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Effects of grain size gradation on the porosity of packed heap leach beds

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ABSTRACT

Fluid flow through packed ore/rock beds is among the critical processes that control the release of valuable metals as well as substances potentially harmful to the environment. The properties of fluid flow in porous media are associated with the structure of the pores through which the fluid flows which, in turn, is influenced by grain size gradation, grain shape and packing method. In this study, we investigated the effect of three types of grain size gradation on porosity and pore size distribution using the bulk density and the computed tomography (CT) scanning methods. It was generally observed with the uniformly graded grains that the porosity decreased as the mean grain size increased until a limit was reached. The porosities of the well graded grains were lower than those of the uniformly graded grains in the coarse size range, but there was no difference in the porosities between the two types of gradation in the fine size range. Furthermore, the influence of the packing method on the well graded grains was more pronounced than on the uniformly graded grains, implying relative ease of compaction of well graded grains. The proportion of fine grains in the gap graded grains influenced the porosities, which firstly decreased and then increased. The pore size distribution of the gap graded grains showed a high degree of heterogeneity compared to those of the uniformly graded and the well graded grains. The findings indicate that in ore/rock dumps fine particles account for the bulk of the porosity and possibly the bulk of any pore water content, suggesting that fine particles are likely to contribute most of the leachable substances.

1. Introduction

The leaching of substances from packed ore/rock beds is of great significance for valuable metal production via heap/dump leaching as well as management of mine waste rock drainage. Heap/dump leaching is a widely applied hydrometallurgical process for treating copper oxides, secondary sulfides, and possibly low-grade primary sulfides (Petersen, 2016; Yin et al., 2018). Mine waste rock drainage is among the most significant environmental challenges facing the global mining industry due to its dynamics and persistence (Johnson and Hallberg, 2005). Examples are selenium release from coal waste rock (Hendry et al., 2015), arsenic contamination in diverse geological and climatic settings (Williams, 2001), and acid mine drainage (Betrie et al., 2016). On the other hand, mine waste and drainage represent vast opportunities for valuable products recovery given the need for low-cost resources, increasingly stringent environmental conditions, and improved mineral processing and separation technologies (Lottermoser, 2011; Nordstrom et al., 2017; Santos and Ladeira, 2011).

The complexity of the leaching process arises from the intertwined fundamental processes occurring simultaneously in packed ore/rock beds that are typically of highly heterogeneous nature in chemical and physical properties (Amos et al., 2015; Zhang and Liu, 2017). Fluid movement through porous reactive materials is a critical process that provides reactants to and mobilizes products from leaching reactions and microbial activities (Liu and Hashemzadeh, 2017; Velleux et al., 2006; Villeneuve et al., 2017). Fluids can percolate slowly and uniformly, leading to a stable wetting front; or move rapidly and preferentially along paths of least resistance, bypassing a considerable fraction of the porous media (Hendrickx and Flury, 2001). Channeled and preferential flow in waste rock piles is common given regions of vastly different porosity and permeability (Eriksson and Destouni, 1997). The ratio of uniform to preferential flow is crucial for determining the amount of solutes leached from solid matrix and transported by moving fluids (Jarvis, 2007).

Grain size distribution is among the key physical properties that control permeability and fluid flow (Stockwell et al., 2006). Various models have been developed to describe the relationships between permeability and the statistical parameters that describe the grain size distribution of the porous media (Carrier, 2003; Chapuis, 2004; Masch and Denny, 1966; Shepherd, 1989). These empirical models relate grain size distribution to pore size distribution and porosity, and use them as dimensionless input parameters (Arya and Paris, 1981; Yu and

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Standish, 1991). Our previous study has shown that dump leach pads contained an extremely wide range of particle sizes and that spatial segregation of fine and coarse particles existed (Zhang and Liu, 2017). However, it was unclear how the segregation would affect porosity behavior and pore structure. To assess the impact of particle size distribution on fluid flow properties, the current study attempted to measure porosity directly in beds of varying particle sizes through the use of computerized tomography and digital image analysis. The image analysis would provide direct visual evidence on the change of porosity behavior as the ratio of fine and coarse particles was varied. These techniques have been applied to examine particle damage and copper grain exposure by crushing (Kodali et al., 2011), and to aid the modelling of particle scale leaching kinetics (Lin et al., 2016). It is not the purpose of this paper to advance the image analysis techniques, but to assess how fine particles affect porosity behavior and the implications for substance leaching from ore/rock dumps.

2. Materials and methods

2.1. Sample grain preparation

Drain rock, i.e., barren gravel, was used in this study as samples to investigate the effect of particle size distribution on porosity. The drain rock with an average diameter of 0.75 in. was crushed and screened to collect grains between two adjacent sieve apertures. Fourteen such samples were collected, the mean particle size of which was calculated as the average size of the two adjacent sieve openings. The calculated mean particle sizes of the sample grains in descending order were 6.83, 4.83, 3.19, 2.19, 1.60, 1.10, 0.85, 0.60, 0.43, 0.30, 0.21, 0.15, 0.11, and 0.045 mm.

