Influence of blasting charges and delays on the energy consumption of mechanical crushing

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Abstract

This article deals with a study performed at the Experimental Mine of the Research Center of Responsible Mining of the University of São Paulo, to examine the correlations between geological environment, blasting parameters and energy consumption in the primary crushing phase. The research is designed to appreciate the relationships between the energy provided for size reduction and the resistances to size reduction. For this purpose, Key Performance Indicators (KPIs) are used to describe the possible improvements on the energy consumption due to crushing. Four blast tests were performed: for each blast, KPIs were recorded regarding the blast design, the particle size distribution, the real power energy consumption at the primary crushing unit and its rate of utilization. The results show that energy consumption at the primary crusher is a sum of two components: energy directly involved in crushing the rock, and additional energy used for winning the inertial resistances of the moving parts of the crusher. We show how explosive energy and delay times influence the production of coarse fragments that jam the crusher, therefore influencing machinery stops and inertia loads related to putting the jaws back into movement.

keywords: Drill & Blast, fragmentation by blasting, comminution energy, crushing.

1. Introduction

Considering the comminution system as a whole (Da Gama, 1983; Da Gama and Jimeno, 1993; McCarter, 1996; Morrell, 1998; Nielsen, 1998; Bergman, 2005), every size reduction phase contributes to the final result, and this has consequences on the global energy consumption. Investigations by several researchers (Kanchibotla, 1994; Eloranta, 1995, Kojovic *et al.*, 1995, Kanchibotla *et al* 1998, Simkus and Dance 1998, Scott, 1996, Kanchibotla *et al* 1999, Kanchibotla 2000, Seccatore *et al.*, 2015a) have shown that all the processes in the "mine to mill" chain are inter-dependent and the results of the upstream mining processes, especially blast results such as fragmentation, muckpile shape and movement, have a relevant impact on crushing and grinding (Mohanty and Chung, 1990; Mancini *et al.*, 1991; Chakraborty *et al.*, 2002; Ouchterlony *et al.*, 2006; Marin *et al.*, 2015). This review focused on understanding the relationships between the energy provided for size reduction and the resistances to size reduction.

The energy sources being considered are: 1) explosive consumption (Powder Factor, P.F.); 2) distribution of the explosive energy in space (drilling mesh); 3) distribution of the explosive energy in time (initiation sequence); and 4) electric energy for mechanical comminution at the primary crusher. The inherent resistances on which the study was focused are: i) the inherent resistance of each lithological material; ii) the size of the rock fragments feeding the primary crusher; and iii) the mechanical resistance of the moving parts of the crusher (including the inertia of the jaws at the start of the equipment). Blasting has a visible effect and a hidden effect: a) it creates macro-fractures (fragmentation) that have a main role in crushing, and b) it creates micro-fractures that lead to the internal softening of individual fragments, making them easier to grind (Nielsen and Kristiansen, 1996, Katsabanis *et al*,.2003 a, 2003 b. 2004, 2006 and 2008, Workman and Eloranta, 2003 and 2009). A parallel research conducted at the same site (Seccatore *et al.*, 2015a) showed how the inherent resistance to comminution (Work Index) is reduced when the P.F. is increased. Nevertheless, this phenomenon is more evident at finer grinding phases, such as milling, and therefore its measurement was deliberately neglected for primary crushing. Further research will address this matter.

The quarry under study

The Experimental Mine of the Research Center for Responsible Mining of the University of São Paulo (NAP.Mineração), Brazil, is a quarry exploiting a dolomitic limestone by drill and blast. In the somewhat out-of-date system employed, the holes are charged with cartridged emulsion explosive and primed by detonating cord. The main blast parameters are shown in Table 1.

Hole diameter	3” – 76 mm
Spacing and burden (square array) [m]	1.5-2-2.5-3
Hole length	(Depending on the bench height)
Holes Inclination	75°
Stemming [m]	2.5
Sub drilling [m]	0-0.5

Table 1
Blast parameters.

The blast is fired by a safety fuse and a fire cap that initiate the main line of detonating cord; delays are provided by means of relays (17 and 42 ms). One electricity meter was installed in the primary crushing unit to evaluate the energy consumption due to crushing. The current system leads to several problems, such as: need of further reducing blocks before the primary crushing; dissipation of blasting energy; the rock that remains in place is often damaged; and the occurrence of bridging and stalling in the jaw crusher is not uncommon. As a result of all these drawbacks, a remarkable waste of economic resources is noticed.

