction of the imposed stress and the compaction characteristics of the particles in the domain. This is an area of very considerable work and is a fundamental civil engineering characteristic.

The tortuosity parameter is one that has generally been treated as a ‘constant’ in most heap leach models as it is not well understood [11,12,13]. This has been shown by the present work to be a significant contributor to the observed leach rate.

In most leach models the particle size is treated as a constant from which an attempt is made to predict the a priori leach rate [1,6,7,14]. From the analysis of the commercial leach data it is shown that the size parameter is also a variable. The magnitude of the ‘leach size’ is determined from a complex interaction of the geo-mechanical ore characteristics, placement bias, mineralogy and irrigation parameters.

The work of Wadsworth, Bartlett and others with the shrinking core model would indicate that during the leach process the smaller particles would be completely leached early in the time and that the larger particles would take a longer time. If this were to be the case the $Tr(R)/\text{time}$ rate would also decrease as $r_{0}$ increased. This is illustrated in Figure 1.0 where the recovery is calculated from a size distribution of various mono sized spheres.

![Figure 1.0 Theoretical Recovery from a combination of a range of mono sized spherical particles](image-url)

```
3mm - 6mm
1.5mm - 3mm
32mm-50mm
25mm-32mm
12mm-25m
6mm-12mm
Ave size
wt\*Tr(R)
```
However all the commercial and column leach data that has been analysed to date indicates that this model is not applicable in its interpretation of the effect of particle size. Figure 2.0 shows a typical commercial heap leach recovery with nearly constant leach conditions.

![Figure 2.0 Typical Leach Recovery with Constant Conditions](image)

In this data it is evident that the rate of recovery remains the same throughout the whole of the leach period. There is no change in extraction rate as the small particles are fully leached. This shows that the leaching is dominated by a single characteristic ‘particle’ size that is sufficiently large that it dominates the leaching for the entire extraction cycle. The size of these effective particles is discussed later in this paper.

4. TORTUOSITY

Tortuosity is the least well understood of the parameters in the diffusion rate equation. It is generally treated as a parameter of fixed magnitude in most models [1,2,3,7,14]. However there is a very considerable body of work on diffusion in porous media that indicates that the tortuosity is not only a characteristic of the material but also varies with the local total porosity. As the porosity decreases, the tortuosity increases.

This aspect of variable tortuosity has not been included with the individual particle leach model approach, as the particles are assumed inter alia to be incompressible. However, if the concept of a larger ‘leached particle’ domain is adopted, then this domain can now be considered compressible, and the value of the tortuosity can vary as the domain is subject to changes in voidage. These changes in voidage are the result of local stresses generally imposed from the placement method and the surcharge of material over the domain of interest.

The definition of tortuosity is not one that is consistent across all disciplines. The definition used in equation (1) is that generally used in the chemical engineering field and results in typical tortuosities for porous medium made from near spherical particles of 1.5 to 6.0 [2,6,19 and many others]. The other major significant definitions are from the soil science discipline where tortuosity in solute diffusion is defined by [9,10]:

\[
D_{\text{eff}} = \tau D_{\text{ext}} \epsilon
\]  

(3)
Under these circumstances the tortuosity for typical soils takes up values of between 0.5 and 0.01 from mono-sized sand to dispersive clays [10]. When used with the Chemical engineering definition the tortuosity values are between 2.0 to 100.

From the above, it is evident that the tortuosity from chemical engineering is the reciprocal of that used in soil science. Care is needed when using data from one discipline in the relationships developed for another.

Hydrology also has a definition of tortuosity for fluid flow in pores under hydraulic pressure [9]:

\[ \tau = \left( \frac{l_e}{l} \right)^2 \]  

(4)

This definition serves to confuse the other two when flow in porous media is a contributor to the recovery. However values of this tortuosity definition are not readily available and have not been included in the present study.

5. EFFECTS OF CLAY ON GEO-MECHANICAL PARAMETERS

Fines particularly clays have a number of effects on the geo-mechanical characteristics of the leach ore mass.

Increasing fines increases the limit moisture holding capacity. This means that the moisture occupies a greater proportion of the total void space. This is in turn indicates that there are a larger number of domains within the heap where the moisture is held and that these domains are generally of larger size. The double effect of this will discussed in detail later. However the effect is to increase the particle size by increased proportion of the moisture held up and to increase the sensitivity of the domain size to further compaction and reduction in the total voidage.

