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EXPERIENCES FROM EXPERIMENTAL MINING IN BRAZIL

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ABSTRACT

The Experimental Mine (EM) of the Research Center of Responsible Mining of the University of São Paulo became the subject of investigation in a few years after its development; it is an open-pit quarry currently exploiting marble and gneiss, used to produce industrial limestone and construction aggregates. It is a developing enterprise, dealing with the challenges of a technological upgrade from a small-scale operation to the characteristics of a medium-sized company. The Experimental Mine Project (EMP) was born to attend a double demand: to provide research and development (R&D) support to a growing company and to provide experimental opportunity for a field of knowledge such as mining engineering that requires a large scale for its experiments.

The main challenges of the EMP are related with the remaining small-scale mining features, such as large variety of equipment available, high level of operational flexibility, scarcity or absence of mine planning, being focused on daily operations. In such an environment, the first role of the EMP was to evaluate in a quantitative way the effects of unit operations over the whole mining process.

The current excavation technique is by drilling and blasting. Many experimental campaigns have been conducted on site, with different purposes. One of the main research lines was to increase the productivity of the quarry by lowering production costs and improving the quality of the product, then optimizing the entire production cycle; the relationship between the unit costs of drilling and explosives were evaluated, as well as the link between the blast design and some factors affecting the downstream processing of the product.

The paper describes the methods employed to conduct the research and the improvements to be pursued, with the due consideration to the influence and interference of the many parameters involved, from the rock-mass characteristics to the final products.

KEYWORDS

Blast design, rock fragmentation, downstream processing, damage control, comminution energy

INTRODUCTION

In designing a blast, the geometry is a very important factor, but also the amount and type of explosive and the timing sequence play an important role. Everything should be established in view of the desired effect, and containing, as much as possible, the side effects (Mancini & Cardu, 2001). Drill and blast is an important step in this process and the results such as fragmentation, muck-pile shape and looseness, dilution, damage and rock softening affect the efficiency of downstream processes (Richard et al., 1982; Roy & Singh, 1998; Konya & Walter, 1990; Oriard, 2005). The importance of blasting to downstream processes has been studied and discussed by many researchers. Nielsen and Kristiansen (1996) investigated the effect of blasting on crushing and grinding operations and discussed how to evaluate the application of the comminution system. They pointed out that the gap between mining and mineral processing should be harmonized, and suggested that blasting could be considered as the first step of the integrated comminution process for the optimization of the mine operations. Size reduction represents one of the most energy-intensive and costly processes in the excavation of rocks. Drill and Blast, being the first operation in the size reduction chain, may have a significant downstream effect (Kim, 2010). One of the goal of the research conducted at EM under this aspect was to examine the effect of different timing sequences on fragmentation, although the subject has been extensively treated in many aspects (Katsabanis et al., 2006; Kim, 2010; Stagg, 1987). In the same way, it is quite common for quarry operators to be concerned with fragmentation when difficulties in drilling and loading are encountered, or when a large amount of oversize is produced, resulting in a general loss of productivity in secondary blasting: this was the problem encountered at the quarry site under study and, on this basis, a number of experimental blasts were performed and the blasting size reduction effect was recognized, as shown below.

The influence of the blasting activity on the grindability of the basted material has been thoroughly researched in recent years. Nowadays it is widely accepted that blasting produces two effects on the broken rock: it induces visible fracturing, that is measurable by means of image analysis or sieving and, at the same time, induces invisible fracturing, which means a system of micro-fractures, invisible at the naked eye, that are detectable only by microscope analysis but show their direct effect by decreasing the grinding energy to reduce the material to a desired particle size distribution; it can be said that this effect "softens" the material.

