# Mathematical modelling of a vertical shaft impact crusher in size reduction of aggregate rock

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**Abstract.** Vertical shaft impact (VSI) crushers were introduced in the 1970s and achieved great popularity in some important applications, with a highlight in the aggregate industry, primarily owing to their ability to produce material with good cubicity. A VSI crusher (Barmac B7150SE from Metso) was installed in an aggregate plant in Rio de Janeiro in size reduction of a gneiss rock for manufactured sand production. Owing to varying production demands and the dynamics of the circuit, the crusher may be fed with material contained in a variety of size ranges, with particle sizes that may be as coarse as 45 mm and as fine as below 1 mm. Because of the importance of identifying the optimal conditions for operating the circuit, a mathematical model of the crusher was sought. After attempts to use published models were not successful, the need to develop a customized model became evident. The work describes the development of a crusher model, based on modification of the traditional Whiten crusher model. It recognizes that the VSI crusher may be described as two crushing processes operating in parallel: one represented by particles ejected by the rotor and the other by particles cascading through the ejected particles. Data from a total of 19 surveys with the crusher operating under a variety of conditions were used to fit the model. Results demonstrated that the model was able to capture the effects of feed throughput, feed size distribution, rotor opening and rotation frequency in predicting the product size distribution with high fidelity.

## 1. Introduction

Vertical shaft impact (VSI) crushers were introduced in the 1970s [1] and have since found a variety of applications in the minerals, aggregate and cement industries [2]. One of its most successful applications has been on manufactured fine aggregate production, owing to its ability to generate good aspect ratio material [3]. Different types and models of VSI crushers have been proposed, with the original being the Barmac, in which particles are projected against a bed of crushed rock deposited on the impact chamber of the machine, while a cascading curtain of rock crosses the projected flow from the crusher. Unlike compression crushers, whose throughput is highly limited by the gap, this type of crusher can tolerate highly variable feed rates, owing to the ability of the crusher to bypass material to the cascade flow.

Various attempts have been made to mathematically model the performance of VSI crushers. These have varied from phenomenological models, based on the concepts of breakage and selection/classification functions [4-6] to, more recently, the Discrete Element Method (DEM) [7,8]. In spite of the potential fidelity of the latter in describing microscale phenomena, its large computation demand prevents its use in integrated circuit simulations. Phenomenological models remain the only practical option in this task.

Whiten and White [9] considered that particle breakage in vertical shaft impact crushers could be described by a combination of a classification function followed by breakage of the selected particles. Bengtsson and Evertsson [5] used a similar approach but further discriminated volume and surface breakage, in a model that also described breakage of particles projected by the rotor and a bypass through the cascading flow. The authors demonstrated to be able to predict, with confidence, crusher power and product size distribution. More recently, Grunditz et al. [10] built on the same approach, only changing the classification/selection function by an energy-dependent function.

Some authors used the Whiten crusher model [11], which considers that particles are subjected to repetitive stressing events, to simulate the VSI. Justification for its use in VSI crushers was provided, indirectly, by Cunha et al. [7], who demonstrated that particles both projected by the rotor and cascading are subject to multiple impact events. Kojovic et al. [4] proposed this approach, with the breakage function being described as a function of specific impact energy. Segura-Salazar et al. [6] then considered that both the breakage and the classification functions were dependent on feed throughput, whereas the latter was also dependent on rotor frequency.

After unsuccessful attempts to represent results from an industrial-scale VSI crusher with models from the

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literature, a new approach is hereby proposed for a cascade-type crusher. It recognizes that the crusher can be optimally described as two parallel crushing processes: the primary that corresponds to breakage by projection of particles from the rotor and the secondary that represents breakage of material that falls under gravity cascading around the rotor. The model has been developed and fitted to data collected in an industrial circuit in operation with gneiss rock.

## 2. Modelling background

The framework of the model is illustrated in Figure 1, showing that the feed is split in two streams inside the crusher, depending on the feed rate, the feed coarseness, besides the opening of the hopper slit. Each of the flows is modelled as an individual crusher following Whiten´s model [11]. As demonstrated by Cunha et al. [7], the severity of impacts varies significantly if the material is projected from the rotor or if it cascades, being this captured in the energy-dependent breakage functions (*B*). Particles entering the cascade flow are subjected to breakage by particles projected from the rotor. Therefore, the greater the amount of material projected by the rotor, the higher the probability of breakage of the cascading particles. This behaviour is captured by the cascade classification function ($C_c$) being a function of rotor feed rate.

