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The effects of simulated stacking phenomena on the percolation leaching of crushed ore, Part 1: Segregation

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ABSTRACT

Size-segregation and stratification (layering of ore into zones of different hydraulic characteristics which results from commercial stacking practices), are commonly believed to affect heap leaching performance. However, little systematically collected data has to date been published on the subject. This first part of the study reports on the effects of deliberate segregation observed under laboratory conditions.

An ore sample was segregated on an artificial slope and the geophysical and hydrodynamic properties were determined of the resulting Upper, Middle and Bottom fractions of the segregated ore bed. The same was done for a stack composed of these three fractions layered on top of one another.

It was found that the three-layered stack exhibited less favourable bulk density and hydrodynamic conductivity than un-segregated ore (i.e. ore which had not been deliberately segregated). It is therefore suggested that when those parameters are determined for the purpose of heap design, it would be conservative to conduct the tests on a stack of segregated layers of the ore, instead of the un-segregated ore.

However no statistically significant difference could be observed in column leaching performance (770 mm high, 153 mm diameter), either between the individual segregation fractions, or between the un-segregated column of ore and the column composed of Bottom, Middle and Upper layers. It therefore follows that segregation cannot account for the differences reported between laboratory column tests and commercial heap leaching results. Furthermore, laboratory column leaching tests cannot emulate commercial scale leaching performance more realistically by merely segregating the ore samples prior to column leaching.

1. Introduction

The rate of metal extraction observed during laboratory column leach tests usually provides an over-optimistic indication of heap leaching kinetics to be expected at commercial scale. Experience-based scale-up factors are therefore applied to column leaching data. For example, authors such as Jansen and Taylor (2002) and John (2011) suggest that the ultimate extent of extraction obtained in the laboratory could be multiplied by 0.8–0.9, and/or the time required for achieving the ultimate extraction under commercial conditions is taken as 50 to 200 percent more than the time required in the laboratory columns.

Many differences exist between laboratory column leaching tests and commercial heaps that could contribute to the differences in rate of leaching observed between the two, such as channelling along column walls that is absent from commercial heaps, and a minimum unavoidable amount of human and sometimes vehicle traffic that (depending on design) might be required on top of commercial heaps for ore stacking, ripping, levelling and installation of the irrigation systems.

The homogeneity of the heap is furthermore influenced at commercial scale by both segregation (separation of particles by size) and stratification (layering of ore into zones of differing hydraulic permeability) as an inevitable consequence of current stacking practice, as noted by such authors as Gross and Gomer (1992), Bartlett (1995), Kerr (1997), Miller (1998), O'Kane et al. (1999), Kappes (2002), Smith (2002) and Guzman et al. (2006). Dixon (2003) identifies segregation as one of the '*non-linear effects'* (quoting his terminology) which had up to the date of his publication not been considered in any heap leaching models to account for its effect on heap leaching performance. While ore agglomeration may reduce these effects, agglomerated ore still possesses a size distribution and therefore agglomeration cannot eliminate the occurrence at least of segregation (O'Kane et al., 1999).

Deliberate attempts are usually made to avoid, as far as possible, segregation and stratification during the loading of columns in preparation for laboratory column leaching tests. Columns are usually

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Nomenclature

Abbreviations

Cor	pearson correlation coefficient
GAC	gangue acid consumption
SSR	sum of squared residuals

Symbols

$C_{i,j}$	mass fraction of species *i* in phase *j*.
D_e	effective diffusivity, m^2/s
k	copper leaching rate constant, h^{-1}.
k'	GAC rate constant, h^{-1}.
M_i	molar mass of species *i*.
n	uniformity constant in the Rosin-Rammler size distribution expression
R	radius of spherical regime through which diffusion occurs, m.
s_i	rate of production of species *i*, moles/(litre.s)
t	time, s
W_{imm}	immobile moisture content as mass fraction of wet solids.
x	particle size, or average of a size range, in any convenient units of length.
x_0	characteristic particle size in the Rosin-Rammler size distribution expression.
X_i	extent of extraction of species *i*.
$Y(x)$	mass fraction of particles with (average) size *x*.

Greek symbols

α	mass fraction of mineral that is liberated and reactive to the lixiviant in the particle-scale kinetic rate expression.
Γ	diffusion time, days
ϵ_{imm}	Immobile moisture content on dry-mass basis, kg_moisture/kg_dry_solids.
Θ_{imm}	immobile moisture content as a volume fraction of the moist bed.
ϕ	power of the unreacted fraction
ξ	dimensionless radial distance.
ρ	bulk density, t/m^3 dry basis
ρ^*	true density, t/m^3 dry basis

filled using homogenously mixed ore while taking care to ensure the ore is homogenously distributed in the columns.