The downstream effects of the first aspect are widely researched and discussed (Mackenzie 1967; Clerici et al., 1974; Scott, 1996; Božic, 1998; Sastry & Chandar, 2004; Morin and Ficarazzo, 2006; Mansfield & Schoeman, 2010; Seccatore et al., 2011; Cardu et al., 2012; Dompieri et al., 2012). Rather precise models have been developed over the years to achieve a good prediction of the output of the blast in terms of particle size distribution, such as the widely-used KUZ-RAM (Cunningham, 1983, 2005) and the SWEBREC (Ouchterlony et al, 2006) among other studies. Nielsen and Kristiansen (1996) pioneered the research on the latter subject, showing that increases in P.F. lead to higher presence of micro-fractures in the material, therefore achieving significant reductions in Bond Work Index (WI, Bond 1961). Workman and Eloranta (2003) quote Nielsen and Kristiansen's data (sedimentary iron ore - taconite - as an experimental material), and show the comparison between WI of the blasted material (WIB) with the one of the intact rock (WIR), leading up to -74% in the WIB with a P.F. = 0,42 kg/m^3. Katsabanis et al (2008) obtained similar but less incisive results in different granite formations: P.F. = 1,15 kg/m^3 led to the maximum reduction of WIB of -11% compared to WIR. Workman and Eloranta (2003) point out that, since mill feed is relatively small (usually smaller than 19mm (3/4"), the fractures that survive at this size must have at a microscopical level an effect on the WIB. On the other end, Katsabanis et al. (2004) discuss the limits of the influence of blasting on grinding efficiency. From what previously reviewed, it is evident that the effects of micro-cracking highly depend on the lithotype. Workman and Eloranta (2009) discussed the different ways to achieve higher P.F. for the benefits of grinding: this can be done by increasing the amount of explosive per hole or by changing burden and spacing, that is to say varying the distribution of charges. Nonetheless, Eloranta's considerations on this subject remained theoretical and based on an economical point of view. In the present work, the influence of different geometrical distribution of the charges on the grindability of the blasted material was then investigated empirically.

Moreover, It is a well-known fact that the performance of blasting has a significant effect on loading, secondary breakage and crushing, as established by numerous studies (Cheatham, 1968; Chi et al., 1996; Michaux and Djordjevic, 2005; Kanchibotla et al., 1999; Nielsen and Lownds, 1997; Kojovic, 2005; Nielsen and Kristiansen, 1996; Workman and Eloranta, 2003 and 2009; Roy & Singh, 1998; Konya & Walter, 1990; Oriard, 2005). Nonetheless, these researches have been carried out in major mining operations, in both metallic and non-metallic ores, in situations where there was a proper control of all the factors involved, from drilling to crushing. All the proper controls led to refined fragment size distribution prognosis models, such as the most recent Swebrecf unction (Ouchterlony, 2005). The present research takes a look at a completely different situation, such as a small mining operation in Brazil. Mining operations such as the small-scale situation analysed here should not be confused with what is defined in literature as "Artisanal and small-scale mining" (Seccatore et al., 2015): the definition here adopted merely refers to the scale of production, that encompasses ventures that produce between 10 and 100 mtpa, but still are considered industrial operations, in the Brazilian context. Such small mines are characterized by a large variety of equipment availability and a high level of operational flexibility. Therefore in this context, mine planning is usually scarce or absent, and mine management generally focuses on daily operations. Therefore, the analysis of the effects of unit operations, such as blasting, over the whole mining process is often neglected. To overcome these aspects, the research was focused to propose answers to the following questions: the dependence of the performance of drill and blast on the loading, secondary breaking and crushing time in a small-scale limestone quarry; the way to properly analyze the operations in a small-scale quarry, considering the restrictions due to the scale and the constrains of costs.

THE EXPERIMENTAL MINE

The Experimental Mine of the Research Center for Responsible Mining of the University of São Paulo, Brazil, is a quarry, located at the city of Taubaté, Brazil, exploiting dolomitic limestone for acting as acidity buffer for agricultural soil or as an aggregate for civil construction. It is a small operation, that faced constraints due to old methods that were considered the regular operation procedure before the beginning of the Experimental Mine Project. At present, since the start of the project, there have been great changes in the regular practices as well as the continuity of the modernization of the equipment used.

The goal of the research is to depict a way to improve the rational use of the explosive energy for the benefits of the quarrying process. An extensive literature review shows how a good fragmentation by blasting favourably influences the profitability of the whole mining process. Many methods allowing prediction and estimation of the fragmentation are available: if carefully and reasonably used, they can be very helpful to obtain an optimal fragment distribution which lowers the total cost of the whole production process and not only that of drill and blast. The quarry operates with two different crushing systems, one for the aggregate and another for the acidity buffer. The reason for this is due to the lower specification standards that the aggregate has on the market. While the aggregate goes through a primary- and a secondary crusher only, the limestone for use as an acidity buffer must go through a cycle of grinding and milling in order to achieve the particle size distribution for industrial standards.