5.1 SOME RELATIONSHIPS WITH VOID FRACTIONS

The relationships of the various parameters with void fraction are fairly straight forward and have been subject to a significant amount of research by soil scientists. Some of the more straight forward ones are:

Moisture void fraction from limit moisture capacity \(m_l\)

\[ \varepsilon_l = \frac{\rho_p}{\rho_w} \left( \frac{m_l}{1 - m_l} \right) \]  

(5)

Total void fraction (moisture plus air space)

\[ \varepsilon_t = \frac{(\rho_p - \rho_b)}{\rho_b} \]  

(6)

5.2 TORTUOSITY

The tortuosity factor is an attempt to measure the effect of a longer diffusion path length than is indicated by the 'typical' dimension of the diffusion path (=particle radius). This might be the particle size, the agglomerate size or more often the size of the saturated domain within the leach heap. The moisture holding capacity, and the other parameters sets these saturated domain sizes. As a result of a lot of work by many authors a number of relationships have been developed for the tortuosity and voidage. Some of the more relevant ones are:

\[ \tau = k \]  

typical for rock pores [2]

\[ \tau = \frac{1}{\varepsilon^{0.5}} \]  

typical for mono sized, incompressible sand and rocks [15]
\[ \tau = k + \varepsilon(1-k) \quad \text{ditto} \quad [16] \]

\[ \tau = 1/\varepsilon \quad \text{typical for soils with a wide size distribution with significant fines} \quad [17] \]

\[ \tau = (2-\varepsilon)/\varepsilon \quad \text{typical for clays and high clay content materials.} \quad [18] \]

These are shown in Figure 3.0 along with some data from various types of solid materials; ranging from very platey mica to mono sized sand and rock pores currie [19]. There appears to be an increase in tortuosity dependence as the particles change from rigid spheres (sand) to soil and various clay particles. This data set suggests that the tortuosity may have a modest upper limit of 2.0 or 3.0.

From Figure 3.0 it is evident that none of the models fit all the data and that data for the different materials show quite different responses. Some of the models fit some of the data quite well. It is easy to see that as the size distribution changes from mono sized sand to higher inclusions of fines (in soil) to clays; that the response sensitivity of tortuosity to changes in voidage increases. This tends to indicate that the higher the clay content the greater the change in tortuosity with changing voidage.

Table 1 shows the values of \( k \) that are required to fit the Currie and Bartlett data.

<table>
<thead>
<tr>
<th>Porous Media Tortuosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>kaolin</td>
</tr>
<tr>
<td>Macle &amp; Myers</td>
</tr>
</tbody>
</table>

![Figure 3: Data from Currie [19] and Bartlett [13] on Changes of Tortuosity with Porosity.](image)

One of the more flexible models is that of Suzuki and Smith [16] which has a second parameter that can be related to soil type.

\[ \tau = \varepsilon + k(1-\varepsilon) \quad \text{where } k \text{ is related to material type} \quad (7) \]

Table 1 shows the values of \( k \) that are required to fit the Currie and Bartlett data.
Table 1: k values for best data fit from Currie and Bartlett

<table>
<thead>
<tr>
<th>Material</th>
<th>k value</th>
</tr>
</thead>
<tbody>
<tr>
<td>rock pores</td>
<td>1.1</td>
</tr>
<tr>
<td>sand</td>
<td>2.1</td>
</tr>
<tr>
<td>soils</td>
<td>2.75</td>
</tr>
<tr>
<td>kaolin</td>
<td>4.0</td>
</tr>
<tr>
<td>mica</td>
<td>20</td>
</tr>
</tbody>
</table>

Here it is evident as the material gets more clay like and with a greater proportion of platey particles the tortuosity can increase significantly. This is not surprising as greater proportion of non spherical particles will induce a longer path length for diffusion and hence produce a larger value of tortuosity.

One further relationship has been developed by Cussler [19] for the tortuosity of ribbons of infinite length arranged that overlap with very tortuous paths. The aspect ratio ($\alpha$) of the ribbon is the thickness/width.

$$\tau = \varepsilon + \alpha(1 - \varepsilon)$$

Aspect ratios for clay and mica minerals can be very high with 100 for clay and +300 for mica being common values for commercial material. From this, it can be inferred that the tortuosity values predicted by the Cussler model could be extremely high.

