Influence of blasting charge distribution on the energy required for communition of rock

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Abstract

The most energy-intensive process in the mining industry is particle size reduction – comminution. The first phase of this process is blasting to fragment the rock from the initial Boussinesq's half-space size. Scientific literature demonstrates that the output of a blast in terms of fragment size distribution can be manipulated by varying the specific charge (powder factor) and charge distribution. This study focuses on the influence of blasting on the internal resistance of the blasted fragments; in particular the influence of the spatial distribution of charges. Small-scale blasts were performed on 14 marble blocks using different powder factors and charge distributions. Three control blocks were fragmented by mechanical means for comparison. The results show the correlations between charge distributions and the specific energy of mechanical comminution. Opportunities for adjusting charge diameter and distribution in opencast blasts to improve the performancet of comminution circuits are discussed.

Keywords

blasting, powder factor, fragmentation, comminution

Introduction

This study addresses the pre-conditioning of rock for comminution by blasting, and how different spatial distributions of the blasting charges affect fragmentation for the same specific charge. When explosive charges detonate, they produce two effects:

1. They fragment the rock at a macroscopic scale: this is measurable by means of image analysis or sieving.
2. They weaken the rock at a microscopic scale: the result is a system of microfractures within the grains in the blasted fragments, detectable only by microscope analysis. Nevertheless, the presence and extension of these microfractures can be measured by analysing the grindability, e.g. by establishing the Work Index (WI) in a ball mill.

Rock fragmentation at the macroscopic scale as been widely studied and published (Mackenzie, 1967; Clerici et al., 1974; Scott, 1996l Bozic, 1998; Sastry and Chandar, 2004; Morin and Ficarazzo, 2006; Mansfield and Schoeman, 2010; Seccatore et al., 2011; Cardu, Dompieri, and Seccatore., 2012; Dompieri et al., 2012). Results from existing models for predicting the fragment size distribution of the blasted muckpile correlate well with size analyses by sieving. To mention a few, the KUZ-RAM (Cunningham 1983, 2005), the SWEBREC (Ouctherlony et al., 2006), among other studies (Ryu et al., 2009). Recently, the concept of the fragmentation-energy fan was introduced (Ouchterlony, Sanchidrián, and Moser, 2017), where percentiles of the particle size distribution (fragmentation) and the specific charges (energy), when plotted on a log-log graph, fit well in a fan fashion where straight lines tend to converge to a focal point (fan).

Studies on the effects of blast-induced microfractures on grindability are not so common. Nielsen and Kristiansen (1996) pioneered research on this topic: by means of microscopic analysis and laboratory tests they showed that increasing the powder factor (PF) significantly reduces the Bond Work Index (WI: Bond, 1961) due to the presence of microfractures in the material. Seccatore (2019) reviewed the beneficial effects on comminution efficiency. The results of laboratory-scale blasting tests are shown in Figure 1. Table I shows the results obtained by various investigators at the industrial scale.

Katsabanis et al., (2004) performed small-scale tests by charging different configurations and then determined the WI in a ball mill. Their observations led to the conclusion that, in the granites they employed as research material, the effect of the explosive decreases at smaller particle sizes, and that it is not possible to induce microfracturing at a scale smaller than that the mineral grains. From what was previously reviewed, it is evident that the effects of microcracking depend strongly on the lithotype. In the present

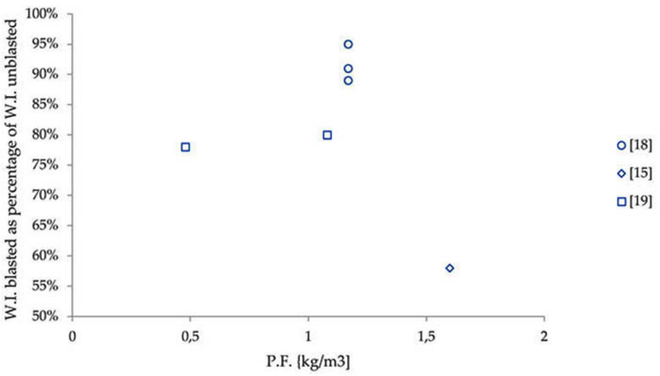

Figure 1—Effect of specific charge on the WI of blasted compared to intact rock

work we aim to investigate empirically the influence of different geometrical distributions of the charge on the grindability of the blasted material.

