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Methodology to develop a coarse liberation model based on preferential grade by size responses

C. Carrasco [a,b,*], L. Keeney [a,b], T.J. Napier-Munn [b]

[a] Co-operative Research Centre for Optimising Resource Extraction (CRC ORE), Brisbane, Australia
[b] Julius Kruttschnitt Mineral Research Centre (JKMRC), The University of Queensland, Brisbane, Australia

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ABSTRACT

Early gangue rejection or metal preconcentration at coarse scale (millimetres) based on size has been identified as a feasible operating alternative whereby energy efficiency and unit metal productivity can be greatly increased. This is achieved by understanding and exploiting ore-specific preferential grade by size responses. Preferential grade by size refers to the propensity of some ores to naturally concentrate metal into specific size fractions during breakage. The magnitude of metal deportment is described through a Ranking Response parameter (RR). This parameter has been used to measure the extent of "liberation at coarse scale". Mineral Liberation is defined as the measurable rock property that can link with a downstream separation technique which aims to concentrate valuable material to produce a saleable product. Liberation traditionally has been defined at grain scale whereby the efficiency of processes such as flotation is greatly dependent on particle properties at micro scale (microns). However, in size-based coarse separation the efficiency relies on having a processing stream with a strong grade variability across size fractions (i.e. high grade by size response) and therefore a high RR value.

This work aims to develop a model to predict preferential grade by size response, in terms of the RR of ores as a function of particle size distribution and size reduction process. To achieve these aims a novel methodology has been developed comprising a new preferential grade by size characterisation method coupled with Monte Carlo and comparative statistical methods (analysis of variance (ANOVA) and *t*-test). Six run of mine (ROM) bulk samples from 3 different geological style deposits (stock work vein hosted, Cu–Mo breccia porphyry and Cu–Mo volcanic porphyry) have been utilised in the analysis.

This methodology provides useful insights for the development of an optimum coarse separation circuit flowsheet design for preconcentration prior to energy intensive and inefficient grinding.

1. Introduction

The mining industry is currently facing several energy efficiency and productivity challenges. Grade depletion coupled with high volatility in commodity prices are adding more uncertainty to the current industry outlook (Prior et al., 2012; Topp et al., 2008). Mining cannot continue to rely on the economic benefits that increasing production scale has historically brought to the industry (Rendu et al., 2006). Over the years innovation has proven to be the key instrument whereby the mining industry has been able to cope with production periods characterised by very tight operating margins, either by improving processing efficiency or reduction of operating costs (Jara et al., 2010; Bartos, 2007; Schmitz, 2005).

Early coarse uneconomic material rejection has been identified as a plausible operating alternative that can significantly increase energy efficiency and unit metal productivity (Carrasco et al., 2015, 2014; Bowman and Bearman, 2014; Bearman, 2012). Size-based preconcentration is based on the propensity of some ores to preferentially deport metal into specific size fractions. This phenomenon is referred to preferential grade by size deportment (Carrasco et al., 2015). Experience to date indicates that this response is highly variable and therefore require characterisation for an effective exploitation (Carrasco et al., 2015, 2014). In this work the extent of this natural rock behaviour is measured through a mathematical model (Eq. (1)) describing the relationship between Ranking Response (RR, dimensionless), metal upgrade (Upg) and cumulative weight (CW) respectively. The particular function used in Eq. (1) will depend on the application. Metal upgrade and cumulative weight are utilised in the model to calculate an RR parameter to measure the extent of preferential grade by size response. Carrasco et al., 2015 depicts the process

* Corresponding author at: Co-operative Research Centre for Optimising Resource Extraction (CRC ORE), Brisbane, Australia.
E-mail address: c.carrasco@uq.edu.au (C. Carrasco).

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of describing Upg and CW shape by using a single parameter. Although in the present work a different mathematical function was employed, the methodology is equivalent.

$$RR = f(Upg, CW) \quad (1)$$

The concept of mineral liberation is defined as a function of the downstream separation technique aiming at selectively concentrating elements of interest to make a saleable product. "Liberation" is a rock based property that allows certain measurable rock characteristics to be linked with separation process efficiency. For example, in flotation the material is "liberated" to the extent that the mineral surface is sufficiently exposed enabling an effective bubble-particle interaction and therefore a high separation efficiency. In size based coarse separation (Carrasco et al., 2015), the separation technique relies on having a feed with a distinguishable grade across size fractions (i.e. a high grade by size response). RR is therefore used to measure the degree of liberation at coarse scale when size is used as the separation lever. There is undoubtedly a link between these two mineral liberation concepts at micro (microns) and coarse (mm) scale. Comminution will certainly affect both. Several studies have focused on understanding the relationship between liberation at a micro scale (grain size) and size reduction processes (Ozcan and Benzer, 2013; Vizcarra and Wightman, 2010; Hosten and Ozbay, 1998; Fandrich et al., 1997; Petruk, 1988). However almost no attention has been given to what occurs at a coarse scale (mm), prior to grinding.