Due to budget restrictions, changes must meet certain conditions: not to involve any financial investment, not to change the excavation technique, and not to interfere with the well-known practice of the operators.

2. Research method

Key Performance Indicators are a set of quantifiable measures generally used to gauge or compare performance in terms of meeting strategic and operational goals (Painesis, 2011). KPIs can vary depending on the priorities or performance criteria of a given company. The KPIs used in this research, to evaluate the possible improvements on the energy consumption due to crushing, are reported and described in Table 2.

KPI	Symbol	Unit	Meaning	Measurement method
Powder Factor	*P.F.*	*kg/m³*	the amount of explosive employed per unit of volume of blasted rock	Analysis of the Blast Plan
Passing size	*P80, P50, P20*	*mm*	the grain size under which 80% or 50% or 20% of the particle size distribution of blasted muck piles lays	Photography of the muckpile and digital image analysis via software
Specific priming	*S.P.*	*n° delays/t.*	the density of delays per unit of mass of blasted rock	Analysis of the Blast Plan
Percentage of stops	*S*	*%*	the percentage of time the primary crusher stopped its production over the total operational availability of the equipment	Chronometer measurement at the crusher

Table 2
Key Performance
Indicators employed on the research.

Attention must be paid to the last parameter: the stopping time of the primary crusher. The main reasons for stopping is the jamming of the jaw of the crusher due to oversize fragments. This event entails energy consumptions not directly related to mechanical crushing, and is thoroughly discussed below. Four full-scale blast tests were performed. The reason for the limited number of tests is due to the logistic and economic constraints related to design, performance and full-scale blast analysis within the production schedule of an operating industrial facility. For each blast, the research was developed according to the following steps: data collection related to the blasting project: bench height, stemming, burden, spacing, rock type, amount of bridging (formation of an arch) of fragments or oversized fragments that jam the jaws; the explosive used, (delay density); calculation of the volume to be blasted and the Powder Factor; collection of pictures of the muckpiles to be analyzed through image-analysis software, in order to determine the particle size distribution; evaluation of real power and calculation of energy consumption, both in a monthly period and in a daily period, by using the data measured by the electricity meter in the primary crushing unit; and plotting of the results to evaluate a correlation between the observed parameters and energy consumption. The purpose was to identify anomalous peaks and to understand why they occurred.

3. Results and discussion

The parameters evaluated are shown in Table 3. A classic trend can be noticed: increasing PF shifts to lower values of particle size. As a consequence, the energy consumption at the primary crusher decreases as P80 decreases.

Blast test	P.F.		Spacing=Burden	P80	Energy consumption
	kg/m^3	kg/t	m	mm	kWh/t
1	0.39	0.15	2.5	440	0.183
2	0.25	0.09	3	450	0.228
3	0.85	0.31	1.5	370	0.181
4	0.48	0.18	2.5	400	0.216

Table 3
Parameters evaluated for each blast test and energy consumption.

The grain size distribution curves obtained for different values of P.F. are shown in Figure 1.