Materials and methods

The research was conducted at the experimental mine of the Research Center for Responsible Mining of the University of São Paulo. The lithology consists of white dolomitic marble with a medium to coarse grain size. The blocks for the blasting tests were collected from a single area of the mine. The geomechanical characterization included the tests reported in Table II. Five tests of each type were performed on each sample.

The linear relationship between UCS and IS is 15.5 for the coarse-grained marble and 26 for the medium-grained marble. For both materials the best equation for correlating R and UCS appears to be the one proposed by Kidybinski (1980): $\mathrm{UCS} = 0.447\ exp\ [0.045\ (R + 3.5) + \gamma]$.

Blasting tests

Small-scale blasts were performed on 14 marble blocks using different PFs and charge distributions. For every PF, the charges were designed to simulate concentrated and distributed geometries. In particular:

- Holes 6 mm in diameter and 60 mm deep were drilled in the blocks.
- Each hole was charged with a strand of detonating cord with a linear charge of 10 g/m, yielding a 6 g charge per hole.
- Each block was assigned a theoretical PF (PF_{th}). Adjusting the number of holes per block resulted in a PF (PFreal) as close as possible to PF_{th}, i.e. the design PF). Adjusting the geometry of the holes allowed us to simulate different charge distributions.

Two charge distributions were simulated:

Table I

Selected studies showing the effects of increased blasting energy on comminution

Blasting practice	Effects on comminution	Material	Type of test	Ref.
Shift from spherical charge to column charge	WI –10%	Granite	Small-scale	[20]
Drill and blast costs increased by 400%	Comminution costs –40%, Total production costs –36%	Marble	Small-scale + simulation	[21]
PF+240%, Specific priming (delays/t) +400%	Stops at primary crusher –9%, Electricity consumption at primary crusher –27%– Total production costs –3–4%	Marble	Full-scale + simulation	[22]
PF +40% (D&B costs +40%)	Mill throughput +6%, Grinding costs -19%	Gold ore	Full-scale	[23]
PF +42%	Excavator productivity +14% Crusher throughput +30% Grinding throughput +10%	Uncited	Full-scale	[24]
PF +25%	Mill energy -10%	Metal ore	Full-scale	[25]
PF +33%	Comminution energy at SAG mill -29%, total greenhouse emissions -20%	Gold ore	Full-scale	[26]
P.F. + 65%	SAG mill throughput + 14%	Gold ore	Full-scale	[26]

Table II

Geomechanical properties of marble test specimens

Lithology	Density (kg/m^3)	R (mm)	UCS (MPa)	IS (MPa)
Marble, coarse-grained	2.85	51	71.56	4.62
Marble, medium-grained	2.79	44	63.82	2.45

IS: Point load index. R: Schmidt's hammer rebound

- Concentrated charges simulating opencast blasts with large-diameter holes, with large burdens and spacings. An example is shown in Figure 2.
- Distributed charges simulating bench blasts with small-diameter holes and reduced burden and spacing. An example is shown in Figure 3.

Three control blocks were fragmented mechanically (by hand using a sledgehammer) for comparison of the results. The test blocks and charging characteristics are listed in Table III. All test blasts were conducted on a field to ensure safety.

Sieving and WI tests

The blasted material was analysed in two ways:

- ➤ Sieving tests, to evaluate macrofracturing (i.e. the particle size distribution)
- ➤ Work Index tests in a Bond ball mill, to evaluate microfracturing by establishing the grinding energy.

The material from each blasted block was first separated in a vibrating sieve column in a dry state. Material from blocks 2, 6, 15, and 16 was sent directly to comminution without sieving due to operational issues in the laboratory.

