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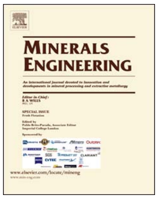

Mathematical modeling of a vertical shaft impact crusher using the Whiten model

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ABSTRACT

Vertical Shaft Impact (VSI) crushers have been used as interesting alternatives to cone crushers, particularly in the production of aggregates for the construction industry, not only due to their good energy efficiency but also to their ability to generate more isometric and tougher particles, which is highly desirable in cement mortars and concrete applications. Several mathematical models for the VSI crusher have been proposed in the last two decades or so. The Whiten crusher model, originally developed for cone crushers, has served as the basis of several approaches to model VSI crushers. In the present work, the Andersen/Awachie/Whiten model has been used as the basis for modeling a VSI crusher operating in an industrial plant in Brazil, processing quarry rock to product manufactured sand. Nineteen industrial experiments, covering a range of feed rates, rotor speeds, feed distributor types and feed size distributions, have been carried out. The approach demonstrated to be capable of providing satisfactory estimates of the VSI performance, being able to predict the product size distribution and the specific energy consumption with confidence over a wide range of operating conditions. Since it uses a model that is already available in commercial plant simulators, it may be used, with additional expressions, in simulating any desired circuit. Model parameters such as $K3$ and $T10$ were found to be particularly influenced by key operational variables such as feed rate and rotor frequency. The significant effect of feed rate on the performance of the VSI crusher studied has been discussed on the basis of simulations of the material flow pattern inside its feed distributing system, simulated using the discrete element method. According to these simulations, it has been inferred that change in the behavior of VSI from lower to higher feed rates may be related to the transition from material being fed predominantly to the rotor, to the increasing contribution of the cascading effect.

1. Introduction

Impact crushers have become particularly useful in manufactured aggregates production because of the nature of the breakage mechanisms, which allow direct fragmentation of the particles without leaving residual stress in them (Wills and Finch, 2016). As such, material produced in a particular size range, which may be controlled by the combination of crushing and classification stages, may be directly used in construction and building. This contrasts with the metal-mining industry, where the machine has been used in stages that are upstream from grinding.

The issue of residual stress and damage associated to crushing process has been studied by Briggs and Bearman (1996), who conducted fundamental breakage tests in a Modified Hopkinson Pressure Bar to quantify the level of damage in rocks crushed using two different VSI crushers (Barmac and Canica) as well as a cone crusher. They found evidence that the material consistently becomes more competent as it is processed by both VSI crushers, in contrast to the product of a cone crusher.

Another noticeable feature of impact crushers is their ability to improve particle shape in the product (Wills and Finch, 2016), which can be advantageous in applications where the rheological properties of the crushed material must be considered, such as in pumping of ore concentrate and in concrete and cement mortars (Gonçalves et al., 2007; Lindqvist, 2008).

A number of studies have been reported in the literature showing the operational benefits achieved in comminution plants when either cone crushers are replaced by VSI crushers, or when conventional grinding circuits are enhanced with the incorporation of a pre-crushing stage based on VSI technology. Examples of these improvements are:

- Barmac crushers replaced roller crushers in the final crushing stage of a nepheline syenite processing plant, allowing feeding with a coarser feed, at similar circuit capacity, greater ease of operation,

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smaller space requirement, lower energy consumption and less demand for maintenance with slightly higher generation of fines (i.e. material less than 74 μm) (Sandvik et al., 1999);

- A significantly higher energy efficiency of a VSI compared to a cone crusher in a crushing plant processing gneiss (feed size distribution below 50 mm), with additional increase in both capacity and energy efficiency in subsequent grinding operations, due to the production of a considerably finer crushing product in the former (Lindqvist, 2008);
- A potential increase of 10–20% in the throughput of a conventional cement grinding circuit (two-compartment dry ball mill in closed circuit with an air-swept classifier), as well as potential energy savings in the whole clinker grinding circuit with the incorporation of a fine pre-crushing stage using a Barmac crusher, which may result in a lower capital investment compared to a pre-crushing stage based on HPGR (Jankovic et al., 2004).

Given its relatively wide applicability, VSI crushing has also attracted researchers interested in mathematically modeling its performance. Recent activity has been focused on attempting to model the process in a mechanistic way, with the aid of the discrete element method (Cunha et al., 2013, 2014; Sinnott and Cleary, 2015). Despite the substantial advances in these mechanistic approaches, phenomenological models retain much of their importance, mainly due to the greater simplicity of the model implementation, which facilitates the integration with other unit operations in plant simulators, in optimizing entire size reduction circuits.

For instance, Whiten and White (1979) considered that particle breakage in impact crushers could be described by a combination of a classification function followed by breakage of the selected particles. More recently, Bengtsson and Evertsson (2008) considered a similar approach, further discriminating the mechanisms of volume breakage and surface breakage (attrition). This model relied on the description of the flow of particles out of the rotor given by Rychel (2001), which demonstrated to be able to appropriately predict power and size distribution of the product.

