METHODS FOR CRUSHING OPERATIONAL CONTROL

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ABSTRACT

This study is being conducted in an iron ore plant that processes friable and compact itabirites. The plant is being adapted to the new conditions of the ore in situ: harder rocks and with lower quality. The ROM is dumped directly by trucks into a primary gyratory crusher. The product of the primary crusher is classified by double deck screens (64 and 32mm). The material retained in 32mm feeds two secondary conic crushers. The product came from the secondary crushers is discharged on the same conveyor belt of the product of three tertiary crushers. Double deck screens reclassify the product of both secondary and tertiary crushers. The material retained in 32mm feeds back the tertiary crushers. This study aims to show some methods for crushing operational control in order to increase productivity. Sampling and simulating of the crushing circuit helped to evaluate and increase the efficiency of the secondary-tertiary crushing stage. It was also possible to verify changes in the work index of the ore.

KEYWORDS: crushing; crushing and classification efficiency; comminution; iron ore.

RESUMO

Este estudo está sendo conduzido em uma planta de minério de ferro que processa itabiritos friáveis e compactos. A planta está sendo adaptada as novas condições do minério in situ: rochas mais duras e com menor qualidade. O ROM é basculado diretamente por caminhões num britador giratório primário. O produto do britador primário é classificado por peneiras de duplo deck (64 and 32mm). O material retido em 32mm alimenta dois britadores secundários cônicos. O produto dos britadores secundários é descarregado sobre a mesma correia do produto dos britadores terciários. Peneiras de duplo deck reclassificam o produto de ambos britadores secundários e terciários. O material retido em 32mm alimenta de volta os britadores terciários. Este estudo objetiva mostrar alguns métodos para controle operacional de britagem com objetivo de aumentar a produtividade. Amostragem e simulação do circuito de britagem ajudou a estimar e aumentar a eficiência do estágio de britagem secundário-terciário. Foi também possível verificar mudanças no índice de trabalho do minério.

PALAVRAS-CHAVE: britagem; eficiência de britagem e classificação; cominuição; minério de ferro.
1. INTRODUCTION

Figure 1 illustrates the plant design that processes up to 6,000t/h of iron ore (itabirites) came from Conceição and Dois Córregos Mines (MG, Brazil). The primary crushing stage consists of one gyratory crusher with 2 meters of gape in Conceição I. The product of the primary crusher is classified by double deck screens (64 and 32mm). That is the primary classification. The material retained in 32mm feeds two secondary conic crushers. The product came from the secondary crushers is discharged on the same conveyor belt of the product of three tertiary crushers (TC3025). Double deck screens reclassify the product of both secondary and tertiary crushers. That is the secondary-tertiary classification. The material retained in 32mm feeds back the tertiary crushers (TC3034). The passing material is conducted to a quaternary crushing stage. From this stage, the material is classified in 32 and 12mm. The material passing in 12mm will feed the mills. The liberation size of the ore is 105um.

![Figure 1. (a) Crushing circuit; (b) secondary-tertiary crushing and (c) grinding circuit.](image)

In the Dois Córregos Mine there is the same design of the crushing circuit (primary and secondary stages) and the retained in 32mm from the primary classification goes to the silos and is reclassified in Conceição I (secondary-tertiary classification).

The recommended range of the close side setting (CSS) varies from 11.4cm to 15.2cm for the primary crushers. For the secondary and tertiary crushers are recommended 44 and 28mm respectively.

The plant is being adapted to the new conditions of the ore in situ: harder rocks and with lower quality. This study is being conducted in an iron ore plant that processes friable itabirites and, in minor amounts, compact itabirites (a blend up to 10% of the ROM currently). In order to guarantee the optimum conditions of feed to the milling circuit, it is important to determine the particle size distributions, W1, as well as, the crushing and classification efficiency according to the blending and blasting. This study aims to show practical methods that may be implemented to identify problems associated with decreases in productivity of a crushing circuit. This methodology can be applied when the grinding circuit is not yet operating.
2. MATERIAL AND METHODS

Sampling and analyses by images from video recording device were made on both stopped and moving conveyor belts to determine particle size distributions. The samples were collected along one meter of the feed and product conveyor belts in order to validate the results. The conveyor belt was stopped five times in 2014, and the differences between the size distribution obtained by image analysis and screening were calculated. There are linear cut-samplers (primary and secondary cutter) located on the product of the secondary-tertiary classification (Figure 1 (b)). These samples were collected at a regular time interval (one hour).