Totally dispersion in clay systems is not common in the minerals industry, but is a common feature of nano-composites engineering materials. The data from Swannack [20] has been analysed using the Cussler model. Tortuosities up to 40 were evident in a fully disperse clay particle system (particle $\alpha =100$) shown in Figure 4.0.

Figure 4.0: Cussler ‘2D Flake Model’ applied to the data of Swannack.

Two interesting points are: the Cussler model can very accurately track the data, and the aspect ratio needed for the 2D model is approximately the square root of the actual 3D based data. The actual value of the exponent is 0.55. The tortuosity value is very high.
when compared with other ‘normal’ values used in previous leaching models. Evidently materials containing significant proportions of flaky particles (ie clay) can exhibit high tortuosity values.

The two models of Suzuki & Smith and Cussler have been used to analyse Currie’s data [19]. This provides a greater degree of understanding of the drivers behind changes in tortuosity with changing material parameters. Initially a two component model has been assumed; with a proportion of near spherical particles (with characteristics modelled by the Suzuki & Smith correlation) and the remainder as flaky particles (modelled with the Cussler relationship). In the absence of an alternative proven methodology, a linear volume weighted average has been used.

\[ \tau_{\text{tot}} = Y_s \tau_{\text{sphere}} + (1 - Y_s)\tau_{\text{flake}} \]  

(9)

The results of the analysis are shown in Figure 5.

Figure 5: Analysis of Currie [19] and Swannack’s [20] data with a combination of Cussler and Suzuki & Smith models.

The sandy material is well modelled with the spherical model alone, using a k factor of 2.1. This is not surprising as the sand was closely sized. The mica, with a very large aspect ratio, has very similar characteristics to the data from Swannack in this restricted range. The \( \alpha \) value is high at 14.04 and reflects the increased aspect ratio that is shown by the mica mineral.

Kaolin shows a ‘modest’ aspect ratio for the Cussler correlation of 4.26. This is significantly less than that for the Swannack data. The kaolin however is not likely to be totally dispersed as was the case for Swannack. The overall aspect ratio of the tested material is likely to be much lower than for individual flakes due to the structured (plate stacked) way in which it is found naturally, Carty [22]. He found from SEM analysis that the aspect ratio of fully dispersed kaolin is approximately 10:1. Further work is required to characterise ‘as found clays’ but an effective aspect ratio, for partially dispersed clay, of around 4.0 is not unreasonable. The value for the three dimensional effective aspect ratio also needs to be related to the two dimensional model. If this is similar to that for
Swannack then a value of 3.6 results ($=10^{0.55}$). This is further confirmation that the value used is reasonable.

The soil crumb curve is a combination of the sand and kaolin curves with a back-calculated clay content. There is no indication in Currie's paper as to the actual proportion of clay in the soil. However the calculated value of 11% clay, is reasonable for a soil that will produce 'crumbs' rather than sand or balls.

The benefit of this method of analysis is that there is now a simple method of calculating the tortuosity from known data for sand, clay (kaolin) and their proportions. A change in the fundamental characteristics of each is not likely and the method of combination is the only untested area.

It is not likely that the data for clay effective aspect ratio can be predicted based on the SEM derived aspect ratio(s). This fundamental parameter is modified by the degree of dispersion of the clay mass and may be as low as zero for un-dispersed clays. Again this is a parameter that is not amenable to a-priori prediction and means that the resultant leach rate is also not predictable a-priori [23].

6. VOIDAGE

The voidage of the leach pile is inherently a simple concept to encompass. The problem is to apportion this into the various voids that occur. The total voidage ($\varepsilon_t$) is the total volume minus the rock volume, and is directly related to the bulk density ($\rho_b$) and particle density ($\rho_p$) through:

$$\rho_b = \rho_p (1-\varepsilon_t) \quad (10)$$

The rock mass has a limited moisture holding capacity, which is the drained moisture content ($m_l$) after partial saturation by irrigation: $\varepsilon_i$

$$\varepsilon_i = \rho_b / \rho_w (m_l / (1-m_l)) \quad (11)$$

Within the moisture held by the rock mass is the saturated voidage within the particles themselves: $\varepsilon_p$. This is part of the limit moisture capacity. Within the domains where the limit moisture is held will be fully occluded gas voids [23] surrounded by capillary moisture: $\varepsilon_o$.