This work focuses on understanding the interaction between "coarse liberation", measured by an RR factor, and comminution. Information obtained from a novel preferential grade by size characterisation test is employed to predict RR values as a function of parent particle size and changes in particle size distribution. A set of analytical techniques have been utilised, spanning non-linear regression coupled with Monte Carlo simulation and comparative statistical tools, including analysis of variance (ANOVA) and the *t*-test.

It is implicit in this analysis that impact breakage is the mechanism being assessed. However, the same framework can be used to assess other breakage mechanisms. Particle bed breakage has been proposed as a breakage mechanism that might increase mineral micro scale liberation (Ozcan and Benzer, 2013; Hosten and Ozbay, 1998; Fandrich et al., 1997; Berube and Marchand, 1984) and therefore it could also foster coarse liberation. It seems that this mechanism accentuates the material physical difference of the mineral phases, which promotes preferential breakage (Fandrich et al., 1997).

2. Progressive crushing test

Six ROM bulk samples were extensively characterised for preferential grade by size. The aim was to obtain a RR parameter that represents the "global" preferential grade by size bulk sample response (RR_g) as well as a RR factor per size fraction at given size reduction step (RR_i).

The model (Eq. (1)) describes mathematically the preferential grade by size response for a particulate system. Although this is quite helpful for a rapid domain assessment and inter/intra deposit comparison (Carrasco et al., 2015, 2014), for production implementation and process optimisation a more detailed assessment needs to be conducted. Eq. (1) does not consider the interaction between RR and changes in particle size distribution. For instance, for some rock types a further size reduction step might enhance coarse liberation, (i.e. more metal concentrates into finer particles) thus an increase in the initially estimated RR value.

The characterisation of bulk samples for preferential grade by size comprises three steps:

1. Screening material into previous defined size fractions.
2. Obtaining chemical assays in each screened size fraction.
3. Calculating of the RR parameter to quantify the preferential grade by size response.

The source of error within first step (screening) can be easily managed by controlling the screen loading which might neglect screening efficiency. Nevertheless, information obtained within the second step, chemical assays, is more prone to errors, since its resulting error is the sum of the errors (in its variance form) related to the prior sample preparation processes. The management of chemical assays error is particularly difficult for coarse samples (mm) due to material sampling and its associated sampling statistics requirements (Gy, 1982). For this is usually addressed by reducing its top sizes via crushing to ~3 mm (6 Mesh) top size, where fundamental sampling error (σ_{FE}) is within tolerance limits, (typically 5%) (Napier-Munn, 2014).

Fig. 1 depicts a ROM grade by size progressive crushing characterisation. A sample is initially sieved using 6 size fractions, 5″, 3″, 1 ½″, 3/4″, 3/8″ and 1/8″. Grade by size results representing the global preferential grade by size responses (RR_g) can be determined by chemical assays per size fraction (once each of size fractions are crushed to an adequate size for splitting) as well as its related mass. This process does not take into account the intermediate size reduction steps. To determine RR per size fraction at each reduction step while avoiding any splitting process during size reduction of coarse material (to manage σ_{FE}), each initial fraction is crushed and sieved independently (Fig. 1). The size reduction step during the sample preparation for assays is then exploited to assess changes in preferential grade by size response (RR) due to size reduction at each size fraction. The crusher's closed side setting (CSS) needs to be appropriately adjusted to produce a product that can be sieved utilising the aforementioned sieves. In order to control the amount of energy that is delivered to each coarse fraction the crusher CSS is adjusted approximately to top size, to avoid over crushing. Therefore, each crusher and sieve operating setting located in the same vertical zone in Fig. 1 is identical (i.e. CSS and screen aperture). This "cascade" process enables a back calculation of the RR in each reduction step at a given particle size (parent size) by knowing the grade and related mass of the size fraction (mass balance). For example, the head grade of the +5″ size fraction is obtained by compositing the assays of their corresponding branch, where in this case the first 16 assays are used (Fig. 1 and Eq. (2)). In this case the size reduction steps are not considered. Nevertheless, to calculate the grade by size for a given parent size at any size reduction stage, the intermediate size reduction steps need to be considered. For instance, when the +5″ size fraction (parent size) is crushed to 100% passing 1½″ (3rd size reduction step, Fig. 1), the assays and masses are balanced accordingly (Eq. (3)). Grade by size data sets are then obtained per size fraction at each size reduction step, resulting in 7 discrete data sets (Table 1). This information in conjunction with Eq. (1) is used to determine the RR related to each grade by size data set. This is in addition to the "global" grade by size responses (RR_g), where grade by size data merely comprises the grade of each parent size originally sieved.

This characterisation method is robust since it does not jeopardize grade by size data analysis due to sampling preparation error, ensuring that RR truly reflects the natural rock propensity to concentrate metal in the finer fractions after breakage.

$$A_{+5''} = \frac{\sum_{i=1}^{16} M_i A_i}{\sum_{i=1}^{16} M_i} \quad (2)$$

$$A_{+5''}^{100\%-11/2''} = \frac{M_i A_i + M_{i+4} A_{i+4} + M_{i+8} A_{i+8} + M_{i+12} A_{i+12}}{M_i + M_{i+4} + M_{i+8} + M_{i+12}}; 1 \leqslant i \leqslant 4 \quad (3)$$