Admittedly, the larger the diameter of the columns or cribs becomes, the more difficult it becomes to avoid segregation and/or stratification of the ore. Furthermore, Ilankoon and Neethling (2016) have shown that even localised micro-deviations from uniformity, which cannot be avoided, causes uneven solution distribution through packed beds. Hence by either taking all practically possible care to avoid segregation/stratification during the loading of leaching columns, or by deliberately inducing the phenomena as is being done during this study, a phenomenon that is actually always present to a certain extent is merely being minimised or accentuated.

This part 1 of the study aims to isolate the extent to which specifically segregation contributes to the difference between laboratory- and commercial-scale performance, so that its effect can be accounted for rigorously, eliminating the need for empirical scale-up factors.

The manner in which segregation occurs is illustrated in Fig. 1, where a conveyor or dump truck adds ore to a side slope of the heap. Thus the heap is not stacked in layers from the bottom up but advanced horizontally. The stacker discharge end remains slightly above the required heap height. The ore drops from the conveyor onto the upper end of the side slope, and spreads by rolling some distance down the side slope, at the internal angle of friction of the ore, before coming to rest. The particles arriving at the ore landing point possess momentum both due to that imparted on them by the conveyor upon discharge and by the gravitational acceleration during the fall onto the slope. The larger (and hence heavier) particles possess more momentum and therefore roll on average further down the slope before being brought to rest by collisions with the previously stacked layer of stationary particles, while a disproportionate amount of the finer particles remain near the top of the slope.

As the stacker advances, each layer of ore being added to the side slope contains a larger proportion of fines along the top and a larger proportion of coarse particles towards the bottom, and the entire heap inventory becomes vertically segregated by particle size.

The visualisation of segregation as shown in Fig. 1 is simplified to facilitate the analysis required for this study. It shows namely vertical segregation only, without the stratification that can be expected to occur simultaneously down the slope; that phenomenon will be addressed in Part 2. It is further simplified and exaggerated in that it shows segregation to have occurred in three clearly distinguishable discrete layers of equal height, whereas of course the phenomenon occurs as a gradual continuum from top to bottom.

There are limited studies on the effect of segregation on heap leaching. Formal studies on segregation and stratification and attempts at modelling these in the context of solids conveying include those by Ottino and Khakhar (2000) and Cizeau et al. (1999). The team of O'Kane et al. (1999) presented a study on the effect of what they termed segregation, on simulated heap leaching performance. However what was simulated with flow passing through two layers parallel to one another from top to bottom in the column, was more akin to stratification than to segregation, according to the formal terminology used in recent publications on the subject by Shimokawa and Ohta (2007), Fan et al. (2012) and Benito et al. (2013), which is adopted here. The laboratory studies by the latter three groups of authors were limited to binary systems only, i.e. considering only mixtures of particles of two distinctly different sizes or shapes or densities, with the particles being stacked one by one into a transparent container where they can be individually observed based on size, shape and/or colour. In a binary system it can be clearly distinguished whether particles of different sizes are appearing in alternating layers, in which case it can be stated unambiguously that segregation or stratification is observed. That distinction becomes harder to make with ore that exhibits a continuous size distribution.

Kinard and Schweizer (1987) showed photographs of excavations into heaps in which, by visual judgement, the ore can be seen to be non-

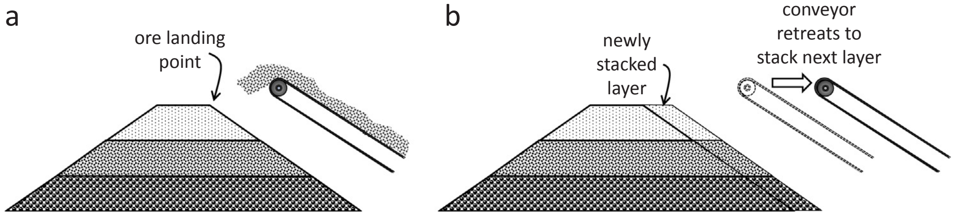

Fig. 1. Simplified illustration of segregation during stacking, (a) upon initiation of a new layer, (b) upon completion of a new layer.