2.1. Sampling and analysis by images

The video devices were located on the feed of the tertiary crushers (TC3034) and on the product of the secondary-tertiary crushers (TC3025). Video devices recorded during 30 min up to one hour per sampling day. Images were obtained from these films (Figure 2). Each analyzed image corresponded to a time interval of about 15min. More than one hundred fragments along one meter of conveyor were counted on each image (after scaling). The area of each fragment was measured. The number of fragments inside a size class was recorded as well. Each size class is equivalent to an interval between a superior and inferior screen of square opening. It was used a free software (Fiji) with some macros implemented as a routine to analyze the images. From these measurements, particle size distributions were determined. Following this, the conveyors were stopped in order to collect material along one meter of conveyor (Figure 2). Then, material was screened to validate results.

Figure 2. Image on conveyor (feed- tertiary crushers) and sampling on stopped conveyor.
The particle size distributions obtained using image analyses were compared directly to those curves obtained by screening. Actually, there are fragments that cannot be measured because they are under the “photographed” surface or are very small. This generates a bias, which was determined comparing particle size distribution curves obtained by screening and image analysis.

It is recommended for sampling in the feed of crushers and autogenous mills to remove the coarse rocks (at least 50 +75mm) and collect carefully along 2-5m belt which represents a typical fines loading (Napier-Munn, et al., 1996, p.110). This typically is a total sample of at least 500/800kg. The amount of sample depends on the variance of the particle size distribution along the belt, as well as, the feed rate (t/h). When the conveyor belts were stopped, the total sample was about 254kg (one meter of belt comprising coarse and fine fragments). The focus of this methodology was to observe the bias, initially, comparing image analysis and screening, which would not be related to the coarse rocks in this case. The coarse rocks of the feed of the tertiary crushers vary from 150 to 60mm, for example. This size of rock still appears due to the lamellar shape of the ore, regarding the maximum CSS of the primary crusher, which is 150mm. This bias and variance of the particle size distribution related to the fine material should be better determined, collecting a longer length of the belt. Then, the solution was to verify the results of the simulation based on the linear cut-samplers located on the product of the secondary-tertiary classification and to exclude from the data set the particle size distribution curves with bias above 12% (absolute) for any size class smaller than 32mm.

2.2. ROM Particle Size Distribution Simulations

Methodology to sample ROM and determine particle size distributions was described in a prior publication (Silva, et al., 2014). The particle size distribution of the ROM has a cumulative retained in the 32mm size of 55% for semi to compact itabirite and 25-30% for friable itabirite. These last results (friable itabirite) were very similar to those obtained during pilot scale test.

All sampling for ROM has been accomplished using image analysis (for large blocks) and screening (for smaller fragments). A conversion factor has been applied in order to convert from area to volume and finally mass (Silva, et al., 2014). It has been possible to determine a combined and compatible size distribution curve of the sampled ore in the mine (ROM). The results were considered validated because differences between these curves and those obtained for pilot scale tests are below 5%.

The operational WI and equivalent to the laboratory were calculated basing on the samplings in the crushing circuit. The crushing circuit shown in Figure 1 (b) was considered equivalent to the grinding circuit of the Figure 1 (c). Results were validated by linear cut-samplers on the product of the secondary-tertiary classification.

The work index (WI) was determined according to the Bond Law (Napier-Munn, et al., 1996) as:

\[ WI_{(op)} = \frac{P}{R} = 10 WI_{(lab)} \cdot \frac{1}{(P_{80})^{0.5}} \cdot \frac{1}{(F_{80})^{0.5}} \]  (1)
where \( W_I^{(op)} \) and \( W_I^{(lab)} \) is the operational and laboratory work index (kWh/t); \( P \) is the power draw of the secondary and tertiary crushers; \( R \) is the feed ratio (t/h); \( P_{80} \) and \( F_{80} \) are the size at which 80% of the product and feed passes (um)-cumulative passing.

It was applied the JKMRC crusher model (Napier-Munn, et al., 1996, p.142-144) to the conic crushers. This describes breakage by a single parameter, \( T_{10} \), defined for a single breakage \((t_{10})\) as the percent of product passing \(1/10^{th}\) of the original particle size, after breakage. This parameter is characteristic of a particular operation and can be back-fitted from feed and product size distribution data. \( T_{10} \) varied according to the CSS, throughput (dry-t/h) and \( F_{80} \). \( T_{10} \) varied from 10 up to 12 for the secondary crushers and from 15 up to 20 for the tertiary crushers. The appearance function was represented in the simulator by spline functions according to the data input for each operational condition set. Care should be taken, therefore, when a new blend will feed this plant (more than 10% of compact itabirites). The design of the crushing circuit, the nominal opening of the screens and the CSS can be changed. In addition to, the sampling was made under specific conditions of wear of the liners. The \( K_1 \) and \( K_2 \) parameters varied also with the CSS, throughput and \( F_{80} \). The parameter \( K_3 \) was maintained constant and equal to 2.3.