GEOLOGY OF THE BASIN

The area under study is inserted into the *Terreno Embu*, which includes the Central Segment of the *Mantiqueira Province* (Heilbron et al, 2004), called *Ribeira Belt*, which origin is Neoproterozoic/Cambrian. The region is divided into five tectono-stratigraphic areas (Howell, 1989) separated by thrust faults, sometimes by oblique shear zones (Heilbron et al, 2004). The complex corresponds to the *Embu* meta-sedimentary structures (Hasui, 1975), and constitutes the *Açungui Group*. Meira (2014) identified maximum ages of sedimentation through the dating of zircon grains, very old: Paleo-proterozoic and Meso-proterozoic. The lithological associations were divided into three stratigraphic units (Fernandes, 1991): the *Rio Una* Unit, superior and dominated by mica-schists and quartzites; *Rio Paraibuna Unit*, dominated by quartzite and silicates, with intercalated biotite gneisses and amphibolites; and *Redemption Serra Unit*, composed of gneiss, amphibolites, and marbles (Heilbron et al, 2004). The main metamorphic *Embu* complex is in the region of sillimanite-muscovite, locally reaching the sillimanite-K-feldspar zone (Vlach, 2001), and relates to the first two of the five phases of deformation affecting the *Embu Complex*. The first phase of deformation was observed only in relict structures associated with high temperature parageneses. The second deformation phase generated the main foliation folds and small recumbent folds, and is associated to a quite intense mineral lineation (Heilbron et al, 2004). The third deformation phase is related to reverse and tight bends. The fifth phase is delayed and transversal to the NE orientation. The shear zones bordering the ground are milonitic and vertical, and control the placement of granites (Janasi et al, 2003). Meira (2014) identified bimodality of metamorphic ages of *Embu Complex*, between 650-600 My and 600-560 My, and the metamorphism occurred in the first indicative range of metasedimentary successions at depths of up to 25 km, reaching amphibolite facies. The newest metamorphism is characterized by an almost isobaric decompression up to about 10 km deep, at temperatures between 550-600° C. The large shear zones mark the third phase of deformation (mylonitic foliation).

The rock at the quarry is exploited along an elongated strip according to NE-SW direction, and was mapped by Orcioli (2010), who identified four main rock types: dolomitic marble; biotitic gneiss, commonly milonitic; amphibolite, which occurs between marble and biotitic gneiss and granite, intrusive in metasedimentary units (Figure 1). According to the author, the sequence shows a structure that is cut by a thrust fault in direction WNW-ESE, in the central portion of the polygon of the quarry.

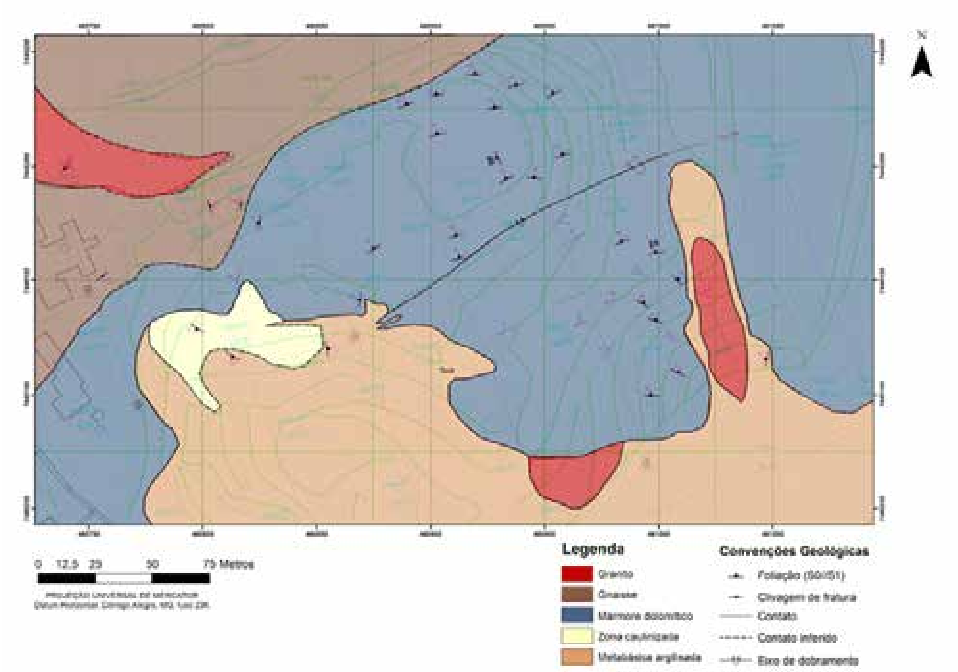

Figure 1. Geologic map of the quarry following Orcioli, 2010 (unpublished-internal report).