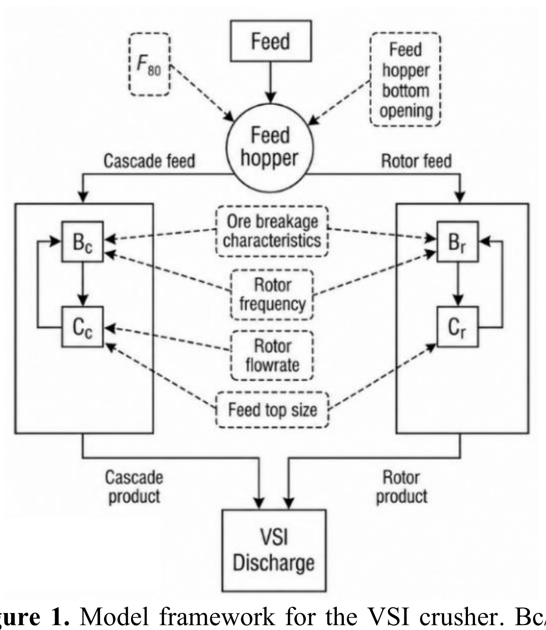


**Figure 1.** Model framework for the VSI crusher. Bc/Br indicate the breakage functions of cascade/rotor and Cc/Cr indicate the classification function of cascade/rotor, respectively.

## 3. Materials and methods

The VSI crusher has been installed in an aggregate plant located in Itaguaí, a city in the metropolitan area of Rio de Janeiro. It is a Barmac B7150SE from Metso, with 320 kW power motor, which allows changing the rotor hopper opening and frequency of rotation, this later in real time during operation. It is part of a circuit that crushes rock to produce manufactured sand and filler for applications that include concrete and mortars Besides the crusher, the circuit also contains several vibrating screens, conveyor belts and an air classifier (Figure 2). Depending on circuit configuration, the crusher may operate in open or closed circuit, this later with recycle of material contained in different size ranges.

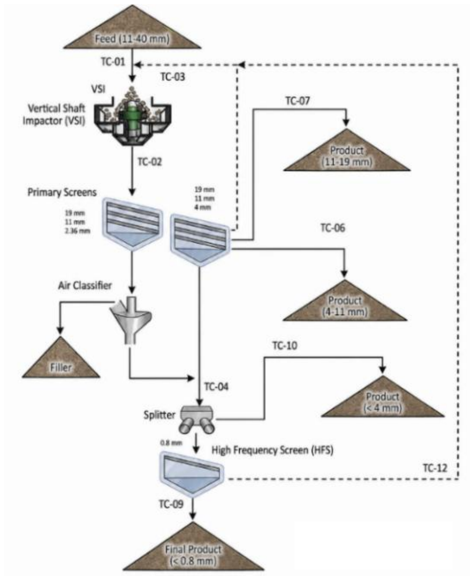


**Figure 2.** Simplified circuit flowsheet. Dashed lines represent de variable recirculation flow.

Nineteen surveys were carried out of the circuit when operating under a variety of conditions, including different feed size distributions, throughputs (51 to 540 t/h), openings of hopper slit (74 to 100%) and rotor frequencies (1100 to 2100 rpm). From each survey, samples from relevant streams were collected and subjected to size analyses by sieving. This, along with estimates of flowrates of the various streams of the circuit, were reconciled, serving as the basis for the development of the model. In addition, power drawn by the crusher in operation and running empty were measured.

Figure 3 shows composite feed size distributions to the crusher, which shows that it varied from nearly 45 mm down to below 1 mm, with 50% passing sizes varying from 28.6 to 12.4 mm. Such wide range is the result of differences in fresh feed size distribution, besides the stream in the circuit that is being recycled (Figure 2).

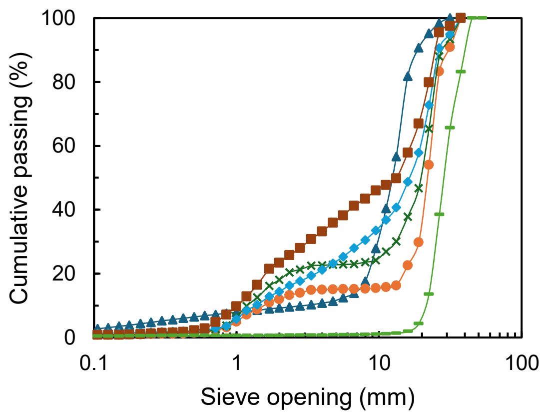


**Figure 3.** Composite feed size distributions to the VSI crusher from selected surveys

A sample of the material from the feed to the circuit was then subjected to drop weight tests with the aim of analysing the breakage characteristics of the rock.