2.2. Sample grain gradation

The method for grading the sample grains, i.e., the classification of the particle size distribution of the sample grains, was in accordance with the Unified Soil Classification System. The sample grains were classified as well graded and poorly graded. The latter was further divided into uniformly graded and gap graded. A well graded sample contained grains of a wide range of sizes, with each size well represented in the sample. A gap graded sample had an excess or deficiency of certain particle sizes, also called the bimodal size distribution. The uniformly graded grains referred to the case where the grains had similar sizes with a narrow size variation. Fig. 1 shows a schematic of the three types of grain gradation used in this study.

The gradation of the sample grains was characterized by three

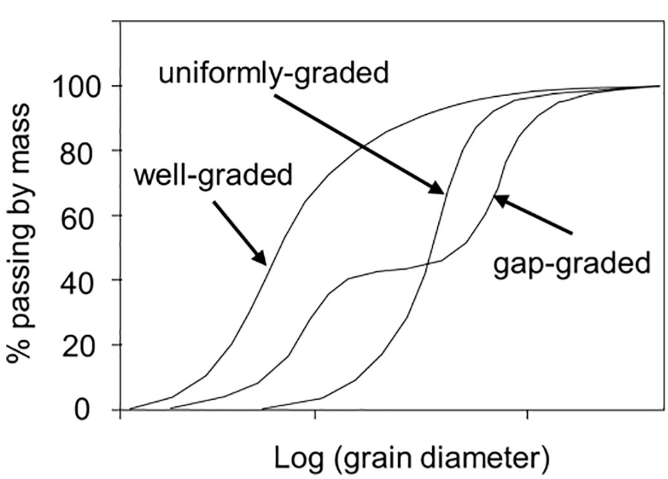

Fig. 1. A schematic showing the particle size distribution curves for the three types of grain gradation: uniformly graded, well graded and gap graded.

Table 1
Three well graded samples tested, each as a mixture of four uniformly graded grains with each size accounting for 25% by mass in the mixture.

Sample no.	Sizes of the four uniformly-graded grains in the mixture, mm			
1	6.83	4.83	3.19	2.19
2	1.60	0.85	0.60	0.30
3	0.21	0.15	0.11	0.045

parameters: the mean grain size d_{50}; the coefficient of uniformity, defined as $C_u = d_{60}/d_{10}$; and the coefficient of curvature, defined as $C_c = d_{30}^2/d_{60} \bullet d_{10}$. The terms d_{10}, d_{30}, d_{50} and d_{60} are the screen sizes being passed by 10%, 30%, 50% and 60% by mass of the particles. The higher the value of C_u the larger the range of the grain sizes in the sample. For the grains to be classified as well graded, the following two criteria must be met: $C_u \geq 6$ and $1 < C_c < 3$. If such criteria were not met, the grains were classified as poorly graded, either uniformly graded or gap graded.

The 14 samples collected between the two adjacent sieves had a narrow size variation and their C_u values were calculated to be approximately 1. Therefore, they were used to represent the uniformly graded grains. These uniformly graded grains were mixed in different size combinations and at various proportions to prepare the well graded and the gap graded samples. Three well graded samples were prepared, each as a mixture of four uniformly graded grains with each size accounting for 25% by mass in the mixture (Table 1). Table 2 shows the coefficient of uniformity and the coefficient of curvature of the three well graded samples, which met the two criteria: $C_u \geq 6$ and $1 < C_c < 3$. Six gap graded samples were prepared, each as a mixture of two uniformly graded grains, one representing fine grains and the other representing coarse grains (Table 3). For each size combination, the proportion of fine grains was varied as 0%, 25%, 50%, 75% and 100% by mass.

2.3. Porosity measurements

2.3.1. Bulk density method

The sample grains were packed into a custom designed test column of 3.75 in. in diameter and 5 in. in height using two packing methods: random loose packing and random close packing. For the random loose packing, grains were directly packed to the target volume without tapping or shaking the test column, while the random close packing involved tapping and shaking the test column until no further decrease in the volume was observed. The porosity of the packed grains was calculated from its bulk density and the density of the solid grains, which was measured to be 2.64 g/cm^3 by the water displacement method. Each test was repeated five times to obtain the average porosity and the standard deviation as the error bar.

2.3.2. Computed tomography (CT) scanning method

The computed tomography (CT) scanning method allows for non-invasive 3D imaging of specimens up to 100 mm in diameter and 160 mm in length, with resolution of 5–200 μm. In this study, a micro-CT specimen scanner (Scanco Medical μCT100) was used to acquire images of packed grains. Table 4 shows all the grain sizes tested and the

Table 2
Coefficient of uniformity (C_u) and coefficient of curvature (C_c) of the well graded samples.

Sample no.	d_{10}, mm	d_{30}, mm	d_{50}, mm	d_{60}, mm	C_u, d_{60}/d_{10}	C_c, $d_{30}^2/(d_{60}d_{10})$
1	0.02	0.06	0.11	0.12	6	1.6
2	0.14	0.43	0.60	0.86	6	1.5
3	0.67	2.02	3.19	4.05	6	1.5