When the heap is being irrigated there is an additional moisture hold up which is due to the advection flow [24] of the solution around the outside of the domains holding the limit moisture: $\varepsilon_a$.

The free gas voidage is the remaining void space eg:

$$\varepsilon_g = \varepsilon_t - \varepsilon_l - \varepsilon_o - \varepsilon_a \quad (12)$$

Within these various voidages there are a number of relationships that are important for the heap leach diffusion control rate.

The overall heap tortuosity is related to the nett heap void space (total voidage less particle voidage).

The void space for diffusion is the limit moisture voidage as this is the domain through which the various solutes diffuse to the outer surrounding advection flow regime. Within this diffusion domain the tortuosity of the domain is related to the nett domain voidage:
\[ \tau = f(\varepsilon_l - \varepsilon_p) \]  

(13)

This is a low voidage in relation to the overall heap voidage and can lead to extremely large effective tortuosities if there is any clay present.

7. EFFECTS OF COMPACTION ON THE OVERALL LEACH PARAMETERS

The total voidage is reduced with any increase in bulk density.

The limit moisture voidage is generally constant until the total voidage approaches the sum of \( \varepsilon_l + \varepsilon_o \). When the ore saturation nears 100% the held moisture is released until the internal pore pressure is equilibrated with the external applied pressure. These pressures are not normally found in the active leaching part of heap (but may be present in lower lifts that are subject to higher static loads from overlying lifts).

The proportion of the total heap volume occupied by the limit moisture increases with increasing dry bulk density.

A typical clayey ore type with a strong relationship between bulk density and stress is shown in Figure 6. with the resultant change in total voidage shown in Figure 7.

![Bulk Density vs Height of Heap](image)

**Figure 6: Change in bulk density with Depth from the surface for a ‘clayey’ ore.**
For this ore type the bulk density quickly reaches an inflection point and thence increases only slowly with further stress. The typical lift height of 6m indicates that the total voidage, even near the top of the lift, is less than the limit moisture voidage. When the advection flow voidage (2%) and the occluded voidage (3%) are taken into account it is seen that the available total voidage is less than the required operation voidage at a depth of 1.0m from the surface. Below this depth the total heap mass will be saturated with resultant problems of slow leaching and geotechnical stability. It is no wonder that this material suffered significant problems with low recovery rates even from low lift heights.

8. PARTICLE SIZE

The term ‘particle’ has a number of meanings when considering the heap leach process. For the ore, it is the particle size distribution of the crushed material. This is a wide range generally from 50mm to zero. Most heap leach operations now recognise the need to agglomerate the ore to improve the percolation rate distribution and minimise channelling in the heap. The agglomerated ore has a separate size distribution with a slight increase in the top size but a very large increase in the bottom size. Typical sizes are 60mm to 2mm with all of the –2mm adhering to the coarser fractions (and themselves) to form the agglomerates.

The concept of macro pores with advective flow and micro pores with no flow is used in soil dispersion models to account for both convective and diffusive transfer [9, 23]. The model is most useful in strongly structured soils which have large macro pores for advective flow. This is equivalent to a heap leach situation where either agglomeration has been conducted or large channels of coarse and fine material exist from the placement activity.

The real effect of this approach is to propose large volumes of the heap domain where advective flow is not occurring, and the static water acts to define an effective in-situ particle. These volumes are the result of the moisture holding capacity of the ore / soil. As a result, the total moisture holding capacity is a measure of the total ore volume that is tied up in stagnant spaces subject only to diffusion for ionic transfer. This is further increased by the inclusion of occluded air pore spaces within the overall stagnant zone.
Within the heap are formed meta particles with very large size. In a heap with a very biased size distribution after placement the meta particle size may approximate to the horizontal distance between adjacent coarse channels. Other large meta particles are formed whenever a perched water table is evident. The saturated area is the meta particle where diffusion of the chemical species into and out of the saturated domain are the dominant rate determining steps.

Other large meta particles can be formed if the ore or agglomerates have any significant plasticity. In other words, the particles are not rigid but are deformable. The plastic agglomerates can coalesce / merge under the imposed load of the lift and create effective macro particles. This coalescence needs only to be to the stage where the internal saturated pore spaces are in hydraulic contact (effectively aqueous phase filled) to create the larger macro particle. The heap depth below which these macro particles form will consist effectively of a few large particles. Delineation of the outer extremities of the meta particle surfaces will only be provided by any size-biased channels that may have been formed during placement.