In the area under study several experimental campaigns have been carried out for the geotechnical characterization of the material; four structural domains were detected and, through the *Dips* software, fracture families for each domain were investigated. The frequency of fractures for each lithotype was determined on field, and used for the calculation of the J_v index. The geomechanical characterization of the rock mass was based on data acquired from experimental investigation. Particular emphasis was given to the differences between the various rock types, by association of the geotechnical parameters to the structural features, textural and mineralogical characteristics of the rock types. The results showed that the rock mass has, in general, good features, with values of RQD preferentially high: from 50 m depth under the ground level, there are no significant intervals with values less than 50 (average values being from 69 and 100).

DRILL AND BLAST OPERATIONS

Drilling was performed until the third quarter of 2014 using light pneumatic crawl mounted rigs, quite out-dated. This equipment was later changed for more modern models of crawl mounted rigs by a local manufacturer. In both equipment's the drilling operation is controlled manually by the operator. The borders of the drilling area are determined by means of optical topography; then, the locations of the holes collars are determined with pre-dimensioned wooden rods and marked on the ground using small boulders found on site. The blasting process involves charging the holes with 50.8 mm cartridges of explosive emulsion, primed by a strand of detonating cord along the hole, leaving an upper stemming of about 2 m. The stemming is done using a mixture of two gravels coming from two of the quarry's product piles, without the particulate generated by the drilling operation. The blast is fired by safety fuse and a fire cap that initiate the main line of detonating cord; delays are provided by means of relays (17 ms series). The standard deviation presented on the delay time around the nominal delay is quite large, due to the quality of the manufacturing process of blasting products, as well as the issues that arise from pyrotechnical delays, provided by local suppliers. The typical blast parameters are given in Table 1.

The situation presented at the beginning of the research showed no proper control of drilling, no proper attention payed to the firing sequence and distribution of the relays amongst the holes, and issues with the geometry presented on the blast. This situation proved to be ideal to analyse a typical low efficiency operational condition.

During the implementation of the project, the researchers have been able to change the habitual practices, introducing the following improvements:

1. Drilling is supervised in order to grant correct collar positioning, inclination and use of torque and thrust feed;
2. Charging is adjusted to the bench conditions, leaving intermediate stemming to reduce linear charging according to the drill speed rate encountered and to the presence of depressions or indents on the bench face;

Table 1. Typical Blast parameters.

Parameter	Symbol	Unit	Value
Hole diameter	ϕ	mm	63,5
Spacing	S	m	2
Burden	B	m	2
Blasthole length	Hdl_{bh}	m	6 to 9 m
Sub-drilling length	l_{sub}	m	0,5
Hole inclination	α	°	75
Stemming length	l_s	m	2
Specific Charge	q	kg/m^3	0,40 to 0,47 kg/m^3

3. The point of initiation of the firing sequence must take maximum advantage of the free surfaces to favour the movement of the blasted material;
4. Simultaneous holes in the firing sequence (due to linear combination of 17 ms relays) must be located as far away as possible, to avoid undesired cooperation of charges that may induce the explosive energy to work with shear effect instead of producing fragmentation.

THE INFLUENCE OF CHARGE DISTRIBUTION ON TH ECOMMINUTION ENERGY

Small-scale blasts have been performed on 14 marble blocks with different Powder Factors (PF) and charge distributions. For every PF, charges have been designed to simulate concentrated and distributed geometries. In particular:

- Holes were drilled with Ø = 6 mm (diameter), L = 60 mm (hole depth);
- Each hole was charged with a strand of detonating cord with linear charge of 10 g/m, achieving a 6g charge per hole;
- To each block has been assigned a desired theoretical PF (PF_{th}). Adjusting the number of holes per block allowed to achieve a PF (PF_{real}) as close as possible to PF_{th}; adjusting the geometry of the holes allowed to simulate different charge distributions.

