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Rapid ore breakage parameter estimation from a laboratory crushing test

Fernando N. de Magalhães, Luís Marcelo Tavares *

Department of Metallurgical and Materials Engineering, Universidade Federal do Rio de Janeiro, COPPE/UFRJ, Cx. Postal 68505, CEP 21941-972, Rio de Janeiro, RJ, Brazil

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A B S T R A C T

Drop weight testers have been widely and successfully used to characterize ore breakage parameters for simulation of crushers and mills. In some cases, limitations of time, sample availability, and even cost, can prevent the conduction of these tests when preparing samples for chemical analysis and/or grindability and flotation/concentration testing. The present work demonstrates how a laboratory cone crusher equipped with a power meter, in conjunction with Whiten–Awachie crusher model, has been used to quickly estimate the $A * b$ breakage parameters. With an average absolute error of 36% when applied to a variety of materials, it is demonstrated that the method is not a priori restricted to the particular crusher used, neither to the crushing conditions employed. It is discussed that the method, when part of a variability study, can be used as a convenient tool for geometallurgical mapping of ore deposits regarding ore breakage response.

1. Introduction

A number of questions should be answered when selecting the appropriate crusher to an application, which include crusher capacity, power consumption, product size distribution and wear rate of liners, amongst others (Bearman et al., 1997; Tavares and da Silveira, 2008). In estimating the product size and the corresponding specific energy consumption, a number of options exist, although it is not uncommon to solely rely on data provided by crusher manufacturers or to use data from other plants that processes similar ores.

Throughout the life of a mine, crushers may be fed with ores with highly variable crushing responses, so that characterizing the amenability of ores contained in different parts of a deposit to crushing is worthwhile. This requires, however, proper crushability tests as well as mathematical expressions that can use characterization data to predict equipment performance.

Briefly, two main indices have been used to access the response of ores to crushing (Tavares, 2007; Tavares and da Silveira, 2008). The crushing work index (CWi), estimated on the basis of the twin-pendulum test, has been proposed by Fred Bond and accumulates a long track record in predicting the performance of crushing operations, although with several cases of poor performance. On the other hand, the $A * b$ breakage parameters, obtained using the drop weight test (Napier-Munn et al., 1996) and, more recently, the rotary breakage tester (Shi et al., 2009), has been used with reasonable success in conjunction with Whiten's model of compression crushers (Whiten, 1972) to predict the performance of full-scale machines.

The $A * b$ breakage parameters are calculated on the basis of impact tests on individual particles contained in five standard size classes, ranging from 63–53 mm down to 16.0–13.2 mm. In several instances, however, sample availability and even cost represent challenges to conducting the test, so that it may not be included in the suite of tests that are carried out when processing drill core samples, especially when preparing samples for assaying. Although alternative tests have been proposed that use more limited sample volumes (Chieregati and Delboni, 2002; Morrell, 2004) there are instances that not even these tests are used. In all cases, however, laboratory crushers are invariably used to prepare the sample for grindability or concentration tests or, at least, for assaying or mineralogical analyses. Indeed, some researchers (Kojovic et al., 2010) have identified that the response of the samples, normally diamond drill cores, to this crushing operation could provide information on breakage response of ores to size reduction, and proposed an additional comminution index, the *Ci*.

Evidently, a number of measures of breakage response of ores have some degree of correlation with the $A * b$ breakage parameters. For instance, Kojovic et al. (2010) show that it is correlated to the *Ci*. Napier-Munn et al. (1996) show the correlation between $A * b$ and the Bond ball mill work index, whereas Tavares and da Silveira (2008) demonstrates that it is correlated with the Bond crushing work index (CWi) and even the Los Angeles index, more commonly used to characterize the amenability of a rock to be used in pavements. However, empirical correlations with no physical background carry the risk of only being valid for the cases for which they were developed, besides requiring strict adherence to the standard used in the test.

The present paper demonstrates that the laboratory crushing operation that is used to prepare drill core samples for grindability or concentration tests, or even assaying, can be, after proper calibration, used to estimate the breakage indices $A * b$ of ores.

* Corresponding author. Tel.: +55 21 2562 8538.
E-mail address: tavares@ufrj.br (L.M. Tavares).

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2. Background

Comminution in compression crushers can be described by the well-known model from W. Whiten (Whiten, 1972; Napier-Munn et al., 1996). The mass balance equations can be defined in matrix (Napier-Munn et al., 1996) or in algebraic form (King, 2001). King (2001) showed that the size distribution in the crusher product p_i can be calculated from

$$p_i = (1-c_i)x_i \tag{1}$$

where the various x_i can be calculated sequentially from the coarsest size class in the feed ($i = 1$) using the expression

$$x_i = \frac{1}{1-c_i b_{ii}}\left(p_i^f + \sum_{j=1}^{i-1} c_j x_j b_{ij}\right) \tag{2}$$

which requires the knowledge of the size distribution of the feed p_i^f, the classification function c_i and the breakage or appearance function b_{ij}, which corresponds to the fraction of particles contained in class j that report to size class i after a single breakage event. c_i is a function whose parameters are machine-dependent. A useful model for the classification function is given by (Whiten, 1972)

$$c_i = \begin{cases} 1 & \text{for} \quad d_{pi} \geq d_2 \\ 1-\left(\dfrac{d_{pi}-d_2}{d_1-d_2}\right)^n & \text{for}\, d_1 < d_{pi} < d_2 \\ 0 & \text{for} \quad d_{pi} \leq d_1 \end{cases} \tag{3}$$

where d_{pi} is the representative size of particles contained in class i and d_1, d_2 and n are model parameters that must be fit from experimental data. Whereas n is usually constant at 2.3, d_1 and d_2 are normally influenced by operating variables of the crusher, mainly varying with crusher setting, thoughput, feedrate and eccentric throw (Napier-Munn et al., 1996). d_1 is the size below which all particles escape breakage, whereas d_2 is the size above which all particles are broken inside the machine.