Figure 2—A block with drilling set out to simulate concentrated charges for PF_{th} = 0.3 kg/m^3

Figure 3—Ablock with drilling set out to simulate distributed charges for PF_{th} = 0.3 kg/m^3

Table III

Charging and characteristics of test blocks

Block no.	Theoretical PF	Charge distribution d = dispersed c = concentrated	Mass of block	Bulk volume m = measured e = estimated		Bulk density	Charge per block		No. of holes	Det cord length	Achieved PF
	PF_{th}		MB	V		r_{rock}	Q_{th}	Q real	n_h	Ldt	PF_{real}
	(kg/m^3)		(kg)	(dm^3)		(kg/m^3)	()			(cm)	(g/dm^3 = kg/m^3)
1	0.7	d	10.90	**3.85**	m	**2.83**	2.70	2.4	4	24	0.623
2	0.5	c	14.25	5.24	e	2.72	2.62	2.4	4	24	0.458
3	0.4	d	16.10	5.92	e	2.72	2.37	2.4	4	24	0.405
4	0.4	c	20.60	7.57	e	2.72	3.03	3	5	30	0.396
5	0.7	d	8.70	3.20	e	2.72	2.24	2.4	4	24	0.750
6	-	-	8.60	3.16	e	2.72	-	-	-	-	-
7	0.6	c	10.80	3.97	e	2.72	2.38	2.4	4	24	0.604
8	0.6	d	12.20	**4.35**	m	**2.80**	2.61	2.4	4	24	0.552
9	0.7	c	21.00	7.72	e	2.72	5.40	5.4	9	54	0.699
10	0.5	d	12.55	**4.5**	m	**2.79**	2.25	2.4	4	24	0.533
11	0.8	c	7.30	**2.5**	m	**2.92**	2.00	1.8	3	18	0.720
12	0.3	c	21.65	7.96	e	2.72	2.39	2.4	4	24	0.302
13	0.8	d	5.55	**2.25**	m	**2.47**	1.80	1.8	3	18	0.800
14	-	-	29.30	10.77	e	2.72	-	-	-	-	-
15	0.3	d	30.30	11.14	e	2.72	3.34	3.6	6	36	0.323
16	0.3	d	27.60	10.15	e	2.72	3.04	3	5	30	0.296
17	-	-	12.25	4.50	e	2.72	-	-	-	-	-

Results

Sieving results are reported in Figure 4 for blocks simulating concentrated charges and Figure 5 for blocks simulating distributed charges.

Concentrated charges led to a particle size distribution closer to the 'dust-and-boulders behaviour', as expected. Distributed charges led to a more uniform particle size distribution, especially as shown by the particle size curves for higher PFs. Figure 6 shows the variation of the passing diameters P80, P50, and P20 with increasing PF_{real}.

Distributed charges led to a steeper reduction in size for all the passing diameters. The high value of P80 and the increasing value of P20 for $PF_{th} = 0.8$ kg/m^3 with concentrated charges can be seen as another indication of the 'dust-and-boulders behaviour'. The results for $PF_{th} = 0.7$ kg/m^3 are outliers for all the distributions, both for concentrated and for distributed charges, being systematically higher.

After sieving, the material from every block (both blasted and fragmented mechanically) was crushed in three stages to obtain 100% passing 6#, then fed to the ball mill for the determination of the WI (Bond, 1961). Figure 7 shows the results and the correlation between WI and PF for concentrated and distributed charges.

It is evident that material blasted with distributed charges presents a steeper decrease of WI. This is in accordance with the steeper decrease of particle size seen in Figure 6. Again, as for the particle size analysis, material blasted with $PF_{th} = 0.7$ kg/m^3 stands out as an outlier. No valid explanation could be found for this behaviour, neither for theoretical reasons nor by looking at the execution of the experiments. A hypothesis is that the metamorphic nature of the marble at the experimental mine (see Figure 8) gave rise to a varying lithology, invisible to the naked eye. Samples collected within a few metres of each other might have different lithological characteristics (crystal shape and size, mineralogical composition).