As it is clear from the shrinking core model the change in particle size has an inverse squared effect on the effective leach rate. Any small increase in effective particle size can have a significant effect on the overall diffusion leach rate. One of the challenges in understanding heap leaching is to determine the actual effective particle size (of the meta particle) being leached.

9. UN-SATURATED FLOW AND CHANNELLING

The heap leach hydraulics are by definition unsaturated flow systems. Under these conditions a number of authors [24, 25] have shown the application of leachant solution with either drippers or wobblers produces fingering of the solution within the heap. The fingering is worse with drippers [26] but is still evident with a uniform distribution over the heap surface. Typical spaces between fingers are of the order of 50mm to 150mm [25]. This is a complicating factor in the determination of a leached particle size and may be one of the main factors behind the commercial experience where leaching is generally controlled by a single large ‘particle’ size and does not show an early high rate with smaller particles.

Some indication of these effects is provided by Chae and Wadsworth [1] who reported an increase in effective leach particle size (R_{eff}) with a decrease in the actual particle size (R) as shown in Figure 8.
In attempting to assess the effective particle size being leached there are two limits to 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 set by the effective advection flow ‘finger’ spacing.

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

\[ \frac{R_{\text{eff}}}{R} = 1 + \frac{a}{(\varepsilon_t - \varepsilon_l - \varepsilon_o - \varepsilon_a)^b} \]  (14)

Where a and b are constants that are related to the ore plasticity and clay content.

Assuming that there is an inverse relationship of the form:

\[ \frac{R}{R_{\text{eff}}} = Y = \frac{a}{X^b} \]  (15)

with axes shifted to :

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

The net relationship will be:

\[ Y = 1 + a/(X - X_d)^b \]  (16)

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:

\[ Rv = \frac{Vv}{Vp} \]  \hspace{1cm} (17)

And \[ Y = 1 + a/(Rv - Rd)^b \]  \hspace{1cm} (18)

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

\[ \frac{Vv}{Vp} = R_p = \frac{\varepsilon_t}{(1 - \varepsilon_t)} \]  \hspace{1cm} (19)

And \[ \frac{Vv}{Vd} = R_d = \frac{\varepsilon_d}{(1 - \varepsilon_d)} \]  \hspace{1cm} (20)

\[ Vp = Vv/(\varepsilon_t/(1 - \varepsilon_t)) = Vv(1 - \varepsilon_t)/\varepsilon_t \]  \hspace{1cm} (21)

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 \( \nu_l \) is related to the particle and solution densities by:

\[ \nu_l = \frac{Vl}{Vp} = \frac{m_l \rho_p}{\rho_l} \]  \hspace{1cm} (21)

And \[ Vl = Vp \frac{m_l \rho_p}{\rho_l} \]  \hspace{1cm} (22)

The volume of the occluded voids is given as a straight volume fraction of the particle volume \( Vo = k_1 Vp \)

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:

\[ V_a = Vp \frac{m_a \rho_p}{\rho_l} \]  \hspace{1cm} (23)

The total domain volume is:

\[ V_D = Vp + Vl + Vo + Va = Vp(1 + m_l \rho_p/\rho_l + k_1 + m_a \rho_p/\rho_l) \]  
\[ V_D = Vp + Vd \]  \hspace{1cm} (24)

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

\[ V_d = k Vp \]
\[ V_D = (1+k)Vp \]  \hspace{1cm} (25)

The total domain voidage \( \varepsilon_d = Vd/(Vd + Vp) \)  \hspace{1cm} (26)

\[ \varepsilon_d = \frac{Vd}{Vd+kVp} \]
\[ \varepsilon_d = \frac{k}{k+1} \]  \hspace{1cm} (27)

Substituting (27) & (18) into (17):

\[ \frac{R}{R_{eff}} = 1 + \frac{a}{(\varepsilon_t/(1 - \varepsilon_t)) - \varepsilon_d/(1 - \varepsilon_d))^b} \]  \hspace{1cm} (28)
The data from Chae and Wadsworth 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 later modelling, 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 9.0.