The breakage function in density form b_{ij} is calculated from the cumulative breakage function by

$$b_{ij} = B\left(D_{i-1}; d_{pj}\right) - B\left(D_i; d_{pj}\right) \quad \text{and} \quad b_{jj} = 1 - B\left(D_j; d_{pj}\right) \tag{4}$$

where D_i is the ith screen size.

The power model relates the actual power drawn by the crusher to the power required by the laboratory drop weight tester to achieve the same size reduction (Morrel et al., 1992). It is of the form

$$P_c = S P_d + P_n \tag{5}$$

where P_c is the actual power drawn by the crusher under load, P_d is the calculated power in the drop weight tester, P_n is the power drawn by the crusher under no load, often also regarded as a fitting parameter, and S is a dimensionless factor for a particular crusher, estimated by regression (Napier-Munn et al., 1996).

The drop weight equivalent power P_d is given by

$$P_d = W \sum_{i=1}^{N} Ecs_{t10i} c_i x_i \tag{6}$$

where N is the number of size intervals and W is the throughput. P_d is therefore the total energy required to reduce the crusher feed to the product size distribution, as if all the size reduction took place in the drop weight tester at a specific impact energy Ecs, given in kWh/t.

Values of S for industrial-scale secondary and tertiary cone and gyratory crushers have been found to vary typically from 1.2 to 1.55 (Napier-Munn et al., 1996). The inverse of this number is considered the efficiency of the crusher, which typically ranges from 70 to 80% (Napier-Munn et al., 1996).

3. Experimental

3.1. Materials

Samples of over 25 materials have been collected for testing, which include several samples of bauxites, copper ores, limestones, acid rocks, coals and an iron ore. They have been prepared for testing by sieving in the appropriate size fractions. Samples were dried to moisture contents below 0.1% prior to all tests. More details on the sample characteristics can be found elsewhere (Tavares and Carvalho, 2007).

3.2. Drop weight tester

In the impact load cell (Tavares, 2007), such as in any drop weight tester, the energy-size reduction relationship can be analyzed by impacting single particles at variable input energies. In the test, standardized at the Julius Kruttschnitt Mineral Research Centre (Napier-Munn et al., 1996), drop weights from about 3 to 50 kg are used to determine the impact breakage characteristics of particles contained in five size ranges, namely 63.0–53.0 mm, 47.5–37.5 mm, 31.5–26.5 mm, 22.4–19.0 mm and 16.0–13.2 mm. Following preparation by sieving of lots contained in these five classes, the mean weight of each set of particles to be broken is calculated. Based on the required specific input energy for each test, which is variable from 0.1 to 2.5 kWh/t, the height from which the drop weight is to be released is determined assuming free-fall conditions. The test results in a breakage index, t_{10}, which is related to the specific input energy as (Napier-Munn et al., 1996)

$$t_{10} = A[1-\exp(-b\,Ecs)] \tag{7}$$

where t_{10} is the percentage of breakage product that passes 1/10th of the initial particle size; Ecs is the specific input energy (kWh/t) as calculated from the input energy of the falling weight and the average weight of the impacted particles.

Parameter A in Eq. (7) is the maximum value of t_{10}, i.e., the highest level of size reduction from a single impact event, typically varying from 35 to 70%. The product $A * b$, that is, the derivative of (7) at $Ecs = 0$, can be used to compare the amenability of the ore to fragmentation by impact. A high value of $A * b$ means that the rock has a low resistance to impact breakage and vice versa. Materials used in the present study presented values of $A * b$ ranging from 21 (copper ore #1) to 633 (limestone #3).

3.3. Laboratory crusher

Crushing experiments were conducted in a laboratory-scale shorthead cone crusher (Denver No. 12) equipped with a power meter (Fig. 1). The crusher has a stroke of 5 mm, a cone angle of 44° (in relation to horizontal) and a mantle length of 150 mm. The feed opening gap is 25 mm, which is particularly convenient, since it allows feeding 50 mm diameter (2¨) split cores. A constant closed-side setting (CSS) of 7.6 mm was used in all experiments, which was measured with the aid of a lead spacer. The motor runs at about 1725 rpm, transferring torque to the crusher bowl that turns at a frequency of 616 ± 5 rpm, via a rubber belt.

Crushing experiments consisted of continuous feeding samples containing from 7 to 15 kg of material, depending on specific gravity, with size in the range of 22.4–16.0 mm to the crusher and collecting timed samples of the product. Choke-fed conditions were maintained during the tests, but reasonably limited particle interaction existed, given the relatively coarse feed size distribution. In order to ensure that, care was taken to reject the material generated in the beginning and final portions of the test, when non-choke conditions prevailed. Size analyzes of the crusher discharge were measured by wet-dry sieving. From the