Discussion

The results of this research confirm the general conclusions of previous work (Nielsen and Kristiansen, 1996;, Workman and Elloranta, 2003; Katsabanis et al., 2004, 2008; Elloranta, 2000, 2009): that increasing the specific charge increases the grindability of the

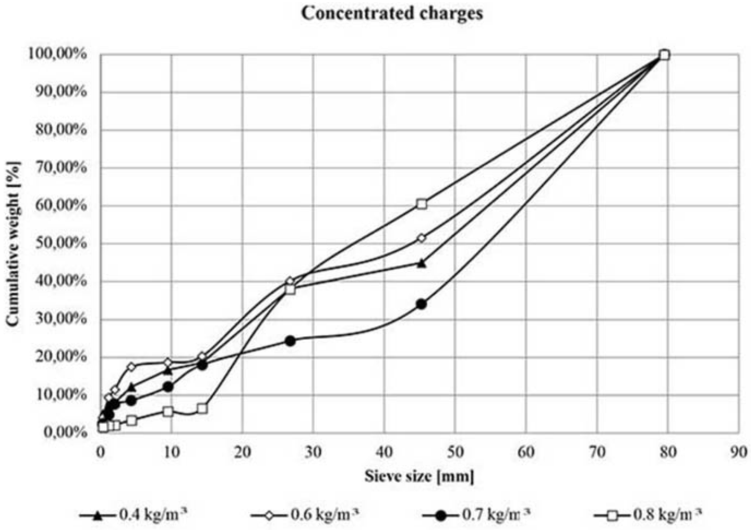

Figure 4—Sieving results for concentrated charges

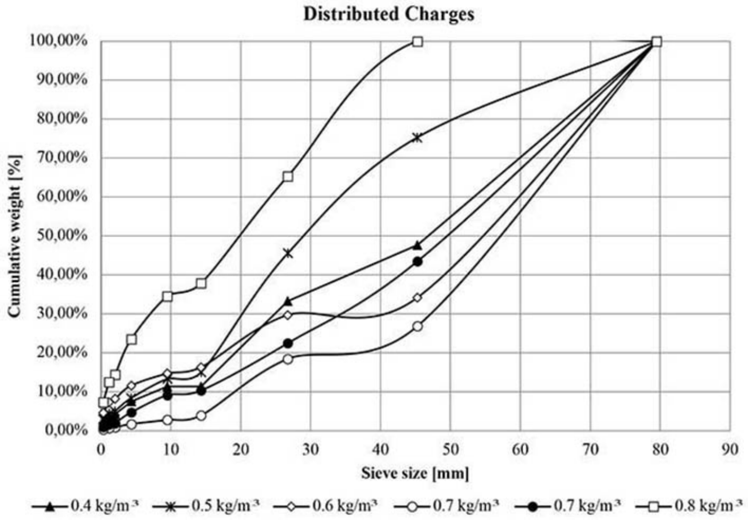

Figure 5—Sieving results for distributed charges

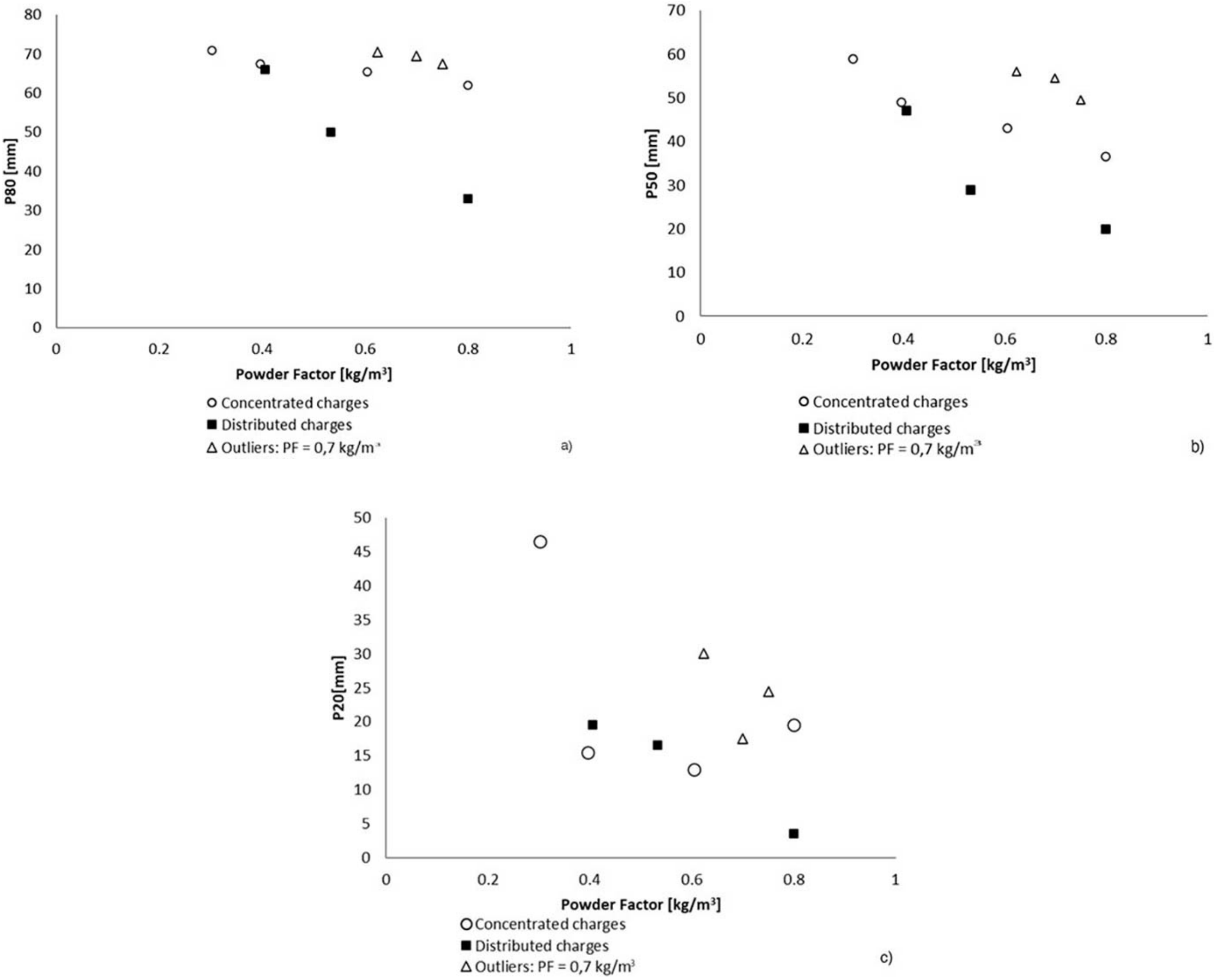