## 4. Results and discussion

Results showing the variation in crusher power is a function of feed throughput are presented in Figure 4. It suggests that, as soon as the flowrate surpasses a minimum value, dictated by the feed hopper bottom opening and the feed particle size, a fraction of the feed starts to cascade. This behaviour was already demonstrated in earlier studies of VSI crushers [6,12].

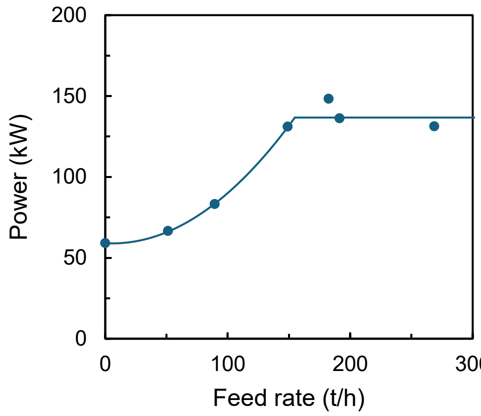


**Figure 4.** Variation in crusher power as a function of composite feed throughput (hopper slit opening of 91 %, 80% passing feed of 15.8 mm and frequency of 2100 rpm.

At first, the model was fit to data in which the power has not yet reached the plateau shown in Figure 4, suggesting no cascade flow. In this case it was possible to model the classification ($C_r$) and breakage ($B_r$) functions of the rotor. A typical result is shown in Figure 5, which shows the excellent agreement, evidence of the ability of the model to represent the main breakage mechanism inside the crusher. While here the breakage function from the drop weight test and the $t_{10}$ procedure were used, a need was identified to modify the relationship of $t_{10}$ with $t_2$ and $t_4$, to account for the more limited rebreakage when particles are projected against a target, which is the case of the VSI crusher, in contrast to the drop weight test.

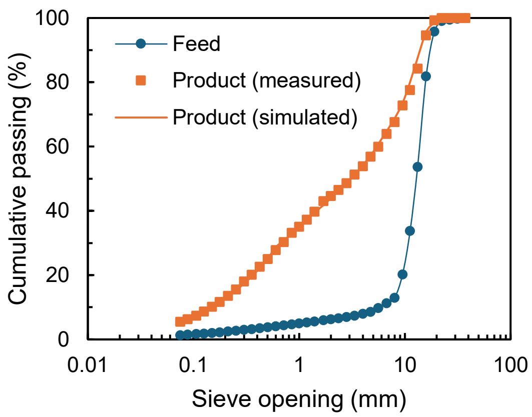


**Figure 5.** Comparison of experiments and predictions for a selected test (hopper slit open at 91 %) where all the particles from the feed is ejected by the rotor.

Now assuming that parameters from the classification and breakage functions remain unchanged for the rotor flow as the cascade flow appears, it then became possible to model parameters from the classification ($C_c$) and breakage ($B_c$) functions of this secondary flow. Figure 6 illustrates a case in which the model predicts separately the contributions from the rotor and cascade products. The rotor stream generates a finer product, since particles projected by the rotor undergo more intense impact conditions. In contrast, the cascade flow produces a coarser product, as particles in this flow are subjected to substantially lower impact energies [7]. The resulting overall product is then a combination of two distinct breakage processes, which is consistent with the physical behaviour of the crusher. This result supports the central assumption of the model, namely that the VSI crusher can be represented as two parallel comminution processes operating simultaneously.

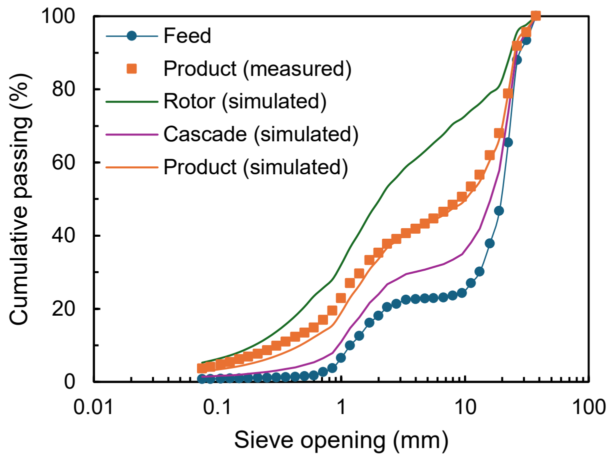


**Figure 6.** Comparison of experiments and predictions for a selected test, showing the predicted size distributions from the rotor and the cascade products.