Two charge distributions were simulated as follows:

a. Concentrated charges simulate open-cast blasts with large-diameter holes, with large burden and spacing.

b. Distributed charges simulate bench blasts with small-diameter holes and reduced burden and spacing. Examples are shown in Figure 2. Three control blocks have been fragmented by mechanical means for comparison of the results. All blast tests took place on field due to safety reasons.

The blasted material was then analysed considering the particle size distribution and the Work Index WI. Results obtained suggest that:

1. Concentrated charges lead to a particle size distribution closer to the "dust-and-boulders behaviour". Distributed charges lead to a more uniform particle size distribution;

2. When increasing the specific charge, distributed charges lead to a greater reduction in particle size than concentrated charges.

3. Material blasted with distributed charges presents a steeper decrease of WI at the increasing of the specific charge.

Small charges with a distributed geometry transmit more uniformly the explosive energy to the rock, leading to better fragmentation and higher induction of micro-fractures. This reduces the total comminution energy necessary to grind the blasted material to the desired particle size. Looking at the application on field, these results suggest that for any given powder factor, choosing to reduce the drilling diameters and increasing the specific drilling will benefit the comminution circuit.

TESTS WITH NON-COAXIAL CHARGES FOR CONTOUR BLASTING

Contour blasting is commonly performed by employing linear charges, decoupled from the boreholes. To achieve the best results in terms of rock breakage and respect of the excavation profile, blasting theory suggests that charges should be inserted coaxial to the holes to grant uniform distribution of the explosive energy and therefore obtaining a uniform Radius of Damage. Nonetheless, non-coaxial charges are often employed in blasting practice. Non-coaxial charging methods include the employ of high-power detonating cord (40 to 100 g/m), low-power detonating cord connecting small-diameter cartridges (commonly 10 g/m detonating cord priming 1" cartridges) or string loading (a thin layer of bulk emulsion pumped with controlled flow and controlled extraction of the injecting rod). This research was focused on evaluating the effects of the first two charging methods on the quality of final walls. Different drilling geometries and charging configurations were applied (Figure 3).

Figure 2. Left: Example of a block with drilling set out to simulate concentrated charges for PF_{th} = 0,3 kg/m^3; right: Example of a block with drilling set out to simulate distributed charges for $P_{\cdot th}$ = 0,3 kg/m^3.

On the other hand, when the rock is poor, any quality of the final wall is hardly achieved at all, in spite of any care in the details of execution of smooth blasting (Figure 4). It is concluded that any design criterion and theoretical approach modelling the effects of contour blasting cannot ignore the features of the rock mass.

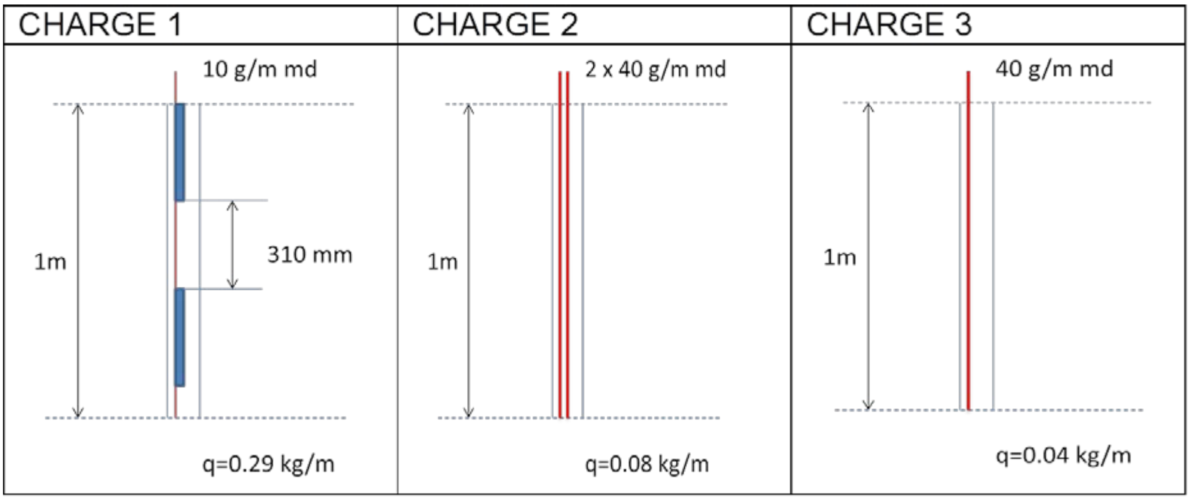

Figure 3. Details on loading adopted for experimental blasts1, 2 and 3.