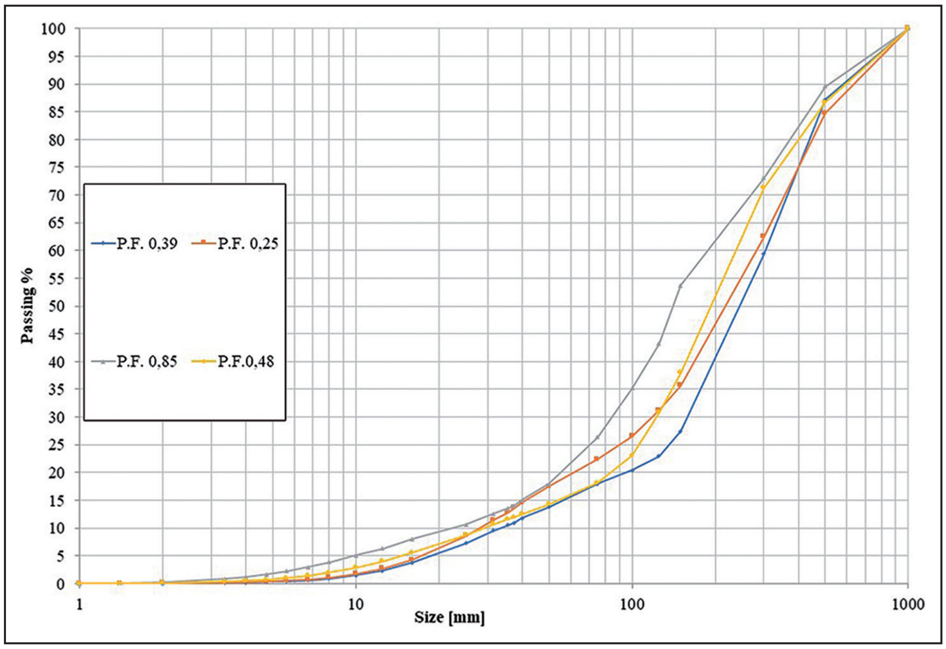

Figure 1
Particles size distribution for different values of PF.

The influence of the drilling mesh is not the same for every particle size distribution: it affects the coarser particles (P80 and P50) more than the fines (P20). The same behaviour was observed in Seccatore *et al.*, 2015a. A key aspect of this research was the evaluation of the real electric power of the engine of the primary crusher. By plotting the measured values of real power in a time domain, it was observed that: 1) higher peaks occur when bigger blocks are crushed and when the engine is turned on: this is due to starting currents, which are usually the largest recorded; 2) the minimum values of real power (different from zero) occur when the jaw crusher is not crushing, but is not turned off: this event corresponds to either an empty crusher or an event of bridging (formation of an arch of fragments blocking the fall of rock in the jaws). The two main resistences offered by the jaw demand a higher amount of current to move it: a) mechannical resistance, when bigger blocks enter the crusher and b)Inertial resistance, when the engine is turned on after a stop and must overcome the inertia of the stopped jaw. Both these events consequently cause higher values of real power. Since real power and energy consumption are related by the equation: $E(t)=\int P(t)\partial t$ or, in discrete terms: $E(t)=\sum^{n}_{i=0} Pi\,(t)\cdot\Delta t_i$ it is clear that a higher value of power leads to a higher energy consumption. As for mechanical resistance, as shown in Table 1, energy consumption increases with P80; during the primary crushing phase, it can be reduced by increasing P.F. As for inertial resistance, it frequently happens that big blocks get stuck between the jaws: in this case the crusher must be stopped, and some time will be needed for operators to reduce the block by jackhammer or remove it from the jaws. As shown in Figure 2, the greater the average block dimension, the higher the frequency of stops (percentage). The stops percentage heavily affects the total energy consumption, also due to the contribution of inertia loads at the motors (Figure 3).

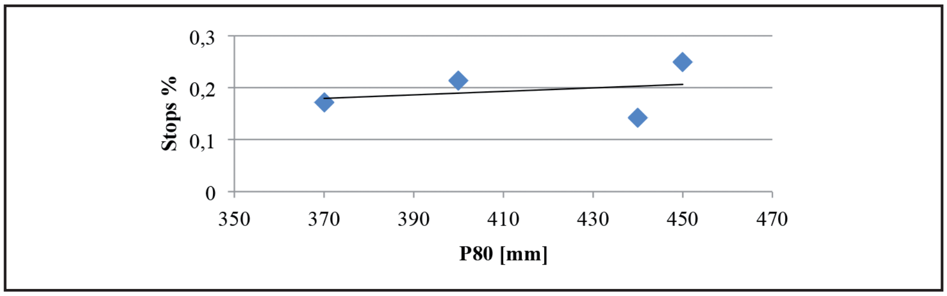

Figure 2
Correlation between stop percentage and P80.