Figure 6—Variation of particle size with increasing blasting energy (powder factor) for different percentages passing (a) P80, (b) P50, (c) P20

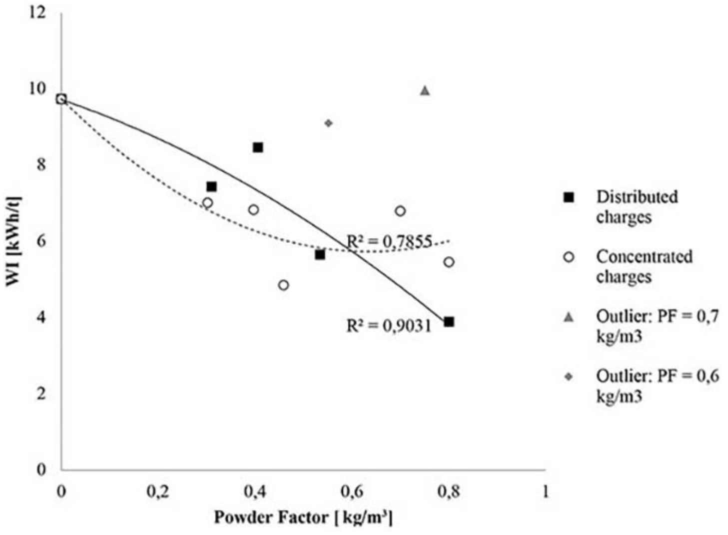

Figure 7—Variation of WI with increasing PF for distributed and concentrated charges. Continuous line: trend for distributed charges; dashed line: trend for concentrated charges. The two outliers were omitted from the regression calculations

Figure 8—The metamorphic environment where samples were collected, possibly a reason for the scattering in the data