The Half-Cast Factor (HCF), the Over-break (OB) and the Under-Break (UB) were evaluated as control indicators. Rock Quality Designation (RQD) and Rock Mass Rating (RMR) were used to classify the rock mass. The research was aimed to push contour blasts to their limits, observing for which geometry and charge configuration the blast lost its design threshold with respect to the final wall for every given rock mass. Results show the operational limits of non-coaxial charges: in good-quality rock, smooth blasting with decoupled linear charge of 40 g/m can be extended to a spacing S = 22Øf with little or no detectable drawbacks in terms of final wall quality, in contrast with theoretical formulae for the determination of the radius of damage.

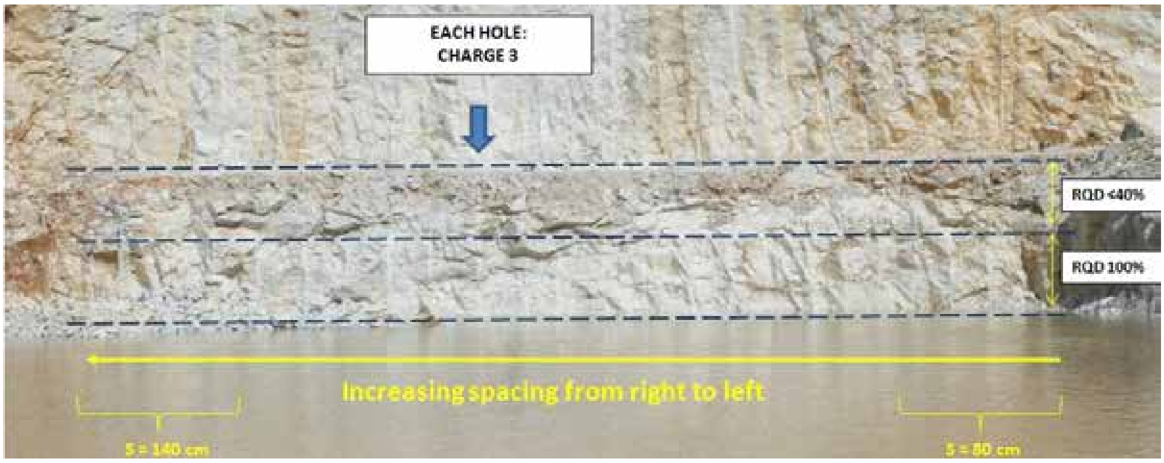

Figure 4. Results of a blast, which was performed by progressively increasing the spacing between the holes. It can be observed that HCF=100% for every spacing in RQD=100% and HCF=0 in RQD<40%.

KEY PERFORMANCE INDICATORS (KPIs) TO EVALUATE THE INFLUENCE OF THE DETONATION SEQUENCE IN ROCK FRAGMENTATION

To monitor any changes that a modification of PF, blasting pattern or timing can cause to the downstream process, some Key Performance Indicators (KPIs) were chosen. They possess the common characteristics of being representative and simple to obtain on field: the objective is to create a database that can provide some valid correlations between different factors, and this is possible only if the operators can get in autonomy and simplicity these values. The KPIs selected are listed, defined and described in Table 2. Changes had to be gradually introduced for practical and economic reasons. Only few blast tests were completely designed and performed according to the new blasting method. The project involved a delay between each blast-hole; moreover, relays delayed by 42ms have been used for the first time, so as to increase the time difference between the ignition of the blast-holes of a row and those of the next.

The measured parameters showed good results: homogeneous muck-pile, with a low percentage of fines and a reduced volume of blocks whose size requires secondary breaking; good quality of the final wall, with acceptable values of HCF and B_b; absence of fly-rock; the high cost caused by a high number of delay units was compensated by a reduction in the cost of drilling, thanks to the increase of spacing that has allowed realizing fewer holes to cover the entire surface to drill. As an example, some details of a blast (the last of the experimental campaign) are shown in Figure 5.