It was applied a classification efficiency function to the experimental data. This function is equal to the empirical model suggested by Karra (1979). He proposed a model based on the use of a normalized efficiency curve defined by an \( x_{50} \) value, similar to the Rosin-Rammler distribution. The model was derived from experimental data and predicts the percent to oversize as a function of particle size:

\[
E_i^c = 100 \cdot [1 - \exp(-0.693 \cdot (x_i/x_{50})^m)]
\]

(2)

Where \( E_i^c \) is the weight percent of size in the feed reporting to oversize product, \( x_i \) is the size mean geometric and \( x_{50} \) is the size corresponding to \( E_i^c \) equal to 50%. A limitation of Karra’s model is that since is only valid over the range of data used in its derivation, the exponent would be expected to vary with both feed and screen conditions. The “\( m \)” factor applied was 1.623 instead 5.846 proposed by Karra to adjust the efficiency function of the secondary-tertiary classification.

The equation (3) was applied to convert actual efficiency curves in corrected curves. \( R_f \) is the weight fraction of size which bypasses to the oversize product. In November was assumed a bypass equal to 25% according to the sampling and \( x_{50} \) of 27mm. The nominal opening of the screens is 32mm.

\[
E_i^c = (E_i^a - R_f)/(1 - R_f)
\]

(3)

The crushing efficiency \( E \) was determined according to the equation (4), where \( F_i \) and \( P_i \) are the cumulative retained of the feed and product respectively by each size class.

\[
E_i = (F_i - P_i)/F_i
\]

(4)
2.3. Process Control Strategy (PCS)

Process control strategy consisted of a program of verification of CSS, as well as velocity of the feeders in short time intervals. Process control strategy uses automatic systems along crushing circuit. This process is also helping to control silos level, which feed the crushers. The main objectives of PCS are to: a) increase productivity, b) avoid overload on the screens and conveyor belts and, c) adjust mass ratio of the feeders.

This strategy comprises also the measurement of the main parts of the crushers in order to monitor wear and efficiency, such as mantle and concave.

3. RESULTS AND DISCUSSION

3.1. Sampling and analysis by images

Sampling carried out in the plant and simulations in August 2014 have resulted in particle size distributions very similar to those predicted in project-based pilot scale tests. These were used as reference curves during simulation. Differences between curves determined by screening (Sampling Aug, 2014) and image analyses (Figure 3) were calculated. An underestimation of the amount of smaller fragments than 32mm occurred (product size distribution) using image analyses. This is an important reference size because is practically the desired cut-size of the classification stages in the crushing circuit (x50 varies from 27 up to 30mm). The amount of material passing in 32mm and retained in 12mm indicates if it is necessary a quaternary crushing stage or the amount of equipment that will be necessary. If any change occurs in the blend of the ROM or in the blasting, the size fraction -12 mm and +105um will show what will happen during the grinding. Nevertheless, this last size fraction cannot be determined by image analysis: only by screening (cut-samplers).

![Figure 3. Mean bias of the product size distribution - cumulative retained (TC3025): image analyses and screening (August 2014) compared to the pilot scale test.](image)

The product size distribution (cumulative retained) from the secondary-tertiary crushing stage shows a mean bias around 25% relative to the pilot scale test (extrapolating to 12mm, Figure 3). The bias related to the reference curve (August) is around 10% for the same size. For a point near to the P80 (size at which 80% of the product passes) the bias was accepted to be zero.
The feed size distribution of the tertiary crushers has generally showed values around zero of bias for the +32mm size fraction and up to 10% for the -32mm fraction. Using image analyses is perfectly possible to resolve fragments up to a minimum size of 14mm. Although the sampling by image analysis shows a significant bias in certain cases, the particle size distributions of the larger rocks are more precise and accurate. This last method is also capable of giving a curve with much more size classes.

3.2. ROM Particle Size Distribution Simulations

A summary of the results of the simulations is presented in Table 1. Parameters of the simulations were set to provide simulated particle size distribution with a maximum relative error of 5% from the experimental data.