Originally developed for modeling of cone crushers, the Whiten crusher model (Whiten, 1972) has also been the basis for several important phenomenological modeling approaches of VSIs, with further improvements. Nikolov (2002) considered the dynamic behavior of impact breakage and proposed new breakage and classification functions that were meant to be specific for impact crushers, which were, in turn, coupled to the Whiten crusher model for the calculation of the product size distribution. These functions were related to important operational parameters, including the rotor radius and its frequency of rotation, besides the feed rate. The researcher also established a minimum particle size below which the probability of particles being classified for breakage is equal to zero. This model was validated on the basis of experimental data from pilot plant tests in a horizontal impact crusher (hammer mill) processing limestone (Nikolov, 2002). While potentially applicable also to VSI crushers, it was never applied to this type of crusher.

Researchers from the JKMRC, on the other hand, proposed a methodology for a more direct application of the Whiten crusher model to the VSI (Napier-Munn et al., 1996; Kojovic et al., 1998), which is briefly described as follows:

1. Set the parameters of the classification function (Eq. (1)) as: $K1 = 0$ (all particles have a chance of being broken); $K2$ = top size of crusher feed; $K3 = 2.3$:

   $$C(x) = 1-\left(\frac{K2-x}{K2-K1}\right)^{K3} \tag{1}$$

   where x is the representative particle size.
2. Calculate the $T10$ parameter (fitted value of the breakage parameter known as "fineness index", t_{10}) as a function of A and b parameters (ore-specific constants obtained by non-linear regression from drop weight test DWT data) and the specific comminution energy Ecs (kW h/t), given by

   $$t_{10} = A\cdot(1-e^{-b\cdot Ecs}) \tag{2}$$

   Ecs is approximated as a function of particle peripheral velocity at the tip of the rotor, given by

   $$Ecs \approx \frac{1}{2}v^2 = \left(\frac{2\cdot\pi\cdot N\cdot r}{60}\right)^2 \tag{3}$$

   where N is the rotational speed of rotor (RPM) and r is the rotor radius (m)
3. Calculate the product particle size distribution ($\vec{p}$) from feed particle size distribution ($\vec{f}$), the breakage function ($\underline{\underline{B}}$) experimentally obtained from DWT, and the previously defined classification function ($\underline{\underline{C}}$), using the Whiten crusher model equation

   $$\vec{p} = (\underline{\underline{I}}-\underline{\underline{C}})\cdot(\underline{\underline{I}}-\underline{\underline{B}}\,\underline{\underline{C}})^{-1}\cdot\vec{f} \tag{4}$$

   where $\underline{\underline{I}}$ is the unit matrix

This approach (Kojovic et al., 1998) showed good agreement between the experimental and predicted product size distribution of a VSI crusher, but was only validated for a single set of data. No information was either provided on its ability to predict the power or energy consumed by the machine in operation when coupled to an appropriate power model.

As a further improvement, the Andersen/Awachie/Whiten (AAW) model (JKTech, 2014) – which is based in the original Whiten model and is already available in process simulation platforms such as JKSimMet® – incorporates a sub-model for the estimation of power consumption in crushers (P), as the sum of the power drawn by the crusher under no load (P_n) and the product between a theoretical power (P_p):

$$P = P_n + G\cdot P_p \tag{5}$$

where G is a dimensionless factor that depends on the type of crusher (typically corresponds to 65–80% of energy usage efficiency for conventional cone and gyratory crushers, which means a G value between 1.2 and 1.55, according to Napier-Munn et al., 1996). The theoretical P_p power has been defined as the energy necessary to comminute the feed size distribution to a product size distribution as if all breakage were to occur in a single particle breakage device (such as a pendulum or a drop weight tester), given by

$$P_p = \sum_{i=1}^{j} Ecs_{t10i}\cdot C_i\cdot x_i \tag{6}$$

where Ecs_{t10i} is the specific comminution energy at the prevailing value of t_{10} for size i (kWh/t), obtained from single-particle breakage tests; j is the number of size ranges; C_i is the classification function or probability of breakage of size i and x_i is the particle mass flow of size i in the crusher (t/h), which is, according to the Whiten model, given by

$$\vec{x} = (\underline{\underline{I}}-\underline{\underline{B}}\,\underline{\underline{C}})^{-1}\cdot\vec{f} \tag{7}$$

The AAW model also differs from the original Whiten model (Whiten, 1972) in the fact that the breakage function is experimentally obtained from breakage tests on individual particles on a drop weight apparatus (JKTech, 2014; Napier-Munn et al., 1996). Equally to the original Whiten model, the AAW model solves Eq. (4) to predict the product size distribution.

In the present work, an alternative methodology is proposed with the aim of predicting the performance of the VSI in terms of both product size distribution and power consumption for a wide operational range, using the AAW model as a basis. A discussion on the significant effect of feed rate on the model predictions has been carried out on the