A further examination of the model predictions of the cascade flow is shown in Figure 7. While the product of the rotor (omitted for clarity) remained unchanged, significant differences are observed in the predicted cascade product. As the hopper slit opening decreases, a smaller fraction of the feed is directed to the rotor, reducing the number of projected particles to impact the cascading material. As a result, the predicted cascade product becomes coarser, indicating lower breakage intensity in the secondary flow. This behaviour is result of the assumption that breakage of particles in the cascade stream depends strongly on the amount of material projected by the rotor.

An overall comparison of the model fit to experiments is possible in Figure 8, which shows the parity plots for both the 20% and 80% passing sizes, representative of both extremes of the product size distributions. While the agreement for the 80% passing sizes is excellent, the one for the 20% passing is only good, with the model tending to underestimate the content of fines in the product. The generally good agreement is particularly relevant, since the same set of model parameters was able to cover a broad range of operating conditions. The satisfactory agreement obtained for both coarse and fine size descriptors suggests that the model captures not only the overall product size distribution, but also the sensitivity of the crusher response to changes in operating conditions.

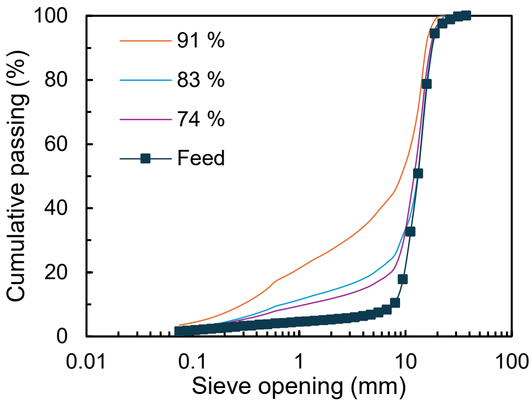


**Figure 7.** Comparison of predictions showing the predicted size distributions from the cascade products with different openings of the hopper slit from a feed throughput of 195 t/h.

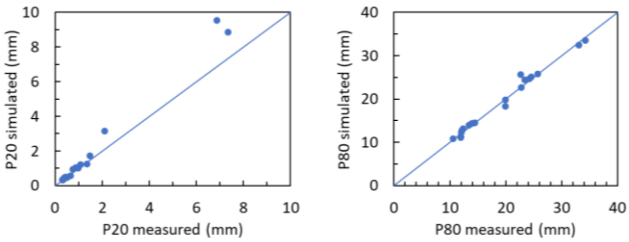


**Figure 8.** Parity plots of model predictions of 80% and 20% passing sizes in the product.

From a practical standpoint, the model provides a useful tool for predicting the influence of operational variables on VSI performance. The results show that the rotor and cascade contributions must be treated separately in order to properly describe the product size distribution. A single breakage environment would not be capable of reproducing the observed behaviour of the industrial crusher.

The proposed cascade-type VSI crusher model demonstrates strong predictive capability under varying operating conditions, which suggests its potential for integration into dynamic plant simulations. By incorporating both rotor and cascade contributions, the model can serve as a reliable unit operation within full-circuit simulations to optimize throughput, energy efficiency, and product quality across complex industrial processes.

## 5. Conclusions

A model of a cascade-type VSI crusher has been proposed that responds to variation in feed throughput and size distribution, rotor frequency and feed hopper slit opening, being capable to deal even with highly bimodal feed size distributions. By treating rotor and cascade breakage as two parallel comminution processes, the model was able to predict the product size distribution with good fidelity. The parity plots showed good agreement for both P20 and P80, indicating that the model provides a reliable description of both the fine and coarse fractions of the product. This suggests that the proposed formulation is a practical tool for simulating and optimizing cascade-type VSI crushers in industrial circuits.

## 6.Acknowledgement


The authors would like to thank the technical and financial support from Mineração Santa Luzia Ltda. The partial financial support of the Brazilian agency CNPq (grant number 313425/2021-3) is also acknowledged. This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.


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