<table>
<thead>
<tr>
<th>Table 1. Result summary of simulations.</th>
<th>Aug.2014</th>
<th>Nov.2014</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROM</td>
<td>2,037t/h</td>
<td>2,607t/h</td>
<td>4,000t/h</td>
</tr>
<tr>
<td>ROM (+32mm)</td>
<td>25%</td>
<td>56%</td>
<td>25%</td>
</tr>
<tr>
<td>Prim. Crush. Efficiency (E, i=32mm)</td>
<td>21%</td>
<td>34%</td>
<td>33%</td>
</tr>
<tr>
<td>Sec. Crush. Efficiency (E, i=32mm)</td>
<td>33%</td>
<td>55%</td>
<td>30%</td>
</tr>
<tr>
<td>Feed-Tertiary Crushers (TC3034)</td>
<td>618t/h</td>
<td>1,309t/h</td>
<td>1,130t/h</td>
</tr>
<tr>
<td>Prod.-Sec.-Tertiary Crushing Circuit</td>
<td>445t/h</td>
<td>1,156t/h</td>
<td>710.6t/h</td>
</tr>
<tr>
<td>TC3025</td>
<td>1,063t/h</td>
<td>2,465t/h</td>
<td>1,840.6t/h</td>
</tr>
<tr>
<td>Circ. Charge (mass ratio: TC3034/TC3025)</td>
<td>58%</td>
<td>53%</td>
<td>38.6%</td>
</tr>
<tr>
<td>Sec.-Tertiary Efficiency (E*, i=12mm)*</td>
<td>75%</td>
<td>55%</td>
<td>75%</td>
</tr>
<tr>
<td>Tert. Crush. Efficiency (E) (i=32mm)</td>
<td>40.5%</td>
<td>45%</td>
<td>37%</td>
</tr>
</tbody>
</table>

*Undersize (i=12mm, is the reference size for grinding feed).

The +32mm fraction of the ROM increased from 25 to 56% (Table 1), comparing August and November samplings. This may explain the effect of segregation in the silos, which was observed comparing the feed size distributions of the tertiary crushers.

The tertiary crushing efficiency increased significantly from August to November (+4.5%, i=32) while the secondary-tertiary classification efficiency decreased (-20%, i=12mm). The primary, secondary and tertiary CSS changed from 15cm, 44mm and 32mm to 14cm, 40 and 28mm respectively. Figure 4 illustrates examples of feed and product size distributions (tertiary crushers): experimental and simulated data.

The particle size distribution and WI of the ore changed significantly (Table 2). The crushing efficiency was higher in November and this probably happened due to a lower WI relative to August: a decrease from 12 to 8 kWh/t. The change relative to the CSS helped to maintain the full chamber condition of the crushers. As these values were measured in a crushing circuit, they could change significantly, according to the physical and operational conditions of the mills and blend (ROM).
Figure 4. Examples of feed and product size distributions (tertiary crushers).

Table 2. Energy specific consumption.

<table>
<thead>
<tr>
<th>Month</th>
<th>F&lt;sub&gt;80&lt;/sub&gt; (um)</th>
<th>P&lt;sub&gt;80&lt;/sub&gt; (um)</th>
<th>Feed (t/h)*</th>
<th>P (kW)</th>
<th>W&lt;sub&gt;I(op)&lt;/sub&gt; (um)</th>
<th>W&lt;sub&gt;I(lab)&lt;/sub&gt; (um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aug.</td>
<td>78000</td>
<td>18000</td>
<td>1063</td>
<td>489</td>
<td>0.460</td>
<td>12</td>
</tr>
<tr>
<td>Nov.</td>
<td>72000</td>
<td>16800</td>
<td>2465</td>
<td>826</td>
<td>0.335</td>
<td>8.4</td>
</tr>
</tbody>
</table>

*Feed of the Sec.-Tertiary Crushing Circuit.

3.3. Process Control Strategy (PCS)

Samplings have showed that there is a large range of variation of feed ratio during a day: from 2,000 to 4,000t/h for example. Preventive and corrective actions have been implemented on the crushing circuit, since May 2014, trying to recover productivity and accelerate ramp-up curve. Nevertheless, until August no recovery had been noted. August was the turning point of the productivity curve. November was marked by a significant recovery. Among practical actions that were implemented since July are: 1- speed increase of the belt feeders prior to the tertiary crushers in order to maintain a full chamber and 2- verification and adjustment of CSS with maximum intervals of 6 hours. These actions were fundamental to recovery productivity.

Regarding the wear of the liners, it was observed a “coarser” size distribution of the feed of the BR3042 crusher compared to the BR3040. This difference is due to a segregation effect of the ore that occurs inside the silos. It was observed increased wear on concave of the tertiary crusher, which processed “finer” material.

4. CONCLUSIONS

Crushing and classifying efficiency, as well as, work index were calculated according to the simulation of the particle size distributions. This was made using sampling by image analysis and validating the data by linear cut-samplers on the product conveyor belt of the secondary-tertiary crushing circuit. Particle size distribution curves showed significant changes. A lower productivity resulted from a decrease in the classification efficiency while crushing efficiency of the tertiary crushers remained higher and WI lower (November). Then, although the CSS of the crushers had been
maintained inside the recommended range, it was necessary to do adjustments in order to maintain the full chamber condition and increase the productivity. The blend and blasting could be responsible for that. Therefore, it is important to continue measuring these parameters in function of the amount of compact itabirites that is increasing.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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