Considering the results obtained, it can be noticed that:

- The shape of the muck-pile S_m improved significantly over time: this has the strong advantage of increasing the productivity of the loader, reducing the idle time that consisted in gather the material spread away from the pile;
- The back-break B_b is strongly reduced. Thanks to a lower loading/hole, and to a different timing, it was possible to obtain a better precision of the residual wall;

- The evaluation of the parameter S_b is obtained by the work of the hydraulic hammer, that is greatly reduced. Despite some blast were made in an area where the rock was particularly strong, a better dimensioning of both the charging and timing of the blast has led to a better quality of the product. By comparing the performance of S_b with the PF employed in the examined blasts, it can be noticed that to a greater amount of explosive/m^3 does not necessarily correspond a greater fragmentation;
- The accuracy of the result obtained as the regularity of the residual wall is concerned is greatly increased, giving rise to a very high HCF;
- As it can be seen on the performance of F_y, fly-rock is completely absent in the last two blasts. This results in increased safety and reduced projections of material away from the pile.

Table 2. KPIs selected for the research

KPI	Symbol	Unit	Definition	Reason for Choice
Shape of the Muckpile	S_M	-	It is the dimensionless ratio of the spread length of the muckpile, normalized with the length of the blasthole before blasting.	This value gives a realistic idea of the expected productivity in phase of mucking and loading due to the easiness of operations of the loaders on the restricted quarry floors.
Backbreak	B_b	*M*	It is the average value of retreat of the bench edge with respect to the alignment of the contour holes. In the case analyzed, it was calculated every 2m, which were measured along the contour of the quarry boundary.	Back-break can generate various problems, whether due to stratification of the rock, or to design errors. To assess this factor, some changes were attempted such as modifying the charge distribution along the blast-holes and varying the blasting sequence, relying on the constant arrangement of the layers.
Specific incidence of secondary breaking	S_b	h/m^3	It is the time of work of the hydraulic hammer employed for secondary breaking, normalized to the volume of the bench before blasting. The operator of the hummer, after a short training, can take this value autonomously.	The good or bad outcome of a blast in terms of particle size can be evaluated according to how many hours the hydraulic hammer has worked on a muck-pile to reduce oversize blocks below the threshold size value.
Half-Cast Factor	*HCF*	*%*	Dimensionless ratio or the percentage between the total length of half-casts observable on the wall remaining after the blast and the total length of contour holes drilled and blasted. It can be taken as an indicator of severe (HCF null), moderate (HCF medium) or low (high HCF) mechanical damage of the residual wall.	HCF is an indirect indicator of the damage induced by contour blast-holes. Good guidance of the fracture occurs only if the pressure in the holes does not greatly exceed the minimum necessary to obtain the detachment;
Flyrock	F_y	*M*	Flyrock was defined as the distance of loose fragments encountered outside of the shaped muckpile.	It is an important indicator of safety, as well as another indicator of the effective energy use, since a thrown fragment is a sign of energy wasted in ballistic rather than in fragmentation.
Cost of the Blast	*C*	$Cost/m^3$	The cost analysis includes: · explosives: cost/kg of emulsion; · drilling: cost/drilled meter; · secondary breaking: cost/liter of fuel (hydraulic hammer); · fine to be separated before going to the primary crusher: cost/liter of fuel consumed along the deviation path to the sieving plant.	The last two factors were considered as representative of the first consequences of the outcome of the blast. The costs were referred to the bench volume (cost/m^3), and reported as unitary costs. For confidentiality, costs have been normalized to the cost of the first blast analyzed, taken as C=1; the costs of the other blasts are reported proportionally.

Figure 5. General view of the bench before (left) and after (right) the blast. The free surface, being left by the previous blast, dimensioned according to the proposed method, is smooth and slightly damaged. The muck-pile generated by the blast has a suitable geometry.

THE EFFECT OF DRILL AND BLAST PERFORMANCE ON TIME OF LOADING, SECONDARY BREAKAGE AND CRUSHING

The quarry under study uses three 25 t trucks for the transport of the material, and one excavator for mucking, hauling and dumping into the truck. In order to properly measure all the events, cycle times were recorded by using a stopwatch from a safe point of observation of the whole pit and the primary crusher (Figure 6). Data were recorded on specific sheets for each truck, allowing a single staff member to properly monitor all the operations relevant to this research.