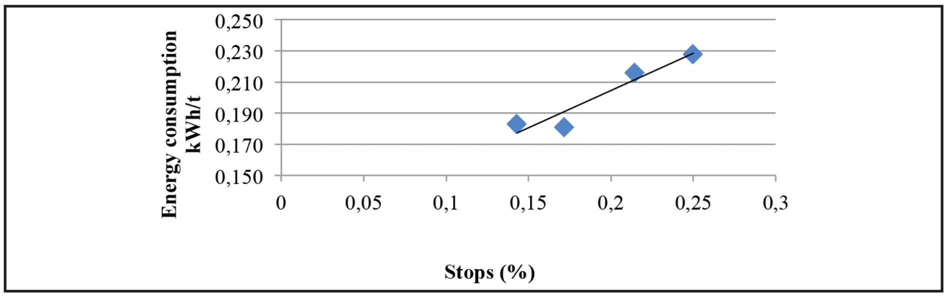

Figure 3
Energy consumption is affected by stop's percentage.

This cost can be reduced by putting either a soft starter or, better, a frequency inverter; alteratively, slowing equipment down instead of turning it on and off. A careful design of transport cycles, and projecting blasts in such a way to obtain blocks having suitable size for crushing, can reduce the effects of inertia loads on energy consumption. Other considerations arise from observing the delay patterns, as shown in the examples of Figure 4 and Figure 5: blasts are designed so that two holes detonate simultaneously.

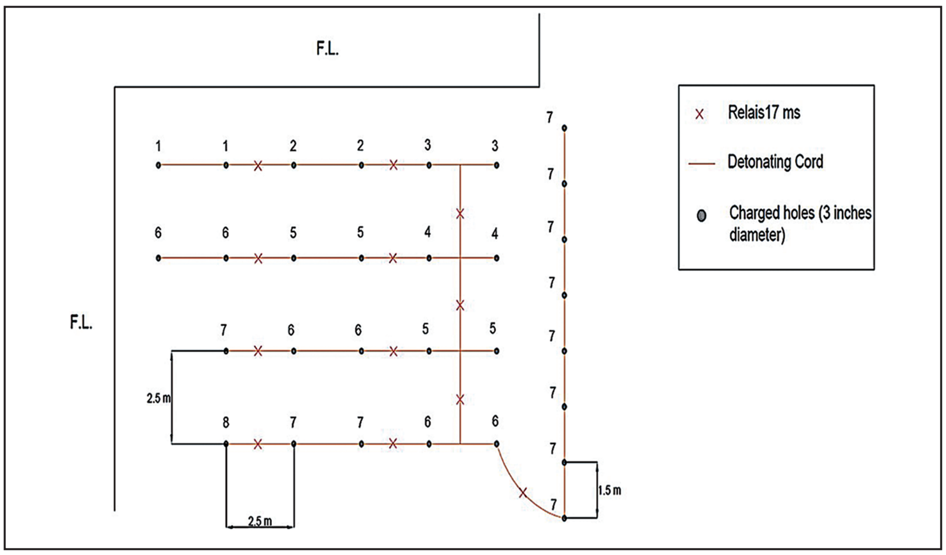

Figure 4
Blast test n.1. Numbers indicate sequence.

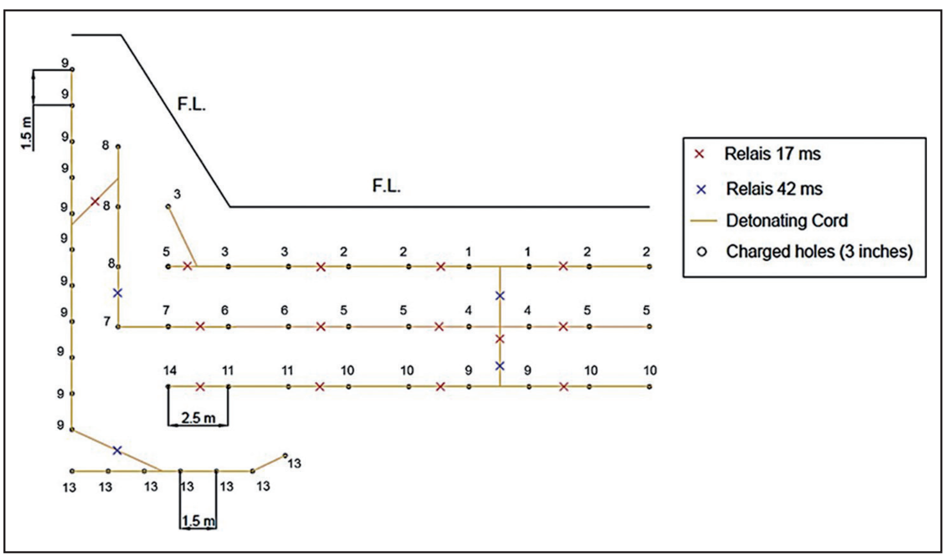

Figure 5
Blast test n.4. Numbers indicate sequence.