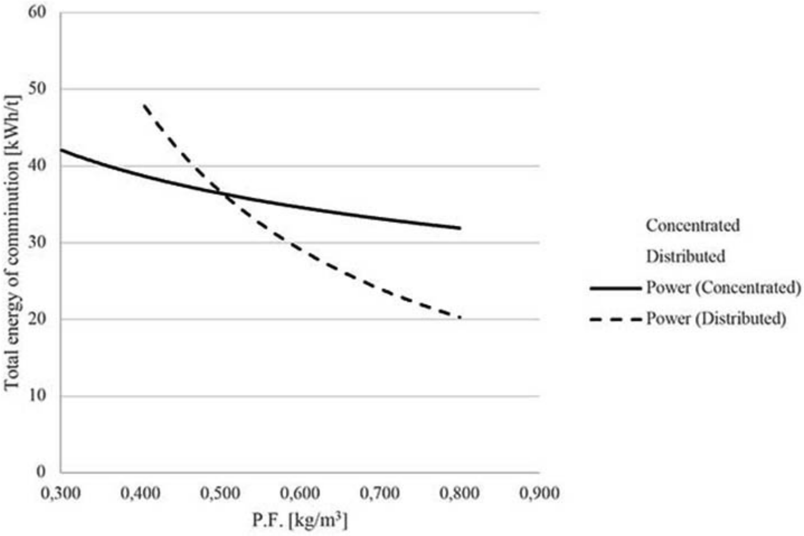

Figure 9— Simulation of Bond's law of total comminution energy

blasted material. This research went further and investigated not only the amount of explosive used, but also the influence of the geometrical distribution of the charges.

By creating macro- and microfractures- in the blasted naterial, small charges distributed as uniformly as possible yield better results than large charges concentrated in few areas. The advantages of distributing the charges in the rock are:

- The particle size is reduced more significantly with increasing PF
- The WI diminishes with a steeper curve with increasing PF.

Both these effects reduce the total energy required to grind the blasted material to the desired particle size. This can be seen by plotting a simulation of Bond's law of total comminution energy (Figure 9). We simulated Bond's law (Equation [1] using the specific WI and the feeding size (F80) corresponding to each charge as obtained during this research. The product size (P80) was deliberately chosen as 2 mm merely for the sake of the simulation. Results are shown in Figure 9.

$$W = WI\left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{F_{80}}}\right) \qquad [1]$$

The graphs show that at very low specific charges, concentrated charges are more favourable for comminution, but at realistic levels of PF for metalliferous and non-metalliferous mines (above 0.5 kg/m³) distributed charge make better use of the energy of the explosive.

Small charges well distributed transmit the explosive energy more uniformly to the rock, leading to better fragmentation and a higher density of microfractures. From an operational point of view, it appears that achieving the PF with small hole diameters and a denser drilling mesh leads to significant benefits for energy consumption during comminution.

Further research is required to address other important issues. Future work is planned to investigate the following aspects.

- The influence of the lithotype. As said, the geology of the experimental mine is highly metamorphic, and material with different lithological characteristics is encountered within the same macro-scale environment.
- The influence of timing between the holes. The present work employed exclusively simultaneous charges.
- The influence of the characteristics of the explosive. Explosives other than PETN will be tested. The VOD of the explosive, in particular, is expected to influence the results.

- The scale effect. Full-scale test blasts will be performed. The influence of discontinuities in the rock mass, especially in a metamorphic environment, must be thoroughly investigated. The scale effect will also be applied to the grinding process: energy consumption will be analysed both in the laboratory and in full-scale tests at the processing plant.

Conclusions

The influence of the geometrical distribution of explosive charges on comminution energy was investigated by means of small-scale blasts on marble blocks using different specific charges and charge distributions to simulate both opencast blasts (large-diameter holes, with large burdens and spacings) and bench blasts (small-diameter holes and reduced burden and spacing). The blasted material was analysed in terms of the particle size distribution and the WI. The results obtained are preliminary, but suggest the following.

- Concentrated charges result in a particle size distribution closer to the 'dust-and-boulders behaviour'. Distributed charges lyield a more uniform particle size distribution.
- With increasing specific charge, distributed charges result in a greater reduction in particle size than concentrated charges.
- Material blasted with distributed charges presents a steeper decrease of WI with increasing specific charge.

Small charges with a distributed geometry transmit the explosive energy more uniformly to the rock, leading to better fragmentation and increased generation of microfractures. This reduces the total energy required to grind the blasted material to the desired particle size. These results suggest that for any given powder factor, reducing the drilling diameter and increasing the drilling density will benefit the comminution process.

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Conflicts of interest

The authors declare no conflict of interest.

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