![Figure 9.0: Effective Particle Size Ratio as a function of Heap Voidage](image)

**Figure 9.0:** Effective Particle Size Ratio as a function of Heap Voidage

**10. EFFECTS OF CLAYS**

Inclusion of clays in a heap leach pile is determined mainly by their grade and the ease or difficulty of removing them in the mining operation. In many cases it is not possible to remove the clayey materials. Even a small proportion can have a significant effect on the resultant leach rate. Clays have the effect of:

- Providing higher tortuosity => slower leach rates
- Higher limit moisture capacity => lower operating margin in heap bulk density
- Lower overall total voidage => higher tortuosities and slower leach rates
- Provide higher plasticity and a more deformable ore mass => larger effective sizes, higher sensitivity of bulk density with stress

All of these effects are additive and can severely impact the leach rate with only modest increases in clay content. In general, these effects are all relatively easy to recognise and appreciate their interactions. However it is entirely a different question to try to predict the effect of increased clay content on the various leach rate parameters. This has been recognised by Addiscott and Bailey [23] by requiring soil parameters to be field determined for inclusion in their model.
11. COMBINED PARAMETER EFFECTS

By using the relationships already discussed, some sensitivity modelling has been done to indicate the magnitude of the leach rate decrease with changes to the main parameter of bulk density. These are illustrated in Figure 10.

![Figure 10: Calculation of leach parameters with change in bulk density](image)

The direct effect of the clay content is to reduce the leach rate for a given bulk density. The most significant effect is the change in bulk density itself and the effect on both tortuosity and relative ‘particle’ size. The greatest changes in bulk density are between column tests and field reality. A typical range would be from 1.5 in a column test and 1.7 in the field. The leach rate for the field would be only 59% of the leach rate tested in the column.

The relative change in the bulk density – stress relationship with increasing clay content also needs to be tested. This is the main driver behind major changes in the leach rate of a given lift height with changing clay content. As the bulk density sensitivity increases with increasing clay content, the overall leach rate of a given lift will decrease substantially.

It is interesting to note that the decrease in leach rate with bulk density is nearly linear. This has been noted by others in the past Scheffel [27] and the model confirms that the interactive effects of the various parameters gives a ‘liner’ correlation. This relationship could be used in the first instance to gauge the relative leach rates of two different bulk densities provided that some other information is available to establish the rate of reduction.

12. COMMERCIAL LEACHING - EFFECTIVE PARTICLE SIZE

A large number of commercial heap leach data sets are in the process of analysis. The preliminary results from a few are provided in Table 2 to illustrate the range of leach conditions and the interactive effects of clay content, agglomeration and particle size on the observed leach rates.
Table 2: Commercial Heap Leach Data – Calculation of Effective Size

<table>
<thead>
<tr>
<th>Project</th>
<th>A</th>
<th>B</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crush Size mm</td>
<td>25</td>
<td>ROM</td>
<td>50</td>
<td>8</td>
<td>ROM</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Ore type</td>
<td>v clayey</td>
<td>siliceous</td>
<td>clayey</td>
<td>clayey</td>
<td>siliceous</td>
<td>clayey</td>
<td>clayey</td>
<td>clayey</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>Surface Cc</td>
<td>Surface Cc</td>
<td>Surface Cc</td>
<td>Disperse Cc</td>
<td>Disperse Cc</td>
<td>ESP dust</td>
<td>ESP dust</td>
<td>oxide</td>
</tr>
<tr>
<td>Limit moisture w/w %</td>
<td>0.2</td>
<td>0.08</td>
<td>0.15</td>
<td>0.175</td>
<td>0.078</td>
<td>0.12</td>
<td>0.12</td>
<td>0.14</td>
</tr>
<tr>
<td>Limit moisture v/v %</td>
<td>0.310</td>
<td>0.149</td>
<td>0.257</td>
<td>0.343</td>
<td>0.136</td>
<td>0.208</td>
<td>0.195</td>
<td>0.211</td>
</tr>
<tr>
<td>Agglomerate</td>
<td>polymer</td>
<td>NIL</td>
<td>YES</td>
<td>YES</td>
<td>NIL</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>bulk density - t/m3</td>
<td>1.3</td>
<td>1.8</td>
<td>1.6</td>
<td>1.7</td>
<td>1.69</td>
<td>1.6</td>
<td>1.5</td>
<td>1.4</td>
</tr>
<tr>
<td>Irrigation rate - L/h/m²</td>
<td>6.8</td>
<td>6</td>
<td>6</td>
<td>7.8</td>
<td>6.8</td>
<td>6</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>stack height - m</td>
<td>3.2</td>
<td>8</td>
<td>6</td>
<td>8</td>
<td>4.48</td>
<td>5</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>[acid] g/L</td>
<td>4.9</td>
<td>10</td>
<td>15</td>
<td>7.75</td>
<td>8.3</td>
<td>6</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Effective Diffusion path length mm (radius)</td>
<td>63</td>
<td>85</td>
<td>258</td>
<td>162</td>
<td>382</td>
<td>129</td>
<td>150</td>
<td>92</td>
</tr>
</tbody>
</table>