To obtain the best result in fragmentation by Drill and Blast, the simultaneous detonation of two blastholes should be avoided, to induce the explosive to work along the burden instead of working along the spacing (Cardu *et al.*, 2015 a and b). In this research, the Specific Priming (S.P., n. delays/t) was compared with the percentage of stops in production (in terms of cost that stops involve) and particle size distribution. It is evident how timing in the initiation sequence influences fragmentation and comminution energy: a 30% increase in S.P. results in finer fragmentation with 15% reduction of P80; Figure 6 shows that the same increase in S.P. results in 17% reduction on stop percentage.

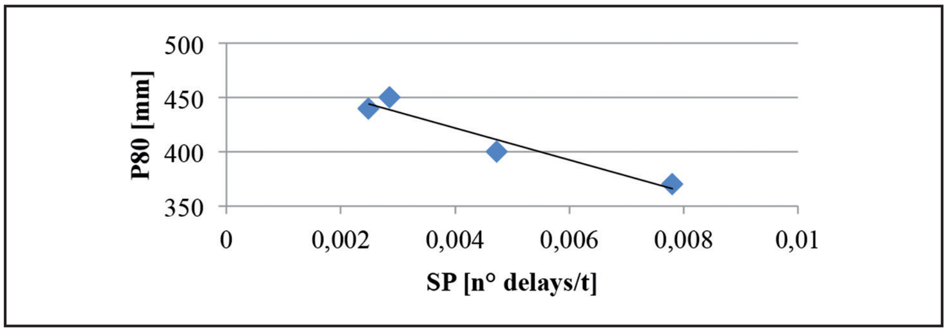

Figure 6
P80 decreases with the number of delays/t increases.

The effects of timing on fragmentation have not been extensively studied for a long time, but have gained much importance in the last 30 years, and many researches address this aspect (Stagg, 1987; Sastry and Chandar, 2004; Katsabanis *et al.*, 2006; Katsabanis *et al.*, 2008; Kim, 2010; Cardu *et al.* 2015a and b; Seccatore *et al.* 2015b; Schimek *et al.*, 2015). The result of the previous and current studies shows that the influence of the detonation sequence on fragmentation results deserves greater research effort. Based on the average electricity cost in Brazil, the lower energy consumption and the consequent saving income obtainable by increasing PF and SP can be evaluated. For this analysiss, three situations were studied: 1) Scenario 1: the current situation; 2) Scenario 2: The situation obtainable merely considering the reduction of particle size; and 3) Scenario 3: The situation obtainable considering both the reduction of particle size and the reduction of engine's stops. Without considering the savings achievable by avoiding stops in production, passing from the situation with the lower P.F. to the higher P.F., the saving achievable is around 20% (Figure 7). By also considering the savings obtainable by reducing stops in production, passing from the situation with the lower P.F. (in the current situation) to the higher P.F., in the hypothesis of reducing stops in production, the energy savings can reach 34%.

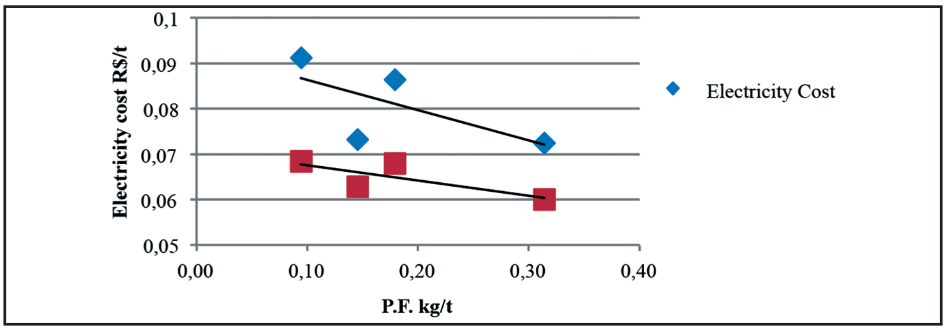

Figure 7
Electricity cost decreases while P.F. increases.