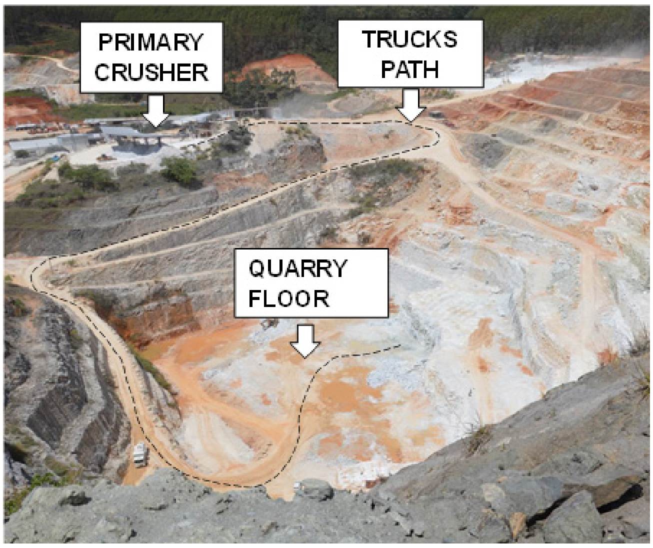

Figure 6. Overview of the quarry from the measuring point.

An analysis of cycle times was performed, considering different scenarios that contemplate different qualities of blasting performance. The quality of the performance is associated to the adherence to good practices of drilling and blasting execution, as supervised by the project team on site. It was evaluated the effect of poor blasting performance on the downstream process, quantified by the loss in terms of operational time when compared to regular or outstanding blasting performance.

The results show how the events that slow the cycle down happen on an irregular basis. From a managerial point of view, this creates a bias for decision-making: were the negative events are a regular issue, this would necessarily lead to a correction and a review of the adopted practices. Since the occurrence of deviating events is scattered along time and does not follow a regular sequence, delaying events are not perceived and therefore neglected. The better blasting practices introduced allowed for smaller and more evenly distributed cycle times, and reduced by an order of magnitude the usage of secondary breaking equipment.

The results led to state that the effects on the downstream process of small-scale operations are visible in the statistical analysis of cycle times. So far, it was achieved a proper indicator that allows to infer the issues that arises from improper blasting practices: the standard deviation of cycle times distribution. The analysis of the standard deviation measured in the distribution of cycle times show that, when exposed to material coming from poor blasting, the primary crusher is randomly fed with oversize material, leading to delays that have unpredictable consequences on the work cycle as a whole.

The main consequence observed are truck lines. Also, that cycle times associated to poor blasting practices are more irregular and unpredictable; cycle times associated to standard blasting practices lead to more uniform flows of operation in the cycle as a whole.

This work is important because it discusses the impact of such operational losses on an industrial environment characterized by high operational flexibility and lack of planning. Solutions are suggested and evaluated for the improvement of the small-scale mining process by Research Center for Responsible Mining team.

CONCLUSIONS

The Experimental Mine provides wide scenery about future tests and research, as characterized by a relatively simple organization of blasts and control of downstream conditions. Regarding the blast initiation, the organization of the circuit with detonating cord leads to various drawbacks. In particular, the risk of severing the circuit is common and is essential to avoid cross connection lines. The goal for the medium term is the shift towards shock-tube or electronic systems. This would allow the chance to experience various combinations of delay times. Another goal is to continue the recording of the drilling speed, in order to create a three-dimensional map of variation of geomechanical strength along the whole quarry. The influence of timing, within the possibilities offered by detonating cord, was examined in this study. As far as fragmentation and the importance of timing are concerned, results indicates that timing, leading to stress wave interaction, is important. Therefore, selection of delay timing can be of significant benefit to downstream processes as well as enhanced fragmentation itself. Blasting is an application of energy and energy distribution. Powder factor, distribution of charges and timing affect the outcome as a complex system. The work needs to be further improved by additional experiments, also with the aim of assessing the mutual influence between some important parameters, such as examining how blasting results are affected by the rock mechanics properties and the effects of charge distribution and initiation timing on the breakage.

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