In all the commercial leaching data analysed to date, for each leach cell there is a single underlying leach rate that varies only with applied lixivant concentration and does not show appreciable fall off with time. This indicates that there is:

- No appreciable consolidation effects on either operating voidage or effective leach size.
- No change in effective leach size throughout the leach period.

These imply that neither the actual crushed size distribution, nor the agglomerate size distribution is the rate controlling mechanism. The rate controlling mechanism is the combination of mineralogy (dispersed or fracture surface controlled), tortuosity, limit moisture capacity, irrigation instability and fingering, ore plasticity and related effects setting a large effective particle size.

13. PREDICTION OF LEACH RATE

Hydrology models can not predict with certainty the flow pattern (fingering and unsaturated hydraulic flow proportions) and therefore can not predict leach rate with any certainty due to the unknown effect on effective finger spacing. Similarly the limit moisture holding capacity can not be predicted with accuracy a priori from sizing or soil texture information. The effective in situ particle size prediction, from the combined effects of clay proportion, compaction, consolidation and tortuosity arguments, is unlikely to be achieved without testing of the material. Similarly the relationship between bulk density and imposed stress can not be predicted with any certainty from other characteristics.
Under these circumstance, it is considered extremely unlikely that a mechanistic model can be developed for heap leaching. There will always be a requirement for testing of the material properties and the ranges of those properties likely to be found during the operating life of the project. By understanding the interactions of the material properties and the leach rate, it should be possible to project a new leach rate from an existing known leach rate under varying circumstance. The most important test parameters are discussed in this paper and will be utilised in further work.

14. CONCLUSIONS

The understanding of the heap leach kinetics can be advanced by the analysis of the geomechanical and geo-technical characteristics of the leached ore. The bulk density and its sensitivity to heap height are important global indicators of the relative leach rate to be expected from previous data. The detailed parameters: tortuosity, voidage and limit moisture capacity can be estimated from changes in the bulk density and clay content of the ore.

The effective leached particle size is significantly larger than either the crushed or agglomerated size. The large meta particles are the result of immobile moisture in deformable materials, in un-saturated flow with fingering of the leach solution.

It is considered unlikely that a mechanistic model can be developed to account for all these parameters; and that only relative changes can be 'predicted' from known leach data.

15. NOMENCLATURE

\[ a \] constant
\[ b \] constant
\[ D_{\text{eff}} \] Effective diffusion coefficient
\[ D_{\text{int}} \] Intrinsic diffusion coefficient
\[ K, k_1 \] constant parameter including other conditions
\[ l_e \] total effective path length
\[ l \] the ‘characteristic’ geometric length measure.
\[ m_a \] advection moisture capacity w/w
\[ m_l \] limit moisture holding capacity w/w
\[ r_0 \] particle radius
\[ R \] particle radius
\[ R_{\text{eff}} \] effective particle radius
\[ \text{Tr}(R) \] Recovery transformed into the diffusion model space (Bartlett).
\[ V_a \] volume of advection moisture
\[ V_d \] volume of leaching domain (particle+moisture+advection+occlusions)
\[ V_l \] volume of limit moisture content
\[ V_o \] volume of occluded gas voids
\[ V_p \] volume of particle
\[ V_v \] total void volume
\[ X \] independent variable
\[ Y \] dependant variable
\[ Y_s \] volume fraction of ‘spherical’ particles
α  aspect ratio of a flake.
ε  Voidage
ε_l  Limit moisture voidage
ε_a  advection moisture voidage
ε_d  diffusion domain voidage
ε_o  occluded air voidage
ε_p  particle voidage
ε_t  total voidage
ρ_b  bulk density
ρ_p  particle density
ρ_w  'water' density
τ  void tortuosity

16. ACKNOWLEDGMENTS

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17. REFERENCES

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