By increasing S.P., a reduction in electricity cost (Figure 8) and a further reduction of stops in production can be reached: passing from the worst blast result of Scenario 1 to the best result in Scenario 3, a 41% reduction of cost is achievable.

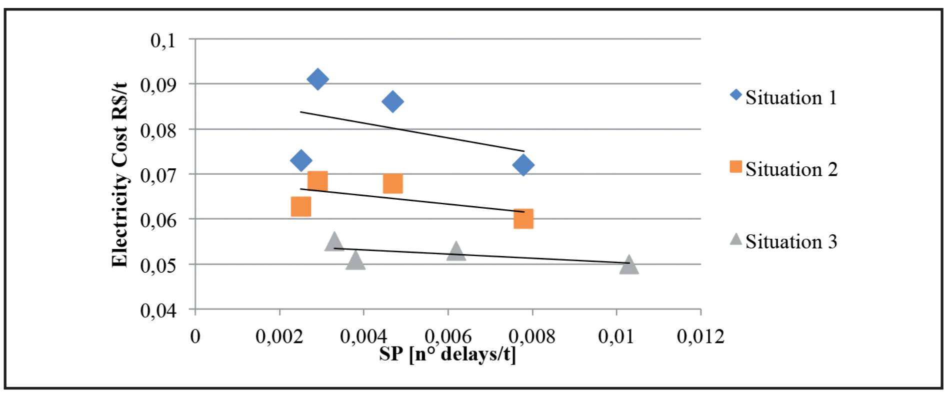

Figure 8
Electricity cost decreases with the number of delays/t.

Figure 9 shows the variation of total costs (electricity cost and delays cost), in R$/t, in the hypothesis of keeping all the blast parameters equal and incrementing S.P. In terms of total cost (electricity and delays), all blast parameters being equal, an average 18% cost reduction is obtainable while incrementing the delay's density.

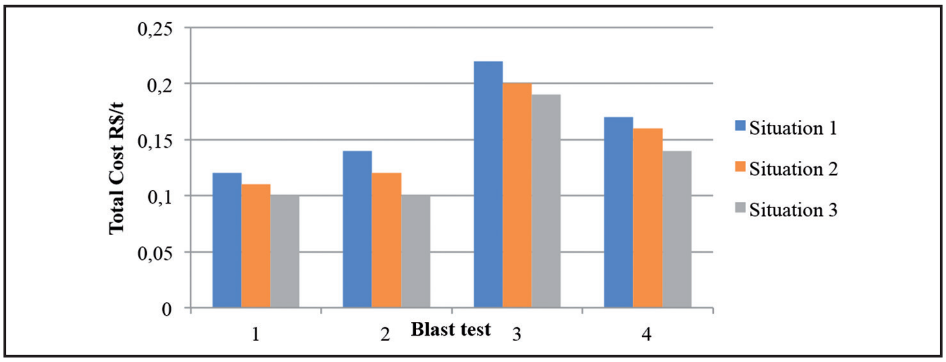

Figure 9
All other things being equal, an increase in delays density can lead to a reduction of costs.

4. Conclusions

Many studies have been conducted in the past to define and understand how to reduce the unit cost of each phase of the mine to mill chain. The phase that requires the majority of energy consumption is grinding, but optimization can be achieved with innovations and improvements in each previous phase. In this framework, this research aimed to understand the relationships between the energy provided for size reduction and the resistances to size reduction. This research led to the understanding that energy consumption at the primary crusher is not only related to mechanical resistance needed to crush the blocks, but to a sum of two components: a) energy used for mechanical crushing, and b) energy used for winning the inertial resistances. Both energy components depend on the particle size distribution of the muckpile: i) energy consumption increases (as expected) with P80 of the blasted material, and also: ii) energy consumption is higher when stops in production are higher. The coarser the particle size of the feeding material, the higher the frequency of stops. Also, timing and initiation sequence play an important role in cost optimization. In this research, the density of delays (n° delays/t) was shown to reduce the size of blasted fragments, the percentage of stops in production, and the total energy consumption. All other parameters being equal, an increase in the delay's density can lead to a reduction of costs.

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